NEW REACTOR PROGRAMS
-- FROM PASSIVE TO PEBBLE BED

Howard J. Bruschi

Senior Vice President and Chief Technology Officer

Westinghouse Electric Company

December 11, 2001

New Reactor Programs
-- From Passive to Pebble Bed

Abstract

The market for new nuclear power plants is small and challenged by alternative means of electric power generation. Customers and countries may vary in their requirements for a new nuclear plant; but all have a common theme of seeking a design that possesses favorable economics.

This paper sets forth the economic challenges a new nuclear plant must overcome. In particular, it delineates the capital cost, construction time, and generation cost required to compete with combined cycle gas electric power generation. The U.S. power generation market is used as a point of comparison. Following this, the portfolio of BNFL/ Westinghouse plant designs are described and the methods by which they will meet the economic challenges previously delineated will be discussed. The portfolio includes the family of passive plants originated by the AP600 Design Certification process in the U.S. These plants are marked by a high degree of safety and simplicity, short construction times, and superior economics. In addition, the effort to meet European requirements for passive plants will be described. Lastly, the paper explores some advanced nuclear designs that are not yet licensed, and the hope that they hold for meeting the industry challenge ahead.

NEW REACTOR PROGRAMS
-- FROM PASSIVE TO PEBBLE BED

Howard J. Bruschi
Westinghouse Electric Company LLC
1340 Beulah Road
Pittsburgh, Pennsylvania 15235 U.S.A

Introduction

In the past 20 years, numerous new nuclear plant designs have been introduced in the hope of generating a mixture of features and benefits that generated enough enthusiasm amongst the utility industry decision-makers to move forward with a new nuclear generation. Not only has there not been enough enthusiasm, there has been little interest in building new plants with advanced features, especially in the U.S. Compounding this predicament are the changing paradigms to which a new plant would be measured. The near hiatus on new plant orders is the clear cause of the significant consolidation in the nuclear industry. Regardless whether the disappearance of old-line nuclear companies is over or not, some paradigms for new generation designs are unmovable, while others are still under discussion as to their role in future plant designs. This paper will address those design goals that Westinghouse deems already having earned the rank of exemplar, and those still open to debate.

Because it is my hope that this paper will lead to a fruitful discussion period, I will provide a list of what I feel are the *champion* design requirements, and those I consider the *contenders*.

The defending champion of the design requirements is still generation cost. This, of course, is no surprise, and if we ever lose sight of this objective, our nuclear business is guaranteed a spot in oblivion. But let me make an important addition to the heavyweight list. Although it may be a source of debate, I remain convinced that because of the nature of the nuclear industry, this key issue facing power generation addition is taken off the table when nuclear power plants are built. I am referring to the pollution issue—specifically, global warming as it relates to human-induced impacts. In fact, this issue is defacto resolved when nuclear plants are built.

For my list of contenders for mandatory design requirements, I offer non-proliferation and small-power modules. Both of these are worth discussion. Certainly, the issues of cost and risk weave their ways into both when identified as mandatory design objectives.

It is not my intent today to debate the pros and cons of adding these criteria to the list of mandatory design requirements, but I do hope some dialogue ensues during the discussion period. What I will discuss during the paper portion of the time allotted me, however, are the primary design efforts underway within the BNFL family that directly address one or more of these design considerations. To this end, I will cover the AP600, EP1000, and AP1000—

advanced passive plants that are on the market today, and the power plants being readied for the future—the Pebble Bed Module Reactor (PBMR) and the IRIS.

Advanced Passive Nuclear Plant Designs

Advanced, passive technology captures many of the strategic goals that are mentioned above, such as low-generation costs, a high degree of modularity and, of course, environmental compatibility.

The Westinghouse design strategy has always been to develop plants that meet globally recognized requirements such as the U.S. Advanced Light Water Reactor utility requirements (ALWR URD) or the European utility requirements (EUR). Designers also continue to incorporate lessons learned from operating reactors. A concerted effort was made to simplify systems and components to facilitate construction, operation, and maintenance. Simplification also enhances operational performance, and increases reliability, thereby improving economics. State-of-the-art, proven technology was used to solidify confidence in the high performance expectations of the passive plant designs.

Plant safety systems performance relies on the natural forces of gravity, natural circulation, and evaporation to shutdown and cool down the plant in the unlikely event of an accident.

Three advanced passive nuclear power plants were developed: the AP600, a two-loop, 600 MWe plant designed in collaboration with the U.S. Department of Energy (DOE), Electric Power Research Institute (EPRI), the Advanced Reactor Corporation, and 22 international partners; the AP1000, a two-loop, 1000 MWe configuration developed using the AP600 to the maximum extent possible; and the EP1000, a three-loop plant producing 1000 MWe, which was developed with 7 European participants to meet EUR requirements. Both the AP1000 and EP1000 are derivative designs of the AP600.

In addition to being simpler, the passive safety systems do not require the large network of safety support systems needed in current generation nuclear plants, such as AC power, HVAC, cooling water systems, and the associated seismic buildings to house these components. These reductions in systems led to the elimination of safety-grade emergency diesel generators and their network of support systems, air start, fuel storage tanks and transfer pumps, and the air intake/exhaust system.

Superior Plant Generation Economics

As identified earlier, improvement in electrical generation economics was a driving force for the advanced passive technology. The long-standing belief that nuclear power capital costs were too high has limited the growth of the nuclear option. Advanced passive plant engineering activities focused on simplification as a primary tenant of the design process, but also became a critical element in cost reduction. However, in addition to design simplification and the associated reductions, aggressive goals were set to find ways to significantly reduce the plant construction schedule, thereby reducing construction costs and their impact on generation costs.

AP600

As part of the cooperative U.S. Department of Energy (DOE) and the Electric Power Research Institute (EPRI) Advanced Light Water Reactor (ALWR) Program, Westinghouse developed a safe, simplified, and economically competitive, two-loop, 600-megawatt plant using the design basis set for advanced passive technology described above. A cut-away view of the AP600 is shown in Figure 1.

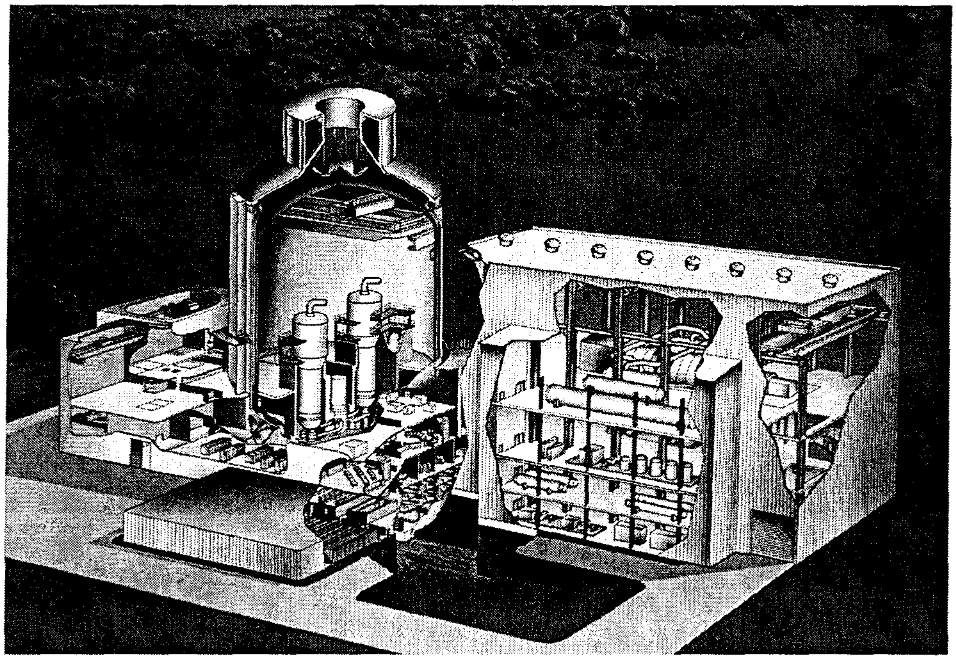

Figure 1 Westinghouse AP600 Nuclear Electric Power Plant

Improved Construction Strategy

The AP600 has a site construction schedule of 36 months from first concrete to fuel load. This schedule is much shorter than current experience because of the reductions in bulk materials, components, and building volumes. Additionally, schedule reductions will be facilitated by the significant use of factory-built modules for both structural members and systems. These modules are designed to be transported by rail or barged via waterways. Figure 2 shows how parallel efforts in the factory and onsite will eliminate the need for events to occur in series sequencing.

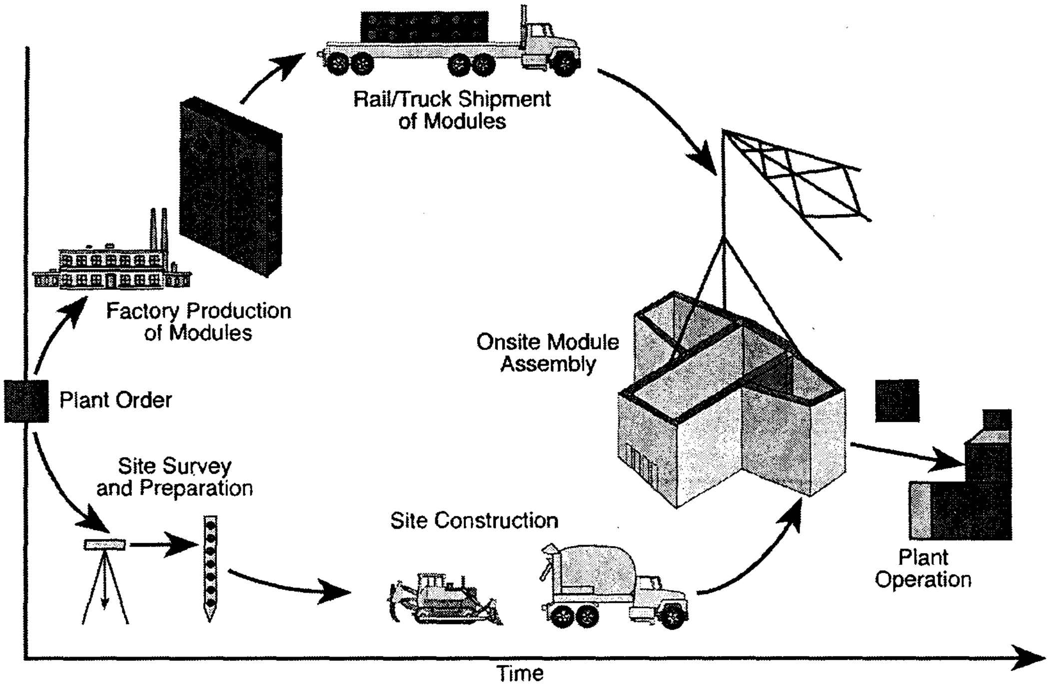

Figure 2 Parallel Tasks on Modular AP600 Shorten Construction Schedule

The economic results of these improvements in plant costs and construction timing have led to plant cost reductions of 20% to 30% compared to current evolutionary plant designs. Plant costs for the AP600 were confirmed by completing a detailed cost buildup using direct quotes in 1900 commodity categories for 25,000 specific items including components, materials, labor, indirect, and owners costs. This evaluation led to the following overnight plant completion costs, assuming a two-unit AP600 site.

• Direct and Indirect Costs	$1650 million
• Owners Costs	$205 million
• Total Cost	$1520/kWe

Measuring Safety

Safety used to be measured in terms of redundancy and multiple levels of defense; i.e., the philosophy of "if one safety system is good, two are better." With the advent of new risk assessment tools, such as the Probabilistic Risk Assessment (PRA), that mindset has changed. The AP600 was designed from the basemat up with PRA guiding the way. The AP600 plant design has achieved an improvement in safety of a factor of 10 over current generation plants. Figure 3 compares the AP600 total internal event PRA result with other standards.

In addition, common-mode-failures (CMFs) can also be evaluated using the PRA design tools. Results of these analyses have led to the incorporation of diversity of functions using passive systems, thereby significantly reducing the two main sources of CMF concerns: maintenance error and mechanical design.

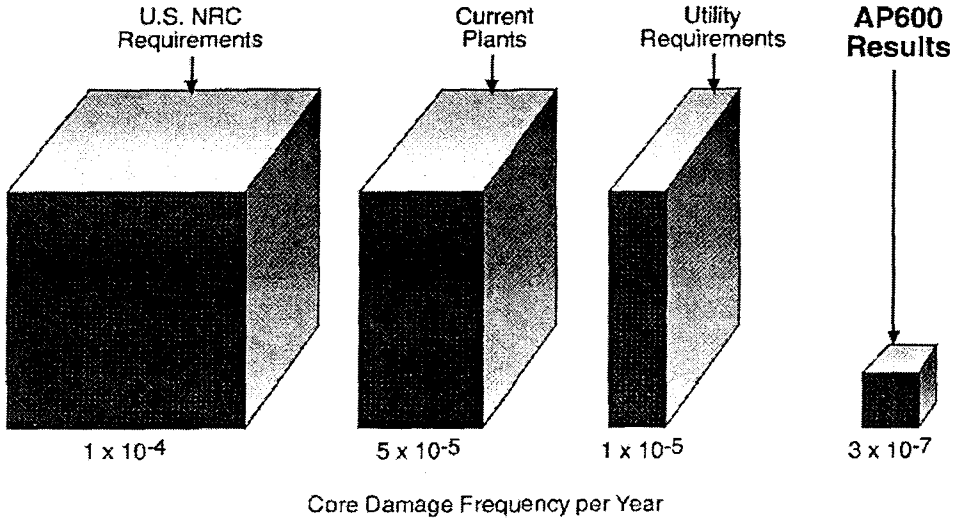

Figure 3 Core Damage Frequency per Year

The Current Safety Assessment of the AP600

In June of 1992, Westinghouse submitted the Safety Analysis Report and PRA to the NRC. The NRC replied with a Draft Safety Evaluation Report, listing its questions, to which Westinghouse responded.

All issues were resolved to the NRC's satisfaction, and they issued their Final Design Approval in September 1998. After an additional year for public rulemaking, the NRC issued a Final Design Certification in December 1999.

EP1000

In 1991, the major European utilities formed an organization to develop the European Utility Requirement (EUR) document. The requirements form the basis for the procurement of the next generation of LWR nuclear power plants by European utilities. In 1994, seven European utilities, together with Westinghouse Electric and Ansaldo, undertook the European Passive Plant Program to develop a 1000 MWe design, known as the EP1000, using Westinghouse passive nuclear plant technology. One of the key considerations of the EPP Program was to design a plant that met the EUR requirements.

The EP1000 is a three-loop, 1000 MWe passive pressurized light water reactor plant design. With respect to safety systems and containment, the EP1000 plant design closely follows the AP600 plant systems design and construction strategies. The plant uses passive safety systems similar to the AP600 to further enhance plant safety and to satisfy the EUR. As in the AP600 and AP1000, the EP1000 uses passive safety systems to establish and maintain core cooling and containment integrity without the need for operator action or AC power.

EUR Applicability

Compliance with the EUR resulted in some design changes made specifically to meet the EUR, including:

- An 18-month, 50% MOX core design will the base design for EP1000.

- Low-boron core designs have been developed for 18 and 24-month core designs.
- The Normal Residual Heat Removal System (RNS) and Component Cooling Water System (CCS) have been redesigned to improve cooldown rates for post-event temperatures.
- The Spent Fuel Pool Cooling Water System (SFS) and spent fuel pool (SFP) have been sized to accommodate 15 years of MOX spent fuel, plus 10 years of UO2 spent fuel.
- The Chemical and Volume Control System (CVS) and Liquid Radwaste System (WLS) designs have been modified to accommodate boron recycling.
- Stringent offsite dose limits have resulted in consideration of containment leak-tightness changes.

The Current Assessment of the EP1000

The Design Definition and Verification phase was initiated in 1997 and is ongoing with objectives of establishing the EP1000 economics and developing the Safety Case Report for submittal to European licensing authorities. Current estimates indicate the EP1000 has a 20% cost advantage over other conventional designs.

AP1000

The AP1000 is a logical extension of the AP600 and EP1000 design activities. Many of the studies coming from these earlier efforts provided a high-confidence level that a two-loop configuration of the passive technology could produce over 1000 MWe with minimal changes in the AP600 design. In fact, maintaining as many aspects of the AP600 design as possible became a design objective of the AP1000. The obvious purpose of moving forward with the AP1000 was to reduce generation costs. The results have been outstanding. The AP1000 is competitive with all types of fossil and renewable generation options.

The AP1000 is a two-loop, 1000 MWe plant that keeps the same basic design of the AP600—the nuclear island footprint stays the same as well as the core diameter. The main differences between the AP600 and AP1000 are identified below. Those component changes that impact the plant the most are the increase of the size of the steam generator, from a delta-75 to a delta-125, and the larger reactor coolant pump, from 51,000-gpm capacity to 75,000 gpm.

All of the plant components use proven technology.

Proven Technology of New AP1000 Components

• Steam Generators	South Texas 1 & 2, Arkansas 2
• Digital Instrumentation & Control	Sizewell B
• Fuel	South Texas 1 & 2, Doel 3, Tihange 4
• Reactor Coolant Pumps	U.S. Nuclear Navy
• Control Rod Drive Mechanisms	Westinghouse plants

Safety Assessment

Using the test data developed for the AP600 and similar designs, the AP1000 is capable of meeting higher power output requirements with proven technology. The PRA shows that the plant simplifications embodied in the Westinghouse advanced passive plant design and providing enhanced safety are not power-level dependent.

Competitive Electric Generation

Evaluation of the generation costs for the AP1000 yields results below 3.2 ¢/kWh for twin AP1000 units constructed at a single site. The bottom line is that the AP1000 will, in general, be more than competitive with generation using fossil and renewable fuels.

The Current Assessment of the AP1000

Westinghouse is currently in discussion with the NRC to identify areas of review that are necessary to obtain Design Certification for the AP1000 beyond those already accepted by the NRC in the AP600 Design Certification process.

Interest in the AP1000 has led to support from the DOE and EPRI, primarily to facilitate the completion of the plant's safety case review.

Environmentally Cost Effective

The environmental impact of fossil fuels is significant, and must be considered when evaluating the cost-effectiveness of power generation. A new ingredient in the cost-of-energy calculation has been added by many countries and utilities in recognition of this, known as carbon credits or taxes. The benefits of nuclear power in reducing the impact of carbon emissions on the environment are irrefutable. The AP1000 is already competitive with coal and gas units *without* the carbon taxes or credits. Clearly, environmental credits for nuclear generation are real and must be considered in future generation addition considerations.

IRIS

Development of IRIS (International Reactor Innovative and Secure) was undertaken at the end of 1999 with the specific intent of addressing the four key requirements identified by DOE, and by the technical community at large, for the future Generation IV reactors: competitive economics, proliferation resistance, enhanced safety, and reduced waste generation. The IRIS approach is to leverage the unmatched design and operational experience of light water reactors in a bold, innovative design to address these criteria.

IRIS is a small-to-medium (the current design is 100 MWe, but it can be uprated to 300 MWe) light water cooled, modular reactor. It has a long-life core—eight to ten years without shuffling or refueling. Plant maintenance is also minimized, with a current target of shutting down for maintenance no sooner than every four years. It has an integral design (see Figure 4), that is, the reactor vessel contains the core, steam generators, pressurizer, and pumps. The safety philosophy is to rely on the design to eliminate most accident initiators first, and to use simplified passive systems to cope with the rest.

IRIS is designed by an international consortium led by Westinghouse/BNFL. Current partners are: Westinghouse/BNFL, Bechtel, Mitsubishi Heavy Industries, Commissariat a *l'Energie Atomique, Cadarache, Japan Atomic Energy Company,* Polytechnic of Milan, Massachusetts Institute of Technology, University of California at Berkeley, Tokyo Institute of Technology, and University of Pisa. As is evident in the above list, the team members represent five countries (France, Italy, Japan, U.K., and U.S.) and cover the entire nuclear industry spectrum: reactor vendor, fuel vendor, architect/engineer, utility, laboratory, and academia. And discussions are underway with other prospective partners, as well.

Let me briefly explain how IRIS embodies a positive resolution to several key requirements:

Competitive Economics:

The international consortium approach and the modular design allow us to offer IRIS throughout the world, satisfying needs from small (a few 100 MWe) to large (1000 MWe) power requirements. IRIS is equally at home in developed countries and in countries with little infrastructure. Cost reductions are realized through plant simplification (reduced piping, elimination of a separate pressurizer, no refueling system, and drastic reductions in safety-grade systems) and the adoption of *customized mass production*, that is, standardization and fabrication of components on a larger scale. Preliminary analyses have indicated that IRIS will be favorably competitive with all types of power generation.

Proliferation Resistance:

The *hands-off* approach of a long-life core and minimized maintenance means that the host country has limited access to the fuel (intrinsic safeguard). Extrinsic safeguards (IAEA inspections) are greatly simplified and strengthened by a design wherein the core is fabricated (and delivered) in large bulk sectors rather than individual assemblies/pins. Inspectors will

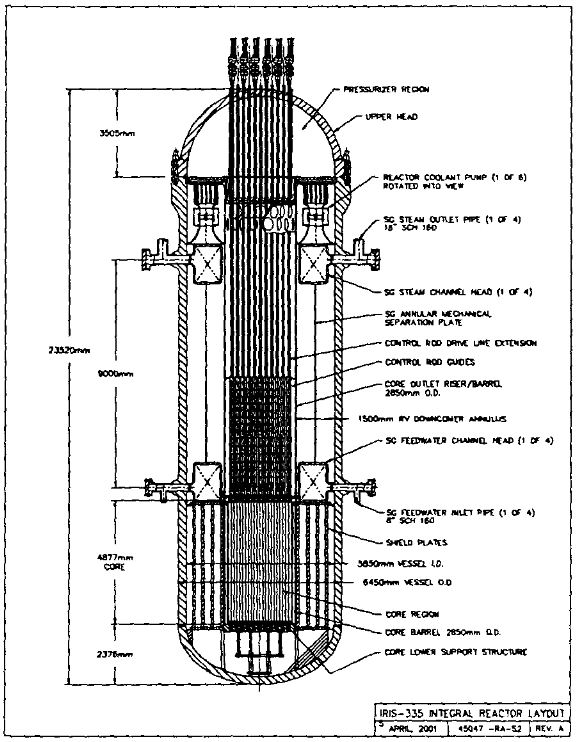

Figure 4 IRIS Reactor System

only have to track a few sectors rather than thousands of pins. Note that a long-life core and reduced maintenance benefit the economic competitiveness of the plant by significantly reducing O/M (and fuel) costs.

Enhanced Safety:

The integral design eliminates large loss-of-coolant accidents (LOCA). IRIS is designed to have enough natural circulation to *ride through* loss of flow accidents without exceeding the safety limits. There is no refueling, so there are no refueling accidents. The only remaining Class IV accident to cope with are small LOCAs, which are are addressed by the very nature of the plant design: use of passive systems and the fact that all vessel penetrations are above the core ensure that the IRIS core will continually be underwater.

Thus, with IRIS we are developing a new generation of light water reactors that requires engineering development but not new technology development. Consequently, we are projecting having a licensed design and the potential for a first-of-a-kind plant built by the end of the decade.

PBMR

In 1992, the South African utility ESKOM initiated a comprehensive review of future power generation options, with the particular aim of identifying systems that would offer economic generation, and would be suitable for installation both close to large population centers, as well as in the remote districts that ESKOM serves. This review included all currently developed technologies. As a result of this review, High Temperature Reactor (HTR) technology was judged to have considerable potential, because of its combination of very high inherent safety, particular suitability for small unit size, and the potential for improved generation economics arising from employing the high temperature coolant gas to directly power a gas turbine.

The ESKOM feasibility study focussed in detail on the German-developed pebble-bed design, which had demonstrated good technical performance, and which had the advantage of online refueling, giving improved availability factors.

As a result, a concept design for a 117-MW(e) modular plant has been developed, based largely on existing German technology, but employing a direct-cycle gas turbine. In 1998, the ESKOM Board acknowledged the potential of the Pebble-Bed Modular Reactor, or PBMR, and agreed to purchase the first demonstration module, subject to government and regulatory approval, and to a satisfactory economic and technical review following a Detailed Feasibility Study (DFS).

Subsequently, a number of partners have joined the project to produce the DFS, including the South African Industrial Development Corporation (IDC), BNFL of the U.K., and the U.S. utility PECO.

ESKOM's requirements are common to most utilities worldwide, including:

- High degree of safety, at least equivalent to the best curr
- Economically competitive with the least-cost alternative.
- Small size, consistent with the needs of small towns without grid access.

- Operational flexibility and high availability.
- Public acceptability, aided by simple (passive) safety arguments and minimal offsite release potential.

Preliminary economic estimates by ESKOM suggest a capital cost of approximately U.S.$100 million per module (equal to $855/kWe), and a production cost of less than 2.0 ¢/kWh.

PBMR Design

The PBMR is a graphite-moderated, helium-cooled high temperature reactor, coupled directly to a gas turbine driving an electrical generator (see Figure 5). The steel reactor vessel is 18 meters in height, and is lined with a 60 cm graphite reflector. During normal operation, the pressure vessel contains a fuel load of 440,000 balls, each 60 mm in diameter. This load consists of 310,000 fuel balls and 130,000 pure graphite balls. These graphite balls form a central column, giving an annular core geometry, and provide additional moderation. The fuel balls contain coated fuel particles, which consist of a kernel of ~8.5 w/o enriched uranium dioxide, around 0.5 mm in diameter, which is coated with successive layers of pyro-carbon and silicon carbide. The resulting particles are approximately 1 mm in diameter. Each fuel ball contains around 9 g of uranium, so that the total uranium in one fuel load is 2.79 tonnes. A reactor will use 10 to 15 total fuel loads in its design lifetime. The fuel and graphite balls are continuously removed from the bottom of the reactor, checked for burnup and damage, and re-inserted at the top. Fuel balls that have attained their target discharge burnup of approximately 75 GWd/tU are diverted to spent fuel storage tanks in vaults underneath the reactor, and are replaced with fresh balls. This on-load refuelling system removes the need for re-fuelling shutdowns.

To remove the heat generated in the core, helium gas at 540°C is passed into the pressure vessel at the top (see Figure 6). It passes between the fuel balls, and then leaves the bottom of the pressure vessel at 900°C. The hot gas then passes through a conventional gas turbine system to drive an electrical generator.

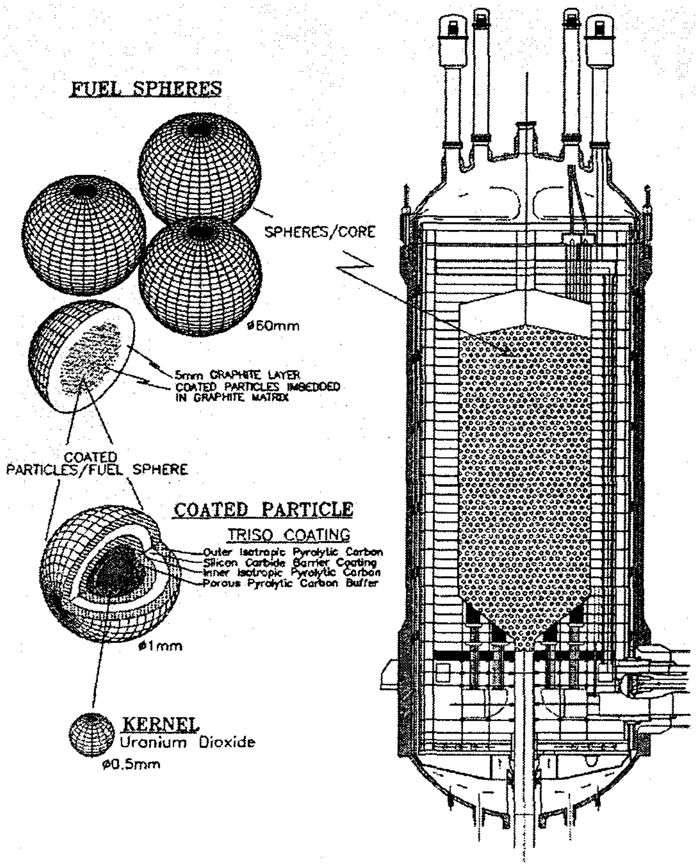

Figure 5 PBMR Core and Fuel Schematic

PBMR Advantages

The PBMR design has a number of significant advantages relative to alternative systems.

The core is composed entirely of refractory materials, resulting in high thermal stability, and has a very strong negative temperature coefficient of reactivity, resulting in a highly self-limiting response to reactivity insertion events. No operator or safety-system intervention is necessary, and the core remains in a long-term coolable state with no consequent fuel failure and no significant increase in fission product release.

The absence of a secondary steam circuit precludes the possibility of steam entering the core, and eliminates heat exchange inefficiencies between the primary and secondary circuits. Combined with a high cycle temperature, this results in a high thermal conversion efficiency of about 43%.

Changes in power output are achieved by changing the helium pressure by means of a bank of helium reservoir tanks that are maintained at different pressures. Thus, changes in reactor power do not result in large changes in the flow rate across the turbo-machinery blading, and the turbines and compressors always operate close to their optimum design conditions. This allows high efficiency to be maintained during part-power operation.

The design is highly modular, allowing rapid learning-curve benefits and economies of production to offset the absence of the economies of scale. Utilities can install capacity in relatively small increments to suit local demand and transmission system capabilities. A shortened construction time allows income streams from early modules to offset investments in later modules.

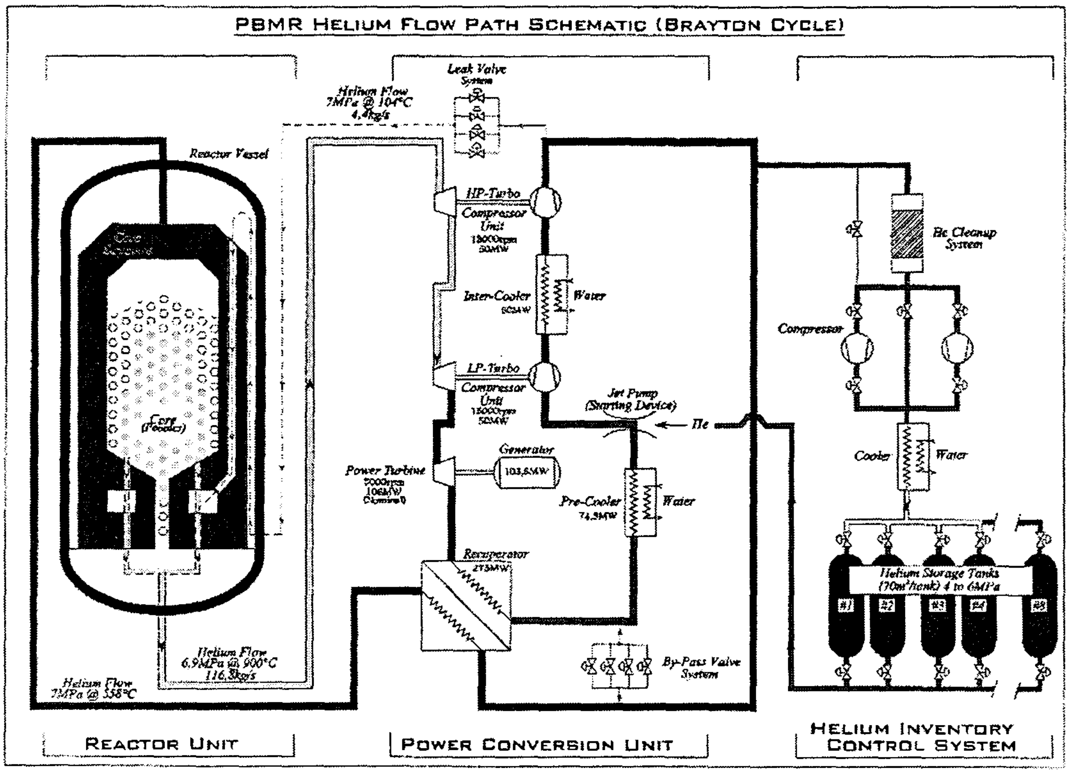

Figure 6 PBMR Helium Flow Path Schematic

CONCLUSION

So there are bright spots for the future of nuclear power as a source of new electrical generation in the U.S. and elsewhere. Plants based on advanced passive technology have met and resolved the challenges given them. These technologies are ready for implementation and are expected to provide clean, competitive electricity anywhere in the world.

Additionally future generation plants planned for implementation in the next decade are also in the "design hopper" with the aim of meeting and exceeding performance expectations for new electrical generation in the 21st century.