Caves and caverns: seepage in man-made caverns

***Description**:* Modelling suggests that a capillary barrier will form in unsaturated rock adjacent to a cavern and that this will act as barrier to water inflow into the cavern [Philip et al., 1989; Philip, 1990], although inflow may not be totally precluded [Williams et al., 1990]. The effectiveness of the capillary barrier will depend on the dimensions and shape of the cavern, the percolation flux, heterogeneity in rock properties, the ambient flow field, and relative humidity [Williams et al., 1990]. There is also some experimental support for the formation of a capillary barrier [Wang et al., 1999].

The nature of fluid entry as drips or by diffuse flow may be important. The formation of drips or diffuse flow is dependent on such factors as the influx rate, roughness of the cavern wall, relative humidity, and the wetting characteristics of the rock surface. In the Yucca Mountain repository design the possibility of drip formation has led to the inclusion of drip shields to prevent water coming into direct contact with the waste canisters.

The U.S. DOE have sought analogues for the volume and nature (drips v diffuse flow) of water seepage into natural and man-made caverns in the unsaturated zone. Evidence from man-made caverns is considered here. There is a separate critical review of the evidence from natural caverns.

<u>Flow entry into man-made caverns and buildings</u>
The underground cities of Kaymakli and Derinkuyu, Cappadocia, Turkey were constructed in a partly welded rhyolite ash-flow tuff. Derinkuyu has a footprint of ~4 km^2 and housed 15,000 to 20,000 inhabitants throughout much of the first millennium A.D. [Toprak et al., 1994]. Eight habitation levels are known above the water table which is at a depth of ~90 m. Some rooms are larger than 3 x 5 m, and the area receives an annual rainfall of 380 mm y^{-1}. Examination of both underground cities has failed to find signs of either active seepage or mineral precipitates indicative of historic seepage [Simmons, 2002].

Ten underground villages remain inhabited today in Tunisia, 20-40 km north of Gabes and near Goreme in Turkey. None of the descriptions mentions the presence of water, so they must remain dry or only occasionally become damp [Simmons, 2002]. However, in a kitchen of the C9th – C13th A.D. monastery at Goreme there is evidence of very limited water seepage along a fracture which caused some bleaching of soot deposits by surface flow. There was no evidence of drips.

<u>Preservation of water sensitive artefacts in man-made caverns</u>
Frescos: Buddhist monks carved thirty one temples into the basaltic rocks of the Deccan Traps near Ajanta, India. They were constructed between the C2nd and C10th A.D. with the majority constructed in the late C5th and C6th A.D. [Behl, 1989]. The inner walls were rendered with mud and plastered with lime wash before being painted. It is an area with a monsoon climate, averaging 800 mm yr^{-1} of rainfall. This has led to severe damage to the exterior of the temples but, apart from some spallation and vandalism, the paintings remain intact. There is no evidence of water damage to the paintings [Stuckless, 2000]. Dimensionally, the Ajanta temples are larger than the proposed tunnels at Yucca Mountain. Similar paintings are also present on the walls of the underground Budhist temples at Ellora, India, dating from the C5th to C10th A.D. At Goreme, Cappadocia, Turkey, churches with painted walls were excavated in a partly welded rhyolite ash-flow tuff during the C9th to C13th A.D. [Toprak et al., 1994]. As in the case of the Buddhist temples there is evidence of spallation and vandalism but there is no evidence of water damage to the paintings [Stuckless, 2000].

Human artefacts: To minimise grave robbing, the Egyptians began excavating underground tombs in bedded limestone on the west bank of the Nile during the Eighteenth Dynasty (about 1,500 B.C.), of which the tomb belonging to Tutankhamen is the most famous. Dating from ~1,331 B.C., it preserved a range of water-sensitive materials, including reed baskets, linen gloves and an ebony and ivory chair, for 3,300 years [Stuckless, 2000]. In China, sixteen Ming Dynasty (1,368 – 1,644 A.D.) emperors were buried in underground tombs near Beijing. The oldest tomb included thirty two sandalwood pillars, 1.17 m in diameter, which remain intact [Golany, 1989].

Drip suppression in man-made structures
Simmons [2002] quotes the example of Building 810 at the Denver Federal Center, Colorado. The roof of this building comprises a number of parallel, convex-up, half cylindrical sections. Their diameter is similar to the tunnels at Yucca Mountain. There is evidence from evaporation-salts that water has infiltrated through cracks in the concrete roof. However, on reaching the inside surface the water has flowed along the underside of the curved roof rather than forming drips. Only on reaching the vertical components of the structures have drips formed. It should be noted however that this structure, while of similar dimensions to the proposed tunnels at Yucca Mountain, is much smoother than is to be expected in a rock tunnel. This may account in part for the absence of drip formation.

These analogues demonstrate that under wetter climatic regimes than expected at Yucca Mountain, inflow into man-made voids is generally limited. This has been attributed to a capillary barrier effect in the cavern wall.

Relevance: This set of analogues is relevant to underground facilities constructed within the unsaturated zone. It is therefore of direct relevance to the Yucca Mountain repository concept and to shallow storage concepts such as those being considered in France.

Position(s) in the matrix tables: Near field, groundwater flow.

Limitations: Percolation rates and inflow rates in the unsaturated zone depend on many factors ranging from present and future climate, infiltration rate, host rock properties especially percolation flux, and the shape and size of the caverns. In practice this means that while these analogues are useful, others in conditions more closely matching the conditions at a specific site will be of maximum relevance. Intersection of perched water cannot be excluded during construction.

Quantitative information*:* Water inflow into caverns in the unsaturated zone may be only a small percentage of the local groundwater infiltration rate, but localised inflow cannot be precluded.

Uncertainties: There must be considerable uncertainty over the groundwater inflow at a specific location since inflow is in part controlled by local heterogeneity in unsaturated rock flow properties.

Time-scale*:* These analogues cover the human (0 – 100 years), historical (100 – 1000 years) and archaeological (1000 – 10 000 years) time-scales.

PA/safety case applications*:* Utilised in the TSPA developed for Yucca Mountain.

Communication applications*:* Not known but used by the U.S. DOE.

References:

Behl, B.K. 1998. The Ajanta Caves. Harry N. Abrams Inc., New York, 256p.

Golany, G.S. 1989. Urban Underground Space Design in China, Vernacular and Modern Practice. University of Delaware Press, Newark, New Jersey, 160p.

Philip J.R. 1990. Some general results on the seepage exclusion problem. Water Resources Research, 26(3), 369-77.

Philip J.R., Knight J.H., Waechter R.T. 1989. The seepage problems for parabolic and paraboloidal cavities. Water Resources Research, 25(4), 605-18.

Simmons, A.M. 2002. Natural analogue synthesis report, USDOE, Yucca Mountain Site Characterisation Office, Las Vegas, Report TDR-NBS-GS-000027 REVOO ICN 02.

Stuckless J.S. 2000. Archaeological analogues for assessing the long-term performance of a mined geologic repository for high-level-radioactive waste. U.S. Geological Survey Open File Report 00-181.

Toprak, V., Keller, J., Schumacher, R. 1994. Volcano – tectonic features of the Cappadocian volcanic province: Ankara, Turkey. 1994 International Volcanology Congress of the International Association of Volcanology and Chemistry of the Earth's Interior, 58p.

Wang J.S.Y., Trautz R.C., Cook P.J., Finsterle S., James A.L., Birkholzer J. 1999. Field tests and model analyses of seepage into drift. J. Contaminant Hydrology, 38, 323-47.

Williams R.E., Vincent S.D., Bloomsberg G. 1990. Hydrogeologic impacts of mine design in unsaturated rock. Mining Engineering October 1990, 1177-1183.

Added value comments: These analogues have already been used by the U.S. DOE in the development of their conceptual model for seepage at Yucca Mountain.

Potential follow-up work*:* Data acquisition at these types of analogue sites could be used to provide quantitative data.

Keywords*:* Yucca Mountain, Seepage, Unsaturated zone, Frescos, Caverns.

Reviewers and dates*:* J.L Knight (October, 2003)