Long-Term Passive Ventilation at Yucca Mountain

Evidence from Natural Analogues

Although natural ventilation is not as efficient at water removal as forced ventilation, it can enhance the effectiveness of a geologic repository in isolating radioactive waste.

By John S. Stuckless and Rickard S. Toomey III

The U.S. Geological Survey has long favored ventilation of any mined geologic repository for high-level radioactive waste within the unsaturated zone.[1] There are two reasons. First, the removal of heat would keep the temperature closer to current ambient conditions, the conditions most readily studied and best understood, and second, ventilation has the potential to remove large quantities of water, which might otherwise be available to degrade waste packages and mobilize radioactive waste. For example, forced-air ventilation in the currently proposed designs for a repository at Yucca Mountain, Nevada, would have the capacity to remove more than three orders of magnitude more water than the amount that infiltrates the 3- by 5-kilometer block of Yucca Mountain, currently estimated at an average rate of 4.6 mm/year.[2]

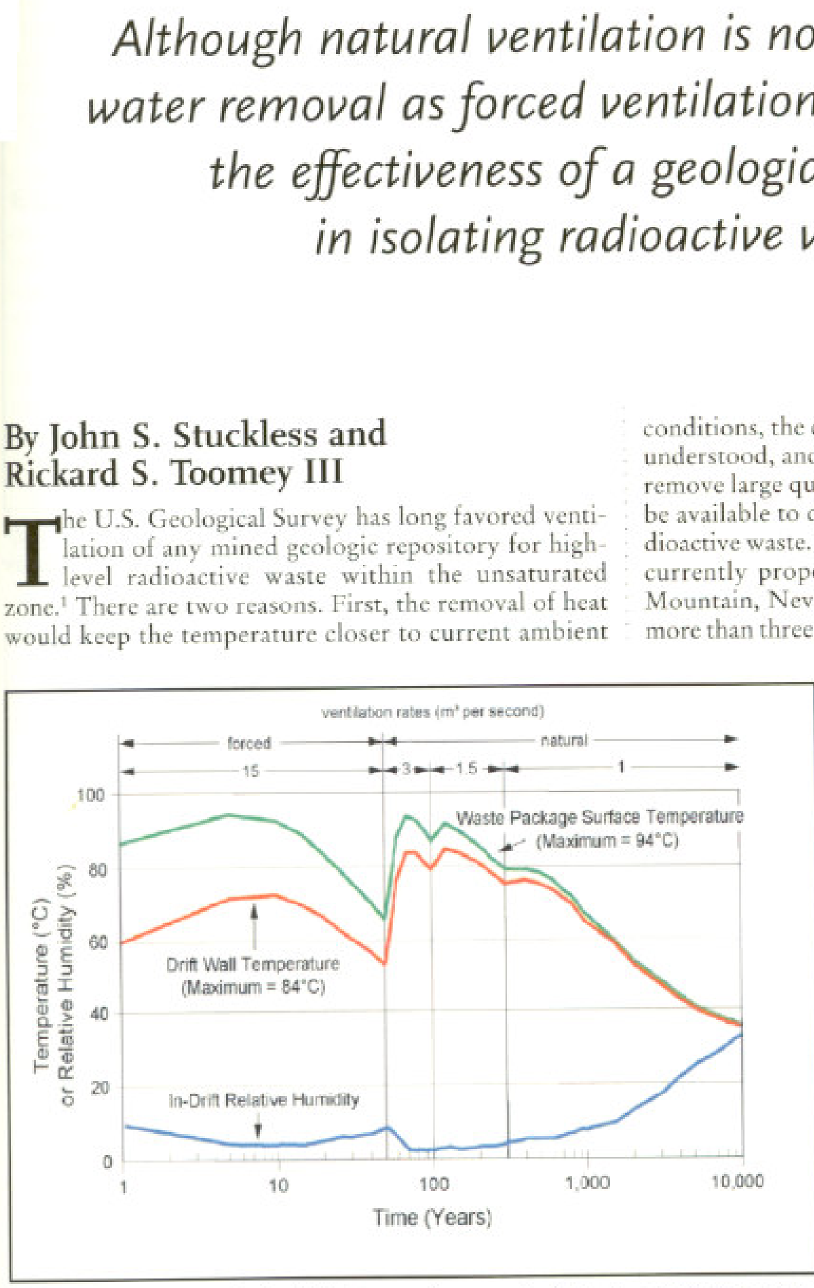

Fig. 1. Plot showing the in-drift temperatures and relative humidity of a potential Yucca Mountain repository as a function of time and at various ventilation rates (from Ref. 2, Figs. 2–15).

Natural ventilation will not be as efficient at water removal as forced ventilation is, but it can enhance the effectiveness of a geologic repository in isolating radioactive waste. The Yucca Mountain Science and Engineering Report[2] documented the possible effectiveness of passive ventilation. The report presents a scenario of initial forced-air followed by passive ventilation in which the relative humidity remains below 40 percent for 10 000 years, even with infiltration modeled at more than 10 times the current rate (see Fig. 1). If there were no seals in the current Exploratory Studies Facility, passive airflow would have a velocity of 0.55 m/s, which could remove about 45 liters of water per square meter of tunnel per year or all of the water infiltrating at a rate of 45 mm/year.[3] Evidence from natural analogues indicates possible benefits from passive ventilation for the repository planned for Yucca Mountain.

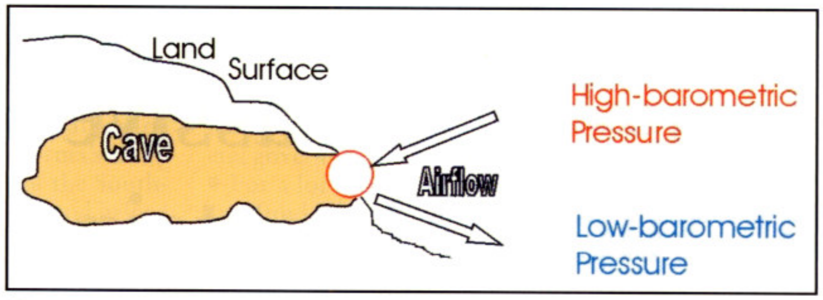

Fig. 2. Wind Cave in South Dakota has a small single opening, and air circulation is controlled by barometric changes. Wind velocities can reach 120 km/h with large pressure changes.

Analogue Examples

Stuckless[4,5] has documented excellent long-term preservation of fragile items found within the unsaturated zone (vadose zone). Examples range from exquisitely painted churches carved in tuff (Gorome, Turkey, 11th century A.D.) to painted Buddhist temples carved in basalt (Ajunta, India, 2nd century B.C to 6th century A.D.) to painted tombs and a variety of fragile artifacts (Egypt, 3000 to 300 B.C.) and Paleolithic cave paintings (France and Spain, 14 000 to 32 000 B.C.). Stuckless[4] noted that the degree of preservation seemed to be best when the artifacts were surrounded by air rather than soil. The terra cotta solders of Qin Shi Huang (2nd century B.C.) were preserved but nearly devoid of their original paint. Likewise, the terra cotta army of Jing Di (1st century B.C.) had lost their wooden arms and cloth uniforms. The implication is that ventilation may play an important role in long-term preservation within the unsaturated zone.

Natural ventilation has been studied in literally hundreds of caves throughout the world, and the general principles are reasonably well understood.[6,7] Furthermore, the study of airflow in some caves has progressed to the point that mathematical descriptions and models of flow have been developed for small, simple systems as well as for parts of large systems. Some examples include the historic entrance of Mammoth Cave in Kentucky,[8] Glowworm Cave in New Zealand,[9] Wind Cave in South Dakota,[10,11] and Kartchner Caverns in Arizona.[12,13] In the majority of caves, air circulation is driven by two general mechanisms: changes in barometric pressure and air density differentials. In most caves where air density differentials drive airflow, the most important variable controlling air-density variations is temperature differentials, generally between the outside and inside air. For that reason, caves with density-differential-driven airflow are commonly referred to as

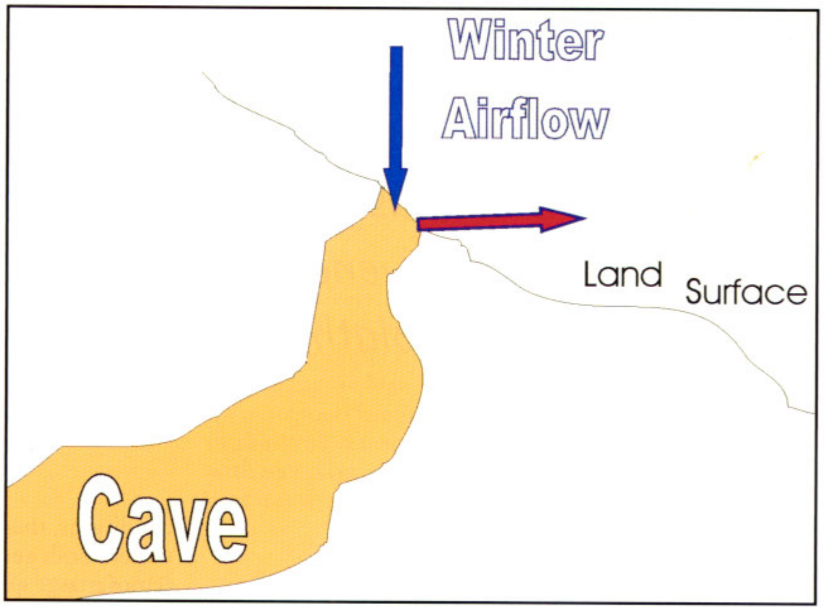

Fig. 3. Carlsbad Caverns in New Mexico is a single-opening cave and is subject to pressure circulation, but air turnover is very seasonal. Cold winter air (blue) sinks into the cave and displaces warm moist air (red).

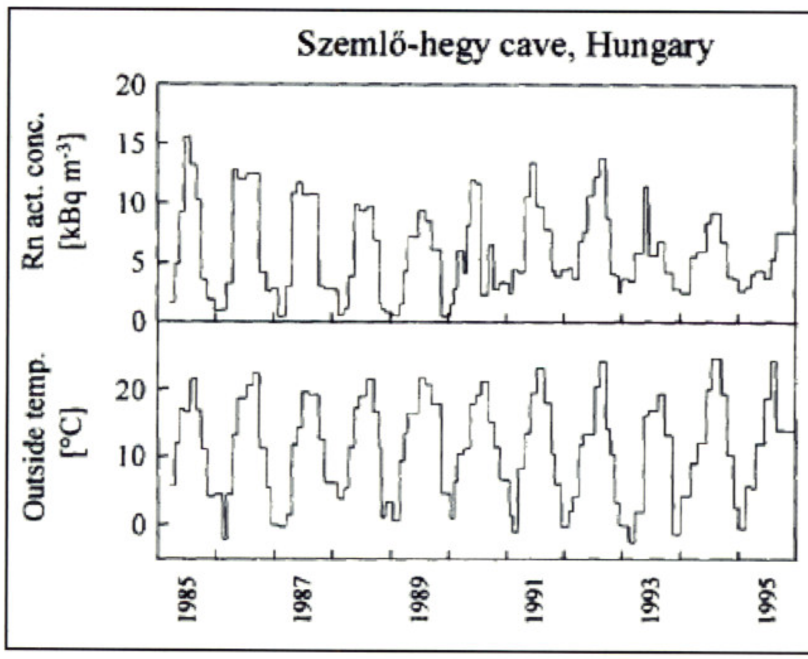

Fig. 4. Radon activity concentrations (in kilobecquerels per cubic meter) and outside air temperature as a function of time in Szemlo-Hegy Cave in Hungary (from Ref. 15, Fig. 4).

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temperature-difference-driven systems or convection-driven systems. In caves with multiple entrances at different elevations, this type of airflow is also known as "chimney effect" airflow. Airflow in any particular cave is dependent on numerous parameters, including (a) the number, size, and configuration of cave entrances; (b) the size of the cave; (c) the presence and configuration of constrictions and obstacles in the cave passages; and (d) the outside and within-cave climates.

Wind Cave in South Dakota provides an end-member case for barometrically controlled air circulation, as illustrated in Fig. 2. In this example, the cave has only one opening, a large volume, and a tight cap rock that isolates the cave from the atmosphere. The passage of a high-pressure system "pumps" the cave full of air. Conversely, the passage of a low-pressure system allows the stored air to exhaust. The small area of the entrance combined with the barometric pumping results in air velocities as much as 75 miles per hour (120 km/h). At Wind Cave, when the walk-in entrance is open, an average of almost 3000 m^3 of air enters or leaves the cave per hour.[14] Lewis discussed the role of air pressure changes in cave airflow in his review.[15]

There are two end members of air-density- (or temperature-) driven air ventilation systems. Carlsbad Caverns, in New Mexico, has a single entrance and therefore responds to barometric pressure change in a manner similar to that of Wind Cave; however, its geometric layout is dominantly vertical (Fig. 3), and thus air exchange is controlled by temperature. In the winter, cold outside air sinks into the cave displacing the warmer moister cave air. This phenomenon of seasonal airflow is best illustrated by the much lower radon content within the cave during the winter relative to summer.[16,17] Figure 4 illustrates this phenomenon over an 11-year period at Szemlo-Hegy cave in Hungary.[18] In smaller caves with this type of seasonal airflow, the air temperature of the cave commonly will be well below the mean annual temperature of the surrounding area in which the cave is located; that is, the cave will be a cold-air trap.

The other end member of an air-density- (or temperature-) driven system is approximated by Mammoth Cave in Kentucky (see Fig. 5). Mammoth Cave has numerous entrances (natural and manmade) at different elevations. These entrances at different elevations allow for a reversal of air circulation depending on the season. In the summer, the relatively cooler air in the cave flows out the lower openings, and warm air is drawn in through the upper openings and cooled. During the winter, the relatively warm, moist air in the cave is lost from the upper openings, and cooler air is drawn in through the lower openings. The velocity of airflow is proportional to the temperature difference between the air outside and inside the cave. Jernigan and Swift[8] discussed mathematical modeling of the airflow at one of the entrances. Studies at Mammoth Cave also illustrate the importance of the area of the openings. The removal of a gate and stone wall at the upper entrance in 1991 caused such an increase in winter airflow that radon levels in the cave decreased by a factor of 9.[19] There was also a relative dry-out and decrease in mean temperature much farther into the cave than had existed previously.

Przylibski[20] studied radon distribution in two caves in Poland. Niedzwiedzia Cave is largely isolated from the atmosphere by air gates. Nonetheless, the radon concentrations vary with outside temperature much as described at Carlsbad Caverns. Radon was measured at seven locations within the cave—at the floor, ceiling, and midpoint levels at each location. The results show a slight tendency for increased radon concentration near the floor of the cave and a more pronounced increase away from the entrance. Thus, "as a rule, locations farther from the entrance have poorer ventilation and higher radon concentrations."[20]

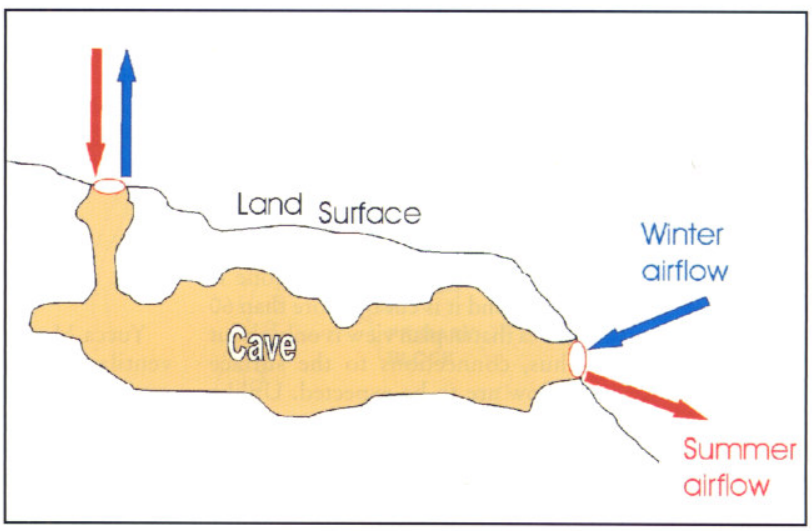

Fig. 5. Caves like Mammoth Cave in Kentucky have multiple openings, and air circulation is driven by temperature differences.

Lechuguilla Cave, within the Carlsbad Caverns National Park, has more than 160 km of passageways and an overall depth of 477 m. Most passages are at an average depth of 244 m below the entrance and are farther than 1.6 km away from the entrance.[21] Cunningham and LaRock[22] studied microclimate in the cave by sampling at 48 locations in the cave and found little correlation between air circulation (as indicated by radon concentrations) and outside air temperature or barometric pressure changes except near the entrance of the cave. This lack of

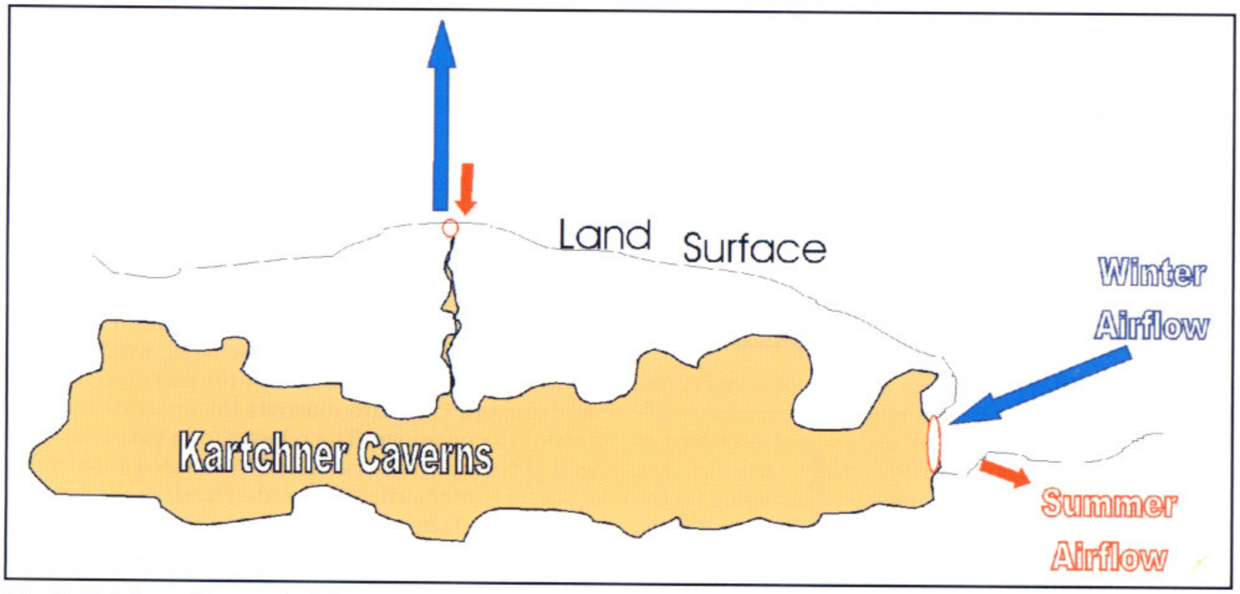

Fig. 6. Kartchner Caverns in Arizona is apparently a single-opening cave, but the high degree of fracturing causes circulation like that of a cave with openings at different elevations. Lengths of arrows show relative difference in airflow in summer and winter.

correlation was observed even though the passage of a low-pressure system during a sampling period caused a 0.16 km/h airflow out of the cave during one sampling period and a high-pressure system caused an airflow into the cave of 40 km/h during another sampling period. Some air mixing within the cave was attributed to elevation differences within the cave, but commonly the air in the deeper, more remote reaches of the cave was fairly stagnant. Four exceptions were found where fresh air (as indicated by temperature, radon, and CO_2 concentrations) suggested connection to the surface where none is known; alternatively, these anomalies could represent a deep fracture flow system.

Kartchner Caverns, Arizona, provides an example of a cave with only one known opening, but which must have communication with the land surface by fracture systems, as shown in Fig. 6. The airflow is similar to that at Mammoth Cave. During the winter, warm moist air is lost to the surface by an upper opening, even though none is known. This cave is shallow, and it is cut by more than 60 mapped faults within an area that in plan view is only about 5500 by 3600 m.[23] Thus, connections to the surface through which air can flow are to be expected. Unlike Mammoth Cave, the velocity of airflow does not seem to be proportional to temperature differences,[13] probably owing to the greater resistance to air movement provided by the fracture system relative to that provided by large openings. This difference also explains the tendency for Kartchner Caverns to be more responsive to pressure changes than to temperature changes during the summer months.

Ventilation may play an important role in long-term preservation within the unsaturated zone.

Airflow in caves is not generally large enough to decrease the relative humidity below 99 percent, and, in fact, a conscious effort is made in "show caves" to keep airflow at a minimum to prevent dry-out of the caves and the concomitant cessation of speleothem formation. Several caves, especially those where the size of the natural opening has been expanded to accommodate public access, have a system of air-lock doors that prevents large volumes of air exchange. At Kartchner Caverns before development for tourism, the average moisture lost from the cave by evaporation was estimated to be 21 000 gallons per year (92 500 L/year). Air-lock systems on the manmade entrances now keep the postdevelopment moisture loss similar to that observed predevelopment.

Yucca Mountain

Yucca Mountain provides a self-analogue for passive ventilation and water removal. The mountain is composed of Miocene pyroclastic units that are welded to varying degrees. Many boreholes have been drilled in the mountain as part of the site characterization conducted by the U.S. Department of Energy. Two boreholes were drilled near Yucca Crest USW UZ-6 and USW UZ-6S, about 1 km south of SD-6 (see Fig. 7a); both exhibit constant airflow. Borehole UZ-6 is drilled through the Tiva Canyon Tuff into the top of the Topopah Spring Tuff and has only shallow surface casing. Borehole UZ-6S is drilled through the Topopah Spring Tuff and is cased to the base of the Tiva Canyon Tuff. In the winter, both boreholes exhaust air that is at a near-constant temperature and is saturated with water vapor.[24] The total water lost from the two boreholes is about 650 L/day. The airflow is caused by the air in the well being warmer and moister and therefore less dense than the atmospheric air. The latter is presumably drawn

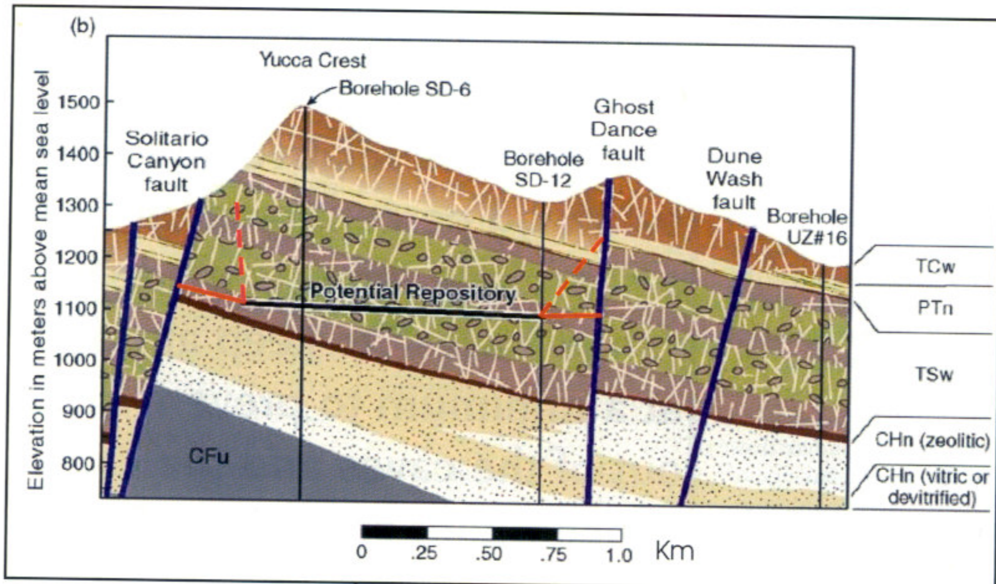

Fig. 7a. Schematic cross section of Yucca Mountain (modified [red lines] from Ref. 2, Figs. 4–9) showing the hydrogeologic units, principal faults, a potential repository, and possible augmentations to passive ventilation (in red).

in through the fractured Topopah Spring Tuff, where it crops out in Solitario Canyon. Direction of airflow during the summer is erratic, and, as with Kartchner Caverns, barometric effects are much more important than in the winter.

Figure 7 presents a schematic cross section and plan view of a potential repository at Yucca Mountain. The geohydrologic system of the mountain is favorable for a passive ventilation system similar to the naturally occurring one at Kartchner Caverns, even after access tunnels and ventilation shafts have been sealed. The welded part of the Tiva Canyon Tuff has a very high air permeability (about 100 darcies); therefore, residence time for air in the tuff ranges from 1.6 to 3.0 years with a mean value of 2.5 years.[25] The intervening nonwelded tuff (PTn) between the welded parts of the Tiva Canyon Tuff and the Topopah Spring Tuff has a much lower air permeability,[26] and where wet is nearly impermeable to the flow of air. The welded part of the Topopah Spring Tuff is hydrologically similar to the welded part of the Tiva Canyon Tuff. Studies of carbon isotopes and chlorofluorocarbons in samples of air from the unsaturated zone

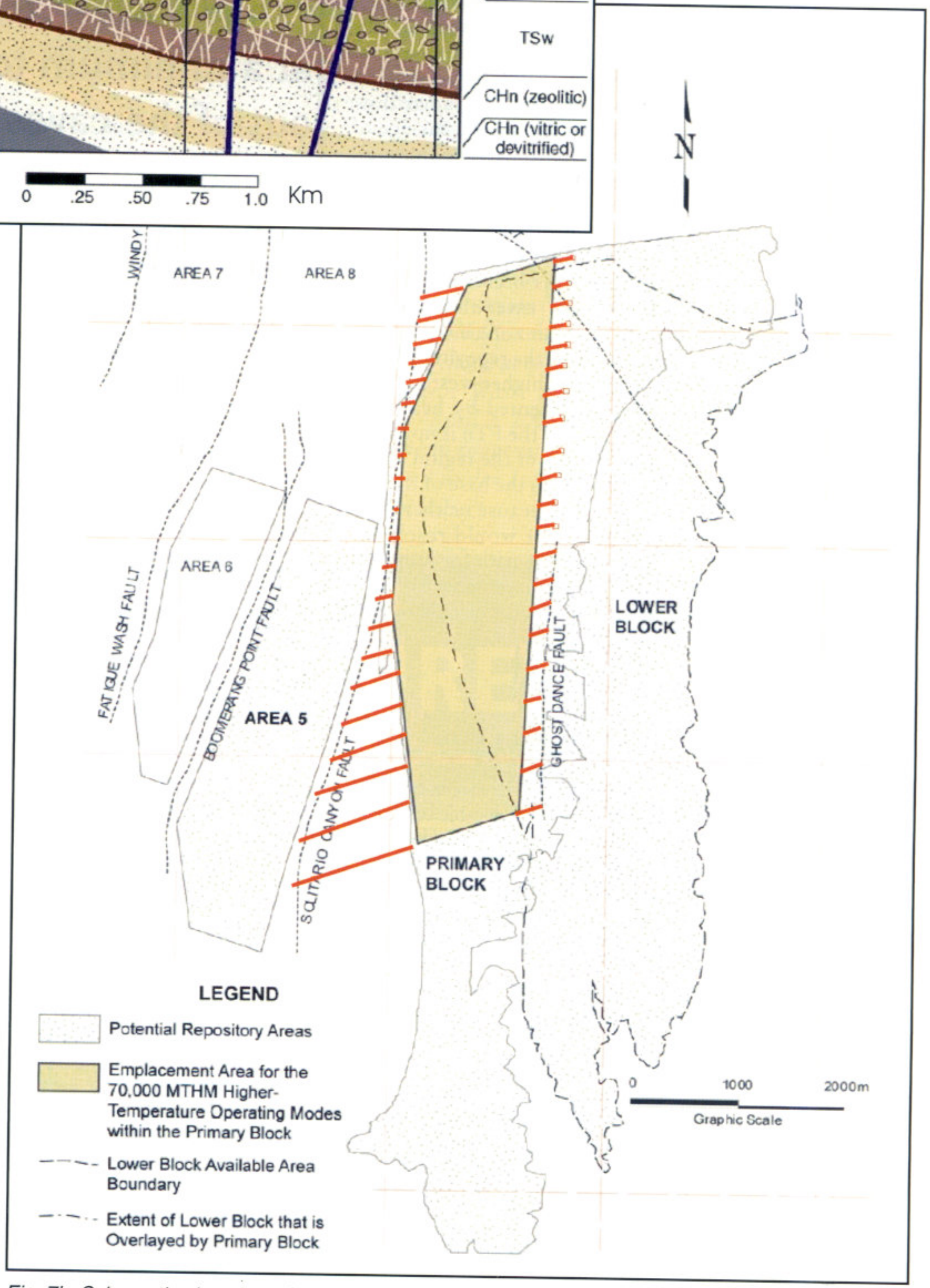

Fig. 7b. Schematic plan view of a potential repository at Yucca Mountain showing ventilation drifts (in red) that terminate in faults or raises that extend to the base of the welded part of the Tiva Canyon Tuff (modified [red lines] from Ref. 2, Fig. 2.5).

show that air circulation is rapid from the surface to the base of the Tiva Canyon Tuff but that the Topopah Spring Tuff is at least partly isolated from the atmosphere except where it is connected to the surface by boreholes or outcrop.[27]

A cross drift has been constructed through the proposed repository block. This drift has been bulkheaded at three places to simulate the final closure and sealing of the proposed repository. However, the drift has natural pneumatic connections to the surface by way of the Solitario Canyon fault and through outcrops of fractured Topopah Spring Tuff (see Figs. 7a and 7b). These pathways may explain the airflow out of the first bulkhead during the passage of a low-pressure system (barometric pumping). Unfortunately, after sealing of the proposed repository, this pumping might ventilate only the western side of the proposed repository in a manner analogous to that seen in single-entrance caves. If the PTn is brecciated by the Ghost Dance fault, then extending drifts from the perimeter drift into the fault zone might create a natural ventilation flow through the repository from the lower eastern side and out the higher western side with the flow being strongly augmented by heat from the radioactive waste (Fig. 7a). If the PTn is not brecciated by faulting, or is absent north of the region of known offset, raises could be driven to the base of the welded part of the Tiva Canyon Tuff. Because neither the raises nor the western perimeter drift would reach the surface, there would be no accessible path for human intrusion. Seals at the ends of the emplacement drifts would need to be designed both to allow air circulation and to prevent radiation leakage.

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Passive Is a Plus

The information developed here from natural analogues suggests that there may be considerable benefit to the Yucca Mountain Project if the feasibility and benefits of long-term passive ventilation are investigated. This is especially true with respect to the impact on unsaturated zone hydrology. The dry-out period may be extended, and the seepage flux likely would be decreased or even totally abated.

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John S. Stuckless is a senior science advisor with the U.S. Geological Survey in Denver, Colo. Rickard S. Toomey III is cave resources manager at Kartchner Caverns State Park in Benson, Ariz. This article is based on a presentation made at the 10th International High-Level Radioactive Waste Management Conference, held March 30–April 2, 2003, in Las Vegas, Nev. This work was done in cooperation with the U.S. Department of Energy under Interagency Agreement DE-AI08-02RW12167.