Improved and Safer Nuclear Power

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Recent progress in advanced nuclear power development in the United States is revealing high potential for nuclear reactor systems that are smaller and easier to operate than the present generation. Passive, or intrinsic, characteristics are applied not only to provide inherent stability of the chain reaction but also to ensure continued cooling of the fuel and its containment systems even if a major breakdown of the normal cooling and control functions were to occur. The chance of a severe accident is thereby substantially reduced. The plant designs that are emerging are simpler and more rugged, have a longer life span, and place less burden on equipment and operating personnel. Modular design concepts and design standardization are also used to reduce construction time and engineering costs, giving promise that the cost of generating power from these systems will be competitive with alternative methods.

THE HIATUS IN NUCLEAR POWER GROWTH HAS PROVIDED time for introspection by the U.S. electric utility industry, which has resulted in new trends in nuclear power development. If these trends are successfully realized, future nuclear power capacity will be substantially improved and safer. This article summarizes the issues faced during that introspection, the new design features that are emerging, and the level of progress achieved to date by three reactor systems of primary interest in the United States—those cooled by ordinary, or light, water, by liquid metal, and by gas.

Introspection

The pattern of this technical introspection has been to assess the strengths and weaknesses of the existing technology and then to pursue new technological opportunities and remedies that enhance the strengths and minimize the weaknesses of future systems. The strengths have been considerable. In the United States, 107 nuclear power plants have full power licenses and are generating approximately 18% of the electricity for the nation. Worldwide, 414 plants are operating in 26 countries, generating 298,000 megawatts of electricity (MWe), accounting for 16% of the world's total generating capacity (*1*). This tremendous block of power has been delivered, on the average, with greater safety, with less environmental impact, and at less cost than most other prevailing methods of generating base-load electricity.

But there have been two major flaws in the U.S. record. A severe accident occurred in 1979 at the Three Mile Island (TMI) plant, a light water reactor design of the type that now generates 85% of the world's nuclear-generated electric energy. Meltdown of about half of the fuel occurred, but the public was protected from hazardous radiation releases by the rugged containment that had been provided for that purpose. Even though this stringent test of nuclear power safety had been passed, public and political apprehension as to safety rose sharply. Concern on the part of utility management rose in addition because of the loss of the TMI plant investment and related financial consequences that brought the utility to the brink of bankruptcy.

The second flaw has been economic. The oil shocks of the early 1970s brought on a sharp reduction in electricity demand, emphasis on energy conservation, and de-emphasis on large, base-load plants. The rapid escalation of construction costs of those nuclear plants completed in the United States in that period has made them uneconomic compared to coal plants at present-day coal prices. This has been principally a U.S. phenomenon. The other major industrial countries have kept their nuclear costs in line: their nuclear power plants have remained economically competitive compared to their coal plants. Two reasons for this difference in cost have been (i) the strong effort to standardize nuclear plant design and (ii) the ability to maintain an orderly regulatory process, particularly in France and Japan. The United States for the most part did not standardize plant design, and the regulatory process has been subject to constant change and legal delay.

In addition, the opportunity to counter these high capital costs with high operating capacity factors and low operation and maintenance costs was missed in the United States. Although some U.S. plants have operated as well as any in the world, others have experienced poor performance. The end result is that the average capacity factor in the United States is about 60%, compared to a range of 75 to 85% in some countries. In addition, U.S. operations and maintenance costs are averaging roughly twice those of other countries.

The U.S. utilities have set goals to bring their average performance and cost effectiveness to a world-competitive level while keeping top priority attention on safety in what is termed by the industry the "drive for excellence." Central organizations have been set up by the industry to help implement this drive: the Institute for Nuclear Power Operations to establish operating and training standards, to monitor compliance by the utilities with them, and to exchange safety-related field experience; the Nuclear Management and Resources Council to address safety and regulatory issues and obtain industrywide commitments to resolve them; and the Electric Power Research Institute (EPRI) to evaluate and sponsor related R&D to resolve safety issues and improve reliability. A parallel and equally important remedial action is the responsibility of the Department of Energy (DOE)—the development of a permanent repository for the radioactive spent fuel discharged from these operating nuclear plants, although progress toward this goal is painfully slow.

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Common Advanced Reactor Development Goals

In addition to the improvements being made on current plants, the lessons from past experience can be more fully reflected in future plants. The primary thrust in U.S. advanced reactor development is to remedy these past flaws by design improvements that achieve five primary development goals. These goals, which have been set for all three reactor systems, are as follows:

1) Assured safety with features that minimize the negative consequences of human error: especially a reduction in the chance of occurrence of severe core damage by at least a factor of 10 less than the rate of present designs.

2) A significantly simpler design, with increased safety and performance margin in key operational parameters.

3) High reliability throughout a lifetime on the order of 60 years; an increase in plant availability to ≥85% from the present average of less than 70%.

4) Reduction in capital, operating, maintenance, and fuel costs to meet the economic competition with coal-burning generators; a reduction in construction time to the range of 3 to 5 years as compared to more than 10 years for recently completed nuclear plants.

5) A design that is standardized at a high-quality level and predictably licensable.

A survey of the reactor development effort on the principal systems—the light water reactor (LWR), the liquid metal reactor (LMR), and the high-temperature gas-cooled reactor (HTGR)—shows that common generic technical features are being developed to respond to these goals: passive stability, simplification, ruggedness, ease of operation, and modularity. These features, coupled with standardization and assurance that the plant is licensable, can achieve economic competitiveness.

Passive stability. A primary means of achieving the improved safety goals is to increase the passive stability of the reactor plant. The use of passive design characteristics to ensure core stability, that is, to eliminate the potential for a runaway chain reaction, has been a hallmark of reactor development from the outset. These passive characteristics are internal governors; that is, physical laws ensure that the reaction rate decreases instantaneously as the temperature of the coolant or fuel or the power of the reactor increases, without the aid of external control devices.

Recent emphasis in reactor development is to use passive features in the plant cooling processes to ensure that the core is cooled adequately at all times. As a result, dependence on active equipment and prompt operator actions, particularly for emergency cooling, is reduced. Examples of such features are natural circulation, gravity, gas expansion, and built-in heat sinks.

The primary purpose of these features is to prevent the occurrence of a severe accident that would release radioactive material from a core meltdown. But protection of the public and the environment is also provided through containment or confinement systems that keep radioactive material from escaping from the plants even if a severe accident were to occur. In the advanced LWR, the integrity of containment is improved by providing passive containment cooling. In both the LMR and HTGR designs, confinement systems are being used because confinement, in lieu of containment, tends to enhance the passive core cooling features of these designs.

Simplification. A great increase in the number of components, piping, instrumentation, and cabling has occurred in more recent plants as new requirements were identified. For the most part, these requirements were met by adding more systems to the existing design, an approach that creates complexity. If all of the requirements are known at the start, a far simpler design can be achieved.

Table 1. Principal parameters of passively stable LWR power plants.

Power plant	Thermal power (MWt)	Electric output (MWe)	Net efficiency (%)	Steam conditions (°F/psia)	Core exit coolant conditions (°F/psia)	Core power density (W/cm^3)
PWR	1819	600	33	518°/800	600°/2250	74
BWR	1800	600	33.3	574°/1020	547°/1020	42

Further, the introduction of passive features for cooling permits the elimination of active equipment that previously had performed those functions. Simplification is also achieved by reducing the amount and complexity of equipment used in present systems to optimize thermal efficiency. Field experience has shown a net economic loss from reduced availability caused by maintenance of the more complex systems. Overall, this emphasis on simplicity is expected to result in significant cost savings for future designs.

Ruggedness. Extensive field experience has shown that long-term reliability of certain components and systems has been impaired by trying to achieve the highest in efficiency and economic performance. In response to this negative experience, the margin in certain key performance parameters is being increased in order to lessen the burden on the equipment. For example, by reducing power densities and coolant temperatures, higher reliability will be achieved over a longer lifetime. In addition, field experience has identified more effective methods of coolant chemistry control and materials selection that will contribute to the long-lived reliability of the components of future systems. Finally, greater emphasis is being placed on the selection of proven, high-quality materials and components and on improved methods and quality control over assembly and construction.

Ease of operation. The single greatest concern reflected by the presidential (Kemeny) commission (*2*) that investigated the TMI accident was the lack of attention to the human factor. This issue is being addressed in the development programs in several ways. The computer and telecommunication revolution has made it more practical to use improved technology and human engineering methodologies to revamp the control rooms and the reactor instrumentation systems. These improvements will make the plant easier to operate and provide the operator with a greatly increased amount and quality of information on plant conditions. Graphic displays, diagnostic aids, and expert systems are being developed for such advanced control rooms.

The other design goals complement the new technology to make the operator's task even easier. The passive safety features extend substantially the response time required of the operators in an emergency condition. The margin being built into the systems provides broader normal operating regimes and longer response times for operator action. Simplification also can improve the human factors.

Modularity. Economic competitiveness requires that the construction time be shortened dramatically. Modular construction techniques are a key contributor to achieving this goal and are a proven approach to cost control in major construction projects. Modularization provides for a larger percentage of factory construction, rather than field construction. Most of the design concepts that will rely heavily on modularization are centered around lower unit power outputs, because factory assembly and transportation of modules to a site become much more difficult for very large plants.

Standardization. The French and Japanese LWR experience as well as some limited experience in the United States shows that standardization can reduce capital costs as well as expedite licensing in a

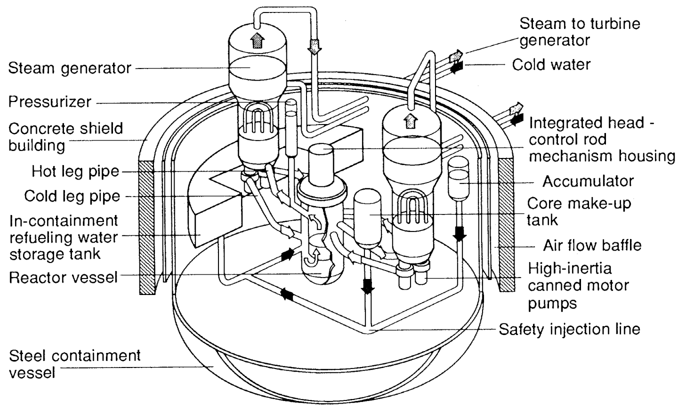
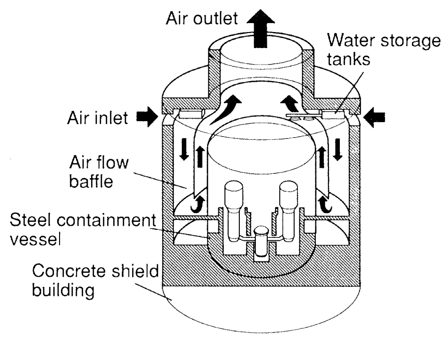


Fig. 1. Advanced passively stable PWR.

Fig. 2. Passive containment cooling system of the PWR.



multiple plant construction program. Both the industry and the Nuclear Regulatory Commission (NRC) are now firmly committed to standardization. Congress and NRC are considering laws and regulations to implement a standardization policy. The development of common utility requirements, including their review and approval by NRC, is an important step toward standardization.

A fundamental technical need is knowledge of which design, fabrication, testing, and licensing characteristics to use as standards. It is in this respect that the standardization task for the LWR systems is further along and easier to achieve than for the more advanced systems.

Improving the licensing process. Although the regulatory process is primarily an institutional matter, the technical features of future designs can contribute to reducing the uncertainties in licensing. The additional passive safety features, the greater margin in performance parameters, factory construction, standardization, and, most importantly, reduction in the probability of a severe accident will contribute to an unambiguous definition of licensing requirements.

Other severe accident experience. After extensive evaluation of the Chernobyl accident (*3, 4*), no new technical lessons have been derived beyond those learned from TMI, principally because the Chernobyl design—light water–cooled but graphite-moderated—is very different from the TMI LWR design. The Chernobyl accident did reinforce the need for core stability and the key importance of the human factor.

Each of the three reactor systems, LWR, LMR, and gas-cooled, has been subjected to a severe accident. In addition to TMI, the Enrico Fermi sodium-cooled reactor in Detroit and the Windscale gas-cooled reactor in England have had accidents that resulted in severe core damage. Each accident has taught essential lessons that have greatly improved the safety of subsequent reactors of each type. In addition, extensive R&D results and field experience have provided detailed and accurate knowledge of accident vulnerabilities and safety system performance and have enhanced the ability to perform analytic evaluations of the total plant risk. The goal of reducing severe accident probability is of economic, as well as safety, importance. The TMI accident demonstrated that public safety was preserved but the plant investment was lost.

The Passively Stable Light Water–Cooled Reactor

The prime U.S. effort to develop a passively stable LWR (*5–7*) is sponsored jointly by EPRI and DOE with substantial contributions from the major U.S. suppliers. The funding to EPRI comes from most of the U.S. utilities as well as utilities in France, Italy, the Netherlands, Japan, Korea, and Taiwan.

Conceptual designs of both a boiling water reactor (BWR) and a pressurized water reactor (PWR) passive plant have been developed. A 600-MWe unit output was selected for two main reasons: (i) to provide the utilities the option of a smaller nuclear power plant and (ii) to make it easier and less costly to incorporate the passive cooling features and provide modularity.

The passively stable PWR. The principal characteristics of the advanced passively stable PWR, called AP-600 (*8–12*), are given in Table 1; schematics of the nuclear steam supply system and the containment system are shown in Figs. 1 and 2, respectively. The conceptual design has been developed by Westinghouse under DOE/EPRI sponsorship.

The power train of the AP-600 uses proven technology: a UO_2-fueled core and field-proven plant components. The burden on the equipment and systems has been reduced by increasing design margins through reductions in coolant temperature, flow rate, and core power density and by selecting higher quality materials and more robust components. Examples of the latter are the selection of alloys with more corrosion resistance such as Inconel 690 for steam generator tubes, the use of canned motor primary coolant pumps proved in naval propulsion application, a larger volume pressurizer, a high-pressure system for the removal of decay heat, and the reactor vessel materials and weldments chosen to reduce radiation embrittlement and shielded to reduce the fast neutron fluence.

Passive cooling in the AP-600 is provided by a passive emergency core cooling system (ECCS) and a passive containment cooling system. The passive ECCS (Fig. 1) consists of a combination of cooling water sources: gravity drain of water (from two core make-up tanks and a large refueling water storage tank suspended above the level of the core) and water ejected from two accumulator tanks under nitrogen pressure. If a feedwater accident renders the steam generators inoperable, core decay heat is removed through a passive residual heat exchanger (located in the refueling water storage tank), which transfers core decay heat to the refueling water by natural circulation.

Containment integrity is ensured by cooling the containment shell by evaporating water that is gravity fed from a large tank located above the containment. The heat is ultimately removed to the atmosphere by a natural circulation air system (Fig. 2). Only automatic valve operations (no operator action and no pump, diesel, or fan operations) are required to provide emergency core cooling and containment cooling after a major energy release into containment from the maximum loss-of-coolant accident.

The use of passive cooling features has effected a substantial simplification of the plant. By comparison with a conventional 600-MWe PWR, bulk commodities of a passively stable PWR are reduced as follows: valves by 60%, large pumps by 50%, piping by 60%, heat exchangers by 50%, ducting by 35%, and control cables by 80%. Because no on-site emergency ac power is needed, many

Table 2. Comparison of major mechanical equipment in passive and conventional BWR, showing number of components.

Component	Passive BWR	Conventional BWR
Pumps	11	41
Valves	171	204
Fans	6	30
Safety-grade pumps and valves	136	185

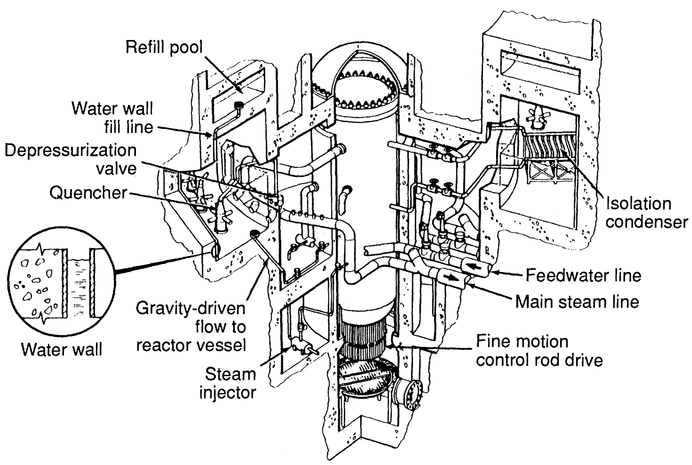


Fig. 3. Features of the passively stable PWR.

safety-grade active components have been eliminated, and the volume of buildings designed to nuclear grade seismic requirements is reduced by 60%.

Experimental verification of these passive cooling features is being carried out under the sponsorship of DOE. Large-scale studies on the construction of modules are also being carried out by Avondale Shipyards and Westinghouse to develop economical assembly techniques in the factory or shipyard. Construction planning also reflects Japanese experience in fabricating, assembling, and installing large modules in their nuclear plants. It is estimated that the smaller, simpler plant, having these modular techniques, can be constructed in 3 to 4 years, because the design is essentially complete before construction starts. The simplified design and shorter construction times are leading to capital cost estimates that counter the loss of "economy of scale" in larger plants and make the smaller passive plant economically competitive with a comparable coal plant.

The passively stable BWR. The passively stable BWR design concept (*13–16*) is an analogous approach developed by General Electric (GE) in the EPRI/DOE program. A schematic of the plant design is shown in Fig. 3, and the principal plant parameters are listed in Table 1.

The power train is composed of fully proven components and systems operating at reduced burdens: lower power density and increased thermal margin resulting in an increase in the minimum critical power ratio margin from the current level of 10% to more than 30%. The reactor operates at full power under natural circulation, which eliminates the recirculation pumps, piping, valves, and controls and probably will reduce the number of operational transients.

To achieve passive cooling capability, the suppression pool has been located above the reactor core, allowing the emergency core cooling process to be driven by gravity and eliminating safety injection pumps and associated valves, piping, and diesel generator power supplies. (The suppression pool is itself a passive cooling device that is a standard feature of present BWRs and that provides a heat sink to reduce the temperature and pressure in the containment building in the event of a severe accident.)

A passive containment heat removal system, which cools the suppression pool wall by naturally circulating water, provides a 3-day passive cooling of the containment building. An isolation condenser transfers reactor and containment heat to the pool. It is located in the suppression pool and is used to control reactor pressure automatically (passively) without the need to remove fluid from the reactor vessel. This eliminates the need for safety-relief valves for the discharge of steam to the suppression pool.

Improved stainless steel alloys, advanced welding techniques, and improved water chemistry control, including the addition of hydrogen to the water, are used to eliminate intergranular stress corrosion cracking of materials in the nuclear steam supply system. As shown in Table 2, major reductions have been achieved in the amount of mechanical, instrument, and electrical equipment of passively stable BWRs compared to conventional BWRs. The decrease in pumps, valves, controls, and safety-grade systems results in lower maintenance and surveillance test time and costs. Preliminary cost estimates by GE show that a dual 600-MWe passively stable BWR has about 4% higher unit capital costs and about 2% lower power generation costs on a per kilowatt basis than a conventional 1100-MWe BWR built on a comparable construction schedule.

Utility and NRC participation. Utility (owner-operator) requirements governing the design, construction, operation, and maintenance of future LWRs are being defined to encompass the goals summarized here. These requirements are being submitted to the NRC for its review and comment, with the object of receiving approval that a plant design meeting the requirements resolves all safety issues and is licensable. The document setting forth these requirements will be a large volume containing 13 chapters that cover both the nuclear and nonnuclear parts of the plants; it is expected to be completed by 1990. The actual license for a plant meeting these requirements would be sought through NRC certification of the entire plant design along with approval of the plant siting provisions.

Many in the utility industry feel there is still a place in the U.S. market for larger nuclear plants, particularly in regions of the country where electric power capacity shortfalls are predicted in the near future. What would be needed in this situation is a substantially improved large "evolutionary" LWR design. Utility requirements have been established, detailed designs completed, and NRC certification is now being sought for such evolutionary LWRs. These 1300-MWe designs reduce the probability of a severe accident by a factor of 10, have increased margin in key areas, and permit longer operator response times. The type of active equipment is the same as that used to handle the emergency core cooling functions in present plants, but significant reliability improvements have been incorporated. Three designs are being pursued: two advanced PWRs—one designed by Westinghouse and Mitsubishi and a System 80+ designed by Combustion Engineering—and an advanced BWR, designed jointly by GE and Hitachi/Toshiba and authorized by Tokyo Electric Power Company for construction in Japan in the early 1990s. The schedule for completion of the certification process is 1992.

The Advanced Liquid Metal–Cooled Reactor

The centerpiece of the DOE LMR development program is a modular, passively stable reactor concept called Power Reactor Inherently Safe Module (PRISM) (*17, 18*) designed by GE, which uses a new metal alloy fuel being developed concurrently by

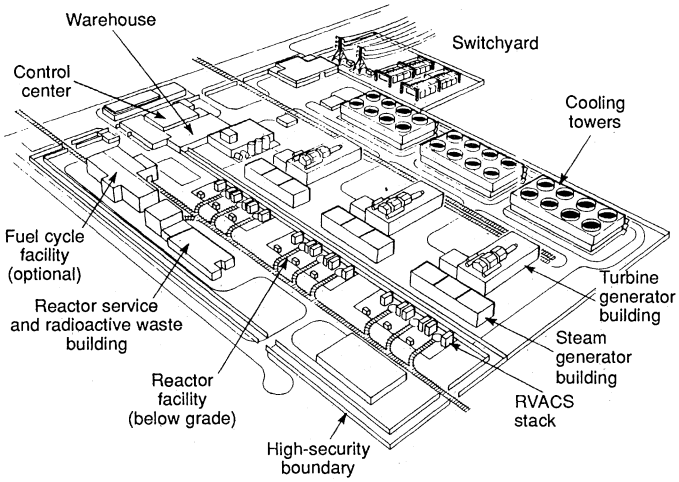


Fig. 4. PRISM 1395-MWe power plant.

Argonne National Laboratory (ANL). PRISM is a 465-MWe nuclear power plant, the principal parameters of which are as follows: thermal power, 4239 megawatts thermal (MWt), from nine nuclear modules; electric output, 1395 MWe, from three turbine generators; net efficiency, 33%; steam conditions, 540°F/955 psi absolute (psia); exit sodium temperature, 905°F; core power density, 199 W/cm^3; and equilibrium fuel burnup, 150 MW-day/kg. It comprises three liquid metal–cooled nuclear heat supply modules, each capable of producing 155 MWe. These reactor modules provide heated sodium through a common header to a single sodium-to-water heat exchanger that generates steam for a single 465-MWe turbine generator. A commercial PRISM plant is envisioned to consist of a series of three such 465-MWe power packs, each of which would be functionally independent of the other two (Fig. 4). The three packs would be located on the same site to achieve economies in the common refueling services, administrative and security arrangements, and site evaluation and licensing efforts.

The PRISM reactor module is a pool reactor with annular flow (Fig. 5). The sodium is circulated through the core by four cartridge-type electromagnetic pumps. The pool system consists of a large tank of sodium into which are placed the reactor core, the sodium pumps, and two intermediate heat exchangers. This tank is inserted into a containment vessel, which would collect sodium if it were to leak from the reactor vessel to provide assurance that the core remains covered and coolable by sodium.

The heat from the reactor module is transferred from the primary sodium coolant loop to a secondary sodium coolant loop through the two cartridge-type intermediate heat exchangers. The secondary sodium from the intermediate heat exchangers connects to a common header leading to a single steam generator that provides steam for the turbine generator.

The reactor vessel auxiliary cooling system (RVACS) (*19*) provides for emergency core cooling after any incident that causes a loss of the normal emergency heat conversion systems. The residual heat removal path consists of radiant heat transfer from the reactor vessel to the containment vessel, where the heat is removed by the natural circulation of air between the containment vessel and the biological shield.

The combination of passive reactor stability and passive cooling provides assurance of residual heat removal without operator action (*20*). For example, if all cooling through the intermediate heat exchangers is lost and the control rods do not automatically insert to cause reactor shutdown, the reactor will shut itself down by increased leakage of neutrons from the core and by expansion of the control rods as the temperature rises. The RVACS removes the residual decay heat, keeping the peak temperature below the maximum allowable vessel temperature, and thus protects against a severe accident. No operator intervention is required during the entire transient.

The reactor vessel and all the components contained in it will be factory fabricated and factory assembled. The containment vessel assembly has been sized to permit its shipment by rail to U.S. inland sites. Upon receipt at a power plant site, the containment vessel assembly would be inserted into the biological shield cylinder (Fig. 5) previously fabricated at the site. The entire heat supply module would then be inserted into its operating position, its fluid connections would be completed and control mechanisms installed, and then it would be loaded with sodium and fuel. The reactor module would be fully standardized.

The reference fuel for the PRISM concept is a uranium-plutonium-zirconium alloy with plutonium concentrations of about 25%. Work to date shows that the metal fuel has competitive power performance characteristics when compared to the more fully proven oxide fuel and has, in addition, potential economic superiority in both fuel fabrication and fuel reprocessing. The metal casting fabrication process has been fully developed by ANL and is a less costly method than the oxide pellet fabrication process. ANL is in the process of developing a pyrometallurgical reprocessing system that has potential for lower costs than the Purex process used for oxide fuel reprocessing, because of the lower volume of reprocessing materials.

Another feature potentially more readily achievable in the pyrometallurgical processing method is the separation of uranium, plutonium, and the transuranic elements from the fission products, so that the long-lived transuranics can be recycled in the LMR rather than sent to a disposal site. The PRISM concept is also capable of using standard oxide fuel in the event that the development promise of the metal fuel is not realized.

ANL has applied its experience in metal fuels operation, fabrication, and reprocessing to develop the Integral Fast Reactor concept (*21*), which envisions a colocated nuclear power plant, fuel fabrica-

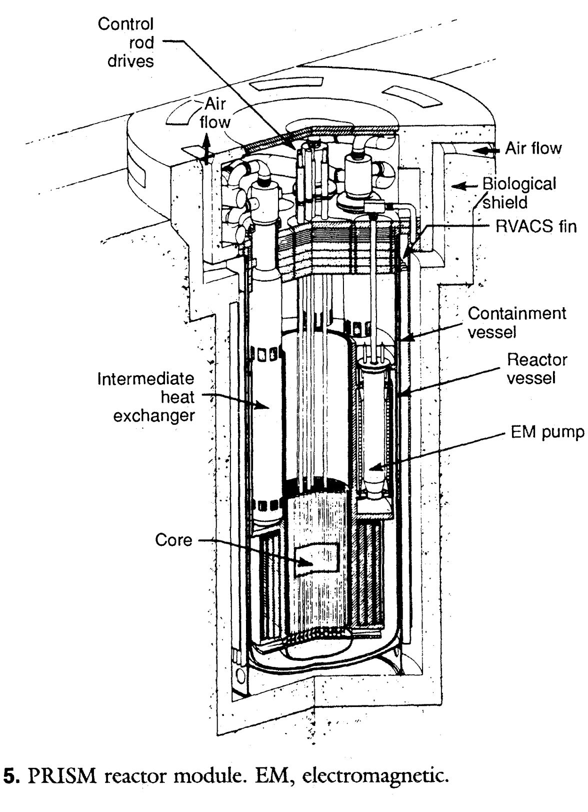


Fig. 5. PRISM reactor module. EM, electromagnetic.

tion, and fuel reprocessing center where PRISM would function as the power plant. Although such a colocated concept is not essential to PRISM, it would provide for greater proliferation resistance because plutonium-bearing materials would not have to be transported outside the security boundaries of the site.

Tests have been carried out, both at the Experimental Breeder Reactor in Idaho and the oxide-fueled Fast Flux Test Facility at Hanford, to demonstrate the passive cooling capability of the sodium system (*22, 23*). It has been proposed that one way to demonstrate that the PRISM concept is capable of meeting NRC regulations without containment is to build and test a single heat supply module. In addition, special simulation tests of the control system are planned to ensure effective and safe control of a three-module power pack from a single control station.

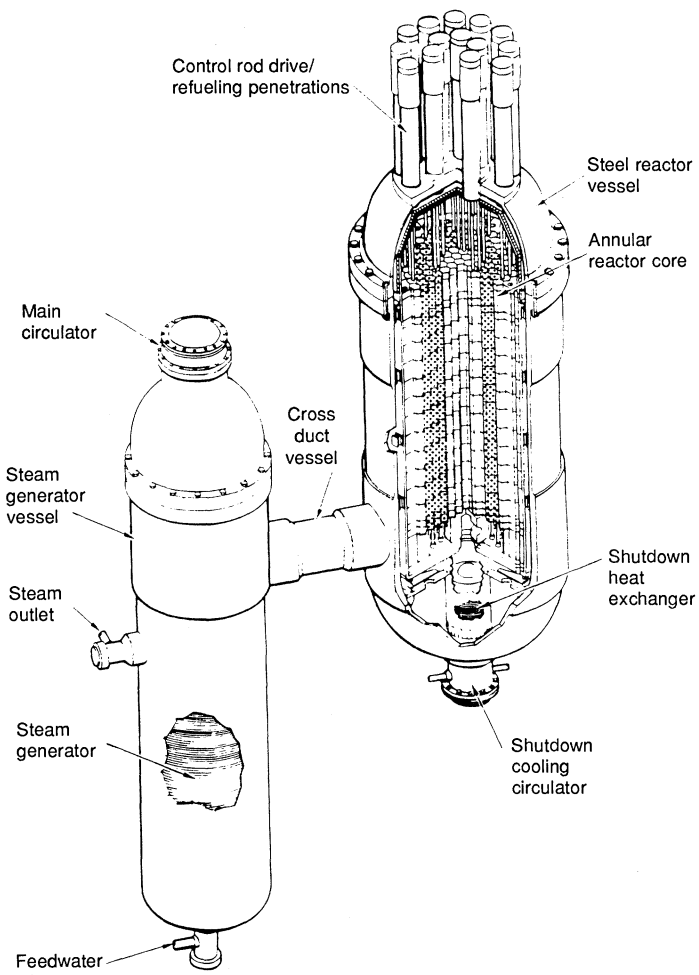


Fig. 6. MHTGR side-by-side arrangement with prismatic fuel.

The Advanced Modular Gas-Cooled Reactor

The modular high-temperature gas-cooled reactor (MHTGR) (*24*) is the primary focus in advanced gas-cooled reactor development. Its principal parameters are as follows: thermal power, 1400 MWt, from four nuclear modules; electric output, 538 MWe, from two turbine generators; net efficiency, 38.4%; steam conditions, 1005°F/2515 psia; core exit coolant temperature, 1268°F; core power density, 5.9 W/cm^3; and equilibrium fuel burnup, 92,200 MW-day/ton. It is sponsored by DOE and the utilities' Gas Cooled Reactor Associates with technical support by EPRI. The MHTGR nuclear steam supply module, designed by GA Technologies, is graphite moderated, helium-cooled, and made up of three steel vessels: a reactor vessel, a steam generator-circulator vessel, and a connecting concentric cross duct vessel (Fig. 6). The reactor vessel contains the reactor core, reflector, and associated supports. A shutdown heat exchanger and shutdown cooling circulator are located at the bottom of the reactor vessel to provide for the removal of decay heat.

The reactor core is composed of hexagonal blocks of graphite fuel elements in an annular array. A reflector of unfueled graphite blocks surrounds the annular core. The fuel is in the form of coated particles of low enriched uranium oxycarbide and thorium oxide. The particles are bonded together in fuel rods that are placed within sealed vertical holes in the graphite fuel element blocks. This fuel and graphite moderator arrangement has been termed "prismatic fuel." The fuel particle, about 350 μm in diameter, has an inner coat of porous graphite covered by three successive layers of pyrolytic carbon, silicon carbide, and pyrolytic carbon.

With fuel rods in close contact with the graphite box, the massive graphite moderator reflector and support structure provide a large heat sink that is immediately available during emergency conditions. Test data have shown that essentially no failure of the refractory coatings occurs if the fuel is maintained below 1800°C. Even if all active cooling systems are unavailable, decay heat is dissipated by conduction and radiation to the reactor cavity cooling system (RCCS) in the reactor enclosure. If the RCCS is unavailable, passive radiation and conduction of heat directly to the silo structure and surrounding earth will occur because the MHTGR does not have a conventional containment. This heat transfer will limit maximum fuel temperatures to about 600°C, well below the fuel failure temperature. The economic advantages of direct heat transfer to the surrounding earth are made possible by the lack of a conventional

Table 3. Comparison of characteristics of passively stable reactors. NA, not applicable.

Reactor	Unit reactor power output (MWe)	Operating coolant temperature at core exit (°F)	Passive containment cooling	Passive decay heat removal	Passive emergency core cooling	Modular design	Negative temperature coefficient	Conventional containment	Number of reactors of generic type operating worldwide	Average capacity factor of generic type worldwide (%)	Prototype required for licensing	Applications
LWR	600	615	Yes	Yes	Yes	Yes	Yes	Yes	338	63	No	Electricity generation
PRISM	155	905	NA	Yes	Yes	Yes	Yes	No	7	60	Yes	Breeds more fuel than it uses to generate electricity
MHTGR	135	1268	NA	Yes	Yes	Yes	Yes	No	50	55	Yes	Cogenerator of electricity and high-temperature process heat

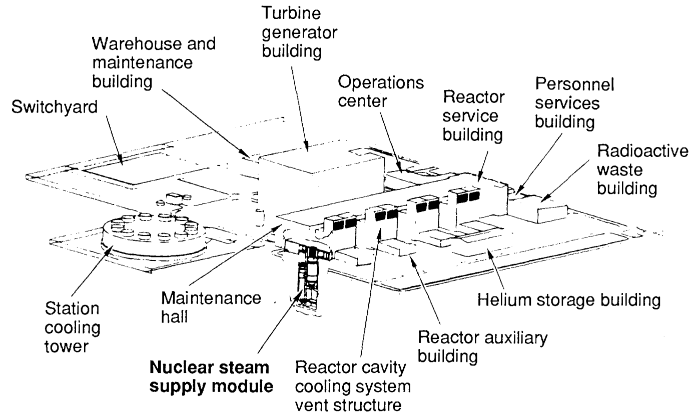


Fig. 7. Reference four-module MHTGR plant.

containment. Whether the MHTGR, with its unique, accident-resistant fuel design, can forgo the conventional containment in order to achieve this significant cost savings has not been resolved.

Tests at the West German gas-cooled reactor facility Arbeitsgemeinschaft Versuchs-Reaktor have demonstrated this passive cooling capability after a loss of all coolant flow and with no intervention by the operator (*25*). The strong negative temperature coefficient shut the reactor down automatically, and the graphite heat sink and passive cooling were sufficient to keep the fuel well below its failure temperature for several days.

The reference MHGTR nuclear power plant comprises four 350-MWt nuclear steam supply modules, each identical to that shown in Fig. 6. The modules are paired to two turbine generators, each of which generates 538 MWe. Each reactor module is placed in a concrete enclosure that is embedded in the earth (Fig. 7). The four modules and the turbine generators are operated from a common control room.

Substantial construction time and capital cost reductions are expected as a result of factory fabrication of the modules. GA Technologies/Bechtel estimate construction time to be about 4 years and the total costs to be competitive with those of coal-fired generating plants.

The conceptual design of the MHTGR is presently under review by NRC to assess licensability. Recently, DOE has chosen the MHTGR concept to be developed for production of nuclear weapons materials as an alternative to the heavy water reactor.

International Cooperation

The major industrial countries outside the United States also have advanced nuclear power development programs, several of them stronger than those in the United States. The largest of these programs are in France and the United Kingdom, where the LWR and LMR are being developed, and in Germany and Japan, where all three types are under development. Compared to these countries, the U.S. program has a substantially heavier emphasis on small, passive systems and on different fuel systems: metal versus oxide in the LMR and prismatic versus pebble-bed fuel in the HTGR. ASEA Brown Boveri in Sweden has proposed a passive LWR, called the Process Inherent Ultimate Safety (PIUS) reactor (*26*), a concept that has arisen from studies of reactor systems suitable for central heating applications. PIUS is a 640-MWe PWR plant; its core is enclosed in a large prestressed concrete vessel. A fluidic valve is located at the bottom of the core that introduces, through intrinsic thermal-hydraulic properties, emergency core cooling from the pool of water surrounding the reactor. The concept reduces active equipment further than the U.S. passive designs discussed here. The Canadian nuclear industry is continuing its development of the 600-MWe heavy water–cooled reactor called CANDU, which has achieved a superior performance record. A 300-MWe CANDU is being developed to provide a smaller size system for the utilities.

Conclusion

The technical shape of future U.S. nuclear power plants is emerging from the R&D programs being sponsored by government and industry and is broadly outlined in Table 3. The different potential applications of the three systems identifies the complementary role each plays in the long-term future of nuclear power. Although each produces electricity, the LMR has the unique capability of expanding greatly the supply of nuclear fuel, and the HTGR greatly expands the use of nuclear power to the process heat energy sector. Although the electric utility industry supports all three developments because of their complementary roles, this comparison shows why there is an electric utility consensus judgment that, if the nuclear option expands again in the United States, the initial expansion will be with the LWR (*27*). It has taken two decades and extensive operating experience with many LWR plants to uncover all the reliability issues, particularly those associated with corrosion-erosion and stress-induced materials degradation. There is also a conviction that safety is strongly based on the in-depth knowledge of a reactor system that guides operational, maintenance, and safety evaluation practices. However, a substantial development program must be completed to verify the safety and cost objectives of these advanced conceptual designs, including detailed design, licensing review, and cost estimation of all of them, extensive testing of the LWR passive cooling features, and prototype operations of the modular LMR and HTGR advanced systems.

In simple terms, nuclear power plants of the future will be designed to better fulfill their role as a bulk power producer that, if invulnerable to severe accidents, will be more broadly accepted and implemented. Their use will help stem the tide of environmental damage caused by air pollution from fossil fuel combustion products. The potential abundance and concentrated energy of nuclear fuel makes it practical to dedicate the design of future nuclear power plants to achieving that invulnerability: systems that increase their dependence on natural laws rather than on active equipment to protect against upset; systems that reduce the dependence on rapid operator response to abnormal conditions; systems that are simple and rugged, not complex and excessively high performing; systems that are workhorses, not racing thoroughbreds.

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"I understand you're a high-energy physicist, Dr. Morris. Dr. Morris?"