# Geoscience Essentials of Radioactive Waste Management

E. Bruce Watson

With this issue of *Elements* we bring you an up-to-date perspective on environmental aspects of the nuclear fuel cycle in the form of six articles written by recognized leaders in their fields. We hope the contents will be of value to educators, policy makers, and citizens who may soon have to grapple with the implications of a re-emergence of nuclear energy in the coming decades. As we think about the future, however, there may be benefits to reflecting on the convoluted history of the nuclear energy versus environment dialog and the vital role that geoscientists have played in influencing policy.

In discussing nuclear energy issues with my Environmental Geology class, I begin by reminding students of the numerous intersections of the nuclear fuel cycle with geology. The first of these intersections involves the basic geochemistry of uranium and the origin of exploitable uranium deposits, and the last is the geologic storage—or "biosphere isolation"—of spent nuclear fuel. Along the way are issues such as the dispersal of mill tailings at mine sites and the disposition of depleted uranium and the by-products of its use in the manufacture of projectiles. I encourage my students to appreciate the value of geochemical knowledge and of perspectives from specific subdisciplines including (but not limited to) chemical hydrology, isotope geochemistry, and geochemical reaction kinetics. These disciplines provide the basis for evaluating the environmental risks of geologic storage of radioactive waste in several ways, including assessing site suitability from the standpoint of future climate trends, modeling the integrity of waste forms over extended time periods, assessing radionuclide mobility in the face of possible groundwater incursions and other natural assaults, and predicting the performance of overpacking materials such as clay minerals and zeolites in a repository setting. There are two invaluable perspectives brought to these issues uniquely by geoscientists: we are comfortable with the enormously long time frames (~100,000 years) over which radioactive waste must be secured, and we understand that in most cases the clearest window into the future emerges from deciphering the past.

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All of what I've stated above is probably second nature to those knowledgeable about the Earth. However, through the history of the radioactive waste discussion, our views have not always been prominent—perhaps because we have not been sufficiently vocal, and perhaps because government staffers, planners, and strategists have not always known where to turn. A fascinating (sometimes alarming) perspective on early ideas for disposing of high-level waste can be found in an environmental impact statement filed not long after the founding of the U.S. Department of Energy in 1977. The DOE's predecessor (the Atomic Energy Commission) had begun exploring radioactive waste disposal options at least 15 years prior to this, but the early efforts predated the National Environmental Policy Act of 1969, which required an environmental impact statement for any project or program involving federal licensing or the use of federal funds. The impact statement to which I refer is contained in several volumes, which at one time occupied about 20 cm of shelf space in my office (I've long since lost track of the volumes themselves, but I made extensive notes for teaching purposes). The topics addressed in the document are especially interesting as we consider a renewed thrust to develop nuclear energy. One section of the impact statement takes the reader through several possible scenarios for the disposal of high-level radioactive waste, which I'll briefly summarize because they are interesting and diverse—some are definitely "outside the box"—and because it was the dismissal of most of these ideas that marked the beginning of the tumultuous path to Yucca Mountain, Nevada (the probable site of the U.S. national repository for commercial radioactive waste).

The disposal scenarios considered by the U.S. Department of Energy in the late 1970s included launching the waste into the Sun or into space, but even at the time, this idea seems to have been recognized as prohibitively expensive. Other options included "reverse-well" technologies (pumping of rad-waste-laden slurries into expended hydrocarbon wells), disposal in "very deep" wells in crystalline rock (seemingly to increase the level of comfort with the "out of sight, out of mind" philosophy), and long-term storage on isolated islands. This last option was recognized as raising certain security and jurisdictional issues, as well as the need to understand the island aquifer system very well in order to avoid contamination of surrounding ocean water. Three other ideas have always struck me as especially interesting, for very different reasons. The first is placing a canister filled with radioactive waste on the surface of a continental ice sheet and relying on its remaining heat-generating capacity for "self-descent" to bedrock and safe disposal (I usually ask my students at this juncture "What is dumb about this particular idea?"). Another idea enjoyed a much more favorable reaction: i.e. loading high-level waste into torpedo-shaped canisters and dropping them from ships into abyssal-plain sediments. Enough was known about plate tectonics at the time that

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some geologists responded favorably to this suggestion—stability of the abyssal sediments could be guaranteed for tens of millions of years. However, hydrogeologists hastened to point out that, despite the inherently low permeability of pelagic sediments, the introduction of a localized heat source would likely destabilize the highly porous sediment and initiate a convection system that would effectively move radionuclides toward the sediment–water interface and into the ocean itself (the argument was also put forth that radionuclide influx into seawater wouldn't be so bad because dilution to the point of harmlessness would be assured). The last scenario I'll describe was referred to in the environmental impact statement as "planned in situ rock melting." The idea was to deposit in a borehole a mass of radioactive waste sufficient to induce melting of the host crystalline rock. Subsequent solidification of this "magma" body would seal the radionuclides in a sarcophagus of artificial igneous rock, with dangerous radionuclides sequestered in durable accessory minerals. This idea is not without merit, and has been discussed recently in the geologic literature.

Not long after the filing of the environmental impact statement described above, the U.S. Congress moved relatively quickly—with passage in 1982 of the Nuclear Waste Policy Act—toward a commitment to "geologic" isolation of high-level commercial waste using conventional mining technology.

Each time I describe these and related ideas in class, I come away with a renewed conviction that we are extremely fortunate to have a basic working knowledge of Earth systems. Much remains to be learned, of course, but the information accumulated through the work of geoscientists of past decades has built an understanding that allows us to evaluate the wisdom of exploiting certain Earth systems (bedrock, glaciers, sea-bed, etc.) for storage or recycling of our waste products. Geologic knowledge has been important to greater or lesser degrees in the decisions of nuclear nations worldwide on disposal options for high-level radioactive waste. This should be a clear and effective lesson in why it is important for society and governments to support basic research in the geosciences, even when the immediate benefits are not apparent to everyone. It is a lesson, also, that I believe politicians may learn all over again when they eventually acknowledge the need to re-inject $CO_2$ into the Earth as a measure aimed at curtailing global warming. In developing a strategy for $CO_2$ sequestration, we face challenges not unlike those of radioactive waste isolation. Intimate knowledge of geosystems—and assurances of very long-term stability—will be crucial to success.

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## THIS ISSUE

With the Nuclear Fuel Cycle issue, we end the "Ewing Cycle." Rod has been closely involved with *Elements* from the very beginning. Even though his term as principal editor officially ended at the end of 2005, he continued on until the Water on Mars issue, for which he acted as principal editor, was in press and he has worked actively on this issue as guest editor. We cannot thank him enough for his vision and for "selling" it so successfully to the community.

This issue highlights the contributions of mineralogy and geochemistry to nuclear waste disposal. If nuclear power is making a comeback, then the waste disposal issue has to be addressed, and mineralogists and geochemists are at the forefront of evaluating waste forms that will lock in radioactive wastes for time periods of geological length.

## LOOKING BACK

As we close the final issue of 2006, it is an appropriate time to reflect on the accomplishments of the past year. You are holding the 11$^{th}$ issue of *Elements*. For every issue that is delivered to your desk, an extraordinary feat of collaboration must happen. Authors of each of the articles have to be shepherded to produce their articles according to a firm deadline; society news editors must send news from their societies; book reviews and conference news must be assembled. Our technical editor, Thomas Clark, then combs through every manuscript and adds a layer of polish. The managing editor follows suit and prepares the manuscripts for return to the authors for review. When the manuscripts are returned they are sent to our design team for assembly. Michel Guay, the graphic artist responsible for the look of *Elements*, and his assistant, Vincent Boivin, make their magic to produce an innovative colorful layout. A number of people then pore over the proofs: the authors and guest editor, the copy editors, Dolores Durant and Thomas Clark, and the managing editor. Then it is press time, and the printer Caractéra takes over; our representative, Sylvio Proteau, follows all the production steps to ensure a high-quality product. Then our mailer, Glenn Graham at APC Postal Logistics, has the shipment delivered to their New Jersey facilities for processing and mailing. APC Postal Logistics provide bulk airmail shipping to our international members at very reasonable costs. The dedication of all these people makes *Elements* happen. We thank them all.

### *A Few Numbers*

In 2006, we published 37 thematic articles. Of the 49 authors who contributed to our second-year lineup, 24 were from the USA, 9 from France, 7 from the UK, 3 from Germany, and 1 each from Canada, Spain, and Australia.

### Elements *and Citations*

One of the highlights of this year was learning in March that *Elements* had been accepted for the following Thomson ISI products, beginning with volume 1 (1), January 2005:

- *Science Citation Index-Expanded (SCIE)* including the *Web of Science*
- *ISI Alerting Service*
- *Chemistry Citation Index (CCI)*
- *Current Contents/Physical, Chemical & Earth Sciences (CC/PC&ES*

This means that references to articles in *Elements* are counted and that *Elements* will have a citation index starting in 2007. The most cited issue so far is "The Geochemical Origin of Life," followed by "Diamonds." Which journals have cited *Elements* so far? *Earth and Planetary Science Letters*, *Journal of Petrology*, *Astrobiology*, *Journal of Colloids and Interfaces*, and *Organic Geochemistry*, to name a few.

### Elements *at GSA*

It was heart warming to receive such positive feedback on *Elements* at the recent GSA meeting. You told us that you liked *Elements*, that you use it in the classroom, and that you liked the topics covered.

## LOOKING FORWARD

In the next issue, we will welcome five new societies —the Association of Applied Geochemistry, the Società Italiana di Mineralogia e Petrologia, the Deutsche Mineralogische Gesellschaft, the International Association of Geoanalysts and the Polskie Towarzystwo Mineralogiczne (Mineralogical Society of Poland)—for a total of 13 participating societies and three affiliated societies. They will all introduce themselves in the society pages of the next issue.

We are also pleased to present you our 2007 line-up in the next two pages.

### *Back Issues*

Starting in 2007, it will be possible to order back issues of *Elements* via the MSA website. We envision that many small colleges with limited budgets might want to obtain a subscription to *Elements* and order past issues to have a complete set. Prices reflect the cost of processing orders and handling payments.