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Underground Collocation of Nuclear Power Reactors and Repository to Facilitate the Post-Rennaissance Expansion of Nuclear Power

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ABSTRACT

Underground collocation of nuclear power reactors and the nuclear waste management facilities supporting those reactors, termed an underground nuclear park (UNP), appears to have several advantages compared to the conventional approach to sitng reactors and waste management facilities. These advantages include the potential to lower reactor capital and operating cost, lower nuclear waste management cost, and increase margins of physical security and safety. Environmental impacts related to worker health, facility accidents, waste transportation, and sabotage and terrorism appear to be lower for UNPs compared to the current approach. In-place decommissioning of UNP reactors appears to have cost, safety, environmental and waste disposal advantages. The UNP approach has the potential to lead to greater public acceptance for the deployment of new power reactors. Use of the UNP during the post-nuclear renaissance time frame has the potential to enable a greater expansion of U.S. nuclear power generation than might otherwise result. Technical and economic aspects of the UNP concept need more study to determine the viability of the concept.

INTRODUCTION

Five historical issues— high capital cost, nuclear waste management, physical security, safety in the event of extreme accidents, and proliferation of nuclear material — have individually and collectively impeded the expansion of nuclear power, to varying degrees, in most countries. Today they continue to constrain the expansion of nuclear power beyond what would otherwise be case if these issues were resolved, in spite of nuclear power's new and more favorable status

Work to date by the authors and colleagues has produced a concept for deep-underground, collocated deployment of nuclear power reactors and the nuclear waste management facilities supporting those reactors. This concept is termed the underground nuclear park (UNP). Deployment of nuclear power reactors and waste management facilities according to the UNP concept has the potential to mitigate the five issues listed above. At UNP sites these issues could be reduced to the point of insignificance.

Currently, nuclear power reactors and waste management facilities are deployed in the U.S. as follows: reactors are sited at the earth's surface in groups of 1 to 3 at dispersed locations selected by utilities. At-reactor dry cask storage is used, as is away-from-reactor low-level waste disposal. Independent spent fuel storage facilities are viewed as eventually becoming available, as is the Yucca Mountain repository for high level waste disposal. In this paper this approach is termed "conventional siting".

The purpose of this paper is to describe the UNP concept and compare it to conventional siting , especially as related to nuclear waste management, environmental impact, and public acceptance, and to discuss potential advantages of the UNP approach should a major, accelerating 21st century expansion of nuclear power occur in the U.S.

The following point must be emphasized. Work to date on the UNP concept is limited, conceptual and qualitative. Detailed engineering, system, and economic studies will be necessary before the technical and economic feasibility of the UNP concept can be determined. And even assuming the determination is positive, before the first UNP could be sited, constructed, licensed, and operated, a regulatory framework enabling UNP deployments must be developed; political, public acceptance, and industry acceptance must be favorable; and market conditions must be promising. Consequently, full-scale UNP deployments in the U.S., even under favorable circumstances, probably could not begin until the 2025 – 2030 time-frame. The UNP concept is not, therefore, an alternative to the conventional approach for the 30+ new reactors now planned, and referred to as the "nuclear renaissance," nor as an alternative to the need for the Yucca Mountain repository. Instead, if a growth scenario develops that involves a major, accelerating, 21st century expansion of nuclear power in the US—which is certainly possible given growing recognition of the energy security, environmental, and reliability aspects of nuclear power—then deployment of UNPs should be considered.

UNDERGROUND NUCLEAR PARK (UNP) CONCEPT

Concept Overview

The purpose of a UNP is to produce multi-gigawatt-levels of baseload nuclear electricity. Essential to a UNP, but not part of it, would be long-distance, high-capacity electrical transmission lines connecting the UNP to regional distribution grids and users.

The UNP concept has two fundamental features: 1) Nuclear power reactors sited underground in sufficient numbers and manner to produce major capital and operating cost savings relative to conventional siting and as a secondary benefit to automatically realize increased margins of operational safety and physical security at little or no added cost. 2) Waste management facilities [spent nuclear fuel (SNF) storage, low-level waste (LLW) storage and high-level waste disposal (HLW repository)] supporting the reactors are also sited underground and nearby to the reactors. Tunnels would interconnect the waste management facilities and reactors meaning that transport of UNP-produced nuclear waste can largely avoid the public concern, security risks, and safety risks associated with conventional nuclear waste transport along surface roads and railroads.

UNP studies to date (1, 2, 3, 4, 5) have included consideration of different host rocks (bedded salt, domal salt, and granite), reactor types (high temperature gas reactors and light water reactors), underground layouts (reactors in individual chambers and reactors in individual segments of a tunnel), excavation methods (road header and tunnel boring machine), turbine/generator placements (underground and surface), reactor chamber cooling methods (passive, active, and use of heat exchangers), working fluid transfer methods (direct and multiple circuits using heat exchangers), excavation cost estimates, advantages relative to conventional siting, and issues.

UNP capital and operating cost savings arguments are also presented in past studies. An example is the use of underground space to house reactors, turbine/generators, and other large equipment thereby eliminating much of the capital cost associated with constructing large surface buildings (e.g., containment structure) required by conventional siting. Other examples include in-place decommissioning [described below], reduced cost to meet seismic design requirements (earthquake waves are attenuated at depth in bedrock), reduced physical security cost afforded by the inherent increased protection against aircraft impact, for example, simply by being underground.

In addition to electricity production, energy systems using UNPs could possibly be developed to produce peaking power, desalinated water, hydrogen and process heat. For example, UNP reactor heat energy could be used to produce hydrogen and oxygen. Waste heat could perhaps be used for water desalination and process heat applications. Compressed air or pumped hydro energy storage is also possible and could be used to supply peaking power.

UNPs for an Open Fuel Cycle and Closed Fuel Cycle

The original UNP concept (1) was introduced using the hypothetical example of nuclear power reactors sited 200 meters deep in the central portion of the ~ 500-meter-thick Salado Formation, a bedded salt unit in the North Delaware Basin near Carlsbad, NM. Thereafter, the UNP concept was expanded to its full, open fuel cycle configuration (2, 3). The open fuel cycle UNP consist of a reactor array (~ 10 to 20 reactors with a capacity of ~3 to 18 GW), a SNF storage facility, and a HLW repository (Figure 1) (For simplicity in Figure 1 the LLW storage facility is considered part of the SNF facility.) Subsequently, and in response growing interest in reprocessing, the UNP concept was modified to include the option for a closed fuel cycle configuration (4, 5) with the addition of underground reprocessing facilities, fuel fabrication facilities, and—possibly--fast reactors.

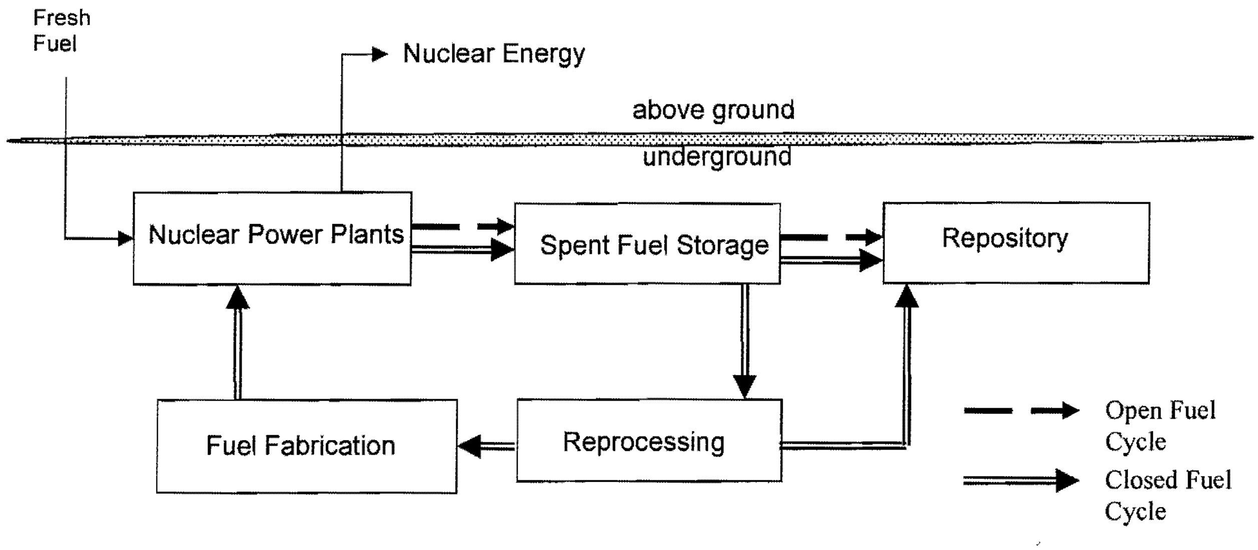

Figure 1. Underground Nuclear Park(UNP), Open Fuel Cycle and Closed Fuel Configuration [After Figure 1 in reference 6]

A modification of the UNP concept is to assume the closed fuel cycle becomes U.S. national policy and includes regional recycling centers described in the Global Nuclear Energy Partnership Draft Programmatic Environmental Impact Statement (GNEP PEIS) (7). The open fuel cycle UNP configuration could be modified to allow removal of SNF from UNP SNF storage facility and shipped to a GNEP-proposed regional recycling center. The LLW and HLW produced by reprocessing the SNF from the UNP reactors could then be returned to the UNP for disposal. Doing this allows the UNP concept to support a closed fuel cycle national policy involving surface-sited regional recycling centers as envisioned in the GNEP PEIS.

Thus, the UNP concept is fuel-cycle neutral, able to accommodate either a continuation of the current open fuel cycle national policy or a future closed fuel cycle national policy. Low level and high level nuclear waste generated through UNP operations could be disposed of in the UNP. The back end of the fuel cycle for the reactors in the UNP could be closed at a single underground location under either an open- or closed- fuel cycle national policy. To a first approximation, fresh fuel would enter the UNP and electrical and/or heat energy would exit the UNP, and nothing else.

It should also be noted that UNPs would provide new non-Yucca-Mountain repository capacity, admittedly in small increments. But it would have the effect of decoupling the waste disposal pathways for the UNP reactors from Yucca Mountain repository or a second repository. Therefore, waste disposal capacity needed for UNP reactors would not compete with waste disposal capacity needed for conventionally sited reactors

Past Experience with Underground Reactor Siting

A basis for confidence in the ultimate viability of the UNP concept is the fact that underground reactor siting and operation has already been demonstrated, and has received serious study and consideration for the deployment of full-size, commercial nuclear power plants. Actual proof that underground siting and operation of nuclear reactors is technically feasible comes from Russia, near Zheleznogorsk, located in central Siberia, north of the city of Krasnoyarsk (8). Here, three reactors were sited deep underground inside a large granitic rock mass; cooling water was drawn from the nearby Yenisey River. The first two reactors, commissioned in 1958 and 1961, were used for plutonium production, and the third reactor, commissioned in 1964, was dual-use and also produced electricity and district heat for local use. All three underground reactors were operated successfully for decades. Especially noteworthy is the fact that a radiochemical plant was also sited underground. This is important for the UNP concept because it demonstrates the feasibility for underground collocation of reprocessing facilities. In addition to the

Russian experience, in Scandinavia and western Europe, beginning in the 1950s, four small experimental reactors and a demonstration reactor were sited underground (9), some operated for several years.

Rapid growth of nuclear power in the 1970s led to a consideration of underground siting of commercial nuclear power plants as an alternative to surface siting. Results of underground siting studies by the U.S., Canada, Japan and others are summarized in proceedings from a conference held in Hamburg, Germany, in 1981 (10). Studies included detailed conceptual designs describing cost, safety, and security issues, and an evaluation of advantages and disadvantages of underground siting. Conclusions were that underground siting was feasible from an engineering standpoint and within the current state of the art, and that underground siting could provide greater protection against extreme accident consequences, security threats, seismic activity, and severe weather conditions. However, an additional conclusion was that cost increases would be associated with underground siting, primarily because of the added cost of shaft sinking, tunneling and other underground construction. But these studies did not consider the merits of siting multiple reactors underground, as does the UNP approach. The UNP approach circumvents the increased cost problem by increasing the number of reactors to a number that will reduce the per-reactor cost of the underground infrastructure to an acceptable level.

ENVIRONMENTAL IMPACT CONSIDERATIONS

Assuming future technical and economic analyses and political considerations indicate the UNP concept is viable, the result could a national policy decision to promote deployment of UNPs. If so then a federal agency, probably the Department of Energy (DOE), would be assigned responsibility to implement a program to achieve that goal. An environmental impact statement would eventually be required. It is useful even at this early time to consider, if only conceptually, what such an EIS might reveal. Results are shown in Table I. For purposes of simplification only two alternatives are considered, the UNP approach and the conventional siting approach. To simplify comparisons, the current national policy of an open fuel cycle is assumed. Information from the GNEP PEIS was used to guide preparation of Table 1. In Table I the terms "High" and "Low" are used in a relative sense; for example, water requirements are considered "High" for the UNP approach relative to the conventional approach, and the human health impacts to workers for the UNP approach are considered "Low" relative to those from the conventional approach. Table 1 gives a few examples only and is not a listing of all environmental impact factors needed for a complete EIS analysis.

Table I. Conceptual Comparison of Selected Environmental Impacts of the Underground Nuclear Park Approach Relative to the Conventional Siting Approach

Environmental Impact Factor	UNP Approach	Conventional Siting Approach
1.Resource Requirements		
--water	High	Low
--commodities	Low.	High
2. Socioeconomics	Uncertain	Uncertain
3. Human Health		
--workers	Low.	High
--public	Uncertain.	Uncertain.
4. Facility accidents		
--external events, including natural phenomena	Low.	High
--internal events	Low.	High
5. Sabotage and Terrorism	Low.	High
6. Transportation Impacts	Low.	High
7. Land Use	Low	High
8. Aesthetics	Low.	High

Discussion

Water resources. Because of the comparatively large number of reactors in a UNP (~ 10 to 20), water use impact could be high in the UNP vicinity if UNP reactors are water-cooled and if the turbine/generators require water for heat rejection. Use of non-water-cooled reactors and/or the atmosphere for heat rejection could reduce this impact.

Concrete Requirements. Properly lined and supported tunnels, rooms, and chambers in the UNP would create the necessary underground space to house the reactors, turbine/generators, and other large equipment. This eliminates the need for the large surface buildings required by conventional siting, and the large amounts of concrete required to construct those buildings. Per-reactor concrete requirements for the UNP would be lower.

Socioeconomics. Socioeconomic impact is uncertain because it depends on the specific UNP site under consideration. The economic impact could be positive and long-term, however, because craft and professional personnel would be employed for many decades during construction of underground openings and during operation of the reactors and waste management facilities.

Human Health. Worker health impacts during waste transport would probably be lower under the UNP approach because layout of underground openings and planning for waste transport operations could be designed to take advantage of the natural shielding provided by the host rock. ALARA could perhaps be enhanced beyond levels common for waste management workers under the conventional siting approach. Natural containment provided by the hundreds of feet of rock mass between the UNP and ground surface combined with the use of multiple engineered barriers (e.g., redundant seals and bulkheads) within access tunnels would contain emissions in case of an accident and reduce the probability of public exposure. However, PRA might indicate an increased exposure risk to the local population caused by the cumulative effects of having multiple reactors and waste management facilities at a single location, even if the location is underground. For this reason the public health impact is considered uncertain at this time.

Facility Accidents. Deep underground siting according to the UNP approach greatly reduces the probability of accident-induced containment loss caused by external events such as explosions, fires, missile impact, and aircraft impacts—deliberate or unintentional. In addition, a UNP provides a high level of protection against natural phenomena such as extreme weather events (e.g., tornados) and earthquakes. Usually, seismic shaking at a given site is strongly attenuated at depth in bedrock. Accidents caused by internal events would have lower impact because natural barriers combined with multiple engineered barriers would act to both contain and retard accident-induced radionuclide movements, confining them to the near-field of the underground opening where the containment loss occurred.

Sabotage and Terrorism. Probability of loss-of-containment caused by acts of sabotage or terrorism is low for a UNP. Knowledge of underground operations by unauthorized individuals could be made lower for UNPs because transparency of underground operations from surface locations is eliminated and access to the underground can be effectively controlled at the limited number and type of access points into the subsurface (e.g., tunnel portals). Personnel movements within the UNP can be controlled at key locations inside tunnels. Geophysical techniques can be used to detect clandestine attempts to tunnel into the UNP. Individual sectors of the UNP can be isolated in the event of a radionuclide release through the use of multiple engineered barriers.

Transportation Impacts. The UNP approach eliminates the need for any surface transport of spent nuclear fuel and nuclear waste. The UNP approach therefore largely eliminates the public exposure risk associated with transportation-related accidents or attacks that might occur under the conventional siting approach.

Land Use and Aesthetics. UNP approach lowers the land use impact because the the amount of acreage that needs to be disturbed during construction is lower than for the conventional siting approach. Moving the reactors and turbine/generators underground eliminates the surface buildings needed under the conventional siting approach, thereby lowering the view-scape impact.

IN-PLACE DECOMMISSIONING AND LOW LEVEL WASTE MANAGEMENT

Prior studies (11, 12) have recognized the value of in-place decommissioning of underground reactors, and for UNPs it is considered to be a major safety, health and cost advantage relative to conventional siting (1,2, 3). In-place decommissioning of a UNP reactor would eliminate many issues of safety, security and public concerns compared to decommissioning a surface-sited nuclear power reactor. In-place decommissioning reduces worker and public health impacts, air emissions impacts and probability of transportation accidents. In-place decommissioning is expected to cost in the range of a few tens of millions of dollars (13), which represents a savings that could be significant, as is indicated by comparison with the decommissioning cost for three U.S. reactors that have undergone decommissioning, $429M (Trojan), $500M (Maine Yankee), $790M (Connecticut Yankee) (14)

A possible strategy for in-place decommissioning of a UNP reactor would be as follows: Terminate the operating license. Remove the final loading of SNF and any reusable or salvageable components. Leave in place the reactor vessel, contaminated components and any existing LLW and GTCC waste. License the reactor chamber as a LLW disposal site. Return to the reactor chamber any LLW or GTCC produced by that reactor and in storage in the UNP LLW storage facility. Fill chamber voids with crushed host rock and additives as needed. Complete closure.

In-place decommissioning eliminates the need for a separate LLW disposal site located away from the reactor undergoing decommissioning, as the case with the conventional decommissioning. Additional, conventional LLW disposal capacity would not be needed for UNP reactors.

If in-place decommissioning for UNP reactors is feasible from an operational and regulatory standpoint, and if the cost reductions are indeed as significant as they appear to be, then it follows that an argument could be made that the amount of the annual payment to the special trust fund to cover future decommissioning cost could be lower for UNP reactors relative to the payment required for conventional decommissioning

PUBLIC ACCEPTANCE

Benefiting from WIPP Lessons

Siting a UNP will be challenging, as is the case with all nuclear facilities. Applying the lessons learned during the 30-year course of achieving public support for the WIPP project, located near Carlsbad, N.M., will be key. These lessons include creating, nurturing and sustaining a positive, proactive partnership between local DOE officials and Carlsbad civic leaders and citizens; recognizing the desire of the community for economic and educational benefits and quality of life improvements to accrue as a result of the WIPP project; and an unrelenting commitment to safety and environmental protection in all phases of WIPP development and operations. Strong, local public support from the Carlsbad community has been instrumental in allowing continued progress to achieve the U.S. national goal of transuranic waste disposal.

Another factor, which could be important in UNP siting is an overall awareness within the community of the subsurface conditions in the region and a willingness to develop the region's earth resources for the benefit of the community. In the case of Carlsbad, because of past and on-going oil and gas drilling, potash mining, and WIPP operations--and the number of people employed directly or indirectly in those activities –the true nature of the earth's subsurface is common knowledge to many residents of the city and region. Most people have either first-hand, experience-based, practical knowledge of the local rock types, groundwater conditions, and overall geology, or have relatives or trusted friends who do. In candidate areas for UNPs, if communities similar to Carlsbad should exist, with similar histories of drilling, mining or other underground-related activities, there would probably also be residents with accurate knowledge of the local and regional subsurface conditions. Such individuals could be of great value as means to more effectively communicate to others in the community and region a factual and rational picture of the subsurface, allowing the probable UNP risks, impacts and benefits to be better understood.

Greater Environmental Equity

Siting the high level waste repository at Yucca Mountain has been delayed because of resistance by its opponents, and there have been repeated failures in efforts to site new low level waste disposal facilities (15). Such delays and failures could perhaps be avoided under the UNP approach because of the inherent "fairness" of the environmental equity aspects of the UNP approach. Specifically, the UNP approach collocates the reactors and the SNF storage facility and HLW repository that support those reactors at the same location. Therefore, under the UNP approach only the waste generated by UNP reactors will be disposed of in UNP waste facilities. Waste from reactors outside the UNP would not be allowed. This means that the community and region that benefit economically from the construction and operation of the UNP reactors is obligated to accept the waste from those reactors, but none other. Thus, environmental equity is promoted by the UNP approach in the sense that it avoids the "unfariness" of a community having to accept the waste from distant power reactors without enjoying the employment and economic benefits associated with the construction and operation of those reactors. The fairness aspect of the environmental equity inherent to the UNP concept should enable UNPs to be sited without the level of delays and failures associated with the conventional approach wherein the communities hosting reactors and those hosting waste disposal facilities are widely separated.

REGULATORY FRAMEWORK

The regulations and regulatory processes currently in place for licensing and operating new reactors and nuclear waste storage and disposal facilities would need to be reviewed to determine their adequacy with regard to the UNP approach. These would include, for example, 10CFR100, reactor site criteria; 10CFR52, standard design certifications, early site permits, and combined construction and operating licenses; 10CFR73, physical protection of reactors and waste management facilities; 10CFR72, licensing facilties for independent storage of SNL, HLW and reactor-related GTCC waste; 10CFR71, nuclear waste transport; 10CFR61, licensing of LLW disposal facilities; and 10CFR60, licensing HLW geologic repositories. Modifications of some of these regulations would probably be necessary as a minimum and new rulemaking might be necessary. For example, changes might be necessary to 10CFR100 to add requirements for extensive drilling, testing and geophysical investigations to understand geological, hydrological, and rock properties within and surrounding a candidate UNP site. Reactor designs deemed suitable for underground siting would need to be certified under 10CFR52, and specific reactor-site locations within the UNP, and specific reactor chamber designs for the reactor-site, would have to be approved. It would be useful to have the ability to obtain early site permits for several reactor-site locations within a UNP for a specific reactor and chamber design, and to be able to "bank" those locations for future use. The adequacy of 10CFR60 for licensing the UNP HLW repository would need be reviewed inasmuch as 10CFR63 is specific to Yucca Mountain.

It would be useful to have a regulatory process that allowed the UNP HLW repository to be granted a construction license prior to or concurrent with the COL for the first UNP reactor. This would allow the first and all subsequent UNP reactor operator/owners to see a clear pathway for the ultimate disposition of waste from their reactors prior to the beginning of reactor construction, in contrast to the conventional approach.

IMPLICATIONS OF THE UNP CONCEPT FOR THE EXPANSION OF NUCLEAR POWER

Support for a 21st Century, High-Growth-Rate Nuclear Power Scenario

Nuclear is a proven technology for generating multi-gigawatt levels of electricity, reliably and continuously. Moreover, because nuclear generation is free of significant greenhouse gas emissions and does not introduce atmospheric pollutants that reduce air quality, strong environmental arguments have been made for a major 21st century global expansion of nuclear power. Deutch and Moniz (16), for example, use environmental arguments to propose a global growth scenario leading to 1000 GWe deployed nuclear generating capacity by 2050. Reich (17) also uses environmental arguments, and the growing need for abundant clean energy, to project a global growth scenario ranging from 2000 GWe (low) to 11,000 GWe (optimistic).

To illustrate the utility of the UNP approach for the U.S., we assume a hypothetical global growth trajectory leading to 4000 MWe global deployed capacity by 2100 of which the U.S. would have about 1000 GWe, slightly less than the current 27% U.S. share of global capacity (18). A trajectory leading to 1000 MWe nuclear capacity in the U.S. by 2100 contrasts sharply with the modest growth projections in the Energy Information Agency's 2008 Annual Energy Outlook (19), which leads to only 115 GWe (reference case) by 2030, and the GNEP projection (7)which leads to 200 MWe by 2060 – 2070. Under such modest growth projections, nuclear will continue to supply only 20% or less of U.S. electricity, and therefore continue to play a secondary, supporting role for U.S. electricity generation. If so, the need for UNPs would be questionable.

However, achieving on the order of 1000 GWe U.S. deployed nuclear capacity by 2100 might become desirable, and therefore become national policy, for many reasons. For example, it is a level that would allow more displacement of new construction of greenhouse-gas-emitting fossil generating capacity than would be possible under the EIA and GNEP projections, and it might strengthen energy security by helping position the U.S. to transition more readily to electric or alternative fuel vehicles. Under this circumstance the value of the UNP approach would be greater because, as per the arguments in this paper, deployment of UNPs could significantly reduce environmental impact and facilitate public acceptance of new nuclear power plants. This combined with the probable reduced cost, increased safety and increased physical security for UNPs would increase the chance that the desired growth trajectory for nuclear power in the U.S. would be achieved.

UNP/Renewables Siting Strategy

One strategy for UNP deployment under the scenario of 1000 GWe U.S. deployed nuclear capacity by 2100 would be to site a network of UNPs in the U.S. in parallel with expanded conventional siting. UNP deployment could begin, for example, at remote locations across the central and southwest U.S. near regions with large solar and wind resources. At such locations UNP electricity could perhaps be integrated with wind and solar electricity and share the high-capacity, long-distance transmission lines that will be needed anyway to move solar and wind electricity to users on the east and west coasts. Such transmission lines could be used to supply integrated nuclear/renewables electricity across the nation. In addition, it is conceivable that such a strategy would allow daily peaking power to be supplied to population centers on the east coast to help meet high demand early in the day, and then to west coast later in the day when peak demand was high there but less in the east.

Strategic Electricity Reserve

Another benefit of the UNPs is that they would be secure underground sources of electrical power, immune from attack and severe weather effects, and could be used during times of national emergency to supply electricity to areas across the U.S. suffering from power disruptions. In this sense UNPs could be considered as a "Strategic Electricity Reserve", with a function analogous the Strategic Petroleum Reserve.

ISSUES

Many issues associated with the UNP concept require further study. An example is the power transmission cost associated with moving multi-gigawatt levels of electricity to distant users. Another is safety risks (e.g., fire, rock-fall, and ventilation) common to all underground construction and operations, and their impact in the context of underground nuclear operations. Host-rock-specific issues need to be examined, an example is to determine measures needed to control introduction of water and movement of airborne salt particle in a salt UNP. A safety analysis is needed to evaluate UNP reactor and waste management facility accident scenarios. Water requirements could be a significant issue in regions with limited surface and ground water resources, given the number of reactors in a UNP. First-of-a-kind economic and technical risks are associated with the start-up of a UNP. None of these issues are viewed as sufficient to preclude further study of the UNP concept, but all are important and require analysis and resolution.

CONCLUSIONS AND RECOMMENDATION

If high-growth-rate nuclear energy scenarios in the U.S. for the 21st century should materialize, then the continuation of the conventional approach of installing one or a few new reactors at the earth's surface at widely dispersed locations, and having their HLW repository, and/or recycling centers, and LLW disposal sites located at a great distance from the reactors, will probably mean a continuation of controversies regarding capital cost, nuclear waste, physical security, and safety. If so, the high-growth-rate scenario could be jeopardized, with the result that even less than the current level of 20% of U.S. electricity would be nuclear generated in the future.

This unfortunate situation could perhaps be avoided in part by an alternate approach that, beginning ~ 2025-2030, would involve deployment of underground nuclear parks, each consisting of an array of reactors with a collective multi-giga-watt capacity, and collocated with the reactors would be the nuclear waste management and other facilities that support those reactors. Deployment of UNPs could significantly reduce environmental impacts and facilitate public acceptance of new nuclear power plants. This combined with the probable reduced cost and increased safety and physical security for UNPs, would increase chance that a high growth trajectory for nuclear power in the U.S. would be achieved.

The UNP approach should be examined in detail to assess its merits relative to conventional siting.

REFERENCES

1. W. MYERS and N. ELKINS, "Concept for an Underground Nuclear Park and National Energy Supply Complex at Carlsbad, N.M.," Report LA-24064, Los Alamos National Laboratory, (2003).

2 W. MYERS and N. ELKINS, "Siting nuclear power plants underground: Old idea, new circumstances," *Nuclear News,* 47(3) pp. 33-38. (2004).

3 C. W. MYERS, N. Z. ELKINS, J. F. KUNZE and M. M. MAHAR, "Potential Advantages of Underground Nuclear Parks," Proceedings of the 14th International Conference on Nuclear Engineering, 14-8913, Miami, Florida, July, 17-20, 2006 (2006).

4 J. M. MAHAR, J. F. KUNZE, C. W. MYERS, and R. LOVELAND, "Advantages of Co-Located Spent Fuel, Reprocessing, Repository and Underground Reactor Facilities," American Nuclear Society, Advanced Nuclear Fuel Cycles and Systems, Boise, Idaho, September 9 – 13, 2007 (2007).

5 J. M. MAHAR, J. F. KUNZE, and C. W. MYERS, "Underground Nuclear Power Parks – Power Plant Design Implications," 16-48889, Proceedings of the 16th International Conference on Nuclear Engineering," Orlando, Florida, May 11-15, 2008 (2008).

6 C. W. MYERS, J. M. MAHAR, J. F. KUNZE, AND N. Z. ELKINS, "Underground Nuclear Parks: New Approach for the Deployment of Nuclear Energy Systems," *Underground Spaces: Design, Engineering and Environmental Aspects* , WIT Press, Ashurst Lodge, Ashurst, Southampton, SO40, 7AA, U.K. (2008).

7, U. S. DEPARTMENT OF ENERGY, "Global Nuclear Energy Partnership, Draft Programmatic Environmental Impact Statement," DOE/EIS-0396, U.S. Department of Energy, Washington, D.C. (2008).

8 GLOBAL SECURITY, "Krasnoyarsk-26/Zheleznogorsk Mining and Chemical Combine [MCA] N 56^{o} 22' E 93^{o} 41'," http://www.globalsecurity.org/wmd/world/russia/krasnoyarsk-26_nuc.htm (2003).

9 P. J. BACH, "A Summary of Studies on Underground Nuclear Power Plant Siting," *Underground Space*, 2(1) pp. 47-51. (1977).

10 H. F. BENDER, (Ed.) 1982, *Proceedings of a Symposium on Underground Siting of Nuclear Power Plants*, E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, Germany (1982).

11 V. N. DOLGOV, "Inherently Safe Power-Generating Unit for an Underground Nuclear Power Plant," *Atomic Energy,* 76(2), pp. 136 - 138 (1994)

12 C. W. FORSBERG AND T. KRESS, "Underground Reactor Containments: An Option for the Future," Paper No. 159, 2nd International Topical Meeting on Advanced Reactor Safety, American Nuclear Society, Orlando, Florida, June 1 – 4, 1997 (1997)

13 W. MYERS, N. ELKINS, J. KUNZE, AND J. MAHAR, "DD&R if Nuclear Power Plants are Sited Underground," American Nuclear Society, 2006 Annual Meeting, Reno, Nevada, June 4-8, 2006. (2006)

14 M. HOLT, "Nuclear Energy Policy," RL, 33558, *CRS Report for Congress*, Congressional Research Service, (2008).

15 S. L. ALBRECHT, "Final Report: Low-Level Radioactive Waste Siting Toward the Development of More Effective Policy Through Understanding Failure", EPA Grant Number, R823191, National Center for Environmental Research, Office of Research and Development, U. S. Environmental Protection Agency. Washington, D. C. (1998).

16 J. DEUTCH AND E. J. MONIZ, "The Future of Nuclear Power," Massachusetts Institute of Technology, http://web.mit.edu/nuclearpower (2003).

17 J. RITCH, 2008, "Welcome and Presentation of the WNA Award", Speech, World Nuclear Association, 33rd Annual WNA Symposium, September 4, 2008. http://www.world-nuclear.org/John_Ritch_speeches/John_Ritch_London040908.html (2008).

18 WORLD NUCLEAR ASSOCIATION, Table: "World Nuclear Power Reactors 2007-08 and Uranium Requirements," World Nuclear Association, London, UK. http://www.world-nuclear.org/info/reactors.html (2008).

19 ENERGY INFORMATION AGENCY, "Annual Energy Outlook 2008 with Projections to 2030," DOE/EIA-0383, Energy Information Agency, U.S. Department of Energy, Washington D.C. (2008).