Perspective

U.S. Nuclear Power in the Next Twenty Years

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FROM 1965 TO 1975, the use of nuclear power in the United States grew dramatically. However, after 1975 this growth slowed down, and it has now almost stopped. New nuclear power plants are too expensive, and the public does not have confidence in them. Therefore, the product must be improved if it is to be salable. Work toward this end is in progress. The service life of existing nuclear plants must also be extended. These two developments permit some cautious estimates of the status of nuclear power 20 years from now. From about 1990 to 2005 there will probably be a pause in the installation of nuclear plants. During that period the nuclear community will be developing and testing new reactor designs for economic and demonstrably safe nuclear power.

The travail of the nuclear industry began in about 1975, when it became obvious that the shock of the oil price set by the Organization of Petroleum Exporting Countries had brought about an industrial recession and a sudden leveling of demand for electricity. Utilities, faced with unnecessary capital commitments, curtailed the purchase of new generating plants. Nuclear plants suffered the most, because most of the plants on order were nuclear and because nuclear power is capital-intensive.

Nevertheless, nuclear power remained economically attractive until 1979. Its generating cost was less than that of coal power, and, in refutation of public opposition, it had an excellent safety record. Therefore, the nuclear industry expected orders to resume as soon as electrical demand began to climb again.

Then the accident at Three Mile Island (TMI) unit 2 occurred. In the aftermath of TMI, major changes were made in nuclear regulations. The number of nuclear plant personnel and the training required of them were greatly increased; extensive backfitting of hardware was also required.

These measures increased the cost of nuclear power, but initially the increase was expected to be modest. However, in the 1980s, plant capital costs escalated. The cost of new nuclear plants reached three to five times what had been originally expected. The price charged for electricity normally includes a "reasonable" return on investment, but at standard rates of return these high costs caused sudden jolts in electricity rates. Some utility commissions began to disallow costs judged to be excessive in setting rates, forcing these costs to be absorbed by stockholders. Only a few, very well-managed nuclear utilities were able to avoid these embarrassments, and nuclear power lost its support in the utility sector.

Many theories as to the cause of this cost escalation have been propounded, most of which blame factors outside the nuclear industry. My theory is that the cause is within the industry. The plant designs now being offered are large, costly, and complicated. Regulatory requirements have been patched into plant designs rather than incorporated into the basic design. The nuclear industry did not see any long-term profit in going beyond incremental design changes for the existing types of nuclear plants. Under these circumstances, the enthusiasm of the design staff waned. Errors began creeping into design and construction, requiring extensive reworking. These problems were combated by hiring larger staffs to do more checking and rechecking, inspection, and paperwork. Nuclear power plant design and construction have become highly bureaucratized—and more expensive.

Nuclear power has also lost its base of popular support. Public confidence plummeted after TMI, and recovery of confidence was frustrated by the Chernobyl accident. A nuclear project will be strongly fought at all governmental levels. Public interventions and lawsuits will delay the project. The public image of the utility will be hurt, which will jeopardize the utility's case in other disputes. Under these circumstances, the utility can only justify the project to its stockholders and the public if it can guarantee that cheap electricity will be produced; but the recent cost history of nuclear plants does not make such a guarantee feasible. Nuclear power will not be a significant factor in new electricity generation unless or until its economy can be ensured.

A "second nuclear era" seems to be needed if nuclear power is to make a growing contribution to generation of electricity. The term was coined by Weinberg (*1*) to denote a period when nuclear power is again publicly accepted and cheap. The environmental benefits of nuclear power are compelling, and if they are associated with both economy and safety they will be hard to oppose. Public response to safety issues becomes muted if the industry being questioned maintains a good safety record for a decade or so (*2*). These, then, are the conditions for the second nuclear era. The questions are what types of systems will characterize it, and when will it begin.

The prevailing view in nuclear circles is that new reactor designs will be needed, but not new reactor types. Types in use today—the light water reactors, the heavy water reactor, the sodium-cooled fast reactor, and the helium-cooled graphite reactor—were selected for valid reasons, and they are the points of departure. They all have attractive intrinsic safety features, but concerns about safety will not be appeased unless safety is clearly apparent. Thus, the design task is to provide transparent safety and economic construction and operation.

One key to economy may be to decrease the size of individual reactor units. This amounts to abandoning economy of scale in favor of economy of standardization and replication. Smaller units would also (i) limit the cost exposure of each incremental unit, (ii) provide a better match to growth of the utility load, and (iii) take greater advantage of the economies and cost management of factory construction, as opposed to field construction. A precedent for smaller units is found in the unit sizes of fossil-fueled plants, which are typically built in the 250- to 400-MW range, and hardly ever exceed 800 MW.

Another change in philosophy concerns automation. Nuclear plants have been designed for a high degree of human involvement in operation. This is no longer the practice in modern manufacturing, and it is not considered conservative in the sense of safety. Now, the nuclear industry is also starting to consider automation (*3*), particularly for situations that do not permit the exercise of operator judgment. Moreover, utilities are installing a variety of computerized, on-line expert systems to guide both maintenance and operations. These automation changes should improve both economy and safety: economy by reversing the trend toward

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increased staffing, safety by removing a demonstrated weak link—as illustrated by both TMI and Chernobyl—from many of the safety chains.

Another technical opportunity comes from robotics (*3*). Human surveillance and servicing of many plant components are costly in terms of radiation exposure and money. The exigencies of TMI led to the use of robots in inspection and cleanup after the accident. These experiences were successful, and plant design for optimum use of robots and teleoperators is now in favor. These techniques will be useful, but the second nuclear era must be based on better reactors. Design programs are under way for several types.

The workhorse reactor type today is the light water reactor (LWR). Advanced LWRs are now under design (*4*). They are likely to be smaller (about 600 MW, compared to today's reactors of 1200 MW), more durable (60-year design life rather than 30 years), more conservative with larger safety margins, and, above all, simpler to make proof of safety less equivocal.

Advanced fast reactor design and development is also under way. A consensus has developed in favor of the pool type with all primary components in a single, low-pressure sodium pool, a low power of less than 500 MW per unit, modest breeding, and moderate specific power. Metal, rather than oxide, fuel is now preferred, on the basis of experiments at Argonne National Laboratory that showed metal fuel to have impressive safety characteristics. These characteristics permitted the Experimental Breeder Reactor (EBR-II) to survive severe operational accident simulations without damage to fuel or major stress on the system (*5*). The pool concept and small size permit emergency cooling by natural circulation of building atmosphere (possibly nitrogen) around the pool tank (*6*). Illustrative designs by General Electric (*7*) and Rockwell International have been published (*8*).

Proponents and developers of helium-cooled high-temperature reactors (HTGR) in both the United States (General Atomic) and West Germany were the first to downsize their concept to small modular units, making conventional pressure vessels and emergency cooling by circulation of air in the building feasible (*9*). Finally, the Canadian heavy water reactor line, known as CANDU, could possibly be adapted to U.S. practice; these reactors have compiled excellent operational records.

These advanced and alternative reactor types will need to have their safety, operability, and economy tested by experimental construction and operation. However, with so many possible reactor types, I expect at least one of them to pass this test and to be commercialized. The small unit size of the final product is important in this process, since it would require much less time, money, and extrapolation to go from an experimental plant to a commercial line.

Success in at least one of these programs is the real key to a second nuclear era. I anticipate such a success, but it will take time. A scenario for the process might be as follows: Experimental construction begins in 1992; experience justifies a prototype plant in 1999; and commercial orders begin around 2005. This scenario puts the second nuclear era a full human generation into the future. Most large-scale industrial innovations are realized over that length of time. It took that long for the first nuclear era, which is tailing off now, to bloom, and our present circumstance is indeed one of beginning again.

In the interim, many existing nuclear plants will reach the end of their license periods. They will still be in generally excellent condition, which is a requirement as long as they are licensed. Some components will be at the end of their useful lives and will need refurbishing or replacement, but most of the equipment will be available for continued long-term use. For comparison, fossil-fueled plants are retained in operation as, first, intermediate-load units and, finally, as reserve units. They are only decommissioned when continued maintenance becomes too expensive.

The economic incentives for refurbishing nuclear units are compelling. Even if if took $1 billion to refurbish the plant, the fact that the original costs have been fully amortized favors refurbishment over, for example, building a replacement coal plant. Besides, fueling costs for nuclear plants are, and will remain, less than half the fueling costs of coal plants.

The importance of this effort is now appreciated (*10*), and a program for extending plant life is under way. Necessarily, the requirements will vary from plant to plant, ranging from requalification of equipment to complex rework, including in some cases partial reconstruction of the plant. For some plants, running at reduced power would suffice. The variety of work to be done will undoubtedly keep the U.S. nuclear community busy over the next 20 years.

A forecast of the next period in U.S. nuclear power is possible based on the themes of introduction of new reactor designs and the extension of plant life. Nuclear power in the United States is scheduled to grow to about a 95,000-MW generating capacity by about 1995 (*11*). Not all these plants will remain operational until 2010, but enough will be so that the occasional new nuclear plant in growth areas of the country should maintain a plateau of about 90,000 MW until installation of the new models begins. That should happen around 2010 to 2015, and this is the time I choose for the start of the second nuclear era.

Our pause in the installation of new nuclear power plants is being imitated elsewhere in the world, so we cannot expect export business to sustain our domestic nuclear industry indefinitely; instead, we must make innovative changes. Nuclear power is still an attractive option, but it will take ingenuity and perseverance, as well as an impeccable operating record over the next decade (*2*), for its potential to be realized.

REFERENCES AND NOTES

1. A restatement of Weinberg's views is in A. M. Weinberg *et al.*, *The Second Nuclear Era: A New Start for Nuclear Power* (Praeger, New York, 1985).
2. I have observed that opposition to nuclear power peaks whenever an accident occurs and declines to a background level of dedicated opponents in about 10 years. Both the degree of opposition and the time scale for forgetting the accident mark the issue as being fundamentally a political one.
3. New directions in thinking about nuclear systems are usually presented in special sessions at meetings of the American Nuclear Society. Automation and robotics have been discussed [*Trans. Am. Nucl. Soc.* **49**, 306 and following reports (1985) (eight papers)].
4. Electric Power Research Institute (EPRI), "Advanced light water reactor utility requirements document" (EPRI, Palo Alto, CA, 1986).
5. H. P. Planchon *et al.*, *Trans. Am. Nucl. Soc.* **50**, 349 (1985); L. K. Chang, D. Mohr, H. P. Planchon, P. R. Betten, E. E. Feldman, *ibid.*, p. 350.
6. R. D. Coffield, R. F. Wright, R. A. Markley, J. E. Kalinowsky, *ibid.*, p. 337.
7. J. N. Fox, E. L. Gluekler, N. W. Brown, *ibid.*, p. 336.
8. R. T. Lancet and J. C. Mills, *ibid.*, p. 336.
9. T. F. Dunn, F. A. Silady, A. J. Goodjohn, *ibid.*, p. 343; N. W. Brown and A. P. Kelley, Jr., *ibid.*, p. 344.
10. A session of an American Nuclear Society meeting (*3*) concerning plant life extension has been summarized [*ibid.* **49**, 328 and following reports (1985) (six papers)].
11. The "World list of nuclear power plants" [*Nucl. News* **30**, 75 (February 1987)] gives nuclear plants, with a generating capacity totaling 87,262 MW, now operable in the United States, but some of these units are shut down and may not be restarted. Of units having another 8978 MW that were scheduled to be added in 1987, some may not make it through the operating-license process. Of reactors with an additional 11,210 MW scheduled to operate in 1988 and 1989, only a few units are likely to be completed. Almost all reactors with later schedules can be considered to be on indefinite hold.