Synchrotron Environmental Science—I

Workshop Report

RECEIVED
OCT 12 1999
O S T T
SES-I

July 1999
Argonne National Laboratory

Argonne National Laboratory, with facilities in the states of Illinois and Idaho, is owned by the United States government, and operated by The University of Chicago under the provisions of a contract with the Department of Energy.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Reproduced from the best available copy.

Available to DOE and DOE contractors from the
Office of Scientific and Technical Information

P.O. Box 62

Oak Ridge, TN 37831

Prices available from (423) 576-8401

Available to the public from the
National Technical Information Service

U.S. Department of Commerce

5285 Port Royal Road

Springfield, VA 22161

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Synchrotron Environmental Science-I Workshop Report

Table of Contents

Executive Summary	1
Overview and Workshop Charge.....	2
Workshop Questions.....	3-20
Question 1. Identify and briefly describe the environmental research issues discussed. Include the principal scientific discipline(s) that address each issue and current experimental approaches and methodologies	3
Question 2. Do the environmental research issues discussed involve current or foreseeable significant measurement obstacles?.....	8
Question 3. Are any of these obstacles already being addressed at some level through synchrotron radiation experimentation? If so, what is the potential for synchrotron radiation studies?.....	10
Question 4. For the issues discussed and other environmental research problems, can one envision new approaches where synchrotron radiation might provide significant new insights to ongoing environmental research?	12
Question 5. Are there impediments (cultural, experimental, etc.) to the use of synchrotron radiation with the environmental issues discussed?.....	14
Question 6. How easy would it be to integrate a synchrotron radiation approach into your discipline as a complement to or replacement for existing methodologies?	17
Question 7. Should an effort be made to apply synchrotron radiation methodologies to the environmental issues discussed?	18
Question 8. What are the next steps and possible outcomes?.....	19
Appendixes.....	21-30
Appendix 1. Workshop Program.....	21
Appendix 2. List of Participants.....	24

Argonne National Laboratory is operated by The University of Chicago for the
U.S. Department of Energy under Contract W-31-109-Eng-38.

Executive Summary

Attendees of the Synchrotron Environmental Science I (SES-I) workshop represented a broad spectrum of environmental science research areas and expertise in all of the current synchrotron techniques (X-ray scattering and diffraction, X-ray absorption spectroscopy, and two- and three-dimensional X-ray imaging). These individuals came together to discuss current measurement obstacles in environmental research and, more specifically, ways to overcome such obstacles by applying synchrotron radiation techniques. Significant obstacles in measurement affect virtually all of the research issues described. Attendees identified synchrotron approaches of potential value in their research. A number of the environmental research studies discussed are currently being addressed with some success by synchrotron-based approaches. Nevertheless, improvements in low-Z measurement capabilities are needed to facilitate the use of synchrotron radiation methodologies in environmental research.

Participants in the SES-I workshop attempted to identify specific applications of the unique capabilities of Argonne's Advanced Photon Source (APS) that would make it the synchrotron of choice, as opposed to applications that might be more fruitful at other synchrotrons. A synchrotron approach cannot mediate all measurement issues, because a number of potential limitations are inherent. A discussion of such limitations identified applicability issues, potentially destructive properties of radiation, issues of scale, and required experimental conditions. Another limitation is the logistics of using a synchrotron research tool not co-located with the experimental system. In most cases, synchrotron radiation methodologies would complement, not replace, current research techniques. The attendees identified a number of specific environmental research applications for each of the common synchrotron techniques. Potential users can be categorized in two groups: (1) occasional users conducting work to confirm or validate results obtained by other methods and (2) regular users employing the APS continually as a major component of their research efforts.

The success criterion for SES-I was that the workshop's deliberations would foster among the environmental scientists attending, new ideas for collaboration and plans to apply synchrotron radiation. That goal was achieved, because the workshop was successful in initiating new dialogues between environmental scientists and synchrotron scientists and expanding the dialogues that already existed. However, for all of the environmental issues discussed, the group believed that access to the needed APS beamtime was problematic, whether the access was to be arranged directly by the environmental scientists or through collaborative arrangements. Current beamline capabilities might not be sufficient for the potential range of environmental issues that could benefit from synchrotron radiation approaches. One conclusion was that environmental and synchrotron scientists need to educate major sponsors of environmental research about the value of synchrotron radiation approaches. The group made recommendations on access today and in the future and considered the potential for another dedicated facility for environmental research at the APS. The workshop concluded with a call for a second workshop, SES-II.

Overview and Workshop Charge

An Argonne staff visit to Michigan State University in July 1998 revealed with striking clarity that environmental scientists would benefit from a broader understanding of the potential value of synchrotron radiation, particularly APS X-rays, in environmental research. A conclusion of the visit was that enhancing the dialogue between environmental scientists and synchrotron scientists would have significant value. A workshop attended by a preponderance of environmental scientists would enhance interactions between the two communities, leading to a better understanding of the potential of synchrotron radiation as a powerful measurement tool in environmental science and educating both the environmental research and synchrotron communities about opportunities for collaboration. Ongoing collaborative research at the APS involving staff of Argonne's Environmental Research Division and the University of Notre Dame's Center for Environmental Science and Technology led Argonne, Michigan State, and Notre Dame to agree to sponsor this workshop.

The goal of the SES-I workshop was to establish better communication between the environmental research community and the synchrotron research community, so that synchrotron radiation can be applied wherever it has value. As the logo of the conference indicates, the major components of the environment (air, water, and land) are not isolated but are interrelated by dynamic biological, geological, and chemical processes. Much is yet to be learned in the areas of interaction, particularly at interfaces. In some cases, synchrotron radiation can be a significant research tool.

The first day of the workshop (see Appendix 1) was devoted to tutorials, intended primarily to teach the languages and concepts of the environmental research and the synchrotron research communities. Building on these enhanced skills, the second day was devoted to break-out sessions focused on communicating between the disciplines. Participants in each break-out session were asked to address a standard set of questions, then come together to share the outcomes of all sessions. A narrative summary of the discussions in the break-out sessions and the combined recommendations is provided below.

Workshop Questions

QUESTION 1. IDENTIFY AND DESCRIBE THE ENVIRONMENTAL RESEARCH ISSUES DISCUSSED DURING THE WORKSHOP. INCLUDE THE PRINCIPAL SCIENTIFIC DISCIPLINE(S) THAT ADDRESS EACH ISSUE AND CURRENT EXPERIMENTAL APPROACHES AND METHODOLOGIES.

The SES-I discussion groups were composed primarily of university professors and national laboratory scientists with environmental research interests and a broad range of scientific expertise in the following areas: environmental chemistry, radiochemistry, microbiology, biochemistry, analytical chemistry, plant physiology, geology, and soil science. (See participant list in Appendix 2.) Each discussion group also included both individuals familiar with synchrotron radiation techniques and those who currently use only other approaches.

The individual research issues discussed can be grouped into several broad categories, with considerable overlap among many of them. Each category includes a number of research questions that could be amenable to analysis through synchrotron-based techniques.

The broad categories include the following:

- **Interaction of heavy metals, natural organic materials, bacteria, and geosurfaces**

One comprehensive issue involves interaction of microorganisms with the environment. Specific areas of work include molecular analysis; imaging of microorganisms; biochemistry of contaminant degradation; bioavailability; interaction of microorganisms with metals, including metal binding with organic ligands; biofilms, biocatalysis, and bioprocessing in two-phase (aqueous and nonaqueous) systems; and surface interactions of microbes.

Several investigators were interested specifically in the role of bacteria and other microbes in the speciation of metals and metal contaminants in field samples of soils, sediments, and aquatic environments, as well as in the general question of the global cycling of metals. This research varied from investigations of biological processes internal to microbes, to the geomicrobial interactions that influence the transport of metals through the environment.

Another issue involves metal binding sites on bacterial surfaces and metal binding to organic matter like humates and fulvates. The research objectives included gaining a better understanding of data generated through solution chemistry approaches such as equilibrium binding constants. This understanding is important for the validation of mathematical models being developed for the simulation of solute transport and sequestration in metal-contaminated soils. Distinguishing between adsorbed and precipitated metals phases is critical to the interpretation of compleximetric titrations. Determinations of the nature of the metal binding, the sites that are occupied, the ligands involved, the metal species present, and the coordination

environment all need to be addressed, often in the context of spatial distributions and structure.

- **Issues in soil science, including the process of soil formation, contaminant transport, availability, and solubility**

One researcher is interested in contaminant solubility, mobility, and bioavailability in natural soils (specifically those from Superfund sites) and their relationship to aerobic and anaerobic conditions. There is also an interest in understanding the redox effects on phosphorus in soils. Finally, this researcher is also interested in the nature of Cu^{2+} , Hg^{2+} , and AsO_4 binding on goethite-humic acid complexes.

Another researcher studies contaminant transport in subsurface environments via colloidal mechanisms (i.e., using negatively charged particles of 10 microns). These studies involve transport equations, particle dispersion/convection, deposition on stationary grains, and colloid detachment.

Two other scientists deal with related subjects in soil science. One researcher is interested in increasing the understanding of the process of soil formation. Particular issues included the integration and stabilization of organic matter into soil aggregates. Ultimately, insights will be made into the relationship between microaggregate structure and plant growth. The interactions between plant roots and mycorrhizal fungi are being investigated by another scientist. The relevant issue in this research is the mechanism by which fungal hyphae facilitate the uptake of metals by plants. It appears that the plants and fungi participate in a mutualistic relationship that may be functionally uncoupled. Thus, different regions of the hyphae are involved in carbon uptake from plant exudates and the transport of nutrients to the plant hosts. The particular issue addressed was the role of arbuscules in the transport of metals to the host.

One scientist studies the effects of climate change on wetlands, general wetland ecology, impacts of environmental factors on wetlands, wetland restoration, and sulfur cycling via oxidation/reduction processes.

- **Photoactivation, photosynthesis, and aerosols**

One investigator works on the surface chemistry of photoactivation and is interested in the resultant structural aspects and reaction mechanisms (chemistry of atmospheric aerosols, soot, light and dark processes, scrubber chemistry, and catalytic converters).

The study of photosynthesis by means of a systems approach was also described. All inputs (light, water, CO_2 , other nutrients) and outputs (oxygen, other metabolic wastes) are controlled, and live organisms are used. Concerns expressed with synchrotron radiation approaches included radiolytic damage and the necessity to maintain an aqueous environment.

Another scientist studies the structures of atmospheric particles (aerosols and particulates) and the interaction of organic and inorganic species with the particle surface. Levels of concern are often in the parts-per-trillion range. The dynamics of atmospheric transport process are being studied by means of radiochemical tracers.

- **Environmental health concerns**

A number of presentations can be loosely grouped under the heading of environmental health concerns. Among them is the problem of characterizing radioactive waste materials (often drums that may contain loosely packed dry wastes but also more dense wastes) to determine their safe disposal. X-ray techniques are now being used extensively to study the composition of these and other high-level radioactive wastes that are present at former DOE nuclear weapons material production sites.

Another study is a legacy problem from the 1950s and 1960s when the government stored grain and used carbon tetrachloride as a popular fumigant. Carbon tetrachloride has begun to show up in groundwater; the consequent research program involves geological characterization of sites, transport of carbon tetrachloride, and analysis of carbon tetrachloride in plants and in the soil vadose zone.

The bioavailability of organics and the role of the formation of intermediates in the biodegradation of recalcitrant organics is being studied to enable better design of biodegradation reactors.

An understanding of the structures, fate, and transport of inorganic and organic platinum, palladium, and rubidium species that stem from the pollution of the environment by catalytic converters in automobiles is another area of interest.

Particulate organic matter released during the combustion of coals or the refining of oils is often heavily laden with toxic metals (Ni, V, Zn, Pb, As). The smaller particulates (<2.5 microns) exhibit the highest metal concentrations. Little is known about the speciation of metals in these particles or the spatial distribution of metal phases. It is hoped that chemical signatures can be defined so that it will be possible to determine whether the unknown particulates arose from petroleum processing or combustion.

Another health-related issue involves lead intoxication, which is being studied in a trout model system. Here the issues include the binding and distribution of lead in bony tissues and the effectiveness of current chelation treatments in extracting lead from contaminated bones.

A final project in this category focuses on the metabolism of gold-containing drugs. The issues of transport, uptake, and efflux were mentioned, but two

specific points were emphasized: the interaction of Au(III) with the immune system and the accumulation of gold in intracellular aurosomes.

- **Transport and fate of trace elements and radionuclides in aquatic systems**

One issue is related to trace element fate in aquatic systems. Specifically, there is a desire for a better understanding of the processes responsible for the removal of metals and organics from water in water- and wastewater-treatment processes. This issue is closely related to the development of efficient sludge management. The basic research information required is an understanding of the nucleation, growth, sorption, precipitation, and aging (time dependence, different time scales such as seconds-minutes and days-months) of precipitates and the role of chemical adsorption in these precipitation processes. Also in question is the role of organics as they interfere in the precipitation process. All of this information will be helpful in the design of water-treatment reactors.

Measurement of radionuclide transport and accumulation in aquatic environments provides insights into environmental processes, especially as markers of cycling associated with large lakes (e.g., Cs-137 as sediment time markers for 1963). A major effort is to understand why cesium profiles in sediments do not have the expected properties.

- **Characterization (chemical and physical speciation) and bioremediation of radionuclides, actinides, and Group VB elements**

One project involves the determination of kinetic and thermodynamic parameters for phosphorus release from natural sources for use in stabilizing radionuclides.

Another concern is bioremediation of actinide-organic complexes in subsurface environments in which redox reactions are extremely important (bio-uptake and association, bio-precipitation). Here, reduction of actinides is of positive benefit, so oxidation states need to be determined.

The chemical and physical speciation of Group VB elements (e.g., As, Sb, Bi) in the environment is under study with a variety of approaches. Currently used techniques are electrochemistry (for valence speciation), chromatography-mass spectrometry (for structure elucidation), and XAS (for determining the local chemical environment around the absorber atom in model and authentic solids [soils, sediment, biota]).

- **Mineralogy**

Reaction mechanisms and energies of reactions at mineral/solution interfaces are being examined by mathematical simulation of such interfaces. The synchrotron radiation approaches, XANES and EXAFS, are two of many spectroscopies that furnish direct evidence of mechanisms and speciation, and are thus synergistic with molecular modeling.

Low-temperature mineralogy is another research interest. The investigator is interested in determining crystal structures to better understand mineral paragenesis (the evolution of crystal structure transformations).

Another area described was the sorption of phosphonates to mineral surfaces. The specific question related to multiphosphonate head groups on an organic molecule and determination of whether a single phosphonate or multiple phosphonate head groups participated in the sorption process.

Another researcher is interested in gaining a better understanding of the local chemical environment of Fe(II) in a predominantly Fe(III) oxide. It is postulated that the local structure of Fe(II) incorporated in an Fe(III) oxide is much different than an Fe(II) atom at a structural defect on an Fe(III) surface. This may explain some of the surface reactions of Fe oxides.

QUESTION 2. DO THE ENVIRONMENTAL RESEARCH ISSUES DISCUSSED INVOLVE CURRENT OR FORESEEABLE SIGNIFICANT MEASUREMENT OBSTACLES?

The answer to this question is clearly yes. Virtually all of the research issues described above have some significant measurement obstacles.

The following research questions were identified in which a synchrotron approach might overcome a measurement obstacles:

- How can the speciation of sulfur be tracked as it rapidly cycles among FeS compounds and organic phases in wetlands?
- What role is played by silica and pH effects on binding of cesium in lakes? What is the nature of the Lake Michigan particles and how do they change over time?
- For colloidal transport, all data is inferred from breakthrough curves. Colloid deposition on single grains has not been studied mechanistically and no one has actually looked at the surface coverage. How can polystyrene-latex particles and their deposition and detachment to/from larger granular materials be looked at in order to understand colloid breakthrough? Tomography of colloids at less than 1 micron is very hard to determine.
- Where does metal accumulate in microorganisms? How do bacteria interact with surfaces, and then with metals in biofilms? Can nondestructive characterization of biofilms be done given that organisms and biostructures must be maintained in moist environments?
- How can volatile solvents be studied mechanistically in soils and plants? How can adsorption/desorption processes be studied with spectroscopies that are more suited to 10- to 100-eV binding energies to achieve better surface sensitivity?
- How can aerosol structures, pore sizes, and adsorption characteristics be studied?
- How can oxide surface functional groups and pH-dependence be mapped and quantified to describe the natural organic coatings on mineral surfaces and surface topologies of these composite solid phases? What are the mechanisms of ligand exchange? How do redox reactions happen at surfaces?
- How can waste matrix surrogates that correctly represent heterogeneous waste forms be designed and constructed so that photon transmission standards, that allow more quantitative characterization of wastes, can be quantified?

The following measurement needs were identified:

- X-ray beams smaller than the single particles that are being measured (micron-sized beam spots) in single-crystal microdiffraction and X-ray absorption spectroscopy.
- Element-specific, valence-state, and coordination chemistry information.
- Spatial distributions of metal species, as well as chemical speciation and coordination environment of metals in a sample.
- *In-situ* measurement of the real-time chemical reactions and physical interactions involved with the growth of particles in a treatment vessel.

Among the key obstacles discussed were the following:

- Relevant environmental concentration levels that are, in most cases, below the state-of-the-art detection limits, particularly for radiochemical and atmospheric species.
- Complexity of environmental samples (e.g., as an impediment in interpretation of spectra and images). Biological samples are especially problematic due to the presence of multiple layers of cells.
- Sample heterogeneity.
- Necessity of maintaining a saturated aqueous environment for biologic tissue samples to preserve proper function.

For synchrotron radiation approaches, the following concerns were expressed:

- The semi-quantitative nature of synchrotron-generated information, i.e., the relative imprecision in estimating concentrations.
- The need for high-purity, well-characterized standards as a prerequisite for successful XAS data interpretation.
- Radiolytic decomposition of the sample as a result of X-ray beam effects (including the formation of highly reactive free radicals).

QUESTION 3. ARE ANY OF THESE OBSTACLES ALREADY BEING ADDRESSED AT SOME LEVEL THROUGH SYNCHROTRON RADIATION EXPERIMENTATION? IF SO, WHAT IS THE POTENTIAL FOR SYNCHROTRON RADIATION STUDIES?

Again, the answer to this question is yes. Among the projects represented at the Workshop that are currently being addressed at some level by synchrotron-based approaches are the following:

- XAFS studies of metals and metal oxides at the APS.
- X-ray microdiffraction experiments at the APS.
- XAFS studies of soils at the NSLS.
- EXAFS measurements of gold particles on auroosomes.
- XRF images of metal distribution on bacterial cells adhered to surfaces.
- Cesium measurements, especially the nature of cesium-containing colloids, along with the issue of distinguishing low concentrations of Cs-137.
- Biofilms grown on kapton tape and other supports. These films are usually micron to millimeter thick and the aim is to determine metal interactions with biofilm surfaces. Issues that need to be addressed are biological timing, cell fragility, scale of measurement, and 3-D mapping. Also needed are grazing-angle techniques for spatial mapping so that one could grow the biofilms on minerals and thus be more realistic.
- Redox of transuranics using XANES. Experiments have been done to establish the effects of oxidation state and geometry on XANES edge position, and XANES spectra have been modeled in the energy range 5-30 keV with 0.3-eV resolution. Shifts for oxidation are small. Thus, there is a need for good energy resolution. Enclosures for actinides have been developed with sample sizes of 30 to 40 micrograms. The potential is there for further exploration of redox mechanisms and crystal structures within waste sludges.
- Phosphorus and sulfur sorption to aluminum and iron colloids studied with synchrotron techniques. (This work should be extended to more dynamic studies of nutrient-cycling kinetics and mechanisms, i.e., wetland geochemistry.)

A number of concerns and suggestions about the applicability of synchrotron techniques to current projects were expressed.

- A common general comment was that the nuclei of broadest interest tend to be the light elements (low Z), so more small-gap undulators are required. Low-Z capability would greatly increase beamtime demand.

- The APS is not suited to binding energies in complex systems, which tend to be <100 eV, but structure questions can be addressed.
- Could graphite or amorphous carbon be used as models for smog particle surfaces? (Again, there are low-Z limitations.)
- The potential of synchrotron research is often not understood clearly because of the data manipulation that must occur before one gets "real-world" numbers. As with all spectroscopies, spectra are open to interpretation. Are the adjustable parameters used to fit EXAFS reasonable? Bond distances of high accuracy (to 0.01 Å) are always reported, but line widths are typically more than 1 Å. Teaching scientists how to trust those numbers is an educational issue to win new converts to the methods.
- XANES imaging might be used to identify where sulfur is in sediments and follow its oxidation state.
- It might be useful to look at catalytic converter materials, their interactions with fuel sulfur and the role of cerium, and how to develop sulfur-resistant catalysts.
- It might be possible to produce a microtomographic image of a colloid deposited on a surface, then change the ionic strength and monitor the effect of the ordering of the colloids.

Provided that the concerns identified above can be addressed, the potential for synchrotron radiation studies appears very positive, particularly for spatial and speciation questions.

QUESTION 4. FOR THE ISSUES DISCUSSED AND OTHER ENVIRONMENTAL RESEARCH PROBLEMS, CAN ONE ENVISION NEW APPROACHES WHERE SYNCHROTRON RADIATION MIGHT PROVIDE SIGNIFICANT NEW INSIGHTS TO ONGOING ENVIRONMENTAL RESEARCH?

The consensus opinion is that synchrotron radiation techniques are available that would positively impact most of the research projects discussed.

Commonly suggested techniques were EXAFS and microEXAFS, in particular to study metal speciation in various matrices (particles in air, soils, sediments, and biota). For those interested in metal speciation alone, bulk EXAFS was suggested. This technique would encompass those interested in the binding of metals to bacterial surfaces, humic materials, or combustion products. Model minerals and authentic samples can be studied effectively with EXAFS and XANES. Key questions include the following: What other species result from biotic or abiotic processes? What are the interactions of these species with minerals, humic/fulvic acids, microorganisms, plankton, or more-complex flora/fauna? What is the extent of organic complexation? What is the specific interaction with minerals (minor phases or defects)? How are these species transported (soluble, colloidal, particle)? Can accurate solid/liquid partition coefficients be determined?

Imaging techniques generated the most interest. Particulate airborne particles, the bacteria-geosurface interface, lead distribution in bone, gold distribution in cells, metal-transporting arbuscular structures, and material accumulation in cells and on biofilms could all be examined by means of XRF imaging techniques. The availability of a high-precision "universal" sample stage would make experiments in imaging more convenient because such a device might ease the transition of the sample to other experimental apparatuses (e.g., IR microprobes or electron microscopes) and thus make comparative data analysis much easier than is currently possible.

MicroEXAFS or microXANES imaging tomography could also be used to obtain spatially resolved speciation data, particularly in three-dimensional biological structures such as plant tissues.

Scattering techniques were also suggested for particulates. The use of SAS to monitor the growth of particles in a sludge reactor, as well as examine atmospheric particle structure, seems very promising. Reflectance measurements of bio-corroding metal surfaces was also suggested. The ongoing development of microbeams seems very promising for enabling the investigation of even smaller micron-sized single particles, for obtaining better spatial resolution of the valence state of elements in a single bacterium, and for obtaining better spatial resolution of elements in smaller soil aggregates and particles.

Three key problems in plant physiology that might be amenable to synchrotron-based experiments were described: study of the dependence of stomata function on the leaf surface to changes in $[K^+]$; study of the

distribution of $\text{Cu}^+/\text{Cu}^{2+}$ in the plant cell; and study of the effect of ozone on the "leakiness" of the plant cell wall.

Continuous flow methodologies (e.g., flow injection) were suggested as possible ways to study the kinetics of transient processes (e.g., metal ion-mineral surface interactions).

In several cases, non-synchrotron techniques were suggested. These included various SEM, EDS, and XPS methods. The group also tried to distinguish between synchrotron techniques that could be performed at any synchrotron and those that specifically required the unique abilities of the APS. It was felt that imaging and tomography techniques are best done at APS. EXAFS of samples with low (sub-ppm) levels of metals may also require the power of the APS. Low-Z element studies with soft X-rays may be more appropriate for the ALS.

QUESTION 5. ARE THERE IMPEDIMENTS (CULTURAL, EXPERIMENTAL, ETC.) TO THE USE OF SYNCHROTRON RADIATION WITH THE ENVIRONMENTAL ISSUES DISCUSSED?

Some potential limitations on the use of synchrotron radiation to solve environmental problems were identified in the SES-I break-out groups. The following summary organizes those comments by category:

Applicability: Environmentally relevant samples (especially biological and geochemical) are, by their nature, complex. Environmental systems can often have low-ppm or sub-ppm concentrations of metals. Such samples may be successfully studied using EXAFS, depending on the metal and the matrix. EXAFS is a good technique for obtaining useful data on *simple* samples (e.g., one metal interacting with one ligand in one coordination environment). Interpretation of EXAFS data from samples where metals may be bound to carboxyls, phosphates, and sulfides with complex mixes of possible coordinations may be very challenging. Some clarification may be gained by comparing experimental EXAFS results to a variety of standards, but highly complex systems are still beyond interpretation. There is a lack of suitable model compounds to act as standards (e.g., a model humate), further complicating accurate data analysis.

For X-ray fluorescence imaging, low target metal concentrations can be a great impediment. Imaging could also potentially be used to determine the location of sulfur.

Tomographic techniques are limited by the size and shape of the sample and by the inability of the signal to escape the matrix in dense samples.

Most of the biological systems discussed would be below expected detection limits (as limited by the detector hardware, not by photon availability).

Effective study of some environmental issues will require exceedingly small X-ray beams.

The APS may not be the best-choice synchrotron for all environmental experiments due to its high-brilliance, high-energy X-rays. The APS is also limited to hard X-rays (other sources are available for soft X-ray applications). The energy range of the APS makes it unsuitable for the study of light elements; again, other light sources may be more applicable, especially for low-Z elements.

Destruction: Penetration of the X-ray beam into thick biofilms may impact the nominal properties of the film or possibly affect surface cell distribution.

Environmental researchers are often interested in oxidation states. It has been shown, however, that the oxidation states of manganese and iron surfaces in contact with solutions are sensitive to beam effects.

Aqueous samples are subject to the radiolysis of water that can lead to unforeseen free-radical reactions. A possible solution to this problem is the use of frozen samples or samples stabilized with free-radical scavengers be used to minimize this effect.

Scale: The problem of scale is the greatest issue in terms of bioecological research. For example:

- Aerosols may be too small to analyze; voids may not be resolved.
- Submicron resolution is absolutely required to apply synchrotron radiation X-ray fluorescence techniques to environmental problems. Resolution on the scale of tens of nanometers is very desirable. Submicron particles of interest (especially aerosol and condensed-phase particles) may be difficult to study due to beam resolution limitations (except for determination of minor impurities).
- Individual submicron-size colloids may be difficult to image. The imaging of submicron colloids may be possible in solution, but the sample size is limited to 1 mm of water. Such physical limitations imposed by hydrated samples may not be easily (if at all) overcome. Tradeoffs between resolution and freezing samples were discussed.

Experimental condition limitations: The actual conduct of many environmental experiments will have to coincide precisely with sample preparation. This can be especially problematic for sample preparation and/or transport of biological samples. Biological systems are not as predictable as chemical or physical systems. Samples must be generated and used in real time, which can present problems in maximizing use of a limited amount of assigned beamtime.

Software incompatibility was cited as a possible problem since each CAT uses its own systems for data acquisition. The compatibility of experimental hardware (e.g., detector integration) may also present an impediment. (It is unlikely that hardware *could* be standardized due to the great diversity of experiments.)

Logistics of facility use: Familiarity with the established protocols for accessing the facility will have to be developed in the environmental science community. Concerns expressed included:

- Identifying an appropriate CAT for each project (in terms of proper technique and equipment), and establishing contact with CAT staff.
- Establishing a user agreement and signing up to be a user.
- Obtaining the training and education necessary to efficiently and fully utilize the facility, including learning about APS infrastructure.

It was felt that a mechanism to effectively provide details about all current activities at the facility was needed. In addition to current information about beamline design and capabilities, information should be available to supply some sense of future developments, advances, and improvements to researchers to assist with experiment planning.

Service and assistance issues for users were a primary topic. The system at SSRL was touted as highly successful: Experimenters are put in touch with a veteran synchrotron scientist who walks them through the proces, from identifying the correct experiment to analyzing the data. Cultural differences between the APS and SSRL were acknowledged. Some concerns were also expressed about ensuring that Independent Investigator-related issues are carefully evaluated as the facility grows so that these issues are addressed efficiently in the methodology of the facility's operation. Use of the APS will necessitate costs in terms of time and money to travel to the facility.

QUESTION 6. HOW EASY WOULD IT BE TO INTEGRATE A SYNCHROTRON RADIATION APPROACH INTO YOUR DISCIPLINE AS A COMPLEMENT TO OR REPLACEMENT FOR EXISTING METHODOLOGIES?

The break-out groups included both scientists who had already integrated a synchrotron radiation research component in their experimental programs and scientists who were eager to attempt to begin use of synchrotron radiation methodologies in their programs. In most cases, the use of synchrotron radiation techniques would complement (not replace) current research techniques. Again, the key issues surrounding the integration of synchrotron radiation into an environmental research program are the cultural and experimental issues discussed earlier. It was generally recognized that these projects would have to be run collaboratively with APS scientists. Potential users could be divided into two categories: occasional users conducting work to confirm or validate results obtained by other methods and regular users using the APS on a continual basis as a major component of their research efforts.

The establishment of an environmental science beamline was discussed. From a financial perspective, operating funds to develop a beamline, support experimental activities, and provide support to visiting scientists are difficult to obtain. There is a perception that there are insufficient funds to support the existing beamlines, resulting in researchers being directed to second-generation sources.

QUESTION 7. SHOULD AN EFFORT BE MADE TO APPLY SYNCHROTRON RADIATION METHODOLOGIES TO THE ENVIRONMENTAL ISSUES DISCUSSED?

It was felt that all available techniques should be used to solve environmental problems. Possible techniques and applications were discussed in response to earlier questions.

Since research programs are largely driven by funding issues, a concerted effort should be made to convey the usefulness of the APS as a tool for environmental research to the major sponsor organizations (e.g., Environmental Protection Agency, National Science Foundation, Department of Energy, Department of Defense, United States Department of Agriculture, etc.).

In terms of the potential projects discussed throughout the paper thus far, it is clear that the use of synchrotron radiation would advance environmental research greatly. Some participants felt that many of these issues can *only* be resolved by using the techniques mentioned in conjunction with the power available at the APS.

QUESTION 8. WHAT ARE THE NEXT STEPS AND POSSIBLE OUTCOMES?

Access by an "outside" user to the APS can be obtained in two ways:

1) Collaboratively working with scientists who are members of an existing CAT or 2) Applying for "Independent Investigator" beamtime that is available at every CAT. Typically, 25% of the beamtime at each CAT is allocated for Independent Investigators through a proposal mechanism. Access to the APS as an Independent Investigator will be increasing as more and more CATs are declared operational and begin accepting proposals. Environmental scientists need to be made aware that an infrastructure for submission, review, and acceptance of Independent Investigator proposals has been developed and will serve to ensure that each experiment is optimally matched to CAT facilities and experimental techniques that best complement the proposed work. Detailed information about CAT scientific programs, beamline facilities, and technical contact information is now available in the *Advanced Photon Source CAT Guide and Beamline Directory*, which can be used as a starting point.

There is a need for greater access to synchrotron radiation technology for solving environmental problems, whether in the form of increased utilization of existing CATs or a new beamline. It was generally agreed that GSECARS is a good model organization for diverse environmental research. There is resident support staff to initiate newcomers and to develop new methods in ongoing collaborations. However, it is already oversubscribed for access.

Break-out group participants felt that other CAT facilities may be underutilized at this point in time (although that perception will probably change significantly as more CATs begin accepting Independent Investigator proposals). A new CAT will probably not be politically feasible until other existing CATs show that they are also oversubscribed. The current feeling is that there is already insufficient support (DOE or other) for existing beamlines, so another beamline would strain an already stressed operational situation.

Recommendations made include the following:

- The APS as a facility needs to reach out and bring more environmental scientists into the fold. Collaborations between environmental scientists (with no experience with synchrotron-based research) and physicists will greatly enhance environmental research. Additionally, the examination of environmentally relevant samples may encourage APS scientists to advance the development of synchrotron methodologies.
- Environmental scientists already using synchrotrons should continue their work and continue to progress toward using smaller X-ray beam sizes, and improving the sensitivity of existing detectors. Novice synchrotron users should get involved in collaborative feasibility studies as a "next step."
- As stated earlier, since travel time and costs and the learning curve to use the facility can be barriers, perhaps an APS service could be developed in

which researchers send prepared samples to APS and have technicians do routine observations (e.g., COM-CAT). This would not be used for methods development work, but for common measurements handled with a flat hourly fee that includes routine data analysis.

- It was felt that there should also be hazardous-materials handling facilities available at the APS.
- A SES-II meeting should be developed with the goal of developing funding sources and support for a new environmentally dedicated beamline for the intermediate-term future. An organized management and marketing plan for obtaining ongoing funding, including non-conventional sources, is needed to pursue this goal. When budgeting for beamline services, operating money (which has been traditionally difficult to obtain) must be included to support resident staff who will be responsive to the visiting scientists.

A number of participants felt a SES-II Conference would be beneficial. The desire for a follow-up meeting led to several suggestions for an enhanced format:

- The recommendation of one Group was to begin planning a new beamline. Given the oversubscription of GSECARS, it is not too early to begin thinking about another dedicated environmental beamline. It was recognized that it would be very difficult to develop one CAT capable of handling the full diversity of environmental research. It is hoped that other CATs will become interested in developing specialized capabilities for environmental research.
- Several of the SES-I tutorials seemed to focus more on the speaker's own research. Focus tutorials on more general discussions of key challenges to environmental research.
- More emphasis could be placed on the atmosphere. Despite the meeting logo, the atmosphere was hardly discussed relative to the litho-, hydro-, and biospheres.
- Break-out groups should be structured along problem-oriented themes (e.g., air, water, soil). This might stimulate more in-depth discussions and recommendations while retaining a broad range of expertise.
- If future break-out groups are asked to prepare summary reports, the headings should be simplified to "research interests," "obstacles," and "new approaches."

Efforts like SES-I should be made to continue the dialogue between environmental scientists and synchrotron scientists. This continued collaboration may be assisted by a newly formed group called *Envirosynch*.

Appendix 1. Workshop Program

Sunday, April 18, 1999

Pre-conference Activities

6:00 - 8:00 p.m. REGISTRATION AND HAPPY HOUR
Argonne Guest House

Monday, April 19, 1999

7:20 - 8:20 a.m. BUSES DEPART FROM HOTEL FOR APS
Argonne Guest House Lobby (continuous departure)

7:30 - 8:30 BREAKFAST
APS Bldg. 402, Gallery
REGISTRATION
APS Atrium

Opening Remarks and Session I
APS Bldg. 402, Lecture Hall
Chris Reilly, Session Chair, Argonne National Laboratory

8:30 - 8:35 a.m. LABORATORY WELCOME
Harvey Drucker, Associate Laboratory Director,
Energy, Environmental Science and Technology

8:35 - 8:45 CONFERENCE WELCOME
Chris Reilly, Session I Chair

8:45 - 9:15 INTRODUCTION TO THE APS
Gopal Shenoy, Experimental Facilities Division
Director, Advanced Photon Source

9:15 - 10:15 ENVIRONMENTAL CHEMISTRY TUTORIAL
Alan Stone, Johns Hopkins

10:15 - 10:30 BREAK
APS Bldg. 402, Gallery

Session II
APS Bldg. 402, Lecture Hall
Thomas Voice, Session Chair, Michigan State

10:30 - 11:00 a.m.	X-RAY SCATTERING/DIFFRACTION TUTORIAL Paul Fenter, Argonne National Laboratory
11:00 a.m. - 12:00 noon	ENVIRONMENTAL GEOLOGY TUTORIAL Sam Traina, Ohio State University
12:15 - 1:30 p.m.	LUNCH APS Bldg. 402, Gallery

Session III
APS Bldg. 402, Lecture Hall
Chuck Kulpa, Session Chair, University of Notre Dame

1:30 - 2:00 p.m.	X-RAY ABSORPTION SPECTROSCOPY TUTORIAL Ken Kemner, Argonne National Laboratory
2:00 - 2:30	2-D AND 3-D X-RAY IMAGING TUTORIAL Mark Rivers, The University of Chicago
2:30 - 3:30	ENVIRONMENTAL BIOLOGY TUTORIAL Ken Nealson, Jet Propulsion Laboratory / Caltech
3:30 - 4:00	BREAK APS Bldg. 402, Gallery

Session IV
APS Bldg. 402, Lecture Hall
Ken Kemner, Session Chair, Argonne National Laboratory

4:00 - 5:00 p.m.	SYNCHROTRON-BASED ENVIRONMENTAL RESEARCH Gordon Brown, Stanford University
5:00 - 5:30	SUMMARY / EXPLANATION OF TUESDAY ACTIVITIES
5:30	BUSES RETURN TO HOTEL FROM APS APS Atrium
7:00	CONFERENCE BANQUET Argonne Guest House

Tuesday, April 20, 1999

- 7:20 - 8:20 a.m. BUSES DEPART FROM HOTEL FOR APS
Argonne Guest House Lobby (continuous departure)
- 7:30 - 8:30 BREAKFAST
APS Bldg. 402, Gallery
- 8:30 - 10:30 BREAK-OUT SESSIONS AND WORKING TOURS OF THE APS
- Group #1 APS Bldg. 402, Room E1100
Group #2 APS Bldg. 402, Room E1200
Group #3 APS Bldg. 401, Room A1100
Group #4 APS Bldg. 401, Room B3100
Group #5 APS Bldg. 401, Room B4100
- 10:30 - 11:00 BREAK
APS Bldg. 402, Gallery
- 11:00 a.m. - 12:30 p.m. BREAK-OUT SESSIONS AND WORKING TOURS OF THE APS
See location(s) listed above
- 12:30 - 2:00 LUNCH
APS Bldg. 402, Gallery
- 2:00 - 4:00 BREAK-OUT SESSIONS
See location(s) listed above
- 4:00 BUSES RETURN TO HOTEL FROM APS
APS Atrium

Wednesday, April 21, 1999

- 7:50 - 8:50 a.m. BUSES DEPART FROM HOTEL FOR APS
Argonne Guest House Lobby (continuous departure)
- 8:00 - 9:00 BREAKFAST
APS Bldg. 402, Gallery
- 9:00 - 11:30 SUMMARY OF BREAK-OUT SESSIONS
APS Bldg. 402, Lecture Hall
- 11:30 CONFERENCE ADJOURNS
BUSES RETURN TO HOTEL FROM APS
APS Atrium

Appendix 2. List of Participants

Joseph H. Aldstadt
Department of Chemistry
University of Wisconsin-Milwaukee
3210 North Cramer Street
Milwaukee, WI 53201
ph 414.229.5605
fax 414.229.5530
aldstadt@uwm.edu

Scott D. Bridgham
Department of Biological Sciences
University of Notre Dame
P.O. Box 369
Notre Dame, IN 46556-0369
ph 219.631.4921
fax 219.631.7413
bridgham.1@nd.edu

Bruce A. Bunker
Department of Physics
University of Notre Dame
225 Nieuwland
Notre Dame, IN 46556
ph 219.631.7219
fax 219.631.5952
bunker@nd.edu

Bill Burgos
Civil & Environmental Engineering
Penn State University
212 Sackett Building
University Park, PA 16802
ph 814.863.0578
fax 814.863.7304
bburgos@psu.edu

Steven Conradson
MST-11
Los Alamos National Laboratory
Mail Stop D-429
Los Alamos, NM 87545
ph 505.667.9589
fax 505.665.4292
conradson@lanl.gov

Paul R. Anderson
Chemical & Environmental Engineering
Illinois Institute of Technology
10 West 33rd
Chicago, IL 60616
ph 312.567.3531
fax 312.567.8874
pra@charlie.cns.iit.edu

Gordon Brown
Department of Geological & Environmental
Sciences
Stanford Synchrotron Radiation Laboratory
Stanford University
Stanford, CA 94305-2115
ph 650.723.9168
fax 650.725.2199
gordon@pangea.stanford.edu

Grant B. Bunker
BCPS Department
Illinois Institute of Technology
3101 South Dearborn Street
Chicago, IL 60616
ph 312.567.3385
fax 312.567.3576
bunker@biocat1.iit.edu

Peter C. Burns
Department of Civil Engineering and
Geological Sciences
University of Notre Dame
156 Fitzpatrick Hall
Notre Dame, IN 46556
ph 219.631.7380
fax 219.631.9236
peter.burns.50@nd.edu

Mark I. Donnelly
Environmental Research Division
Argonne National Laboratory
Building 202
9700 South Cass Avenue
Argonne, IL 60439
ph 630.252.7432
fax 630.252.7709
donnelly@anl.gov

Harvey Drucker
Energy & Environmental Science &
Technology
Argonne National Laboratory
Building 202
9700 South Cass Avenue
Argonne, IL 60439
ph 630.252.3804
fax 630.252.3847
drucker@anl.gov

Peter Eng
CARS
The University of Chicago
5640 South Ellis Avenue
Chicago, IL 60637
ph 773.702.2064
fax 773.702.5454
eng@cars.uchicago.edu

Paul A. Fenter
Environmental Research Division
Argonne National Laboratory
Building 203
9700 South Cass Avenue
Argonne, IL 60439
ph 630.252.7053
fax 630.252.7415
fenter@anl.gov

J.-F. Gaillard
Department of Civil Engineering
Northwestern University
2145 Sheridan Road
Evanston, IL 60208-3109
ph 847.467.1376
fax 847.491.4011
jf-gaillard@nwu.edu

Steve M. Heald
EMSL
PNNL/ANL
Building 435E
9700 South Cass Avenue
Argonne, IL 60439
ph 630.252.9795
fax 630.252.0580
heald@aps.anl.gov

David N. Edgington
Great Lakes Water Institute
University of Wisconsin-Milwaukee
600 East Greenfield Avenue
Milwaukee, WI 53204
ph 414.382.1700
fax 414.382.1705
dnedge@uwm.edu

Jeremy B. Fein
Department of Civil Engineering and
Geological Sciences
University of Notre Dame
156 Fitzpatrick Hall
Notre Dame, IN 46556
ph 219.631.6101
fax 219.631.9236
fein.1@nd.edu

Jeffrey S. Gaffney
Environmental Research Division
Argonne National Laboratory
Building 203
9700 South Cass Avenue
Argonne, IL 60439
ph 630.252.5178
fax 630.252.7415
gaffney@anl.gov

David Grummon
Materials Science & Mechanical Engineering
Michigan State University
3525 Engineering Building
East Lansing, MI 48824
ph 517.353.4688
fax 417.353.9872
grummon@egr.msu.edu

Dean L. Hesterberg
Soil Science Department
North Carolina State University
Box 7619
Raleigh, NC 27695-7619
ph 919.513.3035
fax 919.515.2167
dean_hesterberg@ncsu.edu

Gerald P. Huffman
Consortium for Fossil Fuel Liquefaction
Science
University of Kentucky
111 S. J. "Sam" Whalen Building
533 South Limestone Street
Lexington, KY 40506-0043
ph 606.257.4027
fax 606.257.7215
cfls@pop.uky.edu

Julie Jastrow
Environmental Research Division
Argonne National Laboratory
Building 203
9700 South Cass Avenue
Argonne, IL 60439
ph 630.252.3226
fax 630.252.8895
jdjastrow@anl.gov

Shelly D. Kelly
Environmental Research Division
Argonne National Laboratory
Building 203
9700 South Cass Avenue
Argonne, IL 60439
ph 630.252.7376
fax 630.252.2959
skelly@anl.gov

Ken M. Kemner
Environmental Research Division
Argonne National Laboratory
Building 203
9700 South Cass Avenue
Argonne, IL 60439
ph 630.252.1163
fax 630.252.2959
kemner@anl.gov

Jeremy Kropf
Chemical Technology
Argonne National Laboratory
Building 205
9700 South Cass Avenue
Argonne, IL 60439
ph 630.252.9398
fax 630.252.9373
kropf@cmt.anl.gov

Anthony K. Hyder
Department of Physics
University of Notre Dame
501 Main Building
Notre Dame, IN 46556
ph 219.631.8591
fax 219.631.6630
ahyder@nd.edu

Philip R. Johnson
Department of Civil Engineering and
Geological Sciences
University of Notre Dame
156 Fitzpatrick Hall
Notre Dame, IN 46556
ph 219.631.5164
fax 219.631.9236
johnson.228@nd.edu

Anne Marie Kraepiel
Department of Geosciences
Princeton University
Guyot Hall
Washington Street
Princeton, NJ 08544
ph 609.258.1052
fax 609.258.1274
kraepiel@geo.princeton.edu

Charles F. Kulpa
Department of Biological Sciences
University of Notre Dame
107 Galvin Life Sciences
Notre Dame, IN 46556
ph 219.631.5592
fax 219.631.6940
kulpa.1@nd.edu

Barry P. Lai
Advanced Photon Source
Argonne National Laboratory
Building 401
9700 South Cass Avenue
Argonne, IL 60439
ph 630.252.6405
fax 630.252.9303
blai@aps.anl.gov

Jennifer A. Linton
BESSRC CAT, Materials Science Division
Argonne National Laboratory
Building 433
9700 South Cass Avenue
Argonne, IL 60439
ph 630.252.5007
fax 630.252.0365
linton@anl.gov

John F. Manning
Center for Environmental Science &
Technology
University of Notre Dame
Notre Dame, IN 46556
ph 219.631.8376
fax 219.631.6940
jfmanning@ibm.net

Michael E. McIlwain
Waste Technology Development
Idaho National Engineering and
Environmental Laboratory
Lockheed Martin Idaho Technology
Company
P.O. Box 1625
Idaho Falls, ID 83415
ph 208.526.8130
fax 208.526.0690

John B. Miller
Chemistry Department
Western Michigan University
1201 Oliver Street
Kalamazoo, MI 49008
ph 616.387.2871
fax 616.387.2909
john.b.miller@wmich.edu

Barry M. Lesht
Environmental Research Division
Argonne National Laboratory
Building 203
9700 South Cass Avenue
Argonne, IL 60439
ph 630.252.4208
fax 630.252.2959
bmlesht@anl.gov

Stephen P. Long
Crop Sciences & Plant Biology
University of Illinois
190 ERML
West Gregory Drive
Urbana, IL 61801
ph 217.333.2487
fax 217.244.1336
stevel@life.uiuc.edu

Jörg M. Maser
Experimental Facilities Division
Argonne National Laboratory
Building 401
9700 South Cass Avenue
Argonne, IL 60439
ph 630.252.1081
fax 630.252.9303
maser@aps.anl.gov

W. Tim Meyer
Environmental Research Division
Argonne National Laboratory
Building 203
9700 South Cass Avenue
Argonne, IL 60439
ph 630.252.5781
fax 630.252.5747
wtmeyer@anl.gov

Mike Miller
Environmental Research Division
Argonne National Laboratory
Building 203
9700 South Cass Avenue
Argonne, IL 60439
ph 630.252.3395
fax 630.252.8895
rmmiller@anl.gov

Clive R. Neal
Civil Engineering & Geological Sciences
University of Notre Dame
156 Fitzpatrick Hall
Notre Dame, IN 46556
ph 219.631.8328
fax 219.631.9236
neal.1@nd.edu

Matthew Newville
GSE CARS
The University of Chicago
Building 434A
9700 South Cass Avenue
Argonne, IL 60439
ph 630.252.0431
fax 630.252.0443
newville@cars.uchicago.edu

Constance Pittroff
Experimental Facilities Division/APS
Argonne National Laboratory
Building 401
9700 South Cass Avenue
Argonne, IL 60439
ph 630.252.0909
fax 630.252.9250
pittroff@aps.anl.gov

Donald T. Reed
Chemical Technology
Argonne National Laboratory
Building 205
9700 South Cass Avenue
Argonne, IL 60439
ph 630.252.7964
fax 630.252.4431
reedd@cmt.anl.gov

Mark L. Rivers
CARS
The University of Chicago
c/o Argonne National Laboratory
9700 South Cass Avenue, Building 434A
Argonne, IL 60439
ph 630.252.0422
fax 630.252.0443
rivers@cars.uchicago.edu

Kenneth H. Nealson
Department of Geology and Planetary
Sciences
Jet Propulsion Laboratory/Caltech
170-25
Pasadena, CA 91109
ph 626.395.6143
fax 818.393.4445
knealson@gps.caltech.edu

Anna C. Palmisano
Biological and Environmental Research
U.S. Department of Energy-HQ
SC-74
19901 Germantown Road
Germantown, MD 20874
ph 301.903.9963
fax 301.903.8519
anna.palmisano@science.doe.gov

Stephen T. Pratt
Chemistry Division
Argonne National Laboratory
Building 200
9700 South Cass Avenue
Argonne, IL 60439
ph 630.252.4199
fax 630.252.4470
stpratt@anl.gov

Christopher Reilly
Environmental Research Division
Argonne National Laboratory
Building 203
9700 South Cass Avenue
Argonne, IL 60439
ph 630.252.4140
fax 630.252.2959
creilly@anl.gov

Mark Schneegurt
Department of Biological Sciences
University of Notre Dame
P.O. Box 369
Notre Dame, IN 46556-0369
ph 219.631.7187
fax 219.631.7413
schneegurt.1@nd.edu

C. Frank Shaw III
Chemistry Department
University of Wisconsin-Milwaukee
P.O. Box 413
Milwaukee, WI 53211
ph 414.229.5037
fax 414.229.5530

Alvin Smucker
Crop and Soil Sciences
Michigan State University
530 Plant and Soil Sciences Building
East Lansing, MI 48824
ph 517.355.8370
fax 517.355.0270
smucker@pilot.msu.edu

David A. Stahl
Department of Civil Engineering
Northwestern University
2145 Sheridan Road
Evanston, IL 60208
ph 847.491.4997
fax 847.491.4011
d-stahl@nwu.edu

Susan B. Strasser
Experimental Facilities Division/APS
Argonne National Laboratory
Building 401
9700 South Cass Avenue
Argonne, IL 60439
ph 630.252.5981
fax 630.252.9250
barr@aps.anl.gov

Neil C. Sturchio
Environmental Research Division
Argonne National Laboratory
Building 203
9700 South Cass Avenue
Argonne, IL 60439
ph 630.252.3986
fax 630.252.7415
sturchio@anl.gov

Brian J. Teppen
Crop and Soil Sciences
Michigan State University
Plant and Soil Sciences Building
East Lansing, MI 48824-1325
ph 517.353.5215
fax 517.355.0270
teppen@pilot.msu.edu

Gopal Shenoy
Experimental Facilities Division/APS
Argonne National Laboratory
Building 401
9700 South Cass Avenue
Argonne, IL 60439
ph 630.252.5537
fax 630.252.3222
gks@aps.anl.gov

Lynda Soderholm
Chemistry Division
Argonne National Laboratory
Building 200
9700 South Cass Avenue
Argonne, IL 60439
ph 630.252.4364
fax 630.252.9289
soderholm@anlchm.chm.anl.gov

Alan T. Stone
Geography and Environmental Engineering
Johns Hopkins University
313 Ames Hall
GWC Whiting Engineering School
Baltimore, MD 21218
ph 410.516.8476
fax 410.516.8996
astone@jhu.edu

W. Elane Streets
Analytical Chemistry Laboratory
Argonne National Laboratory
Building 205
9700 South Cass Avenue
Argonne, IL 60439
ph 630.252.4460
fax 620.972.4460
streets@cmt.anl.gov

Stephen R. Sutton
Geophysical Sciences and CARS
The University of Chicago
5640 South Ellis Avenue
Chicago, IL 60430
ph 630.252.0426
fax 630.252.0443
sutton@cars.uchicago.edu

Sam Traina
School of Natural Resources
Ohio State University
2021 Coffey Road
Columbus, OH 43210
ph 614.292.9037
fax 614.292.7432
traina.1@osu.edu

Jeanne VanBriesen
Department of Civil Engineering
Northwestern University
2145 Sheridan Road, #A330
Evanston, IL 60201
ph 847.467.5710
fax 847.491.4011
j_vanbriesen@nwu.edu

Nicholas Woodward
SC-15
U.S. Department of Energy-HQ
19901 Germantown Road
Germantown, MD 20874
ph 301.903.4061
fax 301.903.0271
nick.woodward@oer.doe.gov

Jack T. Watson
Department of Biochemistry
Michigan State University
168 Wilson Boulevard
East Lansing, MI 48824
ph 517.353.0855
fax 517.353.9334
wastonj@pilot.msu.edu