Particles and Health: Environmental Forensic Analysis

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Introduction

Cloistered away in the depths of my laboratory or moving carefully and quietly, collecting samples at the "scene of the crime" I have been analyzing environmental particles for nearly forty years. The wonder I experienced in the beginning as I learned about the significance that a particle could have is solving a mystery has never left me. This text is a distillation of what I have learned as it applies to indoor environments. It is necessarily brief and is intended to be practical. The intimate behavior of particles, the physics of particle interaction with surfaces and fluids, is presented only to demonstrate the importance of sample location, sample type, and sampling technique. Much of what is presented here may be contrary to accepted practice but that, I suppose, should be expected. Much of my time has been spent protecting billion dollar projects and sophisticated hardware, things far more important than people. My success was measured in hardware saved, cost avoided, and productivity improved. Every project was different and the solutions were project specific. Over the years I have been able to apply these techniques to urban air problems, household dust problems, health complaints in offices, school classrooms, laboratories, and even yurts[1]. The results have been very successful as measured by problems going away when the agent identified as responsible was removed and the problem reoccurring when the responsible agent reappeared. Lets begin as I began early in my career, at a crime scene.

Why Particles are Important

A murder has been committed. No one witnessed the crime but the victim is unequivocal evidence that a crime was committed. A fundamental principle of criminalistics is that the events leading up to the crime, the events during the crime, and the participants in the crime are recorded in the particles at the scene and the particles on the clothing worn by the perpetrator [2,3]. The criminalist begins by documenting the scene, photographing the scene with close-ups of any evidence that will be collected later. Detectives are interviewing any witnesses of unusual events that may have occurred around the estimated time of the crime. The criminalist takes notes to augment the photographic documentation. The evidence and all of the supporting documentation is used by the criminalist to determine what happened, when it happened, where the victim and the perpetrator had been recently, and who did what. It's all in the particles.

"When two objects come into contact, there is always a transfer of material from each object to the other. Often, this transfer is obvious, at least in one direction, but even when the amount of material transferred, or its nature is such that nothing is visible, there is always some transfer".

Figure 1.1: Locard's Law of Contact

An environmentally induced health complaint is similar. The exposure is recorded in the particles at the scene. The primary suspect is the air in the environment at the time of the

complaint. Every surface in the environment that has not been cleaned since the event has had some contact with the suspect air. The air in the environment is not a single entity, but rather a blend of air volumes from different sources. The air volume responsible for the complaint may or may not still be present but Locard's Law of Contact is still applicable. The investigation begins with an interview just as in the case of the crime scene. The interview establishes what is alleged to have happened, where it happened, and when it happened. Next the scene is documented, a sampling plan is made, and the samples are collected. The analysis is expected to determine if there was an agent present at the location and the time that could produce the effects reported. But how much effort do we put into the solution of this problem? Certainly a murder is orders of magnitude more serious than a health complaint. That does not mean that we don't want the correct answer. It just means that we can not justify the same level of expenditure in time, facilities, and effort. How do we maximize return on investment? What level of resource allocation and expenditure is justified? What evidence is still available after the fact? It's all in the particles. Does that mean that every problem is a particle problem? No, but every air volume that traveled through that space leaves a signature of particles. Knowing the air volumes that have been present and the contaminants they carry is an essential key to solving the problem.

The concept of an "air volume" is a model used to track particles from sources to receptors, either hardware or people. Particles often travel through the air. The volume of air into which the particle was injected has carried the particle to its new location. In a sense the air at any given location can be considered as a blend of air volumes from many different sources. Each air volume is identified by the particles it carries with it from its source. The questions then becomes, which air volumes were present at the time of the complaint.

Not every investigation begins with a health complaint. There are three basic reasons for analyzing either the indoor or the outdoor environment. The first is to determining if health problems may be attributable to the environment. The second is to determining if the environment may affect the health of the people who are exposed to it. The third is largely cosmetic, determining where all the dust is coming from. In each of these cases, it's all in the particles.

1. **Is the environment causing my health problems?**
2. **Will the environment cause future health problems?**
3. **Where is all of the dust coming from?**

Figure 1.2: Reasons for Indoor Environmental Investigations

In each case we start with the interview, a subjective interpretation of the events and conditions resulting in the concern. If we are fortunate we may have some reliable medical data in the case of a health complaint (not "it must be mold!" in the Doctor's opinion). The second step is to evaluate the scene of the crime; is it clean, is it well ventilated, is there obvious water damage, are there a number of potted plants in the area, etc. Ultimately we come to the point of deciding what samples to collect and how and

where to collect them. The subject of this seminar is how the forensic analysis of particles in an environment can help us answer the question of the relationship between the environment and the issue or issues of concern.

Particles as Evidence

Particles bear the fingerprints of the air volumes (suspects in the crime) that have impacted the scene. Any given location is visited by volumes of air and their associated particles from many locations. There is the volume of air created by the people in the space and their activities. This air is humid, warm, carbon dioxide enriched, air that is loaded with skin flakes, clothing fiber, cosmetics, shoe wear, the dog and cat dander from home, the cigarette smoke from that last cigarette, and the food debris from lunch. It is also the volume of air that carries the particles created by the activities in that space, paper fiber, ink, paper sizing, pencil debris, copy machine toner, ink jet printer ink, welding debris, painting debris, etc. A second and third volume of air is that which comes through open doors, open windows, the "fresh" air ventilation to the space. The natural part of that air volume carries the natural background particles, pollen, mold spores, natural minerals, soils, humus, plant parts, insect parts, etc. The anthropogenic part of that air volume contains tire wear and other vehicle emissions, industrial fugitive emissions, smoke from fireplaces, flyash from power plants, etc. The final volume of air to be considered is that generated by the facility, the building itself, as it stabilizes after construction or remodeling, as it ages and corrodes, as it expands and contracts, as it grows and releases new particles created in the ventilation system or through the action of water on construction materials, glass fiber, sawdust, plaster, paint spheres, efflorescence, mold, mites, rust, etc. Each air mass is labeled by the particles it contains. The history of this environment is all

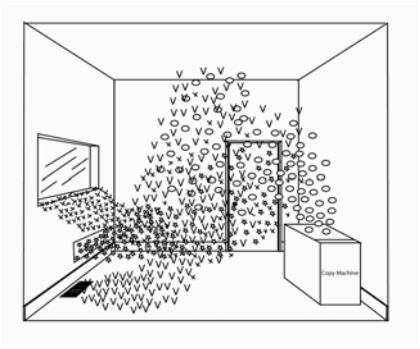
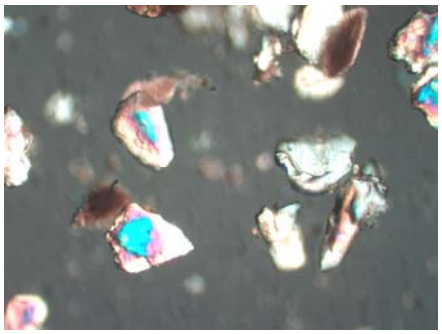


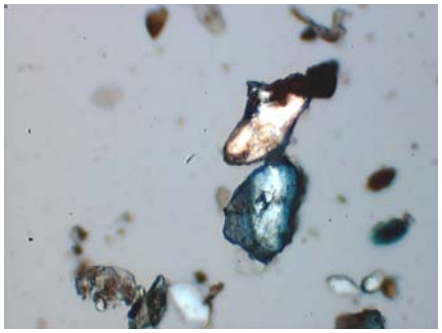
Figure 1.3: Air Volumes in an Indoor Space

The air volumes mix but may be distinguished by the unique compliment of particles each contains.

1. **People and Activity Air**
2. **Outdoor Air, Natural**
3. **Outdoor Air, Anthropogenic**
4. **Building and Ventilation System Air**



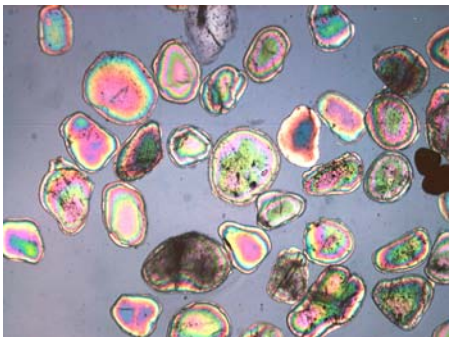
Photograph 1.1: Freshly Formed Grains of Quartz



Photograph 1.2: Weathered Quartz Grains from a River

in the particles.

There is far more information in a particle than its name, its size, its elemental composition, its crystal structure, its shape, its color, etc. Each particle is an entire file of information just waiting to be read. Particles are marked by when they were created. Freshly formed mineral grains have jagged, sharp edges and sharp projections on their surfaces. Photograph 1.1 is freshly ground quartz. The thin, sharp edges and points are evident in these particles. Surfaces "weather", or age, with time and become more rounded as they are exposed to the environment. In Photograph 1.2 quartz grains that have traveled down to the river are shown. These grains are clearly more rounded and most of the sharp points are absent. Over time the surface of the particles have been modified by exposure to reactive gases such as nitrogen oxides, sulfur oxides, carbon dioxide, moisture, and ozone and by microbial activity. Clays and other minerals adhere to the surfaces of the grains. The dark brown deposits on these grains are adhering clays from the environment and the lighter orange deposits are iron hydroxide films formed by bacteria on the surface. Ultimately, the grains become cemented into an agglomerated grain or become completely round, losing all sharp edges (see Photograph 1.3). Biological particles loose "vitality". Interior components can often be seen to have degraded with time. Particles are also marked by the transport mechanisms that brought them to this locality. Large particles suggest mechanical transport on shoes or clothing. Small particles suggest distance. Just as at a crime scene, things that aren't generated in the local environment must have come from another source. The identity of the particles indicates the source and their size indicates their method of transport. Many sources are not identified by a unique particle but rather by a set of particles called an assemblage. The analysis of assemblages will be presented in Chapter 2.



Photograph 1.3: Rounded Quartz Grains from an Ocean Beach

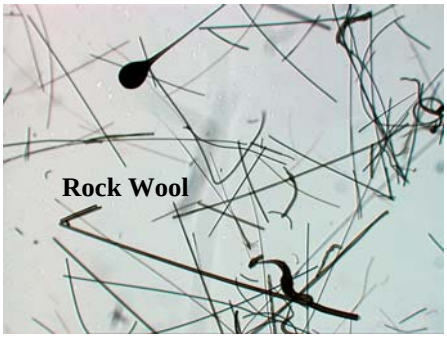
Figure 1.4: Particles are like Memory Chips full of Information

The question for the analyst is how much of the file for each particle does he or she need to read. This has a significant impact on the cost of the analysis and it depends on the questions to be answered. Reading the title of the file (particle identity) may be enough. Sometimes the number of files (particle quantification) is enough. If we need to

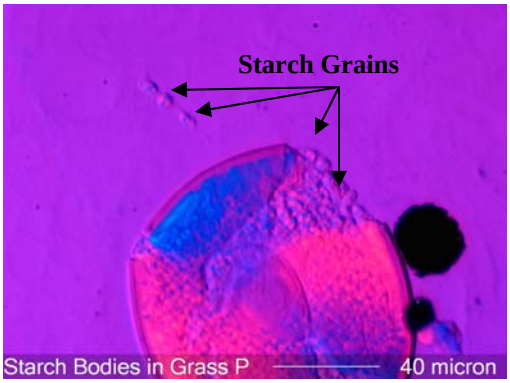
know where the particle came from we need to read further. Do we need to know its parents? Do we need to know where and when it was born? Do we need to know nearest relatives? A typical forensic particle analysis involves the observation of thousands, even tens of thousands of particles. We can't afford to read every file in detail. Once again to visit the analogy of the crime scene, the analyst and the detective need to work together. In our case the industrial hygienist or environmental specialist needs to provide some background information and some specific questions. The analyst can then assess the evidence for compliance to the background information and try to answer the questions posed[4]. Forensic particle analysis is not like asking how much lead is present in a sample. The answer to that question is a single number generated by an established protocol at a fairly minor expense. The forensic particle analyst can tell you the chemical form of the lead containing compound or compounds, how they were used, how they came to be in this environment, how old they are, and how they are behaving in the environment, if you want to know and are willing to pay for the information. You can't afford to have the analyst tell you everything about every particle. The more clearly the situation is described, the more succinct the questions to be resolved, the more detailed the report you will receive from the analyst for a fixed cost.

1. **Statement of the Problem**
2. **Symptoms**
3. **Sample Locations**
4. **Volume of Air Sampled and/or Number of Contacts to Surface with Tape and/or Square Units of Area Sampled**
5. **Modifying or Compromising Activities Since the Event of Concern**

Figure 1.5: The Forensic Particle Analyst Should be Provided -



Photograph 1.4: Particles Can Be the Active Agent



Photograph 1.5: Particles Can Carry the Active Agent

Photograph 1.6: And Particles That Are Active Agents Can Carry Other Active Agents

Particles can be the active agent such as rock wool glass fiber (see Photograph 1.4); a carrier for the active agent, such as starch granules released by a pollen grain[5,6] (see Photograph 1.5); or be associated with the active agent such as the numerous agents carried under the skin by a ventilation system glass fiber (see Photograph 1.6). Particles such as short glass fibers are irritants to the respiratory system by themselves. Long glass fibers are a surface irritant that can be responsible for contact dermatitis. But particles may also carry other agents that are active in causing health complaints. For example, particles can carry allergens that are not inherently associated with those particles[7,8,9,10]. Many active pollen grains are full of starch granules that seem to carry the active allergen for the pollen. When the pollen comes in contact with moisture it releases these starch grains that can attach themselves to other particles. These other particles then stimulate an allergic response. Long glass fibers may carry surface materials, that when inoculated under the skin, cause an increase the severity of the response.

To really understand the environment we must understand the particle populations in that environment with sufficient detail to answer all of the relevant questions. Understanding the particle populations means that we know their identity, how they were created, and how they got to the location where they were found in a quantity large enough to cause the response. The analyst must, at least in a small way, be a partner in the project to cost-effectively arrive at this goal.

Case Histories

The three case histories that follow show how simple biases or unsuspected hazards were detected by Forensic Particle Analysis. The first case history is one example of over fifteen similar schools that the author has been involved with in the last few years. All fifteen of these cases were reported as mold problems and have probably been included in that category in national statistics, but the real problems included glass fiber, mite infestations, poor ventilation, and accumulated dust. The second case history is an example of applying the results of an analysis in an inappropriate manner. Forensic Particle Analysis forced the correct interpretation. The third example is one of discovering an unsuspected hazard. Forensic Particle Analysis is both very specific in its ability to identify a hazard as well as being remarkably general in the types of hazards it can identify.

The Case of The Mold That Wasn't There

An elementary school located in a rural environment was having a problem in one classroom. The class in that room was studying the planets. The students had all made papier-mâché planets and the teacher hung the planets from the T-bar supporting the acoustic ceiling tile in the room. That was when the problems began. A consultant was called in who was also a mold remediator. A single spore of Stachybotrys was found in one of the many air samples collected. A second Stachybotrys spore was found in the outdoor sample but that was clearly contamination from the school building. It was decided that the spore must have come from the top of the ceiling tile since there was no evidence of water damage inside the school. The ceiling tile was removed in every

classroom and the back surface was thoroughly vacuumed. The tiles were then replaced. In the mean time walls were opened up looking for any mold growing inside the walls since there was no evidence outside the walls of any water damage. No mold was found.

The children were allowed back into their class rooms and shortly health problems were experience in every classroom. New air samples were taken and a Stachybotrys spore was found. The newspapers heard of the presence of the deadly mold problem and the school was evacuated. Parents formed a special committee to investigate the need to tear the school down and rebuild. The search of mold in the school was intensified. No mold was found until, finally, deep in a wall a small black patch of mold was found. It was Stachybotrys. It was at the far end of a separate wing of the school from the original problem classroom and was taken as another testimony to the human sensitivity to Stachybotrys. It had taken nearly three months and over seven hundred thousand dollars ($700,000.00) to solve the problem. The mold was removed and the school was opened once again. Again there were problems. The same type. Apparently mycotoxin from the Stachybotrys had permeated the building and was being slowly released back into the occupied space over time. The school was evacuated and it was clear that the building, only six years old, would have to be torn down and rebuilt. Another Consultant was called in for a second opinion. That consultant took air and tapelift samples throughout the school. A forensic particle analyst was asked to evaluate the samples. The samples were heavily loaded with glass fiber from acoustic ceiling tile. There was no evidence of a mold problem in the school. The school was thoroughly cleaned repeatedly and the teachers were told no objects of any kind could be hung from the ceiling in any way. Subsequent tapelift analysis indicated very low levels of glass fiber. The students were allowed back in school. Three teachers refused to return and were placed in other schools. The parents of ten of the children refused to let their children attend that school. The first day back there were two complaints, one each from two classrooms. It turned out to be the flu. There were no more problems at that school. The official report was that the mold had been successfully removed from the school and some other particle problems had also been resolved.

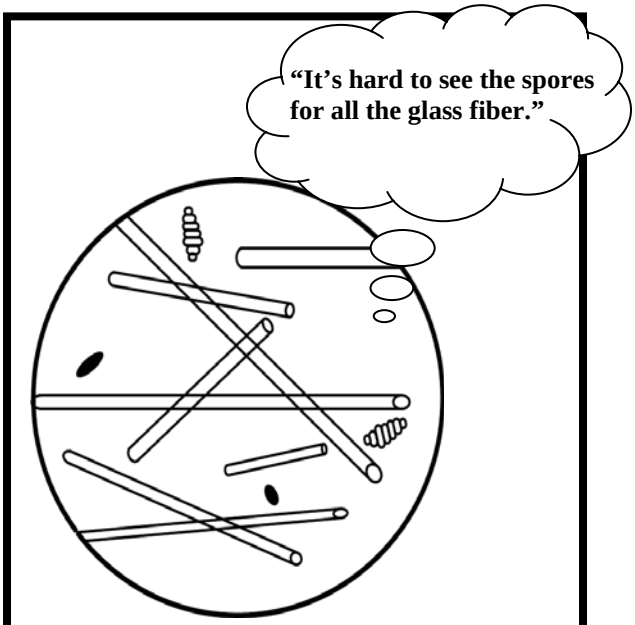


Figure 1.6: Case History One Glass Fibers and Spores

Although the original samples had been destroyed and so were not available for confirmation the pattern is a common one in schools with acoustic ceiling tile. Glass

fiber from acoustic ceiling tile or from ventilation systems is a commonly overlooked source of health complaints in schools and office buildings.

The Case of The Chrome Plated Bridge

A residential neighborhood in the shadow of a large municipal bridge complained of the paint dust and grit falling out from a project to upgrade and repaint the old bridge. Air samples were collected and sent out for analysis to determine if there was any hazard to the occupants in the neighborhood. The sample was digested in nitric acid and analyzed for heavy metals. The only metal of any concern was chrome, which was present at 0.5 milligrams per cubic meter. The personal exposure limit (PEL) was 1 milligram per cubic meter so the residents were assured that there was no hazard. A forensic particle analyst was presented with an air sample from the neighborhood and determined that the chrome present was a hexavalent form used as a paint pigment. The bridge was indeed painted and not chrome plated. The exposure limit for hexavalent chrome was 0.001 milligrams per cubic meter.

Figure 1.7: Case History Two
The Chrome Plated Bridge

The Case of The Asbestos Driveway

Air and tapelifts from a home in which some individuals were have respiratory problems were submitted for analysis. The dust loading alone in this home was at a level often associated with health complaints, but there was another finding of interest. Both air and tapelift samples collected indoors contained chrysotile and actinolite asbestos fibers. Air samples collected outdoors also contained chrysotile and actinolite fibers. The home owner had recently collected sand from an old local quarry and used it to cover his driveway. Analysis of a sample of the sand identified grains of both chrysotile and actinolite. The home and the driveway were remediated. The cleaning brought the airborne particle loading under control and the health complaints ceased. The asbestos fiber in the environment would not have been discovered were it not for the fact that the samples were analyzed by a forensic particle analyst. There are many areas in North America where this scenario could be playing out. It will only be discovered if

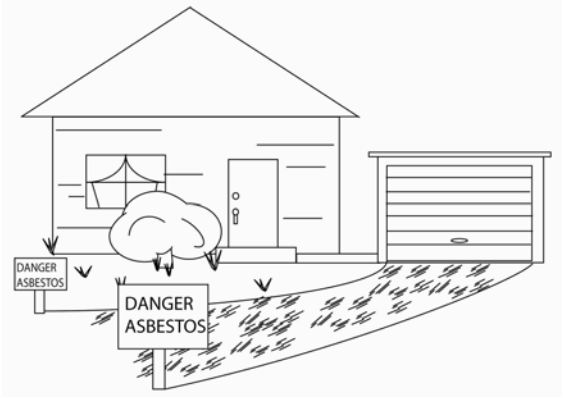


Figure 1.8: Case History Three
The Asbestos Driveway

there is another problem in the building because the harm done by asbestos exposure would not be noticed for years.

In each of these cases the forensic analysis of airborne or settled dusts was crucial to identifying the hazard. Forensic particle analysis would have saved hundreds of thousands of dollars in the case of the school with the "mold" problem. These are just a few of the hundreds of cases where the problem in the environment required forensic particle analysis for resolution. A mold lab identifies mold. An allergy lab identifies a few specific allergens out of the hundreds in the environment. The mold lab may be a more reliable source for information on the genus and certainly for the species of a mold. The allergy lab will do a better job quantifying the allergen specified in the sample but will not detect any of the hundreds of allergens not specified. A forensic particle lab will identify all those particles that are relevant to the symptoms being experienced and more. The analysis is more expensive but the amount of information gained can be well worth the added expense. It doesn't replace the mold lab or the allergen lab but will identify problems those labs can't see and will also identify mold and allergen problems as part of the analysis. The next chapter will address the problem of reducing thousands of individual variables to a few manageable variables relevant to indoor air quality problems.

Questions:

1. What is Locard's Law of Contact and how does it apply?
2. What are three basic reasons for conducting an indoor air quality investigation?
3. How may the air in a room be partitioned with respect to the particles carried?
4. How are particles like memory chips?
5. What information should be provide to the forensic particle analyst and why?
6. How may particles affect health directly and indirectly?

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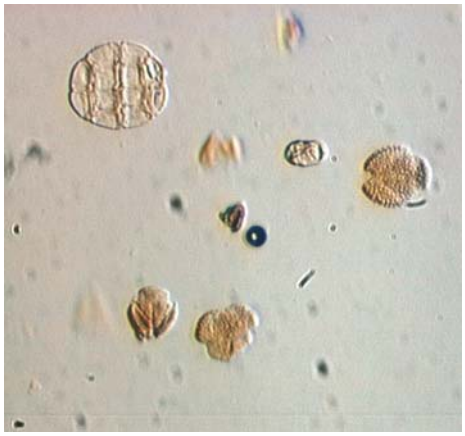
CHAPTER 2: ASSEMBLAGE ANALYSIS

Introduction

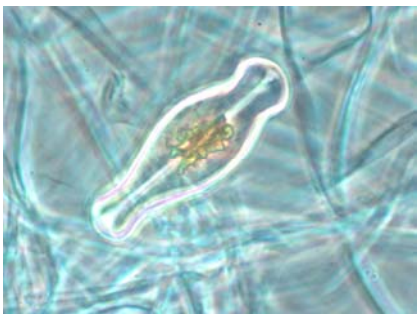
A hand full of dirt is an assemblage of particles. If this hand full of dirt is from an archeological site it might be full of important information. What was the weather like thousands of years ago at this location? The pollens mixed in the dirt will identify the plants that grew in this area. By identifying the plants and analyzing their current range the climate at that ancient site can be described in great detail. The average temperature, the amount of rainfall, the pattern of precipitation, the high temperature, the low temperature, the number of frost-free days, the amount of sunshine in the summer, and other characteristics can all be determined by the assemblage of pollen grains.[1] There are also diatoms in the dirt. What was the quality of the water available at the site? Diatoms will help with that.[2] What was the degree of technology at this site? Rare particles of furnace slag, copper ore, and prills of copper indicate copper smelting.[3] Small, sharp flakes of flint indicate the use of stone tools.[4] Fragments of bone, feather barbules, and fragments of plant matter indicate diet, animal husbandry, and agriculture.[5] This hand full of dirt is in reality a picture of a society that lived at this location thousands of years ago. Each collection or assemblage of particle types reveals something about the site. This type of analysis is called ASSEMBLAGE ANALYSIS.

Photograph 2.1: An Assemblage of Particles

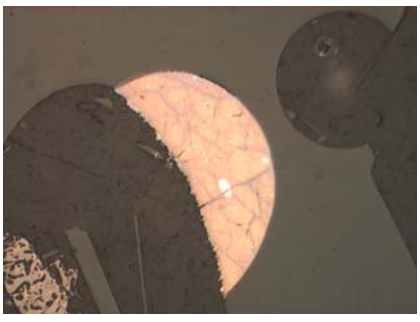


Photograph 2.2: Pollen Assemblage

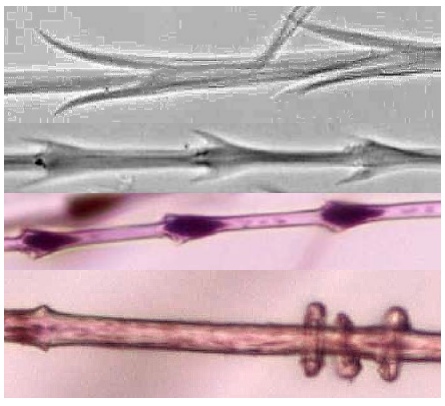
Assemblage analysis is based on the concept of "contextual assemblages". A contextual assemblage is defined as a group of objects or features that in combination establish a fact or context not established by any individual feature or object. For convenience this phrase is typically referred to as simply an



Photograph 2.3: Diatom in Water Quality Assessment



Photograph 2.4: Copper Prill in Smelter Furnace Slag



Photograph 2.5: Feather Barbules Chicken, Parakeet, Finch, Pheasant

Assemblage with the understanding that the objects or features are related in some specific manner. The examples given above indicate some of the useful assemblages that may be available in a sample. The first contextual relationship is a very important one: that they are all part of the same handful of dirt. This "super assemblage" allows us to relate all of the information generated by the other, more restrictive assemblages. Examining all of the more restrictive assemblages at a site results in a detailed characterization of that site. There is an assumption built into this analysis even at this very fundamental level. The assumption is that the objects assigned to the assemblage actually belong to the assemblage in the way we are inferring. More on this issue later.

There are two basic types of assemblages, monotypic and polytypic. A monotypic assemblage is established based on particles that are all of the same type and are generated by the same process but that differ slightly in ways that reveals useful information. Pollens,[6,7] diatoms,[8] phytoliths,[5,9] and sand grains in sediments or sandstones[10] are examples of different monotypic assemblages. Table 2.1 illustrates some of the data that is present in common monotypic assemblages. Monotypic assemblages are widely used in sedimentology, paleoclimatology, paleontology, and in archeology. The goal of a monotypic assemblage analysis is to characterize conditions at the site. The pollen assemblage in an indoor environment can reveal the contribution of exterior particles to the indoor particle loading and the residence time of particles in the environment.

Members Present	Feature of Interest	Inference
Pollens	Blooming Season Varieties Present	Time of Deposition/Time of Residence Climate at the Site
Sand Grains	Degree of Roundness Size Distribution	Geography of the Particle Source Characterization of Sedimentary Process
Diatoms	Varieties Present	Water Quality, Condition, Temperature

TABLE 2.1: Monotypic Assemblage Analysis Characterizes the Site

A polytypic assemblage is based on the set of particles that have a source in common though individual members of that assemblage may have more than one source. Cement plants, smelters, highways, lumber mills, construction, and coal fired power plants are examples of sources generating polytypic assemblages. Table 2.2 illustrates how a collection of particles from indoors

Photograph 2.6: Acoustic Ceiling Tile

Photograph 2.7: Particle from Acoustic Ceiling

may be attributed to different sources. Consider the first source, the acoustic ceiling tile. One type of acoustic ceiling tile is composed of glass fiber, paper fiber (bleached wood pulp), perolite, epoxy binder, and small particles of calcite. Vibration in the T-bar can abrade the edge of the tile, which generates small particles of glass fiber with adhering colorless, clear epoxy containing small calcite particles; paper fiber with the same calcite filed epoxy; perolite flakes and fragments; epoxy fragments; and other mixtures of these components. When collections of these particles are seen in a sample then the probable source is the acoustic ceiling tile. Polytypic assemblages are used in receptor source apportionment (identifying distant sources that impact a specific site),[11,12] criminalistics,[13,14] and archeology[15]. The goal in a polytypic assemblage analysis is to identify the sources of the particles affecting the site rather than to characterize the site.

Members Present	Assemblage Members	Source Inferred
1. Glass fiber with Calcite filled Epoxy, 2. Paper Fiber with Calcite filled Epoxy, 3. Glass Fiber (Similar Optical Properties), 4. Human Skin Flakes' 5. Paper fiber, 6. Blue Nylon, 7. Blue Orlon, 8. Blue Cotton, 9. Ink, 10. Quartz,	1, 2, 3, 5, 11	Acoustic Ceiling Tile
11. Calcite,	11, 16, 18, 19, 20	Construction/Remodeling
12. Black Rubber Wear (short irregular) 13. Charred Hardwood, 14. Soot, 15. Iron-based Wear Metals, 16. Wood Sawdust, 17. Cenospheres, 18. Magnetite Spheres, 19. Plaster, 20. Paint Spheres, 21. Pollens, 22. Insect Parts 23. Fungal Spores, 24. Moss Spores,	10, 12, 14, 15, 17, 18	Road Debris
25. Charred Softwood Etcetera (hundreds more)	13, 14, 25	Fireplaces

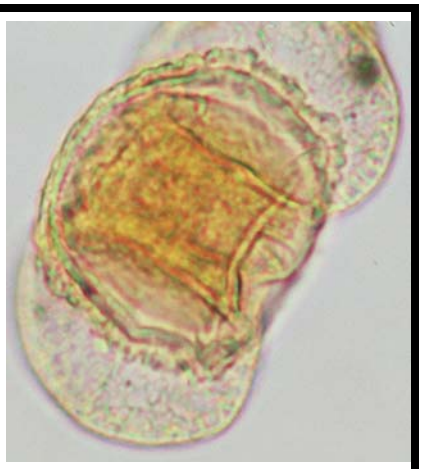
TABLE 2.2: Polytypic Assemblage Analysis Identifies the Sources for Particles at the Site

Both types of assemblages, monotypic and polytypic, are used in the characterization of sites occupied by humans[5,15] and for identifying the sources of contaminants in clean

rooms[16], instruments, and machinery[17]. Assemblages can also be used in a much less diagnostic way. Broad source categories can be used as "Super Assemblages". An example of a super assemblage would be all of the particle types that come from outside a building. There are four super assemblages that are useful in characterizing an indoor environment. These super assemblages can then be reduced to specific assemblages as required to answer the questions relevant to the concerns in each specific case. Before examining the super assemblages lets consider the strengths and weaknesses of the two main types of assemblage analysis based on particles.

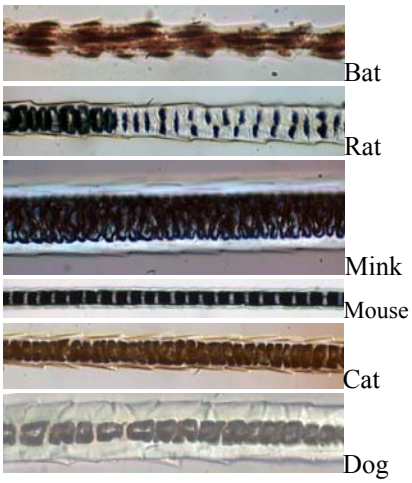
Monotypic Assemblage Analysis

Monotypic assemblage analysis begins with particles that are known to belong to the assemblage. It is generally assumed that the assemblage has a well defined source. In most cases this assumption is true but alternative assumptions should be considered for members that are outliers or rare members. Each member has a number of attributes that may be relevant for our analysis. Let's consider pollens as an example. Pollens are only produced during a relatively short time in the life of a flower. The interval of time over which a plant may produce flowers varies from species to species and from region to region for the same species. Some plants produce flowers for only a brief interval while others may bloom over a period of months. The plants that bloom for a brief interval tend to be prolific producers of pollen. Members of the Pine family (see Photograph 2.8) and Birch Family produce so much pollen that the edges of ponds will be ringed with a thick, bright yellow line of billions of pollen grains. Other plants produce relatively little pollen. Some pollen grains are designed for airborne dispersal and others rely on insect dispersal alone. All of this information is available to the analyst when the pollens in a sample are identified.



Photograph 2.8: Pine Pollen

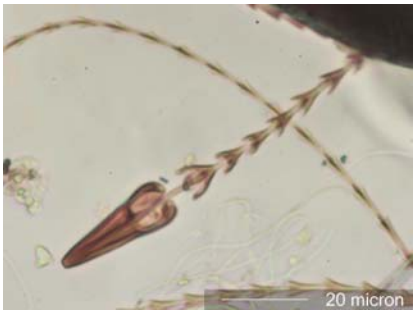
Fungal spores, fern spores, moss spores, hair, feather barbules, insect parts, minerals, glass fibers, skin flakes, clothing fiber, etc. are not particle identifications but rather identifications of individual monotypic assemblages. In any given indoor sample the number of discrete, different members belonging to each assemblage may range from three or four to hundreds of members. Human hair, cat hair, dog hair, sheep hair (wool), mouse hair, rat hair, ferret hair, hamster hair, mink hair, bat hair, fox hair, squirrel hair, etc. may be found in a sample of settled dust in a home. The presence of hair from people and pets or clothing is not as alarming as rodent hair (see Photograph 2.9). Similarly, bird feather barbules (see Photograph 2.5) from chickens, ducks, and geese used as feather padding in clothing



Photograph 2.9: Some Hairs Seen in Settled Indoor Dust

and furniture in a home or from a parakeet pet are of little concern while feather barbules from starlings, pigeons, and other wild birds may indicate an attic infestation. Insect parts may be from rather innocuous species, such as moth wing scales, or from more bothersome species, such as cockroach or carpet beetle. Mite parts may be from some of the hundred plus mite species that can live in a home[18] or from some of the thousands of mite species that live outdoors as plant pests.

Monotypic particle assemblages are common and can reveal important information about an environment, but the specific identification of individual members can be complex. Only those members of the monotypic assemblages that are relevant to the problem at the site can be characterized in detail and still control the cost of the analysis. Some members of some assemblages will automatically trigger a more detailed study of the assemblage. A rodent hair will trigger a check for cat or dog hair[19] that may indicate the presence of a pet that could be a transport mechanism (vector) for bringing rodent hair from outside to the inside. Members of assemblages can be identified without the need of an analysis of the assemblage. The presence of the distinctive hairs of the Demisted beetle larvae (see Photograph 2.10) will not trigger a detailed analysis of the insect part assemblage. On the other hand, the detection of a plant parasite mite part will make the analysis for the presence of mites living in the home more difficult. Mite parts that are not sufficiently distinctive, such as individual setae (mite hair), can not be attributed to one of the species commonly found in homes. The more diagnostic mite parts must be examined more carefully in assessing the potential impact on a person at this site. An allergen test may be useful but the common commercial tests available detect only two mite species out of at least eight household mite species that are known to trigger allergic responses in people[20,21].



Photograph 2.10: Carpet Beetle Larvae Hair

Recognizing monotypic assemblages in a collection of particles is critical to understanding the amount of information available in a sample. In any given sample there may be only one or two monotypic assemblages that need to be analyzed in detail. Which ones need further analysis will vary from sample to sample and will vary depending upon the symptoms exhibited or the questions to be answered.

Polytypic Assemblage Analysis

Polytypic assemblage analysis begins with a variety of particles identified, which then suggests assemblages from likely sources; or with a list of likely sources and a search for the expected particles that would be part of the assemblage for each one of those sources. Sources indicate the types of assemblages that should be present. The expression of the assemblage from that source will be modified by distance and obstacles in the path (filters) between the source and the

Sources imply Assemblages

Assemblages suggest Sources

Figure 2.1: Sources and Assemblages

sample site. Heavier particles will settle out more quickly than lighter particles. Particles with high surface area to volume ratios will tend to stay airborne longer than spheres of the same material. We will examine these issues a little more closely in chapter 3.

Assemblages suggest sources. It is possible to construct an assemblage for one source out of the members that actually come from multiple other sources. For example, a coal fired power plant may be suggested by the particles present. Flyash from all the expected mineral impurities common in coal are present[22]. Fully fused iron oxide indicates efficient combustion and elevated temperatures. Fugitive powdered coal is present. Some of the flyash shows reaction products with sulfuric acid, which is created in the plume as a result of the combustion of iron sulfide impurities. The probability that a coal fired power plant is the source for these particles seems high, but when an inquiry is made no coal fired power plant is present. There is a coal shipping terminal five miles away, a hog-fuel boiler nearby, and a heavy equipment maintenance facility with high speed grinding, welding, and metal cutting activities. These three sources produce particles as part of their assemblages that could be combined to produce particles as part of their assemblages that could be combined to produce an assemblage consistent with a coal fired power plant. Figure 2.3 illustrates the relationship between the particles seen in a sample and typical particle assemblages from these various sources. These are not complete lists of the particles from each source and the remaining particles in the assemblages from the other three sources would be problematic or lead to the other suggested assemblages.

Assemblage		Particle Types
Coal Fired Power Plant Assemblage	has	Particles a, b, c, d
Maintenance Yard Assemblage	has	Particles b, e, f, g, h
Coal Transfer Station Assemblage	has	Properties c, h, i
Hog-Fuel Boiler Assemblage	has	Properties a, d, i, j, k

Particle Types: a: Flyash (Glassy Spheres from Minerals)
b: Fused Iron Oxide Spheres
c: Powdered Coal
d: Sulfate Reaction Products
e: Weld Slag
f: Abrasives
g: Grinding Debris (Surface Oxidized Metal)
h: Wear Metal (Scuffing Wear)
i: Large Cenospheres
j: Small Cenospheres
k: Charred Wood

Figure 2.2: Relationship between Particles Assemblages, and Sources

Given sufficient budget (open budget) all of these sources could probably be correctly identified based on the particles in the samples, but had the analyst been informed of the local sources the particles could have been quickly assigned to the proper assemblages. This is not a hit or miss type of guessing game. It is instead a form of statistical modeling called Bayesian Statistical Analysis. This form of statistical analysis is the basis for all criminal cases in which physical evidence or circumstantial evidence is used to convict a

defendant. Bayesian statistical analysis is considered powerful enough to condemn a person to death for the perpetration of a crime.[13]

Polytypic assemblage analysis is based on the known facts and the probability of specific events given those facts. In forensic particle analysis the "facts" are particles and the "specific events" are sources. Mathematically stated the expression is:

$$O(J \mid I) = O(J)\{[P(I \mid J)]/[P(I \mid \text{not } J)]\}$$

In our earlier example this expression can be verbalized as 'the odds of a coal fired power plant, source J, being present given the particle assemblage, I (written as $O(J \mid I)$), is equal to the odds of a coal fired power plant being present in any given location ($O(J)$) times the probability of a coal fired power plant particle assemblage being present when a coal fired power plant is present ($[P(I \mid J)]$) divided by the probability of a coal fired power plant particle assemblage being present when there is no coal fired power plant present ($[P(I \mid \text{not } J)]$). The odds of a coal fired power plant being present ($O(J)$) depends on the region of the country where the sample was collected. The East Coast of the United States has a much higher population of coal fired power plants than the West Coast. Urban centers have more than rural areas as a rule, though the Four Corners Power Plant and a few others are exceptions to that rule. The probability of a coal fired power plant particle assemblage being present if a coal fired power plant is present ($[P(I \mid J)]$) is essentially 1. As we have seen, the probability of a coal fired power plant particle assemblage being present in the absence of a coal fired power plant ($[P(I \mid \text{not } J)]$) is a finite though small number requiring the correct combination of other sources at appropriate distances. Bayesian statistics would place a single source for the assemblage as more likely than three or four contributing sources in the absence of information on sources.

Providing a little more information to the analyst can significantly improve the value of the confidence in the conclusions based on the polytypic assemblage analysis. Notice that the particles identified have not changed. Only the conclusion on how those particles are associated has changed. This type of analysis is most powerful when the environmental investigator works with the analyst. The environmental investigator has not seen the particles and so can not determine if the particles could, with reasonable probability, be part of a given assemblage. The forensic particle analyst has not seen the site in order to properly assign a value to the ($I \mid$ not-J) term. The ($I \mid$ not-J) term is actually the probability of features a, b, c, and d in Figure 2.3 being present together given sources $k_1, k_2, \ldots, k_i, k_{(i+1)}, \ldots, k_j$ are represented at the sample site and that none of them are a coal fired power plant. The contribution from each source of the features a, b, c, and d are summed and the feature with the lowest representation would establish the value of the term ($I \mid$ not-J). This term could then be further reduced by identifying other particles that would constitute an assemblage requiring that most limited feature in the coal fired power plant assemblage. We will now see how to minimize the incorrect allocation of a feature to an assemblage, first through the use of super assemblages, and then through the process of evaluating particles created by sources and sources identified by assemblages.

Four Super Assemblages

It is easy to become overwhelmed by the variety of particles in the typical indoor environment. The typical analysis will involve the observation of tens of thousands of particles. No two particles are identical though many may be similar. In order for a human observer to deal with this complexity a number of mental tools need to be applied. The human brain has a processing hierarchy. It is limited in the number of things it can keep track of at any given time[23] but it can quickly identify familiar complex patterns[24] and recall related data relevant to the perceived pattern. For instance, from a single still photograph from a movie it is often possible to remember much of that movie. Out of hundreds of thousands of frames, the pattern on that single frame was recognizable and resulted in the retrieval of a significant body of information about the movie. The process occurs subconsciously but it involves an iterative processing of the image through selective criteria. Particles on a microscope slide are the same but the process is cognitive. A particle is selected for analysis. It is then placed in an assemblage of particles that is more restrictive for that particle but includes a larger population of particle types that are part of that assemblage. If the assemblage is present the analysis continues, but if the assemblage is not supported by the particles that are present then a new assemblage is selected until a match is found. This process can continue until the most restrictive useful assemblage has been reached. So what has this got to do with super assemblages. Super assemblages are the first layer of assemblages to which we assign particles. They are few in number, well defined, and always present. An initial step in the discipline of forensic particle analysis is to quickly assess the members of each of these super assemblages by scanning the sample at low magnification, occasionally going to higher magnification to check on specific features. This quick over view often alerts the analyst to interferences present in the sample that are best recognized before the detailed analysis begins.

The four super assemblages selected are somewhat arbitrary but they are an essential tool for processing the collection of particles. The four super assemblages I have found most useful are activity generated, facility generated, exterior natural, and exterior anthropogenic.

Activity Generated Particles

Facility Generated Particles

Exterior Natural Particles

Exterior Anthropogenic Particles

Figure 2.3: Four Super Assemblages

Activity Generated Particle Assemblage

The activity generated particles are those particles generated by the human activities in the occupied space. This includes the particles that come from people; human hair, human skin flakes, cosmetics, human skin flakes with cosmetics, sweat evaporites, clothing fibers, fingernail filings, shoe wear, and hair spray. This list contains four monotypic assemblages. These are cosmetics, sweat evaporates, clothing fiber, and shoe

wear. Eye shadow, rouge, and mascara are the most common types of cosmetics but those can be even further divided. Clothing fiber includes a wide variety of both natural and synthetic fibers. Sweat evaporites are chemically similar though the relative amounts of nitrogen containing compounds (amino acids etc.) vary depending on the conditions under which the sweat is generated. If the volume of water is low then the nitrogen compound are relatively high and the chlorides crystallize in X-patterns. If the volume of water is high, as in heavy exercise, then the amount of nitrogen containing compounds are low and the chlorides crystallize as cubes and octahedrons. The soles of shoes are made from a variety of materials and blends of materials. These materials wear from the bottom of the soles of the shoes and become particles in the environment.

Other activity generated particles include those particles generated by the activity other than from the human body. Paper fiber, toner, ink, paper sizing, floor wear, abrasives, pencil debris, erasure material, and other debris depending on the types of activities being conducted in the area. All of these members are monotypic assemblages. Paper fiber is distinct from other plant fiber used in clothing by virtue of its source, wood.[25] Paper sizing is the material added to the paper to prevent ink from "bleeding" into the paper. Clay, starch, and plastic coatings are a few of the sizings commonly used.[26] Toners and inks come in many formulations as do flooring materials. The lists of particles that could belong to this assemblage would include thousands of members but each particle is taken one at a time, and any given sample will contain a small subset of the particles that belong to this super assemblage.

Facility Generated Particle Assemblage

The facility generated particle assemblage includes sawdust, concrete dust, paint debris, glass fiber, insulation, fireproofing, sound proofing, fungal spores, insect parts, weld debris, ventilation system debris, corrosion products, efflorescence, wear metals, abrasives, and track debris. Every member on this list is a monotypic assemblage. All of these facility generated assemblages should be low in the environment or complaints can be expected (see Chapter 4).

Exterior Natural Particle Assemblage

The exterior natural particle assemblage includes pollens, spores, plant parts, insect parts, natural minerals, natural aerosols, and soils. These are particles that are foreign to the interior of the building and that enter the environment through open doors, open windows, on shoes and clothing, and through the ventilation system. These particles collected in the interior of a building can be compared with the particles collected outside the building to assess the contribution of unfiltered exterior air.

Exterior Anthropogenic Particle Assemblage

The exterior anthropogenic particle assemblage includes tire wear, cenospheres, flyash, charred wood, charred plant, industrial emissions, vehicle emissions, and other sources, depending on the local activities. Road dusts, dredging debris, earthmoving, land clearing, crop harvesting, crop spraying, all have distinctive attributes useful for identifying these activities. Every member listed here is a monotypic assemblage.

Sources Generating Assemblages

A fundamental assumption of polytypic assemblage analysis is that sources don't generate pure emissions. Emissions are not intentional products except in the monotypic assemblages from living things such as pollen, spores, etc. That means that most sources produce a variety of particle emissions and it is that variety that labels the source. We have already seen the assemblage from people and a few other assemblages from industrial processes given as examples. A forensic particle analyst is familiar with a wide variety of processes and the particles emitted by various stages of those processes. There are a number of resources available to help characterize processes by the particles they produce. Engineering references on processes and materials can be a valuable aid in understanding the types of emissions that may come from a source[27,28,29]. There are many other references to specific source emissions in the air pollution literature. Unfortunately, most of these source emissions are not characterized in terms of how they would be identified using the light microscope, or any other instrument for that matter. There is some information on the Web (see www.microlabnw.com)[30]. It is the responsibility of the microscopist to determine what properties will be used to identify those particles that are part of a given source assemblage. Those characteristics must be documented for future reference.

Particle sources are not necessarily where the particles are created, they can also be an area, activity, or process associated with the resuspension of particles. Heating elements, light bulbs, fans, cleaning activities, etc. are also sources and can result in the modification of particles in distinctive, identifiable ways. Particle sources are everywhere. The goal of forensic particle analysis is to use particle characterization to identify source. It is the source of the particles that are causing a problem that is important, not just the identification of the particle.

Identifying Unknown Sources

The forensic particle analyst approaches the sample with specific questions in mind. Those questions may be as simple as the distribution of the super assemblages. It may be as specific as: is activity x impacting site y, or, what particles in the environment might be associated with a given symptom and where do they come from. Figure 2.5 illustrates how a particle may be related to a source through identifying its assemblage in the sample.

Emery is a common industrial abrasive, it's used in fingernail files (emery board), and it is a natural mineral. It can be found as a contaminant in any piece of equipment that was assembled or cleaned using abrasion. It tends not to be a cause of health complaints but it can be a member of an assemblage that is a good indicator of industrial emissions impacting a site. It is one example of how a specific particle can lead to the search for other particle types in the sample that will ultimately form an identifiable assemblage.

This assemblage then identifies a likely source. Once again it is important for the analyst to be familiar with the particle assemblages that characterize specific sources.

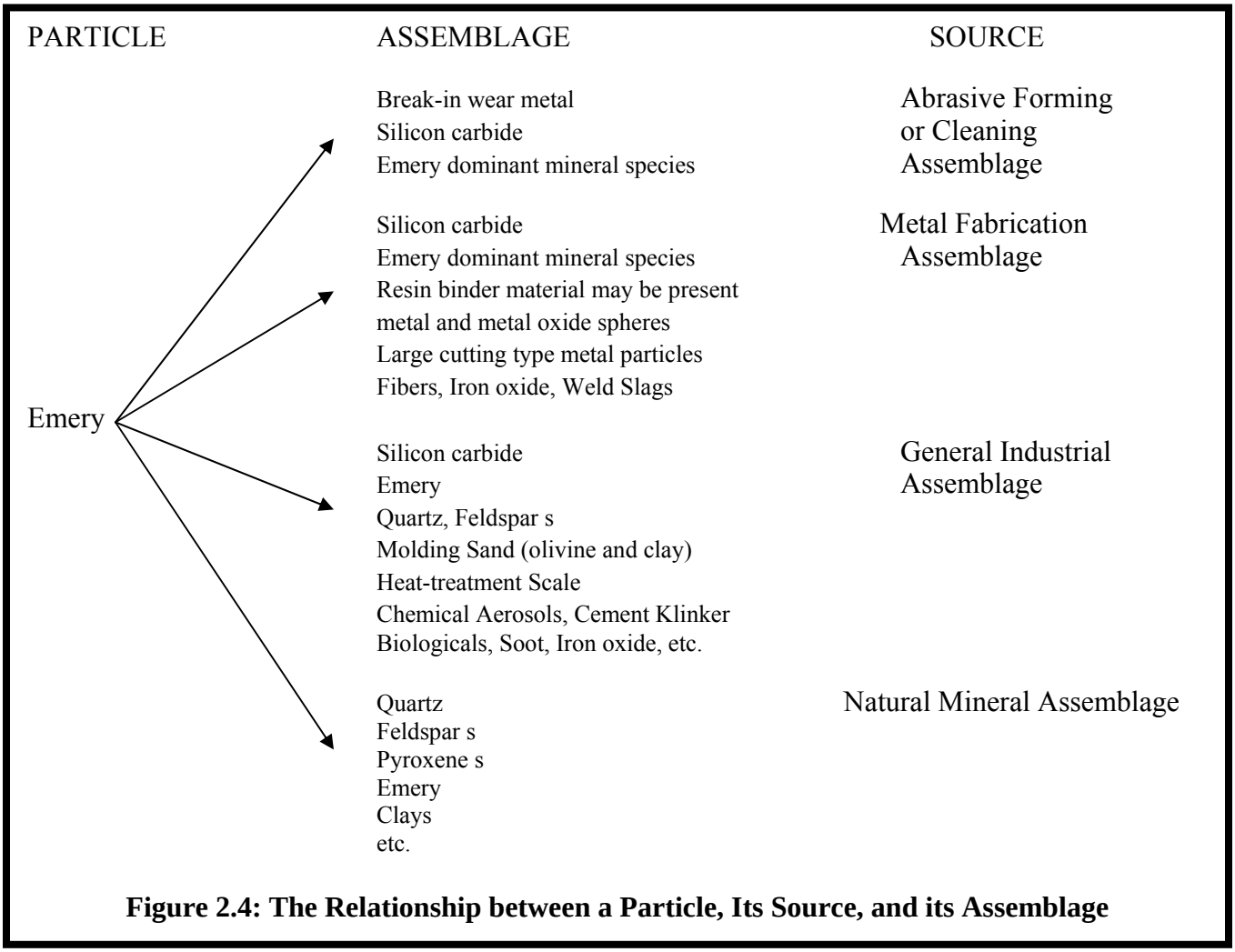


Figure 2.4: The Relationship between a Particle, Its Source, and its Assemblage

Conclusion

Assemblage analysis is a fundamental technique that uniquely qualifies the forensic particle analyst. It is a mental process that provides a framework into which the complexity of an environmental particle sample can be reduced to a relevant set of well defined source related assemblages. This mental tool is useful even if the assemblages are very widely defined as in a super assemblage. The analysis can also be very specific

as in the search for glass fiber and its origin or the presence of an indoor source of fungal spores.

There are two basic types of assemblages, monotypic and polytypic. Monotypic assemblages have unique member particles and well defined sources. Monotypic assemblage analysis has been much more formally discussed in the literature than polytypic assemblage analysis. The presence of any one member establishes the presence of both the assemblage and the source. Polytypic assemblages are not defined by individual members. In fact, individual members may belong to more than one assemblage in the same sample.

This has necessarily been a very brief introduction into a complex, multifaceted tool that has been widely used though rarely formally defined. Many analysts use the technique though they may not have considered it as a process. Consistency and reliability in the analysis will be improved by the recognition and more formalized application of this process.

Questions:

1. What is a contextual assemblage and how does it relate to assemblage analysis?
2. How are the particles in a monotypic assemblage related?
3. How are the particles in a polytypic assemblage related?
4. What is the role of Bayesian Statistics in assemblage analysis?
5. What are super assemblages and what function do they serve?
6. What is the relationship between proposed assemblages and sources?

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CHAPTER 3: PARTICLE BEHAVIOR IN INDOOR ENVIRONMENTS

Introduction

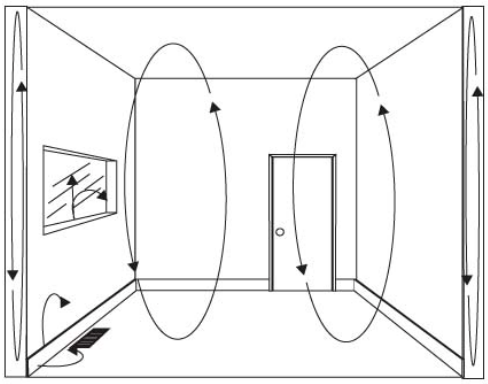


Figure 3.1: Currents, Whorls, and Eddies of Indoor Air.

Particles are dynamic in an occupied environment. If we could see airflow velocities as colors we would see swirls of yellow and red as a person walked by, trickles of blue from wall outlets on a cold wall, flood of crimson from the baseboard of a sun-lit wall. As we sit in our chairs an upwelling of bright orange bathes the front of our body while a flow of yellow green moves upward from our back. A jet of red and orange extends above our head. Lamps, baseboard heaters, computer fans, ventilation system diffusers, all contribute to the whirlpools, eddies, torrents, and jets of different colors. These flows splash against, channel over, or spiral above the surfaces in the room.

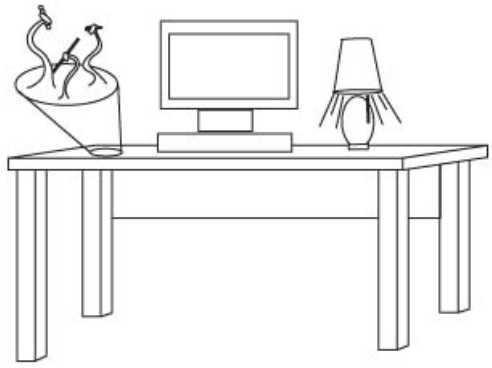


Figure 3.2: Surfaces Actively Interact with Airborne Particles.

Surfaces are not static either. Surfaces effectively reach out into space with tentacles of different types and different lengths. They reach out and stop the air flow above the surface to trap particle in this "boundary zone". Tentacles of static electricity extend out into the air passing over the surface. Short little tentacles of van der Waal's forces and the turbo-static effect make the surface "sticky" to some materials of proper size.

Entrained within all this movement of air, or resting on these living surfaces in the room are the particles that are of interest to our study. In this chapter we will be looking at the conditions and forces that regulate particle interaction with both the moving air and the stationary though active surfaces in an indoor environment. We will begin with some of the simple equations that model the forces applied to airborne particles. We will then consider models for particles moving toward surfaces, particles on surfaces, and particles that escape from surfaces to resuspend in the airflow.

After modeling the conditions of state for particles we will consider the patterns of air flow and forces acting on particles in an indoor environment. Much of this knowledge has been well documented as a result of two developments in human history, the development of the nuclear bomb and the Space Program. Testing the nuclear bomb inside the United States lead to the development of a country-wide monitoring program

and the construction of the bomb significantly improved techniques for monitoring and cleaning in indoor environments. The Space program improved those techniques when a few misplaced particles could and did cause tens to hundreds of millions of dollars worth of damage. We will review some of those lessons learned and up-date those with more recent work. We will also look at the nature and distribution of micro-environments in homes, offices, and schools. These micro-environments are often more important than the environment in general. Many experienced environmental specialists are cognizant of these micro-environments though they generally do so without a consistent approach because they haven't formalized the model. We will consider a more formal model. These micro-environments we look at will include the human "personal cloud".

Finally, we will bring all these models together and generate a first-order model of how they combine to affect the personal cloud. Contaminants that don't penetrate the personal cloud will not cause any health complaints. Looking at how particles penetrate the personal cloud will provide the locations and methodologies for the best samples. Our goal is to understand the relationship between particle analysis and the perception of environmental quality as seen by an occupant of the building. The objective quality of the environment in general is not our primary concern at this point. We are concerned about the personal space as it moves through the environment and interacts with specific micro-environments.

Forces Moving Airborne Particles

Gravity vs Drag

Perhaps the most obvious force acting on a particle is gravity. A particle suspended in a fluid such as air will tend to fall toward the earth with an acceleration of 980.7 cm (32 feet) per second squared, provided that the particle is more dense than the surrounding fluid. If things were so simple then airplanes couldn't fly. A force that tends to hold particles suspended is drag. Drag is basically the force required to move air molecules out of the way so the object can fall. The relationship between these two forces when the particle reaches terminal velocity (equilibrium) is given by Stokes' Law[1,2]:

$$(6\pi\eta)\nu r = r^3\pi(4/3)\,(\rho_o - \rho_f)g \qquad (1)$$

where

r = particle radius in cm
η = viscosity of the medium (180×10^{-6} poises for air)
ν = velocity of the particle in cm/sec
ρ_o = density of the particle in g/cc
ρ_f = specific gravity of the fluid (approximately 1.2×10^{-3} for air)
g = acceleration due to gravity (981 cm/sec^2)

In terms of particle velocity at equilibrium the equation becomes:

$$\nu = r^2(2g/9\eta)(\rho_o - \rho_f) \qquad (2)$$

As r becomes small the velocity at which the particle falls becomes very small. Table 3.1 shows the relationship between the terminal velocity of a spherical particle, its density relative to the fluid, and its diameter. The values in this table are approximate and do not include Cunningham's correction, Reynolds number corrections, or any of the other adjustments required to better fit experimental results [3]. The values in the main part of the table are given in miles per hour so that we can relate the sedimentation rate to the typical air velocities found indoors. Keep in mind that these velocities are for spherical particles. Non-spherical particles behave very differently and their sedimentation velocities can be different by orders of magnitude. They behave as particles very much smaller than their longest dimension. As a result they settle much more slowly and are far more affected by airflow. Very few particles in indoor air are spherical. Some of those that are have protrusions of other surface textures that modify their behavior in an air flow. What this all means is that sedimentation velocities calculated based on Stokes' Law are ballpark values for particles in real indoor environments. Bigger particles settle faster than smaller particles of the same shape. As size decreases linearly sedimentation velocity decreases exponentially, assuming that the particles reach their terminal velocity equilibrium.

Density	Diameter of the Sphere in Micrometers								
	1	2	5	10	20	30	40	100	500
1 g/cc	6.81E-05	2.73E-04	1.70E-03	6.81E-03	2.73E-02	6.13E-02	1.09E-01	6.81E-01	1.70E+01
2 g/cc	1.36E-04	5.45E-04	3.41E-03	1.36E-02	5.45E-02	1.23E-01	2.18E-01	1.36E+00	3.41E+01
3 g/cc	2.04E-04	8.18E-04	5.11E-03	2.04E-02	8.18E-02	1.84E-01	3.27E-01	2.04E+00	5.11E+01
Sedimentation velocities above are all in miles per hour (mph) Below: cm/sec and matching mph values at a density of 1 g/cc									
cm/sec	3.03E-03	1.21E-02	7.57E-02	3.03E-01	1.21E+00	2.73E+00	4.84E+00	3.03E+01	7.57E+02
mph	6.81E-05	2.73E-04	1.70E-03	6.81E-03	2.73E-02	6.13E-02	1.09E-01	6.81E-01	1.70E+01

Table 3.1: Sedimentation Velocities Calculated from Stokes' Law
Values are in miles per hour (mph) in order to put the sedimentation values into perspective. Typical airflows in indoor environments range from 1 to 8 mph. Upward convective flows in the vicinity of people often exceed 3 mph.

The main problem with Stokes' law is determining the correct equation for the drag force. This is far from a trivial problem but fortunately not a problem we have to concern ourselves with in regard to sedimentation. Corrections of a few hundred percent are overwhelmed by the other uncertainties common in indoor environments. Again, it is the pattern of how sedimentation velocity changes as a function of size that is important. The forensic microscopist often sees a gradient of particle sizes as a function of distance from the source of those particles. An example of this effect was recently made available as a result monitoring indoor environments using a particle counter that registered particles simultaneously at 0.3 μm, 0.5 μm, 1.0 μm, 2.5 μm, 5.0 μm, and 10 μm. When the particle counts were plotted in descending order by the 0.5 μm particles there was an obvious lack of correlation with the larger particles (see Figure 3.3). The same lack of correlation was evident when the counts were plotted in descending order by the 5.0 μm particle size

range (see Figure 3.4). When the data was plotted by time of day and day of the week distinct patterns became evident (see Figure 3.5). The smaller particles were coming

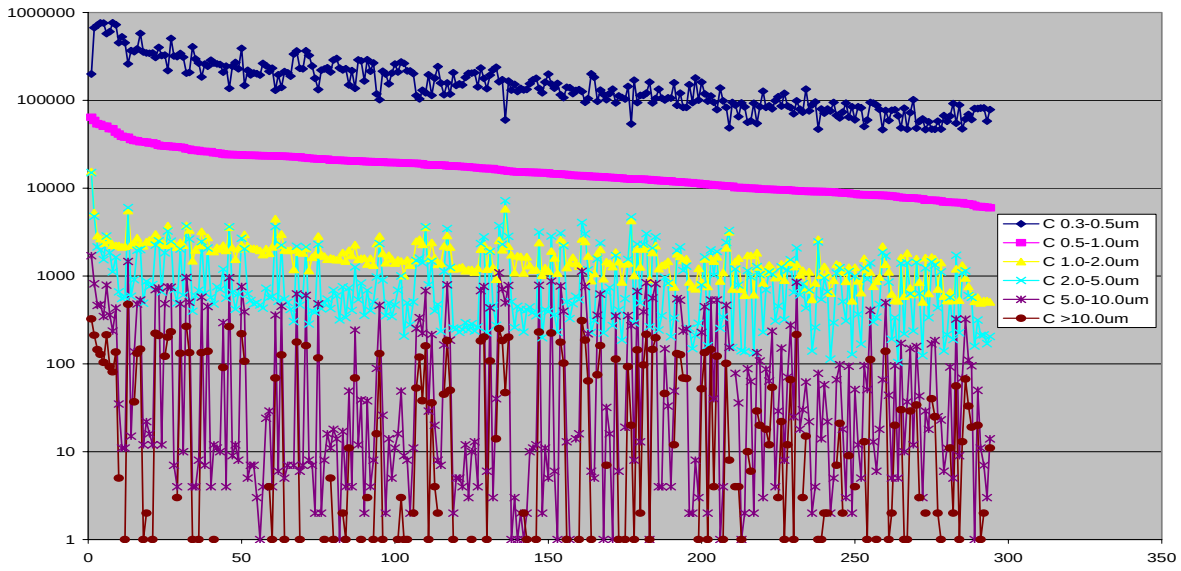


Figure 3.3: Particle Count Data Sorted by 0.5-1 Micrometer Particle Range

The data in this chart was sorted by decreasing count for the particles in the 0.5-1.0 micrometer (µm) size range. The 0.5-1 µm size range couples well with the 0.3-0.5 µm particle size range (counts follow the same trend) but not well with the size ranges over 2.0 µm. as can be seen erratic behavior in the counts when the data is sorted in this way.

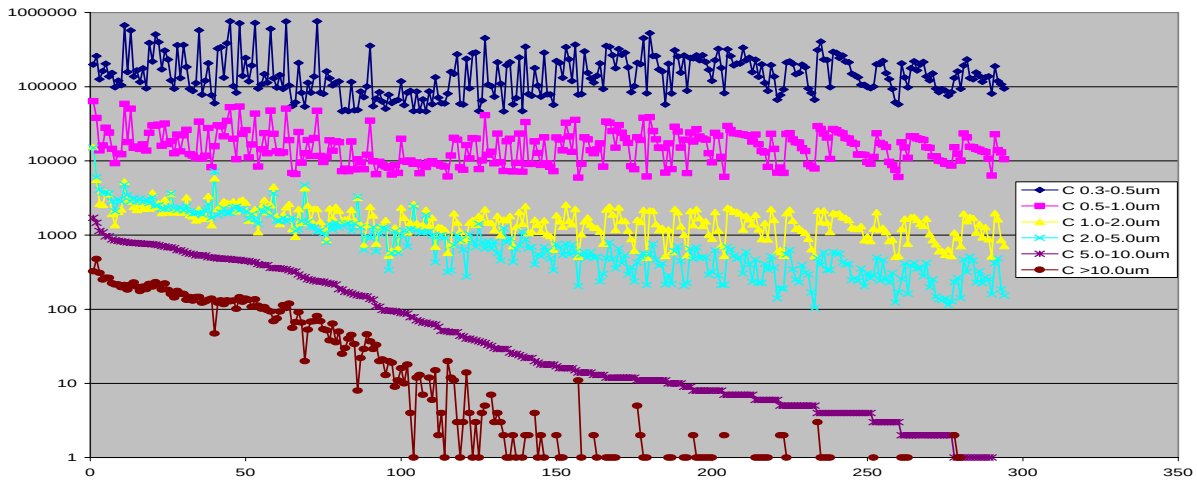


Figure 3.4: Particle Count Data Sorted by 5-10 Micrometer Particle Range

The data in this chart was sorted by decreasing count for the particles in the 5-10 µm size range. The 5-10 µm range couples well with the particles over 2.0 µm but not at all with the particles below 1.0 µm. Chart 3, below, is sorted chronologically and demonstrates how different environmental sources influence the particle counts in each size range differently.

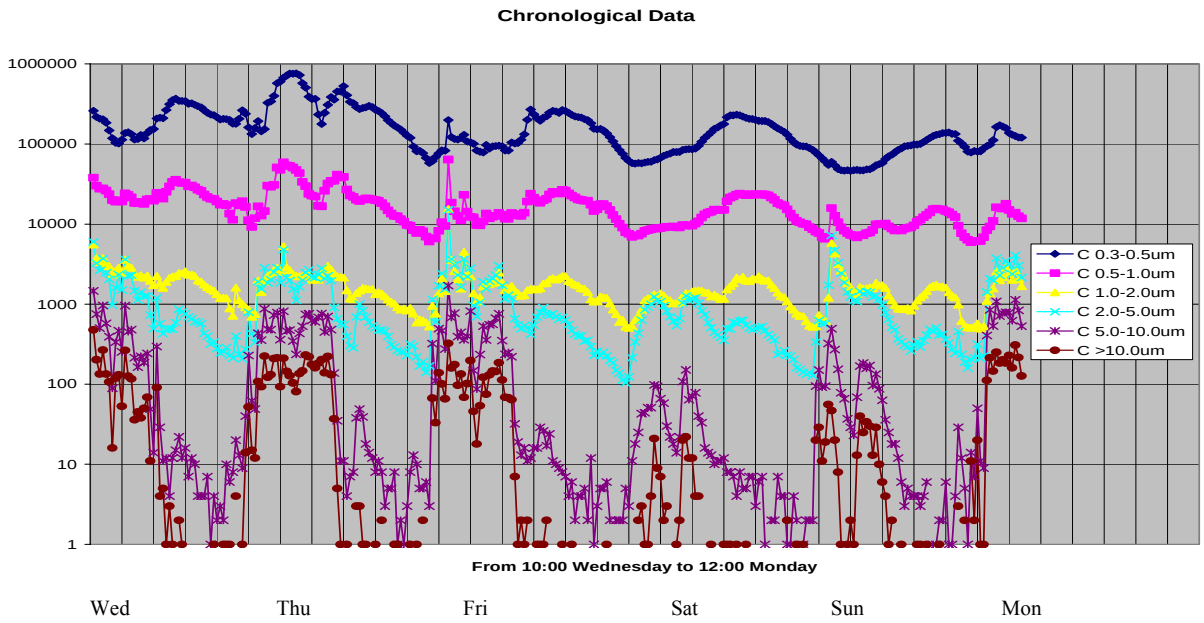


Figure 3.5: Particles by Hour of Day and Day of Week (February 21-26, 2007)

When the data is plotted by hour and day a number of patterns appear. The work day, including lunch break, show up in the 5 to 10 micrometer and greater than 10 micrometer data. Something happens on Sunday that also increases the particle loading but it is not as high as during school days. The particles in the 0.3 to 1.0 micrometer size range show the impact of vehicle emissions. Friday night and Saturday night show a significant increase in vehicle emissions that impact the school. Particles in the intermediate size ranges show the impact of both the outside and inside influences. Something special happened Friday morning and Sunday morning that impacted all size ranges. Tapelift analysis concentrates on the particles larger than 1 micrometer. This allows for the detection of sources contaminating the environment from both inside and outside the building of concern.

from vehicle emissions outside the building in this case. High counts in the ranges of 0.3 μm and 0.5 μm tracked with traffic flow patterns in the general region. The larger particles tracked activity in the room of the building where the particle counter was located.

Although this example appears to shows a textbook example of Stokes' Law in action it really has more to do with the strength of various sources and the characteristic sizes of the particles created by those sources. Vehicle emissions are predominantly in the less than one micrometer size range and are easily transported. The fact that the particle count curve tracks the emission rates of these small particles indicates that they are regularly remove from the air but the process doesn't involve Stokes' Law. The larger

particles from outside of the building are most effectively screened from the indoor environment when doors and other large leak sources are inactive, when no one is working in the building. Once each work day there is a small but distinct increase in particle counts for all size ranges that corresponds to when the cleaning crew comes through, around six o'clock PM.

Stokes' Law can't be usefully applied in most indoor environments, except in the most superficial fashion, because the conditions between the source and where those particles end up are often indeterminable. Stokes Law can be applied within the boundary layer of a surface. The Boundary layer for most surfaces in an indoor environment is on the order of a few millimeters or less thick. There will be more on the boundary layer in the next section when discussing forces near surfaces.

Drag is a measure of the force applied to a particle by moving air. There are a number of equations used to estimate this force, many based on empirically derived constants to fit a specific condition or type of particle[4]. One of the most simple equations is given below:

$$\text{Drag Force, } F_d = C\rho AV^2/2 \qquad (3)$$

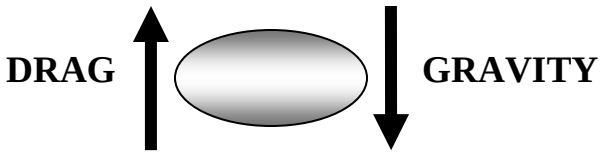
Where

C = coefficient of drag, an empirical value that varies with particle size and shape, kinematic viscosity of the fluid (0.151 cm^2/s for air), and relative velocity of the fluid

ρ = density of fluid (approximately 1.2×10^{-3} for air)
A = projected area of the particle modified by an appropriate shape factor
V = velocity of the fluid (typically the terminal velocity for small particles)

The keys to understanding this phenomenon is that the force on the particle is related to the velocity of the air squared and to the surface area of the particle relative to its volume. The effectiveness of these forces can be seen in the fact that the beach sands on the east coast of Florida are from the Sahara Desert. Half of the airborne particles smaller than 2.5 micrometers in Miami Florida during the summer are from the Sahara[5].

REAL WORLD TURBULANCE:
SAHARA SAND IN FLORIDA



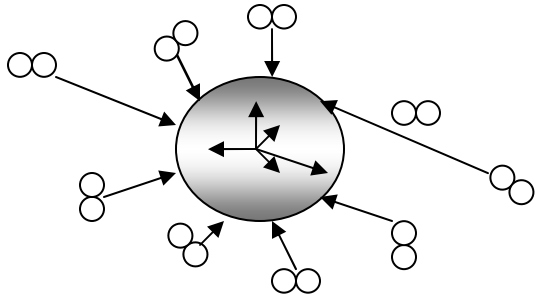
STILL AIR BALANCE:
STOKES' LAW

Figure 3.6: Gravity vs. Drag

Particles up to 500 mm can be held aloft by sustained updrafts of 2 mph.

The forces we have been looking at so far work on particles that experience the air as a continuous medium. As particles get

smaller that continuity breaks down. Small particles begin to interact with the individual molecules in the air and diffusion becomes a significant force acting on the particle (Friedlander pp 24-34). At sea level and 25^{o} Celsius the average distance between air molecules is 0.065 micrometers. Particles roughly in this size range, around a micrometer and smaller, are jostled about randomly as they are impacted by air molecules. Air molecules are moving at different velocities and directions depending on the local conditions. The inertia they impart to the particle is dominated by their velocity, which is determined by the temperature. The higher the temperature the higher the range of velocities in the local gas particles (molecules). In the environment at large the net effect of diffusion is to randomly distribute small particles through the air mass. Differences in temperature will tend to drive the particles toward the cooler areas because they tend to be hit by more energetic particles (faster) on the side closest to the heat. These small particles tend to be the most uniformly distributed particles in the air. Sedimentation and drag have little effect on their distribution. Diffusion is a very important process affecting the deposition of particles onto surfaces.



BROWNIAN MOTION LEADS TO PARTICLE DIFFUSION

Figure 3.7: Molecules impacting the particle cause the particle to jostle (Brownian motion). Over time the motion can produce a net effect (diffusion).

Clearly, particles are highly mobile in moving air. Their motion can be predicted in a statistical fashion, but local conditions and complexities of particle shape and even their chemical nature can produce what appear to be anomalous distributions.

Forces Acting on Particles Near Surfaces

We tend to think of surfaces as having a well defined place in three dimensional space that marks the limit of their effect on the local environment. As we alluded to in the introduction, that is not the case. In this section we will consider a number of ways in which the surface interacts with the environment around it.

Boundary Layer

Any fluid moving over a surface experiences friction. Friction slows the fluid down until at the surface the fluid is stationary. This transition layer of essentially laminar flow fluid with decreasing velocity nearer the surface is called the boundary layer. Stokes' Law works well within the boundary layer where complications of airflow don't exist. The boundary layer in air can be calculated from the velocity of air over the surface.

$$\text{Boundary Layer thickness } \delta = 1.72x(\nu/xU)^{0.5} \quad (4)$$

Where:

x = distance from the edge of the surface
ν = the kinematic viscosity (0.151 cm^2/s for air)
U = the average velocity of the air over the surface.

For an air flow of two miles per hour over a table two feet from the edge the boundary layer would be 0.22 inches thick (0.55 cm). Just in from the edges of tables, desks and other surfaces the boundary layer is much thinner and so the surfaces tend to be cleaner than more toward the center of the surface. The change in boundary layer thickness with distance from the edge of a surface is shown in Table 3.2 for air velocities on the order of those typically seen inside buildings and away from direct blasts from vents or cooling fans.

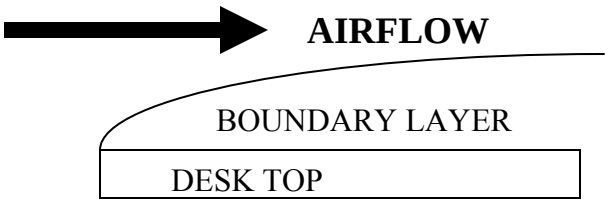


Figure 3.8: The Boundary Layer is a region of stabilized airflow where particles can settle without interference from turbulence. It is present only when fluctuations in the main airflow are low.

Distance From Edge					
Velocity	1 inch	1 foot	2 feet	3 feet	4 feet
1 mph	0.063	0.22	0.31	0.38	0.44
2 mph	0.044	0.15	0.22	0.27	0.31
3 mph	0.036	0.12	0.18	0.22	0.25
4 mph	0.031	0.11	0.15	0.19	0.22
5 mph	0.028	0.10	0.14	0.17	0.19

Table 3.2: Boundary Layer Thickness, in Inches, as a Function of Average Air Velocity and Distance from the Edge

The boundary layer is sensitive to turbulence and one source of turbulence is the leading edge of the surface that initially obstructs the airflow. This results in a line of heaver particle deposition just in from the edge of the surface (see Figure 3.9). Any obstruction in the airflow will create a similar disruption of the boundary layer. When an object is placed on a

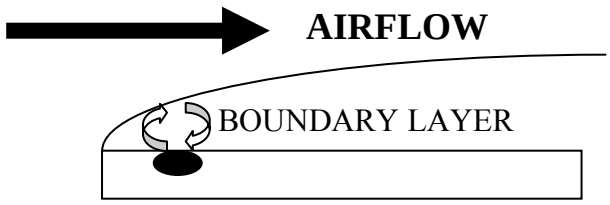


Figure 3.9: Just in from the edge of the obstruction to the air flow a pattern of turbulence is created resulting in the deposition of a band of particles paralleling the edge.

surface that has accumulated particles in the boundary layer the local disruption can result in the resuspension of particles downstream of the object. So turbulence can either deposit particles by impaction, as at the leading edge of the surface, or resuspend particles by locally breaking down a boundary layer that was already filled with particles.

Particles resting in the boundary layer are most susceptible to mechanical displacement and resuspension. This mechanical force can be vibration, wiping, or brushing. A pulsing air column in the HVAC system ducts, changing the filters in an HVAC system, or rapping on duct walls can provide the forces necessary to great a pulse of particles downstream. This mechanical activity is often responsible for peak exposures to irritants, allergens, and even toxins in the indoor environment. That will be discussed more in chapter 4 on complaints resulting from exposure to particles. The boundary layer is the first example of the surface acting at a distance. The distance may be short but it demonstrates that surfaces are not static with regard to particle deposition.

Electro-Static Effects

Another example of surfaces acting at a distance can be seen in electro-static attraction. Particles tend to take on a charge. Many are charged at the time of their creation, flame ionization is an example for soot particles. Others become charged as they move over surfaces. Fine particles moving through a ventilation duct will become charged and tend to grow on the duct wall as chains of particles attracted by the generated charge and grounding to the duct wall. This charging from contact with a dissimilar surface is called tribostatic charging. In the case of tribostatic electrification it is the exchange of electrons between the two materials that creates the charge. The electron moves to the material that is more negative on the Triboelectric Series (see Figure 3.10). This list has been generated empirically because the theoretical model has not been successfully prepared. In fact, the Triboelectric Series from different sources may not have the same materials in the same relative ranking, depending on the configuration of the experiment used to determine which material was the more readily the electron acceptor. The table in Reist's book on Aerosols[7] lists a number of materials in a slightly different order than the chart presented here. Triboelectric charging generally occurs when a particle is removed from a surface. The electro-static attraction of the particle for the

POSITIVE (Electron Donor)
- Air
- Human Hands
- Asbestos
- Rabbit Fur
- Glass
- Mica
- Human Hair
- Nylon
- Wool
- Fur
- Lead
- Silk
- Aluminum
- Paper
- Cotton
- Steel
- Wood
- Amber
- Sealing Wax
- Hard Rubber
- Noble Metals and Nickel
- Sulfur
- Acetate Rayon
- Polyester
- Celluloid
- Orlon
- Saran
- Polyurethane
- Polyethylene
- PVC (vinyl)
- KEL F Fabric
- Silicon
- Teflon

NEGATIVE (Electron Acceptor)

Figure 3.10: Triboelectric Series

surface it just left is one of the forces that must be overcome to successfully keep the particle from reattaching to the surface.

Atomizers, such as hair spray, or copy machines, or any number of other devices used in indoor spaces generate charged particles or ions. These charged particles can share their charges with other airborne particles they encounter. There are a number of ways that particles can become charged without their being exposed to an electrification grid designed for that purpose. The ones mentioned here are a few of the more common processes.

Some surfaces are electrically charged or are well grounded so that in the presence of a charged particle the surface will take on the opposite charge. That process, called "image charging", is responsible for the growth of particle chains protruding from the walls of ventilation system ducts and other similar situations. Electron tube computer monitor screens or television screens are examples of surfaces in the environment that are active collection surfaces for charged particles.

Diffusion and Thermophoresis

Diffusion becomes an important deposition mechanism when small particles get very close to surfaces. This distance is well within the boundary layer and is referred to as the "concentration boundary layer"[8]. As the particle approaches the surface the number of molecules and other particles striking the particle on the side opposite the wall is greater than the number tending to drive the particle away from the wall. As the particle moves closer to the surface the effect becomes more pronounced. Finally the particle is driven onto the surface. This effect is not dependent on gravity and becomes one of the major deposition mechanisms for particles on walls and ceilings. A classic result of this effect can be seen in the deposition of small particles on a wall behind a picture fame. The wall will be marked with a dark pattern of particles that have deposited directly beneath the part of the frame that was closest to the wall. As the hanging frame got closer and closer to the wall (toward the bottom) the dark pattern becomes even more noticeable. This is the direct result of the probability distribution of inertial transfer from atmospheric molecules. Figure 3.11 illustrates the process and Photograph 3.1 is an example of such a deposit on an interior wall.

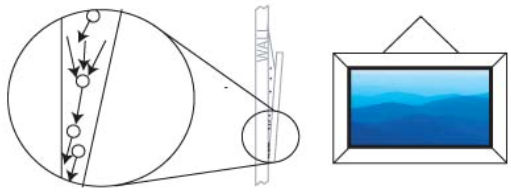


Figure 3.11: Diffusion Deposition Behind a Picture Frame

The same principle of differential inertial transfer can be accomplished by heating one surface and using the higher velocity gas molecules coming from that surface to drive small particles onto another nearby surface. This process is called thermophoresis, the effects of which can be seen above radiators, baseboard heaters, and as the ghosting that follows stud lines and around buried nail heads on ceilings and exterior walls (see Photograph 3.2). Although the explanation is fundamentally correct the theoretical

Photograph 3.1: Deposit Behind a Picture Frame

Notice the decrease in the effect with increasing distance between the picture frame and the wall.

Photograph 3.2: Thermophoresis Ghosting on Ceiling

Cold nail heads are marked by a deposit of soot. Studs are unstained while poorly insulated ceiling is discolored.

model for thermophoresis is more complex. The book by Reist does a good job in presenting some of the models that have been used to predict the effect[9].

Once particles are on a surface they tend to stay there. The forces holding them actually grow in strength with time. In the next section we will investigate some of these processes.

Forces Holding Particles on Surfaces

The adhesion of particles to surfaces is the subject of an extensive monograph by Anatolii Zimon [10]. In its 424 pages it details both the theoretical models and empirical data. A much more concise description is provided by Bardina[11]. In half of one page he lists the four most important forces holding free particles on surfaces: van der Waals Force, Electrostatic Double Layer Force, Electrostatic Image Force, and Capillary Force. The form of the following equations is taken from Zimon's book[12].

$$\text{Van der Waals Force (molecular force)} = Ar/(6z^2) \quad (5)$$

$$\text{Electrostatic Double Layer Force (electrical force)} = \pi\varepsilon_o(\Delta\phi)^2 r/z \quad (6)$$

$$\text{Electrostatic Image Force (Coulomb's Force)} = Q^2/4r^2 \quad (7)$$

$$\text{Capillary Force} = 4\pi r_m\gamma \quad (8)$$

Where:

r = particle radius
A = van der Waals constant
$\Delta\phi$ = difference in work function
ε_o = permittivity of free space, 8.86 pF/m
z = distance between the particle and the surface (typically 0.3 nm)
Q = particle charge
r_m = radius of meniscus from center of contact
γ = surface tension, 73 dyn/cm for water

All of these equations are based on spherical particles and flat, polished surfaces. As the particles deviate from spheres and the surfaces become rougher the forces increase significantly. The forces also increase with an increase in relative humidity and especially with time. With the increase in relative humidity from low to 65% the capillary force grows slowly but steadily. From a relative humidity of 65% to 100% the increase in capillary force grows rapidly. This increase in the force is the result of an increase in the radius of the meniscus from the center of contact between the particle and the surface. The fact that there is an increase in force even at low relative humidity indicates that there is condensation between the particle and the surface at low relative humidity.

FORCES

Van der Waal's Force

Electrostatic Double Layer Force

Coulomb's Force

Capillary Force

CONTRIBUTING FACTORS

Surface Roughness ++

Non-Spherical ++++

Relative Humidity ++

Ageing ++++

Figure 3.12: Four Forces Between Particles and the Surfaces they are Resting On and Four Contributing Factors

The number of "+" signs indicates the relative strength of the contributing effect.

The presence of a liquid water phase between the particle and the surface creates an opportunity for corrosion and for the accumulation of water-soluble salts. These two processes are time dependent. The net effect over time is an increase in the force holding the particle on the surface that is not derived from the four forces we considered above. This is part of the "ageing" effect. Another aspect of the ageing effect is that the forces between the particle and the surface actually deform the surface and/or the particle to increase the effective area of contact. This also increases the force holding the particle on the surface. This force can grow to the point that the adhesive force between the particle and the surface is equal to the cohesive force within the material. These particles will not be removed from the surface without damaging the surface unless the adhesive force can be reduced. This is an important result when we consider the collection of a particle sample from a surface in Chapter 5.

Resuspension of Particle From Surfaces

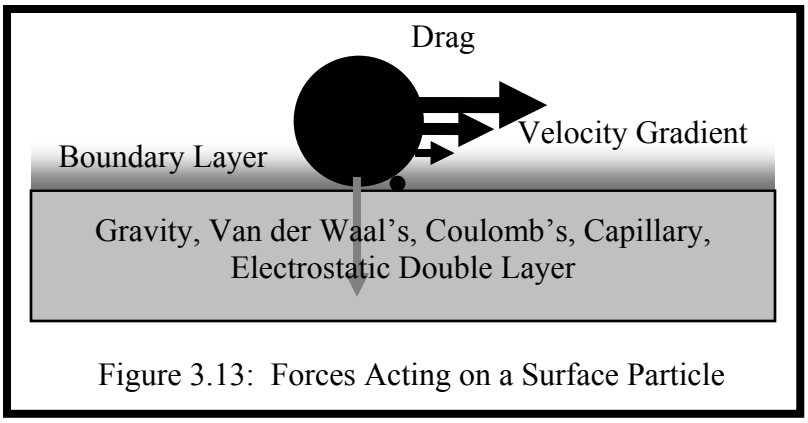


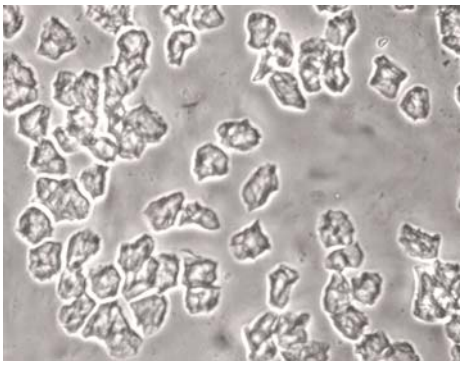
Figure 3.13: Forces Acting on a Surface Particle

With such forces actively holding particles on surfaces how do they become resuspended in the air? Wind shear and mechanical force are the two most common forces resulting in the resuspension of particles. Wind shear requires that the particles protrude from the surface boundary layer. That most often occurs when the airflow becomes turbulent or the velocity increases and the boundary layer becomes suddenly very thin. Drag then takes over and, provided the drag force exceeds the forces holding the particle, the particle will move. The drag force must continue to exceed the electrostatic attraction and gravity in order to prevent the particle from reattaching to the surface. It is clear from this that small particles will not be removed from surfaces by airflow. So where do dust storms come from? Saltation, one example of mechanical force.

Particle motion along a surface caused by fluid flow (airflow) can take three basic forms; saltation, surface creep, and suspension[13]. Saltation involves larger particles that periodically will be removed from a surface but will fall back to that surface quickly, and in the process will create a local mechanical shock that releases smaller particles from the surface. The smaller particles in the cloud of have such low sedimentation velocities that they tend to be carried upward in the airflow over the surface. Saltation plays a major role in the creation of sand dunes through the elimination of smaller mineral grains. Surface creep involves even larger particles that tend to roll or slid along the surface. These are the particles that create "dust bunnies" in indoor environments, fibrous rolls and mats that form under furniture and in the corners of rooms. The particles that get suspended in the air flow, even for relatively short times, are the ones that create most of the health complaints. The paper by G. A. Sehmel sited above and a recent dissertation by A. H. I. Essawey[14] both do a good job of reviewing and updating the resuspension of particles by fluid flow. These processes are important and relevant to an indoor environment, but most indoor health complaints are due to more direct applications of mechanical forces to surfaces.

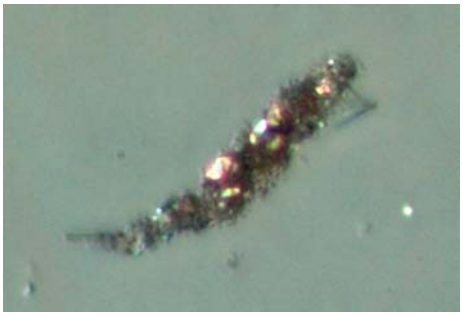
Occupied indoor spaces are full of particle generating activities and mechanical activities for the resuspension of particles. People generate an estimated five million particles per minute from their own bodies as they move through the environment (Photograph 3.3). They also shed debris collected elsewhere. Pet debris is commonly introduced into the airborne particle load of offices and schools by workers and students with pets at

home[15,16,17,18](see cat hair in Photograph 2.9). Dust mite debris is another school or office particle that may be brought in on clothing from some ones home[19,20]. Normal human movement creates mechanical forces that remove these particles from the clothing and introduce them into the office or school air.



Photograph 3.3: Human Skin Flakes

The friction of the shoe against the floor generates millions of both shoe wear and floor wear particles with significant force. Many of these particles are ejected into the air. The mechanical expansion and contraction of the sole of the shoe releases debris on the sole of the shoe into the air and onto the floor. This track-in debris on the floor is subsequently crushed, abraded, and ejected into the air as it is repeatedly step upon. Walking on a carpet is even worse. The rapid airflow under the crushing weight of the walker blows particles into the air. As the foot lifts the pile of the carpet springs back and catapults particles into the air.



Photograph 3.4: Shoe Wear

Using a vacuum cleaner removes some particles but lofts many more particles into the air. Vacuum by itself can not effectively remove particles from surfaces because the velocities are not high enough to create a shallow boundary layer. All commercial vacuum cleaners use a mechanical process to free the particles from the surface and then rely on the airflow created by the low pressure region to draw the particles into the collection device. Many of the particles are so accelerated by the mechanical beating or brushing that they overcome the velocity created by the low pressure region. The result is that the airborne particle loading may increase by a hundred times or more during the period that the vacuum is being used and will persist often for up to an hour, sometimes longer.

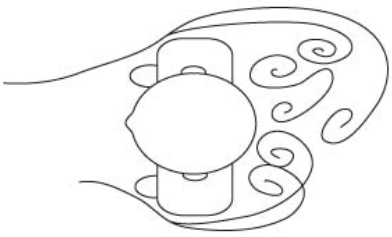


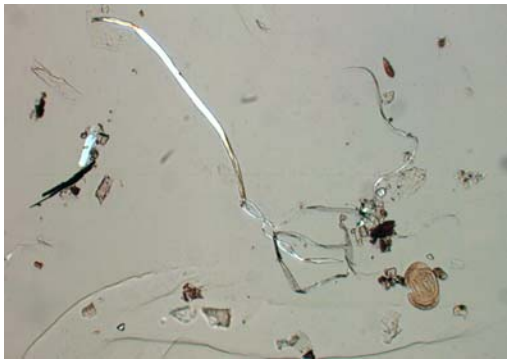
Figure 3.14: Airflow in the Wake of a Person

This turbulence can link to other flows or even to surfaces nearby and collect particles to be carried in the wake.

The airflow created by the movement of people tends to keep the created or lofted particles airborne and creates turbulence to resuspend particles on nearby surfaces. The turbulence in the wake of a walker can exceed the speed of the walker by many times. This also can disturb loose papers, plant leaves, or other potentially particle laden free surfaces.

When a door is opened a pressure pulse may be generated that is translated into vibration and mechanical abrasion, creating wear particles. This is especially the case in buildings with suspended acoustic ceiling tiles. The pressure pulse can lift the ceiling tile slightly and cause it to rub against the t-bar support. The result is abrasion of the edge of the ceiling tile and the creation of millions of particles of glass fiber, resin, perolite and other debris that sifts down onto the people below (see Photograph 2.7). The pressure pulse can also create a vibration with a significant instantaneous acceleration. The acceleration loading can spring particles from surfaces. Loud noises also create acceleration loading and can release particles from surfaces into the air. (acoustic vibration)

People at an office work station continue to create or resuspend millions of particles (see Photograph 3.5). Shuffling papers creates paper fibers, ink particles, toner particles, and resuspends particles settled on those papers in a localized storm of dust. Putting on or taking off a coat creates a cloud of clothing fiber. Sitting in a chair abrades and forcefully ejects particles that have collected on the chair. Opening and closing a file cabinet drawer creates a vibration of the cabinet that releases particles and an airflow to resuspend other particles. Using a pencil or a felt-tip pen generates graphite and clay or ink drops, paper sizing, and paper fiber into the air. Sneezing, coughing, or even talking expels mucoid spheres into the air.



Photograph 3.5: Office Particles

Paper fiber, clothing fiber, natural minerals, skin flakes, Alternaria spore, Pine pollen, charred wood, paper sizing, tire wear, plant parts, and other particles are in this view.

Differences in the thermal coefficient of expansion can create powerful forces for the ejection of particles. When lights are turned on they eject particles as they warm up. The same is true of heating elements and hot plates. Copy machines, printers, cooking, smoking, and other activities indoors create heat and resuspend particles into the air.

The migration of particles in indoor environments is dramatic but so also is the selective distribution of particles in the environment as a result of the influence of micro-environments. Lets begin first by examining the airflows indoors that carry these particles.

Airflow in Buildings

The airflow in buildings can be divided into two basic groups. The first are those that would be present in the empty building that are a result of the buildings design, the buildings air handling system, and the weather outside. The second are those related to

people, equipment being used, lighting, point cooling, point heating, and the obstructions to airflow such as furniture, partitions, doors, etc.

Building Induced Airflow

The airflow in the building that is a product of the buildings design includes the effects of temperature and pressure, the stack effect, the interior segmentation of the space, and the air handling system for climate control in the building. An excellent summary article by Rick Quirouette is available on the web[21]. In that article he points out the five basic processes affecting the overall motion of air in buildings: stack effect, fan pressurization, wind cycling, barometric cycling, and thermal cycling. We will consider these processes here in terms of airflow. Quirouette is more concerned about volume exchange and transport of moisture and less concerned about air velocities. Our concern here is more on the effect of airflow for particle transport, but the same phenomena are responsible. Fan pressurization is important to transport of moisture but it is the flow of air around diffusers and return air grates that has a far greater effect on the transport of particles. The exchange of air in the wall cavity of a building has a significant effect on the transport of moisture into the wall cavity but it also identifies a particle path that is important with respect to health complaints.

Temperature and Pressure Effects. The building itself breaths. That is the beginning of our understanding of airflow in buildings. Buildings are full of air cavities with a fixed volume that are constantly adjusting to changes in air pressure and temperature. Changes in pressure and temperature result in changes of air volume within the confined volumes of the building. Air must move to bring the system back into equilibrium. These changes in volume can all be calculated using the Ideal Gas Law:

$$P_1V_1/T_1 = P_2\ V_2/T_2 \qquad (9)$$

Where:

P_1 = Pressure at Condition 1
V_1 = Air Volume at Condition 1
T_1 = Absolute Temperature at Condition 1
P_2 = Pressure at Condition 2
V_2 = Air Volume at Condition 2
T_2 = Absolute Temperature at Condition 2

The Change in air volume is then:

$$\Delta V = V_2 - V_1 = V_1(P_1T_2/P_2T_1) - V_2(P_2T_1/P_1T_2) \qquad (10)$$

Consider the closed air space in a wall. The wall has a fixed volume and is open to the internal space through outlets and switch panels. It is also open to the inside at the baseboard. If it is colder outside than it is inside the temperature of the air in the wall, T_1, will drop relative to the temperature in the room, T_2. The pressure and the air volume must drop to maintain the equilibrium. Since the room air is open to the air in the wall air from the room rushes in to the wall cavity to equalize the pressure and make up for the loss in volume. Along with the air goes some of the particles in the air and the moisture (water vapor).

If the sun is shinning on an exterior wall the cavity warms up. T_1 becomes larger. The volume of the wall can't increase so the pressure increases. Now the excess air volume from inside the wall pushes out into the room. An examination of the back of a switch plate or a wall outlet plate will illustrate this effect. The plate will be covered with fine particles, much of it will be the finer soot from the environment or even mold spores if fungus is growing in the wall cavity. These plates can be a useful sampling location. That will be discussed more in Chapter 5. The same thing happens with the change in barometric pressure. As the outdoor pressure changes with highs and lows so the volume of air in the wall must change.

There is another phenomenon that is associated with temperature differences that effects air flow. Warm air is less dense than cold air. As a result cold air falls and warm air rises. The actual difference in density is small but the effect can be easily felt above a lamp or radiator type heater. Velocities in excess of 8 miles per hour can result above a lamp light bulb. Velocities of up to six miles per hour can come from a shirt collar. Cold air can leak from a cold wall even while that wall is drawing in warm air from the room to compensate for the loss of air volume due to a decrease in temperature (see Figure 3.15). This is convective flow and we will consider it in more detail when we discuss ***Occupant and Equipment Induced Airflow***.

The air flow coming from openings in the wall can easily be single digit miles per hour, depending on the rate of change. That rate of change is very quick when the sun begins shining on a wall or when the wall suddenly goes

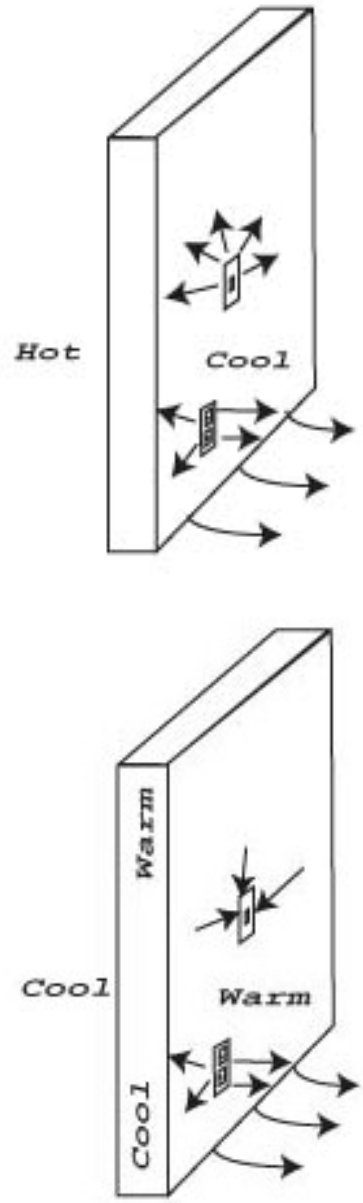


Figure 3.15: Airflow in an Exterior Wall
Some cold air will flow from the lower part of the wall due to density effects.

into shadow. A cold front moving through can change the pressure very quickly. Wind pressure changes can be even more rapid. Wind gusts may occur as frequently as fifty or more times an hour. Each gust causes a change in pressure that can pump a small volume of air in to and out of the wall with each cycle. The pressure created by the wind is proportional to the velocity of the wind squared so as the wind velocity increases the pressure effect increases exponentially. These processes that pump air into and out of a wall cavity work the same way for the larger cavity of the entire building with respect to its atmospheric envelope. The velocities of the airflow are controlled by the change in air volume, the rate of change, and the area of the openings that the volume difference must move through.

Stack Effect. Pressure varies as a function of elevation. The higher in elevation the lower the pressure. Within a closed building this can produce a significant air flow. The pressure difference driving air flow can be calculated from the following equation.

Stack Effect:

$$\Delta P_s = dg(H-H_{Npp})(T_i-T_o)/T_o \qquad (11)$$

Where:

ΔP_s = Stack effect Pressure Difference in Pa
d = density of air, about 1.2 kg/m^3
g = gravitational acceleration, 9.81 m/s^2
H = Height of plane above or below the Neutral Pressure Plane (Npp), m
H_{Npp} = Height of the Neutral Pressure Plane, m
T_o = Outdoor Absolute Temperature, Kelvin
T_i = Indoor Absolute Temperature, Kelvin

The neutral plane (Npp) for a single story building can be taken as grade, while for a multi-story building the height will elevate toward the midpoint as the leakiness of the building increases. The important factor for air flow is the dependence on the relative temperature. In temperate climates the direction of flow changes from summer to winter and even from morning to afternoon. The effects of a ground floor parking garage on a cold winter morning can be profound for the building above while in the summer there is no detectable effect at all. It can even be as subtle as a morning problem that disappears as it warms up outside. The airflow through doorways and other leaks in the building can be significant. The direction of the airflow is important when any kind of particle generation at one location in a building is being considered in terms of its impact on another location in that building.

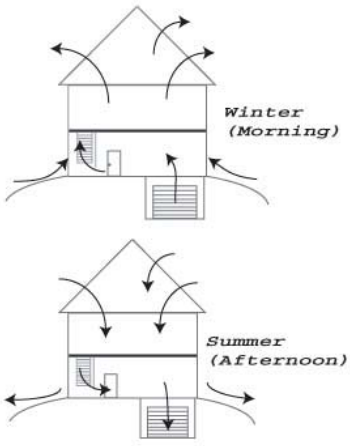


Figure 3.16: Airflow as a Result of the Stack Effect

The Segmentation of Space and the Air Handling System. The segmentation of space in the building controls how the air moves through the building and the velocities required to provide for the equalization of pressure differences. The air handling system is designed with the segmentation in mind in order to optimize conditions over the greatest part of the occupied space. The Indoor Air Quality Handbook[22] and the book, Industrial Ventilation: A Manual of Recommended Practice[23], are excellent resources on how to control and balance conditions inside buildings. They both have a number or illustrations showing generalized airflow in rooms as a function of air supply and return locations, heating or cooling conditions, and exterior walls. The airflows are all based on static rooms rather than real environments because there are just too many permutations of real space to model effectively. Often, an area proposed as a large open bay is later partitioned into a number of closed rooms connected to a common hall. The effect on airflow and heat balance in the different rooms can be profound. Stagnation areas, drafty regions, cold and hot areas can be created at the same time in the same room because the appropriate location for the supply air diffuser and the return grate for the open bay is no longer appropriate for the partitioned area.

The designed airflow in a room can be significantly modified by the placement of furniture or equipment in the room. A jet of air tends to "attach" to surfaces. This is called the "Coanda effect". Placing a tall storage cabinet near a ceiling diffuser can channel a jet of air from the diffuser along the top of the cabinet and down the other side. This can create a draft in an area of the room that had been essentially stagnant. This robs conditioned fresh air from other areas in the room and creates zones even more stagnant than had been the area that is now drafty. This is an example of an airflow modification not anticipated by the engineer designing the air handling system. Real offices, workplaces, schools, and homes are full of such modified zones.

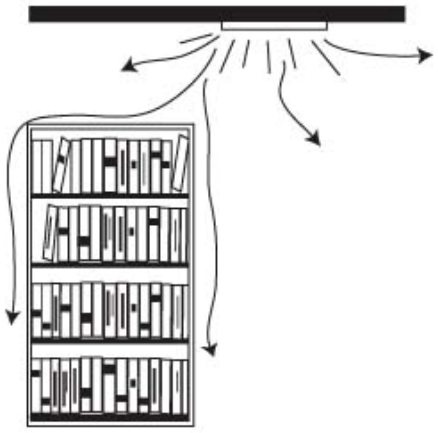


Figure 3.17: The Coanda Effect and Furniture

Air streams tend to link to surfaces. This is known as the Coanda Effect.

The particle implications in the example above are also important. Consider a room with typical acoustic ceiling tiles with the area above the tiles being used as the return air plenum. Fluctuations in air pressure cause the ceiling tile to rub against the supporting t-bar. Short glass fibers are generated and rain down in the area. The rate of their generation is low and the cleaning frequency in the area is reasonably high. The net effect is that there are no health complaints. Now the storage cabinet is moved in. Most of the people in the space still have no problem but the worker on the downwind side of the storage cabinet starts to experience nasal congestion, dry eyes, and a sore throat. These symptoms disappear away from work but return soon after he starts work in the morning. The top of the storage cabinet collects glass fiber twenty-

four hours a day over a relatively large surface area. The accumulated glass fiber over the top of the cabinet is concentrated in the air down flow along the down wind side of the cabinet. The worker at this location experiences this more concentrated exposure. The Coanda effect has resulted in a concentration of short glass fibers just at this work station. This is one example of a micro-environment that results in locally concentrated health effects.

The concentration of particles as a result of airflow tends to be the rule rather than the exception in indoor spaces. Random sampling of indoor spaces is often not relevant to isolated complaints. Complaints are often isolated to specific locations or specific activities. The causes for these complaints are rarely discovered by generalized sampling plans. This will be discussed in more detail in Chapter 5. How can these localized effects be recognized? By looking at the area as a collection of micro-environments.

Random Sampling is Often not Relevant to Isolated Complaints

Figure 3:18: Random Sampling

Occupant and Equipment Induced Airflow

There are a number of localized sources for airflow within occupied spaces. The most obvious is the occupant and the movement of the occupant. Tests in Cleanrooms have shown that a seated person emits about three million particles of skin per minute. These particles filter through clothing, rain out of cuffs, and stream out of collars. Schelerian photographs show strong currents of convective airflow over the clothed body. The flow is enhanced as it escapes from inside the clothing through the collar of the shirt. Football fans are familiar with this phenomenon. On cold days when the cameras turn to a player who just came off the field clouds of moist air can be seen streaming from his body in an upward direction. The same stream comes from every person when they are in an environment that is cooler than body temperature. This airflow is easily fast enough to loft detached skin cells, typically with aerodynamic diameters of less than ten micrometers, upward into the ambient air.

As a person moves through a room they generate more than five million skin flakes per minute along with clothing fiber. Their movement creates air turbulence that can loft particles from surfaces and add to the airborne particle burden. Opening a file cabinet drawer generates wear metals from the bearings and debris from the bearing races. The movement of the drawer and of the person opening the drawer creates additional air movement. Placing a file on the top of the file cabinet creates a high velocity shear airflow as the file drops on the surface of the cabinet. The direction of the airflow and the lofted particles is toward the face of the person standing in front of the cabinet. Lifting the file creates a much stronger mechanical shear to remove collected particles from the surface and an airflow to move those loosened particles into the air. If the file cabinet is in a seldom cleaned storage area the release of particles can be quite high and trigger a fairly rapid onset of upper respiratory and eye health complaints.

Computers, copy machines, and many other common machines in homes, offices, workplaces, and schools contain blowers to get rid of excess heat. These blowers create strong, short range turbulent air currents. These currents mix the air and keep particles from settling out of the air. Personal fans, if allowed, are another source of spurious air currents.

Heated surfaces are a source of airflow and particles as discussed earlier. Hot air at the same pressure is lighter than cold air. The result is that hot air rises and cold air rushes in to take its place. This is called convective airflow. Convective airflow is the source of the airflow around the human body at rest in a cool environment. It is the source of the up-welling of air above a baseboard heater or radiator, a television set, or a light bulb. The convective airflow above a light bulb can reach eight miles per hour. A hot cup of coffee, a hot plate, anything that gets warm or is warm creates convective airflow. The same would be true of objects that were significantly colder than the surrounding air, but they are less common in most environments and the airflow is downward rather than upward into the larger air volume.

Most of the airflows created by these sources are short range but they are as often a cause of exposure resulting in health complaints as the more long range airflows. Health complaints are the result of the local environment interacting with the personal envelope. The personal envelope doesn't extend very far from the physical body. Short range airflows are as significant as longer range patterns because it is this rather thin envelope around people that is important.

Micro-Environments and the Personal Envelope

A micro-environment is a localized set of conditions characterized by a specific set of airflow patterns and particle sources and sinks. The micro-environment is connected to the environment at large but the local conditions are dominated by the local effects. The personal envelope includes the body, clothing, and a volume of air around the person that is directly interacting with the person by depositing particles, by being inhaled, or by carrying particles aloft that will later interact with the person. The personal envelope can be visualized as a flow of air that starts slowly at the feet and grows as it rises by convection to surround the body. Our head is within this envelope and we are affected only by those things that penetrate that envelope. The envelope is not hard to penetrate but failure to

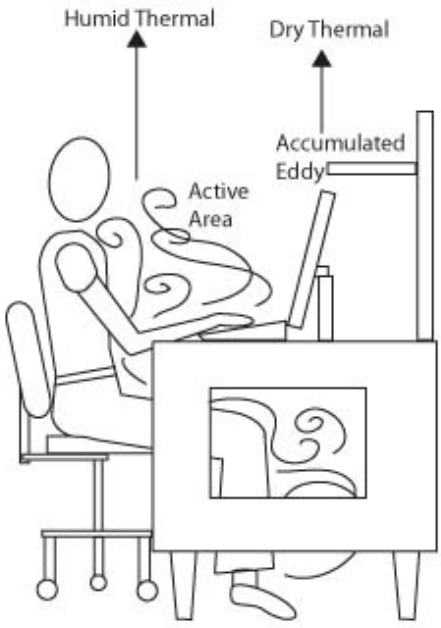


Figure 3.19: Desk Micro-Environments

consider the mechanisms within the personal envelope can lead to less effective sampling strategies. It's the interaction between these two volumes that is the source of most health complaints. In order to collect samples relevant to the complaint the micro-environments to which the person is exposed must be identified. Next, the interaction between the micro-environment and the personal envelope should be evident. We have already considered a few microenvironments, the storage cabinet that concentrated glass fiber and the file cabinet covered with accumulated dust. Lets now consider a few more micro-environments and how they interact with a person.

Consider the simple case of a person working at a desk. There are at least two micro-environments operating on the person. One of these is the area under the desk that is linked to the person by the feet, legs, and lower torso. Another micro-environment is the top surface of the desk that is linked to the person by the hands, arms, and upper torso. Other local micro-environments may include a filing cabinet, a book shelf, cubical partitions, doorways, windows, heating registers, or other unique system. Let's just examine the two desk micro-environments.

The area under the desk includes the floor, perhaps a computer with a cooling fan, drawers or shelves, and the chair. Often the area is enclosed to some extent with a partition at the back of the foot well. The linkage with the person begins when the person sits down. Air and particles that had accumulated on the chair are displaced into the personal envelope by this simple action. Next the person slides into the desk. The feet stir up the particles on the floor below the desk and displace particles that had accumulated on the shoes earlier. These airborne particles can then be captured by the convective flow in the personal envelope that runs up the legs over the torso to the mouth, nose, and eyes. The flow is kept close to the body by the Coanda effect and becomes more efficient over the first few minutes as the turbulence created by other movements begin to dampen out. If there is an allergen, toxin, or an irritant in that micro-environment at a level that will cause a rapid response then the occupant will be aware of its presence within the first ten to fifteen minutes. Insect, rodent, or mold allergens may be concentrated on the floor. Construction dusts or other irritants or toxins may be tracked in from other areas and be concentrated here.

The top of the desk will receive the same particle fallout but there may be a number of additional particle sources not as well represented on the floor. The linkage with the personal envelope is also different. Movement of the arms and hands over the desk stirs up particles and collects particles. Shuffling of paper creates particles and lofts settled particles. When the hands and arms are brought into the body they carry particles with them. When the face is contacted particles can be mechanically transferred from the hands to the face. Placing the hands on the chin, contacting the lips, or placing the hands together under the nose releases collected particles to the air in the convective flow toward the nose for inhalation and toward the eyes.

Conclusion

Particles, spaces, and surfaces are dynamic. As people move about in their personal cloud of particles new particles are being added to their environment. Some of these new particles have health implications. Some occupant complaints may be evident due to errors of design, poorly controlled emission sources, or other more global process. In these situations many occupants may have a similar compliant. Some problems are due to the occupant's interaction with a specific micro-environment. In these cases there may be only a few people, or even one person, with a complaint. In both cases it is the personal envelope that is important. Those areas with the most evident linkage to the personal envelope are important sample sites.

Questions:

1. What two forces dominated the behavior of airborne particles?
2. What must you know to determine how fast a 100 micrometer particle settles?
3. Why do particles collect behind the switch plate on the wall?
4. What is the Boundary Layer?
5. What causes "Ghosting"?
6. What forces hold particles to surfaces?
7. What are the three types of motion for particles on surfaces?
8. How is a Micro-Environment defined?
9. Describe the "Personal Envelope"?
10. Name two mechanisms that allow contaminants to enter the Personal Envelope?

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CHAPTER 4: PARTICLES AND INDOOR ENVIRONMENTAL COMPLAINTS

Introduction

Particles are allergens, irritants, toxins, infectious or infestious agents, and they affect attitudes in the workplace. It has been generally observed that the incidence of asthma and allergies in children and adults has increased. This seems to be true. In any event the incidence of respiratory complaints from homes, schools, and offices has significantly increased. Many of these complaints, including those from asthma, are due to membrane irritants in the environment rather than allergens[1], but allergens are still a major concern.

Toxins in the environment are another serious concern. Many of these toxins are associated with particles or are carried by particles. Some mold spores carry potent toxins. Chemicals tracked in from lawns or gardens can accumulate in the indoor environment. Materials can be carried in from other sites that can cause problems in their new location because they are unsuspected. Soot from a leak in a furnace or pellet stove may indicate an unacceptable exposure to carbon monoxide. Fugitive emissions from a local industry may cause problems.

- **Allergens**
- **Irritants**
- **Toxins**
- **Infectious or Infestious Agents**
- **Mental Anguish**

Figure 4.1: Sources of Complaints

Infectious and infestious agents range from Aspergillus fungus to Scabies mites. Various biting insects may be included here though they are not strictly speaking an infestious agent. There are many fungi that will infect the body. These are most hazardous to people with impaired immune systems. Their detection in the environment can be critical to the health of some individuals. The infestious agents include lice, mites, fleas, and other critters that can cause irritation to the skin, secondary infections, allergic responses, and even localized necrosis. Tapelifts directly from the skin and from surfaces in the living area of the affected individual will often provide evidence of the presence of these agents.

Soiling of clothing or accumulation of dust in the environment can have a negative effect in regard to concern about a latent threat to health, or just annoyance over the lack of cleanliness. Knowing the source of the particles and their potential impact on health can often ease the mind and even reduce the impact of the source.

The effects of these particles are often almost instantaneous or they have short delay intervals, minutes to hours. Recovery times after leaving the environment vary from minutes to a few days depending on the nature of the problem and how much of the particulate matter is carried out of the environment on clothing. There are a wide variety of particles that have been correlated to complaints by building occupants. In this chapter we will list some of these materials and try to put them in some perspective.

Note that the title of this chapter deals with Environmental Complaints and not with risks to health. Complaints affect moral and it is important to address those complaints in order to maintain an effective workforce, to keep student alert in the classroom, and to make our homes comfortable.

Complaints may result from combinations of agents in the environment where each individual agent is below the level at which complaints might be expected. There is an excellent example taken from a paper by G. S. Rajhans[2] on the frequency of "complaints" of all types relative to the carbon dioxide levels in offices. Complaints began as the CO_2 level approached 600 parts per million. By 800 ppm CO_2 complaints were increasing. By 1000 ppm CO_2 complaints were common. A similar relationship has been noticed in commercial aircraft cabins as a result of an increase in the percent of recycled air. The permissible exposure limits, in this case of CO_2, are well above these levels (TWA of 5000 ppm). That same relationship is encountered in the case of most other materials in indoor environments. There may be serious health effects on chronic exposure to some of these things at low levels[3] but that has not been determined. The subject of this chapter is not "Risk to Health" but rather levels that result in complaints. Complaints, in most cases, warn us about conditions before they become detrimental to our health. Reacting to these complaints rather than insisting that no harm is being done can have a very positive outcome. This chapter is an introduction to some of those particles that are the cause or are associated with the cause of environmental complaints. Hazards that can be detected through forensic microscopy that don't cause any immediate symptoms will also be briefly presented.

- Animals
  - Bird
  - Cat
  - Dog
  - Rat
  - Animal, Other
- Insect
  - Cockroach
  - Carpet Beetle
  - Moth
  - Insect, Other
- Fungus (Mold) Spores
  - Aspergillus Spores
  - Cladosporium Spores
  - Penicillium Spores
  - Fungal Spores, Other
- Pollen
  - Tree Pollens
  - Grass Pollens
  - Weed Pollens
  - Pollens, Other
- Mites
  - Dermatophagoides (Der)
    - Der. pteronyssinus
    - Der. farinae
  - Tyrophagus putrescentiae
  - Other Mites
- Plant Parts
  - Cottonwood Seed Hair
  - Wood Sawdust
  - Starches
  - Other Plant Parts
- Chemicals
  - Plastics
  - Metals
  - Cleaning Agents

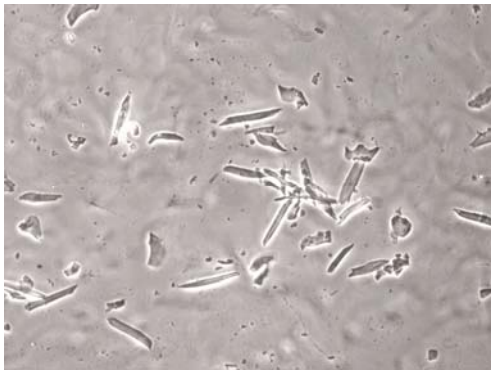
Figure 4.2: Partial List of Particle Allergens

Particle Caused Health Complaints

Allergens

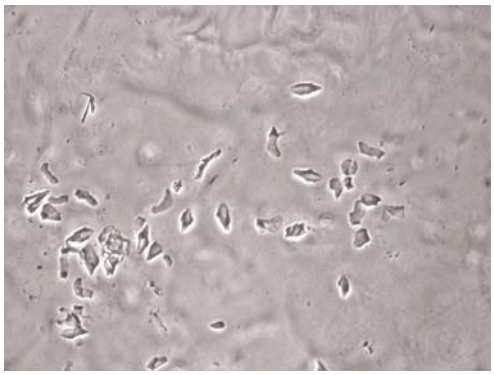
There are a number of particles that are known to cause health complaints. Allergens are one well established group. Allergens are substances that result in the formation of specific, identifiable immune agents in the blood following exposure.

Most allergens are associated with distinct particles. These include pollens[4,5], spores[4,6,7], pet dander (Photographs 4.1 and 4.2), insect parts[8,9], mite parts and frass [10], rodent debris [11], bird debris[12,13], debris from various parts of other living organisms[14], and various chemicals[15,16]. Figure 4.2 is a short list of some of the common particle allergens. A longer list can be found in the index of BIOAEROSOLS HANDBOOK by Cox and Wathes[17]. All of these particles can be identified under the microscope even though they may be present at very low levels (10's of parts per million). The techniques available to the forensic particle analyst include morphological analysis and detection of specific allergens. Morphological analysis, in this sense, includes the analysis of shape and the optical effects that are the result of the nature of the molecular organization of the particle. For many particles the shape is sufficient. Pollens are an example of allergen carrying particles that have a specific and characteristic shape. But the allergen in many pollens are carried by starch bodies[18] (see photograph of pollen releasing starch bodies on page 4 of Chapter 1). These starch bodies are characterized by their shape and the black Maltese Cross pattern across the grains when they are viewed between crossed polarizing filters. There are insect fragments, mite fragments, fungal fragments, bird debris, and various parts of other living organisms that have similar shapes and can be hard to distinguish based on their shape alone, but they have different optical properties detectable using polarized light or other optical technique. This is all part of morphological forensic particle analysis.



Photograph 4.1: Dog Dander

Cell are elongated and higher in birefringence than Human cells (Photograph 3.3).



Photograph 4.2: Cat Dander

Cat dander is more rhomboidal and is thinner at one end.

Forensic particle analysis for allergens also includes the antibody labeling of specific allergens in a mount. This labeling is very selective and marks the particles carrying only that allergen with a distinctive color or fluorescent marker[19]. Antibody labeling allows for the detection of allergens that have migrated to particles not typically associate with that allergen. Tovey and others have made significant strides in the characterization of individual particle carriers of allergens using this and related techniques[20,21,22]. Labeling is limited to testing only a few allergens in any single mount but work is currently being done to extend the capability of this labeling technique.

Airborne concentrations of allergens may be at or below detection limits at any given time but surfaces often contain a history of exposure. That is one of the reasons that pollen counts are generally based on the number and types of grains that have settled onto a slide over a twenty-four hour period. Particles, even those with small aerodynamic diameters, do end up on surfaces. In indoor environments reservoirs of these particles on surfaces can be easily detected. These particles on surfaces have not been removed from the active environment just because they are not airborne for the moment[20]. As we have seen from Chapter Three, particles on surfaces don't stay on surfaces. Under some rather common conditions these particles can become concentrated in the breathing zone of a person in that environment.

Most allergen testing in indoor environments is being conducted using (ELISA) testing. ELISA testing of vacuum cleaner dust is one of the most common methods used for evaluating the presence of allergenic contaminants in an environment. ELISA tests are very specific and provide reliable quantitative data for a specific sample, provided the sample is large enough. The problem with ELISA data as currently used is not with its reliability with regard to the sample but rather with the sample itself. Vacuuming is a very ineffective sampling technique for particles with aerodynamic diameters of less than about 50 micrometers. Most allergen or allergen-containing particles are below that size. Mechanical disturbance of the surface being vacuumed improves the effectiveness but recovery is still rather poor. The result is that the collection efficiency for some of these allergens is in the range of 1%[23]. Variations in collection efficiency from 0.2% to 4% or from 1% to 20% introduce a factor of 20 times between the two results. This is the type of variability seen in many side by side studies of the same areas in the same room[24,25]. That variability may not be significant in a particular case because if a person is reacting to an allergen in the environment and that allergen is demonstrated to be present at levels significantly above the detection limit that may be enough. A drowning man doesn't care if the water is twelve feet deep or two hundred feet deep, it's too deep. If ELISA is to be used in a more discriminating way then the quality of the sample must improve. Chapter 5 addresses this problem in more detail.

Sample size is a major limitation for standard ELISA testing. ELISA requires the collection of a relatively large quantity of material. This requires the collection of dust over a larger area that is relatively heavily loaded. Most locations of interest are simply too small or too lightly loaded to provide a large enough sample. That has lead to the standard carpet vacuum sample. Although carpets are a surface of interest vacuuming has not proven itself to be an effective sampling technique with regard to allergens. Vacuuming of large areas tend to averaged concentrations over a larger area so peak exposures at specific sites may be missed. Forensic microscopy can work with samples many orders of magnitude smaller.

One of the major advantages of forensic particle analysis over ELISA testing is that forensic particle analysis doesn't require the selection of a specific allergen for testing. Even if specific antibody staining is being used the presence of another allergen, such as another species of mite or a rat hair, is easily detected. All allergens are being tested at

the same time using the light microscope. An ELISA test for mites can detect Dermatophagoides pteronyssinus or farinae but only one or the other. Neither of these specific ELISA tests would detect any of the other more than one hundred mites that can live in an indoor environment, many of which are also allergen producers[26,27,28]. Forensic microscopy does detect these other species of mites.

Irritants

Another major source of upper respiratory and eye problems are the mucus membrane irritants. An irritant is defined as any substance that results in inflammation at the site of contact. Short glass fiber, Long glass fiber, stiff plastic fiber, wood sawdust, carbon fiber, toner, paper fiber, quarry dust, cement dust, other industrial dusts, plant hairs, high dust loading of any type are a few of the particle irritants that have been documented. The chemical irritants will be addressed latter in this section.

Short glass fiber is a major cause of these problems in the indoor environments[29,30,31,32,33,34]. Glass fiber is used in construction materials found everywhere in indoor environments. It is used as thermal insulation, sound dampening, and as a reinforcing agent in many materials. It is found in exterior walls, acoustic ceiling tile, ventilation system sound dampening, filters, plaster, joint compound, wallboard, linoleum, paneling, roofing, and glass fiber/resin composites. In numerous studies it has been shown to correlate well with "Sick Building Syndrome"[32]. New buildings can be significantly contaminated with glass fiber. In older buildings glass fiber can become a problem as construction materials degrade or activities in the building change. Many problems attributed to mold in the past have more likely been the result of glass fiber exposure (see Case Histories in Chapter 1).

Environmental glass fiber is not just glass. Glass fiber by itself seems to be sufficient cause for concern but most environmental glass fiber is coated with other substances that may contribute to the final response. When skin tests for allergens are conducted the response is much greater if the skin is irritated. Glass fiber not only irritates the skin or mucus membrane but it also delivers a variety of foreign substances to the surface and sub-surface of the tissue. That is especially the case with glass fiber from the ventilation system.

- Glass Fiber
  - Short
    - Acoustic Ceiling
    - Thermal Insulation
    - Sound Proofing
    - Reinforcing
  - Long
    - Acoustic Ceiling
    - Thermal Insulation
    - Sound Proofing
    - Reinforcing
- Stiff Plastic Fiber
- Carbon fiber
- Wood Sawdust
  - Cedar
  - Mahogany
  - Oak
  - Other Wood
- Itching Powders
- Siliceous Phytoliths
- Picrolite (from Quarry)
- Quarry Dust
- Cement Dust
- Tire Wear
- Total Dust Loading

- Chemical Irritants
  - Cleaning Agents
  - Plant Oils
  - Phenols
  - Toner
  - Styrenes
  - Latex
  - Epoxides
  - Alkyline Minerals
  - Others

Figure 4.3: Some Common Particle Irritants

Sharp fibers of many types are irritants regardless of what other agents may be associated with them. Sawdust is wood fiber with its lignin in place. These are stiff fibers rather than the softer, lignin-free paper pulp. Itching powders of all kinds are plant fibers. They may be taken from maple seed pods or rose hips but it is the morphology and the stiffness of the fiber that seems to cause the problem. In some factory environments stiff polymer fibers are generated, normally as a result of a plastic forming processes. These too result in health complaints. Carbon fiber is another notorious industrial fiber. Phytoliths are a common material in samples from some parts of the country. The phytoliths of interest here are the siliceous structures produced by some plants as a stiffening structure in stems and leaves[35, 36]. When the plant decays these silica structures become part of the soil. The siliceous phytoliths that may be physical irritants are the long, fibrous type commonly formed by grasses. The role of phytoliths in health complaints has not been established but morphologically many of then resemble short glass fibers in the size range that are known to be irritants.

This same morphology is shared by a variety of non-asbestos fibrous minerals. Picrolite fiber from quarries is one well documented fibrous mineral found in igneous rock formations. When the bulk rock is quarried for use in rock walls or rip-rap fibers of picrolite become airborne and can become a physical irritant. Picrolite is one of a number of zeolite minerals generally found in igneous formations, which are often fibrous. One zeolite fiber, erionite, has been implicated in mesothelioma.

Abrasive materials are also irritants but less so than the fibrous materials. This may be due to the fact that their aerodynamic diameter limits respiratory exposure. They are significant irritants to the skin and the eyes. As fine dusts they are a long term health problem causing pneumoconiosis.

Total airborne particle loading can be an irritant to the eyes and the upper respiratory system. This occurs at levels far below the nuisance dust levels of concern to OSHA in industrial environments. Dust concentrations about three orders of magnitude below the nuisance dust limits result in an increase in respiratory and dry eye complaints in schools and offices.

Another major type of irritant in the indoor environment is chemical. Many of the particles mentioned above may also carry on their surfaces chemical agents that irritate the skin and mucus membranes. A number of wood species carry irritating chemicals in the form of "oils", long chain or aromatic carbon compounds. Other plants have similar protective oils that are strong irritants. Clove oil, cinnamon oil, nutmeg, vanilla, and other spices are well known for their effect as irritants. The list of natural plant chemical irritants is a long one, including common flower and vegetable garden plants.[15]

Membrane surfaces can play a role in the complex chemical interaction of particles and health effects. Particles in the nasal passages can cause the release of neuropeptides that restrict airflow in the lung[1]. That is apparently how glass fiber and other irritants can trigger asthma episodes. Particles together on a membrane surface may create a special environment in which chemical reactions can occur that would not have been anticipated.

This may lead to phantom odors or more severe effects that are the result of surface chemistry rather than the bulk chemistry of the substances[37].

Solvents, cleansers, detergents, adhesives, cements, soaps, enzymes, fertilizers, disinfectants, oils, acids, and bases are all irritants in some situations. Many of these are referenced in Fisher's Contact Dermatitis[15] and in Goldner's article[38] on work-related irritant contact dermatitis. Most of these materials can be seen as particles or they are associated with characteristic particle assemblages.

There are a number of other particles associated with irritation of the upper respiratory system not included in the discussion so far. Tire wear (see Photograph 6.3), nitrate and sulfate salt aerosols, cosmetics, soot, cenospheres, metal fume, smoke (see Photograph 6.4), cooking odors (popcorn in particular), floor wear, and toner have also been implicated as irritants in office environments. A special case of acrylate-styrene floor polish wear was sited in one reference[39]. This author has seen a correlation between floor stripping and finishing debris and eye and upper respiratory complaints. One example of these particles types is shown in Photograph 4.4. Paper fiber has been identified as an irritant in some references [40]. Some of the materials implicated by these references may be the result of total loading and not any chemical or mechanical process of irritation. Health complaints correlate well with slit-type air impactor surface obscurations of 20% or more.

Toxins

Industrial, laboratory, and home environments are often toxin rich sites. Toxins are chemicals that adversely affect health by causing injury, illness, or death. Industries and laboratories are places we expect to encounter toxins and there are generally the required Material Safety Data Sheets (MSDS's) to go with them. Fugitive emissions that introduce these materials to office areas can cause problems. The toxins available in households are remarkable and their handling can be unusually casual. Pesticides, herbicides, fertilizers, fungicides, and other toxins are common and may be used indoors or tracked indoors by the householder. Few particle toxins outside industrial environments act so quickly as to alert us to their presence in low doses, but there are a few exceptions. Metal fumes can cause sudden illness on exposure[41]. Chlorine gas from the use of sodium hypochlorite (bleach) can cause sudden trauma and about one householder dies each year from acute exposure in the home. Many more are made ill by exposure[42]. There have been reports of chlorine type exposures coinciding with the use of chlorinated silicones used to "seal" contaminants in ventilation systems. These incidences have not been thoroughly investigated. They are mentioned here only because this is becoming an increasingly popular practice.

Infectious and Infestious Agents

Indoor environments contain entities that can infect the body or infest the body. Infectious agents include a variety of microscopic agents. These may be viral, bacterial, or fungal. The viral and bacterial agents do not lend themselves to identification on environmental samples using the light microscope but they are occasionally associated with particles that are characteristic[43]. The fungal agents, such as Aspergillus, are large

enough for characterization[6,7] though they would require culturing to identify species and to verify that they were live.

Infestious agents include mites, lice, ticks, and fleas primarily. These agents and their fragments are easily seen and identified under the light microscope (see Photograph 4.3).

Photograph 4.3: Flea Frass

Particles Associated with Health Complaints

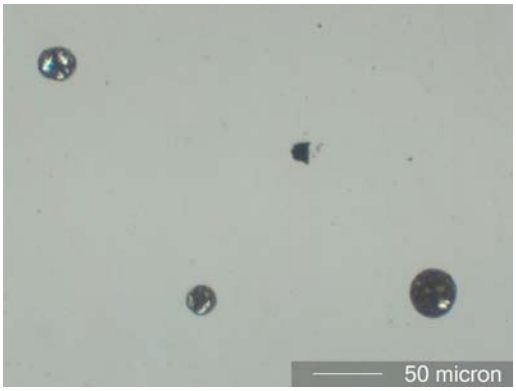
Assemblage analysis can often indicate the probable presence of a gas phase contaminant in an environment. Tire wear and cenospheres are often associated with vehicle emissions, the smell of "exhaust". Particles and gasses behave in predictable ways. Gasses travel with and as the gasses of the atmosphere. Particles travel both by mechanical transport and by the combined effect of airflow, gravity, obstructions, and surfaces. The presence of tire wear does not indicate the presence of vehicle exhaust but the presence of high levels of tire wear and complaints of intermittent vehicle exhaust odors is consistent. Monitoring gasses over time may or may not detect the exposure events, depending on the sampling technique and nature of the exposure. Particles have a much longer residence time in the environment and so often provide better documentation of exposures than an analysis of the gasses that are present.

Soot as an indicator of possible carbon monoxide exposure is another useful association. If the soot levels in a home are unusually high and the symptoms are consistent with carbon monoxide exposure then the environment should be monitored for carbon monoxide. Carbon dioxide is often a routine measurement made in indoor environments and the carbon dioxide measurement may also provide an indication of the exposure. If the carbon dioxide and/or the carbon monoxide level is measured and is found to be low then the person may need to be tested for carboxyhemoglobin in the blood. Environmental sampling is an imperfect science at best. Soot particles track with carbon monoxide. Rapid accumulation of soot in a building is not a good sign even if elevated carbon monoxide levels are not detected using other techniques. Particles are historical documents. They provide a history of exposure that may be intermittent but extreme. Real time monitoring may miss the events entirely or may not be in a position that correctly monitors exposure. That seems to be especially the case with carbon monoxide exposure due to the physiology of that gas in the body[3,44].

"Musty" odors are not always from indoor fungi. Bacteria and algae both create musty odors similar to those from fungi. The presence of humus or diatoms in a sample may indicate an exterior source for the odor. Pooled water around an air intake or local dredging operations are sources of significant populations of diatoms, algae, and humus. High humus content and odors are also associated with digging in boggy soils.

Another source of musty odors is cleaning materials. Some of the ethanolamines commonly used in cleaning products produce a strong musty odor in the environment. Ammonia at low levels in the environment may result in a musty odor. Residual cleaning debris can often be seen in the particle assemblages from indoor environment.

There are a number of situations in which an environmental complaint may suggest a specific source. Even if the agent is a gas phase product there are often particles associated with that source. These particles can aid in implicating that source by demonstrating an active path from the source to the receptor[45,46].



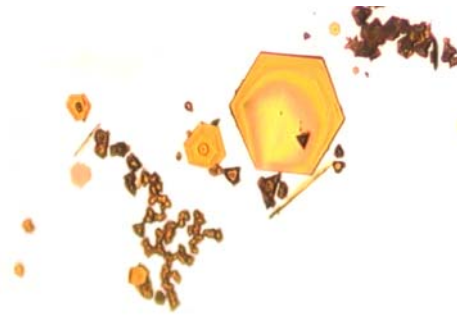
Photograph 4.4: Floor Striping Debris Associated with a "Musty" Odor

Detrimental Particles not Resulting in Complaints

There are a number of particles that will not result in health complaints but are detrimental to health. Asbestos fiber is perhaps the most obvious example. These particles have no short term symptoms but can be detrimental over time as a result of chronic low level exposure or acute event exposure. There are many parts of the world where exposure is part of the natural background[47,48,49]. Little can be done about the natural background but an awareness of the source can significantly reduce exposure. There have been many occasions where asbestos fiber has been detected in indoor environments as part of an investigation for other environmental concerns. Many of these involved an inappropriate use of local materials, assuming they were safe (see Figure 4.5). Had it not been for the other concern the presence of asbestos fibers would not have been detected. Had the analytical approach not included forensic particle analysis the asbestos would not have been detected. The author has been personally involved with such cases in the states of Washington, Oregon, California, Arizona, and Montana.

Photograph 4.5: Chrysotile (brown) and Actinolite (green) Sand Grains from Western Washington State.

Heavy metals in paints and as residues in the environment can cause a number of subtle but detrimental effects that build with time. Their detection is often not the initial intent of the analysis but was discovered during the analysis for other agents. Many of these heavy metal compounds have characteristic optical properties. Conformation of the presence of a heavy metal is typically performed on the particle using a microchemical test[50](see Figure 4.6). Lead paint is one of the most prevalent exposures to heavy metals seen indoors but there are other heavy metal pigments that can be a problem[51]. One of the great advantages of forensic particle analysis is its ability to detect and identify the unexpected.



Photograph 4.6: Lead Iodide Crystals Confirming Lead in Paint: A Microchemical Test

Particles as Indicators of Environmental Quality

Anxiety often drives the concern for environmental purity. A better educated public is aware that factors in their environment can diminish their lives and the lives of those for whom they care. Spectacular claims and unrealistic expectations trigger alarms for conditions that used to be considered "normal" or manageably inconvenient. On the other hand, the rush of new construction materials, new construction methods, and new products into the market place has resulted in some spectacular failures and challenges to the health of the general public. The environmental scientist is in the middle of this caldron. This chapter reflects the current state of environmental science with regard to the relationship between quality of life perceptions and environmental factors. Complaints need to be addressed even if a well defined cause and effect relationship has not been established. That does not mean that all complaints are founded on real environmental factors but rather that in the past we may have been to eager to discount complaints because we couldn't find a suitable cause.

That has now been turned on its head in some cases. Some agents in the environment have been attributed phenomenal impact. They are easily detected, they are always present and the client has been preindoctrinated to believe. That is the current situation with "mold". There is no question that moisture causes problems in buildings and that one of those problems with health ramifications is the growth of fungus, but in many cases mold is not the problem. In many cases only mold is looked for because the environmental specialist is not aware of how to look for anything else or doesn't think it is necessary. If you already know the answer you don't need an analysis.

The goal here is to look at the environment in a new way. It is not just specific particles or gasses that can cause problems but rather the environment as a whole. There may be multiple problems in a building and unless they are all addressed no one in the building

will feel that the problem has been resolved adequately. The problem in a building may have nothing to do with a change observed in the building though the building occupants believe that the change is related. It is important to document the nature and source of the change as well as to document the likely cause of the problem if the goal is to reestablish confidence in the quality of the environment.

If all we did was to look for those things that we know cause problems we would never discover unsuspected agents. The publication, Damp Indoor Spaces and Health[52], lists the four categories of evidence the authors used to assess the relationship between an exposure and a health response based on the quality of the available data. These were:

1. Sufficient Evidence of a Causal Relationship.
2. Sufficient Evidence of an Association.
3. Limited or Suggestive Evidence of an Association.
4. Inadequate or Insufficient Evidence to Determine Whether an Association Exists.

One difficulty with this set of categories is that it assumes an adequate analysis of all the agents present that could produce the outcome observed. Very few studies of specific agents in the indoor environment meet the necessary requirements for level 1, 2 or even 3 due to the fact that they attempt to correlate poorly defined outcomes to an analysis of a single agent. All other agents in the environment that could equally cause the observed outcomes are ignored. Forensic particle analysis provides a mechanism to document the environment in greater detail than any other method. It will be required to continue to advance the understanding causal relationships in the area of health complaints. It can be used to answer questions, calm concerns, and provide perspective on the quality of the indoor environment.

Conclusion

In URBAN ENTOMOLOGY by Walter Ebeling there is a chapter on *"Delusory Parasitosis and 'Cable Mite' Dermatitis"*. It discusses the psychology of imagined complaints. In my experience some of these "imagined" complaints have been the result of real agents in the environment, just not the ones earlier investigators looked for. An equivalent delusionary psychosis is the belief that all things must be caused by "mold". There really are imagined complaints but they are a very small part of the total number. Similarly, the vast number of health complaints attributed to mold are not the result of mold. In each case the main reason for the faulty conclusion is the limitation of the analytical methods used. This chapter is far from complete. There are more agents out there and the synergism between agents has been largely uninvestigated because so few of the agents have been adequately investigated. It is hoped that in the future forensic particle analysis will be more broadly applied.

Questions:

1. What are the five types of agents that can cause health complaints?

2. How is the body's response to Allergens different than to irritants?

3. How can particles suggest the presence of a gas-phase contaminant?

4. How is forensic particle analysis different than other monitoring methods?

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CHAPTER 5: PROJECT DESIGN AND PRESENTATION

Introduction

There is so much variability in the distribution of particles in the environment that it is difficult to justify improving the sampling or analytical accuracy (see the subsection titled ***Fit-For-Purpose Model***). Adequate sampling systems currently exist. Analytical procedures are many orders of magnitude more accurate than they need to be in some instances and even in the worst case they are sufficiently accurate that they have negligible effect on the final variability of the results. Random sampling is an unjustifiable waste of resources (see the subsection titled ***Point-Of-Exposure Bias***). That is not to say that we are as good as we need to be. Quite the contrary. The wrong samples are being collected for the wrong reasons and they are being analyzed incorrectly or incompletely. Particles are not gasses. They don't behave like gasses (see Chapter 3). They are not defined by their elemental composition, their shape, or their crystal structure but by all three together and more (see Chapter 2 and 4). This chapter takes a new look at how we design a project and how we can justify the project costs to a client using existing sampling and analysis technologies. It also examines the cost impact of doing nothing or doing the wrong thing.

- EXPOSURE
  - Changes with time
  - Changes with location
  - Changes with activity
  - Changes with threshold
- SAMPLING
  - Efficiency
  - Efficacy
  - Selectivity
  - Suitability
- ANALYSIS
  - Precision
  - Bias
  - Accuracy
  - Sufficiency
  - Availably
- COST
  - Per analysis
  - Return on investment
  - Cost of false a positive
  - Cost of false a negative
  - Cost of delay
  - Cost of doing nothing
- TIME TO RESULTS

Figure 5.1: Environmental Design Variables

The purpose of sampling for forensic particle analysis is to assess the likely exposure of a person to the particles in that environment that may result in complaints or health concerns. This is a fundamentally different task than randomly sampling the environment to determine environmental loading. Formally, it requires the application of the concept of "fitness-for-purpose". Fitness-for-purpose is an approach that attempts to relate project costs and return-on-investment to exposure uncertainty, sampling uncertainty, and analytical uncertainty.

Exposure Uncertainty

A complaint is registered when a condition becomes sufficiently manifest that an association between the condition and the environment has been assumed. In most situations there will be individuals significantly affected and some with little or no

complaint. This discrepancy may be due to sensitivity to the agent, exposure to the agent, or synergistic conditions that increases the susceptibility to the agent. Sensitivity is the result of a person's physiology. Exposure is the result of an individual's activities and the distribution of the agent through the environment. Susceptibility is the result of personal behavior patterns that may increase exposure to the agent or increase the effects of that exposure. These different aspects of exposure need to be kept in mind when selecting sampling procedures and locations. A point-of-exposure bias may be intentionally introduced.

1. **Sensitivity**
2. **Distribution**
3. **Susceptibility**

Figure 5.2: Factors Affecting Exposure

Sampling Uncertainty

A preliminary condition on the sampling method or methods selected is that they must be efficient at collecting particles in some representative fashion. They must collect all of the types of particles that may cause the compliant. They must collect them in a fashion suitable to the requirements of the analysis planned. The sampling procedures should consider the point or points of exposure. The response of the affected individual may be associated with a specific locality or particular activities. These need to be sampled in a way that reflects the exposure. The complaint may be the result of a cyclic exposure that deposits agents that are effective over time. Cleaning the environment prior to sampling may remove these agents and if we sample prior to the next cyclic event the responsible agent will not be present. Samples that represent exposure history are an important aspect of sampling representative agents.

1. **Collection Efficiency**
2. **Collection Efficacy**
3. **Medium Suitable for Analysis**
4. **Consider Point Sources**
5. **Representation of Exposure**

Figure 5.3: Factors Affecting Design of the Sampling Plan

The sampling method should have the widest possible efficiency for the great variety of particles common in the environment that might result in complaints. Particles settled on surfaces are a critical part of the sampling plan. These settled particles may accumulate to high levels and when they are disturbed they can create a short term extreme exposure within the personal envelope of the individual involved. In chapter 4 we discussed some of the particle types that result in complaints. These vary from allergens to toxins. They include industrial emissions, vehicle emissions, construction debris, combustion products, material degradation products, fragments of minerals, plants, and animals. The sampling procedure must collect all of these particle types or a predictable subset of them and must do so in such a way that the particles can be adequately analyzed. The ability to use Assemblage Analysis (Chapter 2) is restricted if a subset is collected that is too

constrained as a result of the sampling method or location selected. Sampling uncertainty is a measure of how well the sample duplicates the concentration of the agent in the environment responsible for the complaint and includes the uncertainty that is the result of the variability in the concentration of the responsible agent as a function of time at this location. This uncertainty includes both systematic errors and random errors. The systematic errors result from the sampling protocol selected (equipment, application, and cyclic process errors) and the random errors are the result of the variability at the location independent of the sampling protocol.

Analytical Uncertainty

Analytical uncertainty must begin with the processing of the sample received from the field. The sample must be amenable to the analysis planned. Particles collected on a Teflon membrane filter will be very restricted in terms of the quality of the analysis that can be performed. Masking tape is not an appropriate sampling medium for particle analysis. The analytical protocol must be designed to balance cost with the value of the resulting data. That protocol must provide adequate detail for the detection and quantification of the agent or agents that may be causing the complaints (assuming the sampling protocol was appropriate).

The analytical uncertainty is again the product of both systematic and random errors. The systematic errors tend to be the most significant between laboratories in forensic particle analysis because of the dependence on the skill and experience of the microscopist performing the analysis. There are relatively few schools available for the training of a microscopist in particle identification using a "short course" format. Two such schools are McCrone Research Institute in Chicago (www.mccrone.com) and Microlab Northwest near Seattle (www.microlabnw.com). A few universities offer course work in light microscopy such as the University of Florida, the University of Illinois, University of Alabama, and Cornell University. McCrone Research Institute offers an on-line particle identification aid that a laboratory can subscribe to if they have a staff microscopist familiar with polarized light microscopy. Microlab Northwest provides a free service in their on-line Photo Gallery to aid in the identification and interpretation of particles and assemblages. Most of the photographs on the Microlab Northwest site are particles in actual environmental tapelifts so that the particles can be seen as they would actually appear in an environmental sample. The discussion that accompanies the photograph tends to be more directed toward what the particle signifies and how it may have arrived

McCrone Research Institute
(www.mccrone.com)

Microlab Northwest
(www.microlabnw.com)

Microtrace Scientific
(www.microtracescientific.com)

New York Microscopical Society
(www.nyms.org/Courses.htm)

Smithsonian Institute
(www.si.edu)

Figure 5.4: Partial List of Schools for Particle Identification

at that environment. Because of that approach this site may be useful to a non-microscopist in interpreting the results of a particle analysis.

It is important that for this type of analysis the name of the analyst be provided and that the analyst be available for consultation on the results of the analysis and the conclusions reached. There are literally hundreds of different types of particles seen in a typical analysis of which maybe twenty to thirty categories or types will be mentioned specifically in the report. Those will tend to be the most common particles and the particles most typically associated with the concern expressed. It is like answering a friend's question about the types of food carried by a local grocery store. How detailed do you get? If the interest is in chicken soup then the fact that the store carries 28 varieties of chicken soup and all the raw materials for preparing a variety of different versions of chicken soup is relevant information. Then again, simply mentioning they carry chicken soup may be sufficient. If the interest is in buffalo steaks the information on chicken soup is not very helpful. The microscopist can not guess your concern. In Chapter 2 it was pointed out that the analysis only goes as far as is necessary. If there is a specific concern or set of symptoms that will help the microscopist know how far to go in a specific direction. You will get much more useful data if you describe the problem and cite concerns. If the concern has changed or additional issues have become important the microscopist may be able to provide additional insight from the existing samples.

Particle Analysis is like grocery shopping. You pay most attention to what you need. Twenty-eight varieties of chicken soup are still not a buffalo steak. Twenty-eight varieties of mold spores are still not glass fiber.

Figure 5.5: Chicken Soup or Buffalo Steak

The other source of analytical uncertainty has to do with the biases introduced by sample preparation and random effects. The number of samples, the approximate number of particles, and the total area analyzed will affect the uncertainty of the final results. Relative quantification or semi-quantification is also important. Quantification may be by number per unit area sampled, by number per unit volume sampled, by total weight, or may be normalized to another reference particle. The need for quantification places additional requirements on the sampling procedure and can have a major cost impact. The relevance of quantification is intimately connected to the variability within the environment and the efficiency of the sampling technique. It makes no sense to expend excessive effort and expense in order to measure a parameter not reliably preserved by sampling.

At this point it would be useful to consider the value of relative quantification as applied in particle analysis. The key word here is "relative". Human observers are very good at comparing things, there is more of this than that, but not very good at estimating absolute values. The answer to this problem of reliable quantification is not automation. Two different automated particle counters may not agree within an order of magnitude when measuring a real-world environment even though both machines are within calibration limits using a standard aerosol. The answer is in understanding the value of the

information that is gained without a high level of confidence in the absolute numbers that may be present. The relative relationships between things are often sufficient to identify an unusual condition that requires more detailed investigation. To use an analogy from criminalistics, at a crime scene the presence of a single fingerprint from the suspect is sufficient to establish his presence at that location. It is unnecessary to find more or to find the exact number of his fingerprints at the scene. More investigation would be required to establish that he committed the crime regardless of the number of fingerprints present. As we will soon see, variability in the environment limits the usefulness of the absolute numbers of particles in most cases. The ability to detect and identify the "fingerprint" is the critical part of this analysis.

It is impractical to assign quantitative numbers to all the particle types present in a sample but that does not mean that the numbers of some types of particles are not important. One example would be the number of glass fibers present per square inch of surface area. The percent of glass fiber in the environment may be less than 0.001% but if there are four or more glass fibers longer than five hundred micrometers in length and ten micrometers in diameter per square inch of surface area then contact dermatitis could be expected. For this type of analysis intralaboratory precision is about twenty percent and interlaboratory precision is about thirty percent. If it were necessary to establish the percentage of glass fibers in the sample it would be necessary to count about a million particles.

Apportioning Costs

The "shotgun" approach often taken in response to a health complaint in a building is unnecessarily costly. But how can the costs be reduced in a way that makes sense? How do we select a sampling approach and an analytical method? We can follow the traditional methods which are "safe" but are often far from optimal, or we can apply a mathematical model directed toward optimizing data for the dollar spent, and targeted at the broadest range of potential causes for complaint. Using the mathematical model allows a tailoring of the analytical plan to the dollars available and allows us to assess the dollar risk, the liability, to the client as a function of the dollars spent in investigation, sampling, and analysis.

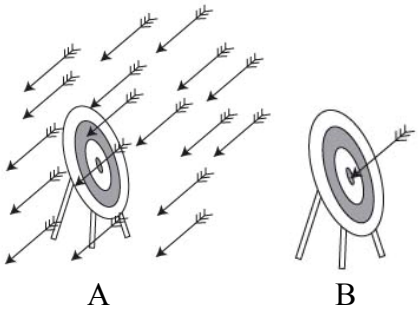

Figure 5.6: A More Ancient Version of the "Shotgun" Approach, A, or a Targeted Approach, B, to Save Resources, Which Would You Choose?

There is no guaranty that any of the untargeted arrows will hit the target.

The "shotgun" approach tends to apply standard procedures and protocols to situations that may be unique or at least not appropriate for all the protocols applied. Tailoring the approach reduces the total number of samples required

and targets specific exposures. But how do we know we are not missing anything? How can we apply logical models to optimize data?

Sampling philosophy is actually the application of mathematical and logical models to the process of sampling complex environments. Projects can be optimized using these techniques to maximize value while minimizing cost with a high probability of identifying and resolving the issue. The first step in this approach involves an application of what has been called the Fit-for-Purpose Model. It provides a mathematical model to help limit sampling and analysis costs without the loss of any real data. The second step involves the use of a logical model to focus the sampling on the microenvironment most likely to be responsible for the exposure. This is referred to as the Point-of-Exposure Bias.

Fit-For-Purpose Model

Environmental analysis can be expensive. The most effective way to control costs is by applying the "fit-for-purpose" (FFP) model.[1,2] This involves a consideration of the total variance in the project data resulting from the whole sampling and analysis process and the costs involved in the sampling and analysis. The goal is to avoid unnecessary expense while retaining accuracy by keeping the total sampling and analytical variance, s^2_{sample} and $s^2_{analytical}$ respectively, at less than 20% of the variance in the environment, $s^2_{environment}$, and keeping the analytical variance to no more that 20% of the total sampling and analytical variance.

$$0.20(s^2_{environment}) > (s^2_{sample} + s^2_{analytical}) \quad (1)$$

and,

$$0.20(s^2_{sample}) > (s^2_{sample} + s^2_{analytical}) \quad (2)$$

Reducing either of these values significantly below the 20% level is fine provided that it does not add to the total cost.

The term $(s^2_{sample} + s^2_{analytical})$ is the total variance of the measurement and can be expressed as:

$$s^2_{measurement} = (s^2_{sample} + s^2_{analytical}) \quad (3)$$

It is not practical to determine the actual sample variance and the environmental variance in the case of the typical environmental analysis but presuming more than one sample is collected the relative relationships can be estimated. It is easy enough to determine if analytical variance

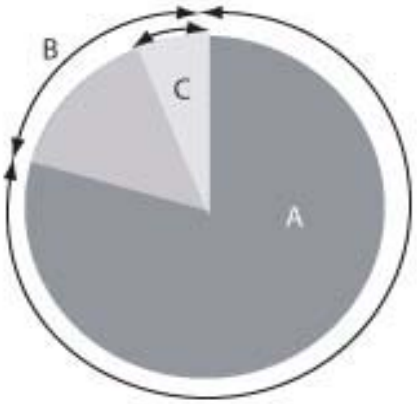

Figure 5.7: Apportioning Variance to Minimize Cost without Loss of Reliability

A is environmental variance, B is the total measurement variance, and C is the analytical method variance.

is negligible relative to the sample and environmental variance. It is a little less clear that the sample variance is less than 20% of the environmental variance if the number of samples is very small but a first-principles analysis of the physics underlying the method can often clarify the issue. These relative relationships are important in assessing the degree of variance that is optimal based on a cost-benefit-analysis applied to the FFP criterion.[3]

The costs of an environmental problem ultimately can be expressed in dollars but it is best considered in terms of the loss of resources. Those resources may be dollars, productivity, property, liability, or public relations. The cost of the analysis may be a minor factor in the total costs but if the analytical costs are not controlled the project may go to a competitor. This model will also be an effective way to demonstrate the relative value of the selected sampling and analysis plan over alternative approaches.

The analysis begins with a consideration of the cost of sampling and analysis with respect to the variance. The cost for a unit of variance, D, can be calculated using the following equation:

$$D = [(L_{sample}\, s^2_{sample})^{0.5} + (L_{analytical}\, s^2_{analytical})^{0.5}]^2 \qquad (4)$$

Where,

L_{sample} = the cost of sampling, L_s in the table below
s^2_{sample} = the variance of sampling, v_s in the table below
$L_{analytical}$ = the cost of analysis, L_a in the table below
$s^2_{analytical}$ = the variance of analysis, v_a in the table below

The tables below provide examples of how this equation would be used.

NUMBER OF TESTS	D COST/UNIT VARIANCE	L_s	v_s	$(L_s v_s)^{0.5}$	L_a	v_a	$(L_a v_a)^{0.5}$
1	$25.61	$500	1.2	$24.49	$25	0.05	1.12
2	$22.37	$540	0.8	$20.78	$50	0.05	1.58
3	$20.59	$580	0.6	$18.65	$75	0.05	1.94
4	$20.70	$620	0.55	$18.47	$100	0.05	2.24
5	$21.11	$660	0.525	$18.61	$125	0.05	2.50

TABLE 5.1: Cost per Unit Variance, Low Analysis Cost, Higher Sampling Cost

NUMBER OF TESTS	D COST/UNIT VARIANCE	L_s	v_s	$(L_s v_s)^{0.5}$	L_a	v_a	$(L_a v_a)^{0.5}$
1	$29.50	$500	1.2	$24.49	$250	0.1	5.00
2	$27.27	$510	0.8	$20.20	$500	0.1	7.07
3	$26.32	$520	0.6	$17.66	$750	0.1	8.66
4	$27.07	$630	0.55	$17.07	$1000	0.1	10.00
5	$28.02	$540	0.525	$16.84	$1250	0.1	11.18

TABLE 5.2: Cost per Unit Variance, High Analysis Cost, Lower Sampling Cost

In the examples provided in Table 5.1 and Table 5.2 the optimal cost per variance, or the maximum value per dollar spent, is for three tests. The total cost in these two examples for the best return on investment would be $655 and $1270 respectively. The cost for a single test would be $525 and $750 respectively.

The cost of sampling and analysis tends to increases as the variance decreases. One way to decrease the variance of sampling is to increase the number of samples or to sample using multiple techniques, each technique having a lower variance for some selected subset of the sample. Both approaches add to the total number of samples collected, the amount of equipment need, the time required to sample, and the variety of analytical techniques that will be required back in the laboratory. Analytical variance can be lowered in a similar way by increasing duplicate analyses and by customizing the analysis for each of the specific agents of interest, each analysis being performed separately. In the case of duplication the cost per sample or analysis, L_{sample} and $L_{analytical}$, is simply doubled. When multiple techniques are applied then the unit cost of variance is the sum of the unit costs of variance for each of the techniques.

$$\Sigma D_i = \Sigma[(L_{sample}\, s^2_{sample})^{0.5} + (L_{analytical}\, s^2_{analytical})^{0.5}]^2_i \quad (5)$$

But there are additional costs related to the project as shown in Figure 5.1 at the beginning of this chapter. The cost of the condition if nothing is done, the cost of a false positive or negative, and the cost of delayed results are real in terms of the effects on productivity and liability. These issues will be discussed latter in this chapter under the section Cost Benefit Analysis.

1. **Attempt to Model Exposure**
2. **Assess Likely Exposure Locations**
3. **Grab Samples**

Figure 5.8: Three Approaches to Point-of-Exposure Bias

Point-Of-Exposure Bias

There are three basically different philosophical approaches to sampling with the point-of-exposure bias. One involves an attempt to simulate the respiratory system within the envelope of the subject. Personal air sample cassettes are an example of that approach. Another is to assess "risk of exposure". Sampling of settled dust from multiple locations in the work space is an example of that approach. The third approach is a grab sample that represents a short interval of time, typically ten minutes or less, or represents dust from a single part of the environment that may be related to the occupied space in some way. This approach includes the quick air sample common in many investigations and the dust sample collected from carpets or other single location. Each of these approaches has its place in trying to understand the quality of the environment and a subject's exposure to particles that may result in complaints.

In Chapter 3 we discussed the way particles moved in the environment. We discussed air movement on the large scale and in microenvironments. We also discussed the human body as a microenvironment and how it interacted with both the major airflows in a building and the patterns in microenvironments. Our goal is to assess the type and quantity of particles that are likely to enter the personal envelope resulting in complaints and to identify the origin of those particles. We need to avoid the assumption that we know the cause of the problem. If we did in fact already know the cause there would be no need for sampling or analysis. If you are sampling and requesting an analysis it must be to detect something unexpected or you are wasting your clients money.

Point of exposure bias is not based on our assumptions but rather on the pattern of behavior of those registering a complaint. Samples from the ventilation system may be useful as background samples but no one works "in" the ventilation system. The presence of the agent responsible for the complaint in the ventilation system may only mean that it is also in the ventilation system. Many things seen in the ventilation system may be present at much lower or much higher levels in the work space. It is the work space that is of interest, those areas immediately adjacent to the personal envelope of the concerned party.

When selecting sites for surface samples consider the microenvironments with which the individual is likely to interact. These are the samples that will be most relevant to the individual's responses. The sample collected should reflect an accumulation of particles over time. If the person's desk were to be selected for sampling (a good idea) then a region of the desk not routinely disturbed would be selected. That would not include an area of the desk under a shelf but may include a top shelf. The top of a file cabinet may be a surface of interest but there are often two distinct areas even on the top of the file cabinet. The front area of the top of the file cabinet may be frequently disturbed with files pulled from the cabinet or files to be placed back in the cabinet. More toward the back of the top of the file cabinet may be much less disturbed and have a better collection of particles for analysis, a better history of exposure.

Air samples may be collected as a personal cassette sample, using timed sequenced impactors, grab sample impactors, membrane filter samples, or other collection device.

The sample should be collected in the vicinity of the complainant. If a teacher in a classroom is having a problem then sampling near the teacher's desk would be better than sampling at the back of the room. Similarly, sampling during the interval that the person is present performing normal duties is preferable to sampling when no one is in the classroom.

The environment to which one is exposed includes the people in the environment and the activities being performed in that environment. Surface samples carry that history but air samples do not. Air samples alone may entirely miss the responsible agent. Surface samples should be paired with air samples and the differences noted. These differences, if present, indicate past or cyclic events. If there are few differences then the environment is probably more steady state. This would suggest that the air sample is representative of the usual types of particles to which the person is exposed. There may still be a total airborne particle loading issue, as discussed in Chapter 4 on page 48.

Considering all of this it is surprising that there are a number of people who enjoy this work. They can't do the work for twenty or even forty dollars per sample. It will take an additional zero ($200 to $400), but the information you get in return will be well worth it.

Analytical Limitations Imposed by Sampling Methods

Any sample limits what can be determined about an environment. A ten minute air sample is only a partial representation of the ten minutes of air it sampled. Many of the most active allergens and irritants in indoor environments are not even collected by the standard air sample.[4,5,6,7] Air samples are important but the window they provide on the quality of an environment is severely limited. The value of air samples is improved if the number of samples collected is increased to a few hundred collected at different times of the year, month, week, and day for all significant microenvironments. Even at that many of the allergens and irritants that may be active in the environment will be missed. Air samples collected next to a wet wall covered with Stachybotrys fungus will often show no Stachybotrys spores. As the wall dries out that will not be the case. So when did you sample? What do the results mean? If no spores are found does that mean there is no problem? The sample is not the environment.

How air samples are collected is also critical to the analysis to be performed. Impaction analysis would not be appropriate for the quantification of airborne asbestos fiber. Many if not most of the fibers would escape. A cellulose membrane filter works perfectly for this application. A glass fiber filter would not work. An impaction sampler is effective in concentrating spores and pollens in a limited area for analysis. Using a filter would capture the spores and pollens but they would be widely dispersed and the cost of scanning the filter at high magnification would be prohibitive. Although a filter would collect the sample it could not be effective analyzed, where as an impaction sample will collect the spores and pollens in an easily analyzed pattern. The issue is not just collecting the agent but collecting the agent in an easily analyzable format. New devices arrive on the market at the time claiming to be more effective at capturing spores or some

other agent. The primary issue is not necessarily becoming more effective, is it easier to analyze?

Tapelifts from surfaces in the environment provide a history of events and sources at the location of the sample. Isolated events at a particular location can dominate the particle population but have no impact on people nearby. A little spilled toner near a copy machine may not represent a significant exposure risk but toner distributed throughout the environment by a faulty copy machine is an exposure problem. Single tapelifts, like any other single sample, must be used very cautiously. Sets of three lifts from an environment are often considered necessary to constitute a single tapelift sample.

Clear tape limits the types of analyses that can be performed on the particles collected. Many of the important particles will be quite small. Their optical properties are often lost in the optical activity of the plastic film backing on the tape. Even the low birefringent tapes can swamp the properties of small particles. The birefringence of the Aspergillus conidiophores is just one example of the importance of polarized light even for fungal characterization.

The value of any approach must be considered in terms of its overall impact on the cost of assessing environmental quality. That cost includes the cost of sampling, the cost of analysis, the cost of false negatives and positives, the cost of liability, the cost of public relations, the cost of education, and all of those other costs that are part of an effective environmental analysis. Improving any one of those costs can end up costing much more than was saved because it ignored the impact on one of the other costs. Consider for a moment a recent example. Collecting particles in a single stage impactor at a higher velocity (not higher volume) with a circular orifice rather than a slit orifice increases the efficiency of collecting important small spores. The sampling time and total volume is decreased due to more rapid loading of the smaller impact area. Particle obstruction becomes a more common problem and statistical sampling becomes a more difficult issue. Quantifying the particle loading is more difficult because parallel fields are no longer statistically random, random passes must be radial sections that don't overlap. Has improved sampling efficiency increased or decreased analytical accuracy and/or analytical costs? By reducing even further the sampling window, both in volume of air sampled and time duration of sample, have we really improved our sampling accuracy? Sampling accuracy and analytical accuracy are good things only when they are balanced with respect to the overall costs. Improving sampling is good provided it doesn't increase analytical costs or even significantly decrease analytical accuracy.

Cost Benefit Analysis

We can not expect the client to be aware of the cost impact to them of a given condition. For the new building owner having a problem the cost impact is obvious, a failure to occupy the building. We can suggest a series of tests to the new building owner or manager that will help determine if the building is ready for occupancy with an acceptably low probability of occupant complaints. For the situation in which the

occupants of an older building are beginning to have health complaints the cost impact is more subtle but can be just as devastating. To help our clients recognize the benefits of our services we need to help them perform a cost benefit analysis. We will have to refer back to the earlier calculations on the cost of variance in the analysis and to documentation of the cost impact from past examples in order to demonstrate the benefits of our sampling plan relative to the client's potential exposure to liability in each situation.

The cost of doing nothing can be estimated by considering similar past cases. For a school that could result in the building being abandoned or torn down and replaced at a cost of many millions of dollars. In an office building it can be the loss of usable space due to occupants rejecting certain areas of the building or the decrease in productivity on the part of occupants within those areas.

The cost of the project can be estimated by calculating the total expected loss, E(L), as a result of the project design. In the case of the school just mentioned that would be millions of dollars. The costs of a false positive, a false negative, or delayed results are different and can be assigned a value, C_i, where the "i" varies to designate each situation. A false positive could result in remediation that was not necessary and that may or may not alleviate the problem. The false negative would incur additional sampling and analytical expense and a significant increase in the stress between the parties involved. This stress also contains a cost factor in terms of productivity. The likelihood of incurring these costs is a function of the statistical uncertainty of the results.

$$E(L) = \Sigma C_i[1 - \Phi(\varepsilon/(s^2_{measurement})^{0.5})] + D/(s^2_{measurement}) \qquad (6)$$

Where,

$E(L)$ = the expectation of loss (total value at risk)
C_i = the cost of each scenario, i
Φ = the standard Normal Cumulative Distribution Function
ε = the error limit, the absolute value of the difference between the average value for a parameter, c_m, and the level at which there is a 50% likelihood of complaints, T

$$\varepsilon = \left| T - c_m \right| \qquad (7)$$

Calculating Confidence

One approach to estimating the term "T" would be to apply the Poisson Distribution assuming some level of sensitivity in the general population at a given exposure level and the number of people in the environment in question. For example, let's assume that two people in a hundred, μ is equal to 0.02, will experience problems and complain whenever the population of short glass fiber in the environment exceeds 13 per square inch of surface. In a classroom with 33 occupants the Poisson distribution would suggest a 50% likelihood of a complaint. We can compute the value by calculating the likelihood of no complaint. The likelihood of a compliant is the additive compliment:

$$P(x) = ((\mu y)^x)(e^{(-\mu y)})/x! \qquad (8)$$

Where,

P(x) = the probably of no complaint
μ = the frequency in the general population of one who would complain at the given level, 0.02
x = the number of people complaining
y = the number of people exposed

$$P(0) = [(0.02)(33)]^0[e^{(-0.02)(33)}]/(0)! = [1][0.51]/1 = 0.51 \text{ or } 51\% \qquad (9)$$

So the likelihood of a complaint is 49%, close enough to 50%.

If the office contained only 5 people then there would be a 90% chance of no complaints.

$$P(0) = [(0.02)(5)]^0[e^{(-0.02)(5)}]/(0)! = [1][0.905]/1 = 0.90 \text{ or } 90\% \qquad (10)$$

That does not mean that glass fiber may not be a source of complaint in that office but that if the glass fiber loading on common surfaces in the office are at 13 per square inch and the five individuals in that office are a random selection of the general population that have not had a prior problem with exposure to glass fiber then there is a low likelihood of a complaint. People with prior exposure to glass fiber tend to recognize the effects more quickly and complain at lower levels of exposure. If glass fiber was a problem in this office earlier then the probability of someone being sensitive to glass fiber is no longer 0.02 but rather 1. The glass fiber will have to be much better controlled. That is often the case when we are called into an environment. Probabilities of a sensitive individual being present are 1. The responsible agent will have to be reduced significantly below what may be tolerable to the general population.

A typical number of short glass fibers per square inch in a classroom, office, or home environment on surfaces with a 15% total particle coverage is about 1, so ε is 12:

$$\varepsilon = (T - c_m) = (13 - 1) = 12 \qquad (11)$$

An analytical method with high accuracy will not be required to detect the threshold level of 13 per square inch, a value 1300% greater than the average value. If the standard deviation of the analytical method was 4 or less then work to increase the accuracy of the measurement, and increasing the cost of the analysis, would not be justified. The term, $\Phi(\varepsilon/(s^2_{measurement})^{0.5})]$, is very near 1. The cost of a false negative or positive, times the probability of a false negative or positive would be small. The high allowable standard deviation would help control the costs of the project in terms of the sampling requirements and the analysis needed. This calculation would be repeated for each of the particles that may cause a complaint to arrive at an optimal test plan that would minimize the total project expected loss, E(L).

Calculating Cost Factors, C_i's

The part of the equation not yet considered is critical to the client, the actual costs to the client if the test plan is not optimal. Those costs are in the C_i terms. These include the loss of productivity, the loss of an employee, the loss of occupancy space, the cost of moving, the cost of building replacement, the cost of additional employee relations, the public relations costs, and the cost of possible litigation. Each of these can be considered individually.

The cost in terms of lost productivity can be calculated in two ways. One is to look at the decrease in the efficiency when performing a specific task for the entire work force as a function of the percentage of the work force declaring that the environment is unsatisfactory[8]. Studies seem to indicate that the productivity at task for the entire workforce is decreased even though only some subpopulation verbalizes their discomfort. There is some sub-population that will feel the environment is less than optimal for any fixed condition. If it is warm enough for some it will be too cool or too hot for others. In the case of an added pollutant, some will be affected severely, some slightly, and some not at all. Some of those affected will complain and some will not. In the study by Wargocki, et al[8], it was found that the productivity dropped as pollutants were added to the environment even for those claiming that the environment with the added pollutants was satisfactory. The calculation based on exposure to pollutants suggests that there is a two percent loss in productivity for each additional ten percent of the workforce finding the environment unsatisfactory. Using a conservative twenty-five percent that will find a workstation unsatisfactory that results in a cost that can be calculated as follows:

$$0.02(\text{total workforce salary})(\%\ \text{complaining} - 25\%)/10 \qquad (12)$$

Where the 0.02 factor is the 2% productivity loss per 10% increase in complaints over the base rate of 25% complaining. This calculation is based on an office environment. In a school environment this calculation will not apply because students tend not to complain about discomfort unless it becomes extreme. The second model may be a better approach for schools though it tends to underestimate the actual loss of productivity if learning efficiency is considered part of the productivity for schools.

A second way to assess productivity is to model the impact on the individuals affected. The use of additional sick days, the decreased productivity of the worker when on site, the use of temporary employees in their absence, and the disruption of the office routine as a result of the affected individual. This data will be specific to each site and would need input from the site managers in order to calculate the costs. It has the advantage of the client being part of the calculation and recognizing that these are actual expenses currently being realized and that will continue if nothing is done.

Another cost is that of replacing the affected individual or individuals with new employees. This cost will vary dramatically depending on the individual being replaced. For a teacher in a public school the cost of replacing a teacher will vary with the experience of the teacher and from location to location in the country. Typically the cost will range from one to two times the annual salary of the one being replaced[9,10].

LIABILITY		COST
Loss of Productivity	(C_1)	2%(total Salary)(% Complaining – 25%)/10
Replacing Employee	(C_2)	
Office Worker		0.75 to 3 Times Salary, Depending on Skill Level
Manager		1.5 to 3 Times Salary
Executive		2 or More Times Salary
Teacher		1 to 2 Times Salary
Loss of Space	(C_3)	\$0.01 (square feet)(day)
Cost of Clean Space	(C_4)	Increased Maintenance Costs
Moving Costs	(C_5)	Client Specific (Thousands to Tens of Thousands)
Replacing Building	(C_6)	Client Specific (Millions)
Public Relations	(C_7)	Client Specific (Tens of Thousands)
Employee Relations	(C_8)	Client Specific (Thousands to Tens of Thousands)
Litigation	(C_9)	Client Specific (Tens of Thousands to Millions)

Table 5.3: Liabilities Related to Health Complaints

Having office space or classroom space that can't be used but must be maintained may cost one cent per day per square foot of area. This is space that is not being used but is maintained so that it doesn't become a problem for the rest of the building.

In some situation increasing the maintenance frequency can remediate the complaint. The cost calculation is very straight forward in this case; cost per hour times the increase in hours spent cleaning[7].

Many of the other factors to consider are client specific. What is the cost of moving to an alternative site? What is the cost of replacing a building? What is the cost in terms of public relations problems within the community or from the standpoint of perception for a potential employee? What is the cost in terms of employee loyalty or teamwork within the working group? The cost of repairing public and employee relations is where the cost of delayed response enters the equation. A perceived delay equates to lack of care. That can have a significant cost impact. In some cases litigation may be involved. Those expenses can be very large.

By sitting down with your client and addressing some of these issues they can get a better idea of their potential risk in dollars and better assess their need for confidence in the analytical results. If their risk exposure is low then the sampling can be directed at the

source of the greatest risk. If the risk exposure in high then the sampling and analysis needs to address the issues in more detail.

The cost of remediation should not exceed the dollars at risk. Once the analysis has been completed and the necessary remediation is identified the costs can be calculated more accurately and decisions can be made on the facts in each case.

Conclusion

An environmental sampling plan can not disassociate the environmental, sampling, and analytical variances from the cost of the project and the liability of an error in the analysis. That is the why the Fit-For-Purpose model is essential to project design. When responding to a complaint we couldn't care less about the quality of the environment on average. Random samples are useless except as background data. Point-of-Exposure is all that matters. The most important samples are samples of settled particles on surfaces in the micro-environments with which the affected individual interacts. The best way to collect those samples is a tapelift using Scotch Brand 810 "Magic Frosted Tape" (see the next chapter). An impaction air sample is a back-up sample to test for the uniformity of the environment. Finally, if you know what the problem is then why sample? If you don't know what the problem is then don't guess; sample for the broadest possible number of agents and test for them all using the only instrument capable of that type of analysis, the analytical light microscope in the hands of a good microscopist.

Earlier in this chapter we talked about the contents of a grocery store (page 61). In that case we were looking through the whole store. What if instead we could only look at what customers brought out of the store? How many customers would we have to check to determine what the store contained? How long would it take to find all 28 varieties of prepared chicken soup? How complete would our list be if we only looked for bottles? Many environmental sampling plans are like that. They are not sufficiently targeted at the micro-environments of concern, the subject of Chapter 3 of this text. The analysis of the samples that are collected is generally far too limited, the subject of Chapter 4 of this text. Identifying the source of a problem agent involves more than just identifying the agent, the subject of Chapter 2. Beginning in Chapter 1 and continuing through all of the chapters the importance of particle analysis using light microscopy has been highlighted. This is not a new concept to Industrial Hygiene. Some of the great developments in environmental microscopy were made by Industrial Hygienist.[11,12] Many of those techniques are still the most powerful analytical tools for investigating environmental problems, even though they were developed more that 60 years ago. The problems that affect human beings have not changed so much over the centuries. Molds were a problem before the time of Moses[13]. Itching powders still worked in Ancient Greece and India. The observations of Ramazzini in 1700 are still valid today[14].

We can and should become much more sophisticated in our approach to environmental analysis. That improvement should include fiscal responsibility. In this chapter we have looked at a model that can be applied to optimize the return on investment for environmental analysis.

Questions

1. What factors affect exposure and response to exposure?

2. What is the "Fit-For-Purpose" model?

3. What is one criteria for cost-effectively balancing analytical variance with respect to sampling and environmental variance?

4. What are three approaches to Point-of-Exposure bias sampling?

5. Why are surface particles important?

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CHAPTER 6: SAMPLING PARTICLES AND ANALYSIS

Introduction

Sampling is the single most critical part of assessing environmental quality or identifying the cause of health complaints. If the samples don't include a representation of the exposure that caused the problem then no amount of analysis will detect the cause of the health complaint. What is a representative sample of the exposure? As we saw in Chapter 5, it is not a representative sample of the environment. It's a sample of the dust accumulated on surfaces around the person complaining or around an area frequented by that person. The micro-environments of Chapter 3 can be an aid in selecting locations to sample. In this chapter we will see the value of surface samples as a source of historical data as well as more current exposures. Tapelifts, wipes, and vacuum samples will be discussed.

We will consider the role of air samples and some serious misconceptions regarding the value of air samples as indicators of exposure. Some of this was obvious based on the physics of particle behavior and the nature of the human body as a sampling device as presented in Chapter 3. Air samples are also notoriously inefficient at collecting the particles that cause health complaints as presented in Chapter 4. This is due to the design of most samplers that intentionally exclude some of the most troubling particle types, such as glass fiber and mite fecal pellets (frass).

This is not a thorough discussion of sampling methods or of analytical techniques. This chapter stresses those techniques that have proven to be quick, reliable, relevant, and most likely to resolve health complaints in home, office, and school environments. The purpose of our testing an environment is not to characterize the environment but rather to characterize the exposure. Some other popular sampling methods will be discussed along with some specific applications where they may be useful. Many of these methods will be shown to fall short of the fit-for-purpose criteria presented in Chapter 5. The information presented here is largely the product of lessons learned about sampling in criminalistics and in the protection of sensitive hardware for the aerospace and micro-electronics industries. Analytical outcomes are far clearer in these fields than they are in the case of human exposures; the equipment works or it doesn't, the evidence is conclusive or it is not. These techniques have been applied to the resolution of environmental problems and health complaints now for over thirty years with good success. Over the next few pages we will consider some of the sampling techniques available and then we will look at some case histories in order to appreciate how these techniques are applied.

Sampling Surface Particles

Sampling surfaces presents, first, the problem of collection efficiency from the surface, and then, the problem of recovering the particles from the agent used to collect the particles; tape, wiper, filter, or trap, for analysis. Some processes may be very effective

at collecting particles but it may be very difficult to recover the particles for analysis. Other processes may not collect the particles very well but the particles can be easily mounted for analysis. Ideally we want a process that is both efficient in collection and easily processed for analysis. An additional desire is that the spatial relationships and associations between the particles be preserved. Tapelifts have proven themselves as the superior sampling method for collecting particles from surfaces with typical dust loading.[1,2,3,4,5,6] If the thickness of the dust layer is such that the color of the underlying surface is no longer evident then other techniques can be more efficient and you already know at least part of the solution to the exposure problem, cleaning. The collection efficiency of a tapelift from a typical surface is around 95% for particles of all sizes, including the important size range below 20 micrometers. Wiping with a moist cloth is next at about 75%. A dry cloth drops to about 45% for the under 20 micrometer particles. Vacuuming is about 20% efficient for particles 20 micrometer in diameter and drops with a slope of 45^{o} for smaller particles (e.g. efficiency at 5 micrometers is 5%). Some vacuum collection systems use a powerful jet of air directed at the surface to be sampled to knock particles free for collection by the vacuum. This is more efficient that vacuum alone but still not as effective as wiping with a moist cloth, let alone a tapelift. That is intuitively obvious if we consider sampling as a form of cleaning the surface. Vacuuming the outside of your car will not get your car as clean as wiping it with a damp cloth, even if you blow on it.

Tapelifts

Adhesive tape consists of a layer of one of a variety of soft adhesives bonded to a supportive film of plastic, metal, or paper. If the supportive film is not transparent then the particles must be removed from the film for analysis. There are specialty tapes designed for that purpose with the adhesive being water or alcohol soluble. The tape is simply dipped into a volume of alcohol or water, the adhesive is dissolved, and the particles are recovered by filtering or centrifuging the wash liquid. Variations on this theme are the tapes where the plastic film is dissolved and the adhesive remains with the particles. These tapes are processed by adhering the sample to a microscope slide and then immersing the slide into the solvent, typically acetone, until the film is removed. This technique retains the relative positions of all the particles on the original surface, as well as the population per unit area. The population per unit area is often critically useful information. Finally, there are tapes with transparent films. These tapes can be placed on a microscope slide and be examined with out further processing, but the plastic film lacks the optical quality for most types of forensic analysis. Each of these tapes has limitations when it comes to analysis.

Collecting Tapelifts: Sample collection begins that same way for all of the adhesive tapes. The tape is pulled free from its storage position, placed on the surface to be sampled and then fixed to its transport carrier. Potential problems begin immediately. If the tape is removed from its storage position too rapidly it can build a static charge due to tribostatic differences between the adhesive and the surface it is being pulled from (see page 28).[7] This static charge can collect particles from the air, hand, clothing, surface to be sampled, and draw particles from the edge of the roll of tape onto the main body of the adhesive. A good precaution is to start by cleaning the edges of the tape before

beginning to collect samples. Simply pull off some of the tape and use it to clean the edges of the roll of tape or other carrier. Once that is done, then pull the tape gently from its storage surface or roll to minimize the generation of static electricity and apply the tape to the surface to be sampled. Prepare the transport vessel, or carrier, to contain the tapelift and then remove the tape from the sampled surface and affix it to the carrier. A convenient carrier is a Ziploc or similar type plastic bag. The inside of these bags tends to be very clean. The bag is typically inverted over one hand and the tape is taken from the sampled surface, stuck to the inside surface of the bag, the bag is drawn back into its normal position and sealed. The outside of the bag is then labeled with the sample position, time, and the sampler's initials or name.

Selection of the Tape

Tapes with Soluble Adhesive: Tapes with soluble adhesives are very useful if the particles of interest are not soluble in the solvent used to dissolve the adhesive. When the tape with its particles is received and logged into the laboratory the recovery process begins. The tape is placed into a clean container with the clean solvent and allowed to soak for the required time. As the film is removed it is rinsed with clean solvent that drains back into the original container with the particles. The film is then discarded and the solvent with the particles is centrifuged or filtered to collect the particles. If the sample is centrifuged then the particles with a density less than that of the solvent will be lost unless the solvent is decanted through a filter. The particles remaining in the centrifuge tube will be washed at least two more times with clean solvent to remove all traces of the adhesive. Each washing represents a contamination risk. The particles can then be collected from the centrifuge tube for analysis. This collection step can introduce a bias if only a sub population is collected.

Using tape with a soluble adhesive is especially useful when looking for a specific particle type whose density is much greater than the solvent and for which particle associations are not important. The results of this process are free individual particles available of further detailed analysis. That may include microprobe analysis or detailed optical characterization. For general environmental analysis it does not pass the Fit-For-Purpose test because many important associations are lost when the particles are suspended in a solvent; but for some special applications this type of tape can be very useful. The tape can be purchased through a number of companies (Liberty, Evident Crime Scene Products, and others) that provide tools and materials for these investigations.

Tapes with Soluble Backing Films: Tapes with soluble backing films and insoluble adhesive layers are easily available. The most common and consistently reliable is Scotch Brand 3M "Frosted Magic Tape", Tape type 810.[8] The tape appears "frosted" but the light scattering is all created in the soluble plastic film. The film is an acetone soluble cellulose ester with an acetone stable acrylic adhesive. There are other similar tapes but this tape is produced in large quantities, is inexpensive, and is readily available in many stores throughout the world. Mass-production facilitates cleanliness and quality in this case. There is very little variation in quality from lot to lot with this product.

There are a number of "frosted" tapes on the market that look similar to this product but they are not the same and can not be used for this application!! Some appear frosted due to rutile particles (titanium dioxide) that are added to the adhesive. These particles interfere with the analysis and essentially make the sample useless. Another frosted tape consists of a plastic bilayer and only one of the layers is soluble in acetone. Still another frosted tape has a partially soluble adhesive so the sample is lost as a gel containing all of the particles. It is critical that the correct tape be used. Be sure the tape used is Scotch Brand 3M "Frosted Magic Tape" or that the tape has been tested by the laboratory and has been found satisfactory before collecting samples.

The adhesive system used by Scotch Brand 810 tape has an adhesive strength of about 30 pounds per square inch. That is a good indication of the tape's particle lifting force because the adhesive deforms around the particle and lifts the particle from the sides as well as the top surface. The large contact area allows the tape to overcome surface adhesive forces for most particles larger than about a tenth micrometer in diameter. This force is also sufficient to remove some weakly held surface finishes or varnishes, paper fiber from paper or cardboard surfaces, and even wood fragments from old wooden shelves. That is generally not a problem but those weaker surfaces may not be the best surfaces to sample with this strong an adhesive system. Weaker adhesive systems are presented below but they are not strong enough for general surface sampling and the adhesive is generally not as stable in acetone. They can often be processes in a horizontal position successfully.

The tape is typically used in three-quarter inch width (¾",about nineteen millimeters) and a section four to six inches in length (4" to 6", about ten to fifteen centimeters). These tapelifts are typically collected in triplicate from the same general location and together constitute a single sample. The three tapes provide an indication of how the particle loading per unit area varies from one surface to another in the space. Differences in the way different particle types are distributed in the environment will also become apparent. These differences are critical to understanding the variability in the sample sites and the environment they represent. Each of the three tapelifts will be in its own carrier (plastic bag) and the information for the location of each tapelift sample and the relationship of that location to the individual at that workstation should accompany the sample to the laboratory. Often a photograph of the site is provided for future reference. This information will be used to reconstruct the microenvironments to which the individual is exposed and relate the samples to that exposure.

Once in the laboratory the tape is fixed to a cleaned microscope slide. Even "precleaned" slides are contaminated from the standpoint of environmental analysis. They often are coated with very small detergent crystals. These crystals look similar to the nitrate urban aerosol salts that are often seen in tapelifts and are identical to some cleaning residues that may be on the surface in the environment. The slide is cleaned by exhaling on the slide, which condenses a thin layer of water on the surface of the slide. The water film along with the detergent residues are then wiped from the slide with a solubles-clean wiper such as a clean cellulose lens tissue or Kem-wipe type product. This removes the solubles but leaves a residue of paper fiber. A layer of tape is then placed over the first

two inches of the slide and left in place to protect the clean surface. The protective tape is removed just prior to mounting the tapelift sample on the cleaned slide. This minimizes the danger of contamination and removes any cellulose fibers or other cleaning residue that may have been present on the slide. The tapelift sample is then removed from its plastic bag and a section of the tapelift about two inches long is placed on the clean surface of the cleaned slide. The remaining portion of the tape will be returned to the plastic bag and be used for any subsequent analysis required. The slide with the tapelift is then placed in an acetone stable staining jar containing clean acetone until the cellulose film on the tape is dissolved. That typically will occur in about 20 minutes to 2 hours but leaving the sample in the acetone over a weekend does no harm. The slide with the film dissolved is then removed from the acetone and is rinsed with clean acetone. The slide with the adhesive layer and particles is then placed, adhesive side up, on a clean surface to dry. This should be done in a HEPA filtered clean work station or the slide can be covered with a large inverted Petri dish for protection from particle fallout. It should be left in this condition until the acetone has completely evaporated. That may require about 30 minutes. It will require longer if it is covered by an inverted Petri dish. The adhesive has a refractive index of about 1.49. A synthetic resin with a refractive index as high as 1.515 is suitable as a mounting medium and still introduces few optical anomalies relative to the adhesive layer. Two suitable mounting media are Eukitt and Shur/mount but there are others also. A #1 coverslip 20X40 or 20X50 millimeters is added to finish the mount. That leaves a sample area of 19X40 or 19X50 millimeters on the tape, more than one square inch available for examination. Typically the entire area of the mount is scanned at a magnification of 40X to 100X (4X or 10X objective with a 10X ocular) to evaluate general particle types and particle distributions. Particles of interest are scanned at up to 600X for more detailed analysis. Random areas are scanned at 200X to 400X in order to more completely characterize the particles and to identify mite and insect fragments, fungal spores, pollens, plant parts, insect fragments, chars, tire wear, and other materials of interest. The high optical quality of the mount and the retention of spatial relationships make this approach especially useful. This is the type of surface particle analysis used in the aerospace industry and in other applications where detailed particle analysis is required.

Tapes with Transparent Films: Tapes with transparent films can be satisfactory for quantification of particles per unit area[1,9] and for some limited particle identification work. The optical quality of the plastic film is marginal for most applications. Blemishes, form birefringence, stress birefringence, air bubbles, and particle bridging are problems difficult to overcome in these mounts. These artifacts in the tape prevent the proper characterization of the optical properties of many common environmental particles, including the characterization of the conidiophore of Aspergillus. The conidiophores of many species of Aspergillus are birefringent and polarized light is useful in their characterization. Polarized light microscopy is essential in order to analyze environmental particles. Polarized light accents all of the listed tape defects, including the stresses introduced by pulling the tape from the roll, pressing it onto a surface, lifting it from that surface and pressing it down onto a microscope slide.

One of the most common uses of this type of mount for environmental studies is spore characterization provided the other particles in the mount are not too large or too many. Most spores are small enough to become immersed in the adhesive. Bubbles can interfere with the interpretation of the shape and surface texture of the spore if the spore is not immersed in the adhesive. Transparent tapes are unacceptable for any other truly forensic analysis for the reasons state above. Plastic films do not have the same optical properties as coverslip glass used for good quality optical characterization of particles.

Provided the purpose of the analysis is limited enough this method may still pass the Fit-For-Purpose test. If the purpose of the analysis is particle loading level alone or the identification of a material of known origin, such as the identification of pet hair or the characterization of a mold growth on a surface, then a clear tapelift may be sufficient. When there is an obvious water problem with visible mold growth and an insurance company requires a mold analysis before committing to remediation this approach works well. It may also be useful as a public relations analysis to satisfy individuals concerned about "mold" though there may be no outward indication. This can also be a useful method for collecting mold for culture. Any clear or frosted tape can be useful as a transfer medium from a site to a culture dish in the absence of a contact plate. Clear tape (BVDA Environmental Gel Lifters, Art. #B-17000) has also been used to quantify and to superficially characterize particles collected on surfaces in a museum[9]. The tape was forced down onto the surface with a rubber roller to eliminate bubbles in the adhesive.

Tapes with Low-Tack Adhesive: Another form of tapelift used more in the laboratory generally than in the field is the use of low tack adhesives. Post-it notepad adhesive is a very useful temporary holding material. Another product from BVDA (bvda.com) called "Instant Lifters" may also be useful in this application. Particles being collected for later study can be removed from substrates using this adhesive or they may be placed on such an adhesive to be held while other particles are being collected for similar detailed analysis. Once collected they can be easily removed when the microscopist is ready to analyze that particle. This can be used as a field technique in much the same way as the other tapelift methods but the particle removal force is far lower and the tape can't be effectively mounted by itself for analysis. Individual particles must be removed or a tapelift using one of the other tapes can be made from the low tack tape. This latter process is used on some occasions when it is desirable to make a tapelift from a surface that would be unstable with a more aggressive adhesive. One such material would be paper or cardboard. The more aggressive adhesives would tend to remove fibers from the body of the material rather than those loose on the surface. Low tack adhesives will only remove those materials that are indeed loose surface deposits. One downside of this approach is that some of the low tack adhesive will be transferred to the stronger adhesive and it has a low enough refractive index to stand out as a separate material. The lower refractive index and its globular appearance are sufficient to identify its presence. When this technique is used in the field this low tack material would then be fixed to the inside of a plastic bag and sent to the lab for analysis, just as in the case with the other tapes.

1. Soluble Adhesive or Soluble Adhesive and Backing Film	
Advantages:	**Disadvantages:**
• Free particles for detailed analysis	• Multiple step recovery of particles • Recovery is labor intensive • Recovery is time intensive • High contamination risk • Recovery may introduce bias • Loss of particles soluble in the solvent • Spatial distribution lost

2. Soluble Backing, Insoluble Adhesive	
Advantages:	**Disadvantages:**
• Particles available for most types of analysis • Spatial relationships retained • Sampling errors (fingerprints) backed out during analysis • Minimum lab handling of particles • Low contamination danger	• Particle in fixed refractive index medium • Loss of particles soluble in the solvent

3. Clear Tape	
Advantages:	**Disadvantages:**
• Spatial relationships retained • Sampling errors (fingerprints) backed out during analysis • Minimum lab handling of particles • Minimum lab processing • Low contamination danger	• Particle in fixed refractive index medium • Optical quality low • Interfering film defects • Most limited analytical potential

Table 6.1: Advantages and Disadvantages of Different Tapelift Approaches

Wipes

Dry Wiping a surface is not a very effective cleaning technique but it may be an adequate sampling technique if the layer of particles is very thick. At that point spatial relationships are not usually important. For thin layers of particles wiping is not only inefficient it is also biased by size, shape, and other parameters in terms of the efficiency of collection. Wiping a cloth over a surface creates a static charge. Particles may be moved by wiping, but many of the smaller particles will not be collected because the electro-static charge on the surface has greater attraction for the particles than the van der Waals force between the particle and the wiper. Once the particles have been move there is an issue of release from the wiper, another sampling problem unless the wiper is processes in total. Dry wipes are subject to a large variance in collection efficiency for thinly loaded surfaces and as a result do not generally meet the requirements of fit-for-purpose analysis because the sampling variance alone is on the same level as the environmental variance (see page 64).

Wet wiping a surface is much more efficient in removing and collecting particles in thin particle films.[10] That follows as a result of the removal of electro-static, van der Waals, and capillary forces holding the particles on the surface and the addition of capillary and shear forces removing the particles. It is still not as efficient as tapelifts and it still introduces various biases, including one for the solubility of the particles in the solvent used to moisten the wiper. It does have the advantage of being able to sample a large area. When relatively large areas of a smooth, non-porous surface need to be sampled this can be an effective approach.

Part of the collection efficiency problem is that when a moist wiper is used it leaves traces of the liquid agent, with the particles it contains, behind. A moist wiper is much better than a dry wipe for collecting particles from relatively clean surfaces but is potentially much worse for thick particle layers of particles. The addition of a moist wiper to a thick layer of particles may significantly increase the strength of the capillary forces between particles and to the surface if insufficient liquid is use. The result is the formation of a thick mud layer that is not easily removed.

Brushing

Brushing, the use of a bundle of fine fibers to move particles on to or into a particle collection device is a reasonable approach for very dirty surfaces. It is not a good technique for surfaces that are lightly loaded because it can be selective by particle size and by the electro-static nature of the particles and the surface involved. The bristles of the brush also behave as little catapults, lofting particles into the air rather than pushing them in the desired direction. A brush can also be a source of cross contamination unless the brush is only used once or it is thoroughly cleaned after each use. A brush does offer a little more precise control over where the particles are being pushed than a wiper. This approach can be useful in some instances.

Vacuuming

All of the techniques for collecting particles from surfaces discussed so far collect particles through the direct application of force. Vacuuming uses an indirect force, and one that is often very poorly defined. Although there is an ASTM Standard for collecting samples of dust from surfaces the technique is very ineffective and the results lack precision.[11,12,13] A vacuum creates a low pressure area and draws air on to a particle trapping devise. For airborne particles it is easier to model what is being collected, as we will see latter, but for surface particles the relevant collection force is fluid shear at the surface and the magnitude of the force is dependent on the drag force on the particle. The drag force is dependent on the shape of the particle, the boundary layer velocity profile, and the slope of the pressure gradient created by the vacuum device at the location of the particle. Because of these limitations vacuuming is a very inefficient method to collect a surface sample. If the airflow caused by the vacuum is all that is used then an efficiency of about 20% can be expected for 20 micrometer particles. (This test was conducted using 20 micrometer spheres on a smooth surface, a critical orifice nozzle, two right angel passes over the same area at a rate of 2 feet/minute and a total flow rate of 600 lt/minute. Efficiency was determined by direct observation of the spheres per unit area before and after the test.). The efficiency can be increased by adding another force to loft the particles and then collect them as airborne particles. The beater-bar on a home vacuum cleaner is an example. One precision piece of equipment designed for using vacuum to monitor surface particle concentrations uses a directed high velocity jet of air and a fixed geometry to direct particles into the vacuum orifice for collection. This system is efficient for spheres but not for flat particles. When hand sampling carpet the inlet apparatus is often used to disturb the surface and knock particles off of the fiber surface to collect them. The vacuum itself turns out to be a very poor agent for the removal of particles. A tapelift is more efficient than the most efficient combination of applied force and vacuum systems.

Vacuuming is used frequently on carpet, cloth, and porous surfaces or on those surfaces with very heavy deposits. This is sometimes the best sample available for those surfaces. At these times it is important to keep in mind the fit-for-purpose model. The sample method, vacuuming, has a high variance. There is no justification in expending resources for a low variance, highly accurate analysis. One of the most common applications of vacuum sampling is in assessing exposure to allergens in carpeted facilities. As discussed in Chapter 4, the top of page 47, the collection efficiency for some common allergens is about one percent.

Sampling Airborne Particles

It is a common assumption that an air sample is a better representation of exposure than a settled dust sample. In the case of particles that has tended not to be the case. When we look for correlations between effects and measured exposures we often find much better correlation between settled dust and the health response than between the measured air exposure and the health response.[11,12,13,14,15] That is also true of complaints regarding "cleanliness".[16] Studies suggesting a greater importance for air samples are often based on comparisons between air samples and surface samples relative to some imagined

optimum. Just one example would be Sayer, et. al. in which an air sample of 225 liters collected in 15 minutes was compared to a gravity settling culture plate exposed for the same 15 minutes.[17] The conclusion was that the air sample was a much better sample. No one would suggest a 15 minute sedimentation time would provide an adequate sample but an air sample of 225 liters is certainly a good sample for any but the cleanest environments. This test does not support the conclusion that air samples are better than surface samples as has been stated. The fact that surface samples correlate better to most health complaints might seem counter intuitive until we consider how an air sample relates to human exposure and what is required for an adequate air sample.

We are normally called in after the incident that caused the problem. If the condition is ongoing and steady-state we have a chance with an air sample. Unfortunately many exposures are episodic. If we don't catch one of the episodes during our sampling interval our air samples are useless. This is one of the reasons settled dust correlates better with health complaints. Settled dust samples represent sampling over a longer period of time, often including the period or periods of the exposure. The particles are time averaged but unusual exposures are still often evident.

Let's say we do catch an episode with an air sample. Does our collection technique capture the agent responsible for the health effect? Our task is to capture particles from the air in sufficient quantity that they can be analyzed and in a fashion that is representative of the exposure of a person in this environment. The particle collection mechanics available to us includes filtration, impaction, scrubbing, electro-static collection, diffusion, thermal deposition, and a few other exotic techniques. We also have a number of preconditioning accessories available or imposed upon us. The most frequent preconditioning device is the aerodynamic cutoff. This involves a sample inlet to the device that by its design decreases the collection efficiency of particles above a given size. Common design limitations are 15 micrometer for many spore traps, 10 micrometers for PM10 devices and 2.5 micrometers for PM2.5 devices. The cutoff size is the size of standard latex spheres collected at an efficiency of 50%. That is to say that with a given concentration of latex spheres at that size only 50% of that concentration will be evident in the volume of air sampled by the device. Figure 5.8 illustrates the way this process works. The efficiency drops off rapidly as the particles become larger than that size.[16] This minimizes the collection of particles above a given aerodynamic size. If the particles of interest have an aerodynamic diameter above the cutoff few of these particles if any would be collected. Many common irritants and allergens are larger than

Figure 6.1: Inlet Aerodynamic Cutoff

The inlet of an air sampler acts as a screen with a few holes. Small particles can enter but few large ones can.

the typical cutoff size for air sampling devices on the market. Little wonder that health effects correlate poorly to air samples.[13,14,15,16,17] So why collect air samples? Some very important particle allergens and irritants are in the right size range and their concentration in the environment can best be monitored using air samples. Another reason is that airborne loading of small particles by itself can cause health problems. If no air sample is collected this exposure can not be measured. A third reason is that many exposures are cyclic or episodic. Air samples collected at different times can document that pattern. Though air samples tend overall not to correlate well with health complaints there are specific instances where the problem can not be detected with out them. Many particle hazards don't result in complaints until years after the initial exposure. Asbestos fibers, silica, plant hairs (e.g. cotton linter), and other fine particles collected in air samples can indicate the hazard though the immediate complaint is generally not related to these materials. Air samples are nearly as important as surface samples in evaluating an environment.

An air sample is no more definitive a term that a surface sample. Just as we saw in the case of surface samples there is a great deal of difference in the value of the sample depending on how you collect and process the particles. An impaction device with a 15 μm cutoff will not collect the same particles as a filtration device with the same 15 μm cutoff. It is important that we know what we are collecting and what we are missing in the sample, and why, in order to properly design our sampling plan. In the next few pages we will consider what is available and how to select an appropriate system to match our goals.

Filtration

There are two basic types of filters used for the collection of particles. They are either filters constructed of fibers or membranes. Each type has its advantages and disadvantages. Each type must be treated differently prior to the analysis of the particles they collect. Most filters used for environmental analysis are very efficient and do a good job of collecting particles well into the submicrometer size range. Their disadvantage is the increase in pressure drop across the filter as they begin to load up. That is generally not a problem for most environmental samples. From an analytical standpoint the biggest problem may be the lack of loading that results in the need to examine a larger surface area in order to retrieve good particle populations on which to base the analytical conclusions.

The choice of filter type to use is often dictated by the application. For asbestos counting analysis a cellulose ester membrane filter must be used. For high volume samples a glass fiber filter is often required. It is a good idea to talk with your laboratory if the type of filter is not called out as a regulatory requirement. Tell the lab what you need to know and they can usually recommend a filter they would prefer to facilitate their analysis.

Fiber Filters

Fiber filters remove particles from an air stream by mechanical blockage, impaction, and diffusion. The fiber filter selected and the filter housing will determine the size of the

particles collected and how the filter will need to be processed to retrieve the necessary information. The housing and sampling rate, in liters per minute, will determine the upper particle size cutoff. The filter will control the lower particle size distribution limits. The physical pore or channel size will define the mechanical blockage diameter. Particles larger than that size that reach the filter will be stopped by the filter. Particles smaller than that but which have a diameter similar to the fibers that make up the filter will be collected by impaction on the fibers. Particles that are still smaller will be collected by diffusion onto the fibers. The efficiency of these latter two processes will be a function of the depth of the filter bed, specifically, how many encounters with the fibers will each particle be likely to experience. If the number of encounters is large because the filter is thick relative to the particle size then the efficiency will be high. There are two interesting gaps in this filter. The first is the gap between the mechanical pore or channel size and the fiber diameter. If that gap is large then the filter will allow particles larger than the fiber diameter but smaller than the pore size through. It will capture the smaller particles that are on the size of the fiber diameter more efficiently than the particles that are larger but still below the pore diameter. The other gap is between the fiber diameter and the diffusion deposited particles. High efficiency fiber filters contain a variety of fiber diameters, down to 0.1 μm, packed close together, with a thickness of hundreds to thousands of fibers. The filter medium may not be physically very thick because the fibers are so small but it is the number of encounters that is important and with the close proximity of so many fibers the number of encounters will be very high. Different fiber filters are designed for different purposes. A low pressure drop requirement may be met by decreasing the fibers per unit volume but increasing the depth of the filter to get the same number of encounters. It is not unusual to have smaller particles collected with higher efficiency than larger particles in a given size range for a given fiber filter.

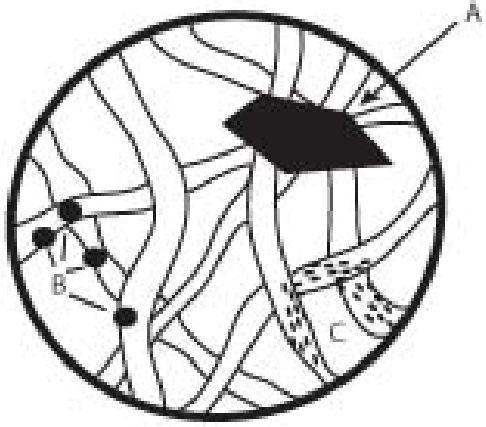


Figure 6.2: A Fiber Filter Collects Particles by Interception (A, Mechanical blockage), Impaction (B), and Diffusion (C).

Fiber filters often require that the particles be removed from the filter for analysis. The fibers themselves interfere too much with the particles for the particles to be optically characterized. That is especially the case with fiber filters made using fibers other than glass fiber. Ultrasonic agitation can be used to collect the particles generally without collecting to many of the filter fibers. Often a low-tack adhesive tape can be use to remove particles from fiber filters for analysis. Glass fiber filters can sometimes be processed with the top layer of the filter still present. The filter is mounted in an immersion oil that has a refractive index that matches the refractive index of the glass fiber. The glass fiber then becomes "invisible" and the particles can be optically characterized. In practice the glass fiber typically comes from different lots of glass and

the refractive index varies a little from fiber to fiber. This becomes especially noticeable when the filter is mounted in the immersion oil, some of the fibers will stand out clearly. Mounting the filter fibers makes a rather thick mount, which introduces spherical aberration in the image through the microscope as the scope is focused deeper into the sample. The particles can be most completely characterized when they are freely mounted but a mount of the filter after removing the particles should be made to observe any bias that may have been introduce by incomplete recovery of the particles from the filter.

Membrane Filters

Membrane filters collect particles by mechanical blockage and by diffusion. They consist of films with holes in them. The filters are identified by an alpha-numeric code where the alpha characters indicate the plastic, metal, or mineral used to make the film and the number indicates the pore size. Some companies use just an alpha code where the first letter indicates pore size and the second letter indicates the film composition. Each different type of film requires a different type of processing in order to analyze the particle they contain. Cellulose esters can be "cleared" using acetone vapors. These filters will collapse entirely into a transparent, optically neutral plastic film containing the particles for analysis. The collapsed film on the microscope slide is typically mounted under a coverslip in a mounting resin with a refractive index of 1.515. Cellulose ester membranes typically have pore sizes from 0.25 μm to about 1.2 μm. Other pore sizes are available but the most commonly used pore sizes are 0.45 μm and 0.8 μm.

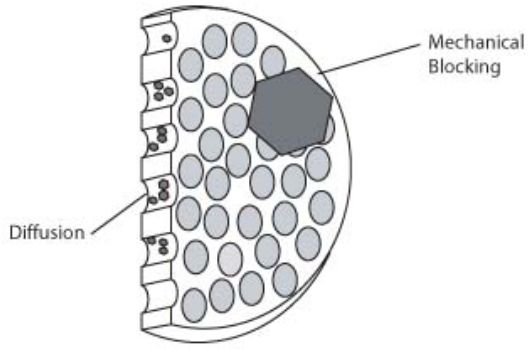


Figure 6.3: Membrane Filter

Particles are captured by mechanical blocking on the surface and by diffusion inside the pores or channels of the filter

Another film commonly used is a polycarbonate membrane. This has the advantage of a surface that is smooth even at very high magnification under an electron microscope. This filter is often used for the characterization of asbestos fibers by electron diffraction. The particles on this type of membrane filter must be removed for analysis because the film is optically active. A low-tack adhesive works well in this case.

For environments where solvent vapors may be a problem or for filtering liquids an aluminum hydroxide membrane filter works well. These filters are almost chemically inert and the aluminum hydroxide is not optically active. It can be "cleared" by mounting the filter whole in Cargille 1.605 Melt Mount mounting medium.

Impaction

Impaction devices remove particles from the air stream by impaction. Diffusion and mechanical blockage play no roll. The advantage is low pressure drop across the device

and selective collection of particles in a specific size range. The pressure drop does not increase with loading but as the loading increases the frequency of particle "bounce" increases and particles can be "lost" from the sample or move to a lower level in the impaction cascade. There are a number of different impaction devices on the market and they all have different advantages and disadvantages depending on what information is needed. The most commonly applied impaction device for general environmental analysis is the "spore trap". The spore trap is a single stage impactor with a high large particle cutoff diameter, about 15 μm. The low particle cutoff is about 2 to 3 μm. Other single stage impactors commonly used have much lower large and small particle cutoffs. Impactors with a large particle cutoffs of 10 μm and 2.5 μm are common in some applications. These also have much lower small particle cutoffs. Multiple stage impactors are also common in environmental studies. These multiple stage impactors can collect a higher particle load because the collection size range is reduced on each plate. This increases the amount of air that can be sampled for each size range of particles in the environment.

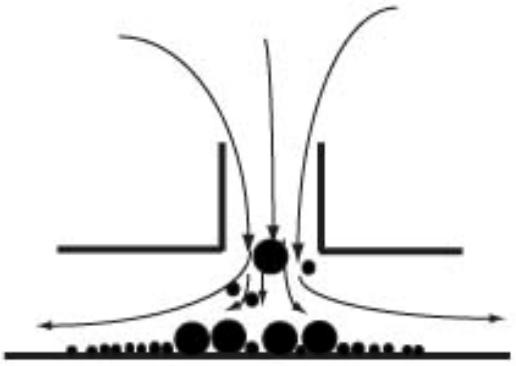


Figure 6.4: Single Stage Impactor

Particles are captured by impaction on a sticky surface. Smaller particles may trail toward the edge of the deposit.

Another approach to collection by impaction is to use the local wind or to create wind by rotating the impaction surface. A simple Pin collector can be created by placing a piece of tape around a needle to create a flag and support the needle in a small glass vial. The tape flag keeps the same face of the needle into the wind to collect incoming particles. A little silicone grease on the front of the needle collects the particles. A roto-rod collector is a little more sophisticated. It consists of an electric motor that rotates a "U" shaped rod. The arms of the "U" are the collection surfaces. Double-back tape or silicone grease can be used on the sampling surface to collect the particles. These systems have the advantage of no upper limit cutoff.

Other Airborne Particle Collection Techniques

There are a number of other airborne particle collection techniques but they tend to introduce additional biases. Electrostatic techniques and diffusion techniques are two of the others most commonly used. Both techniques collect free particle that can be easily mounted for detailed microscopical analysis.

Particle Analysis

The analysis of environmental particles requires an analytical light microscope and a trained microscopist. The microscope is like a symphonic instrument. Anyone can pick

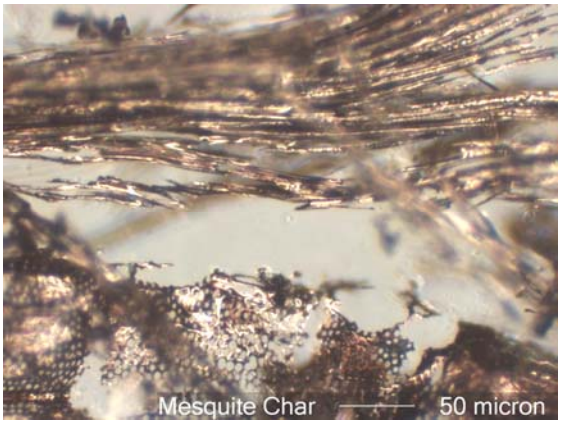
it up and make noise but a master can make it sing. There is more to being a master than knowing how to play the instrument. You also need to know the music. The music is more than just notes. How you approach the note, how you play it, how you allow it to trail off, all add to the quality of the tone, the bar, the movement. So it is with the microscopist. A good microscopist enjoys working and playing with the microscope. The environmental microscopist also needs a diverse background in chemistry, physics, engineering, industrial process, materials sciences, geology, and many diverse areas of botany. To that must be added an analytical protocol that allows a reasonably rapid analysis with good reliability. Fit-for-purpose modeling enters the picture again. The following case histories and then an analysis, added as Appendix 1, on just one field of view from a tapelift collected in a home will hopefully give an idea of the processes involved. A typical analysis of a tapelift consists of a few thousand fields of view. Looking a fewer fields of view could mean missing some agents at levels that can still cause problems.

Case Histories

The four case histories that follow here are in addition to the three given in Chapter 1. These provide additional depth to the capability of forensic particle analysis and add detail to what is involved in environmental particle analysis.

The Mesquite Barbecue

A restaurant moved into a business district and offered Mesquite fired barbecue. Businesses in the adjacent three story building began complaining of mesquite smoke in their work place within a short time. The restaurant contended that they were not the only source of smoke in the area and that the other sources should also be considered. Samples of airborne particles using slit air samplers and membrane filters and samples of surface particles using tapelifts were collected at the work stations in the three story building. The tapelifts immediately substantiated the complaint. Particles of charred mesquite were identified in the tapelifts from different areas in the office. The office air samples failed to provide particles identifiable as mesquite initially. Subsequent air samples from the roof near the building air intake and in the office substantiated the path of entry. The problem was resolved out of court.



Photograph 6.1: Mesquite Char Standard

Mesquite has a unique vessel structure and very long narrow fibers with a high calcium oxalate content.

When a material burns it generates fragments that can often provide very specific information about the original

material. Wood shrinks and chars as it burns releasing fragments of cells and cell clusters that are often sufficiently characteristic to identify them as to the type of wood being burned.[20] Wood from at least three other varieties of trees was identified along with leave and other non-fuel type plant char in this case. The particles that are specifically identifiable tend to be larger particles, in the range of 30 to 50 micrometers. These particles are transported less efficiently than smaller particles and as result are rare in ten minute type air samples. Horizontal surfaces at the target location typically contain these particles and if there has been an exposure it will be evident in the tapelifts. Transport mechanism and the route of entry can be determined once the exposure has been documented. Tapelift samples from the ventilation system and air samples from the roof were provided and helped to complete the story. In this case slit air samples collected over a period of hours were used to document the details. Slit air samplers that collect rows of particles sequentially (see Appendix: Allergenco MIK-3) are especially useful in that ten minute air samples can be automatically collected at regular intervals over a twenty-four hour period. Each sample row can be documented as to the time of its collection.

In this case had tapelift samples not been collected mesquite smoke would not have been found in the initial survey. The client would not have had the evidence to pursue their claim. Tapelifts have proven to be essential to understanding the nature of the environment at any given location. Tapelifts have been used to evaluate crime scenes since the 1930's. They are the core technique for evaluating the cleanliness of Aerospace Cleanrooms and of hardware such as contamination sensitive satellites. Slit air samplers, such as the Allergenco, Zefon, or Burkhart, are ideal for air samples that are to be analyzed under the light microscope because they concentrate the particles they collect into a narrow row that can be quickly examined. This is a much more efficient way to examine the thousands of particles collected in a ten minute sampling interval than the old membrane filter technique but it does not replace the membrane sample. Membrane filters collect by filtering the air whereas slit air samplers collect by impaction. They collect different types and sizes of particles and cannot be considered as equivalent sampling procedures. Membranes are much more efficient when collecting fume or smaller smoke particles and must be used for quantitative elemental analysis.

Photograph 6.2: Parrot Feather Barbule

Bird feather barbules carry traits that can be used to identify the genus of the bird.

Bird Debris

A woman was experiencing respiratory problems and was convinced that local businesses were responsible for polluting the air in her home. Tapelifts were provided for analysis and the home was found to

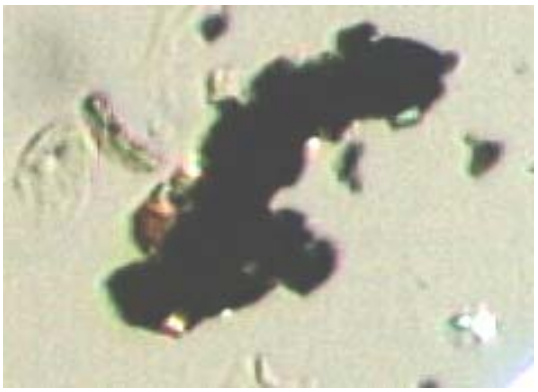
contain a high level of bird related debris. The bird debris include feather barbules and fecal matter. The feather barbules were not identified as to species but they were not from local wild birds and the fecal material ruled out down filled furniture as a source. The fecal material also indicated that the birds were eating a prepared feed rather than a natural food supply.

It turned out that this lady had been a breeder of parrots and she had raised the birds in her home. She had become allergic to the birds and had had to end this occupation. Her home had been thoroughly cleaned she claimed and her symptoms had subsided for a time and then returned. It was clear from these samples that the cleaning had been superficial. As she lived in the home and visited less frequented parts of the home or storage areas she had reintroduced a significant population of parrot debris.

In this case no information had been provided with the samples. The samples had been analyzed and the report indicated a large population of domesticated bird debris. A chicken farm or a heavy application of chicken manure was suggested as a source for the debris. When parrots were later mentioned the source was obvious. The degree to which each particle is characterized is dependent on the issue at hand. Every sample contains thousands of particles and every particle is in some way unique. During the analysis the particles are clustered into related groups, such as bird feather barbules. These groups are then gathered as assemblages. An assemblage indicates a source. In this case the bird fecal material (unique due to the avian waste elimination process) and the feather barbules indicated an intimacy with the creatures. The fact that the fecal material was from a prepared feed clearly suggested a domesticated bird. The amount of material was inconsistent with a few pet birds. The barbules were not consistent with local wild bird barbules and at that the analysis was halted. The barbules could have been more specifically identified if the issue of parrot breeding had been mentioned. Similarly in the earlier case, had mesquite not been specifically mentioned when the samples were provided only charred wood would have been mentioned. Background information or materials of special interest should be provided if possible to increase the amount of information in the final analysis. In some cases, such as where litigation is involved, the information may be provided after the analysis to refine the data. Samples analyzed by light microscopy are not destroyed or significantly damaged by the analysis. The samples become a permanent record and can be reanalyzed or quantified for specific particle types at a later date if necessary.

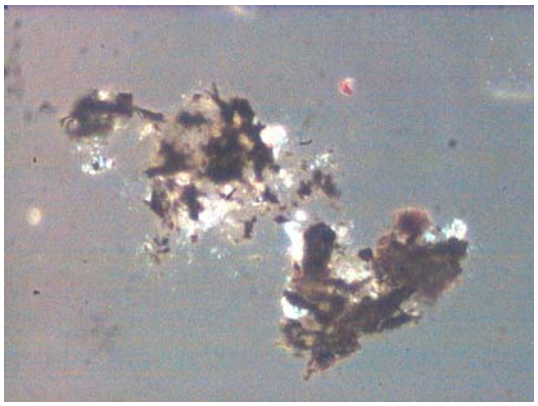
Black Particles

No single case history would do justice to all the complaints involving black particles. Black particles are a common complaint in both the workplace and in the home. Contrary to popular belief black particles do not constitute a unique, single particle type. Combustion particles are typically black but every fuel creates its own unique distribution of particle types as already presented in the case of plant fuels. The combustion need not be local. Soot and charred products can travel considerable distances and deposit over time creating a black particle problem. A neighbor's fireplace can pollute your home much more than theirs. Tire wear from vehicles is another type of black particle that can become a significant problem if there are major traffic arterials nearby. Electric motors generate fine black metal wear and graphite particles that can become a black particle problem. Electric heating elements in baseboard heaters generate both metallic oxides and charred particles in the environment. When an electric heating element first heats up it both chars the particles that collected on the element since its last heating cycle and the element expands thus dislodging the particles into the convective air flow. The odor noticeable when the heater first heats up is the result of this initial burst of charred particles and volatilized pyrolysis products. Many fungal species generate black or dark spores that look black on light surfaces. Computer printers or copy machines can generate large amount of free toner particles. Toner particles can be a significant health risk. This is just a partial list of black particle types common in home and office environments. Each particle type is associated with its own health implications. Charred materials indicate incomplete combustion; carbon monoxide testing may be required. Black spores may be a localized Cladosporium population, possibly a problem; or Stachybotrys, a more serious situation.



Photograph 6.3: Tire Wear

This is a tire wear fragment. Notice the bright included mineral grains and the long tapered cylinder shape. The bottom part of the cylinder is folded up and toward the center. These longer tapered cylinders are more typical of truck tire wear than of automobile tire wear.



Photograph 6.4: Cigarette Ash

This is a fragment of dark ash. Light ash has all the carbon removed but may still retain some characteristic structure in the mineral ash.

At any given location multiple sources of black particles are present. The sample collected must be the black particles that cause the concern and not just any deposit of black particles. Black particles on the bathroom wall, black particles above an electric heating register, black particles on the window sill, and black particles collecting on white plastic surfaces in the kitchen are often all different. If the concern is the black particulate matter in the kitchen then that is the sample that should be taken. Sampling the air in this situation will only confuse and complicate the issue. The question in this case relates to a very specific population of surface particles. That is the sample that needs to be analyzed.

Airborne Sewage

Around a large international airport brown particulate matter fell from the sky whenever a large jetliner took-off. An analysis of the material at a local university identified the material as some type of modified fecal material. Electron microscopy confirmed that the material was a globular carbonaceous particulate matter consistent with fecal material. Local residents were furious. Apparently the aircraft was dumping sewage, or, at the least leaking sewage during take-off Samples of the brown material were received by this laboratory and examined to determine if fecal material was present. Indeed fecal material was present; bee fecal material. Honeybees eat pollen and nectar. As with most insects the pellet they defecate can be a substantial percentage of their body weight. In the case of honeybees the pellet can be a third of their body weight. Bees defecate while flying and typically on the flight back to the hive after they have eaten. The pellet consists of the emptied pollen grains that they have been eating, waxes, and fragments of bee "hair" from their grooming activities. When an aircraft takes off it needs much more power than when it lands and it makes much more noise. The area around the airport had been left wild because it would be unsafe for people to live too close to the airport. Bee keepers had taken advantage of the natural flowers in this area to keep their hives close to their market. The result was that when a large jet took off it frightened the bees that had been feeding and as they approached their hive they dropped their little brown pellets. Bee hives are no longer allowed around this airport. No technique other than light microscopy could have identified this material correctly.

Photograph 6.5: Honey Bee Hair

This is a bee hair from the pollen basket and pollen extracted from a bee fecal pellet.

Considering all the knowledge and experience required to be a good environmental microscopist it is surprising that there are a number of people who enjoy this work. They

can't do the work for twenty or even forty dollars per sample. It will take an additional zero ($200 to $400) to pay for this level of work, but the information you get in return will be well worth it.

Conclusion

At times it's necessary to step back and consider what we are trying to do and whether our approach is still acceptable. What began nearly two hundred years ago as a way to make miners more productive is now trying to make school, office, and even home environments a more comfortable place to work and live. About one hundred years ago the danger of contaminants in our environment for formally recognized. Fifty years ago the health risks of asbestos in indoor environments was acknowledged, followed by lead in homes from paint. Legislation finally was passed in 1978 to control exposures, including exposures in schools and other public places. Allergists detected the role of dust mites in indoor environments during the 1970's. Mold in indoor environments came to the fore during the 1980's and 90's. Only recently has there been a recognition of the difference between mortality, morbidity, and productivity. The sick building syndrome is not fatal though the symptoms are definitely indicative of an illness. These symptoms have a rapid onset and remission associated with a specific location. This characteristic indicates a quick response reflex. Asbestos, lead, carcinogens, most toxins, and other materials for which there are regulated exposures tend not to fit that description. The techniques developed to monitor these regulated materials are not appropriate for the materials that cause quick reflex symptoms. A different approach is needed.

Methods developed for protecting contaminant sensitive hardware, for assessing environmental quality in industrial cleanrooms, for collecting physical evidence at crime scenes, and for evaluating patterns of behavior at archeological sites turn out to provide a better body of sampling and analytical techniques for solving building related health complaints. The collection of particles at the "event horizon" in the office, school, or home indicates the exposure during the time of the onset of the problem. The relationships between particle assemblages indicate sources and coincident activities. More to the point, the successful resolution to the problem has been attained in a very high proportion of the cases in which this approach has been applied.

Air samples provide a snapshot in time and can be compared to the particles on surfaces to assess current environmental conditions. They are far less likely to detect the cause of health complaints but they provide information on the total airborne loading of particles that is not assessable using surface samples. Tapelifts using Scotch Brand 3M "Frosted Magic Tape" combined with an air sample are a very effective technique for sampling the environment. The next step is to find a laboratory capable of analyzing the sample.

How can you identify a laboratory capable of performing this analysis? The first criterion is that you should be able to talk to the analyst directly. The second is that they should be able to talk to you about where the particles in the samples may have come from. They should also be able to provide references on the health effects of the particles they have identified. Finally, they should be willing to grow with you. The analysis is

expensive and it should provide you with the information you need to make an informed decision. If the information is not sufficient work with the microscopist to get the information you need. Direct them to web resources that may help them, such as McCrone Research Institute at www.mccrone.com, Microlab Northwest at www.microlabnw.com, or Molecular Expressions at micro.magnet.fsu.edu/primer/. On some of these sites they can ask questions and receive free assistance. It is to your advantage to know the analyst and have confidence in their ability to detect agents in the samples that may have caused health complaints.

Questions

6. Why are surface particles important?

7. If the particle loading on a surface is less than a mono-layer what is the best way to collect the particles and why?

8. What does an air sample for particles indicate about the environment?

9. What general type of sampler would you recommend for sampling spores?

10. What type of sampler would you recommend for monitoring airborne asbestos?

11. What are some of the characteristics of a laboratory providing acceptable particle analysis?

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CHAPTER 7: SUMMARY AND CONCLUSION

The Three I's: A Perspective

O'Hara, in his book FUNDAMENTALS OF CRIMINAL INVESTIAGTION, stresses the importance of the three I's of investigation, Information, Interrogation, and Instrumentation.[1] Information, the first "I", is the data collected from files, informants, other agencies, and those who might hear things like cab drivers, bartenders, former criminals, and others that might associate with suspects. This gathering of information is by far the most important of the three I's. The perpetrators, or at least the suspects, are most often identified at this stage of the investigation. With out suspects it is very hard to solve the crime. The second "I", Interrogation, is the skillful questioning of witnesses and the suspects. This involves the cleaver questioning that leads to the "AH-HA" moment. This is the second most important "I" because it can lead to a confession. If all else fails then we must rely on the lab geek and his "I", Instrumentation. This is the least satisfying outcome for an investigator. The lab geeks tend to get all the press but if it weren't for the first two I's providing suspects and scenarios there would be nothing for the evidence to verify or contradict. The analytical data must be placed in context to have value. The first two I's establish that context. If the context is impugned the results of the analyses, no mater how good, are open to challenge.

In our investigations we have a similar set of three I's, Inspection, Interview, and Instrumentation. Inspection comes from blueprints, walking the site, and observing water stains, damaged ceiling tile, degrading materials, accumulated dusts, air intakes with respect to sources, and activities and schedules at the site. Our second "I" is interviews with the individuals having difficulties and with others at the site and adjacent facilities to identify specific complaints or issues of concern. Interviews are cooperative exchanges of information with out the dramatics of hostile interrogations. Instrumentation includes the analysis of samples collected at the site, measurements made at the site, and photographs taken to document sample locations and local conditions.

Inspection
- Building Layout,
- Anomalies,
- Ventilation System,
- Activities and Cycles

Interview
- Complainants,
- Background Data,
- Facilities Engineer,
- Building Manager

Instrumentation
- Samples
- Photographs
- Measurements

Figure 7.1: The Three I's of Investigation

Our three I's many not be as exciting as crime scene investigation and it is unlikely to be the subject of TV dramas but the results are none the less important for those suffering from environmental related issues and for those responsible for that environment. Just as in the case of the criminal investigation the first two I's will be the most important with analysis providing confirmation, sometimes detecting unexpected exposures, and providing an "all clear" after remediation. Unlike the crime scene investigation we don't know if the perpetrator has been removed from the environment until we test for its presence. The samples

collected when the agent was still present at levels that caused complaints are critical in determining the effectiveness of the remediation, and in some cases, whether the suspected agent was in fact responsible of the complaint.

Inspection

The inspection of the site is the critical first step in any environmental investigation. It establishes the context in which all other data will be applied. Who are complaining and where in the building are they located? Where does the fresh air supply come from? Is there adequate fresh air? What equipment shares the space? What activities are performed at this location? How many people occupy or come through this space? What is the condition of the HVAC system? What is the condition of local construction materials? What activity cycles impact this area? How is this area different from other areas in the building where no complaints are registered? What specifically is the compliant? Has the complainant seen a doctor? How soon do the symptoms fade after leaving the building? How soon do the symptoms appear after entering the building? This is a minimum list of questions that the investigator should be able to answer after their evaluation of the site. The answers to these questions will be used to construct the hypotheses that will be tested during the interviews.

Interview

If you don't ask questions how can you provide the answers? There is something wrong with that statement, but it is true. It is important that we solve the right crime. If the occupants of the building are concerned about the white powder then telling them that they have too many cockroaches might be important but not relevant to their concern. Ask questions. The answers to those questions will define the task at hand. The investigation can come to a successful conclusion with the right answers to the problem only when the task is adequately identified.

- The Complainants
- The Facilities Engineer
- The Building Manager or Their Representative

Figure 7.2: Interviews Required

Who should you interview? Certainly, the people with the complaint need to be interviewed. Ultimately, they will need to be satisfied, or, in some few cases, designated as extremely sensitive to some agents at this site that were not detected. It is important to assume the complaint is real and that the complainant desires a solution to the problem. That is by far the most common situation. Our inability to detect the cause does not mean that the symptoms are not real. Forensic light microscopy is often a "court of last resort". In my personal experience, and from the experience of other forensic microscopists, many complaints judged "psychological" have had a very real, physical cause. The original analytical approach was far too limited.

Who else should be interviewed? The facilities engineers know about recent upsets in the HVAC system, about remodeling, about leaks, about all kinds of difficulties with the physical plant that constitute the framework of the environment of concern. They are

aware of activities that might and effect on the building occupants of which the occupants may not have been aware. The facilities engineers may not have imaged the impact of the event but they are familiar with the event and can provide essential details. The building manager also needs to have their input. If any remedial action needs to be taken the building manager must agree that the cost of doing nothing is greater than the cost of the remediation. There may be a number of alternative approaches to handling the issue. The building manager will have to be appraised of these alternatives so that an appropriate solution can be formulated.

The interview is not a one-way activity. You are establishing your credibility with your questions and with your response to the answers. A skillful interview, just as a skillful interrogation in a criminal case, can make or break an investigation. If you don't establish your credibility then the results of the investigation will be challenged, no mater how scientifically valid.

Instrumentation

Samples are collected to answer questions. The questions that need to be answered are determined by the information gathered at the scene and the interviews with the participants. There are two basic types of samples that need to be collected. Those that characterize the environment and those that satisfy the observers. Sometimes they are the same but be sensitive to the concerns of observers. Collecting the sample doesn't mean you have to have the sample analyzed. Collecting the sample may increase your credibility with an individual that will need to have confidence in your results later on.

Tapelifts from Surfaces
(Three Minimum)

Air Sample
(One Indoor and One Outdoor Minimum)

Figure 7.3: The Minimum Sample

What constitutes a minimum sample? The history of the environment resides in the particles settled on surfaces. If these are not collected you have lost data that is often critical to the solution. Air samples indicate current conditions and airborne loading, both critical to understanding exposures at the time of sampling and adding context to surface samples.

The question of how the samples are analyzed is next. You need an analyst that can understand what the particles indicate. This is not a mold spore analysis. As should be obvious at this point, the type of analysis that is needed requires a trained microscopist. The microscopist must be familiar with the use of polarized light microscopy and with a broad range of particles from both natural and anthropogenic sources. Assigning a name to the particles is not enough. They must be familiar with assemblages so that they can indicate sources, generation mechanisms, and transport processes. They must be familiar with the mechanisms of that give rise to complaints, what materials can be found in a particular type of air sample and those things that will only show up in a surface sample. They must be able to relate air exposures and surface exposures with regard to the

likelihood of a complaint. This tends to be based on years of experience on the part of individual, often self taught, microscopists that somehow got into careers that required the development of that knowledge. There are a number of them. Asking for their background or a criculum vitie will often make that experance obvious. Be sure they understand the type of analysis required and provide them the questions to be resolved.

The Analyst as Assistant

The analyst is important as your eyes into the world at the level of the particles. You have a perspective of the situation over all. The analyst can't solve the problem, but the analyst can help you solve it. Question, challenge, and suggest alternatives to the conclusions reached. The analyst is your assistant. The analyst should be able to provide the analytical method, the criteria, and the background substantiating assumptions. You may not consider the assumptions adequately supported and often they are not. Most of this work has been done without any funding over the years because the analyst noticed a pattern. That doesn't mean that the assumptions are wrong, just that they are not the product of a rigorous study. Most of the controlled studies that have been conducted were funded through universities or research groups as a short term study. When the funding goes away or the student graduates the study stops. That is to be expected. The problem with that approach is that it limits the level of expertise achieved by the analysts and the subject of the study is often far too limited to control interferences. Universities and graduate student committees are not generally where one finds the type of analyst needed for these studies. The people doing this work are normal so busy doing the work that they haven't published sufficiently, but they often have the data to backup their assumptions. Ask them for it.

Through the Glass Darkly (1 Corinthians 13:12, The Bible, King James Version)

Analytical results are far removed from the environment in which the samples were collected. Proving the gun was in the hand of the suspect doesn't prove he commited the stabbing! Simlarly, proving mold spores are in the building doen't prove that mold is the problem. Your gathering of information, your interviews with complaintants must form the framework into which the analytical data fits. Environments tend to exhibit high variablitiy as a function of time and with changes in activity. The sample collected at any given time is one image of many that may be shown by that invironment. Samples limit information. Air samples have an upper and a lower size cutoff. For filters the lower cutoff is typically below the level of concern. That may not be the case for impaction collectors. For both impactors and for filter air samples the upper cutoff often limits the recovery of agents in the environment that may be the cause of health complaints (see Chapters 4 and 5). Air samples provide a very limited view of the environment.

Tapelifts provide an historical image of the environment but only since the last thorough cleaning. The particles are averaged out over time. Single large contaminating events can easily overwhelm the sample. That is a real exposure and the presence of that material in the environement at an elevated level may still be a problem. The material

could be misrepresented as an accumulation that occurred steadily over time rather than as a single event.

There is a vail between us and "Reality". We must allow for alternative explanations but not permit that possibility to prevent us from putting forward the best scenario to fit the facts. The "facts" are the particles themselves. The scenario put forward can be tested in the field. The scenario has not always been correct but it has more often proven something unexpected to be the case.

Conclusion

We are in search of the "truth" and the truth cannot be found if we hold on to unsupported preconceived notions. The data will speak for itself if the samples are collected and analyzed properly. Testing for molds or a few allergens is to miss 80% of what is causing problems in today's buildings. The world is marvelously more complex than mold and our response to it can be difficult to interpret. Similar symptoms can be caused by allergens, irritants, and toxins. Mold spores will generally be present but that doesn't mean that molds are causing the problem. Environments are wonderfully diverse and rich in information. Forensic particle analysis is the window into that world.

I hope that in the course of this seminar you have gained an appreciation for all the information that is available in a sample of particles from and environment. We have hardly begun to describe all the information that is there. I would encourage you to learn more. Become a critical consumer of analytical data. Are you getting value for your dollar? If you are looking for dinner then a shaker of salt and an empty plate won't do. Fill that plate, savor the variety, and be filled with good food. Now you have something to digest, something that will help you flesh out the bare bones, and something that will carry you on to success.

Questions

1. What are the three I's of investigation?

2. What constitutes a minimum sample for Forensic Particle Analysis of an environment?

3. Why should the microscopist be an "assistant" in the evaluation of the environment?

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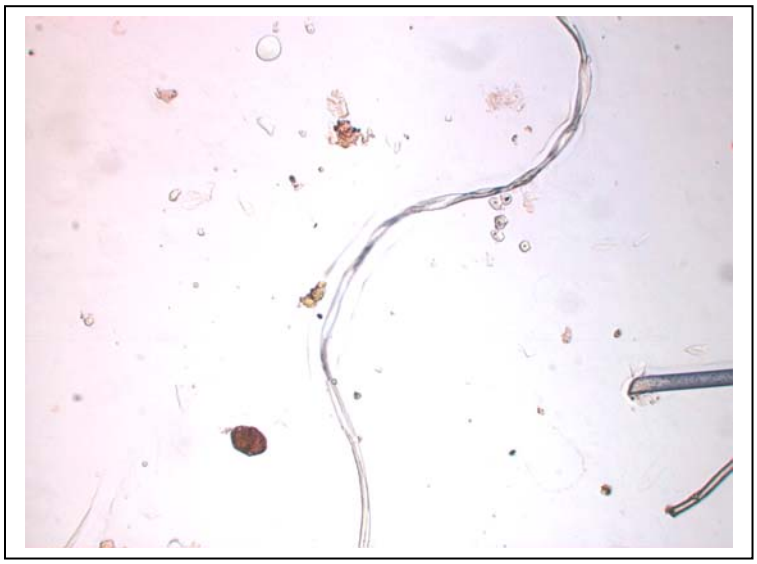
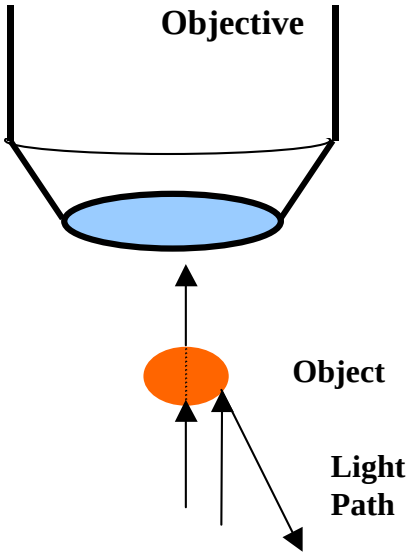
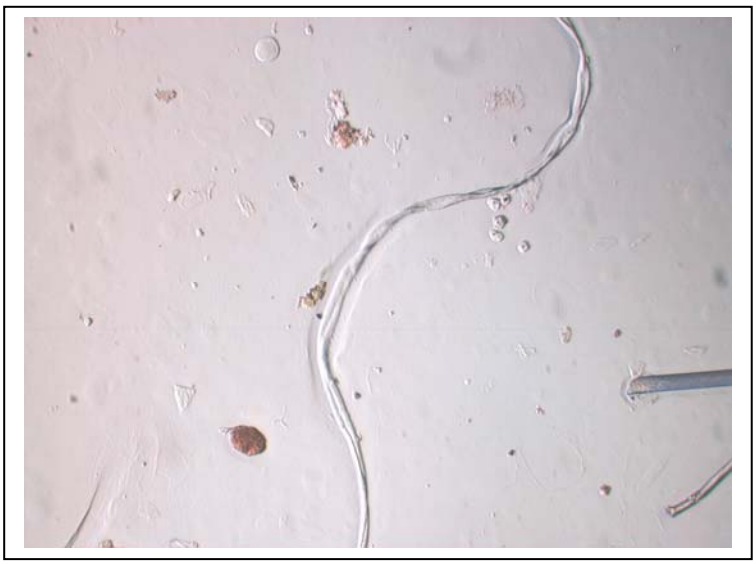
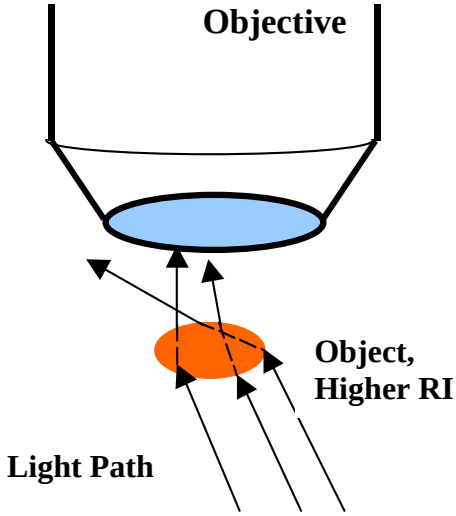
Appendix 1: PARTICLE IDENTIFICATION BY ANALYTICAL LIGHT MICROSCOPY



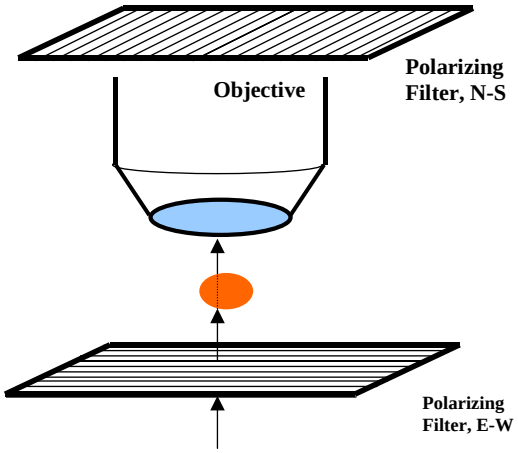


Transmitted Brightfield Illumination, Sample 652-02, TL#4
Light passes through the object and is absorbed, reflected, or transmitted depending on the relationship of the refractive indices and curvature of the particle. Transmitted brightfield illumination allows the observation of particle "relief", absorption, color, shape, size, internal morphology, and optimized resolution.

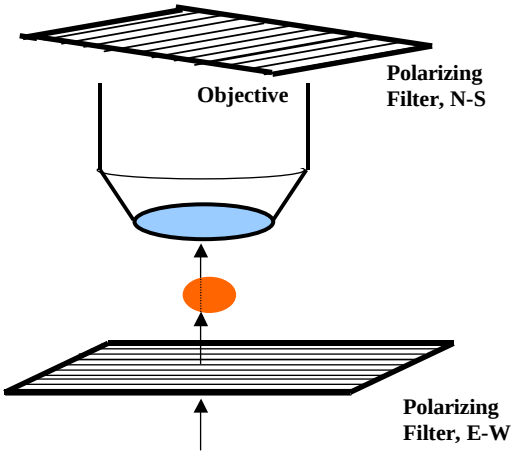




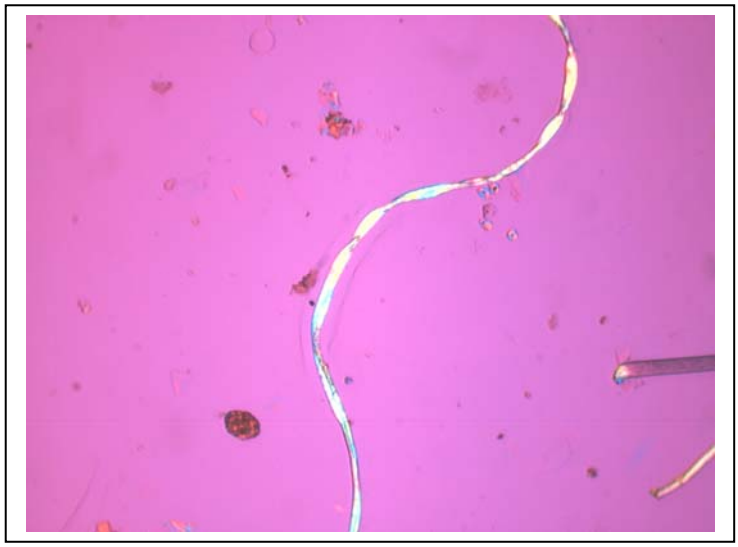
Transmitted Brightfield Oblique Illumination, Sample 652-02, TL#4
Transmitted oblique brightfield enhances contrast, increases rate of recognition, adds 3-D by shadowing, enhances resolution in one direction (east-west) and decreases it at right angles to that direction (north-south). If the object has a higher refractive index than the mounting medium it is dark on the right side.

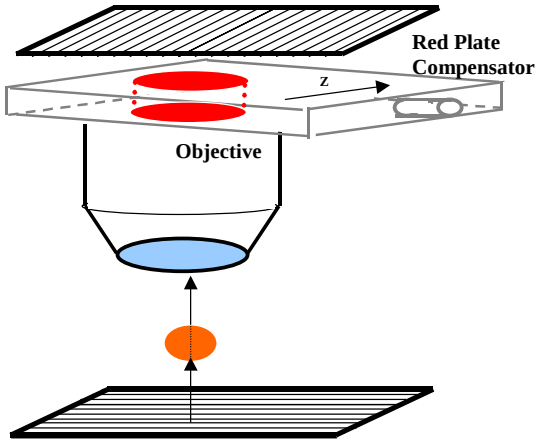


Transmitted Brightfield Crossed Polarizing Filters Illumination, Sample 652-02, TL#4
Crossed polarizing filters detects molecular anisotropy in objects: molecular alignment, crystal structure, and stress. Objects that are bright are anisotropic. Anisotropic particles can be rotated into "extinction" positions where their anisotropy aligns with the linear polarizing filters. The blue fiber on the right is in an extinction position except for the stressed end, where it was cut. Mature cotton fiber has no extinction position as is shown by the large wavy cotton fiber in the middle of the field of view.



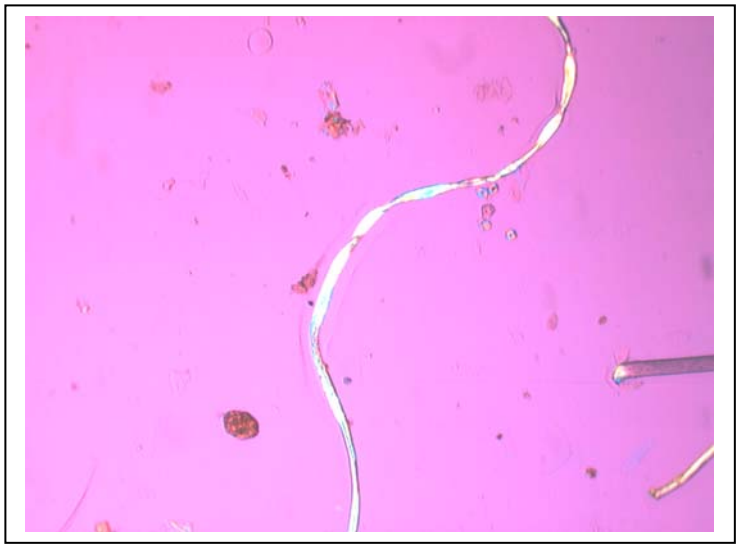
Transmitted Brightfield Slightly Uncrossed Polarizing Filters Illumination, Sample 652-02, TL#4
Rotation of the top polarizing filter by about 10 degrees allows some light to pass through the background so that both isotropic and anisotropic particles can be seen. Particles in extinction position can also be seen. This can be an effective way to scan a slide more rapidly while still detecting all of the particles present. Scanning rapidly and effectively is critical to analytical light microscopy. The analysis is based on the effective analysis of thousands of particles, not just a few hundred. Each slide will require an hour or more for an analysis using the most informative illumination techniques along with rapid changes of techniques where appropriate.

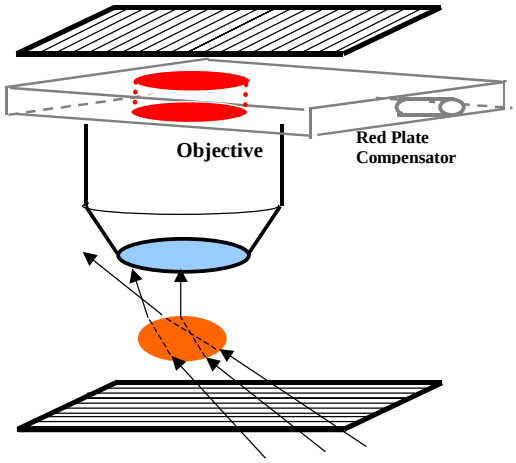




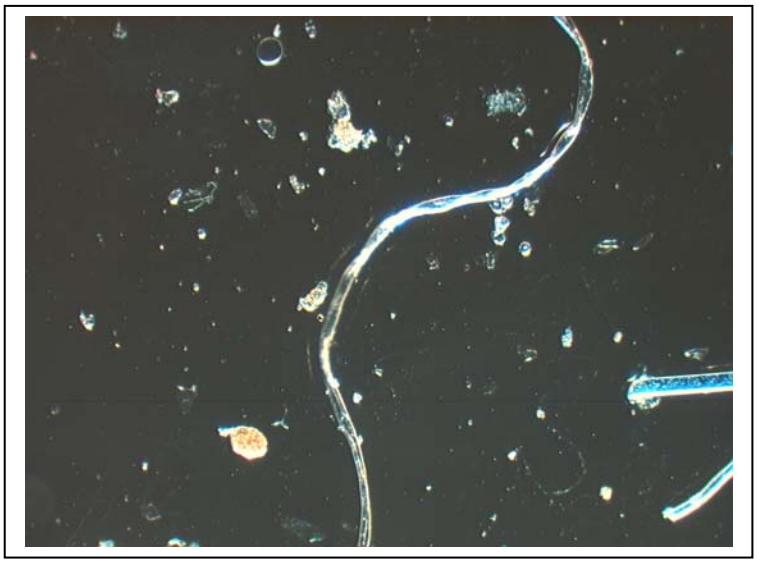
Transmitted Brightfield Crossed Polarizing Filters with Red Plate Compensator Illumination, Sample 652-02, TL#4

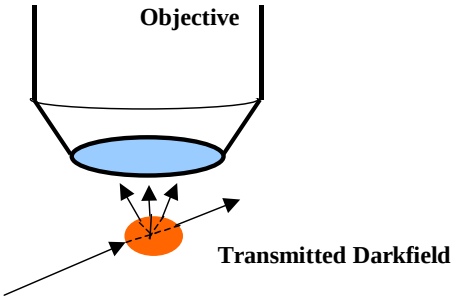
The red plate compensator is a colorless crystalline standard reference plate that is slid into the light path to determine the relative orientation of the two refractive indices shown by anisotropic materials. The small clump of starch grains slightly right and up from center illustrate the effect. The NE and SW quadrants of the starch grains turn blue and the NW and SE quadrants turn yellow. The molecules that comprise the starch grain are arranged so that the high refractive index is always oriented radially from the center of the grain.



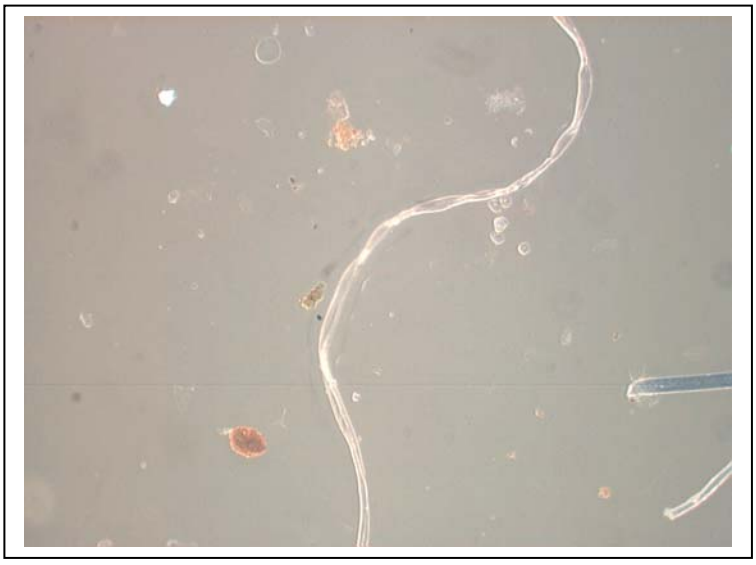


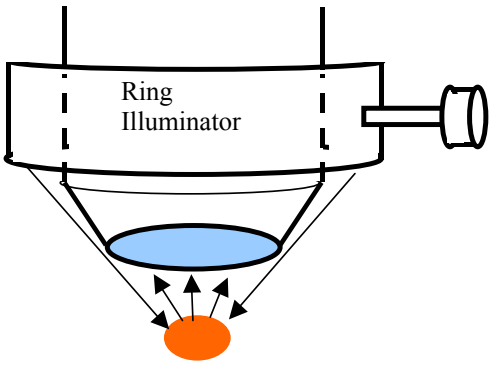
Transmitted Brightfield Oblique Crossed Polarizing Filters with Red Plate Compensator Illumination, Sample 652-02, TL#4
Adding oblique illumination to this configuration or to the slightly off crossed polarizing filters type configuration can speed the scanning rate with good particle recognition. Scanning with the red plate inserted is not recommended because it is more fatiguing to the eyes. Quickly inserting the red plate an noting the relative orientation of the high refractive index for selected particles can be very useful for their identification.





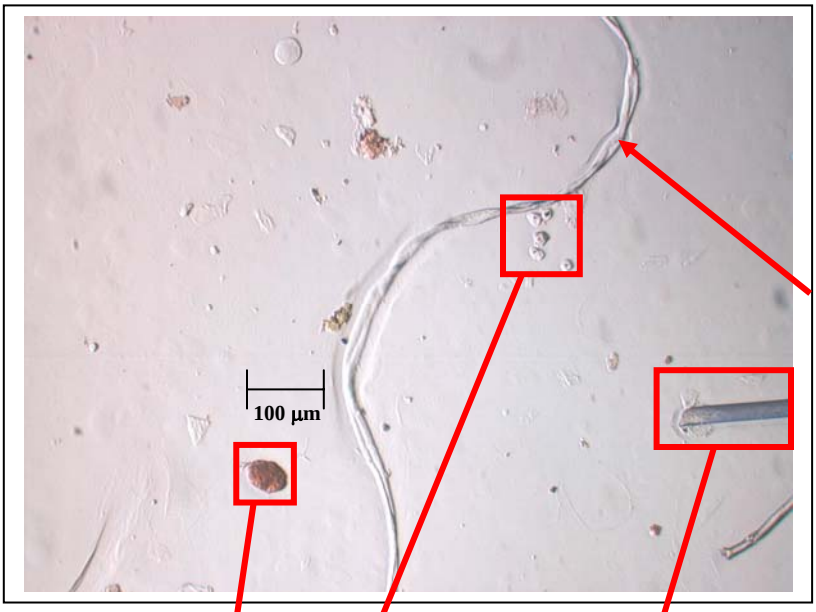
Transmitted Darkfield Illumination, Sample 652-02, TL#4
Particles are made visible by virtue of the light they scatter or refract. Darkfield illumination makes all particles "self-illuminated" objects. This dramatically increases contrast and that contrast can be controlled, even to make particles below the resolution limit of the microscope visible. Darkfield illumination can be centered or oblique. An oblique darkfield results in highlighting one orientation of the particle. Here a N-S oblique darkfield highlights the E-W orientation of the particles. Elongated particles at 45 degrees are less easily seen until the stage is rotated or the oblique direction is changed. The pet dander particle just above the fiber at lower right is difficult to see for this reason.



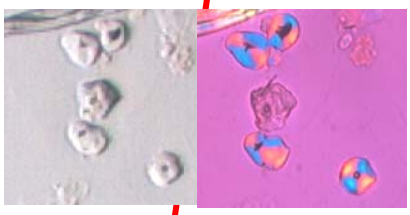


Reflected Darkfield Illumination, Sample 652-02, TL#4
Reflected darkfield illumination can have as much contrast as transmitted darkfield but it requires the removal of all of the reflecting and light scattering surfaces in the light path below the slide. This is sometimes necessary to allow the eye to see essential dark detail on black objects. Generally the scattered light background is not a problem and the reflected color and top surface texture can be seen adequately. The fact that the small opaque particle near the center of the field of view to the left of the cotton fiber is black can be clearly seen. If it were a wear metal particle it would be bright with this type of illumination. The fact that the transparent particle in the upper left is very bright indicates that it is highly reflective and flat, a pearlescent particle used in some cosmetics and inks.

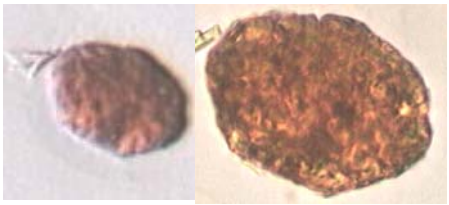
WHAT ARE THEY?



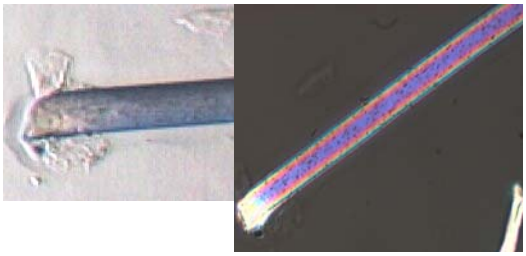
This field of view was photographed at 100X using transmitted oblique illumination. This was the second in the series of photographs that documented the appearance of particles with different types of illumination. The smaller photographs are first a blow-up of the 100X image and then a 400X image to feature specific characteristics.
Particles are identified by their optical characteristics. The most prominent particle in this photograph is the large cotton fiber running from top to bottom. Cotton is identified by its helical twisting, collapsed central channel (lumen), anisotropy, RI greater than the mounting medium, and absence of extinction position. Cotton fiber is often dyed though in this case it is not. These properties are sufficient to uniquely identify mature cotton fiber that has not been mercerized. Cotton is generally included in the "Clothing Fiber" category.



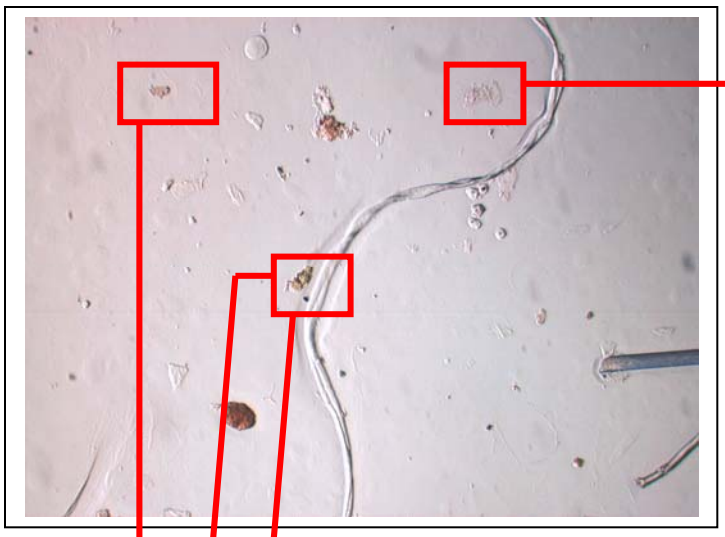
There are a number of "Starch" grains in this photograph, most are smaller than those in this clump of four (center grain is a skin flake). These particles are corn starch grains. They are identified by the central trilete scar in most of them, their polyhedral tendency, their moderate anisotropy, the radial orientation of their high refractive index, size range, good transparency, and lack of color. They can be dyed or may turn brown on heating in the absence of water. If heated with water they swell and become isotropic.

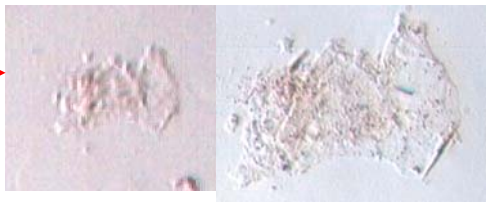


Mite fecal pellets are common in homes with a significant mite population. The pellets are sometimes more mobile in the home environment than are the mites. The pellets are identified by their rounded shape, general size, brownish color, randomly oriented crystalline inclusion with moderate anisotropy, isotropic matrix, surface texture, and heterogeneous inclusions. The recent diet of the mites is often evident by the materials seen in the pellet. Mite parts will be found associated with the samples from this environment. These would be included in the category of "Mite Debris".

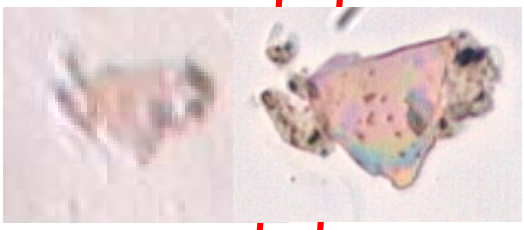


This is a blue nylon "Clothing Fiber" that has been mechanically broken, which creates high molecular stress at that end. The fiber has no cuticle, cortex or medulla (hair), no lumen (plant), and not long fibril bundle structure (mineral fiber). It is filled with high refractive index particles that strongly back-scatter light, they appear dark with transmitted light and white with reflected light. The fiber has parallel extinction and high moderate birefringence so it is dark between polarizing filters when it is oriented in the E-W or N-S position but is bright, showing many colors at 45^{o}. The higher refractive index is oriented along the length of the fiber and both refractive indices are much higher than the mounting medium.

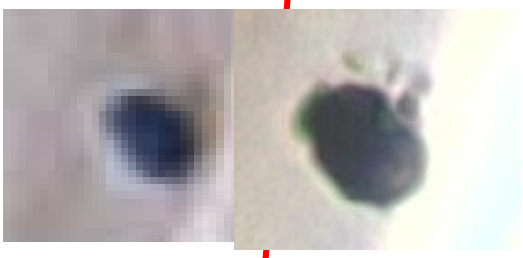




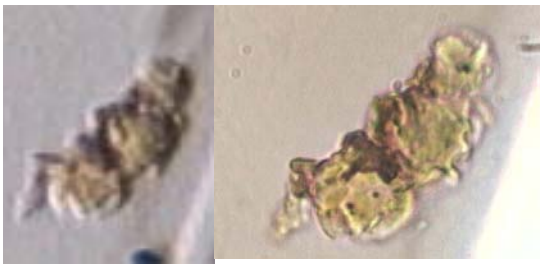
Human "Skin Flakes" are sometimes associated with attached cosmetic materials. This skin flake is associated with red iron oxide pigment. Human skin flakes are broad, thin, colorless (all races), irregular outline, tapered edge, structures with very low stress birefringence, and good scattering texture with darkfield illumination.



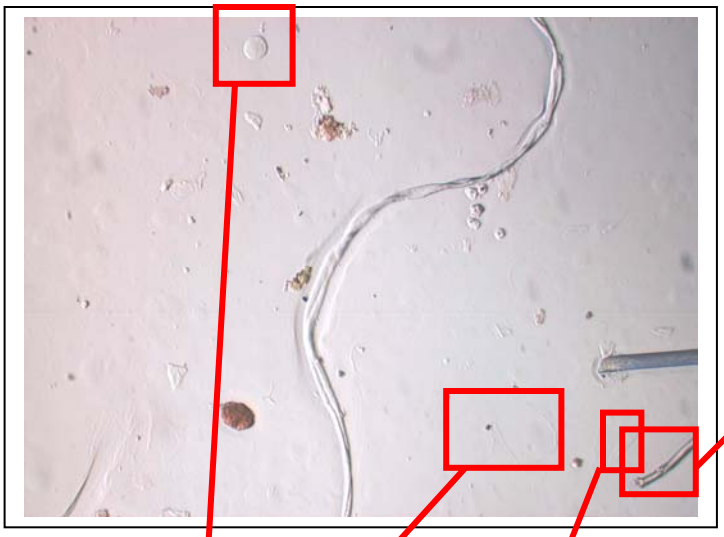
This is a flake of pearlescence used in some cosmetics and inks. This is a synthetic flake material designed to be high reflective, bright in reflected darkfield. It is transparent and isotropic and exhibits thin film interference colors when viewed with transmitted light. It is often associated with other cosmetic pigments and debris. This would be included in the "Cosmetics" category.

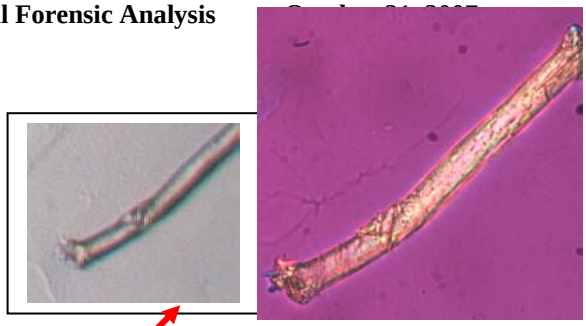


Soot is opaque with transmitted light and black with reflected light. It is a product of pyrolysis and may exhibit a variety of distinctive structures or associated features. This is a fairly large soot particle with some reflectivity off the center of the lower, rounded part. That indicates a surface tension formed shape that can only be formed with a liquid fuel. Its irregular shape would tend to indicate a viscose, poorly aerosolized fuel. An uncontrolled burning of plastics or a heavy fuel (Bunker C or residuum) oil fired boiler can produce this type of particle but a diesel engine will generally not. The range of variation in other soot particles will indicate the dominant pyrolysis sources. This would be in the "Soot" category unless sufficient other particles were found to identify a more specific source.



Chlorophyll colored particles indicate algae or plant residues. This particle is a combination of degraded plant material (brown) and the chlorophyll filled algae cells. This particle is isotropic except for a few very small mineral grain attached and is cellular in structure. It is from the outside environment and is part of the track-in or air exchange loading in the indoor environment. Examination of other particles will help establish the balance of track-in and air exchange burden. This is normally included in the "Algae" or "Humus" category, depending on how frequently algae particles are encountered in the sample.

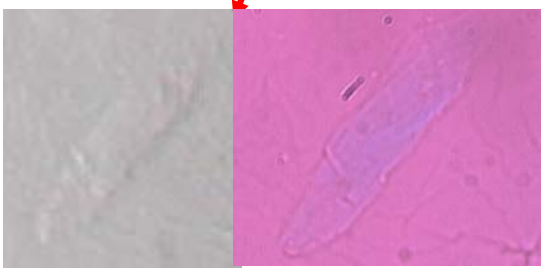




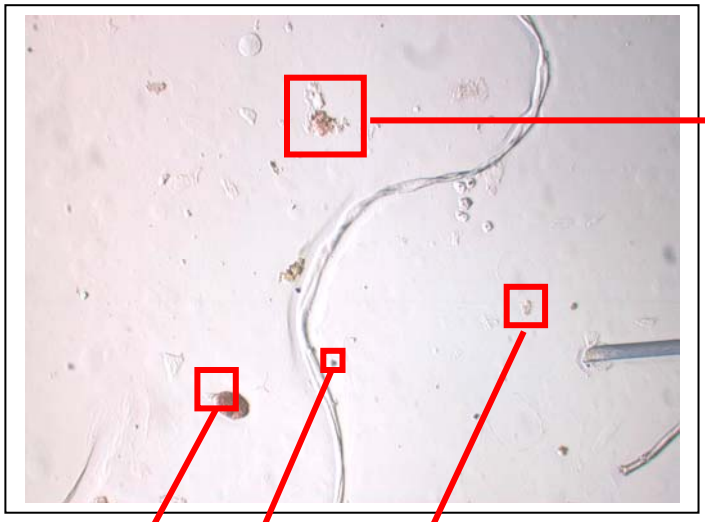
This is a mechanically broken polyester fiber. The refractive index across the fiber is near the refractive index of the mounting medium (1.48). The refractive index along the length is very much higher and the particle has a birefringence that is very high. It has some rutile filling (little black specks with transmitted light). This is normally included in the "Clothing Fiber" category.

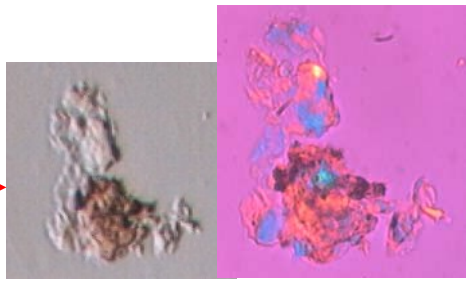
This is a mechanically degraded fibril bundle from a cellulose fiber. It is a thin ribbon with the high refractive index oriented along the long axis. Its refractive indices are well above the mounting medium but its so thin that it can be difficult to see without oblique illumination and polarized light. It is commonly associated with tissue paper use or frequently laundered cotton fiber cloth. Bedrooms, sickrooms, and hospitals show a significant amount of this type of particle. This is usually included in the "Paper Fiber" category.

This type of particle reached the surface as a liquid with a significant soluble solid content. The solid is isotropic, non-crystalline, colorless, has a refractive index moderately higher than the mounting medium, made the liquid viscose at relatively low concentration, and was formed with significant energy or was at very low concentration when formed. The most common source for this type of particle in areas occupied by humans is the mucoid aerosols from the mouth or nose. This is normally included with the "Skin Flakes" category as part of the human generated population of particles.



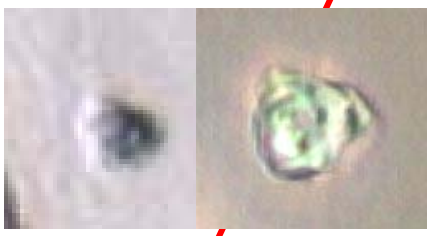
The fur on most pets results in a rather distinctive structure for their dander. It tends to form thin, elongated flakes that have a higher birefringence than human skin flakes. Chemically skin flakes from different mammals and even the hair is the same, keratin, but the morphology and the forming forces active in their release are different and leave distinctive marks. This is a typical particle that would be included in the category "Pet Dander".



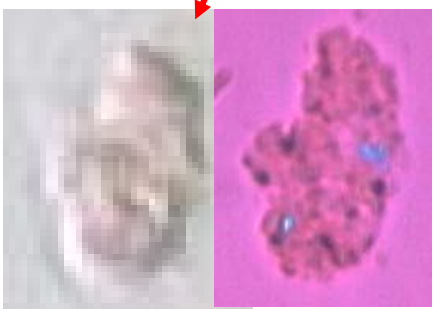


"Humus" particles are predominantly brown in color but may have colorless region also. They often contain optically active materials in random orientation and are heterogeneous, though well integrated, in composition. Their refractive indices are all moderately above the mounting medium. These materials can be from a variety of sources but are typically from outdoors when they have associated mineral grains within the matrix.

This particle has a distinctive structure of reinforcing ridges attached to a thin plate of the same material. Its refractive indices are moderately higher than the mounting medium and its birefringence is very low. This is characteristic of the chitin exoskeleton of insects and arachnids. This is normally included in the "Insect Parts" category.



"Natural Minerals" include a wide variety of optical properties. The mineral here is a green amphibole with magnetite inclusions. Natural minerals are not generally identified specifically in the report unless they are important from a health aspect. Naturally occurring asbestos fiber would be an example of a mineral that would be specifically identified.



The "Soil" category includes agglomerated fine minerals with clay binder that may or may not have a significant organic component. Some organic component or staining is required to be included as a soil. This particle is a cemented clay with a few bright mineral crystals and a significant transmitted light scatter. If a single mineral crystal dominates the sample and the organic component is not obvious then the particle is included with the natural minerals.

The sample reports that follow are examples of reports released by Microlab Northwest. Each of these are actual cases and every case is unique in its own way. In the first report it would have been useful to know that the "Pool Room" was a room in which people played pool rather than swam but that became obvious as the sample was examined and the blue chalk used to increase friction at the tip of the Q-stick became evident. That had actually been noted on an earlier set of samples from this area when their concern had been mold though glass fiber was their primary problem earlier also. Mold never was a problem at this site though they did have an indication of a dust mite problem. Their attempt to clean up was a bit over zealous and they disturbed the insulation above the drop-ceiling. That made the glass fiber problem worse and their complaints continued. When they controlled the glass fiber exposure the complaints went away.

The second report involved a home designed with a "Russian Fireplace". In this design the flue becomes a heat exchange system to warm the home. The family members living in this home were having respiratory problems and the brick flue of the fireplace had developed a crack though no elevation of carbon dioxide was detected by the field technician when the fireplace was in use. As it turned out there were a number of problems in this environment that could have resulted in the symptoms shown by the family.

In each case the analyst must determine what is unusual about the sample or what in the sample could be causing the symptoms reported. The environmental specialist can then use that information in combination with their observations to evaluate the problem at the site. Follow-up e-mails in each case refined the data and lead to satisfactory solutions.

LABORATORY REPORT

TO:

PHONE: FAX: e-mail:
SUBJECT: Particle Identification
SPECIMEN: Tapelift samples from a Senior Center
REFERENCES:

INTRODUCTION

Three tapelift samples from …… were received for evaluation. The samples were identified as follows:

T1. Office Supply (Over Entrance) 1/21/0- 6:30PM
T2. Inside of Duct (Rcpt. Office) 1/21/0- 6:30 PM
T3. Pool Room (NE Supply) 1/21/0- 6:40 PM

The tapelifts were placed on clean microscope slides and immersed in acetone for about two hours and then removed. The slides with the tapelifts were rinsed with clean acetone as they were removed from the immersion tank. The tapelifts were allowed to dry for ten minutes and then mounted using a synthetic resin (Shurmount). The completed mounts were analyzed using analytical light microscopy. The materials identified are listed in decreasing order of frequency, the most common materials first. The significance of a material's location in the list is not necessarily related to its health impact because some materials have a greater health impact at low levels than other materials do at high levels.

RESULTS

The tapelifts contained skin flakes, natural minerals, clothing fiber, paper fiber, charred wood, humus, sawdust, wear metals, tire wear, glass fiber, toner, insect parts, pollen, plant parts, starch, spores, hyphae, diatoms, rust, vehicle emissions, ink, paint spheres, blue chalk, dog dander, shoe wear, flyash, cosmetics, and algae. Glass fiber was elevated in all of the tapelifts. They were most elevated in the "Office Supply", T1, tapelift. There were 216 short glass fibers per square inch and 36 glass fibers longer than five hundred micrometers per square inch. Complaints related to short glass fiber typically begin at about 13 per square inch and at about 4 per square inch for long glass fiber. The glass fiber appeared to be primarily from thermal blanket insulation. The fiber was associated with yellow resin predominantly though clear resin and pink resin associated with glass fiber were also present. There was some glass fiber that had been in

an airflow for some time and was probably from the ventilation system itself. Acoustic ceiling tile may also be contributing. The spores were not at unusual levels and were consistent with an exterior source. The mite population seen in earlier samples from this facility was not present in these samples. This time of year the mite population is often low due to lower indoor relative humidity.

There are some indications of construction activity in the area. The natural minerals are higher than normal for an indoor environment. That is often associated with construction activity along with the elevated sawdust. The paint sphere population is relatively low, which is unusual if construction involves painting.

CONCLUSION

Glass fiber, both short and long, were elevated in this environment. They were both at levels that could be expected to result in health complaints due to skin rashes, upper respiratory irritation, and eye irritation. The glass fiber levels in these three tapelifts are much higher than in the tapelifts collected last June.

Thank you for this opportunity to be of service. If I can provide any further assistance please contact me.

Signed: _____
E. R. Crutcher, Consultant

LABORATORY REPORT

TO:

PHONE: FAX: E-mail:
SUBJECT: Particle Identification
SPECIMEN:
REFERENCE:

INTRODUCTION

One set of tapelift samples and two air samples from a residence were received for evaluation. Soot from a Russian Fireplace was indicated as the major problem. The samples were identified as follows:

Tapelift Samples
- CF-1 Top of Shelf S of Fireplace
- CF-2 Jewelry Stand in Bedroom
- CF-3 Armoire in Living Room

Air Samples
- 7678564 Outdoors 150 Liters
- 7678789 Indoors, S of Fireplace 150 Liters

The tapelifts were placed on clean microscope slides and immersed in acetone for about two hours and then removed. The slides with the tapelifts were rinsed with clean acetone as they were removed from the immersion tank. The tapelifts were allowed to dry for ten minutes and then mounted using a synthetic resin (Shurmount). The Zefon air sample impaction plates were inverted onto a clean microscope slide and sealed with a synthetic resin. Automated Image Analysis was used to quantify the airborne loading in terms of the total area of coverage on the impaction surface of the Zefon air samples per 150 liters of air. The completed mounts of both the tapelifts and the Zefon air samples were analyzed using analytical light microscopy. The materials identified are listed in decreasing order of frequency, the most common materials first. The significance of a material's location in the list is not necessarily related to its health impact because some materials have a greater health impact at low levels than other materials do at high levels.

RESULTS

The tapelifts contained skin flakes, dog dander, clothing fiber, natural minerals, charred wood, paper fiber, soot, ash, glass fiber, pollen, paint spheres, sawdust, insect parts, plant parts, Demisted beetle larva debris, tire wear, spores, starch, humus, hyphae, bird feather barbules, food debris, and cleaning residues. The shelf tapelift, CF-1, contained a higher proportion of soot and ash than the other samples. The other two tapelifts contained more large fragments of charred wood. These large fragments are very fragile and are typical of backdraft debris from a fireplace. A significant amount of soot and ash was also present in these samples. Ash is not normally part of the backdraft

debris because it is below the grate. The presence of ash suggests turbulent flow through the firebox back into the home. Many of the soot particles are quite large. That would suggest a significant accumulation of soot in the heat-exchange area of the fireplace. It is evident from these tapelifts that the fireplace is backdrafting into the home.

There are a couple of other issues that should be considered in this home. First is the glass fiber issue. The glass fiber in this home is elevated. Much of the glass fiber is coated with soot. It is possible that the glass fiber is related to the failure that occurred in the fireplace. This glass fiber should to controlled and reduced in the environment. The second issue is what appears to be an infestation of carpet beetle (Demisted beetle). Demisted beetle larva has been associated with allergic reactions. Both glass fiber, a mucus membrane irritant, and Demisted beetle larva, an allergen, result in respiratory symptoms that may be present along with those caused by the gasses and particles coming from the fireplace. They should be evaluated as part of the remediation of the home.

The air sample collected near the fireplace contained plaster, natural minerals, skin flakes, charred wood, glass fiber, Demisted beetle larva debris, dog dander, plant parts, bird feather barbules, diatoms, spores, pollen, hyphae, starch, ash, and tire wear. The airborne particle loading was quite high at 68% obscuration on the impaction plate. Health complaints due to particle loading alone increase as the obscuration value increases over 20%. Typical values for the impaction plate obscuration in homes ranges from 8% to 18%. This home is very much beyond normal loading.

The particle loading outside the home is less than 1%. It is predominantly fungal spores, plant parts, and natural minerals.

CONCLUSION

Fireplace backdrafting is a major source of particles in this home. The home also has an elevated level of glass fiber associated with soot. This glass fiber may be related to the failure in the heat exchanger portion of the system. In any event the glass fiber exposure should be reduced. There is also very high airborne dust loading in the home. This is again due to a significant contribution from the backdrafting fireplace. There is a population of carpet beetle in the home that may need to be reduced.

Thank you for this opportunity to be of service. If I can provide any further assistance please contact me.

Signed: _____

E. R. Crutcher, Consultant