Nuclear Power in a World With Options

by

Lawrence M. Lidsky

Professor of Nuclear Engineering
Metcalfe Professor of Engineering and the Liberal Arts
Massachusetts Institute of Technology
Cambridge, MA 02139

presented at the

Symposium on (R)Evolutionary Reactor Types
Ultra-Centrifuge Nederland N.V.
Almelo NL

29 May 1991

Nuclear power has the potential to be the least environmentally damaging source of new central station power now available. However, nuclear power is only one of several potential prime movers under consideration for large scale production of electricity. As with any technology, the extent of its utilization depends upon a complex set of interactions determined by its particular physical embodiment and the structure and temper of the society in which its use is considered. The interplay of indigenous resource base, political structure, and history is complex and must be analyzed case by case. In general, however, nuclear power is in disfavor in all countries in which fossil fuels are available at reasonably low cost. This is certainly true of the Netherlands, where natural gas is plentiful and where electricity is available relatively inexpensively from other nations.

It is common to state that society has "rejected nuclear power" but that statement is oversimplified. Society did not reject the abstract idea of nuclear power, it rejected the particular embodiment of nuclear power presented to it by the nuclear establishment - large, enormously complex plants requiring nearly infallible operators, a fuel cycle with continual transport of fuel and waste between reactors and reprocessing plants, and an inexorable shift to a fast breeder reactor economy. The power plants proved to be expensive and often unreliable. The reprocessing plants were an environmental nightmare. Gradually, the public turned against the first generation of nuclear power plants. This was not a failure of society, but of those who presented a scheme that was not well matched to the real world. In the real world, most of the industrialized nations had other choices and most of the less developed countries did not have the infrastructure necessary to manage the complex technology associated with the first generation of nuclear power.

If nuclear power is to be used, either society or the technological embodiment of nuclear power must change. Clearly, it is far easier to change the technology of nuclear power than it is to change society (indeed, it is hard to argue that society should change to accommodate nuclear power). A designer who wishes to ensure that nuclear power is used to its fullest potential must therefore answer several questions: First, what features must a nuclear power plant have if it is to be deployed in a nation that has several choices? Second, what features must a nuclear power plant have if it is to be insensitive to the surrounding social infrastructure? And finally, is it possible to build a power plant that has the necessary features?

Technological Attributes

It is perhaps easiest to develop a list of required attributes if one considers the several participants in a transaction resulting in the deployment of a power plant. There must be a customer, a vendor, and a society willing to allow the power plant to be put into operation. From the viewpoint of the customer, defined narrowly here as those responsible for the provision of electric power, the requirements are straightforward: Nuclear power must produce electricity at a total cost lower than that of alternative power production devices. The total cost includes not just the obvious capital, operation and maintenance costs, but those costs attributable to the risk of investment loss due to shutdown by political or regulatory actions, or to long duration shutdowns due to technical difficulties. These risks are dependent upon a number of political and social factors, and are hard to quantify because society's view is dependent both upon the particular technology in question and on external, other international, factors related to nuclear power. It is clear that a high degree of uncertainty with regard to either regulatory or political concerns is equivalent, if alternatives are available, to the requirement that the *quantifiable* costs of nuclear power be substantially lower than those of alternatives.

The vendor's requirements are easier to list: There should be a reasonable probability of producing enough units that there will be a profit after paying for the development cost of the first plants and for the necessary manufacturing facilities. If the vendor is a national entity, then the investment must have higher returns than other possible national expenditures. In either situation, it is highly unlikely that the customer would allow the development costs to be incorporated into the price of the first commercial plants. From the vendor's point of view, the ideal nuclear power plant would have small unit size, would use existing technology, thus reducing development costs, and be suited to a wide potential market, i.e., be relatively insensitive to siting and regulatory considerations.

Society's interaction with nuclear power takes place through political and regulatory channels. If the public does not trust nuclear power and wishes to put barriers in its path, the obvious tactics include direct political action and restrictive legislation. Even in the event that political action is not feasible, there will be continual pressure on the regulatory agencies to promulgate the equivalent of restrictive legislation. The regulators' formal task is to assure that the technological embodiment of nuclear power is consistent with the society's requirements for environmental and safety compliance. Although the regulators may reflect a more technical, "specialists", approach to nuclear power in the short term, eventually they must come to reflect the general public's point of view. Because the short term is much less than the anticipated life of a nuclear power plant, it is essential that the particular embodiment of nuclear technology used in a power plant be acceptable to the public. Otherwise there is risk of premature shutdown. This is equivalent to the statement that the public believes nuclear power is indisputably safe.

The fuel cycle has more importance for political-social than for technical issues. The public's view of nuclear waste has been conditioned by issues associated with reprocessing, usually for military reasons. Reprocessing enormously increases the total volume of waste and tends to create a large number of new waste streams. For many years, the situation was exacerbated by the assumption that the civilian nuclear industry would also rely upon a closed fuel cycle. The problems associated with the fuel cycle have now been greatly alleviated by the realization that there is no shortage of uranium and that reprocessing will not be necessary for at least half a century, if not longer. There is thus a premium given to a fuel cycle that makes interim storage and geological disposal as simple as possible.

Summing up the requirements associated with the different constituencies we have:

- Low and predictable cost;
- Acceptable regulatory and political risk;
- Low development and manufacturing costs;
- Large potential market;
- Demonstrable safety;
- Fuel cycle amenable to simple storage and disposal.

Satisfaction of all these requirements is essential if nuclear power is to play an important role in the foreseeable future; but demonstrable safety is the quintessential item on the list. Demonstrable safety is essential for public acceptance, because the public has lost faith in all experts and has little trust in probabilistic risk assessments. Safety must be convincingly demonstrated, probably by full-scale, worst case test. Without public acceptance, the regulatory and political situation will remain uncertain, the market will be limited, and problems associated with operations and maintenance will be exacerbated. The cost, including the risk premium, will be high.

It does not suffice to build a safe reactor that does not satisfy the other requirements on the list. There are alternatives in place, and technologies in wide use are notoriously hard to displace. Such technologies benefit by experiential learning, create a community of users, and build a manufacturing and sales infrastructure. In the event of technologies involving risk (e.g., the automobile or the airplane) familiarity tends to build a tolerance for risk. New risks are viewed much more seriously. We are unhappy with, but not afraid of, the costs associated with fossil fuel systems. Acid rain and pipeline fires are viewed with far more equanimity than the less damaging routine nuclear plant emissions and occasional unplanned shutdowns. There is a barrier to the introduction of any new technology. Because of the rejection of the first generation of nuclear power, the barrier to its reintroduction is even larger than it might have been. Nuclear power will never again be seen as a welcome sign that the modern age is dawning; it can at best hope only to be tolerated. Therefore, nuclear power must have a substantial advantage if it is to be used.

Defense-In-Depth

The idea of "acceptable risk" or "safe-enough" involves a confluence of social and technical issues. The political-social issue is one of defining "acceptable" risk; the technical issue revolves about the means used to reduce risk to the required level. It is important to realize that the "acceptable" risk need not be rationally defendable. It is not required that the public be rational. In a democracy the public is, by definition, correct. The public may hold nuclear power to an extraordinarily high standard, but it is a standard that must be met.

If one is willing to accept a probabilistic description for risk of failure, than one can achieve a prescribed level of safety by several qualitatively different means. It is possible to achieve an "acceptable" risk of failure by using either a large number of barriers-to-failure with reasonably low probability of simultaneous failure, or a smaller number of such barriers with extremely low probability of failure. The achievement of an acceptable level of safety by means of multiple, independent, redundant, barriers-to-failure is known as Defense-In-Depth. The application of the Defense-In-Depth philosophy to large commercial power reactors results in very complex and very expensive systems. There are few good measures of complexity per se, but the well-known costs of building a nuclear power plant to design specifications with provable quality is an experiential fact and probably as good a measure of complexity as any. Complexity is also evident in the level of operator training required, and in the unexpectedly high operational and maintenance costs of nuclear power plants.

The most significant drawback of Defense-In-Depth is that it is impossible in commercial power reactor systems to *demonstrate* that the required level of safety has been achieved. It is not just that it is operationally difficult to show that the component-by-component reliability assumed in the computer probability of failure is correct, i.e., to make a convincing argument that a given electric motor has only one chance in a thousand of failing to respond to a start command, or that a generator shaft has less than one in ten thousand chance in breaking the next time its diesel drive engine is called upon. It is not even that possible accident sequences might have been overlooked in our analyses, or that unforeseen events might cause the unexpected simultaneous failure of redundant elements. Even if we could be sure that we had enumerated all possible accident sequences, it would be impossible to actually test all of these sequences in a single plant.

Physical demonstration of Defense-In-Depth requires that chosen components be rendered inoperative or sometimes even be caused to fail in order to show that others would provide the necessary safety margin. In an operating plant even the simplest of these tests can be time consuming and reduce the margin of safety. But the only definitive way to prove that Defense-In-Depth works is to disable, either separately or in combination, all of the major components. These "failures" can lead to actual damage of other components. The extreme test, of course, is the demonstration that the reactor containment will survive a core meltdown without unacceptable radiation release. The way to prove this is to melt the core with one or several of its safety systems inoperable. Three Mile Island (TMI) was one such test, but it was not by itself adequate, because it represented only one of a myriad of possibilities. One would have to melt the core again and again, each time under different conditions, in order to prove that our probabilistic conclusions were complete and correct. One would also have to show that inadvertent or erroneous operator actions would not vitiate the results. Note, for example, that the successful, albeit inadvertent, TMI test of reactor vessel and containment integrity did not make the public feel better about nuclear power.

The impossibility of demonstrating the efficacy of Defense-In-Depth by actual experiment was recognized from the very beginning, and the regulatory system was designed to cope with that problem. Nuclear power plant regulation and licensing is based on a combination of experiment, calculation, and engineering judgement. The process of regulation mirrors the complexity of its subject; it follows that it is equally difficult to prove that regulation is meeting its goals.

Because technical, management, and regulatory structures are ill equipped to deal with complexity, nuclear power plants have proved to be more expensive than competitive sources of power, often extraordinarily more expensive. Their operating record has been poor, subject to mechanical, operational, and regulatory mishap. The operating and maintenance costs are unexpectedly high and growing. As a result, the public and the utilities have turned against nuclear power. Many vendors have abandoned the business. It is tempting to blame externalities for the current state of affairs, but the turning point for nuclear power occurred long before TMI and Chernobyl and the escalation of debate about nuclear wastes. These concerns are real, but if the nuclear power infrastructure had been healthy, these external assaults would have been easily survivable. When the patient is sick, opportunistic infections can appear to be the cause rather than the symptom of the disease.

This is not an argument against the concept of Defense-In-Depth. Anyone who drives a car or sets foot in an airplane has implicitly acknowledged faith in the concept. But Defense-In-Depth is subject to severe strains when the level of acceptable risk becomes extremely low. In that event, the number of backup levels and the degree of redundancy in each level begin to interact combinatorily and the system grows unmanageably complex and expensive. It might well be argued that in a practical sense, complexity puts a lower limit on the risk achievable by Defense-In-Depth.

An oversimplified but nonetheless useful analogy is related to aircraft safety. It could be argued, for example, that the risk of engine failure could be reduced to arbitrarily low levels by increasing the number of engines. A Boeing 747 with eleven engines might, in principle, have lower risk of unacceptable, simultaneous failure but would, in fact, because of the added complexity, maintenance difficulties, control problems, and component interactions probably be more likely to fail. It would also be more expensive, harder to maintain, have less useful payload, and, of course, be extremely fuel inefficient. Defense-In-Depth has its limits and safety can not always be improved by brute force.

There is a practical minimum risk level associated with the application of Defense-In-Depth to any particular technology. The level of risk that the public feels acceptable with respect to nuclear energy is such that it has placed an insupportable burden on the light water reactor.

Demonstrable Safety

There are two keys to the construction of a demonstrably safe reactor. First, it is essential that the nuclear reaction be quenched before fuel-damaging temperatures are reached, even if all the control rods are removed from the system. This feature ensures that neither accident, operator error, nor willful actions can damage the reactor core by overheating. This condition, which requires the proper combination of fuel, materials of construction, and size, is relatively easy to attain in systems that are frequently refueled, so that the internal inventory of fuel is maintained within allowable limits. But the ability to terminate the fission process itself is not the dominant factor. As the LWR demonstrates, the risk-determining events depend upon the need to protect the fuel from its own damaging afterheat, after the reaction is terminated. Fuel integrity after a loss of coolant accident can be maintained if the maximum temperature achieved in the center of the reactor under such conditions does not exceed the failure point of the fuel. The maximum temperature is determined by the size of the reactor and the power density during normal operation. *If the reactor is small enough and the power density is low enough, then the required conditions can always be met.* Unfortunately, the required combination leads, in almost all cases, to a reactor whose power output is much too low to be of commercial interest and whose net power cost is concomitantly high. This requirement cannot be met at all by the LWR.

There is, however, at least one fuel system that permits the construction of a commercially interesting reactor with demonstrable safety. It is surprising, even to many who have a long association with the nuclear industry, to learn that such fuel exists, and that a reactor based on its use has actually been in operation since 1966 in Germany. The reactor, the AVR, is approximately 1/3 scale prototype of the proposed commercial reactor. Commercial reactor designs, the modular gas-cooled reactor, based on AVR technology, illustrate the advantages of demonstrable safety. There may be other technological combinations that achieve the same result (although none are known to me). For this reason, the focus here is on the impact of demonstrable safety rather than detailed description of the MGR itself. The arguments will be the same if the acronym MGR is assumed to stand for any small, demonstrably safe reactor.

The key feature of the AVR is the use of a totally different fuel system. This extraordinary fuel is based on the encapsulation, within multiple nested spheres, of tiny (0.4 mm dia.) uranium oxide kernels. The fuel kernel is successively encapsulated in shells of low density graphite, pyrolytic carbon, silicon carbide, and pyrolytic. The total diameter of the microencapsulated fuel is only 1.0 mm, about one-fortieth of an inch. Intensive testing of the encapsulated fuel spheres shows that they are essentially perfect confinement vessels up to a temperature of 1800$^{?}$C. At that temperature, the spheres begin to leak, but it is not until temperatures will in excess of 2000$^{?}$C are reached that a significant number of failures begin to occur. For ease of handling, 10,000 to 20,000 of these spheres are embedded in the interior of 6 cm graphite balls, or "pebbles." Other designs postulate the use of large graphite blocks, rather than the billiard ball size pebbles, to contain the tiny fuel spheres.

The worst possible accident for any reactor is the withdrawal of all control rods with the simultaneous loss of all coolant. The reactor can survive, without damage or radiation release, only if the natural processes of heat conduction and radiation are sufficient, in this worst possible case, to limit the temperature of the hottest point in the reactor to less than the fuel failure temperature. The effect of this stringent design requirement is to limit the size and power density of the reactor. The AVR meets the goal easily because of the fuel's combination of high temperature capability and high thermal conductivity, and there is ample margin for somewhat larger commercial reactors. Depending upon details of design, the limiting size of these reactors is on the order of 200-250 MWt.

Because the electrical output of a module of this thermal rating is small compared to conventional plants, a number of identical reactor units (modules) would necessarily be used as independent heat sources in such power plants. Modular gas-cooled reactors are given their name not because they are made up of modules, but rather because they would be modules themselves in a power plant of nominal size.

Light water reactors of recent manufacture are typically 3000 MW or even larger in thermal power output. This immense size was motivated by a desire to take advantage of predicted economies of scale. The MGR, despite its very much smaller size, can easily be economically competitive with its larger cousins, because the MGR does not need complex (and expensive) safety systems. Equally important, a reactor of such small size can be produced in large numbers in central factories. Although economies of scale may or may not exist, the economies of serial production are very clear and frequently demonstrated.

The MGR has another economic advantage when the full fuel cycle is taken into consideration.

Fuel that is capable of containing fission products at the center of an operating reactor core during an accident is obviously suited to long term waste disposal under much more benign conditions. In other words, MGR fuel it already packaged for disposal. There is no need for reprocessing and the costs allotted to these functions need not be allocated to the electrical generation cost. This, of course, will accrue to the benefit of any reactor using a once-through fuel cycle.

Will Nuclear Power Come Back?

The first generation of nuclear power has been rejected, but it has left behind a complex matrix of truth and perception. Its successor will not be determined on the basis of simple technological considerations. The ghost image of the first generation remains, even though the active participants have retired from the scene. The battle between the pro-nuclear and anti-nuclear forces continues to grow even more intense, even as the echoes of the first battle fade away. Nuclear power can be reintroduced in the lifetime of the present protagonists only if the object of discussion is obviously different in nature from the LWR. The key measure of such difference is the safety philosophy. Any nuclear system that depends upon Defense-In-Depth will give rise to the same complex issues that mired the LWR. The evolutionary "advanced" LWR's differ in detail but not in philosophy and that is obvious to all the participants in the nuclear transaction.

The MGR is an example of an obviously different reactor system. Its safety is demonstrable, and largely as a consequence of its unique technology, it promises to be a much better match to the needs of all constituencies. If it can be shown that the cost of power generated using this technology is sufficiently low, then it might well be reintroduced as the result of the inexorable action of simple market forces. Other technological embodiments of nuclear power may very well have similar attributes and might also have a chance to displace fossil fuels. In any event, it is clear that the next generation of nuclear power stations must meet the requirements of society, of both politics and the marketplace. Otherwise, nuclear power will play a role only in those few unfortunate nations that have no other choice.