Underground Reactor Containments: An Option for the Future?

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ABSTRACT

Changing world conditions and changing technologies suggest that serious consideration should be given to siting of nuclear power plants underground. Underground siting is not a new concept. Multiple research reactors, several weapons production reactors, and one power reactor have been built underground. What is new are the technologies and incentives that may now make underground siting a preferred option. The conditions and technologies, along with their implications, are discussed herein.

Underground containments can be constructed in mined cavities or pits that are then backfilled with thick layers of rock and soil. Conventional above-ground containments resist assaults and accidents because of the strength of their construction materials and the effectiveness of their safety features that are engineered to reduce loads. However, underground containments can provide even more resistance to assaults and accidents because of the inertia of the mass of materials over the reactor. High-technology weapons or some internal accidents can cause existing strong-material containments to fail, but only very-high energy releases can move large inertial masses associated with underground containments. New methods of isolation may provide a higher confidence in isolation that is independent of operator action.

I. INTRODUCTION

Reactor safety depends upon a multiplicity of technical and institutional factors. Evolving technologies and changing institutional considerations suggest that the concept of underground siting of nuclear power plants should be reconsidered.
If the cold war had not occurred, the initial development of nuclear power might have taken place in Europe and Japan before its development in the United States and Russia. Europe and Japan have very limited fossil-fuel resources and, thus, have stronger economic and security incentives to develop nuclear power as compared to the United States and Russia. The different characteristics of Europe and Japan would have likely resulted in a different reactor safety philosophy. In particular, emphasis would have been placed most likely on avoiding (1) a need to evacuate the population in the event of an accident and (2) land contamination. This stance is a direct result of the high population densities of Europe and Japan. It is no coincidence that the first French pressurized-water reactor (PWR) was built underground and that advanced European power reactor designs emphasize reactor containment concepts that avoid a need to evacuate in the event of very severe accidents.

B. Safety Philosophies

Several approaches are available to minimize the risks from nuclear power reactor operations:

1. Accident prevention and control using active systems characterized as excellent in design and operation,
2. Use of passive and inherently safe reactors that cannot have serious accidents, and
3. Containments. Components of these philosophies are found in all reactors today. In theory, any of these approaches can reduce the risk of a large-scale release of radionuclides to low levels. However, there are different institutional and economic implications for each option:

**Accident prevention via active safety.** Prevention of accidents, provision of active safety systems for assured reactor core cooling, and excellence in operation have received the most emphasis because they are extensions of normal operations and protect capital investments. The long-term profit incentive for a private company is partly aligned with this philosophy.

**Passive and inherent safety.** Prevention of accidents using passive and inherent safety design is a relatively new concept. It was originally derived from the chemical industry after that industry experienced a number of chemical plant accidents. It was recognized then that many accidents can be designed out of existence. There are several possible nuclear reactor designs, but such reactors have not yet been commercialized.

**Containments.** Preventing serious consequences from an accident is possible with appropriate containment design. In this context, a wide variation of options exist—each with different dependencies on operations and different capabilities to withstand accidents.

To avoid releases of large quantities of radioactivity, primary emphasis in the United States is based on operational excellence. This emphasis is an outgrowth of the design philosophy of naval reactors. The risks to populations in and near operating plants in the United States was estimated for a set of plants that “represented” the major types of reactor-containment systems. This study found that core damage frequencies varied among the reactor types but were generally <10^-4/reactor year for all types, with boiling-water reactors (BWRs) usually having lower core damage frequencies than do PWRs. On the other hand, the researchers found a much broader range of conditional containment failure probabilities from ~10^-2 up to 0.6. The higher values are usually associated with BWRs. The resultant risk status of these representative plants was found to be well below the safety goal for early fatalities of 5 × 10^-7/reactor year. The relatively high reliance on active systems (as indicated in the previous values) for safety is a result of historical factors. With care, accident risks can be reduced to very acceptable low levels.

III. A CHANGE IN PHILOSOPHY

Low risks can be achieved using many safety approaches. We suggest that serious consideration be given to the following safety philosophy:

*Nuclear power plants should be designed to ensure that the consequences of the worst-case accidents will be of only limited local concern. The prevention of large-scale release of radionuclides shall not depend upon plant operation and maintenance practice nor on the relative reliability of active safety systems and components. The technology must be physically demonstrable.*

It is further suggested that underground siting may provide a practical method to implement this safety philosophy after only limited modification of the current nuclear power technology. Two issues are associated with consideration of any alternative safety philosophy: (1) Is it technically feasible, and (2) are the benefits worth the costs? Neither of these questions
can now be definitively answered. Nevertheless, we believe that the arguments for underground containment and a new safety philosophy are sufficiently strong such as to be worthy of serious consideration.

IV. TECHNICAL FEASIBILITY

A. Technical Design

For reactor containment systems to provide their intended functions during an accident, they must (1) maintain structural integrity and (2) isolate penetrations (steam, feed water, access ports). Experience with nuclear weapons testing has demonstrated that underground locations can contain energy releases that are many orders of magnitude larger than any possible reactor accident. Additionally, underground siting protects the facility from extreme external events (aircraft collisions, conventional weapons, noncratering nuclear weapons detonations, etc).

The technical basis for underground containments to withstand such forces is that containment is ensured by the inertia of the mass covering the reactor. Conventional containments resist accidents and assault because of the strength of the construction materials. High-technology weapons or internal accidents can result in failure of even strong materials, but only extremely high energy releases can move large inertial masses. While it is difficult to predict accident probabilities and scenarios, bounding accident conditions can be determined\(^5\) with assurance that an underground containment can survive such an accident. The surprising reality is that both industrial accidents and military experiences show that it is extraordinarily difficult to penetrate a large pile of dirt.

If isolation systems work, no radioactive release would occur. The probability of isolation systems working is expected to be higher than for other active reactor safety systems because the former are simpler. Failure of the isolation systems—the equivalent to leaving the door open via access tunnels and shafts or failure of a valve to close—in early studies was shown to be a significant failure mode and that under such conditions improved structural integrity of the containment building would only provide limited gains in safety. That perspective is now changing because of a better understanding of accident events and new technologies.

Research on severe accidents and the experiences during the Three Mile Island–Unit 2 accident indicate that delaying the release of radioactivity from containment significantly reduces potential releases because of the natural gravitational settling of aerosols and other attenuating phenomena. Figure 1 shows the gas-phase aerosol concentration as a function of time that would be typical for a large PWR. It shows the rapid reduction in the aerosol concentrations with time. It is clear, because of underground siting of a reactor, the maximum accident consequences for any accident could be significantly attenuated because of delays in the release of radionuclides. Evidence also suggests (but does not prove) that it may be possible to limit consequences of a severe accident to the local area even in the event of isolation system failure (open door or open valve). This inference is based on several technical observations:

**Travel time.** Increased residence times in release pathways can drastically reduce total accident radionuclide releases to the environment. The residence times inherent in tunnels from the underground reactor siting to the surface can limit radionuclide releases.

**Technology.** Development of fluidic valves; flow limiters; passive (no moving parts) radionuclide traps (i.e., modified steam separators in steam lines, variable diameter access tunnels); and other devices can limit radionuclide release even in the event of containment isolation-system failure. In this context, the efficiency of these aerosol separation systems increases with gas velocity. At low gas flows, the aerosol release is low because of settling and other mechanisms. At high gas flows, aerosol separation processes are more efficient.

**Volume.** Larger internal volumes limit the factors that increase pressure; hence, the flow through and out of leakage paths is slowed.

B. Demonstration of Feasibility

The incentives for underground siting are strongly dependent upon a high confidence in the technology. If underground containment capabilities cannot be demonstrated, the incentives are greatly reduced. In this context, underground containment technologies have a unique characteristic compared to other approaches to reactor safety. It may be possible to demonstrate performance to the scientific community and the public with full-scale tests of underground
containsments in which modified explosives and trace quantities of radioactivity simulate the worst possible reactor accidents. This type of demonstration is fundamentally different from other demonstrations of reactor safety. Demonstrations of other types of reactor safety mechanisms is difficult because in other demonstrations (1) all accident initiators cannot be shown to have been addressed, (2) reactor costs limit the scale of tests, and (3) radioactivity associated with large reactors limits experiments because of potential risks to the public.

V. INCENTIVES FOR A NEW SAFETY PHILOSOPHY AND UNDERGROUND REACTOR SITING

Four considerations are involved in considering a new safety philosophy and the associated technology: (1) institutional acceptance, (2) changing requirements, (3) reactor technology, and (4) economics. These issues are interconnected.

A. Institutional Acceptance and Resultant Impacts on Economics

The strong dependence on operational factors for safety results in a strong dependence on operational excellence and appropriate supporting institutional structures. It is in many cases a workable philosophy. Air-traffic control and operational control of nuclear weapons are examples of complex systems that have the potential for high-consequence accidents which society has successfully operated. If there is strong societal support, such systems can be highly reliable and very safe.

There are, however, difficulties with such approaches to safety. Breakdowns in safety can occur because of (1) the collapse of social institutions (e.g., the collapse of the former Soviet Union) and (2) short-sighted local managers who “cut corners” for short-term economic gain. Both types of breakdowns have occurred and have subsequently placed a large burden on national regulators. Confidence in the
technology then depends upon the confidence of the public in the facility owner, the local and national regulators, and foreign regulators in other countries. Lack of confidence can result in a highly regulated industry with ensuing adverse economic consequence.

Any technology that has the possibility of large-scale accidents with long-range consequences will be regulated on both a national and an international level. A strong political component will be associated with such regulation because of potential consequences regardless of the estimated risks. Technologies with the potential for large-scale accidents but for only local consequences may be regulated on a local or national scale, but they are not usually regulated on an international scale. Large dams and some types of chemical plants can be placed in these categories.

For nuclear power, these factors suggest that serious consideration should be given to “technical fixes” that would reduce the dependence of the technology on operational factors and reduce the need for supporting institutional structures. These improvements would improve public acceptance and economics. Institutional structures (e.g., regulators, law enforcement, liability insurance, international treaties) have real associated economic costs. For example, from a historical context, delay in construction caused by reactor licensing has in some countries (including the United States) greatly increased the costs of building and operating nuclear reactors.

B. Changing Threats for Nuclear Reactors

The long-term, design-basis requirements for reactor safety may change. The end of the cold war resulted in the political environment changing from a bipolar to a multipolar world. A bipolar world seriously constrained what the allies of the two superpowers were allowed to do. In the current multipolar world, these constraints are reduced. Simultaneously, technology is creating low-cost, precision-guided munitions. The combination of institutional and technical changes implies that smaller nations and, ultimately, private groups will have access to precision-guided munitions—even as the political constraints on the use of such technologies are being reduced. In such a world, nuclear power plants might become hostages to political and economic blackmail. In this context, underground siting is a technical fix independent of issues associated with containment isolation.

Underground siting also provides protection from extreme plant accidents and may limit the maximum consequences of a severe accident to acceptable levels. Accidents such as pressure-vessel failure and large steam explosions in a core-melt event are very unlikely—but not impossible. Such extreme accidents have been shown to have acceptable risk but high consequences—a condition that concerns a risk-adverse public.

C. Economics

New approaches to reactor safety are viable only if the economics are acceptable. The economics depend upon a complex set of both technical and institutional factors.

1. Previous studies. In the 1970s, a series of studies were conducted on underground siting of nuclear power plants. The major benefits identified were containment of radioactivity, protection from external assault, and reduced seismic vulnerability. The improved seismic performance results from the characteristic of earthquake motion being largest at the ground-air interface and decreasing rapidly with depth. Ensuring the sealing of containment penetrations in the event of an accident was identified as the critical design problem.

Two underground siting options were identified: (1) placement of the entire plant underground and (2) placement of nuclear-related components underground with placement of the turbines and electric generators above ground. Two types of sites were investigated: (1) an underground cavern blasted out of rock and (2) a reactor constructed in an excavated pit and covered with 100 ft of fill dirt. Depending upon assumptions, the capital costs of underground siting were 15 to 30% higher. However, the impacts on busbar costs were less because the cost of electricity also depends upon operating, fuel, and decommissioning costs.

2. Reactor Technology. Reactor technology—particularly power—technology—is moving rapidly in directions that reduce the construction cost differential between above-ground and below-ground siting of nuclear reactors. Key changes include the following.
Seismic and sabotage. Seismic and sabotage protection have received increased emphasis. With underground siting, location is substituted for concrete, steel, and security guards in meeting functional requirements.

Technology. New reactor technologies are being developed which emphasize the use of passive and inherent safety (e.g., the General Electric Simplified Boiling Water Reactor and the Westinghouse AP-600). In engineering terms, these designs may drastically reduce the amount of mechanical equipment required inside containment. This reduces the concern with underground siting in terms of (1) construction; (2) access to equipment for maintenance; and (3) the number of pipes, instrument lines, and power lines from containment to other parts of the plant which must traverse tunnels from underground to above ground. The complexity of the safety systems was a major factor in increased costs with underground siting compared to above-ground siting in the studies of the 1970s. Changing the design changes the relative benefit of surface vs underground siting.

3. Three-dimensional plant layout. The siting studies conducted in the 1970s took existing plant designs and placed them underground. However, the plant layouts were not changed. The plants were not optimized for underground locations. It is now clear that this simplifying assumption had a major impact on the facility costs of underground facilities.

The vertical dimension is not a major design variable in current power reactors for two reasons: (1) vertical plant layout requires added structural support and (2) seismic considerations make tall structures more vulnerable and more expensive. Underground construction usually removes these constraints. Underground cavities can be built at different elevations. For example, in the mining industry this simplifies the design of underground transport and rock crushing systems. Similar options are available for nuclear power plants. Examples of such options for nuclear reactors include the following:

Emergency core cooling system (ECCS). Several new designs of reactors (e.g., Westinghouse AP-600 and Mitsubishi Simplified-600) propose using gravity-flow, ECCS. If there is a loss of primary cooling water, the reactor automatically depressurizes, and emergency cooling water flows via gravity into the reactor core. The rate of flow depends on, among other things, the difference in elevation between the ECCS water tank and the reactor core. Underground siting can improve the effectiveness and reliability of these systems by allowing larger elevation differences between major components.

Natural-circulation, primary coolant system. Current PWR reactors are equipped with large, primary coolant pumps that circulate water from the reactor core to the steam generator. The pumps are expensive, consume significant amounts of electricity, and can initiate a variety of accidents. Proposals and designs have been made for natural-circulation, commercial power reactors, but these require significant differences in elevation between the steam generators and reactor core. This difference is easy to achieve using underground siting (with its diminished seismic concerns), but it is difficult to achieve using surface siting.

4. Waste management. Underground siting of nuclear power reactors may reduce the difficulty of decommissioning by use of the underground cavities as disposal sites for low-level (radioactive) waste (LLW). Underground siting could minimize the need to demolish, package, ship, and dispose of the facility at the end of its useful lifetime. Reactor decommissioning generates two primary types of waste: relatively small quantities of spent nuclear fuel (SNF) and large quantities of LLW. The SNF may remain hazardous for tens of thousands of years and, thus, must be disposed of in specialized high-level waste repositories. The LLW waste is much less hazardous and is radioactive for only a few hundred years. Thus, there are more options for its disposal.
During the early development of nuclear power, power plant decommissioning was not identified as a major economic, technical, or institutional issue for multiple reasons: decommissioning appeared to be decades away into the future, then-current disposal methods for LLW were cheap, and environmental concerns were only beginning to emerge. In the last several years, a dramatic shift in perspectives has occurred because of several factors, and much analysis of the technical and institutional problems of decommissioning has been done.

**Cost.** Cost estimates\(^9,12\) show decommissioning to be a major cost (with overnight costs 10 to 30% of the original plant costs). Associated with these costs is the institutional complication of how to maintain appropriate financial resources for decommissioning in the context of a more deregulated electric industry worldwide.

**Waste generation.** Decommissioning now appears to generate over half the LLW from nuclear power and is a major source of radiation exposure to nuclear plant employees.\(^13\)

**Waste facility siting.** Siting of LLW management facilities and transportation are major institutional problems.\(^14\)

VI. **SUMMARY**

Many methods are possible to provide economic and safe nuclear power, and no one way is necessarily right or wrong. Historically, the cold war has been the primary determinant of the structure of nuclear power including U.S. safety philosophies. However, there are alternative options and changing conditions suggest that we examine these other options.

Underground siting is one of those options that changes both the technology and the required institutional support structure. New containment and isolation technologies may limit the consequences of worst-case accidents to being only local events. It is an option that does not require a fundamentally new reactor technology. It is also an option for which relatively limited resources will determine if the option is practicable. There have been sufficient changes in technology and institutions such that the option of underground siting of nuclear reactors should be considered afresh.

**REFERENCES**


