Spectrum 2000: Deployed, emerging, and advanced technologies

Spectrum 2000 brought together industry leaders to discuss technology development and deployment for waste management applications.

THE EIGHTH BIENNIAL Spectrum 2000 conference, held in Chattanooga, Tenn., focused on issues that society has had a difficult time bringing to closure: management of the waste generated from more than half a century of nuclear activities. Some of the reasons are political; some, educational. And some, of course, are technical.

The technical aspects of managing cleanup of the nation's nuclear legacy were the focus of the more than 40 sessions at the meeting, held September 24–28, and sponsored by two ANS divisions—Fuel Cycle and Waste Management, and Decommissioning, Decontamination, and Reutilization—in cooperation with the Department of Energy (EM-50). The event was organized and hosted by the ANS Oak Ridge/Knoxville Section.

The conference was held to enable an extensive international exchange of information related to deployed technologies, emerging technologies, and advanced technologies. The aim was also to provide new avenues for business development of products and services for nuclear waste management, including decommissioning and decontamination, and environmental restoration.

"There's more than enough technical capability, creativity, and dedication in this room—and elsewhere among our peers—to solve these problems," said Ambrose Schwallie, president of the Washington Group, during the plenary session. "I'm confident of that because we're really starting to see signs of progress."

Congressman Zach Wamp (R., Tenn.), whose district includes the Oak Ridge complex, argued during the plenary that the nation spends more time and money *managing* the nuclear legacy rather than actually *cleaning* it up. It is not entirely the fault of the industry, though, he suggested. "Really, when the rubber meets the road and it's time to do the cleanup, somebody's going to come in and throw up all these red flags as to why you can't go forward," Wamp said. "And then it becomes political, and then there's a retreat. And that's really sad. It's really sad. Because the same country that was able to produce this technology and break the back of Communism and win the Cold War is totally capable of dealing with the waste."

The Department of Energy's Environmental Management program is leading some of the progress in waste management. During the plenary, Carolyn Huntoon, the DOE's assistant secretary of environmental management, outlined the five areas where the agency has been concentrating its efforts.

The first area, high-level radioactive waste, poses some of the most difficult and often intractable technological challenges for the department, Huntoon said. She cited the progress made using three new retrieval systems at Oak Ridge, permitting the removal of radioactive material from storage tanks where earlier efforts had failed.

The second major focus area is that of the subsurface contaminants left behind in soil and groundwater from nuclear weapons production activities. The department has developed innovative thermal methods, for example, that can mobilize and extract chlorinated solvents from the subsurface—in timeframes measured in months, rather than decades, Huntoon said. "The challenges in this area are not unique to DOE. Other government agencies, the private sector, and other countries face similar remediation problems," she added.

The deactivation and decommissioning of more than 7000 contaminated facilities is the third focus area. To address the technical aspects, the Environmental Management program has conducted seven large-scale demonstration and deployment projects in this area. Huntoon noted that 75 technologies, most adapted from commercial nuclear power or other industries, have improved worker protection from radiation and chemical exposure, and resulted in better performance in remediating buildings and other structures. The impact of these new technologies was evident in the dismantling of hundreds of plutonium-contaminated gloveboxes at Rocky Flats, and the "cocooning" of the C-Reactor at the Hanford site, she said.

The fourth technological challenge is processing mixed, low-level, and transuranic waste. The DOE is currently storing about 170 000 m^3 of such waste, and, until recently, there were few options for its characterization, treatment, and disposal. "I was at the Waste Isolation Pilot Plant [the previous week]," Huntoon said, "to celebrate an event. . . . Three trucks carrying TRU waste from Rocky Flats, Idaho, and Hanford arrived simultaneously at WIPP—a real first."

The last area is one, Huntoon noted, that people do not often think of as a technology issue: long-term stewardship. Many of the department's sites will not be able to be cleaned up sufficiently to allow for unrestricted use. In those cases, the DOE will need to retain long-term monitoring and maintenance responsibilities at those sites. "The department needs to develop the remediation techniques that will allow us to minimize our long-term stewardship requirements," Huntoon said. "This is one of the biggest challenges that will face the department in the future. . . . I want to make sure that we are focusing on the long-term stewardship issues that are beginning to confront us, and that we are integrating science and technology and long-term stewardship considerations into our cleanup decisions."

Wamp, who is set to serve on the Subcommittee on Energy and Water Development beginning in January (he was reelected in November), emphasized that the industry needs to set realistic goals for cleanup and make sure that science guides the activities. The waste industry also needs to maximize the technology that's available, he noted. "The technologies in the environmental cleanup industry are changing. And as the political dimension fails to bring about real, substantive cleanup, technology is passing us by," he remarked.

But what is most needed is courage.

"We've studied it. We've made the plans. We've got to have the guts to go do it," Wamp said.

"We have to show the appropriators and all those in responsible positions . . . that we're making real progress on cleanup, that we're taking buildings down. And that we're doing work and that we're not just stirring the pot every two years and then coming back and asking for more money because the pot's getting bigger. [Otherwise] we're just going to stir the pot and then we're going to study these things until we're blue in the face. And then when [a] study expires we'll go back and study it again, and just keep studying and studying and studying. . . .

"We want to clean it up. We want this legacy to be our legacy, that we were the generation that [cleaned up] this nuclear legacy. Whether you like it or not, it happened; it's reality. Now let's clean it up. Let's get on with it."

The presentations over the course of the week covered an array of topics, from practical, firsthand project experiences, to more innovative, forward-thinking discussions with the future of the waste industry in mind.

Following are some of the highlights, which include a snapshot of current decommissioning activities at one of the nation's premier academic research reactors, an update on present and future D&D work on Department of Energy facilities, and suggestions on shoring up utility onsite storage facilities should the nation continue to drag its feet on the opening of the Yucca Mountain waste repository.

Yucca Mountain, indeed, was foremost on the minds of many at the conference, as was the nation's excess inventory of depleted uranium. Several presentations addressed these topics, including a few notable ones recounted here, which suggested ways to improve the proposed Yucca Mountain repository, while at the same time responsibly disposing of the ever-growing inventory of depleted uranium.

Decommissioning the GTRR

The Georgia Tech Research Reactor was a heterogenous, heavy-water moderated and cooled reactor, fueled with highly enriched plates of aluminum-uranium alloy. The reactor began operations in 1964, and ceased in 1995. Just before the Summer Olympics were held in Atlanta in 1996, the fuel was removed and transported off site for security reasons. Soon thereafter, plans to receive a replacement shipment of low-enriched fuel fell through.

With the fuel already removed and the reactor having fulfilled its 30-year design lifetime, and also considering the renovations needed for relicensing, as well as the declining enrollment in the school's nuclear engineering program, the Georgia Institute of Technology administration announced in the summer of 1997 that the reactor would be decommissioned. During the session, "Deactivation, Decontamination, and Decommissioning Experience," Steve Marske, project manager at CH2M Hill for the reactor's decommissioning, outlined the project's history and lessons learned from the project, which is now in its final stages.

When the decision to decommission was made, the intent was to release the facility for unrestricted use. "Our project vision for the decommissioning of the Georgia Tech Research Reactor is [to have] a facility, to include the reactor building and the grounds, left in the condition that meets required safety codes and suitable for conventional demolition and construction—meaning unrestricted final release," Marske said.

In October 1997, decommissioning activities began with a characterization study. The intent was to determine the nature and extent of the radiological contamination, and use that as a basis for the decommissioning plan and the cost estimate. The following April, a possession-only license amendment was approved by the Nuclear Regulatory Commission.

By November 1999, the work plans and procedures were prepared and reviewed. The contractor began work in December 1999, and the first offsite shipment was sent in January 2000. The decommissioning was to have been completed by the end of November. The final survey should be complete by the middle of December, and the final report should be issued to the NRC by the end of January 2001. Marske said they expect the facility to be released from license by early next summer.

> **Wamp: "The technologies in the environmental cleanup industry are changing. And as the political dimension fails to bring about real, substantive cleanup, technology is passing us by."**

Marske's role as an executive engineer is to oversee the project as a consultant to Georgia Tech and to the state of Georgia. The executive engineers also direct what is called the war room, a central room that contains all of the written procedures, work permits, and updated images of operations. (There are three cameras located throughout the reactor containment building that record the operations.) "The monitors are in the war room," Marske said. "So, students can come in—professors, visitors, whoever it may be—and get the full flavor of what's going on on the project. You can't always get into the reactor due to current conditions, requirements, et cetera."

Marske said there were several lessons learned from the project.

- "Be prepared," he cautioned, "for problems such as less-than-adequate 'as-builts' and unknown embedded pipes. I think we've all experienced this, that the as-builts and the drawings that are available don't always represent what you get when you finally get into operations."
- Rule of thumb: Any accumulated water is a haven for tritium.
- The containment tent around the bioshield, while preventing spread of contamination, also presents ventilation and heat problems. Temperatures inside the tent reached 140 °F, and, because they house heavy equipment, also contained carbon monoxide from the equipment's exhaust.
- The iron density of the concrete in the bioshield turned out to be much greater than expected, 270 lb/ft^3, and "turned into a real bear" to dismantle, Marske said.
- Working closely with the local communities was very helpful. "We're glad we did that right up front," he noted. "We wanted to make sure the community and everybody, including the school, felt comfortable about what we were doing. . . . We met with [a local community association] and told them straight up: This is what's going to happen in the next X amount of months. We made sure that our door was wide open so they could come talk to us, and we could come talk to them. And that actually turned out to be a really good communication process."
- MARSSIM—the Multi-Agency Radiation Survey and Site Investigation Manual, which provides information on demonstrating compliance with government regulations for environmental radiological surveys—is "much more reasonable" than Reg. Guide 1.86. "Knowing what we do now, if we were associated in the start of the project, we would have suggested the use of MARSSIM versus 1.86," Marske said.
- 10 CFR 50.59 was a valuable tool. "Through 10 CFR 50.59 we are not required to go to the NRC every time there's a slight modification to the decommissioning plan. It was very useful in this project," Marske said.

The most important lesson learned, Marske said, was the importance of thorough characterization. "Characterize, characterize, characterize. You must get this done *thoroughly*—not only radiological status, but chemical status, structural status, what the conditions are, extent of the activation, et cetera," Marske said. During the removal of the graphite, it was determined that there was cobalt-60 and europium in the graphite, "which turned out to be quite an issue," he said. "It wasn't expected to be activated to the extent that it was. And it could have been determined through characterization."

The only way to remove the graphite was by hand. To keep individual doses to a minimum, "quite a few" personnel were swapped out, Marske noted. The initial dose estimates to personnel were exceeded because of the unexpected activation. "If it weren't for that one event . . . this would have rolled along very nicely, well below the estimated total project dose."

DOE D&D

The most recent assessment of facilities under jurisdiction of the Department of Energy identified approximately 5000 of those—or one-quarter—as surplus, meaning they have no current or future mission. DOE is therefore deactivating and decommissioning these facilities to reduce monitoring and maintenance costs, decrease the potential for release of radioactive and hazardous materials to the environment and local communities, and decrease the risk of accidents due to their continued deterioration. "We wish to remove those hazards by basically removing those facilities," said Steven Bossart, of the DOE's National Energy Technology Laboratory. Bossart, during the "Deactivation, Decontamination, and Decommissioning Experience" session, presented an update on the DOE's current activities in and plans for deactivation, decommissioning, surveillance, and maintenance of its facilities.

The DOE's estimate of the D&D life-cycle costs through fiscal year 2070 are nearly $10 billion (in constant FY 2000, noninflation-adjusted dollars) for the current surplus facilities. In addition to these facilities, for which the Environmental Management program has responsibility, an estimated 10 000 buildings are owned by DOE's Defense Programs, Nuclear Energy, and Science offices. The DOE has estimated that eventual stabilization, deactivation, and decommissioning of these contaminated facilities and structures will cost the department $25 billion. That brings the total DOE market for D&D services to $35 billion, which Bossart called a conservative estimate. The figure may end being as much as 10 percent higher.

Bossart provided a condensed description of the current and future significant D&D projects facing the DOE at its major sites:

The *Albuquerque Operations Office* currently has D&D operations at Los Alamos National Laboratory, with about 100 structures requiring decommissioning, including a plutonium-processing facility, a tritium facility, and the Omega West Reactor facility.

The *Chicago Operations Office* is responsible for D&D activities at Argonne National Laboratory–East, Brookhaven National Laboratory, and Princeton Plasma Physics Laboratory. D&D work at Argonne should be completed by FY 2003, and includes the Zero Power Reactor and Juggernaut Reactor facilities. Decommissioning work should be completed by FY 2006 for BNL's Graphite Research Reactor. The Tokamak Fusion Test Reactor at PPPL will be fully decommissioned by FY 2002.

The *Idaho Operations Office* will concentrate on surveillance and maintenance projects at the Idaho National Engineering and Environmental Laboratory before FY 2007, including work on portions of the Idaho Chemical Processing Plant that contain fissile material, the Power Burst Facilities Reactor, and the Materials Test Reactor. Deactivation projects to be completed by the end of FY 2006 include work on the PBF reactor buildings and the MTR Fuel Storage Canal. There are also numerous decontamination and decommissioning projects to be completed by the end of FY 2006.

The *Oak Ridge Operations Office* will focus its Oak Ridge National Laboratory efforts on D&D of research reactors, tanks, auxiliary buildings and equipment, isotopes processing buildings, surface facilities, and other contaminated structures.

The *Ohio Operations Office* has responsibility for remediation of the Ashtabula depleted uranium extrusion facility as well as hot cells and a pool-type reactor at Battelle's West Jefferson site. Decommissioning at the Mound Plant's primary buildings involves work on tritiated gloveboxes, tritiated pump oil, uranium beds, and other equipment. Fernald, which processed raw uranium ore, plans to complete environmental restoration at its site by FY 2006. West Valley D&D activities include final disposition of the high-level waste facilities by FY 2015.

The *Oakland Operations Office* will perform D&D work on the Energy Technology Engineering Center, which includes the Nuclear Development Test Facility and the Radioactive Materials Handling Facility, as well as a glovebox and hot cell at a General Electric site.

The *Nevada Operations Office* will oversee D&D work to be completed by FY 2010 at the Nevada Test Site, the Reactor Maintenance Assembly and Disassembly facility, and the Super Kukla Reactor building.

Work at the *Richland Operations Office* is concentrated on the Hanford site. Its eight plutonium production reactors and five fuel reprocessing canyons will be the primary focus, as well as another challenge. "One of the biggest problems that Hanford faces is the Waste Encapsulation and Storage Facility," Bossart said, "where they've got 2000 strontium and cesium capsules containing 150 million curies. That represents the largest concentration of radioactive material in the United States." Present plans are for the disposal of the capsules as high-level waste beginning around 2013 and continuing until 2017, when deactivation of the facility will begin.

The *Rocky Flats Operations Office* will focus efforts on the Rocky Flats Plant and its nearly 1000 gloveboxes and miles of process pipe and ventilation ducts that are contaminated with highly fissile material. Work at the site should be completed by FY 2007.

D&D work out of the *Savannah River Operations Office* for Savannah River will be performed on the HLW facilities, as well as plutonium production reactors, heavy-water facilities, and fuel fabrication facilities. The work is scheduled to be completed after FY 2006.

Bossart said his group has set some ambitious goals regarding lowering costs and implementing improved technologies into the D&D projects. They hope to reduce the cost of pre-FY 2007 D&D work by 25 percent by using improved technologies. "We think this is achievable because, if you look at what we've done in our large-scale demonstration deployment projects, the improved technologies that we've demonstrated have basically shown a 25 percent or more cost reduction, compared to the baseline technologies that these sites have been using," Bossart said.

The other goal, he said, is even more ambitious: Reduce the cost of any post-FY 2006 D&D work by 50 percent. "We think this is going to take some real breakthroughs evolving from the Environmental Management science program . . . as opposed to pure demonstration," Bossart said. Potential cost savings in this area, he noted, are going to arise from the ability to conduct facility survey and characterization down to low levels in real time, as opposed to collecting samples and sending them off site, and using more remote and robotic systems.

Marske: "Characterize, characterize, characterize. You must get this done *thoroughly*—not only radiological status, but chemical status, structural status, what conditions are, extent of the activation, et cetera."

Improving onsite storage

In the Draft Environmental Impact Statement that was issued for Yucca Mountain in August 1999, consideration was given for an alternative for which no action would be taken. That is, instead of storing the spent nuclear fuel for perpetuity at Yucca Mountain, it would be left at the nuclear power plant sites, explained Richard Denning, chair of nuclear engineering graduate studies at Ohio State University, during the session, "Spent Nuclear Fuel—Nuclear Waste Management and Disposition-I."

There were two versions of this no-action alternative that were considered. The first version assumed that institutional controls would be maintained: Every 100 years or so, the onsite dry storage facility would be refurbished.

The other version supposed that after 100 years, institutional controls would be lost and society would no longer be a caretaker for the facility—and it would be left to deteriorate. In such a far-reaching, almost science-fictional scenario, the implications of the events that lead to it may likely be more significant than whatever happens to the spent fuel left in the facilities.

Nonetheless, in such a scenario, the concrete container would degrade with time and, in about 100 years, fail. The roof would collapse. Rainwater would seep into the dry spent fuel shipping cask, and begin to corrode it. And, after 1000 years, water would get into the shipping cask and start to dissolve the uranium oxide, leading to a release of the fuel. The water also would attack the cladding, corrode it, lead to additional exposure of fuel, and, eventually, dissolution of that fuel. The radioactive materials would then be carried by the rainwater out of the facility, leading to a contamination of the groundwater, affecting the drinking water supplies and the farm products produced in the area.

If society, in fact, never decided to move the spent fuel to a geologic repository, are there steps that could be taken to ensure that these grim events would be left to the imagination of science fiction writers? Denning believes there are such measures.

He presented another alternative for consideration: Improve the current onsite facilities to allow deferment of the decision to ship the fuel to a geologic disposal repository or other interim storage site. Future populations would then have the option to decide whether to continue to maintain the onsite storage, where the fuel would be stable in an improved storage system, or send the fuel to a repository.

"I want to make it clear when I promote this strategy—and I'm not really promoting it as much as I am raising it for discussion—that I'm not implying that the risks from disposal for fuel at Yucca Mountain aren't substantially smaller than the risks from onsite storage," Denning cautioned. "I'm confident they are. I'm confident that the right decision is to move and to move quickly toward disposal at Yucca Mountain. But, let's look at this potential option here as an alternative in case the nation doesn't move forward aggressively."

Despite the deterioration of an onsite storage facility, if left unchecked, an analysis conducted by Denning and his colleagues indicated that only 3300 latent cancer fatalities in the United States could be expected over a 10 000-year period. "It was a great surprise to the analysts to find that, in this case, they were predicting such a comparatively small environmental impact for leaving the fuel in a dry storage facility," Denning said.

There were, however, many significant uncertainties in the study. "This whole study is about uncertainties," Denning explained. "If you just look at the 3300 latent cancer fatalities and you believed it, then I think that you can draw the conclusion that onsite disposal is really a logical thing to do—something that one could do responsibly. However, there are uncertainties, and I think that's the whole ball game here."

Denning and his colleagues determined how they could improve the barriers that exist today in licensed dry storage systems—the concrete structures and steel structures—and allow the site to safely store the fuel for thousands of years.

The dominant flaw in concrete was deemed to be its erosion due to seasonal freezing and thawing. They figured they could improve its performance by either replacing it with a different material altogether, or by somehow improving the behavior of the concrete. Given the extensive industry experience in the use of concrete, as well as its low cost, they decided improving concrete's behavior was more viable.

They found little to improve on the stainless steel dry shipping cask, deciding that only a second protective barrier would be needed. By adding the barrier, Denning explained, the time before water can seep in is extended. More important, the second protective material—Hastelloy, for instance—is simply different, and not subject to the same corrosion mechanisms as the stainless steel. "If we were wrong about the corrosion rate of steel, and it really corrodes a lot more quickly, we may not be wrong about the Hastelloy. So, it provides us extra protection in the treatment of uncertainties because it's of a diverse material," he explained.

Denning noted that the integrity of the dry shipping cask is particularly critical in the current, "nonimproved" design. "If you decrease its lifetime to 300 years, then you multiply the consequences by a significant amount," he explained. "And that's because of the much higher fission product content in that spent fuel in this time period. . . . The addition of a diverse barrier provides confidence that you can't get a large early release." The diverse barrier not only extends the time at which water comes into contact with the fuel, but also provides greater confidence that a large, early release of radionuclides is not possible. "It's very important to provide a containment system capable of preventing water ingress for greater than 1000 years because of the benefit of fission product decay," he added.

Quapp: "It's time that we begin managing [the] front-end waste stream similar to the way we've begun focusing on the back-end waste products."

Onsite storage in an advanced dry storage facility, as conceived by Denning and his colleagues, "could be a responsible option for the protection of the environment, as an alternate or interim step to geologic disposal," he concluded.

"The applicability of the deferred decision option could be for small countries that don't have appropriate geologic formations, or for countries for which there's opposition to transportation of spent fuel or for the storage [of spent fuel] in the geologic repository—which effectively means all countries, since there seems to be opposition just about everywhere."

Solution in search of a problem

In the course of the nuclear fuel cycle in the United States over the past 50 years, nearly 740 000 metric tons (t) of depleted uranium hexafluoride have accumulated at waste sites around the country. "You only need to see the photographs of the DU cylinders sitting in Portsmouth and Paducah, and, to a lesser extent, at Oak Ridge, to recognize that it is a vast amount of material," said Bill Quapp, of Teton Technologies, during the session, "Spent Nuclear Fuel—Nuclear Waste Management and Disposition-II." In addition to the existing inventory of UF$_6$, which was generated when the Department of Energy and its predecessor agencies ran the enrichment plants, the U.S. Enrichment Corp. continues to produce 10 000 to 12 000 t of UF$_6$ per year from their operation of the enrichment facilities, Quapp noted.

While enrichment activity must continue to supply fuel for the nuclear power industry, indefinite accumulation cannot continue, Quapp argued. "It's time that we begin managing this front-end waste stream similar to the way we've begun focusing on the back-end waste products."

Depleted uranium metal can be used as shielding in certain cask applications. But its high costs are justified only when space and weight are critical factors in the design. From a taxpayer's perspective, Quapp argued, it is irrational to consider uranium metal as a viable shielding product. "And so I literally asked myself the question one day," he said. "Is there another physical or chemical form that we could use this in that brings its cost to a more tractable level than depleted uranium metal?"

Depleted uranium concrete, or DUCRETE, was then developed by Quapp and his colleagues at the Idaho National Engineering and Environmental Laboratory as a recycle option for large quantities of depleted uranium. It can be used as a shielding material for spent nuclear fuel interim storage casks and high-level waste storage and transportation casks.

The material consists of depleted uranium oxide–based aggregate and typical concrete ingredients. The depleted uranium oxide is fabricated into a ceramic, which is crushed and screened to form an aggregate gradation size. The crushed aggregate is then used to replace rock in traditional concrete mixture. The end result is a very high-density material.

"It's not a rocket science concept. It's a very simple concept," Quapp said. "Heretofore, the paradigm of the nuclear shielding engineer with depleted uranium has always been metal. But, my paradigm shift is to use it in a lower-cost material."

The density of DUCRETE is near 400 lb/ft^3, depending on the aggregate density, compared to 140 lb/ft^3 for concrete. It contains both high Z and low Z material elements, and is therefore both a gamma and a neutron shield. And its compressive strength and thermal conductivity are similar to ordinary concrete.

The key to DUCRETE, Quapp said, is the ceramic aggregate, called DUAGG. It is fabricated by a liquid-phase sintering process where silica is the basic element. During the sintering process, the liquid-phase melts, surrounds the uranium dioxide grains, and, after cooling, forms a mechanically stable and corrosion-resistant material, with densities up to 8.8 g/cm^3.

The most advantageous aspect of DUCRETE is likely to be its shielding performance. Both spent nuclear fuel and high-level waste have gamma and neutron source terms, so a material is needed that will attenuate both of those radiation sources. Most current shielding systems for such applications use either steel or concrete because of their relatively low cost, wide availability, known fabrication characteristics, and effectiveness. Concrete and steel require (if used by themselves) 30-in. and 15-in. thicknesses, respectively, to attenuate these typical source terms. DUCRETE can provide a similar attenuation with a 12-in. thickness, Quapp said.

"The biggest problem in moving this material forward," Quapp said, "is there's only one customer. And that customer hasn't chosen to support very much work on this in the last few years." The initial work that was funded at INEEL allowed the researchers to conceive and conceptualize the material, but manufacture only very small quantities. "This is still a conceptual material. Some of it has been made, but in relatively small total quantities. Somebody has got to decide we need to work with it, get rid of depleted uranium, for this to really move forward. And that's a fairly large financial commitment."

The overall cost-effectiveness of DUCRETE is estimated to be similar to concrete on a performance-adjusted basis, and considerably better than steel for spent nuclear fuel and high-level waste storage applications, Quapp said.

"In very large quantities consistent with the Yucca Mountain environment, the previous studies we've done at INEEL have indicated a production cost of the aggregate [to be] a quarter a pound," Quapp said. In that figure, the aggregate is the major cost element in DUCRETE; the cement and water are negligible. The costs of other shielding materials—steel, lead, uranium metal—are much higher.

Since steel casks can be used for transportation as well as for storage of spent fuel and high-level waste, however, they have a performance advantage over DUCRETE casks, he noted. And so, the key to gaining the full benefit of the material is to devise a transportable cask that uses DUCRETE as shielding. Preliminary design cost estimates indicate that a DUCRETE and steel transportation and storage cask could be sold for about $500 000, compared to steel casks selling for over $1 million, according to Quapp.

"DUCRETE is a material in search of a problem," Quapp concluded. "It has the attributes . . . which make a very unique shielding material compared to all other materials typically used by shielding experts. And, using these materials in cask storage applications provides a technically viable alternative [to other means of depleted uranium disposal]. . . . It can simplify the design of Yucca Mountain by allowing the repository to be a contact-handled system rather than a remote-handled system—which I believe will plague the 'what-if' folks as it goes through licensing and regulatory [processes]. It's reasonably low-cost, and it offers design options in a Yucca Mountain application that were not previously available to designers."

Depleted U as waste package fill

Depleted uranium dioxide is being investigated for use in repository waste packages containing light-water reactor spent fuel. The material can be used either in particulate form as a sand-like fill material in the waste package, or, mixed with steel, as a structural component of the waste package. In doing so, the application provides a means to dispose of the nation's inventory of depleted uranium, reduce criticality concerns, and decrease radionuclide release rates, said Charles Forsberg, of Oak Ridge National Laboratory, who outlined, in the "Spent Nuclear Fuel—Nuclear Waste Management and Disposition-II" session, a plan to use depleted uranium dioxide as a waste package fill.

"Fortunately, we have a small surplus of depleted uranium," he quipped, "about 8 tons of depleted uranium for every ton of spent fuel."

The concept is simple, Forsberg said. "You take a spent fuel package, you load it with spent fuel. After the package is fully loaded, you then add depleted uranium dioxide as a particulate, a sand-type of particulate, to fill the void spaces in the waste package—both void spaces in the corners and the void spaces in the coolant channels of the actual spent fuel."

Or, when used as a component of the waste package structure, the depleted uranium dioxide would be mixed with steel to form cermets (ceramic metal composites). The cermet can essentially replace structural steel components in the waste package, such as the internal baskets.

Using depleted uranium as a waste package fill can help assure long-term criticality control, Forsberg said. He illustrated the point by describing "natural" reactors. "Mother nature has, on occasion, created natural reactors," he explained. The lowest assay at which natural, non-manmade reactors have been found is 1.3 percent U-235 in U-238. "And what that means," he continued, "is if you have more than 1.3 percent enriched uranium and you put it out, mother nature can, as she has in the past, convert it into a nuclear reactor. It may not be a very good nuclear reactor, but she has the capability of doing that."

Even though the average assay of light-water reactor fuel is 1.5 percent, potential criticality can be prevented. As the waste package degrades, there would be significant mixing of the depleted uranium and the spent nuclear fuel uranium. The low fissile assay would then eliminate the potential for nuclear criticality, Forsberg said.

Using depleted uranium would also reduce the potential radionuclide release rates from spent nuclear fuel waste packages. The goal of a repository, obviously, is to contain radionuclides until the most hazardous ones decay to nonradioactive isotopes.

By filling the waste packages with depleted uranium, a natural phenomenon that protects some uranium ore deposits from dissolution can be exploited. Forsberg said there are many uranium ore deposits around the world that should have vanished long ago. In such instances, he explained, groundwater reacted with the deposits. These reactions created boundary layers around the ore deposits, which preserved the interior of the ore deposit against the migration of uranium and other species from the interior. In effect, there was a "sacrificial" loss of uranium around ore deposits for the preservation of uranium in the middle of the deposit.

In Forsberg's plan, the depleted uranium becomes the "sacrificial" uranium, forming a protective barrier that will—if groundwater should seep into the repository—help preserve the spent fuel on the inside. "The idea is to create a miniature ore deposit, except the inside of our ore deposit is spent fuel. The outside of our fuel is depleted uranium."

The plan would provide a means of disposing of excess depleted uranium as well. The worldwide inventory of depleted uranium, a byproduct of enriched uranium production for commercial power reactors and defense applications, is around 1 million tons, Forsberg noted, and about 40 percent of that is in the United States. The consumption of depleted uranium is only around 1000 tons per year, and decreasing steadily. "It's not clear, outside of a repository, that there are going to be large uses of depleted uranium, for a variety of both institutional and technical reasons," he noted.

The plan could use plenty, if not all, of the world's depleted uranium. The first application—filling up the void spaces—would use about 33 tons of depleted uranium dioxide per package. There would then be about 3.5 tons of depleted uranium per ton of spent nuclear fuel. (The gross package weight would be around 75 tons, considerably heavier than the 42-ton packages currently used. "However," Forsberg pointed out, "the heaviest waste packages going into Yucca Mountain, which are some Navy spent fuel packages, are approaching this particular weight [75 tons].")

A different option is to create a self-shielded waste package, with the depleted uranium fill surrounded by the cermet. This adds about 49 tons of depleted uranium dioxide per package, for a gross package weight of around 100 tons. In this 100-ton waste package, however, the depleted uranium dioxide cermet provides sufficient radiation shielding. The current waste packages are not self-shielded, Forsberg pointed out, and require remote operations for emplacement. And so, it becomes a matter of preference: Are lighter packages and remote operations better? Or are shielded packages and contact-handled operations preferred?

"This use of DU can consume half to potentially all of the excess DU," Forsberg said. "If you use it just as a fill application, about half the inventory can be used. If you also use the cermet application, the entire inventory of depleted uranium worldwide can be used."—*Patrick Sinco* **NN**