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The
PARTICLE ATLAS
Edition Two

McCRONE
DELLY

The PARTICLE ATLAS
Edition Two

An encyclopedia of techniques for small particle identification

Volume I
Principles and Techniques

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Preface to The Particle Atlas Edition One

It is a great pleasure to be able to participate in the birth of a work whose conception I attended with a fatherly interest when I discussed a systematic taxonomy of particles with Walter McCrone a decade ago. The field of environmental research and control has long needed such a work as this, as it needs so many tools. There seems little doubt that mankind is rushing toward an ecological crisis. The explosive growth of population and the rise of technology are increasingly pushing many species toward extinction. Because ecology is still far from an exact science, we cannot say upon which of these species our own continued existence depends. We can only be certain that vital dependencies exist.

It is useful to consider the analogy of bacteria. A pure bacterial culture growing on a nutrient surface will develop into individual colonies, each with a large population which rarely grows beyond a certain critical size. The limiting factors are the diffusion of foods to the center of the colony, and the diffusion of waste products from the center to beyond the periphery.

In the long run, the same laws apply to human communities. The squalid condition of some of our great population centers demonstrates this clearly. The difference is that bacteria can take no action to improve their situation, whereas humans—presumably—can at least alleviate the problem through conscious decisions. The bacterium merely lives, multiplies and dies. Humans can consciously choose to control their numbers and distribution.

However, "can" is not "will." To reverse present trends will require a revision of whole cultural patterns, which can be accomplished only through humane application of the proper knowledge.

The greatest need for knowledge in the ecological struggle which confronts us is of the waste products of our technology. R. Buckminster Fuller has pointed out that one measure of our standard of living is the number of man-equivalents of energy which we command. According to his figures, every American can call upon the work equivalent of nearly two hundred slaves. What he neglects to point out is that, while these "energy slaves"—generators, engines and so on—are nonliving things, they excrete their wastes into the environment just as surely as do animals and men. However, these mechanical excreta are strange and new upon earth, and organisms have not yet evolved to utilize them in a continuing food chain. It is the accumulation of these machine metabolites on top of those of overcrowded human populations that constitutes pollution and jeopardizes the ecological balance.

In the fight against excessive pollution, every available technique must be pushed to its limit. There has not yet been a method rejected because it was too sensitive. Yet it has been a bold effort to produce this volume. In a period when the intellectual fashion is to produce scientists who perceive only numbers from a computer, any attempt to train specialists in microscopical observation may seem anachronistic. Yet no instrument has been built which can discriminate with the precision of the eye, nor is any computer the equal of the human brain in remembering and associating images. The mere fact that the words here convey the same meaning whether written in sprawling longhand or in various type faces, or viewed from any angle and from any distance which eye can resolve, is testimony to the associative powers of the eye and brain.

The task of classifying particles in the microscope might seem impossible. One of my children said recently at dinner, "But there must be millions of different kinds!" The truth is that a rather small number of species make up nearly 90% of the particles in our urban atmospheres. Indeed, the same child can distinguish among more than a thousand friends and acquaintances, several score makes and models of automobiles, the *dramatis personae* of several dozen television programs, an enormous variety of foodstuffs and the scenery of a half a hundred ski slopes. Her mind and hands recall the fingering of four different musical instruments as her eyes discriminate the notes. Learning to discriminate a few hundred substances under the microscope would tax her little; she already knows nearly that many wild flowers.

In fact, this last statement contains a major clue to the problem: we are not raised looking through microscopes as we are raised looking at flowers or automobiles. Hence we meet our particles all at once on a strange landscape as if being thrust suddenly among the (putative) vegetation of Mars.

The similarity does not end at this point. A small number of people have been able, for years, to identify airborne particles, just as my daughter identifies wild flowers, at sight. My wife, on the other hand, wants to be able to identify flowers not only in Colorado but also in Mexico or Alaska. She therefore makes use of the conscious·decision processes embodied in *taxonomy*. These permit her to find a totally unfamiliar flower in a suitably arranged atlas by a process other than turning the pages until she sees a picture which looks like the flower (my method).

This was precisely the challenge I handed Walter McCrone a decade ago—to develop a systematic taxonomy of particles. The ability of Dr. McCrone and his co-workers in identifying particles by microscopy is phenomenal; I asked him to codify that knowledge so that it could be perpetuated.

This work is now done, for the moment at least. No doubt new technologies will inject new kinds of particles into our atmosphere, and additions will be needed. The system, however, will remain—that is the real contribution.

It would be unfair, however, to overrate the value of this work. It is merely one tool among many in the struggle to control air pollution. By itself, microscopy cannot solve the problem. After all, one cures pollution by ceasing to pollute. It should not require a microscope to sound the alarm of our peril. Even the measurement of many pollutants is far better done by other methods.

Yet, when the problem is "Who did *that?*" the microscope can be an invaluable tool. Sulfur dioxide carries no brand name, whether it comes from an electric power plant or a cement factory. But the particles carried with it from the two sources are entirely different; in many cases there may even be great differences between the particles from two different power plants or two different cement works. In answering questions of this sort, microscopy is a uniquely capable technique.

Thus we must understand that the factories and homes which are the sources of pollution must find the ultimate solution to pollution problems. The mental attitudes of the people who make up our society must bring them to demand that solutions be found. The use of the microscope, together with scientific developments, can point the way, demonstrate the need, document the successes and failures and dramatize the trends. In its own place, microscopy can be a potent tool. This book should lead the way to its use.

James P. Lodge, Jr.
National Center for Atmospheric
Research
Boulder, Colorado
July, 1967

Preface to The Particle Atlas Edition Two

The preface to the first edition of *The Particle Atlas* stated that there is little doubt mankind is rapidly approaching a crisis with regard to the quality of his environment. That was written five years ago at a time when concern was mounting in many parts of the world with regard to air, water and solid-waste pollution, and two years after the passage of the Air Quality Act, the first U.S. federal law dealing with air pollution that had a reasonable chance of being effective. Much concern was felt at that time by those who had been in the air pollution field for many years that, as has been the case with many fads, interest might wane. Fortunately, this concern has been maintained. Thus, since 1967 when the first edition was published, the Environmental Protection Agency has been established and the Air Quality Act has been strengthened by a number of amendments.

As the earth's population increases and demands on our environment increase, it will become ever more important to concern ourselves with man's role in nature. We can no longer restrict pollution control to cities; pollution on a global scale has become a problem.

Particulate material is, of course, one of the most important constituents of many types of polluted air. Particles undoubtedly play a role in the physiological effects of pollution, and the decrease in visibility associated with particles produces one of its most obvious and most unpleasant manifestations. Identifying these particles is an important step in the control of air pollution.

Of course, air pollution control is not the only reason for particle identification. For example, much of the technology developed since World War II has required ever-decreasing tolerances with a result that contamination by both naturally occurring and man-made particles is an increasing problem. Identifying these particles often identifies their source.

The overall procedures for identifying individual small particles, it seems to me, often have many of the features of the fictional police methods of detective stories. Sometimes the particle, like the criminal, is identified by a single clue. For example, the criminal may be identified by means of a photograph and the particle by means of a photomicrograph. However, the identification often is much more complicated. Many clues must be obtained, examined, their overall significance determined and some even discarded. For particles, these additional clues may be obtained by techniques or equipment such as electron or ion microprobes, x-ray or electron diffraction and polarizing microscopes. Just as in criminalistics, many new techniques are being developed and old ones are becoming more sophisticated.

Pursuing the analogy further, the number of both criminals and the types of crime they commit is increasing. However, not all particles are criminals, and an important aspect of particle identification is separating the "good guys" from the "bad guys."

This book is an atlas in the sense that it provides, by photomicrographs and electron micrographs, the relationship between the appearance of images of many different kinds of particles and their identity. A comparison of the image of a particle to be identified (or better, of many such particles of the same kind) with the plates in Volumes II and III, may identify the particle or at least provide a very useful clue. Thus this book is a tool in a more specific sense than are most books. My own experience has been that identification of particles by appearance alone (their morphology) is especially likely when something is known concerning their source. For instance, spherical particles collected from stack gases almost certainly are fly-ash, while spherical particles collected from ancient ocean sediments are very apt to be of extraterrestrial origin.

Actually, this book is much more than an atlas. Many techniques for particle identification are described in detail as well as the ways in which the clues obtained by these techniques can be combined to provide positive identification.

This new edition not only greatly extends the collection of photomicrographs given in the first edition but also provides a collection of electron micrographs obtained with both a transmission and a scanning electron microscope, thus aiding in the identification of particles too small to be resolved by the optical microscope. Here at the National Center for Atmospheric Research, we have found that the detail provided by electron microscopy often permits identification which cannot be achieved by optical microscopy.

I am delighted to see that this new edition goes far beyond merely updating the old one. It is now an even more sophisticated tool and should considerably alleviate the frustrations of scores of scientists and engineers faced with problems involving particle identification.

Richard D. Cadle
National Center for Atmospheric
Research
Boulder, Colorado
May, 1972

Acknowledgment

About 1950, one of the authors of this encyclopedia (WCM) decided that the microscope should be more extensively used in air pollution control. This necessitated a major extension of previous work since nearly every solid substance can be, at one time or another, a particulate atmospheric pollutant. To identify more than the relatively few a microscopist could remember and to make the method more generally useful requires (1) an identification scheme embracing as many physical and chemical characteristics as possible and (2) carefully prepared data retrieval methods for the results.

A first project to test the possibility of using the microscope for the general identification of small particles was supported by MAPPA, the Midwest Air Pollution Prevention Association, in 1950. A final report to the Association in 1952 confirmed the practicality of the idea and indicated that the results would be generally useful in industrial hygiene, clean room monitoring, criminalistics, and air and water pollution control.

In 1958 the U.S. Public Health Service began a three-year program at McCrone Associates in Chicago; it was hoped that this would lead to a publication which would make these methods more generally available. Samples of known atmospheric particles were submitted by members of the Air Pollution Control Association and considerable work was done on these and other samples.

When USPHS support ended in 1962, the project was well advanced but not yet ready for publication. A major accomplishment during this period was the application of dispersion staining methods to the characterization and identification of particles. During the next four years, various additional government and industrial sponsors made it possible to complete the first edition of *The Particle Atlas.* The first edition appeared in 1967.

Since the first edition, the procedures have been given much wider practical test, many new substances have been studied, and the techniques for handling, characterization, and identification have been greatly improved. Major developments since the first edition include:

- development of automatic image analysis
- development of the holographic microscope
- application of dispersion staining to fibers, in general, and asbestos in particular
- more sensitive microchemical tests
- increased sensitivity of x-ray diffraction techniques
- application of both the transmission and the scanning electron microscope to particle identification
- addition of solid-state x-ray detectors to both kinds of electron microscopes to permit elemental analysis
- improved sensitivity and increased speed of electron microprobe analyses
- computer control of microprobes
- development of the ion microprobe analyzer with its phenomenal sensitivity (10^{-19}g), speed (a few minutes per particle) and versatility (*all* elements)
- improved source testing
- new, more reliable and more sensitive particle-handling techniques
- improved fractionation methods
- new lower cost microscopes, microprobes etc.

The authors of *The Particle Atlas One* were themselves amazed at the progress in this field in five short years. Realizing that the new edition would be at least double the size of the first, we decided to enlarge the list of authors as well. These particle analysts, all with McCrone Associates, number fourteen. They were assisted by an editor, two associate editors, several librarian-editors, typists, and proofreaders. All are listed here along with other contributors to this project ranging back to 1950: Michael Bayard, Charles Bowen, Cleopatra Brown, John Brown, Kenneth Brown, Marigene Butler, Susan Catania, Fay Coppersmith, John Delly, Ron Draftz, Steven Einbinder, Nancy Fleischer, Louise

Forlini, John Gavrilovic, Robert Goodman, Don Grabar, James Graft, Sylvia Graft, Ralph Grau, Gene Grieger, Ralph Hinch, Warner Hudson, Howard Humecki, Yvonne Julian, Richard Kuhn, Vinay Likhite, Bonnie Lovato, Lucy McCrone, Walter McCrone, Robert Muggli, Stanley Nicholson, Pat Pierre-Auguste, Sam Radner, Marvin Salzenstein, Jacqui Smid, Ian Stewart, Ann Teetsov, John Vermillion and Geoffrey Woodard. The editors are most grateful for the wholehearted cooperation of such a group.

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The Michel-Lévy Birefringence Chart

Michel-Lévy published the chart that bears his name in Paris in 1888 (A. Michel-Lévy and A. Lacroix, *Les Mineraux des Roches*). The Birefringence Chart is a valuable analytical aid to the microscopist in that it graphically relates the thickness, birefringence and retardation of anisotropic substances.

Anisotropic substances appear bright on a dark background between crossed polars at some orientation. This arises from the fact that they have more than one refractive index as opposed to isotropic substances which have only one refractive index and remain dark at all orientations between crossed polars. Anisotropic substances which are uniaxial have two principal refractive indices, ϵ and ω; biaxial substances have three principal refractive indices, α, β and γ.

Birefringence is the numerical difference between the maximum and minimum refractive indices, $(n_{max} - n_{min})$, that is $(\epsilon - \omega)$ for uniaxial substances; $(\gamma - \alpha)$ for biaxial substances. We can designate birefringence generally as $(n_2 - n_1)$.

The thickness of a substance, usually expressed in micrometers, μm, is determined with a calibrated ocular micrometer or estimated. In the case of polymer films and some fibers, a machinist's micrometer may be used.

When plane polarized light enters a doubly refracting substance, it is immediately resolved into a slow wave and a fast wave. On leaving the substance, the fast wave exits first and travels a certain distance in air until the slow wave starts to exit. Path difference is the retardation of the slow wave behind the fast, and it is expressed in nanometers.

If white light is used, certain of its constituent wavelengths will be weakened or destroyed through interference for any given retardation. The wavelengths that remain combine to form the interference colors, or polarization colors, that we see using crossed polars. Retardation increases linearly with both the thickness of a substance and with the difference in the maximum and minimum refractive indices. That is,

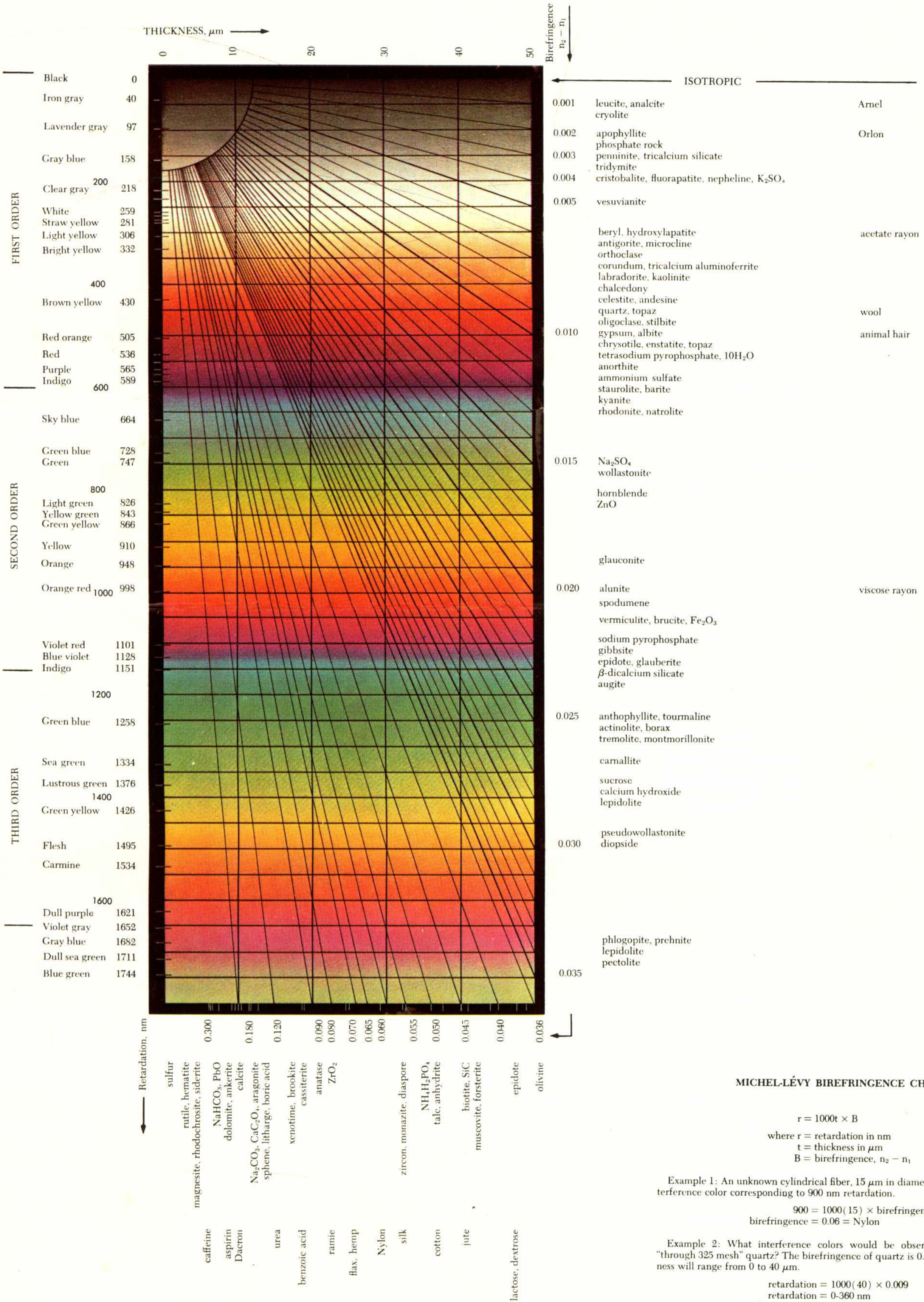
$$r = t(n_2 - n_1)$$

where r is the retardation (interference color) expressed in nanometers, nm; t is the thickness, which must also be expressed in nanometers (so we must multiply our reading in μm by 1000); and $(n_2 - n_1)$ is the numerical difference between the maximum and minimum refractive indices (birefringence).

Interference colors, furthermore, vary in hue with the amount of retardation according to a characteristic sequence known as Newton's series—the same color sequence seen in thin air films between glass, in soap bubbles etc. The Newton series is not a spectrum. It is divided into "orders," with the end of each order marked by a red-violet color. The first order starts with black, and, for the first 250 nm or so, the intensity of all wavelengths in white light is almost uniformly increased; resulting in grayish-white and bluish-gray hues. This is followed by yellow and orange hues and ends with the very important, intensive, narrow "first-order red." The second order has intense blue, green, yellow, orange and ends with a second red. The second-order color sequence is repeated in subsequent orders, but becomes paler and paler until between the fifth and eighth orders we approach "high order white."

Referring to the chart, we see the thickness, t, increasing as we go up the ordinate on the left side. The path difference, or retardation, r, increases as we go right along the abscissa; the names of the interference colors are also given. First-order red occurs at 551 nm, second-order red occurs at twice that, or 1102 nm, third-order red appears at 1653 etc. The birefringence $(n_2 - n_1)$ starts on the top of the chart at the left and proceeds to the right and down the right side for increasing values. The diagonal lines represent birefringence values listed at the end of each diagonal line.

Since the Michel-Lévy chart shows the interrelationships between thickness, birefringence and interference color, the microscopist can determine any one if he knows the other two.



MICHEL-LÉVY BIREFRINGENCE CHART

$$r = 1000t \times B$$

where r = retardation in nm
t = thickness in μm
B = birefringence, $n_2 - n_1$

Example 1: An unknown cylindrical fiber, 15 μm in diameter, shows a yellow interference color corresponding to 900 nm retardation.

$$900 = 1000(15) \times \text{birefringence}$$
birefringence = 0.06 = Nylon

Example 2: What interference colors would be observed on a sample of "through 325 mesh" quartz? The birefringence of quartz is 0.009; assume the thickness will range from 0 to 40 μm.

retardation = 1000(40) × 0.009
retardation = 0-360 nm
interference colors = black, gray, white, yellow

Abbreviations and Symbols

a,b,c	crystallographic axes
a^*,b^*,c^*	reciprocal lattice spacings
A	axis (crystal morphology)
A	angstrom
AA	angular aperture
A_2	twofold axis
A_3	threefold axis
A_4	fourfold axis
A_6	sixfold axis
AC	alternating current
ag	attogram (10^{-18}g)
α,β,γ	principle refractive indices for biaxial crystals
α',β',γ'	intermediate refractive indices for biaxial crystals
ASA	film speed
Bx_a	acute bisectrix
Bx_o	obtuse bisectrix
BCD	binary coded decimal
C	center of symmetry
C	critical angle
C line	spectral line at 656 nm
cfm	cubic feet per minute
CL	cathodoluminescence
cm	centimeter
cps	counts per second
CPS	computer probe system
CRT	cathode ray tube
d	interplanar crystal lattice spacing in Angstroms or nanometers
D line	spectral line 589.3 nm
DC	direct current
°C	degrees Celsius
°K	degrees Kelvin
dn/dT	temperature coefficient of refractive index
DIC	differentiation interference contrast (Nomarski)
DVM	digital volt meter
2E	optic axial angle of a biaxial crystal measured in air
EDXRA	energy dispersive x-ray analysis
EMA	electron microprobe analyzer(s, analysis)
EMMA	electron-microscope-microprobe analyzer(s, analysis)
EMR	exposure meter reading
ϵ	refractive index parallel to the c axis for uniaxial crystals
ϵ'	intermediate refractive indices (between ϵ and ω) for uniaxial crystals
ESCA	electron spectroscopy for chemical analysis
eV	electron volts
f	focal length
F	structure factor
F line	spectral line at 486.1 nm
fg	femtogram (10^{-15}g)
ft	feet
g	gram(s)
2H	optic axial angle of a biaxial crystal measured in immersion oil ($n = 1.515$)
{hkl}	a crystal lattice plane
[hkl]	form symbol, includes all faces in that form
hkl	zone symbol including all faces having parallel intersection edges
h	Planck's constant
IMA	ion microprobe analyzer(s, analysis)
in.	inch
IO	input-output
IR	infrared
K,L,M	inner shells of electrons in the atom
keV	kilo electron volts
kV	kilovolts
λ	wavelength
λ_0	wavelength in dispersion staining at which both solid and liquid have same refractive index

m	meter
mg	milligram (10^{-3}g)
min	minute
ml	milliliter
mm	millimeter
μg	microgram (10^{-6}g)
μm	micrometer
MUM	maximum useful magnification
n	diffraction order
n	refractive index
NA	numerical aperture
ng	nanogram (10^{-9}g)
ν	dispersion of refractive index
OA	optic axis
OAP	optic axial plane
ω	refractive index perpendicular to c for uniaxial crystals
P	plane of symmetry
pg	picogram (10^{-12}g)
PESIS	photoelectron spectroscopy with inner shells
PESOS	photoelectron spectroscopy with outer shells
pm	picometer
ppb	parts per billion
ppm	parts per million
RF	radio frequency
RMS	Royal Microscopical Society
RP	resolving power
rpm	revolutions per minute
s	second
S.U.S.	Saybolt universal seconds, a measure of viscosity
SAED	selected area electron diffraction
SEM	scanning electron microscope(s, microscopy)
S_m	measured diameter of diffraction lines through x-ray diffraction
ssd	stage scale divisions
STEM	scanning transmission electron microscope(s, microscopy)
TEM	transmission electron microscope(s, microscopy)
θ	diffraction angle
torr	unit of pressure equal to $\frac{1}{760}$ of an atmosphere (1 mm)
UV	ultraviolet
2V	optic axial angle of a biaxial crystal measured in the crystal (β refractive index)
x	times
X	magnification
XRD	x-ray diffraction

Introduction

More and more it is becoming important for us to analyze smaller and smaller samples. This is due, in part, to the increased use of microminiaturized electronic and mechanical instruments. It used to be necessary to throw a wrench in the works, now a single small particle of grit, metal or flyash can cause just as much trouble. A new mass spectrometer weighing less than three ounces has been announced. Complex electronic circuits as thin as a sheet of paper and less than ⅛ in. square are commonplace. As the size of microminiaturized electronic, mechanical and optical systems becomes progressively smaller, quality control and trouble-shooting become a problem in ultramicroanalysis, trace analysis or both.

There is another reason for the increased emphasis on ultramicroanalysis. Until recently, accurate detection and measurement of very small amounts of material was not possible. As ultramicroanalytical methods became available, it was soon found that the measurements then possible showed correlations between performance and composition. In other words, when we couldn't detect or measure small amounts of material it wasn't important. The discovery that minute traces of impurities can very directly affect performance has spurred the development of newer and more sensitive ultramicroanalytical techniques. It now seems certain that there is no lower limit in terms of percentage of minor constituents that can affect performance. The only practical long-term goal is atom-by-atom analysis.

At the very beginning the particle analyst must understand the difference between ultramicroanalysis and trace analysis. The detection, identification and measurement of trace quantities of a substance, *i.e.*, ppm or ppb, in an otherwise gross sample, *i.e.*, 1 mg or larger, is trace analysis. The detection and identification of a few nanograms or less of a reasonably pure substance is ultramicroanalysis.

There is, however, another very important factor determining how we approach trace analysis. A trace component dispersed homogeneously as a dilute solution is one thing; a trace heterogeneously dispersed as individual, discrete particles is very much another matter. The microscope is an ideal concentration device for magnifying dispersed particles sufficiently to permit identification *in situ* or removal by a skilled microscopist. In themselves, such particles do not represent a trace analysis problem—only an ultramicro analytical problem.

Many ultramicro analytical tools, *e.g.*, microscopy, diffraction or microprobe, can do trace analysis when the trace is heterogeneously dispersed. Other tools are effective with homogeneously dispersed traces although the sensitivity varies considerably, *e.g.*, microscopy by refractive index variation (1 part in 20); electron microprobe analysis (1 part in 10,000); emission spectroscopy and neutron activation (1 ppm); and ion microprobe analyzer (1 ppb).

After becoming proficient in small particle identification, the microscopist looking through the microscope will be able to say as he looks at each successive particle, "This one is a diatom, this one's wheat starch, here's pine pollen, cement dust, quartz sand, an Orlon® fiber, oil soot, a paint chip." He can identify most of the components in the sample and he should be able to estimate the percentages with considerable accuracy. His ability to do both of these depends on his skill as a microscopist, his powers of observation and his experience in looking at a variety of particles from all sources.

There will always be some particles in any sample that cannot be quickly identified from memory or by comparison with pictures, descriptions or known samples. If important enough to justify the often lengthy and expensive further analytical study, such particles can be identified at least by composition if not by source. The procedures require careful isolation of the particle followed by measurement of suitable additional physical properties: refractive indices, x-ray diffraction pattern or elemental composition. Procedures for micromanipulation as well as use of the necessary analytical tools, *e.g.*, polarizing microscope, scanning and transmission electron microscopes, x-ray diffraction camera, electron and ion microprobes etc. are described in detail in Volume I. Volume II is the atlas of color photomicrographs and descriptions. Volume III is the atlas of electron micrographs and descriptions. Both Volumes II and III cover more than 600 common and important compositions. Volume IV contains all of the analytical tables for the identification of small particles as well as very complete bibliographies, glossary and indexes.

Small particles, although simply a subdivision of solid matter as opposed to liquids and gases, have an importance all their own. Particles differ from other solids by virtue of a high surface area to weight ratio. This single difference creates, in a sense, a new form of matter which has a wholly different behavior. A lump of coal burns, but a suspension of coal dust in air is a violent explosive; a lump of quartz is harmless to humans, but ingested quartz particles can kill a healthy man; platinum jewelry is chemically pretty inert, but fine platinum powder can greatly alter the rates of complex chemical reactions; a 50-carat diamond is smooth to the touch, but an abrasive wheel with embedded diamond powder will quickly penetrate the hardest armor plate. These drastic changes are almost entirely due to the greatly increased surface area in the particulate state.

Some solids become more useful as small particles; *e.g.*, abrasives, powdered fuels, pigments, catalysts etc. Some, on the other hand, become more dangerous; *e.g.*, suspended dust in grain elevators or coal mines can cause explosions, very small asbestos fibers can cause asbestosis, smoke raises cleaning bills, dust in the air causes contamination of tiny mechanical or electrical devices. Small particles of many types can clog synthetic fiber spinnerets or jet fuel nozzles, contaminate photographic film emulsion and cause abrasion of hydraulic cylinders etc. Small particles in parenteral solutions injected into the blood stream can clog vessels and have caused death.

Criminals have been caught because they left small particles from their clothing or body at the scene of the crime—or because they brought away with them particles characteristic of the crime scene. Other kinds of "criminals" can be caught by studying particles. Silting of a harbor or river may be due to industrial pollution, and a study of the silt particles will identify the culprit. Similarly, pollution of the air can be analyzed quantitatively for the amount of pollution from steel mills, paper mills, printing plants etc. Just as important, in some situations the identification of silt or air contaminants can show industry to be blameless.

So, any way we look at particles, they are important. We need to understand how they behave, how to collect and study them, how to characterize and identify them and how to relate their more esoteric qualities to their performance. The latter includes the effects of shape on effectiveness of abrasives and pigments, of adsorbed layers on particle suspensions, of polymorphism on catalyst behavior etc.

Every microscopist is well aware of pollution. Every sample he looks at, whether he's a pathologist, metallographer, or a chemical microscopist, contains a few or often many particles that have settled out of the air. Recent measurements in one of our own laboratories (not one of the clean rooms) showed nearly 1,000 particles larger than 5 μm settling every hour on each square centimeter of bench surface.

These particles include human skin cells, plant and animal hairs, textile and paper fibers, minerals, flyash, pigments, chemicals and a host of other common substances. Perhaps only housewives and microscopists are aware of the extent of this kind of pollution. Every month 6,000 to 8,000 tons of these small particles fall on Chicago, more than 10^{20} individual particles. The housewife thinks of this in terms of dirt soiling the clothes, draperies, walls and furniture she has to keep clean. The microscopist thinks of this in terms of individual particles, distinguishable by ultramicroanalysis as to composition and source. In our laboratory some of us are studying these pollutants as a part of various air pollution projects; others of us are ignoring the same substances in our preparation of foods, pigments, polymers, drugs etc. We have a saying that one man's artifact is another man's sample—by definition, an artifact is an undesired and nonpertinent portion of the sample. We must make this distinction to avoid writing impressive, but misleading, reports and papers on unsuspected artifacts.

As an analytical tool for identifying particles, the microscope has many advantages. Primarily, it extends our limit of vision and permits us to identify microscopic objects at sight. It is important to note that literally thousands of substances can therefore be identified simply by mounting them between microscope slide and cover slip, adding a mounting liquid and looking at the preparation (with an experienced eye). In general, staining, sectioning, recrystallization or precipitation are neither necessary nor desirable.

The microscope is a relatively inexpensive analytical tool (as laboratory instruments go), and it can be used to handle a variety of problems. Unlike a typical chemical analysis, microscopy usually identifies the actual compound present. It even makes it possible to differentiate between different kinds of particles having the same chemical composition; *e.g.*, quartz, vitreous silica, coesite, cristobalite, tridymite, diatoms, opal, lechaterlierite, amethyst, agate, flint and jasper are all silicon dioxide. If the sample is quartz, microscopy will go farther and tell whether the particles are sand (even beach sand *versus* desert sand), ground mineral quartz or even quartz used as a molding sand.

A major limitation to microscopical analysis is the extensive background required. Much time and effort must be expended before the microscopist can observe and identify a wide variety of microscopic particles. To be completely successful, the microscopist must be an accomplished crystallographer and microbiologist as well as a highly skilled manipulator of small particles. But there is no other way to quickly identify single particles too small to be seen with the naked eye. At the same time, some useful information can always be obtained with the microscope even by a neophyte, and continued use steadily increases competence and confidence.

Two specific questions can be answered by using *The Particle Atlas:*

1. What is the identity of an unknown particle?
2. Does the sample contain particles of a specific composition?

This Atlas details the theory, instrumentation and applications for the most effective ultramicroanalytical tools for particle analysis. Each is covered in sufficient detail for a chemical analyst to tell if and when he should use one and for a research manager to tell if he should buy one.

This atlas covers, by light and electron microscopy, most of the substances causing trouble in one way or another. Most of the dust in city air or rivers and lakes, in settled dust or silt can be found in its pages. Dust in homes, offices, industrial plants, even clean rooms is included. Contaminant particles from photographic film, integrated circuits, synthetic fiber spinnerets, fuel nozzles, hydraulic fluids, paint, paper, plastics, foods or fertilizers are very likely here. Particulate evidence from crime scenes or a suspect's clothing or particles from human lungs or a pathologist's slides can all be found in the light or electron micrographs (Volumes Two and Three) or in the tables (Volume Four). Although some substances may not be present, an investigator in any of the above fields should confidently expect to solve well over 90% of his particle problems with *Particle Atlas Two* as background.

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