A NATIONAL STRATEGY FOR VADOSE ZONE SCIENCE AND TECHNOLOGY

Understanding Complexities in the Subsurface Environment & Closing the Circle for the Hydrologic Cycle

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ABSTRACT

The *National Roadmap forVadose Zone Science and Technology,* DOE/ID-10871, was published August 2001. Together with the Subsurface Contaminant Focus Area's *Vadose Zone Science and Technology Solutions*, it represents an important step in rationalizing the Science Program necessary to develop and coordinate long-term interdisciplinary research into vadose zone fluid flow and contaminant transport. A team of scientists from a spectrum of federal agencies, national laboratories, universities and the private sector, identified key areas of research necessary to improve our ability to predict and monitor vadose zone flow and transport. These categories include research to: reveal the fundemental nature of complex processes (geological, chemical, biological, hydrological) and their interactions at various scales; develop sensors for characterization and monitoring; and, enhance our computational capabilities to predict long-term behavior and performance. Significant emphasis was recommended on laboratory and field research programs in both porous and fractured media. Moving existing research and recent technology developments into common practice was identified as an important priority for early implementation.

The Roadmap outlines a long-term (25 year) program which also has short term potential benefits that cut across multiple federal and state agencies subsurface needs. Within DOE, the vadose zone research effort has the potential to benefit some of the on-going environmental restoration as well as long term stewardship efforts. The broad scope of the research needs is applicable to many other programs, including US EPA, Department of Defense, US Department of Agriculture, US Geological Survey, among others.

During this past year, the roadmapping process has focused on obtaining wide stakeholder input. A total of sixteen presentations of the draft road map were given to citizen action groups; tribal, state and federal agencies; and, university organizations. This input from the played an important role in the final version of the roadmap.

WANTED: A BETTER UNDERSTANDING OF THE EARTH'S SUBSURFACE PROCESSES

For much of the twentieth century it was believed that burying radioactive waste and other toxic materials underground was a safe way to isolate potential hazards from the American public. This practice was especially prevalent in the vadose zone - a geologic region between the earth's surface and underground aquifers used for water resources. Until recently the rock and soils in the vadose zone generally were expected to retard the subsurface movement of contaminants and thus protect groundwater supplies. Several studies have now documented the migration of certain hazardous and radioactive chemicals towards groundwater at several contaminated sites, leading scientists to re-examine their assumptions about what really goes on beneath the earth's surface.

Most scientists agree that our ability to predict how contaminants will behave in the vadose zone requires a better understanding of subsurface processes and improved technology to do the job. Once thought to be relatively stable and "unsaturated" with water, the vadose zone actually hosts a number of natural processes – geological, hydrologic, chemical and biological – which are exceedingly complex and often site specific. Understanding these basic subsurface processes and their myriad interactions will be essential for reducing uncertainty in future waste management and long-term stewardship decisions at our nation's most contaminated sites.

Today some of the most daunting waste management challenges in the country exist at Federal facilities once engaged in nuclear weapons production. These "legacy" waste sites are under the stewardship of the U.S. Department of Energy (DOE), which has launched the scientific research initiatives described below to help the agency better understand complex vadose zone processes. While developing their near-term research agenda, the DOE recognized that several other Federal agencies hold long-term stewardship or regulatory responsibilities for sites with a variety of contaminants. These federal agencies are now being approached towards committing to coordinating their future vadose zone research efforts to better protect the subsurface environment.

RESEARCH PRIORITIES FOR THE VADOSE ZONE: DEFINING THE NEED

In 1998 the National Academy of Science was asked by the DOE to identify the most critical contamination problems within their complex of legacy sites and to recommend a long-term basic research program to address the subsurface challenges. The report issued from the National Research Council (NRC)[1] in 2000 identified significant **knowledge gaps** that are impeding the Department's ability to clean up, stabilize or contain subsurface contamination. These deficiencies in scientific or engineering understanding that are related to the vadose zone include:

- *Our inability to locate and accurately describe the wide range of contaminants now in the vadose zone at several sites.*
- *Our inability to characterize the natural processes at work within the subsurface environment, particularly those that operate within highly variable geology.*

- *The lack of good conceptual models grounded in sound theory and underpinned with sound and sufficient data.*
- *Our failure to understand the subsurface interaction (or coupling) of physical, chemical and biological processes and how to represent these coupled processes in predictive computer models.*
- *Our inability to monitor the movement of vadose zone contaminants in both liquid and gas phases before they reach groundwater.*

CHARTING THE COURSE: A NATIONAL ROADMAP FOR VADOSE ZONE SCIENCE & TECHNOLOGY

Following the release of the NRC report, the DOE announced that creating a long-term research agenda for the vadose zone was a national priority. The Department's Subsurface Contaminant Focus Area undertook a major review of the state-of-art associated with the vadose zone and published *Vadose Zone: Science and Technology Solutions (Looney and Falta, 2000).* The Idaho National Engineering and Environmental Laboratory (INEEL) was subsequently charged to build on these two assessments and lead the development of a long-term investment strategy for DOE's R&D portfolio. INEEL convened an Executive Committee and a team of vadose zone scientists and engineers with representation from across DOE, other federal agencies, the national laboratories, industry, academia, and the international community in March 2000.

Over the next year and a half, this committee and three workgroups formed the multi-disciplinary team that has outlined a set of vadose zone research and infrastructure priorities for the next quarter-century. A preliminary draft of the Roadmap was completed on September 25, 2000. This was followed by an extensive stakeholder review via the Internet and at several interactive meetings held across the country. Significant meetings between Executive Committee members and DOE management were held with nationally prominent groups.

Facilitated meetings were held with the National Governors Association, The Association of American State Geologists, the Hanford Advisory Board, and, senior executive leadership from EPA Regions 4 and 10. Several presentations were made to outside organizations such as the United States Geological Survey and INRA. In addition, there was an interplay between the roadmap team and the EM Core Laboratories, the Subsurface Contaminant Focus Area, EMSP, the INEEL Subsurface Science Initiative, the INEEL Groundwater/Vadose Zone roadmap project, and, the Hanford Groundwater/Vadose Zone Integration project to develop synergism towards a successful implementation of the roadmap.

Feedback from these meetings, presentations and interactions was used to shape the final roadmap. The final Roadmap was submitted to the DOE on September 1, 2001, http://www.inel.gov/vadosezone/, and its features are highlighted on the next pages.

A ROADMAP OF RESEARCH & DEVELOPMENT ACTIVITIES

Understanding Basic Processes and Obtaining Basic Data

The natural processes that occur in the vadose zone do not respect the traditional disciplinary divisions between geology, hydrology, soil science, chemistry, and biology. Realistically there must be a multidisciplinary character to what is being discovered, described, monitored and modeled in the vadose zone. To provide a complete picture of this interconnected system, researchers will need to interweave theory (understanding), characterization and measurement (factual description), and prediction/integration (numerical modeling) across their traditional areas of expertise. The ultimate goal is to build a "GHCB Framework" integrating geological, hydrologic, chemical & biological properties and processes to allow scientists to quantitatively describe specific vadose zone environments. Their research will naturally fall into these areas:

- *Physical Description of Flow and Transport Processes*: This includes studying the fundamental interactions between solid, liquid and gaseous phases, thermal and gravitational realities, fractured and porous geologic settings, and relevant hydrologic processes.

- *Chemical Transformations:* Understanding the nature of chemical reactions that occur in varied underground environments is critical to predicting the long-term behavior of contaminants in the vadose zone.

- *Microbiology:* Microorganisms affect the mobility and persistence of contaminants through their biochemical interactions with metals, organic pollutants and radionuclides as well as influencing the geologic environment.

- *Colloidal Formation and Transport:* More must be learned about microscopic particles called colloids that exist naturally in the subsurface, but under certain conditions serve as carriers of contaminants through porous media.

- *Multiphase Flow and Transport:* Scientists need to know what occurs when multiple contaminants, such as heavy metals and radionuclides, become mixed underground and when pollutants are interspersed in gaseous, fluid and/or solid phases.

- *Unstable Processes:* Fluids moving through various geologic settings and under different moisture and pressure conditions can exhibit chaotic behavior that scientists need to better understand.

Gaining a Systems Perspective by Combining the Basics

It will be a long, gradual process before researchers can simulate and visualize the vadose zone of a contaminated site as an **integrated system.** Computations will be needed to interpret and reconcile data that was collected at different instrument support scales, collected over varying time periods, and collected at different spatial scales. A new and different set of tools will be needed for this task, which will help scientists transcend their customary disciplinary boundaries:

- *Understanding Coupled Systems*: Research is needed across disciplinary lines to characterize and model more realistically the complex interactions among mineral, microbial, and colloidal surfaces and among fluid, solid and gas phases.

- *Scaling Issues:* Research is needed to measure and represent properties and processes at multiple spatial and temporal scales, a requirement for quantitative GHCB models.

- *Estimating and Reducing Uncertainty:* The goal of this research is to trace uncertainty through newly developed models and convert that uncertainty into quantities that decision makers can understand, trust and use.

- *Improving Site Monitoring Systems*: Long-term monitoring of vadose zone contamination must verify contaminant isolation by reliably detecting unintended releases. Culling of outdated systems will be key, as will standardizing new approaches to monitoring.

- *Integrating and Validating Site-Wide Models:* Four roadmap activities address the stages of designing, implementing and applying an integrated system model for vadose zone sites.

Necessary Supporting Capabilities and Infrastructure

The results of the research activities outlined above will be improvements in our understanding and our capability to monitor and model the fate and transport of subsurface contaminants. To pursue these activities effectively and achieve the anticipated results within reasonable time horizons, researchers need capabilities and facilities that do not yet exist. Some of these are unlikely to become available without concerted attention and directed resources. Others will become available much sooner, and provide a more powerful boost toward achieving major results, if they are developed systematically rather than emerging haphazardly. Key elements of infrastructure and supporting capability will include:

- *A National Virtual Library*: Geological, hydrologic, chemical, and biological data from contaminated sites will be readily available along with prototype numerical models designed to work with the multidisciplinary datasets.

- *Sensor Instrumentation*: Advances in sensors will be evident, particularly in miniaturization (packaging) and emplacement technology.
- *Sensor Networks:* Advances will be made in design and optimization of sensor networks for monitoring and characterization.
- *Testing Facilities*: A variety of computer, laboratory, pilot and field facilities will be needed to support integrated testing and validation of vadose zone research.
- *The Problem-Solving Environment:* Problem-solving software will be developed and made widely available to integrate vadose zone modeling and analysis tasks.
- *Advanced Numerical Algorithms*: Reducing the range and probability of numerical error will increase the confidence of decision-makers in modeled simulations of the vadose zone environment.
- *High-power Computing Capability:* Priority access to state-of-the-art, massively parallel computers is needed for research into multi-scale processes and process coupling, for characterization, for modeling and prediction, and for visualization.

ANTICIPATED RESULTS

The technical content of the Roadmap is captured in 61 activities, most of which have associated tasks and status points within a time horizon of approximately 25 years. **The details of the roadmap activities provide the basis for selecting alternative R&D initiatives at any of the DOE sites – providing the basis for the development of a program plan for implementation of the roadmap.** Near-term means roughly within four years of beginning roadmap implementation. Mid-term means the results can be expected within a decade. Long-term applies to results over two to three decades.

Many of the **near-term results** expected for both the research and infrastructure activities share a common theme: ***moving the state of the art to the state of practice*** at all the EM sites**.** This means getting the current knowledge and capabilities already existing in the research communities into operational use at the nation's priority sites of vadose zone contamination. One benefit is that these tasks "pick the low-hanging fruit," providing quick returns because much of the research investment has already been made. A less obvious benefit is that concerted effort to get new knowledge and technical capability into practice will bring researchers and solution-oriented problem owners into continuing and close interaction.

For the **mid-term,** the roadmap outcomes of greatest significance are likely to be the cumulative ***advances in monitoring systems*** for vadose zone sites within the EM and LTS complex. A sound and efficient monitoring program is critical at major sites during environmental cleanup and afterward, throughout any period of stewardship required by residual contamination on site. The state of practice has been to monitor the groundwater at and around the site, rather than monitoring the vadose zone. However, for many sites where contaminants are at some distance from the water table, waiting until contaminants appear in the groundwater is less desirable than monitoring the vadose zone. If remediation can remove or isolate source terms and halt plumes while they are still in the vadose zone, groundwater contamination can be prevented. In addition, the effectiveness of the remediation is often greatly enhanced, and the cost significantly reduced, compared with groundwater remediation alternatives.

Many of the **long-term results** anticipated from the roadmap activities will provide ***better tools for supporting site-wide assessments and decisions*** on environmental cleanup and stewardship at EM and LTS sites. Models and data gathering will undoubtedly improve incrementally in the near and mid-term. However, after a decade or so of pursuing the roadmap's activities, a qualitative leap forward is expected in the ability to visualize, quickly and accurately, the current and projected future states of site-wide vadose zone systems. These projections, which will carry levels of certainty and sensitivity unattainable at present, should help rebuild the confidence of regulators and the public.

NEXT STEPS IN THE PROCESS

The commonality in vadose zone environments, coupled with the national interests at stake in protecting our groundwater resources, calls for the creation of a cooperative, coordinated effort among the various federal and other entities engaged in vadose zone research. To this end, a Vadose Zone S&T Initiative would serve three primary functions. It should:

1) Facilitate coordination, integration and communication across the vadose zone research community, problem owners, regulators, and other stakeholders;
2) Focus national attention on the most important research challenges and infrastructure gaps that, as a nation, we must address to protect groundwater from vadose zone contamination; and
3) Sponsor R&D in areas that are critical to meeting these goals.

A VISION FOR 2025

Over the next few decades, dramatic and fundamental advances in computing, communication, electronics, and micro-engineered systems will transform many of the scientific and technical challenges we face today. Given the pace of our technological advances over the past decades, one can envision the following by the year 2025:

- **Our fundamental understanding of vadose zone properties and processes** will be sufficiently developed, tested, and verified that issues of scientific uncertainty exert far less influence on public debates over interventions or on regulatory procedures to implement public policy.

- **In-situ and remote monitoring methods** such as real-time detection and quantification of liquid and contaminant flow in fractures are widely used—and routinely accepted by cleanup managers, regulators, and stakeholders—as an alternative to *in situ* sampling methods, such as groundwater monitoring. Using ultra-sensitive monitoring capabilities, investigators know whether liquid and contaminant migration is occurring within specific fractures or media.

- **A new generation of microscopic sensors,** the size of grains of rice, can take simultaneous multi-channel measurements (e.g., chemical species detection or pressure, temperature, pH and/or electromagnetic measurements) inexpensively and in real time. These sensors are small and inexpensive enough to inject into the material being investigated.

- **Vadose zone simulation and visualization capabilities** compare in their complexity, speed, and accuracy to those used to model nuclear weapons explosions, weather and climate, or molecular processes in biology. Access to these predictive and interpretive tools revolutionize the way researchers, cleanup managers, and regulators think about the vadose zone and contaminant problems. These tools are routinely used to prepare site-wide assessments, with predictive scenarios for alternative courses of intervention, before major decisions on cleanup and stewardship.

FOOTNOTES

[1] National Research Council, *Research Needs in Subsurface Science,* National Academy Press, 2000