Siting nuclear power plants underground: Old idea, new circumstances

BY WES MYERS
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"Plainly, mankind cannot renounce nuclear power, so we must find technical means to guarantee its absolute safety and exclude the possibility of another Chernobyl. The solution I favor would be to build reactors underground, deep enough so that even a worst-case accident would not discharge radioactive substances into the atmosphere."

Andrei Sakharov, Memoirs, *p. 612*

THE IDEA OF siting nuclear power plants underground needs to be revisited. Underground siting provides a means to collocate several reactors, along with spent fuel storage and repository facilities, and create underground nuclear parks. Such underground nuclear parks could produce baseload quantities of electricity and hydrogen that could be supplied to the nation through a transcontinental grid.

Increased margins of safety, security, and proliferation-resistance, as well as improved waste management approaches, could be realized through underground siting. Moreover, underground nuclear parks might be economically competitive with those sited on the surface if built at a suitable geographic location and deep inside a suitable rock unit, such as a massive salt deposit. Greater environmental equity could result because the community that would benefit economically from the park's generation of electricity would be the same community that would accept the nuclear waste generated by the park's reactors.

A transcontinental grid

The Continental SuperGrid (Starr 2001 and Grant 2002) and Grid 2030 (U.S. Department of Energy 2003) are visionary concepts for the creation of a nationwide, high-capacity, low-loss transmission grid for electricity and hydrogen. The Continental SuperGrid concept includes an underground pipeline/cable consisting of high-temperature superconducting material surrounding and cooled by a central tube that transports liquid hydrogen. The SuperGrid would interconnect existing regional transmission systems and provide the means for efficient shipment of electricity and hydrogen, or electricity to produce hydrogen, across the United States.

The purpose of this article is to introduce the concept of underground nuclear parks as points of electricity and hydrogen supply to a nationwide electricity- and hydrogen-transmission system such as the Continental SuperGrid. If such a system materialized, there would be the potential to separate electricity- and hydrogen-generating sources from their loads by far greater distances than are possible today and to load-level—east-to-west and north-to-south—across the nation in response to diurnal and seasonal changes in demand.

If this were possible, nuclear power plants would no longer need to be located as close to their load centers as they are today in order to be economically viable, and they could then be sited at remote locations. Moreover, at such remote locations, nuclear power plants could be clustered into nuclear parks, with the potential for increased economies of scale. If the reactors were underground, there would be the prospect for higher margins of security, safety, and proliferation-resistance and for an improved strategy for managing the spent fuel.

Related advantages would include higher confidence in containment and higher levels of seismic stability. Landscape aesthetics would be enhanced by eliminating the need to disrupt the land surface for reactor construction and by moving structures underground that would otherwise be at the surface.

Past studies and experience

Underground siting of nuclear reactors is not a new idea. In 1958, Russia installed the first of three underground nuclear reactors for plutonium production in Siberia near

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Krasnoyarsk, at the K-26 facility, now known as Zheleznogorsk (Global Security 2003). One reactor continues to operate, producing electricity and district heat. Underground reactor experience in the United States and Europe through the 1970s is summarized in Bach (1977), and Andrei Sakharov (1990) and Edward Teller (1994) proposed underground siting as a means of reducing the risks from reactor accidents that might otherwise discharge radioactive material into the atmosphere.

Studies in the 1970s in the United States, Canada, Japan, and other countries examined concepts for underground siting of nuclear power plants (Bender 1982). Those studies covered technical feasibility, cost, safety, and security. Underground siting concepts addressed in those studies were based on existing designs of 1000-MWe-scale light-water reactors, or in the case of Canada, the 850-MWe CANDU reactor. The reactor, and in some cases the turbine generators and other power plant components, were positioned inside caverns mined in bedrock.

Benefits of underground siting recognized in those studies included stronger containment against the release of gases in case of an accident, reduction of public health impacts from postulated core-melt accidents, reduced seismic motion, and increased protection against external hazards and extreme hypothetical accidents. The studies confirmed that underground siting was technically feasible, and no engineering factors were identified that would preclude it. The studies also concluded, however, that added costs and increased construction schedules would be associated with creating the necessary caverns, tunnels, shafts, and boreholes.

Siting in salt deposits

Massive salt deposits at shallow depths could be especially advantageous for underground siting. Bedded and domal salt deposits are common in many of the world's large sedimentary basins (Zharkov 1984). Thick, massive deposits of salt generally have low permeability, lack of fracturing, and low moisture content. Such deposits can be hundreds of meters thick and, in the case of bedded salt, laterally extensive, covering thousands of square kilometers. Depending on local geological structure and stratigraphy, salt deposits can occur at comparatively shallow, minable depths of less than 200 meters to as much as 1000 meters. Centuries of salt mining experience and decades of experience in solution mining of salt deposits have demonstrated that stable caverns can be constructed with spans that are routinely many tens of meters wide (Thoms and Gehle 2000).

Other rock types in addition to salt might ultimately be demonstrated to be equally suitable. The bedrock types considered in the 1970s studies previously cited included granitic rocks, sedimentary rocks, and alluvium. Salt evidently was not considered. In a Russian study, however, salt was listed as a suitable rock type (Dolgov 1994). Dolgov also mentioned in-place decommissioning of reactors as a possible benefit from underground siting.

A large body of scientific and engineering knowledge has been acquired on salt deposit properties during the last 50 years. It includes results from large-scale *in situ* heater tests, thermomechanical modeling, geohydrological evaluations, and ventilation and heat removal analyses. This knowledge could be used as the starting point to investigate scientific, engineering, and safety issues related to the design, construction, and operation of an underground nuclear park in massive salt deposits. Much of this existing knowledge comes from the research, planning, design, and operations experience for the salt repository at the U.S. Waste Isolation Pilot Plant (WIPP) (U.S. Department of Energy 2000) and from studies related to the salt repositories in Germany (Bollingerfehr et al. 2004 is a recent example). In addition, there are past studies in the United States that evaluated the suitability of salt as the candidate host rock for a geologic repository for spent nuclear fuel (Starr 1986).

An underground nuclear park

A hypothetical concept for an underground nuclear park in salt is shown in Fig. 1. The reactors, spent fuel storage facility, and repository are shown as being located approximately 200 m below the surface in a relatively shallow, massive salt deposit. The underground nuclear reactor area shows sites for 18 reactors (a nominal number). The layout is such that each reactor can be isolated individually from all other reactors. The reactors are assumed to be high-temperature (>900 °C) and suitable for electricity or hydrogen production or both. Nonwater-cooled reactor designs would eliminate the need to introduce large quantities of water into the underground chambers housing the reactors, which would help reduce the risk of corrosion in a salt-rich environment.

The concept includes underground air-cooling of the spent fuel. After removal from the reactors, the spent fuel would be transported from the reactors through the spent fuel tunnel to the spent fuel storage facility, where it would be air-cooled using ventilation shafts (not shown). After sufficient cooling, the spent fuel would be transferred to the repository for direct permanent disposal. Alternatively, the spent fuel could be treated and recycled, should current U.S. policy for direct disposal change at some future date, and the resulting waste disposed of in the repository in the underground nuclear park.

The electricity- and hydrogen-generating facilities, and the heat-rejection facilities, are shown as being located at the surface—although underground siting is a possible alternative. The produced electricity and hydrogen would be delivered to the transcontinental electricity-hydrogen grid.

Two equipment shafts and two equipment ramps are shown in Fig. 1. Both would be sized to be capable of transporting modular reactor components and other large equipment to the main tunnel. The ramps would allow wheeled-vehicle access. Bulkhead/airlock seals in the main tunnel, transport tunnels, access tunnels, and reactor-chamber drifts could serve to isolate each reactor. Access ramps and shafts for material, equipment, and personnel could be sealed to isolate sectors of the underground nuclear park from each other—or the entire underground nuclear park from the surface. Figure 1 does not show the tunnels and shafts for ventilation, personnel, or emergency egress/access, nor does it show offices, control rooms, warehouses, staging areas, and related facilities.

A hypothetical schematic for an individual underground reactor chamber is shown in Fig. 2 (see p. 36). This layout shows a nonwater working fluid (e.g., helium) circulating in a primary circuit between the reactor and a heat exchanger where heat is transferred to a secondary circuit. The secondary circuit, in turn, uses a nonwater working fluid and flow lines in a borehole to transfer the heat to the electricity- and hydrogen-production facilities at the surface. The purpose for siting the primary-circuit heat exchanger underground is to restrict the primary circuit entirely to the underground, thereby confining to the underground the working fluid that circulates through the reactor core. This is a defensive barrier to help ensure that if any radioactive material accidentally leaked from the reactor core it could not reach the surface.

The reactor and a heat exchanger in Fig. 2 are in a single chamber with nominal dimensions of 50 m by 65 m. These dimensions were selected because they approximate the dimensions of a chamber designed for a large underground physics experiment planned at one time for WIPP. Chambers of this size should be sufficient for various designs of passive or active ventilation systems needed to remove operational heat produced by the reactors. Figure 2 shows a passive ventilation system that uses dedicated shafts and tunnels. The reactor has nominal dimensions of 9 m diameter by 35 m long. These dimensions were selected because they approximate the diameters and lengths of the reactor vessels for the advanced high-temperature reactor (AHTR) (Forsberg 2004), the gas turbine-modular helium reactor (GT-MHR) (LaBar, Shenoy, Simon, and Campbell 2003), and the pebble bed modular reactor (PBMR) (Nicholls

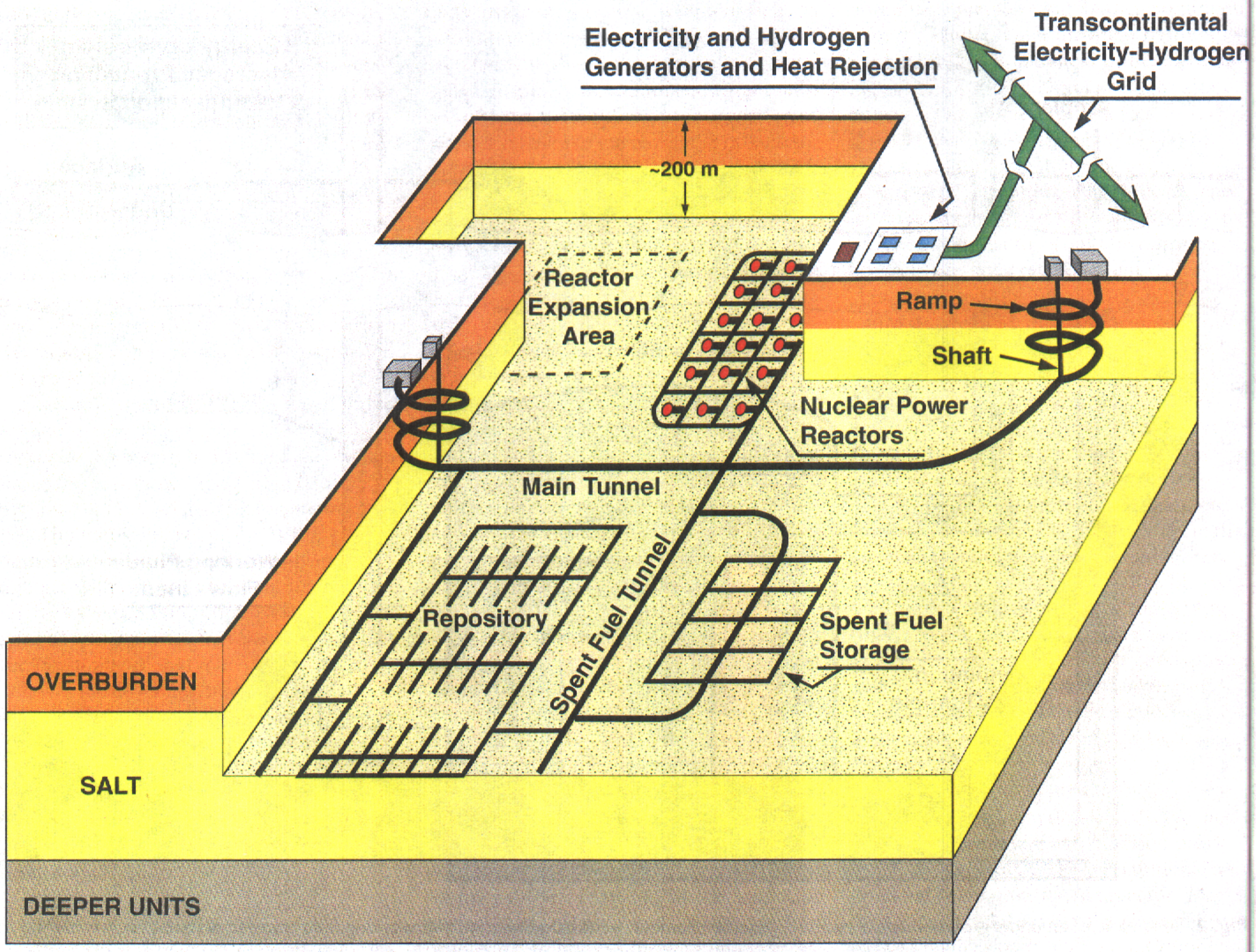

Fig. 1. Concept of an underground nuclear park in a shallow, massive salt deposit (Source: LANL)

2001). The AHTR, GT-MHR, and PBMR are examples of the types of advanced-reactor designs that might possibly be suitable for underground siting.

Spent fuel storage and repository

It is assumed that the high-temperature reactors in the underground nuclear park would use a fuel similar to the coated-fuel-particle, graphite-matrix fuel of the type proposed for the AHTR, GT-MHR, or PBMR. This type of fuel, as pointed out by Alberstein (1997) in his study of a GT-MHR for plutonium destruction, generates a higher volume of spent fuel per unit of power generated relative to light-water reactor spent fuel, but with lower decay-heat generation per unit volume of spent fuel. Storage or disposal casks containing this type of spent fuel could be emplaced in drifts at loading densities adjusted to prevent adverse thermomechanical effects in the nearby salt rock mass, allowing the spent fuel to be stored or disposed of with confidence of retrievability for decades. Because of their lateral extent and other qualities, most massive deposits of bedded salt are an enormous resource of potential repository capacity. In such settings, repository capacity should not constrain the number of reactors that could be sited in an underground nuclear park of the type proposed here.

An added point relative to a repository in salt is the long-standing recognition, demonstrated by numerous tests and experiments, that thick salt beds are relatively impermeable to water. Thus, a geologic repository inside a thick massive salt deposit would provide an effective natural barrier to isolate radioactive releases from the repository and prevent them from reaching any nearby aquifers.

Licensing, engineering, safety

An adequate regulatory framework for underground siting of nuclear reactors does not exist. Regulations for underground siting would need to be developed by the U.S. Nuclear Regulatory Commission, perhaps based on new research and development. License applications would have to demonstrate the long-term stability of the chamber hosting the reactor, the integrity of the proposed reactor design as it would operate in its site-specific underground setting, and containment under various failure modes. Consequently, the time from license application to commissioning would almost certainly be significantly longer for the first underground reactor relative to that for a comparable reactor at a surface site.

For subsequent reactors in an underground nuclear park, however, the licensing time might become progressively shorter for those reactor and chamber designs based on previously licensed reactor and underground facility designs, and at locations where the underground geologic and hydrologic conditions remained unchanged. Nonetheless, the ultimate licensability of underground reactors is an issue that needs more study, as is the licensability of the associated facilities for spent fuel storage and facilities for disposal of low-level and high-level waste, all of which would be part of the underground nuclear park.

The continued stability and integrity of shafts, tunnels, and other underground openings in salt and potash mines around the world is direct evidence of the possibility that large, stable shafts, tunnels, chambers, and other openings needed for an underground nuclear park can be constructed in salt deposits. Nonetheless, experiments and modeling would be necessary to evaluate how the salt rock mass surrounding the reactor chamber would respond over time to heat loading from the operational heat produced by a reactor.

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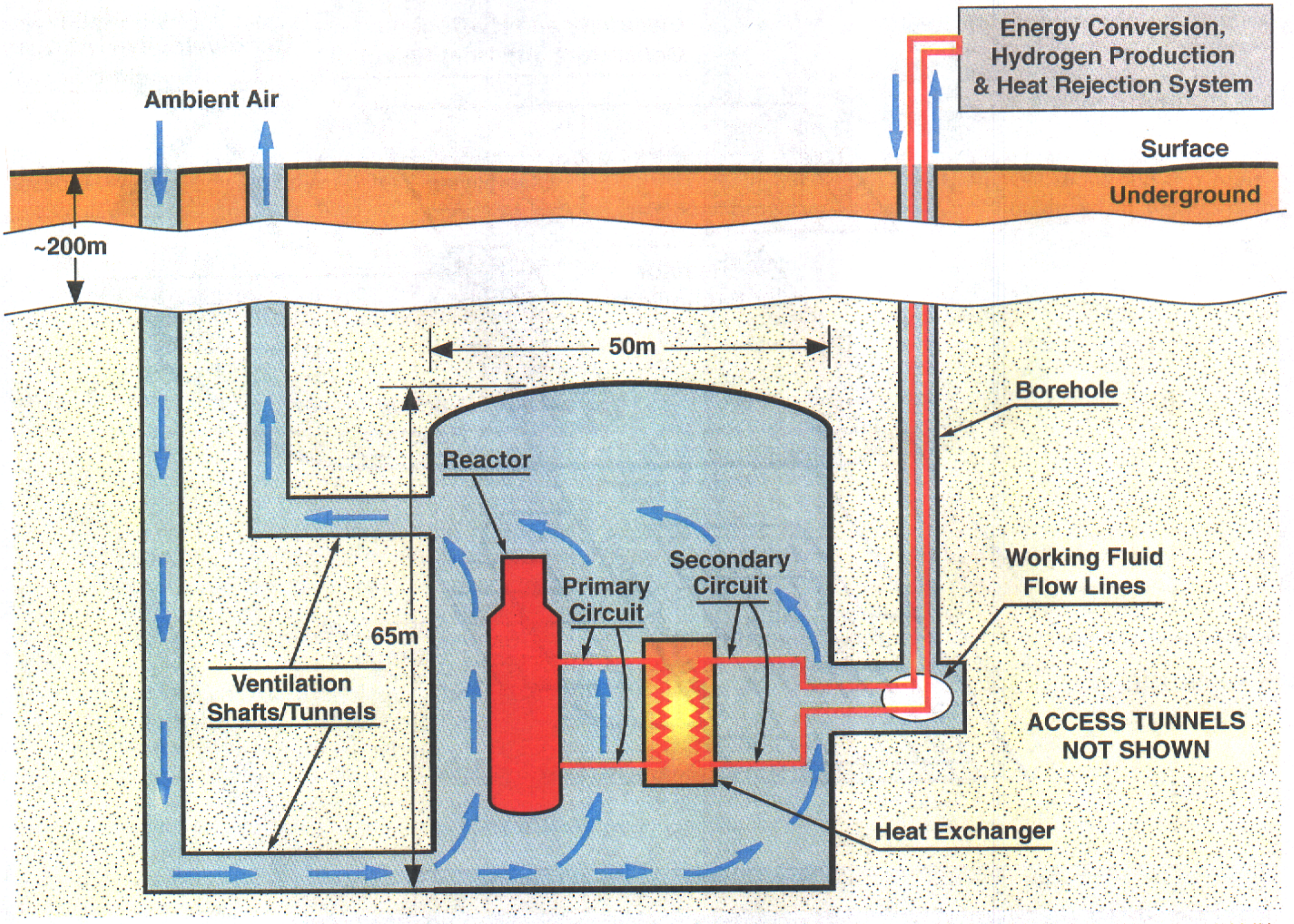

Fig. 2. Schematic of an underground nuclear reactor, reactor chamber, ventilation system, and working fluid transfer system (Source: LANL)

This heat loading, depending on the ambient pressure and temperature at the depth of the reactor chamber, might cause the salt to deform plastically and undergo slow viscous flow (creep) that could disrupt the reactor system and other components in and near the reactor chamber. Preventing unacceptable creep, specifically in the rock mass in the near-field of the reactor chamber, and more generally in the tunnels, shafts, and other underground spaces, is an important engineering and safety issue. Unacceptable creep deformation is considered preventable through the use of proper chamber and reactor-foundation design, adequate ground support (rock bolts, steel sets, or complete steel or concrete linings for the chamber), and multiple and redundant ventilation systems or other active or passive means of heat removal.

The practicality of underground transport and installation of the reactor components is also an issue, but one that is viewed as tractable. Large underground hydroelectric plants are installed and operating at numerous locations around the world. The turbines and other equipment installed in these underground hydroelectric plants are direct evidence that reactor components comparable in size could be similarly transported and installed underground. It is significant that Kammer and Watson (1975), in their conceptual design for light-water reactor underground nuclear power plants, concluded that a BWR reactor pressure vessel 22 ft in diameter and 68 ft in length could be transported by trailer inside a 38- to 40-ft-diameter tunnel and installed upright in a 65-ft-diameter reactor chamber.

Multiple access/egress paths, ventilation control, and redundant ventilation circuits would be essential safety and operational requirements for an underground nuclear park. These requirements would apply during the excavation, construction, and operational phases for the reactors, spent fuel storage facility, and repository. Engineering and safety analyses are needed to define ventilation, moisture, and water control requirements. A safety analysis is needed to evaluate accident scenarios, such as loss-of-coolant or depressurization accidents, and the extent to which layouts can be designed so that the access/egress ramps and shafts that are part of one chamber can provide backup and emergency ventilation, feedwater, and access/egress for another chamber. In addition, normal risks associated with mining and underground operations, such as fire and hazardous gases, should be analyzed for their effect on an underground nuclear system. Other issues that would require analysis include the space requirements inside the reactor chamber for fuel loading and unloading, and adequate space for workers between the reactor vessel and the chamber surfaces.

WIPP operations and nearby potash mining operations have shown that salt is never an abrasive. In addition, salt can be a highly effective desiccant and can act to remove limited amounts of water that might enter underground workings. Potash mining and WIPP underground operations have also revealed that although salt dust can penetrate electronic circuits and seep into machinery, it does not cause corrosion because of the low moisture content in the underground environment. Nonetheless, it is important to recognize that corrosion could occur in an environment rich in salt and salt dust unless water ingress is adequately prevented and unless moisture concentrations are controlled to sufficiently low levels. Also, brine under the influence of a thermal gradient in the salt rock mass could migrate toward the heat source.

Consequently, an evaluation of salt and salt dust effects under varying moisture levels and expected operating and upset conditions, as well as an evaluation of brine-migration effects, would be necessary. Careful planning and engineering measures should be adequate to resolve these issues. For example, the surfaces of the chambers and tunnels could be cleaned and covered with paint, sealant, or other material to control salt dust, and tunnel inverts could be covered with concrete, both to control salt dust and to create a floor. Measures such as these should effectively control resuspension of existing dust and creation of new dust. The introduction of external dust into chambers and tunnels can be prevented through the use of seals, filters, air locks, and ventilation—in addition to administrative controls on personnel, equipment, and vehicles.

Questions could also arise related to the long-term integrity of concrete in proximity to salt or in a salt-rich environment. Again, the WIPP experience and potash mining experience in the Carlsbad region are insightful. The requirements of the WIPP project demanded that concrete remain in direct contact with salt and maintain its integrity through the design lifetime. Many investigations and evaluations were conducted at the beginning of the WIPP project. The result was the development of different mixes and additives that have been successful in the WIPP facilities. Combining the WIPP experience and successful use of concrete in the potash mining operations demonstrates that concrete can last for more than 50 years in a salt environment with no deterioration.

Economic viability

Siting several reactors underground in a massive salt deposit to form an underground nuclear park and managing the spent nuclear fuel using a collocated spent fuel storage facility and repository could potentially be accomplished at a lower total life-cycle cost relative to siting the same number and type of reactors at the earth's surface and following conventional waste management practices. This claim is based on the following eight arguments:

1. The avoided decommissioning costs could be substantial. A strategy for in-place decommissioning of an underground nuclear reactor in salt would be to remove the spent fuel from the final loading and change the license from that for an operating reactor to that for a low-level waste (LLW) disposal site. Thereafter, the chamber void space could be filled with crushed salt, or a mixture of crushed salt and other material, and the reactor and LLW produced during the reactor's lifetime sealed in place. Doing this would have the effect of disposing of the LLW deep underground, encased in salt, where there would almost certainly be higher confidence of safety, security, and isolation than at a conventional surface-sited LLW disposal facility. In addition, the transportation risks associated with transporting LLW from a surface reactor undergoing decommissioning to an LLW disposal site would be avoided, as would much of the worker safety risk associated with the decommissioning operations. In-place decommissioning could probably be accomplished for a fraction of the cost relative to the current approach for an equivalent surface-sited reactor. It would follow that an argument could be made that trust fund payments for in-place decommissioning of underground reactors should probably also be a fraction of the trust fund payments for decommissioning surface-sited nuclear reactors.

2. Collocating the spent fuel storage facility and repository that serve the reactors has the potential to reduce the spent fuel transportation costs and public concern associated with transportation. The transportation cost reduction could be substantial relative to that for reactors separated by a great distance from their spent fuel storage facility or repository. The net result could be a significant reduction in cost, schedule, and public concerns.

3. Underground excavation costs in salt can be confidently predicted to be lower than for most other rock types. This might be contrary to the common perception and experience of many who have worked in or toured underground workings in other rock types or hydrologic settings and who are unfamiliar with salt's geohydrologic and geotechnical properties. Decades of experience have shown that shafts, tunnels, and rooms can be excavated in salt and supported with relative ease; water inflow problems are largely absent in properly designed facilities; and the physical and chemical properties of the salt beds are comparatively uniform and predictable.

Past planning for underground physics experiments proposed for the WIPP site resulted in cost estimates of approximately $20/m^3 for underground excavations similar in volume and geometry to excavations that would probably be needed for nuclear reactor chambers. This cost covers ventilation, power, and ground support adequate to meet federal requirements for safety and environmental quality for the underground physics experiments. In contrast, excavation costs ranged from a minimum of $40/m^3 to $60–$80/m^3 in granitic rocks for caverns of equivalent volume and geometry to the WIPP cavern. Thus, the unit cost of excavation in salt deposits can be expected to be two to four times lower than excavation in granite.

It is important to note that the actual cost estimate for a reactor chamber in salt deposits would have to include the cost of added ground support that might be needed to control thermal loading from the decay heat produced by the reactors. The result could be a cost of somewhat more than $20/m^3.

4. Conventional containment structures should be unnecessary. Multiple seals in boreholes, tunnels, and shafts, combined with the containment afforded by the low permeability and thickness of the enveloping salt mass itself, should provide suitable containment. Therefore, much of the capital cost for constructing a containment structure could potentially be avoided.

5. Although the engineering, procurement, and construction costs of the first-of-a-kind underground reactor would be higher than for a surface-sited reactor of equivalent design, the cost of the *n*th reactor (where *n* is approximately 12 or more) would probably be significantly lower. For the *n*th reactor, the risk factors would be better known and the cost of the access ramps and shafts and other common infrastructure could be shared by distributing their costs across multiple reactors. In this context, it is important to understand that thick, massive salt beds in undeformed basins typically have enormous lateral extent and have relatively homogeneous and predictable rock qualities. Features such as topography, roads, rivers, homes, and towns are obviously nonexistent inside such salt deposits and would not be barriers to the unimpeded, lateral expansion of an underground nuclear park that could include 12 or more reactors.

After regulatory approval for specific reactor, cavern, and layout designs, the engineering/procurement/construction process should proceed routinely, with minimal and predictable costs for the *n*th reactor. Therefore, the potential exists to create an underground nuclear park with a total life-cycle cost much lower than if the same number and types of reactors were installed as single reactors, or in groups of two to three, at dispersed sites across the United States.

6. Use of reactor designs with modular components could reduce costs. Modular components could be fabricated at a distant factory and transported to the underground nuclear park. Shafts with heavy lift–capacity hoists and large-diameter ramps could be used to transport the modular components underground, where they could be moved laterally through tunnels to the reactor chambers for final assembly.

7. An argument can be made that some of the requirements for physical protection need not be as rigorous for an underground reactor as for a surface reactor. An underground site affords greater inherent security because of the enveloping rock mass and because access can be rigorously controlled at the ramps, shafts, and tunnels. Consequently, the same number of external security guards per reactor might not be needed to achieve the same level of physical protection for the reactors in an underground nuclear park relative to the number of guards needed for the same number of reactors conventionally sited at the surface. Also, collocating numerous reactors and their spent fuel storage facilities and repos-

itory in an underground nuclear park would probably permit economies of scale that could lower the overall cost of physical protection and safeguards.

8. Underground siting with properly designed seals, bulkheads, and ventilation systems for the ramps, shafts, tunnels, and boreholes offers the potential to reduce the probability of release of radioactive material to the environment that might arise from an accident or terrorist attack, relative to the probability for a surface-sited reactor. It follows that the liability insurance premiums for nuclear reactors in an underground nuclear park might be reduced relative to those for equivalent surface-sited nuclear reactors.

Public acceptance

Although public and policy-maker support for nuclear energy has grown (Bisconti 2004), public concern with nuclear waste disposal persists. Thus, the question arises about whether having an underground nuclear park that would include both nuclear reactors and waste disposal facilities would be acceptable to the local public.

The experience of the community of Carlsbad, N.M., with the WIPP Project demonstrates that strong local public support for a nuclear waste disposal facility is indeed possible and sustainable. The development and maturation of the relationship between the community of Carlsbad and the U.S. Department of Energy over siting, development, regulatory permitting, and compliance-based operations of the WIPP is a success story lasting 30 years.

The two most important elements are the strong and visible desire of the community to improve the economic welfare and quality of life for its citizens, coupled with a steadfast requirement for, and universal commitment to, safety and environmental protection in all phases of development and operation of the facility. Transparency is required and is formalized through groups like the Mayor's WIPP Task Force, which is made up of civic leaders and concerned citizens. Proactive partnering between the Carlsbad community and WIPP has been comprehensive and successful, and is the most important factor in WIPP's having acquired and maintained strong local support for an operation that in other locales has fostered broad-scale attitudes of "not in my backyard." The Carlsbad/WIPP experience could serve as the model for developing community support that would be necessary for developing an underground nuclear park.

Public and local community opposition to siting a nuclear waste repository has been based on an equity argument: If a community did not significantly benefit from the production of electricity from a nuclear power plant, why should it accept the waste from that nuclear power plant? This argument might be mitigated if the same community that realized the economic and other benefits from a nuclear power plant also accepted the nuclear waste from that plant, but not from others. Collocation of the reactors, spent fuel storage facility, and repository according to the concept proposed could achieve that equity.

Energy storage and desalination

Energy storage and desalination opportunities could result from siting underground nuclear parks in sedimentary basin settings where in addition to salt deposits, there are large brackish or saline aquifers and oil and gas fields. Energy storage might be possible using compressed-air energy-storage caverns constructed in the salt deposits. The stored energy could be used to supply peaking electricity. Cogenerated heat could perhaps be used to desalinate water drawn from brackish or saline aquifers and to treat associated water produced by operations at nearby oil and gas fields.

Looking to the future

Although a high-capacity transcontinental grid, such as the Continental SuperGrid, is perhaps decades in the future—and the construction of many of the new nuclear reactors that might supply electricity and hydrogen to such a grid is also perhaps decades in the future—it is important to begin considering options for siting those reactors. The option proposed here is to site the reactors and their collocated spent fuel storage facilities and repositories in underground nuclear parks, specifically in underground nuclear parks created using chambers, tunnels, and drifts mined in massive salt deposits located in remote regions near access points to the transcontinental grid.

Public confidence in nuclear power is closely tied to concerns about safety, waste management, proliferation, and security against terrorist attack. Investor confidence in nuclear power is closely tied to economics. Underground siting of nuclear reactors with collocated spent fuel storage facilities and repositories could be a means of creating underground nuclear parks with higher margins of security, safety, proliferation-resistance, and public confidence. For underground nuclear parks in massive salt deposits, there is also the potential to reduce total system life-cycle costs, thereby increasing investor confidence in nuclear power. Carefully sited underground nuclear parks, therefore, might offer a superior option for some of the new nuclear power plants being contemplated in the United States and other nations.

References

Alberstein, D. 1997. "Weapons Grade Plutonium Destruction in the Gas Turbine Modular Helium Reactor (GT-MHR)." *Advanced Nuclear Systems Consuming Excess Plutonium,* E. R. Merz and C. E. Walter, eds. (Kluwer Academic Publishers, Netherlands), pp. 135–146.

Bach, P. J. 1977. "A Summary of Studies on Underground Nuclear Power Plant Siting," *Underground Space* 2, p. 4751.

Bender, F. 1982. *Proceedings of a Symposium on Underground Siting of Nuclear Power Plants,* Hanover, Federal Republic of Germany (E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart).

Bisconti, A. S. 2004. "Energy Concerns Drive Record Public Favorability for Nuclear Energy." Perspective on Public Opinion, Prepared for the Nuclear Energy Institute. Available at <www.nei.org/documents/PublicOpinion_04-06.pdf>.

Bollingerfehr, W., W. Bechthold, and T. Rothfuchs. 2004. "The BAMBUS Project in the Asse Mine (Germany), Full Scale Testing of the Direct Disposal of Spent Fuel Elements in Salt Formations." Waste Management 2004 Conference, Tucson, Ariz., February 29–March 4, 2004, Paper WM-4460.

Dolgov, V. N. 1994. "Inherently Safe Power-Generating Unit for an Underground Nuclear Power Plant." *Atomic Energy* vol. 76, pp. 136–138.

Forsberg, C. W. 2004, "A Large Low-Pressure Advanced High-Temperature Reactor (AHTR)." 14th Pacific Basin Nuclear Conference: New Technologies for a New Era, Honolulu, Hawaii, March 21–25, 2004.

Global Security. 2003. "Krasnoyarsk-26/Zheleznogorsk Mining and Chemical Combine [MCA], N 56° 22' E 93° 41'." Available at <www.globalsecurity.org/wmd/world/russia/krasnoyarsk-26_nuc.htm>.

Grant, P. M. 2002. "Energy for the City of the Future." *The Industrial Physicist* vol. 8 (February/March), pp. 22–25. Available at <www.aip.org/tip/0202.html>.

Kammer, W. A., and M. B. Watson. 1975. "Underground Nuclear Plants with Surface Turbine Generators," *Nuclear Engineering and Design* vol. 33 (October), pp. 308–335.

LaBar, M. P., A. S. Shenoy, W. A. Simon, and E. M. Campbell. 2003. "The Gas Turbine-Modular Helium Reactor," *Nuclear News* vol. 46, pp. 28–37.

Nicholls, D. 2001. "The Pebble Bed Modular Reactor," *Nuclear News* vol. 44 (September), pp. 35–40.

Sakharov, A. 1990. *Memoirs* (Alfred A. Knopf, Inc.).

Starr, C. 2001. "National Energy Planning for the Century," American Nuclear Society Winter Meeting, Reno, Nev., November 13, 2001.

Starr, S. 1986. "Bibliography of Studies for the Salt Repository Project Office of the Civilian Radioactive Waste Management Program, April 1978–May 1986." National Technical Information Service, U.S. Department of Commerce, DOE/CH/10140-05(86), Springfield, Va.

Teller, E. 1994. "Underground Nuclear Reactors," NATO Workshop on Disarmament Technologies, Erice, Sicily, Italy, August 19–23, 1994.

Thoms, R. L., and R. M. Gehle. 2000. "A Brief History of Salt Cavern Use," Solution Mining Institute's Salt 2000 Meeting, Keynote Presentation. Available at <www.solutionmining.org>.

U.S. Department of Energy, Office of Electric Transmission and Distribution. 2003. "Grid 2030, A National Vision for Electricity's Second 100 Years," Results from the National Electric System Vision Meeting, Washington, D.C., April 2003.

U.S. Department of Energy, Carlsbad Field Office. 2000. *Pioneering Nuclear Waste Disposal,* DOE/CAO-00-3124.

Zharkov, M. A. 1984. *Paleozoic Salt Bearing Formations of the World* (Springer-Verlag, New York).

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