safety—that is, one based on the National Academy of Sciences recommendation of a peak dose compliance period, which figures from the Department of Energy (DOE) indicate is several hundred thousand years. The NAS study, issued in 1995, recommended “that compliance with the standard be measured at the time of peak risk, whenever it occurs.”

According to DOE’s projections, the peak risk to an individual from leaking radioactivity would occur about 300 000 years after closure of the dump. But recent research by the State of Nevada indicates that the metal storage containers can corrode and fail quickly in the Yucca Mountain environment. Without the estimated benefit of long-lived containers, the peak risk could occur in as little as 2000–3000 years.

EPA should revise its standard to encompass the time of peak dose. Limiting the compliance period to less than the time of peak risk threatens public health and safety for future generations. The Yucca Mountain project should not be continued if these standards cannot be met.

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July is becoming a tough month for nuclear waste. In July 2003, US District Court Judge Lynn Winmill in Idaho ruled that all of the approximately 90 million gallons of tank wastes at the Savannah River Site in South Carolina and Hanford Nuclear Reservation in Washington State are high level and must be buried in repositories. In July 2004, the US Circuit Court of Appeals for the District of Columbia ruled that a 10 000-year radiation standard for Yucca Mountain is inadequate. Congress will no doubt have to intervene to short-circuit the latter decision, or repositories in the US will never open.

Any geologic burial site will be fractured before—and especially after—tunnel boring. The very best that can be done is to supplement the rock’s containment ability with engineered barriers such as thick-wall steel casks and titanium drip shields.

The least the tank wastes weigh is 360 000 tons, or nearly five times the weight that’s slated to go in Yucca Mountain. The Department of Energy is committed to removing tank wastes from Savannah River and Hanford. In 1984, the department had potential crystalline repositories in North Carolina, New Hampshire, Maine, and Wisconsin on its radar screen. Rocks in those states are granitic, which means each of the sites is already fractured and will be further fractured with drilling. Anyone wanting proof of that need only consult the Oskarshamn repository, a granite site about 150 miles south of Stockholm.

At some point, we’re going to have to be practical. We’ve enjoyed nuclear energy, and we’ve enjoyed our status as the world’s greatest nuclear power, but everything comes with a price. We now have 410 000 tons of spent-fuel rods and tank wastes spread all over the country, and all of us would breathe easier if they were out of sight, out of mind.

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Despite the astronomically long half-lives of fission products that will be contained in waste scheduled to be stored at Yucca Mountain, the politicking and debate over whether 10 000 years is a sufficiently long safety standard is absurd. It is entirely reasonable to imagine that innovative ways of treating, more securely storing, or productively utilizing nuclear waste will be developed on much shorter time scales. America needs to address energy policy, and greater use of fission will have to be an important component of that policy over at least the short and medium terms. Our elected leaders could more productively spend their time and our money on developing sensible policies toward greater national energy independence.

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Probing Pyramids to Identify Internal Structure

The news that Mexican physicist Arturo Menchaca and archaeologist Linda Manzanilla have launched a cosmic muon search for hidden chambers in the Pyramid of the Sun in Mexico (PHYSICS TODAY, February 2004, page 31) opens a new and exciting chapter in cross-disciplinary research. The two researchers have chosen the technique of pyramid probing with vertical muons—that is, those making an angle less than 45° to zenith. Vertical muons were first used in 1955 in Australia (ref. 5 of ref. 1). Luis Alvarez and coworkers used the method in their 1967–68 probing of Chephren's pyramid, the second of the great pyramids of Egypt. The Alvarez team searched for equivalents of the king's and queen's chambers that had been found in the first pyramid, that of Chephren's father, Cheops.

The vertical muon probing method consists of measuring, from beneath the pyramid, the absorption pattern of the muons as a function of their angle to zenith after they pass through the pyramid. The detector was placed in the only known chamber beneath Chephren's pyramid. As a result of the probing, Alvarez concluded that no other chamber existed.[1] "It's not that we did not find the chamber," said Alvarez. "We found that there wasn't any chamber."[2]

Menchaca and Manzanilla appear to be unaware of an article by two French architects[3] that was published two decades after Alvarez's investigation. In describing their search for cavities in the Cheops pyramid, the architects pointed out an important construction feature, unknown to Alvarez at the time of his search, that brings into question the feasibility of observing hidden chambers from beneath the pyramids.

Alvarez assumed that the pyramids were filled with only one kind of stone—limestone—so that their interior density is uniform. The architects reported that the Cheops pyramid was built of two kinds of stone with different densities: limestone, at 1.8 g/cm^2, and granite, at 2.7 g/cm^2. While most of the first pyramid's interior consists of limestone, the roofs and walls of all chambers and galleries are made of granite. The mass of the granite roof above the king's chamber is equal, within 5%, to the sum of the missing mass of the chamber plus the mass of the roof if it were made of limestone;[4] the apparent area density of the king's chamber, as detected by the vertical muons, approximately equals that of limestone. By accident or by design, the excess density of granite over that of the limestone nearly exactly masks the void. Had Alvarez first tested his system in the Cheops pyramid, from beneath, he could not have detected the king's chamber with vertical muons.

Are these considerations, based solely on our knowledge of the Cheops pyramid, valid for Chephren's as well? They would be invalid if Chephren's pyramid was built without granite. However, the lower chamber's granite roof suggests that no such radical departure in architecture took place between the father's pyramid and the son's.

I first saw the French architects' article[3] in January 1987 while in Cairo filming a documentary about the pyramids.[2] I immediately informed Alvarez of the French group's findings. He confirmed that he was unaware of the use of granite in the pyramids.

I suggested to Alvarez that to unambiguously state that there are no other chambers in Chephren's pyramid, one would have to repeat the measurement using horizontal muons—those that make an angle greater than 45° to zenith—and that the detector should be on the ground outside the pyramid.[5] The intensity of the horizontal muons is much lower than that of the vertical ones, but the horizontal muons have the advantage of being "hardened" by their longer passage through the atmosphere. In fact, Alvarez's experiment[1] had confirmed the feasibility of using horizontal muons: The muon absorption pattern had clearly shown the ridges of the peak of the Cheops pyramid viewed from the Chephren pyramid's lower chamber.

In a letter written to me less than a year before his death, Alvarez stood by his conclusion that no king's or queen's chambers exist in Chephren's pyramid. He argued that if a hypothetical king's chamber had included a granite roof, his detector would have observed it as a density bump. Because no such bump was observed, Chephren's pyramid must have been constructed differently from Cheops's. Alvarez did tacitly imply, however, that the issue was not closed; he said another measurement, using horizontal muons, would confirm his conclusion.

Actually, the issue is wide open, because the only chamber found in the Chephren pyramid was built like all chambers in the Cheops pyramid—with a granite roof. To exclude the existence of chambers in the Chephren pyramid, an experiment with horizontal muons is called for.

How is this story relevant to the Pyramid of the Sun? If the Mexican pyramid's interior density is homogeneous, it will be irrelevant. If the density is not homogeneous, the story may be quite relevant. According to the PHYSICS TODAY story, Menchaca says the Pyramid of the Sun has a more irregular shape, is less dense, and is also less homogeneous.

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