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MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

The Fast-Neutron Breeder Fission Reactor: Development, Operational Experience, and Implications for Future Design in the United States [and Discussion]

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The fast-neutron breeder fission reactor: development, operational experience, and implications for future design in the United States

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As the need for breeder technology in the United States has receded into the more distant future, it has become clear that an alternative justification must be found for continued priority development of sodium-cooled fast-reactor technology. Both the modular high-temperature gas-cooled reactor and the liquid-metal-cooled reactor (LMR) have technical attributes that provide more simple and transparent solutions to some of the problems confronting the nuclear enterprise, in addition to their potential for greater market penetration, resource extension, and waste management improvements. For the past five years, the LMR development programme in the United States has attempted to use these technical attributes in more innovative ways to provide more elegant solutions for the practical commercial application of nuclear energy.

This paper discusses the reasons and status of the technological approaches that have evolved to support these policy considerations. For the LMR, efforts are focused on four interrelated development thrusts: (1) increased use of standardization; (2) passive safety approaches; (3) modularity; and (4) improved fuel cycle approaches. The paper also discusses the status of related design activities being conducted by the General Electric Company and a team of U.S. vendors.

HISTORICAL PERSPECTIVE

The sodium-cooled fast-neutron breeder fission reactor has been the subject of intense research and development efforts in the United States and throughout the world during the past 40 years. In addition to the logical benefits of breeder technology, such as increased efficiency of uranium consumption, these efforts were driven by a seemingly inescapable future scenario: world demand for electricity was rising steeply while reserves of obtainable uranium were being rapidly depleted. Without uranium to fuel reactors, the clean, inexpensive, nuclear energy that provided a growing share of the world's electricity would be unavailable to meet the needs of the 21st century.

Thus, in the early 1960s, the planning of the U.S. Atomic Energy Commission (AEC) was predicated on a future shortage of uranium ore that would eventually lead to destabilization of the market price unless the uranium fuel were used more efficiently. Electricity consumption before the energy crisis of 1973 was growing at an annual rate of 7%, with nuclear energy rapidly displacing coal as a prime source of additional power for much of the world. In 1974, the AEC projected the U.S. electrical generating capacity from nuclear energy would reach between 850 and 1400 GW_e by the year 2000. This estimate was half of the total U.S. electrical generating capacity forecast for that same year. This rate of growth, coupled with a shrinking uranium supply, made it clear that few light water reactors (LWRS) could be operated beyond the early 1990s. Obviously, a significant commercial breeder deployment would be required near the end of this century. As commercial deployment of LWRs proceeded, planning for the next generation of reactors was begun. These new reactors would be capable of recycling the enrichment plant tails from the LWR fuel cycle and the reprocessed plutonium stockpiles accumulating from spent LWR fuel. Eventually, the excess plutonium produced in these breeders could be used to fuel additional LWRs, substantially reducing the need for enriched uranium. To meet these requirements, increased emphasis was placed on the early development and demonstration and rapid deployment of breeder reactors (see figure 1).

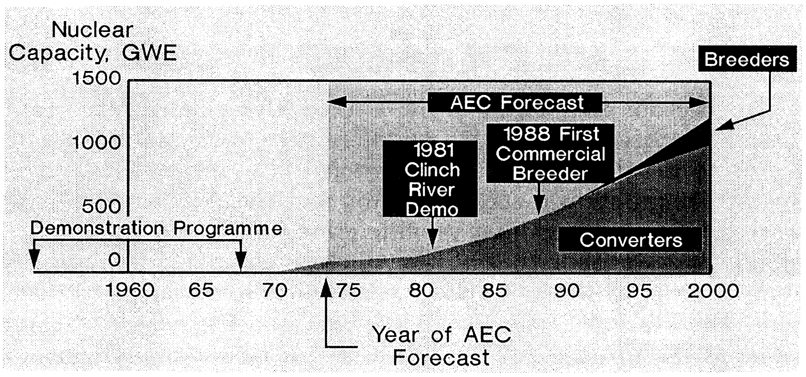

FIGURE 1. Early assumptions for the nuclear R&D programme.

Plans were made for several liquid-metal fast-breeder-reactor demonstration projects, the first being an intermediate-sized plant in the 300–400 MW_e range that ultimately became the Clinch River Breeder Reactor Project. The plant was scheduled to begin operation in 1981. This new breeder reactor would demonstrate a more efficient utilization of uranium resources by recycling spent fuel and consuming the waste products of the LWR fuel cycle. The anticipated success of the Clinch River Breeder Reactor Project led to plans for building the first commercial breeder reactor, scheduled to begin operation in 1988.

However, predictions of future uranium shortages and a continued high growth in electricity demand did not materialize in succeeding years. Following the energy crisis of 1973, growth in electricity demand averaged less than half of that predicted, creating an excess of electrical generating capacity. This excess capacity caused a decrease in the need for large central station power plant construction and by 1977 36 reactor orders were cancelled. Double-digit inflation in the 1970s also contributed to the cancellations of new plant orders, as estimates of investment costs escalated and extreme financial constraints were experienced by electric utilities. Also during this period, reserves of recoverable uranium doubled as a result of new exploration and assessments, further easing concerns about long-term uranium supply (see figure 2).

To keep breeder reactor R&D viable and continue the pursuit of its potential benefits, several difficult realities had to be confronted in the late 1970s and early 1980s. In 1977 the U.S. government announced a ban on commercial reprocessing and recycling of plutonium. Between 1977 and 1983, 75 reactor orders were cancelled by electric utilities. These cancellations were largely due to increasing financial risk and regulatory complications, as well as growing public concerns about nuclear safety after the 1979 incident at Three Mile Island. Also, growth in electricity demand had slowed and the cost of new plant construction was rising dramatically as interest rates on loans escalated to nearly 20%. These factors slowly eroded Congressional support for the Clinch River Breeder Project, until the U.S. Senate discontinued

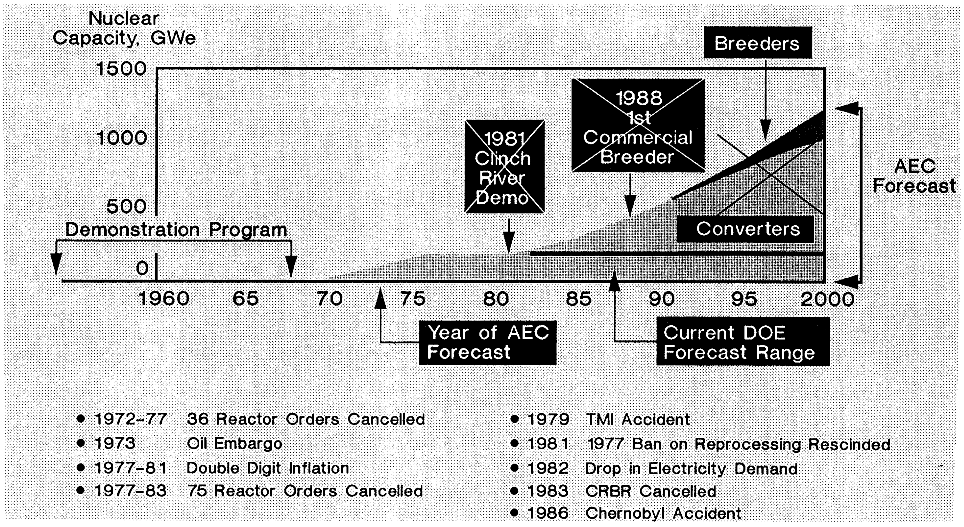

FIGURE 2. Realities of the 1980s for the nuclear R&D programme.

funding for the project in 1983. Finally, the accident at Chernobyl in 1986 raised world-wide concern about the safety of nuclear power plants, even in those countries like France that depend on nuclear power for over 70% of their electricity supply.

These negative factors have been offset by positive developments in recent years. New, advanced reactor and fuel cycle systems have been designed to incorporate the latest safety and engineering features with improved economic performance potential. The 1977 ban on commercial reprocessing and recycling of plutonium was rescinded by the Reagan Administration in 1981. Passage of the Nuclear Waste Policy Act of 1982 offered hope for progress in establishing a programme for long-term management of high-level radioactive wastes. Very recently, the U.S. Nuclear Regulatory Commission (NRC) approved a new licensing rule, representing a potentially significant step towards a reduction in regulatory uncertainty and the time required to construct new nuclear plants.

CHALLENGES TO THE FUTURE OF NUCLEAR ENERGY

Although new breakthroughs in breeder technology have put us within reach of producing an almost unlimited supply of safe, clean, nuclear energy, there are challenges to the future of nuclear energy that still must be confronted. Growth in electricity demand is uncertain. For example, the U.S. Department of Energy (DOE) now forecasts the demand for nuclear energy will range between 50 and 189 GW_e in the year 2020. The cost of new plant construction has increased tremendously, creating an unacceptable financial risk for investors. Decisions by state Public Utility Commissions affecting cost recovery have created more economic uncertainties, as have the regulatory, licensing and retrofitting requirements placed on plant construction and operation. Public support for nuclear energy is still mixed. Though public opinion polls reflect serious concerns about nuclear reactor safety and new plant construction, polls also show that a large majority of the American people believe that nuclear energy must play an important role in supplying the energy needs of the future.

Other challenges must also be met. The cost of plant operations and maintenance are rapidly escalating. The complexity of plant operations and repairs is increasing, due to the multitude of engineered safety systems added to plants following the accident at Three Mile Island and the greater attention paid by utilities to preventative maintenance. Many plants are nearing the end of their licensed lifetimes, raising the issue of extending plant lifetimes and licences. Finally, waste management plans for burying high-level waste in storage repositories are coming under increased scrutiny by the public, the U.S. Congress and electric utilities.

TECHNICAL RESPONSES

To meet the challenges now confronting nuclear energy and revitalize nuclear power as an alternative energy source, the United States DOE has focused on advanced reactor concepts incorporating four key technical responses: (1) passive safety, (2) modular construction, (3) standardization and factory fabrication, and (4) improved fuel cycle approaches. The challenges are many: waste management; financing; uncertain load growth; plant life, operations and maintenance; complexity; public attitudes; regulations.

Passive safety

In contrast to currently operating nuclear power plants that rely on engineered back-up systems to provide an adequate safety margin, plants incorporating passive safety features use the laws of physics to achieve emergency cooling and control the nuclear reaction. Passive means such as gravity and natural circulation automatically match heat production to heat removal and provide emergency cooling to the reactor core. Should a heat imbalance in the reactor occur, radiation would be contained and core damage avoided without reliance on operator action or external power. Such a system of passive safety features would eliminate the possibility of human error in response to unusual events in the reactor core, effectively preventing the repetition of accidents like those at Three Mile Island and Chernobyl. Other benefits of passive safety design include simpler plant operations and maintenance, better protection of capital investment, reduction in plant investment cost, and an improved public perception of reactor safety.

Modular construction

The development of modular, standardized, factory-fabricated reactors would allow a more simplified licensing procedure and more cost-effective construction and operation activities. Quality control and quality assurance would be improved due to standardized design and shop fabrication of components. Factory-fabricated modules and components could be shipped overland or by barge and assembled on site. This minimizes site erection time, difficulties, and inspections thereby greatly reducing total construction time. Finally, a modular design would allow utilities to add modules by increments, increasing capacity as increases in electricity demand occur.

Standardization and factory fabrication

Standardization of plant design is an important, cost-effective aspect of the advanced reactor concept. Design standardization would eliminate the cost of custom designs and make NRC certification and one-step licensing possible. Certification of reactor designs, factory-fabricated components, and preapproved plant sites would also decrease the time and cost required for construction. Operations and repairs would be less costly and time-consuming, because standardized reactors would feature optimum placement of systems and components, as well as improved control and operating systems.

Improvements to the fuel cycle approach

Improvements to the fuel cycle include simple, economical fuel fabrication as well as reprocessing and recycling of spent fuel back into energy production. Reprocessing and conversion of spent LWR fuel into fuel for advanced reactors offers a partial solution to the problem of long-term storage of high-level LWR wastes. Recycling reactor waste products consumes the long-lived actinide elements like plutonium 239, neptunium, and americium that require extensive, long-term storage. Depletion of almost all of these actinides, i.e. a 10^5 reprocessing depletion factor, reduces the level of radiological risk associated with high-level reactor wastes to $\frac{1}{100}$ or less of the risk from natural uranium ore and shortens the required storage term of reactor waste products from a million years to only two or three hundred years (see figure 3).

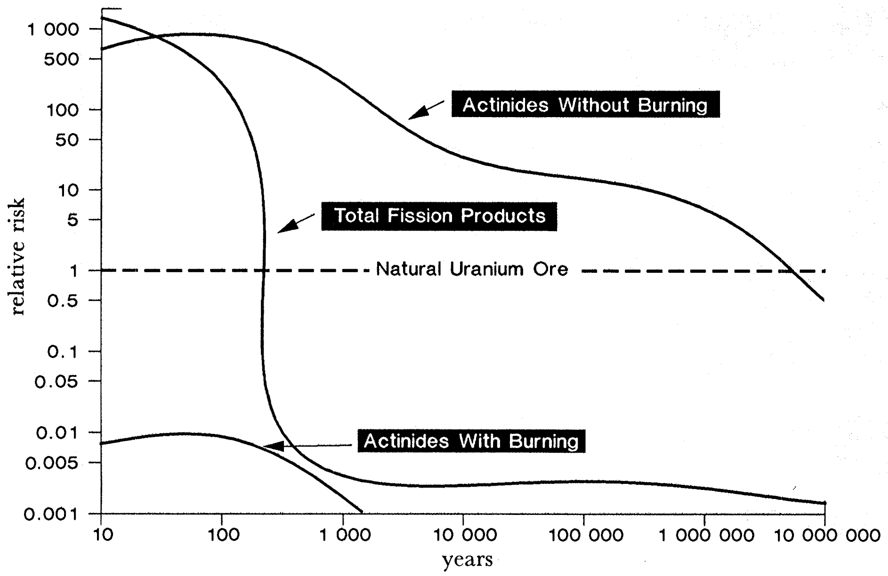

FIGURE 3. Relative risk for spent fuel waste.

DOE's LIQUID METAL REACTOR CONCEPT

The LMR concept has a sound technology base, with over four decades of R&D conducted in the United States and other countries. A network of government and industry research facilities and engineering test centres in the U.S. is currently providing test capabilities and the technical expertise necessary to conduct an aggressive advanced reactor development programme. Notable among these research facilities are the two operating LMRs, the Fast Flux Test Facility (FFTF) at Hanford, Washington, and the Experimental Breeder Reactor-II (EBR II) at Argonne National Laboratory (ANL-West) in Idaho. Both facilities have compiled excellent performance records, including numerous achievements that contribute to confidence in the choice of the LMR concept for advanced development.

Following three years of advanced liquid metal reactor (ALMR) design studies and development progress related to integral fast reactor (IFR) technology, which will be described later, the DOE programme is centred around two specific, technical objects: (1) the consolidation of LMR development activities around the IFR programme, merging ALMR design R & D with the new IFR technology, and (2) the development of breakthroughs in IFR waste technology that may reduce high-level waste to low-level waste and lead to the establishment of a synergistic fuel-cycle–waste-management relationship between ALMRS and existing commercial reactors (see table 1).

TABLE 1. DOE LMR PROGRAMME HIGHLIGHTS

consolidate LMR development activities around the IFR programme
IFR fuel cycle programme (ANL)
advanced LMR design (GE-PRISM)
advanced IFR technology development
international cooperation
develop breakthrough in waste technology
actinide burner may significantly reduce waste management cost and public concerns (i.e. high-level waste reduced to low-level waste)
establish synergistic fuel cycle/waste management relationship between LMR and/or LWR and HTGR

DOE strategy is to integrate those advancements in IFR technology that best meet the challenges ahead into a national LMR system concept. The DOE's role in this process is to advance the concept to a level such that private industry and international interests can support further development and cooperate in the demonstration of a prototype plant.

ADVANCED LMR DESIGN STUDIES

The DOE assessed the feasibility and economics of two concepts submitted by private corporations: the Rockwell International Corporation's sodium advanced fast reactor (SAFR) and the General Electric Company's power reactor innovative safe module (PRISM). Both concepts incorporated the use of modular, pool-type reactors with core inherent reactivity feedbacks and passive decay heat removal capabilities that bring the reactors to a safe, stable condition following the occurrence of off-normal events. Both designs also utilized liquid sodium as a coolant, because of the advantages of its greater stability of temperature and pressure under normal operating conditions.

Both PRISM and SAFR design concepts were evaluated against programme objects and criteria for commercialization developed from market assessments of utility requirements. These reviews included a formal evaluation process plus independent reviews and assessments by national laboratories and utility organizations, as well as the NRC in the form of preliminary licensing reviews. An NRC safety evaluation report for each of the concepts was prepared.

Throughout 1988, while proposals were being prepared and evaluated, trade-off studies on advanced concept features were conducted. Areas of focus included decay heat removal systems, beyond-design-basis accidents, and technologically advanced plant control systems, in addition to other potential areas of investigation such as steam generators, pumps, refuelling systems, constructability, and containment. These trade-off studies were used to reduce design uncertainties leading to improved safety margins and more cost-effective plant construction and operation.

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IFR TECHNOLOGY DEVELOPMENT

While LMR conceptual design studies were being conducted on two designs, many excellent results were being obtained from the evaluation of the potential of metal fuel based on the IFR concept developed at the Argonne National Laboratory. This concept can be basically described by six attributes: (1) sodium cooling, (2) pool reactor configurations, (3) metallic fuel, (4) spent fuel electrochemical processing and injection-cast fuel fabrication, (5) an optional on-site fuel processing facility, and (6) actinide recycle.

The foundation of this concept is the performance evaluation of the metal fuel cycle that has been used in the Experimental Breeder Reactor II (EBR II) for about 25 years. Due to its greater thermal conductivity, metal fuel has the potential for a significantly improved performance over oxide fuels. Metal fuel offers greater margins of safety, because of its negative reactivity feedback and the generally lower temperatures required for reactor operations. Metal fuel makes possible the use of a smaller core with fewer control rods and provides a better breeding potential. Other benefits include simple, economical fuel fabrication and the possibility of inexpensive, compact fuel recycling. Finally, the flexibility of deployment offered by optional on-site fuel processing and the low cost of demonstration are strong incentives in favour of the use of the metal fuel cycle.

Perhaps the most significant object of the DOE strategy is the achievement of new breakthroughs in waste management technology. The use of metal fuel combined with pyroprocessing techniques that effectively separate the hazardous actinides from other reactor wastes has opened the door to the possibility of actinide-burning reactors, a central theme of the ALMR concept. These actinide-burning reactors can greatly lower the risk of waste management by consuming the long-lived actinides produced as waste products of operation and reducing the current stockpiles of waste actinides produced by LWRS.

The ultimate goal of actinide burner development is the establishment of a synergistic fuel-cycle–waste-management relationship between LMRS and the LWRS and HTGRS. In this way, the waste produced by non-recycling reactors would be reprocessed and used as fuel for LMRS, eliminating much of the worst of the problems of waste storage and providing an efficient, cost-effective method of uranium consumption. Such a system would also serve to ease public and governmental concerns regarding the storage of these high-level actinide wastes.

Two national engineering test facilities, the EBR II and the FFTF, are principally involved in the development of metal fuel technology. A ternary alloy, uranium–plutonium–zirconium, is currently receiving primary attention. A major demonstration of the fuel cycle is planned for EBR II in 1993.

POWER REACTOR INNOVATIVE SAFE MODULE (PRISM)

In late 1988, DOE focused its future LMR development activities on the PRISM design concept. Accordingly, the General Electric Company (GE) was awarded a three-year contract for Advanced Conceptual Design for DOE's ALMR programme. This contract includes an optional two-year extension for the preliminary design phase.

Overall plant design

The initial conceptual design for PRISM emphasizes low operating pressure, with compact, pool-type reactor modules sized to enable factory fabrication with minimum site installation labour. Modular design also makes possible economical overland shipment of factory-fabricated modules to inland sites, as well as barge shipment to waterside sites, and an affordable full-scale test for licensing a standard design. Reactor modules can be replaced if necessary and their capacity can be expanded by the addition of incremental power block units. As currently conceived, these power blocks would consist of three reactor modules. The plant (as shown in figure 4) would be expandable in 465 MW_e module units to 1395 MW_e for a full-scale plant.

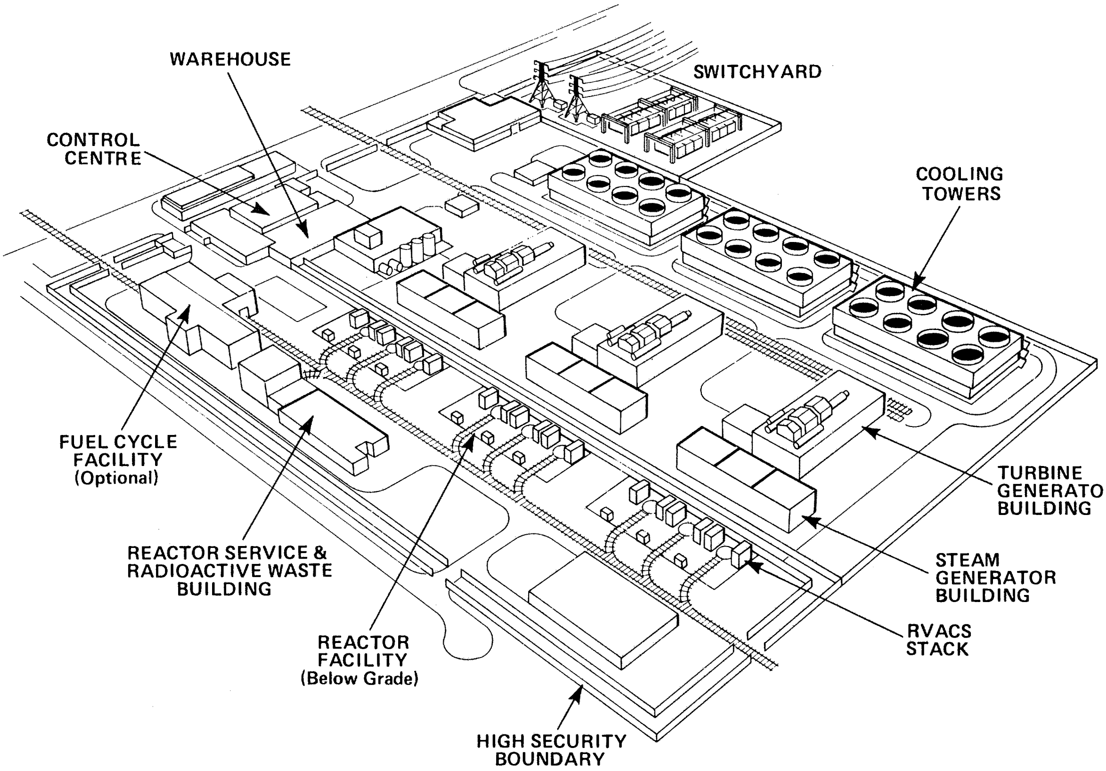

FIGURE 4. PRISM power plant (three power blocks).

The PRISM reactor design features a reference metal core with an oxide core as a back-up. Safety-related equipment is limited to the reactor module and service systems shown in figure 5. The balance-of-plant (non-nuclear section) is to be constructed to industrial-grade, non-nuclear standards to keep construction costs low. The reactor module, the intermediate heat transport system, and most of the steam generator system are below ground.

PRISM's tall, slender reactor geometry enhances uniformity and natural circulation for shutdown heat removal. The relatively small diameter of the reactor offers a vertically stiff structural design, permitting use of simple, horizontal seismic isolation and eliminating any need for vertical isolation. Refuelling operations are planned to be conducted one module at a time, with the reactor shutdown and the primary sodium cooled to 200 °C. The other two modules of the power block would continue to operate during refuelling to maintain availability. PRISM design characteristics are shown in table 2.

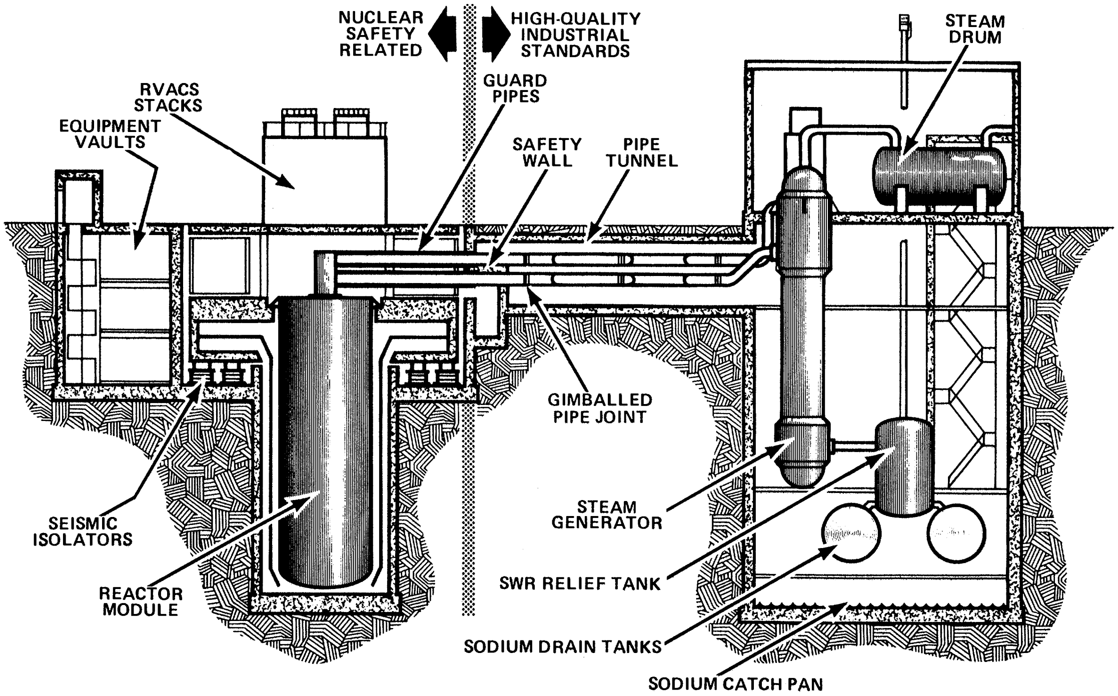

FIGURE 5. PRISM nuclear steam supply system.

TABLE 2. PRISM DESIGN CHARACTERISTICS

overall plant	
number of reactors per power block	three
number of power blocks	1, 2, 3
net electrical output	465, 930 or 1395 MW_e
net station efficiency	32.9%
turbine throttle conditions	6.6 MPa/282 °C (saturated)
reactor module	
thermal power	471 MW_t
primary sodium inlet/outlet temperature	329 °C/485 °C
secondary sodium inlet/outlet temperature	282 °C/443 °C
reactor core	
fuel	metal (oxide back-up)
refuelling interval	18 months
breeding ratio	1.12, reference 1.23, capability

Fuel

Uranium–plutonium–zirconium metal fuel is the reference fuel for the PRISM concept. This selection was based on the excellent negative reactivity feedback it provides for loss of cooling and transient overpower events; the expected, competitive fuel fabrication costs; and the excellent, inherent safety performance of metal fuel demonstrated in the Experimental Breeder Reactor at the Idaho National Engineering Laboratory (see figure 6).

Inherent safety design

In the unlikely event that the normal intermediate heat transport system becomes unusable during power operation, as in the case of a main sodium pipe break or a sodium dump, the reactor will scram and the continuously operating reactor vessel auxiliary cooling system

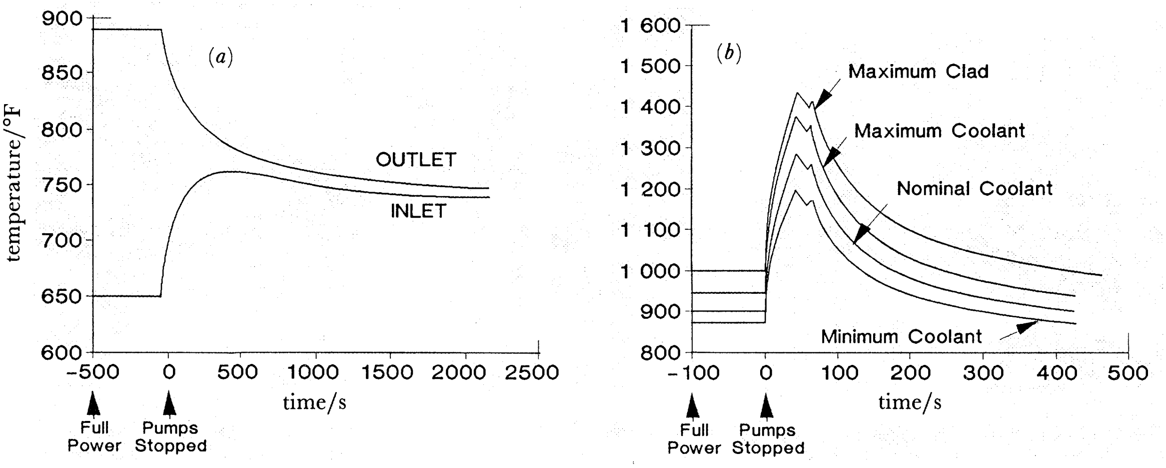

FIGURE 6. EBR-II tests demonstrate inherent safety. Reactor temperatures remain within design limits and drop quickly without human or engineered intervention. (*a*) Loss of heat sink without scram (secondary pumps circulating sodium through reactor stopped; plant protection system not activated). (*b*) Loss of flow without scram (primary pumps circulating sodium in the pool stopped; plant protection system not activated). (To convert from the Fahrenheit to the Celsius scale: subtract 32 and multiply by $\frac{5}{9}$.)

(RVACS) will automatically and passively take over the function of full decay heat removal. As temperatures rise, heat transfer to the atmospheric air circulating upward around the containment vessel will increase, until an equilibrium between reactor heat generation and RVACS cooling is established.

The redundant air flow passages, combined with substantial margins in the design, make RVACS extremely tolerant of accidental flow blockages as well as surface fouling. Even with 90% air blockage, the temperature remains well within safety margins.

The PRISM core is designed to provide a strong negative temperature reactivity coefficient. This design characteristic, combined with the RVACS heat removal capabilities, makes PRISM capable of safely withstanding accidental transients without scram.

Technical and policy issues are being resolved to support NRC licensing activities, while critical trade-off studies, evaluations, and assessments to support the initial conceptual design have been completed. Independent cost verification studies and assessment of potential cost reductions have also been performed. Ongoing activities to support advanced conceptual design include more critical trade-off studies and interaction with the NRC on advanced reactor licensing.

Progress on licensing

Interaction with the U.S. NRC has been ongoing and will continue throughout the PRISM design development process. Efforts are being made to resolve licensing issues at the earliest possible stages of development. These efforts are primarily targeted at establishing an efficient, 'one-step' procedure for licensing advanced reactors. A Preliminary Safety Information Document (PSID) has been submitted to the NRC and a Draft Safety Evaluation Report on the PRISM design is expected to be released by the NRC in 1989. Based on this evaluation, the DOE will prepare a 'safety issues' resolution plan for required technical work related to the reference power plant design. A Preliminary Safety Analysis Report (PSAR) will be submitted to NRC. Required licensing documents such as the PSID and PSAR detail reference concept safety features and systems, R&D test results, and plant design data. Fulfilling the requirements needed for

NRC licensing and design certification is considered a necessary milestone before proceeding with further development and demonstration.

OTHER TECHNOLOGY DEVELOPMENT

Crucial to the pursuit of the DOE's goals for PRISM is the performance testing of new components and materials to be used in the advanced LMR design. Extensive use is made of the national laboratories and engineering test centres to verify predicted behaviour of components, materials, and systems.

Core R&D

Core systems R&D involves testing of passive safety features, materials properties and performance, and core design technology. Passive safety testing includes design and testing of the self-acting safety features proposed for use in advanced LMR designs. These features assure termination of the fission chain reaction process, returning the reactor to a safer, cooler state under a wide range of component and control system conditions. Also included are tests of the decay heat removal systems, the mechanical features of the core design, and the temperature-dependent reactivity feedback coefficients.

Materials R&D

Materials R&D is conducted to test the high-temperature properties and irradiation performance of core alloys and out-of-core structural alloys to the fluences and temperatures desired for LMR applications. This programme develops engineering property data and manufacturing processes for cladding, ducts, structural materials and absorbers, and other materials. The programme also provides irradiation testing services and material behaviour correlations for use in design and performance analyses. Completion of the proposed R&D tasks is expected to increase fuel life and reduce fuel cycle costs by a factor of two or more over currently available technology. This will result in major cost savings in the operation of advanced LMRS.

Systems R&D

Systems technology includes work on components, advanced instruments and controls, and auxiliary systems. This type of R&D attempts the improvement of overall plant performance, which is needed to ensure cost-effective construction and operation of the proposed PRISM advanced LMR.

Advanced instruments R&D

Advanced instruments and control R&D addresses the design, testing, and performance demonstration of new, state-of-the-art instrumentation and control systems, which will reduce plant cost and improve the licensability of advanced LMRS. Systems being tested include radiation detection, sodium pressure and temperature measurement, automated plant control, 'smart' sensors and diagnostics, and in-core neutron flux monitoring.

Work also continues on the long-term task of testing and validating advanced control system designs using simulation, with emphasis on the applications of parallel processing to the improvement of simulation speeds and real-time simulation techniques. A large reactor simulation programme has been converted to parallel processor code and is in the final stages of debugging. Significant speed-ups have been obtained with parallelization, with the code currently running up to 600 times real time. The knowledge and techniques acquired in this exercise will be applied to the advanced controls programme demonstration projects.

Auxiliary systems R&D

Research and development is required to determine the best design for major auxiliary systems, including fuel handling, vessel support, in-service inspection, sodium leak detection, and remote maintenance. R&D is directed at those critical features that differ significantly from FFTF or EBR II operating systems, and offer potentially significant future cost savings, improved reliability, and increases in plant availability. One area generating interest is a bottom-support plant design concept that features reduced seismic loads and a lower cost.

At the Energy Technology Engineering Centre (ETEC), emphasis is currently being placed on steam generator performance testing. Activities centre around helical coil steam generator testing and preparations for testing a double-wall-tube steam generator in a cooperative programme with the Japan Atomic Power Company (JAPC). This programme also includes testing of a JAPC few-tube model steam generator, as well as testing of advanced technology and materials such as modified 9Cr–1Mo steel and improved chemical and acoustical leak detection systems.

Oxide fuel R&D

In addition to continuing these development activities, the United States is completing the R&D necessary to validate the oxide fuels database for use domestically and internationally as a back-up to metal fuels. To this end, the United States and Japan have entered into an agreement to complete the oxide fuel R&D programme on a equal cost-sharing basis. Although current emphasis in U.S. LMR R&D is on the utilization of metal fuels, great benefit is attached to the completion of oxide fuel development as a contingency for the future. Continued cooperation with Japan in this area is considered a highly important part of the U.S. nuclear research programme.

DEPLOYMENT

As a closed system, the LMR complex is composed of a reasonable number of reactor modules and facilities for accepting feed material, fabricating fuel elements, reprocessing spent fuel, and storing waste products all within a single site. The LMRS can be loaded initially with uranium or plutonium, or with the converted spent fuel from LWRS. Non-actinide waste products would eventually be moved to a terminal storage repository.

LMR complexes of this type would be deployed in numbers that would consume spent LWR fuel at a higher rate than it is produced. Utilizing spent LWR fuel in this way would reduce the stockpiles of spent LWR fuel currently in storage and lower the associated biological risks.

ECONOMIC BENEFITS OF ADVANCED REACTORS

In addition to improved safety and waste management, one of the most important goals of the DOE's ALMR programme has been the lowering of costs associated with nuclear energy. While historically nuclear energy began as a much less expensive alternative to coal, increasing capital, operations, and maintenance costs have reversed that earlier advantage. Reasons for these rising costs have been predominantly associated with lengthened construction time, increased regulation, and higher labour costs.

As shown in figure 7, the indirect costs associated with extended construction time (loan interest, architect and engineering fees, repeated field inspections, management and administrative fees, etc.) are the largest uncertainties affecting investment and cost-recovery. These indirect costs comprise the greater share of the overall capital cost of commercial reactors today. However, these indirect costs are estimated to be significantly lower for advanced reactor designs like the ALMR, for which equipment and materials make up the largest share of investment expenditures.

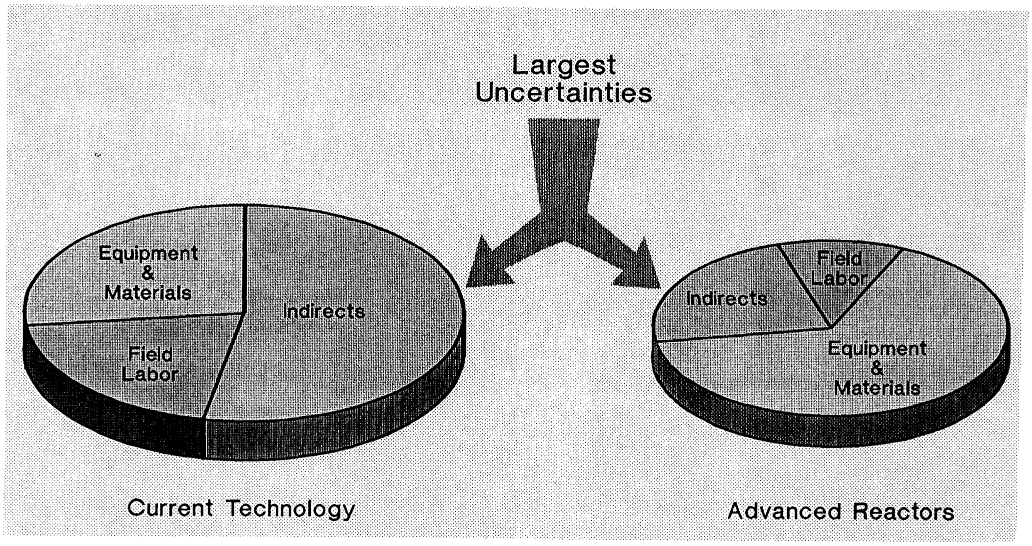

Figure 7. Nuclear plant estimated cost distribution can be favourably altered.

Standardized design, factory-fabricated components, and more simplified licensing procedures are the major reasons for the lower indirect cost of ALMR construction. Standardization and factory-fabrication enable certification of design and preapproval of sites, thereby reducing construction time. Necessary licensing reforms are in progress, as evidenced by the recent NRC ruling to streamline licensing procedures for standardized advanced plants. This potential advantage of ALMRs represents a major improvement over present commercial reactor designs.

Other factors have contributed to the rising cost of nuclear plant operation. Greater plant complexity as a result of design changes, added safety systems, and backfitting have adversely affected labour productivity and raised operations and maintenance costs. Standardized ALMR design and factory-fabricated components make normal operations, maintenance, and repairs much more simple, less expensive procedures.

As shown in figure 8, the estimated future cost per kilowatt hour of electricity produced from advanced reactor systems with conventional balance-of-plant construction is significantly less than that of sources like coal and present-day, commercial LWRs.

Table 3 shows the advanced technology goals each of which has a direct impact on future economics.

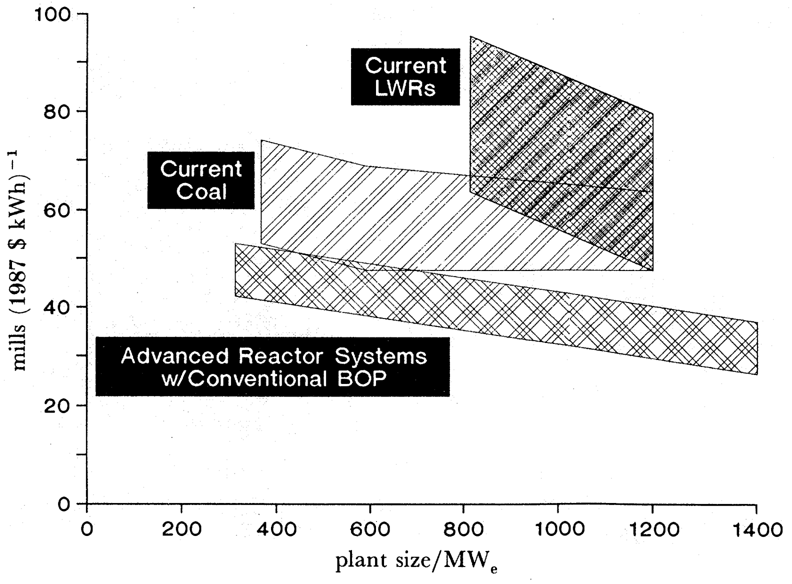

FIGURE 8. Estimated economic benefits from advanced reactors.

TABLE 3. COMPARISON BETWEEN CURRENT LWRS AND ALMRS

	current LWRS	advanced LMRS
plant availability	≈ 70 %	$\ngeqslant$ 87 %
plant life	40 years	60 years
construction schedule	6–10 years	4 years
life cycle costs	100 mills kW h^{-1}	65 mills kW h^{-1}
low-level waste production	10–35000 cu ft[a]	2500 cu ft[a]
severe core damage	1/10000 reactor years	1/100000 reactor years

[a] 1 cu ft ≈ 2.8×10^{-2} m^3.

FUTURE DIRECTIONS IN ALMR RESEARCH

Future directions of the United States ALMR programme are centred around two activities. First among these is the continued pursuit of PRISM–IFR concept development through design evolution, trade-off studies, and the development of advanced systems and components technology, leading to a completion of the PRISM preliminary design by 1993. This design would incorporate the use of metal fuel with other IFR technology so that electrical utilities and international interests can evaluate the preliminary design for potential commercialization (see figure 9). Second, is the completion by 1993 of the IFR fuel cycle demonstration to confirm its potential for improved cost-effectiveness, safety, performance, licenseability, and effective waste management. It is planned that the EBR II facility will perform a prototypic demonstration of the IFR fuel cycle with fuel at target burn-up levels and spent fuel being recycled and returned to the reactor. With continued progress in research and development of the IFR concept, the ALMR technology could be available for commercial deployment early in the next century.

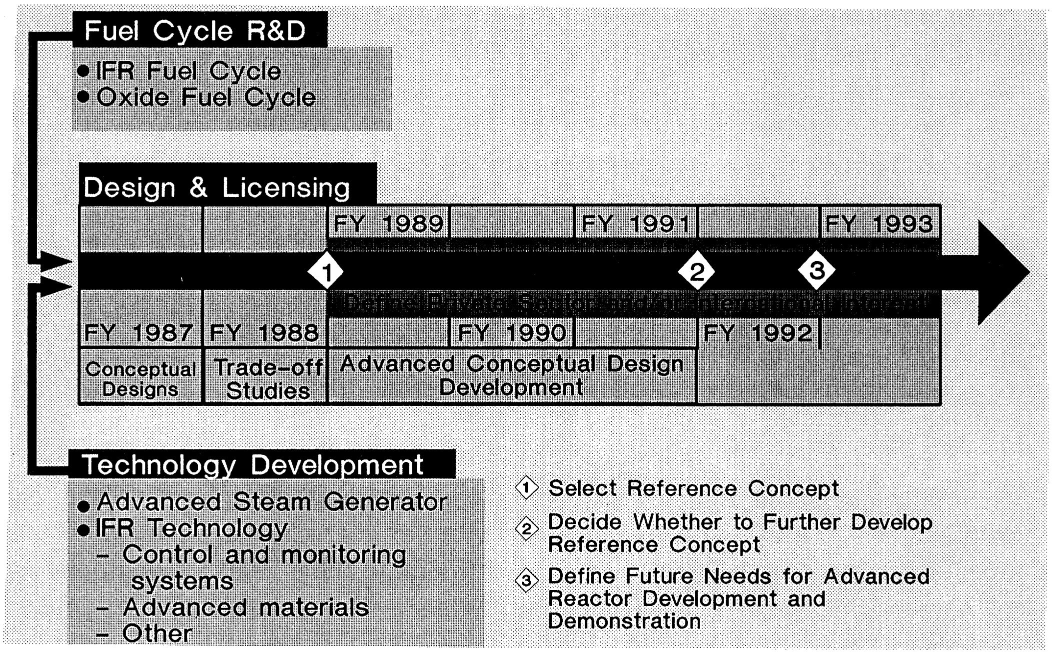

FIGURE 9. Advanced LMR programme schedule.

CONCLUSION

The United States Nuclear Energy programme is committed to the development of the sodium-cooled, fast-neutron breeder reactor as an improved approach for supplying the energy needs of the next century. Though many challenges confront the future of nuclear energy in the United States, the technology appears available to overcome those challenges. The most difficult issues facing the use of nuclear power today are the safety of nuclear reactors and the benign management of the waste products they produce. We believe the ALMR design can offer improved solutions to those problems, making nuclear energy the safest, cleanest, and least expensive source of energy.

The PRISM–IFR concept is already making great progress towards the achievement of that goal. With continued research and development, the United States and participating nations may soon demonstrate to the world an advanced nuclear reactor design that will liberate future generations from the problem of obtaining electrical power at the cost of environmental pollution and provide a potentially limitless source of energy for the century to come.

Discussion

D. E. J. THORNTON (*UKAEA*, *Risley*, *U.K.*). As the former chairman of the OECD Nuclear Energy Agency (NEA) committee concerned with making forecasts of future nuclear growth, I was interested that Dr Griffith's demand projections were much higher than those favoured by the Americans on that committee, who tended to press for the adoption of low or zero growth rates and low energy:GDP ratios. Has there been a change of heart on the part of the U.S. forecasting agencies and if so why?

J. D. GRIFFITH. Some of my illustration was based on facts, for example, growth rates up to the end of 1988. I also showed a range for the future as given by the Energy Information

Agency. It is important to note, though, that we do not need growth rates as high as $3\frac{1}{2}\%$ for there to be a need for new capacity in the 1990s, 1–2% will be sufficient.

P. Dastidar (*IAEA, Vienna, Austria*). For the requirement of future water reactors, I understand that Electric Power Research Institute (U.S.A.) is working out detailed criteria and requirements for safety and good economic performance. Some of these requirements could be generic to all reactor types. Are the advanced fast reactor designs taking these criteria and requirements into account?

J. D. Griffith. Yes, the long time between now and 1993, when we hope to gain a licence for operation, will be taken up with this time-consuming work.

L. E. J. Roberts, F.R.S. (*University of East Anglia, Norwich, U.K.*). (1) What is the temperature of the molten salt reprocessing step and what experience does Dr Griffith have of dealing with the species that are volatile at that temperature? (2) Recent research shows that actinides need not be mobile in a waste repository because they are insoluble under alkaline conditions. Is the major advantage of a technology that removes the actinides thus a presentational rather than a technical one?

J. D. Griffith. (1) The temperature is around 600 °C. There are no particular problems in dealing with volatiles, some of which are produced when the clad is stripped from the fuel anyway. (2) I believe that removal of actinides is mainly advantageous in terms of public perception rather than for technological reasons, though there are possible cost benefits and earth movements can occur.

R. H. Allardice (*BNFL, Risley, U.K.*). Dr Griffith and I have debated cost projections for the metal fuel cycle before and I will not raise those questions here. However, would Dr Griffith say how much tertiary alloy fuel has been manufactured and recycled?

J. D. Griffith. Less than 10 prototypic elements are under irradiation and none have been recycled. However, laboratory scale tests have been carried out.

F. Penet (*CEA, Cadarache, France*). Although Dr Griffith said that the PRISM reactor concept gives increased safety margins, is this not due to the reduced reactor size rather than its use of metal fuel? Metal fuel may be advantageous in some specific incidents due to the smaller Doppler effect but oxide fuel could be better in other types of transient. In addition, the possibility of a eutectic being formed between metal fuel and clad at around 700 °C reduces the operating temperature safety margin.

J. D. Griffith. Metal fuel is not superior in all respects to oxide fuel. Its melting point is inferior for example but the design has a power-to-melt factor twice that of oxide. We see no problems with the temperature at the fuel–clad interface, though we are considering replacing the glass liner used in fuel fabrication with a zirconium one. The fundamental advantage of the PRISM or metal fuel design is that it can tolerate all transients without calling on the scram system to operate. With oxide fuel the scram system is required.