Nuclear Power Plant
Design Project

A Response to the
Environmental and Economic Challenge
Of Global Warming

Phase 1
Review of Options
&
Selection of Technology of Choice

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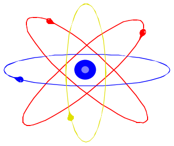

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NUCLEAR ENERGY PLANT DESIGN PROJECT

The Environmental and Economic Challenge

1 INTRODUCTION

As the nations of the world seek to meet the increasing demands for energy of their people, environmental pollutants from the burning of coal, oil, and natural gas continue to build. The use of fossil fuels for transportation, generating electricity, heat and industrial production account for 85% of the world's energy consumption. The environmental consequences of this heavy reliance on fossil fuel are only now being fully realized.

Sulfur dioxide emissions are said to cause acid rain. Nitrous oxides are said to cause smog. Particulates in the air, from the burning of coal and oil, cause all manners of lung ailments. The majority of the scientific community now believes that emissions of carbon dioxide, resulting from the burning of fossil fuels, is the leading contributor to global warming. Accordingly, the leaders of almost every nation in the world met in Kyoto, Japan in December 1997 to establish aggressive limits on the future use of fossil fuels.

In spite of these concerns, fossil fuels are necessary to meet the world's energy demand. How long can the planet's environment continue to withstand the pollutant load caused by the emissions from these fossil sources? The answer is not certain, but the leaders of the world concluded in Kyoto that dramatic action is necessary even without having all the scientific data because the consequences of being wrong are too severe.

As the world's demand for energy continues to increase, how is this target to be met? Improvements in energy efficiency, conservation and decrease in the use of fossil fuels will all be required if there is any hope of achieving the aggressive targets established by the political leaders. It is also necessary to develop non-carbon alternatives for energy production. Solar, wind and hydropower are often mentioned for electric generation as they have been for many years.

One source of energy, noticeably absent from serious discussion at Kyoto was nuclear energy. Nuclear energy is a non-fossil, non-carbon, and non-air-polluting source of energy that has provided many nations of the world with vast amounts of electric power. The United States depends on nuclear energy for 20% of its electricity. France, Japan, Germany, Korea, Taiwan, Sweden to name but a few, also have high reliance on nuclear energy. Why the omission of this obvious answer to the global climate change problem?

The United States, which is arguably one of the most environmentally conscious countries, has not supported the development of nuclear energy as an answer to global climate change. There has been no new order in the United States for a nuclear energy plant for over 20 years. Yet 105 nuclear plants are operating in the United States. This is more than any other nation in the world. What is the problem?

There are several. The plants are perceived by the public to be unsafe despite their positive safety record. Presently, the costs of new nuclear plants as designed are more expensive than gas or coal fired plants. Nuclear plants operate in a strict regulatory regime, which is perceived by the industry and the financial community as lacking the predictability necessary to make financial decisions on building new plants. There are international concerns about the spread of nuclear weapons and materials capable of being used as weapons by terrorist states or terrorists. The permanent disposal of high level nuclear wastes has yet to be accomplished by any country operating nuclear power plants.

It is likely that these are some of the reasons that the obvious environmental benefit of nuclear energy was not seriously considered by the environmental and political community assembled in Kyoto. These are also the reasons that no US utility executive is considering building the new advanced nuclear plants that are presently being certified by the Nuclear Regulatory Commission.

The purpose of this student project is to design and develop a nuclear energy plant that addresses these concerns such that the environmental benefit of this non-polluting energy source can continue to be used. Energy supply is a global problem for all nations of the world as they seek to meet the increasing energy needs of their people to support an improved standard of living and quality of life in a sustainable manner.

The environmental challenge of meeting the increasing demands for energy is real and the advantages for nuclear energy are obvious. The economic challenge is to develop a nuclear energy plant that can:

1. Compete economically with natural gas
2. Addresses the safety and proliferation concerns of political leaders and public
3. Convince the investment community that the plant can be built and operated for the price stated
4. Be used world wide in developing and developed nations
5. Make money for the investors.

We, who are working on this project, have a large stake in this project’s success, since the product of this effort may make the world better.

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2 EXECUTIVE SUMMARY

This project began as part of the American Nuclear Society's design competition aimed at stimulating interest in nuclear energy in the universities that still teach the subject. The original title of the competition was "The Economic Imperative" which challenged students to think creatively about what it would take to bring the cost of new nuclear power plants down to levels that would be competitive with new natural gas fired fossil plants. Combined cycle natural gas plants are the choice of generating companies today due to their low capital and low fuel costs. At MIT, we took a much broader view by renaming our effort as "The Economic and Environmental Imperative" to respond to the challenge that it will take more than economics to bring the benefits of nuclear energy to bear in addressing the problems of air pollution and global climate change.

The issues confronting reintroduction of new nuclear power plants in the United States energy mix are many. While nuclear plants are continuing to be built in Japan, Korea, China, and Taiwan, their expansion has slowed elsewhere. The use of nuclear power for developing nations has not even begun. The reluctance to use nuclear energy is based on public and political perceptions about safety, nuclear waste, radiation, regulatory stability and financial success given the history of nuclear power to date. We took a broad view to these issues to ensure that the acceptability of the technology was as much a part of the solution as favorable economics.

This project began with a review of the present issues confronting nuclear energy that prevent its widespread use. This review provided a basis for issues our new design needed to address for acceptance. The nuclear industry has been developing new advanced reactor designs under guidance documents prepared by the Electric Power Research Institute and implemented by major nuclear plant vendors in the United States. Each of these new designs is under review by the Nuclear Regulatory Commission for design certification. Some have already been granted approval and detailed first of a kind engineering is underway under the new rules promulgated by the NRC to improve the licensing process.

In the early stages of this project, industry leaders and technology experts (see Appendix A) were invited to the class to describe the new plant options that were being developed. In addition, the issue of nuclear proliferation was explored to determine what kinds of design features were important to substantially reduce the risk of the spread of nuclear materials to terrorists or terrorist states. Presentations of "new" technologies were also heard which included gas-cooled reactors, lead bismuth reactors and light water breeder reactors.

Based on these presentations and student research, a matrix of important factors was developed with weighting factors and each plant was subjectively ranked against these criteria. The key factor used to judge acceptability was demonstrable safety. Economics was second. There were

30 criteria used to identify important issues with the aim of enhancing ease of operation and public support for each of the designs evaluated.

Based on this review, the design selected was a small modular pebble bed gas reactor cooled by helium using a gas turbine to generate electricity. A small modular reactor about one tenth the size of today's large nuclear power plants was chosen because of its inherent safety, ease of operation, and ability to be mass produced which is expected to yield lower costs. The 110-Megawatt electric size of the plant is “naturally safe” with no operator action required for even the worst contemplated accident in which all cooling systems are turned off. No meltdown can occur. The plant size and design is such that it will naturally shut itself down without fuel failure and without the need for active plant systems. This size is also suitable for developing nations, as they seek to build their electric grids and developed nations who want to add incremental capacity based on market demands.

The pebble bed design was also chosen because it allowed for online refueling which would increase the generating potential of the plant. The gas generating cycle is also very efficient, with possible efficiencies as high as 45% to 50% with less wasted energy. The secondary side consists of a gas turbine operating well within the range that is currently used in natural gas burning fossil plants. Although initial designs would include an intermediate helium to helium heat exchanger, future designs would eliminate this feature as fuel performance data is developed. The "direct" gas cycle compares very well with conventional natural gas plants and far exceeds present nuclear plant efficiencies of 33%.

The fuel type used addresses the proliferation concerns. The uranium fuel is contained in carbon spheres, which provide the containment for storage and disposal and is of a form that makes reprocessing extremely difficult, if not impossible. The fuel is also used to a point out the plutonium from the other materials (where if even if it could be reprocessed to separate); it could not be used in a weapon since the other plutonium isotopes would generate too much heat to allow for fabrication.

The basic design features of the plant are a 250 MW thermal rating with inlet helium coolant temperature of 400° centigrade and a turbine inlet temperature of 810° centigrade, at pressure of 7.13 Mpa (1040 psia), at a turbine flow-rate of 149.2 kg/s. The plant operates on a Brayton thermodynamic cycle, which includes a recuperator and an air precooler to reject waste heat either to the environment or other low grade heat application. The helium gas is inert, and because it can be operated at high temperatures without oxidation, this eliminates a major cause of corrosion and stress normally found in air fired gas turbine systems.

Key innovative features in this design include high modularization, factory production of major plant components, a control room that is state of the art in that it employs modern computer controls with a high degree of automation that operates equipment through touch screens and terminals. Other features are the configuration control system that is integrated into procedures and design, and a plant that has no reliance on human action in the event of a total loss of coolant.

This plant should require a small staff to operate and maintain due to its automation and simplicity.

For the purposes of this study, the economic evaluation was benchmarked to a 1992 US Committee on Energy Awareness (CEA) study, which evaluated the leveled cost of advanced large and small nuclear plants and combined cycle gas turbines. This evaluation used the same initial assumptions regarding cost of labor and construction rates for the modular gas reactor proposed. The results show that using a consistent set of assumptions the small pebble bed plant can produce electricity competitively with natural gas. This conclusion is based largely on the economic scale of production, not size. The small size of the plant allows for a great degree of modularization and factory production. Another significant factor is that since this plant is small, it can be built much more rapidly, and in a sequential manner. The first module can be brought online rapidly and start generating cash flow to support the financing of the next incremental units.

The comparative analyses indicate that a large new 1200 MWe light water reactor levelized power cost amortized over 30 years is 3.8 c/kWh. Similar analyses for the AP600 show 3.62 c/kWh; combined cycle gas turbines come in at 4.2 c/kWh; and 1200 MWe of modular gas cooled reactor (10 plants) are costed out at 3.4 c/kWh. It should be noted that the US CEA study assumed a real cost of gas fuel increase of 3.5% per year, which is not the case. A more realistic value is no inflation, in the price of gas, which brings the cost of combined cycle gas down to about 3.8c/kWh on a levelized basis.

Financing this plant was also a major consideration. As a rough check of whether the economic analysis was representative of what could be expected, a financial model was developed based on a required revenue stream to support the capital cost of the plant and its operation. It was assumed that it would be financed with 50% common equity at a 16% rate of return, 10% preferred equity at 10% and 40% debt at which 10% yielded a net finance charge of 12.3%. A 30-year amortization period was assumed.

Back calculation of revenues against generation yields a cost of power of about 4.2 c/kWh. If a consortium approach was used, which would mean developers were part owners, lower returns of equity could yield a cost of power in the range of 3.8c/kWh which is consistent with current market prices. This very rough calculation indicates that the plant could be financially viable.

A challenge that needs to be overcome relative to combined cycle gas turbines is that their amortization period is on the order of 7 years. More detailed analyses need to be done to determine whether the modular gas reactors can be built to support a shorter amortization schedule or the price of gas needs to increase in order for the nuclear version of the gas plant, to compete on the same amortization schedule.

The conceptual work performed to this point identifies the potential for this design. A small (20 Megawatt thermal) pebble bed reactor has operated in Germany for over 20 years. The Project's proposed plant is 10 times larger but the concepts are similar. A 300-Megawatt plant also operated in Germany for several years before it was shutdown. Thus there is a good experience base with pebble bed nuclear plants. What remains is performing more detailed analyses in all areas of the concept proposed to ascertain whether the bases for the assessments are valid. If it is, there could be a new generation of nuclear plants that could be deployed world wide without fear of proliferation or safety, which could make a substantial contribution to efforts to avoid global climate change.

3 ASSESSMENT OF THE ISSUES AND NEEDS FOR A NEW PLANT

The nuclear technology currently in use across the country has several shortcomings that limit its desirability as the type of nuclear plant for the future. Most of the shortcomings stem from the size and complexity of the various integrated support systems, which have driven up capital costs, staffing requirements, and regulatory requirements. Today's plants were expensive to build, are expensive to maintain and operate, and difficult to maintain within regulatory requirements. Due to these factors, extraordinary management attention and skill is required to keep the plants operating. The high demand for management attention, far exceeding the alternatives, is a serious deterrent to new orders. Prescriptive regulatory constraints imposed by the Nuclear Regulatory Commission stifle innovation, which makes current and even future nuclear plants hostage to old technologies.

Despite ample scientific evidence to the contrary, the public perceives the current nuclear stations as unsafe. Additionally, existing nuclear stations are faced with an increasingly critical lack of a spent fuel disposal facility. Decreasing coal and natural gas prices, when coupled with expensive modifications to nuclear plants (following the Three Mile Island accident) resulted in the elimination of much of nuclear power's generation cost advantage over fossil fuels. Ultimately, the combinations of adverse public opinion, regulatory pressures, and economic challenges that exist today have resulted in two decades of no new orders of nuclear stations.

Worldwide concern over greenhouse gas emissions is prompting a reevaluation of the role nuclear power should play in the world's energy generation. Conservation efforts and renewable resources will simply be unable to meet growing global demand for electricity, let alone reduce current dependence on fossil fuels. United States Secretary of Energy Frederico Pena recently called nuclear power "an important part of our energy mix"[1] and noted that the Department of Energy's proposed FY 1999 budget contains $44 million in funding for nuclear energy research and development. When pressed, even the most vocal nuclear power opponents are beginning to admit that emission-free nuclear power will continue to play a vital part in meeting the world's growing energy needs without accelerating the greenhouse effect.

Yet the prospects for building future nuclear reactors in the US are questionable. What is not in question, however, is that any future plant must be perceived as a significant improvement over current designs if it is to warrant serious consideration. Experience gained after thirty years of commercial nuclear operation has shown that development of a successful design must address much more than just engineering issues. Political and economic considerations play just as important a role in determining the eventual success or failure of a nuclear station.

Perhaps the three largest public (political) hurdles facing the nuclear industry deal with the eventual disposal of spent fuel, the potential for proliferation, and eventual plant

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[1] Speech delivered to the National Press Club in Washington DC, Feb 13, 1998

decommissioning. The long delayed nuclear waste disposal facility at Yucca Mountain is becoming a multi-billion dollar monument for why nuclear power is in decline in the US. Additionally, political instability and the threat of terrorist use of nuclear material, no matter how remote, make growth of nuclear power unattractive to many governments. Finally, decommissioning of some current nuclear stations is costing as much as ten percent of the original construction cost.[2] These issues were not considered during the design and construction of our current nuclear plants. However, future designs must be able to effectively address these issues if they are to receive serious consideration.

Therefore, even with renewed interest in commercial nuclear generation; we feel problems associated with current designs make them unattractive for consideration for future construction. Because the public, regulatory, and economic factors that have caused existing designs to loose favor have not significantly changed, it is apparent that any future commercial nuclear stations must be a significant departure from stations built in the past. To that end, we feel the following attributes are essential for the new design:

- The plant design must be "naturally safe". The plant should be “inherently” safe and not need external safety systems. In other words, operators should be able to withdraw all control rods and simultaneously stop all coolant flow (place the plant in the most vulnerable condition) and walk away, without any adverse impact. The safety of the plant must be obvious to both the public and the regulators. The design must support risk-informed regulation (the safety must be demonstrable).

- The plant design must support short construction time. Construction costs should be low and predictable. To facilitate rapid construction, future designs should emphasize modular construction. This will not only reduce total assembly time, but offers the improved quality and economic advantages of production line fabrication.

- The plant must also be designed with the eventual decommissioning in mind. Sizing and design of systems to facilitate rapid disassembly, ease of decontamination, and ease of disposal should be performed so that a decommission plan can be developed before construction even begins.

- In order to reduce operating costs, the plant must be designed to minimize lost generation due to refueling or maintenance shutdowns. Accordingly, the design should provide the capability to refuel and perform maintenance online. If online refueling is not possible, the design should allow for rapid refueling. Components that are expected to require replacement during the life of the plant should be designed for ease of removal and installation.

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[2] Based on current projected average decommissioning cost of $250M per station

- The plant design should be simple to operate, i.e. amenable to automation, and maintainable in order to allow for small staffs that require less technical expertise.

- The design should be able to be used in a country without the extensive nuclear infrastructure through a turnkey type of contract for operations and support.

- The design should provide a plant with lower radiation dose levels and less radioactive contamination.

- The design should ensure minimal environmental impact. Additionally, it should be capable of operating at high thermal efficiencies and allow for the use of waste heat for other commercial applications if desired.

- The design should use a simple fuel cycle that provides the highest possible resistance to proliferation, does not depend on reprocessing, have high fuel burn up, and support burning mixed oxide fuels. Additionally, the fuel type used must offer ease of fuel storage and disposal and good fuel integrity.

- The design should be acceptable for the international market in terms of safety and proliferation resistance under a standard international safety authority.

- The plant should be able to be site assembled quickly using prefabricated units shipped by barge or by train to potential sites.

4 REACTOR DESIGN OPTIONS

In order to meet the needs identified in the previous chapter, an evaluation was made of current new designs being offered by the industry to establish whether the designs can meet the criteria established. The nuclear industry in the United States has developed several new designs for the future. In addition, there are several alternative concepts that have been proposed in the past.

With support from the Department of Energy and substantial industry investments by corporations such as Westinghouse, General Atomics, General Electric, and ABB have developed their advanced design concepts, which are undergoing NRC regulatory review for certifications. The primary purpose of these advanced designs is to take advantage of the many lessons learned through years of operation and analysis. The Electric Power Research Institute (EPRI) has coordinated these efforts with some generic guidelines. In the following chapter, we take a cursory look at some of the designs that have been proposed as possible solutions to some of the problems that have plagued the nuclear energy industry over the years.

These advanced designs will aid in the decision process of choosing the final design of the reactor. It will also serve as a reference and a benchmark for our final design decision. There are four specific types of reactors from which we could model our solution: the AP600, System 80+, ABWR, and the HTGR. A summary of each of these systems follows. AP600, System 80+, and ABWR represent specific designs. The HTGR is more of a concept and has been proposed by General Atomics in an “annular core” style. The United States, Germany and Russia have developed and operated the “pebble bed” style cores. A brief summary of each type of reactor follows.

4.1 AP600[3]

AP600 is a 600 MWe pressurized advanced light water reactor designed by Westinghouse. Westinghouse designed AP600 as a next generation ALWR that is simpler and safer than current LWR plants. Through many years of operating and design experience, AP600 design is modular, which allows some components to be factory built and assembled faster on site. AP600’s standardization, safety, and modularity offer affordable electric power at a competitive price.

The primary plant of the AP600 is very similar to conventional LWR plants with some notable differences, which increase simplicity, safety, and maintainability. The primary consists of two hot legs, four cold legs, and two steam generators with the hermetically sealed canned reactor coolant pumps mounted directly to them. Canned reactor coolant pumps eliminate required seals therefore preventing a seal Loss of Coolant Accident (LOCA), which is a major industry issue. The pressurizer is 30% larger, which allows for better transient response and helps eliminate

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[3] The specification and data for the AP600 were obtained from the Westinghouse marketing information.

spurious reactor trips. Several reactor internals, such as stainless steel radial neutron reflectors and reduced-worth control rods improve neutron utilization, which results in lower fuel enrichments, therefore extending core life. Several other reactor components have been redesigned to increase simplicity and maximize safety.

Passive safety means that reactor safety is met by not relying on active systems for safety intervention, but instead uses natural driving forces such as gravity flow, natural circulation, and pressurized gas. The main steel containment is designed to allow for internal condensation and natural circulation to remove heat from the core to the steel containment. Natural circulation of air, established between the steel containment and a surrounding shield building, provides cooling to the containment vessel. The natural convection heat transfer process is enhanced by gravity-fed water tanks mounted on the top of the containment, which are intended to provide initial cooling to the steel vessel. The use of natural forces requires less operator intervention during a reactor accident and does not rely on complex active systems for the primary mode of reactor safety.

Reduced regulation complications and reduced capital costs are achieved by a simplified plant design. The AP600 uses 50% fewer valves, 80% less pipe (safety grade), 70% less control cable, 35% fewer pumps, and 45% less seismic building volume than other conventional reactors. Modularization allows prefabricated modules to be shipped and assembled on site. Modularity helps ensures quality assurance and allows an AP600 design to be built in three years (time from first concrete pour to fuel loading). Based on 1994 dollars these simplifications result in a 15% saving over the existing twin 600 MWe units.

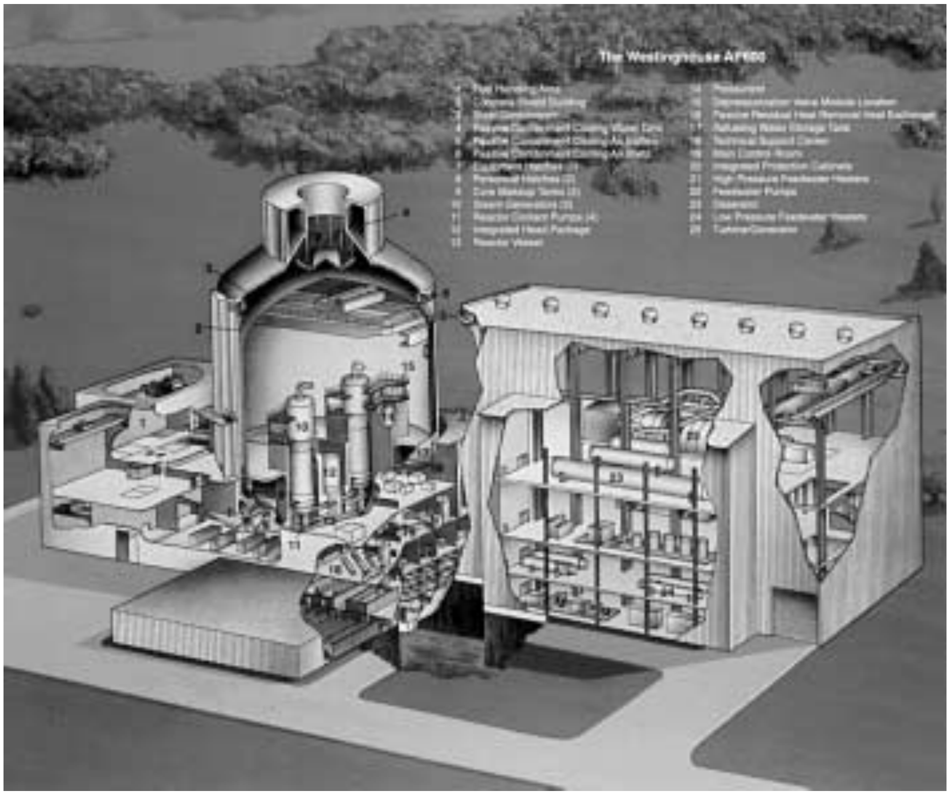

Figure 4.1
Westinghouse
AP 600

AP 600
Specifications:
- **600 MW(e)**
- **Modular design**
- **Passive safety**

4.2 System 80+[4]

System 80+ is essentially an improved version of ABB's System 80+ design currently in use at the Palo Verde Nuclear Generating Station. The operating principles and systems are similar to those found in all PWRs. As with other designs that fall into the ALWR category, System 80+ is the embodiment of over 30 years of LWR operating experience.

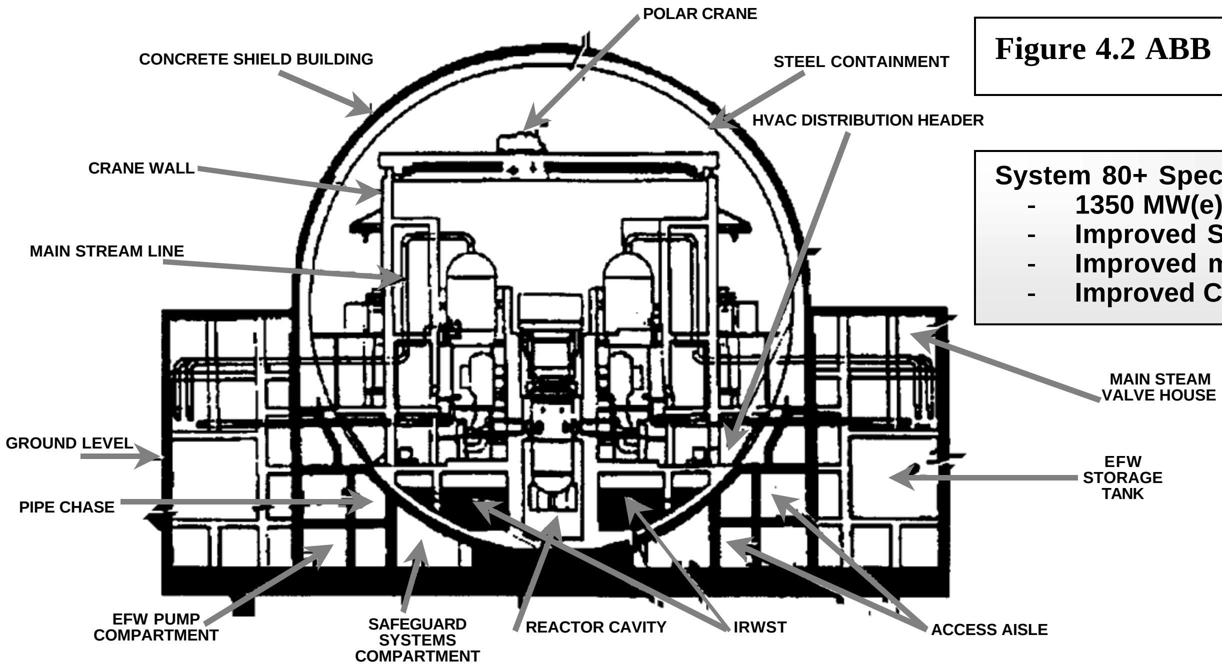

Figure 4.2 ABB System 80

System 80+ Specifications:
- **1350 MW(e) PWR**
- **Improved Safety**
- **Improved maintenance**
- **Improved Control Room**

A focus area for development of System 80+ was further improvements in the inherent safety of the design. To that end, additional features include:

- Pressurizer volume 33% larger.
- Increased core thermal margin.
- Secondary volume in steam generators increased by 25%.
- Cavity flooding system.
- State-of-the-art control room with human factors engineering.
- Estimated core damage frequency is 2.7×10^{-6}, which is two orders of magnitude lower than its predecessor.
- Large Size (1350 MWe).
- Equipment accessibility and permanently installed work platforms and handling equipment.
- Provisions for one-piece removal of large components in containment.
- Online testing capability for fluid-mechanical safety systems.
- Multiple stud tensioner that permits tensioning/detensioning all reactor vessel studs at once.

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[4] The System 80+ specifications and data were obtained from an unmarked, untitled ABB publication.

System 80+ complies with the procedural requirements and criteria of NRC regulations. A full level III Probabilistic Safety Assessment has been completed for the design, and the design meets the NRC Severe Accident Policy.

4.3 Advanced Boiling Water Reactor (ABWR)[5]

For over 40 years, General Electric has been designing boiling water reactors. The ABWR is their latest generation of BWRs, and is the result of a partnership between GE, Hitachi Ltd. and Toshiba Corp. One of the two ABWRs recently began operation in Japan (Kashiwazaki-Kariwa 6 & 7) with the second scheduled to start up shortly. The ABWR design features improvements in efficiency, safety, reliability, and cost effectiveness over previous BWR designs.

The following is a summary of key design objectives for the ABWR:

- Plant availability factor of 87% or greater.
- 24-month refueling cycle.
- Design life of 60 years.
- Core damage frequency of $<10^{-6}$.
- 52-month construction schedule.
- 20% reduction in capital cost ($/kWh) vs. previous Japanese BWRs.

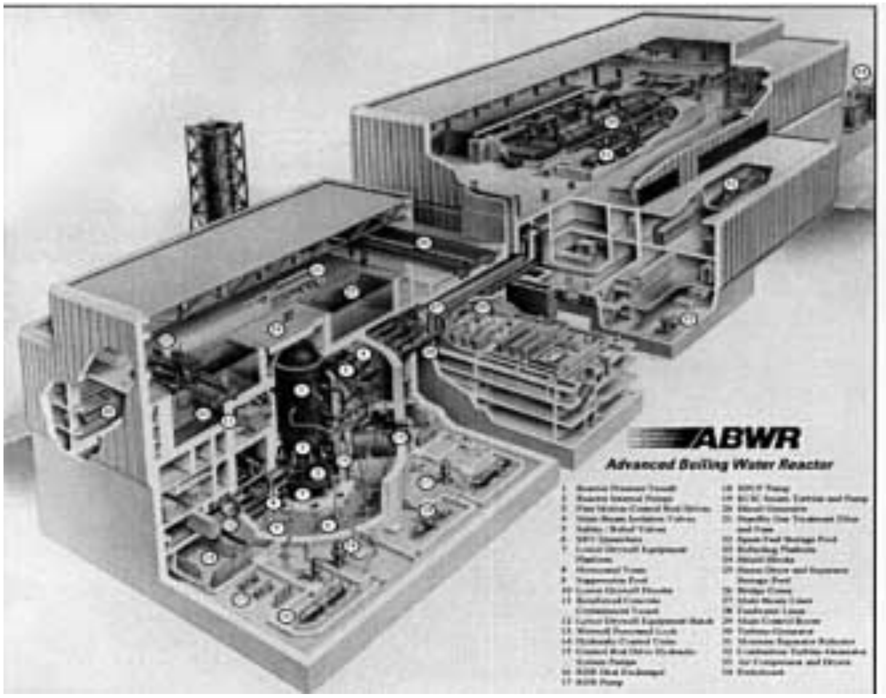

Figure 4.3 General Electric

ABWR Specifications:
- **1350 MW(e) BWR**
- **24 month refueling cycle**
- **52 month construction**
- **Improved cost effectiveness**

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[5] Lungman, GE Nuclear Energy, "The ABWR: General Design Description," January 1998.

At 1350 MWe, it is one of the largest capacity nuclear plant designs available. The most significant design improvements from previous BWR designs include:

- Reactor internal pumps.
- Fine motion control rod drives.
- Advanced control room.
- Fiber optic data transmission / multiplexing.
- Increased number of fuel bundles.
- Titanium condenser.
- Improved ECCS: high/low pressure flooders.

The boiling water reactor design differs from that of the pressurized water reactor in that it is a direct cycle system. As such, there are no steam generators to contend with. Additionally, the ABWR features a reactor vessel that is made of forged rings rather than welded plates. This eliminates 30% of the welds from the beltline region and below which require periodic in-service inspection. Simplification of design with fewer components than previous designs is expected to reduce construction time to five years or less.

4.4 High Temperature Gas Reactor

The High Temperature Gas Reactor is a completely different design and concept than any of the above mentioned systems. There is really nothing new and advanced about this design. The ideas have existed since the 1960s. Early in the history of nuclear power, the industry decided to concentrate on the light water reactor technology based on a perceived short supply of natural uranium. This led planners to believe natural uranium would be depleted by 1980. The logic, which turned out to be a flawed assumption, was that fast breeder reactors would be the norm after 1980 since the breeder reactor produces its own fuel. The first generation of nuclear reactors would be light water reactors. From that experience, the fast breeder reactors would evolve. Gas reactors competed for attention, but lost out to the light water reactors because they did not naturally lead to the next advancement that was planned which were liquid metal fast breeder reactors. This, combined with elements of the nuclear Navy steering the industry, favored the light water reactors. Since that time, the nuclear industry has not constructed anything beyond the first generation of reactors.

The common aspects of gas reactors under consideration are graphite cores, coated fuel particles and helium coolants. They have a higher efficiency than light water reactors because of the higher exit temperatures. The fuel used in gas reactors has a higher enrichment level, approximately 12-20% Uranium-235. They typically operate to higher burn-up levels which makes the spent fuel more proliferation proof. Gas reactors, because they have higher efficiencies, have lower thermal discharges[6] to the environment.

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[6] W.A. Simon, General Atomics, January 20, 1998.

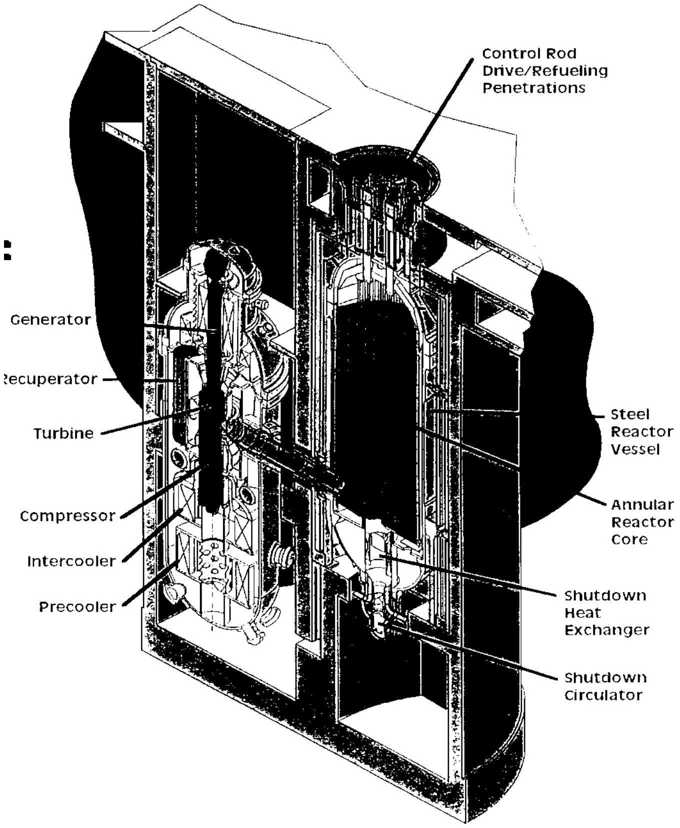

Figure 4.4 General Atomics Annular Core

Light water reactors have a relatively inexpensive core with a high power density and a "defense in depth" type safety system. Gas reactors have a more expensive core with a lower power density. The economics are potentially better because of a higher efficiency, compact balance of plant, and longer fuel life.[7]

There are two fundamental design choices when considering the HTGR. One proposed by General Atomics is a large, annular prismatic carbon block core (Figure 4.4). General Atomics designed this reactor as a 600 MW(t), direct cycle system. The second type is a much smaller, "pebble bed" core with which Germany has extensive experience (Figure 4.5). The smaller, pebble bed reactor is limited to about 250 MW(t) in order to maintain its inherent safety.

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[7] Lidsky, notes from January 13, 1998.

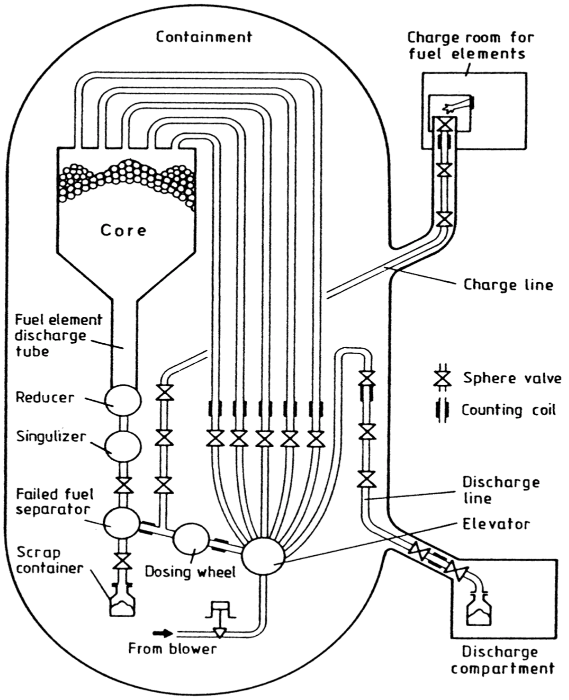

Figure 4.5 German AVR Pebble Bed Reactor

Pebble Bed HTGR Specifications:
- **100 MW(e)**
- **Passive safety**
- **Online refueling**
- **Extremely modular**

Germany is the leader in developing pebble bed gas reactors. In addition to the 20 MWth AVR, they have built and operated a 300 MWe electric pebble bed gas reactor that transferred heat to a steam generator for the production of electricity. This larger scale reactor was also developmental in nature. The plant operated for over two years and recently the German government decided to permanently shut down the plant. The Germans also have a 500 MWe pebble bed gas reactor on the drawing boards. Given the German financial and political situation, it is unlikely that this plant will be built. In any case, there is significant data available on the operations, fuel fabrication and support of pebble bed gas cooled reactors.

Two gas reactors have operated in the United States. Peach Bottom was a small, experimental 40 MWe HTGR that operated from 1967 to 1974. Successful on many counts, the reactor shut down primarily because the objectives of the prototype were met. The next plant constructed was Fort St. Vrain, a 365 MWe plant, which operated from 1979 to 1989. There were significant regulatory and design problems primarily because this gas-cooled reactor converted the heat from the helium gas to steam, using steam generators, to power conventional steam turbines, to make electricity. There were many successes in this large scale up from Peach Bottom, however the low availability created by some initial design flaws could not be overcome. These flaws dealt largely with performance of the pumps used to circulate the helium, which were water-cooled. This reactor also used fuel rods in a prismatic carbon core typical of General Atomic designs.

As stated above, gas reactor technology has existed since the 1960s, but has not been significantly developed. This is largely due to the US decision to pursue light water technology and the relatively poor performance of Fort St. Vrain. Even though gas reactors have not been accepted in the United States, Russia, Germany, South Africa, China, and Japan have or are currently investing in this technology as an option for their next generation of reactors.

4.5 Other Options Reviewed

There were several other concepts reviewed that have been considered in the past for new advances in nuclear power plant technology. Although, not a great deal of material was available for these designs, a cursory review of the available literature was performed to determine whether there were any features worthy of consideration to address the criteria identified for this project.

4.5.1 Lead Bismuth Reactors[8]

The lead-bismuth reactor is a fast reactor cooled by lead-bismuth instead of sodium. It uses a metal alloy fuel, Uranium – Zirconium instead of Uranium – Oxide. This results in a very hard neutron spectrum. The breeding aspect of this reactor solves the possible uranium shortage problem. This reactor allows for a very high breeding ratio. It can fission all actinides efficiently. The reactor starts up with less than 20% U-235 and will then operate only on natural uranium, adding a non-proliferation advantage.

4.5.2 Thorium Breeder

This breeder reactor is capable of operating using water but with thorium fuel which makes the design less susceptible to proliferation. It’s advantage is that it is a breeder reactor which will be important as the supply of natural uranium becomes tight with the reintroduction of nuclear power on a large scale to combat global climate change.

4.5.3 Liquid Metal Breeder Reactor

This reactor has been extensively studied in the US. Small breeder reactors were operated in the US from 1960 through 1996. In France, small and large breeder reactors have also operated. Due to concerns relating to the use of plutonium and the fear of proliferation generated by the plutonium economy, this design was not considered due to political opposition. There appear to be no technical obstacles to the design. Presently it is too expensive to complete.[7]

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[8] The specifications and data for lead bismuth reactors was obtained from Dr. Driscoll’s notes, January 8, 1998.

5 EVALUATION PROCESS USED TO SELECT DESIGN TYPE TO BE DEVELOPED

Three reactor types are considered for a final design decision: AP600, the advanced light water reactors were grouped into an ALWR (System 80+, ABWR), and the pebble bed HTGR. For the purposes of this design, we have chosen the Pebble Bed high temperature gas-cooled reactor largely because of its online refueling capability and the small size to which it is adapted to making modularity easier. There was insufficient information available on the other reactor designs evaluated such as lead bismuth and thus a fair assessment was not possible. Given the objective of having a reactor design available for purchase and construction early in the next century, also precluded serious consideration of these options.

In order to compare the remaining reactor options, a decision matrix was constructed (Figure 7). Each criterion was given a relative level of importance from 1-10. Each reactor type was rated 1, 2, 3, or 4 for their relative performance in each category, with “1” being the best rating.. Using the locus of top ratings, a clearer picture of the reactors’ ranking relative to the criteria set forth was established.

5.1 Summary of Decision Criteria

5.1.1 Safety: HTGR, AP600, ALWR

Safety is the most important criterion in evaluating the options. All reactors must meet a minimum safety level, but those that are more inherently safe are more likely to win government and public support. The small modular pebble bed gas reactor is considered to be the safest of all designs considered. Its passive, inherent safety with no possibility of core melt make it the most attractive. AP600 has a passive safety defense, but is less passive than the HTGR. The AP600 contains a large water tower inside the containment building, located above the reactor vessel. Valves are blown to activate this system when the temperature of the core exceeds a certain level. No operator involvement is necessary; however, the system is more reliant on an engineered solution than the inherent safety of the HTGR. All systems have improved on safety from their ancestors by increasing the time required to take emergency actions. In most advanced designs, no operator action is needed for at least 24 hours.

5.1.2 Economics: AP600, ALWR, HTGR

The final economic situation of the plant cannot be determined until the detailed design is complete. Only a rudimentary analysis is available prior to a complete design. Based on several factors, the light water reactors have an advantage. The AP600 and ALWR designs have the distinct advantage of pre-approved license from the Nuclear Regulatory Commission. The HTGR will have to bear the costs of the regulatory process. The AP600 and ALWR have much more construction experience in the United States because of their “evolutionary” nature. There is much uncertainty involved with the gas reactors because they have not been constructed or tested nearly as extensively as the light water reactors.

5.1.3 Payback: AP600, HTGR, ALWR

The determining factors of payback are economics and the size of the plant. Because of the bigger capital investment associated with the larger ALWR plants, it is expected that the smaller, more modular plants will generate quicker paybacks. Although the entire plant may take as long to build, several of the modules will be online and producing revenues prior to final completion of the entire system. Therefore the potential for a quicker payback is with AP600 and HTGR.

5.1.4 Government Support: HTGR, AP600, ALWR

Our expectation is that the government support of a safer, more proliferation proof reactor would be greater than it would for one that has lesser capability in these areas. The HTGR is this reactor. If this reactor is to be exported, the United States government would feel much better about the dramatically reduced chances of a receiving country obtaining weapons material from the waste streams of the HTGR.

5.1.5 Local Support: HTGR, AP600, ALWR

Marketed as a new, different idea from what the public has come to expect from the perceptions associated with light water reactors, it is expected that a public reaction to an HTGR would be more positive than a new and improved light water reactor. Any advanced light water reactor will still encounter public skepticism from the perceived difficulties of this type of reactor in the past. Another significant advantage of the HTGR is the live testing of the safety system. This could not be done in light water reactors without wreaking havoc on the system. Gas reactors may be proven safe through tests that will not damage the systems.[9] This "licensing by test" approach will prove to the public by test, not theory, that gas reactors are safe.

5.1.6 Construction Time: AP600, HTGR, ALWR

The ability of much of the reactor to be assembled in a factory, shipped to the construction site, and pieced together will decrease construction time. The smaller reactors have this potential. The large ALWRs will have to be completely assembled on site. The ALWRs have an experience advantage over the gas reactors. However, this advantage is outweighed by the modularity of the smaller gas reactors. It is expected that many of the components, particularly the balance of plant turbines, recuperators and precoolers will come from standard production technology and production lines. Estimated construction times for the AP600 is three years; HTGR: five years; ALWR: five years. HTGR has an advantage over the ALWR because some of the plants will come online after three years.

5.1.7 Modularity: AP600, HTGR, ALWR

As stated above, the smaller reactors are designed to be assembled in the factory and pieced together on site. HTGR has the potential to surpass the AP600 in this respect. But, it must

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[9] Yan and Lidsky, ASME Conference, 24-27May 1993

first overcome the lack of construction experience compared to light water reactors. The bigger ALWRs have virtually no modularity by design.

5.1.8 High Efficiency: HTGR, AP600, ALWR

The gas reactors outperform the light water reactors in efficiency. Gas reactors operate at 45% while typical light water reactor efficiency is 33%.[10] The higher exit temperatures of the gas reactor are the main source of this difference.

5.1.9 Regulatory Transparency: HTGR, AP600, ALWR

Regulatory transparency is a concept that would allow reactors to need less or simpler regulatory control due to the inherent safety of the design. The regulatory effort agencies would need to expend to determine compliance is minimal. For some of the same reasons we believe the gas reactors will have greater government support, they will also have more regulatory transparency. Our hope is that the NRC will see the passive safety features and the proliferation proof systems as a different concept. The current regulations are based on light water reactors. Many of these would not apply to a gas reactor.

5.1.10 Fuel Integrity: HTGR, AP600, ALWR

The pebble bed design of the HTGR gives it a significant advantage over the light water reactors. The pebble fuel is virtually indestructible. It could also be a suitable long-term storage waste form due to the characteristics of the hard graphite spheres.

5.1.11 Staff Size: HTGR, AP600, ALWR

The gas reactor will take a smaller number of people to operate, maintain and secure than the light water reactors. Because of the inherent safety and the lack of “defense in depth” systems to monitor and maintain, the gas reactor will have a smaller staff. The proliferation proof spent fuel will also allow for less security. The turbine plant should also be easier to automate much like conventional gas fired fossil plants that are currently allowing for smaller staff sizes.

5.1.12 Low Level Waste output: HTGR, AP600, ALWR

Because it does not have extensive water purification systems to maintain, it is expected that the low-level waste generate by the gas reactors would be lower.

5.1.13 Refueling Time: HTGR, AP600, ALWR

The gas reactors have a dramatic advantage in refueling time because of their online refueling capability. Light water reactors typically will have to shut down every 12-18 months for about 45 days to refuel.

5.1.14 Burn Up: HTGR, AP600, ALWR

Gas reactor fuel is designed to achieve burn ups of up to 100,000 MWD/MT. This is higher than the current 60,000 MWD/MT limit for light water reactors. This advantage allows the fuel to be

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[10] Ibid.

used more completely and burns more of the long-lived actinide products that pose difficulties in long term waste disposal.

5.1.15 Operating Cycle Length: HTGR, ALWR, AP600

The gas reactors again have an advantage in operating cycle length. Because no shut down for refueling is necessary, the operating cycle will last as long as the durability of the components. The ALWRs have a 24-month operating cycle.[11]

5.1.16 Decommissioning: AP600, HTGR, ALWR

The smaller, more modular plants would be easier to decommission. Transportation costs would be significantly less because of the smaller size of the reactors. Also, less production of low and high level waste could allow savings.

5.1.17 Proliferation: HTGR, AP600, ALWR

The high burn up of the gas reactors make it more proliferation resistant than light water reactors. Because of the high burnup, isotopes of plutonium are produced that make it extremely difficult to use for a weapon.

5.1.18 Ease of Replacement: AP600, HTGR, ALWR

Smaller, more modular plants would allow for an easier replacement of components. The smaller components will also take less time to install, increasing the capacity factor.

5.1.19 Simple Design: HTGR, AP600, ALWR

Again, smaller, more modular plants allow for a simpler design. This directly relates to maintenance and ease of replacement. The AP600 is slightly more complex than the gas reactors because of its safety systems.

5.1.20 Once Through Fuel Cycle: HTGR, ALWR, AP600

There is considerable US pressure not to reprocess spent fuel because of the concern about proliferation. While France and England are presently reprocessing spent fuel for the international market, it is not economic given the low price of uranium. Given the concerns about reprocessing, due to the higher burnup of the HTGR fuel, it is viewed as more desirable since it utilizes the fuel more efficiently. The decision not to reprocess may change in time.

5.1.21 Life of Plant: AP600, ALWR, HTGR

The light water reactors have an advantage because of the tremendous experience the industry has with these types of reactors. Until a full scale HTGR is built and operated extensively, the light water reactors will have an advantage. In theory, the HTGR could have a longer life because of the far less corrosive effects of helium gas compared to steam.

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[11] Rodwell, EPRI class presentation, 7 January 1998.

5.1.22 Electrical Conversion: HTGR, AP600, ALWR

The gas reactors allow for much smaller gas turbines. The cost and maintenance of these turbines is significantly less than the larger steam turbines of the light water reactors.[12]

5.1.23 Spent Fuel: HTGR, AP600, ALWR

The amount of spent fuel produced by the HTGR is higher than conventional LWRs due to its lower power density despite the higher burnup. The spent fuel of the gas reactors is in the form of graphite coated balls that are extremely stable, proliferation proof, and are believed to be an excellent long term waste storage form.

5.1.24 Contamination: HTGR, AP600, ALWR

Given the design of the fuel and minimal support systems required, it is expected that the contamination of the plant will be lower for the HTGR. The corrosion products found with water systems will not be present and the use of helium, since it is an inert gas, should greatly reduce the potential for contamination.

5.1.25 Production line capability: HTGR, AP600, ALWR

Directly related to the modularity of the plant is the production line capability for the manufacture of plant components. The smaller size plant equipment of the gas reactors are much more suited to production line assembly than the light water reactors. Twelve 100 MW(e)-gas reactors would require assembly while only two 600 MWe AP600s and only one System 80+ or ABWR of 1350 MWe would be assembled on assembly lines. It is hoped that the entire reactor vessel and its internals can be factory assembled and shipped to the site by barge or even possibly by train.

5.1.26 Other considerations that have equal weight across all designs:

Online Maintenance, Advanced Control Room, Material Properties, and Modern Information Management System are important aspects, which are not currently in the advanced designs. We want to include these aspects into our final design, regardless of the type of reactor.

5.2 Conclusions

Based on the results of the evaluation according to the criteria established, the design that has the most 1's as shown on Table 5-1 is the modular high temperature pebble bed gas reactor with a direct gas turbine cycle. The decision matrix was simply used to help evaluate options. The review of all currently available designs demonstrated that the light water reactors were "evolutionary" by the guidelines established by the industry. This constraint affected the ability of the new designs to eliminate many of the obstacles identified for making dramatic improvements either in performance or economics. The final choice was between the AP600 and the HTGR. The HTGR was selected largely for its inherent safety, small size and that it brings to the market a "new" approach. Also, this approach doesn't have the negative public

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[12] Yan and Lidsky, ASME Conference, 24-27 May 1993

perceptions associated with light water reactors no matter how the current light water reactor designs have improved.

This is a radical shift from the standard beliefs in the nuclear industry. The most important characteristics that make the pebble bed HTGR more attractive are the inherent safety design, and high degree of modularity. It is believed that a new approach to nuclear power production will have a better chance at winning public and governmental support. The disadvantages considered were the uncertainty in how much it will cost to build, how the NRC will react to a system that the regulatory environment is not familiar with, and limited operating experience when compared with the highly tested and analyzed light water reactor technology.

Many engineers, designers, and the NRC have grown up with light water reactors and are comfortable with them. This recommendation will, no doubt, face scrutiny from an industry that has invested billions of dollars in the current and next generation of light water reactors. The conclusion of this evaluation is that the Pebble Bed HTGR has the greatest future potential for the reintroduction of new nuclear power plants both in the United States and elsewhere.

Table 5-1
Reactor Design Decision Matrix

Attribute	Importance	ALWR	HTGR	AP600
Safety	10	3	*1*	2
Economics	10	2	2	1
Payback	9	2	2	1
Government Support	9	3	1	2
Construction Time	8	2	2	1
Modular	8	3	2	1
Local Support	8	3	1	2
High Efficiency	8	3	1	2
Regulatory Transparency	8	3	1	2
Fuel Integrity	7	3	1	2
Small Staff	7	3	1	2
Low Level Waste	7	3	2	2
Short Refuel Time	7	3	1	2
Online Maintenance	7	3	1	2
High Burn Up	7	2	1	2
Long Operating Cycle	7	2	1	2
Decommissioning	7	3	2	3
Proliferation	6	3	1	2
Advanced Control Room	6	2	1	2
Easy Replacement	6	3	2	1
Simple Design	6	3	1	2
Once Through Fuel Cycle	6	3	2	1
Life of Plant	6	2	3	1
Electrical Conversion	6	3	1	2
Spent Fuel	6	2	1	3
Materials	6	1	1	1
Low Contamination	5	3	1	2
Production Line	5	3	1	2
Modern IMS	5	1	1	1

6 CONCEPTUAL DESCRIPTION OF REACTOR PLANT DESIGN

6.1 General Plant Overview

Several reactor plant designs have been considered for this project, but the modular high temperature gas reactors (MGR) show promise for greatest simplicity, inherent safety, modularity, and economic viability. Two MGR schemes are being considered, an indirect cooling design (MGR-GTI) and a direct cooling cycle (MGR-GR). The general cycle, primary and secondary constituents, and fuel cycle will be discussed.

Gas reactor technology has existed since the mid 1960's and has been thoroughly studied by Germany and Russia. Most of the plant systems, which contribute to the design of the reactor system, will be adopted from extensive research performed by groups in Europe, Russia and by members of the Energy Laboratory at MIT. Xing L. Yan and Lawrence Lidsky of the Energy Laboratory proposed a MGR design in the early 1990's as an answer to the next generation of nuclear power. In their words, "The modular high temperature gas-cooled reactor (MGR) is an attractive option for the next generation of nuclear power. It relies on intrinsic physical laws for inherent safety. The reactor's ability to survive worst case accidents, without relying on safety control systems or operator intervention, permits experiments to prove reactor safety. This allows a "Licensing by Tests" approach to nuclear regulation, providing the strongest possible basis for satisfying the social and political prerequisites for next-generation nuclear power". [Lidsky]

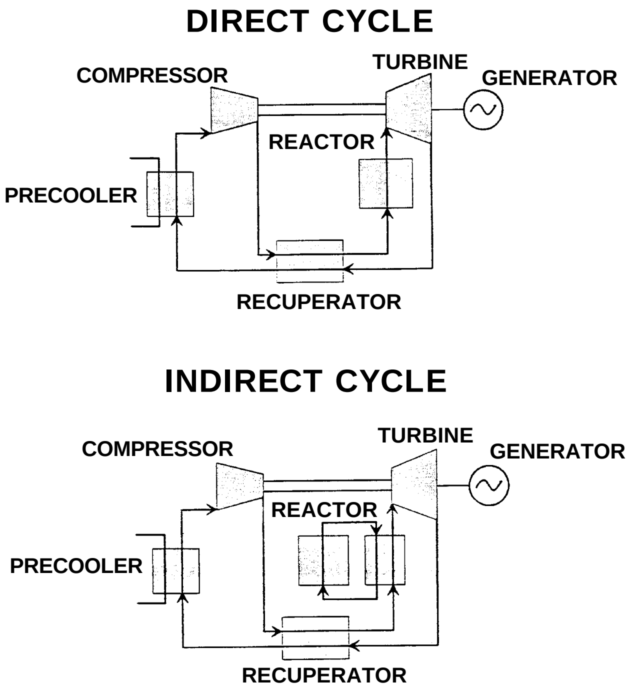

Figure 6.1 Cycle Schematics

Figure 6.1 shows schematically the major components of both the indirect and direct helium cycle gas reactors and table 6.1 summarizes the important operating parameters of each cycle. The direct cycle (MGR-GR) will be the ultimate gas cycle plant due to its simplicity and economic potential. Initially the indirect cycle will be developed because it will be significantly easier to license due to the fact that it eliminates the possibility of fission product contamination of the helium turbine and other components. Once a successful operation of the helium cycle is obtained with the indirect cycle, plans to shift to the direct cycle can be considered.

Table 6-1
MGR Operating Parameters

Parameter	Indirect-Cycle	Direct-Cycle
Reactor Power (MWth)	200	200
Fuel Type	Pebble Bed	Pebble Bed
Core Temp. (Inlet/Outlet) (C)	400/850	576/850
Core Coolant Flowrate (kg/s)	149.2	245.6
Core Coolant Pressure (MPa)	7.0	8.0
Turbine Flowrate (kg/s)	149.2	245.6
Turbine Inlet Pressure (MPa)	7.13	7.80
Turb. Cycle Press. Ratio	4.2	2.2
Turbine Inlet Temp. (C)	810	850
Gross Power Output (MWe)	~110	~110
Net Plant Efficiency (%)	45.2	45.6

Figure 6.2 shows the modified closed Brayton thermodynamic cycle that both the MGR-GTI and MGR-GT operate.

The working fluid for both cycles is helium. Helium has many advantages in power conversion systems, namely helium systems face less technical challenges than standard air turbines. Since helium is an inert gas it can experience very high operating temperatures without oxidation. This allows components, such as the disks and blades to be less stressed. Another mechanical advantage of helium is that it has a sonic velocity three times that of air, which eliminates aerodynamic limitations on rotor speeds experienced by air turbines. Thermodynamically, helium is superior to air because its thermal conductivity and heat capacity are five times greater than air. The larger heat capacity allows more work to be done per mass of helium as compared to air and the larger thermal conductivity allows for smaller heat transfer equipment.

As seen in the cycle diagram, a recuperator is used to capture the heat rejected by the turbine to help heat the helium coming out of the compressor. This allows less heat transfer from the nuclear fuel to the helium, which results in increased plant efficiency. Plant efficiency is also increased by the use of precoolers and intercoolers. The coolers lower the temperature of the working fluid entering the compressor, therefore reducing the amount of work the compressor must perform. It can be shown that two stages of intercooling in the compression stages are optimal since there is no economic advantage for adding more than two stages. Increasing the turbine inlet temperature, (which is a function of the nuclear fuel capabilities) also improves plant efficiency. Current technology recuperator effectiveness can be as high as 0.95, turbine inlet temperatures as high as 850°C, and the use of intercooling allow for efficiencies of 45.2% and 45.6%, for the indirect and direct cycles respectively. With new fuel technologies and advances in component designs, efficiencies exceeding 50% will be possible.

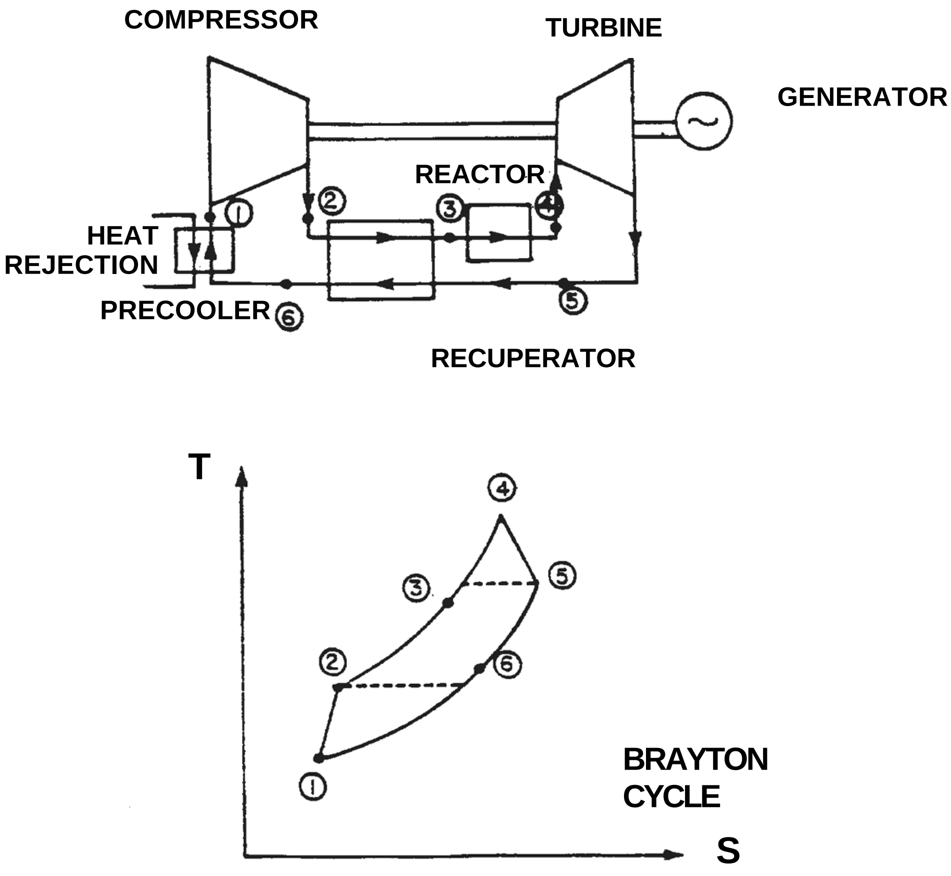

Figure 6.2 Thermodynamic Cycle

6.2 Indirect Cycle Plant

The indirect cycle proposed by Dr. Lidsky's group is shown in Figure 6.3. The reactor and intermediate heat exchanger (IHX) make up the nuclear island and the gas turbine power conversion system establishes the secondary loop. Heat produced by the reactor is transferred to the turbomachinery via the IHX; an IHX is used separate from the reactor and secondary components to avoid possible fission product contamination in the secondary components. Figure 6.3 also shows relative scaling for the indirect cycle plant.

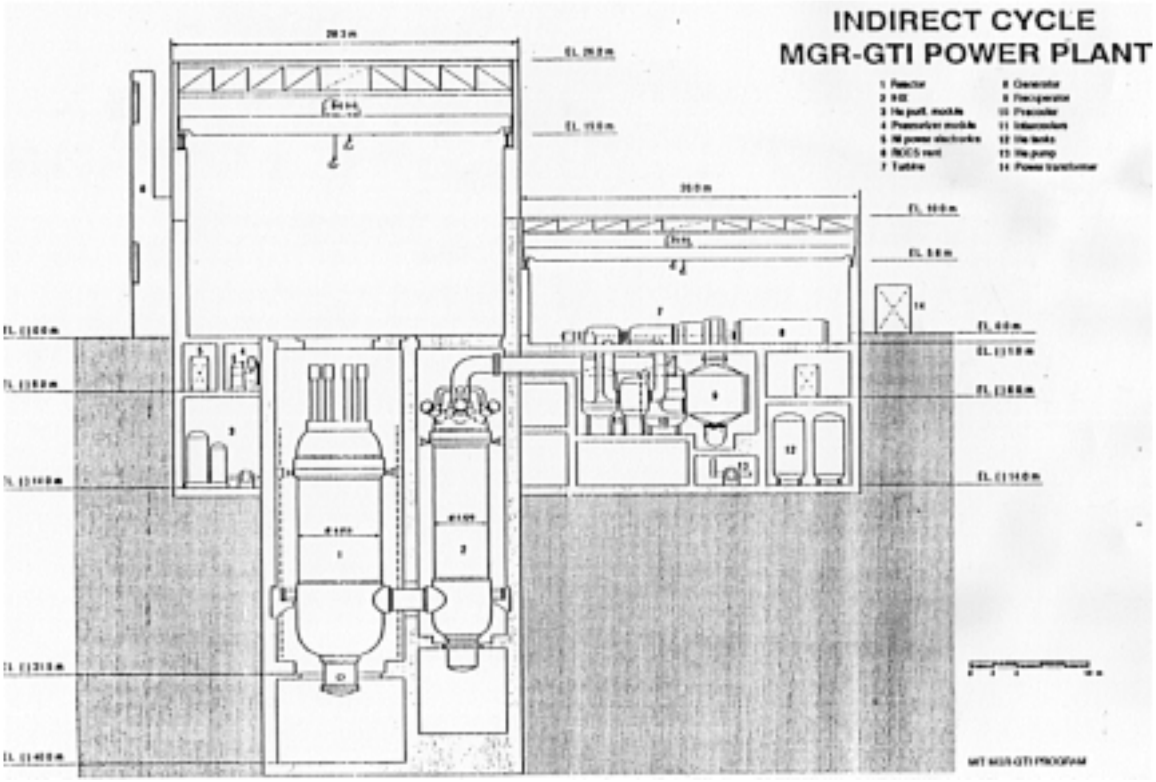

Figure 6.3 Indirect Cycle Plant

6.3 Direct Cycle Plant

Figure 6.4 shows the schematic of direct cycle plant (MGR-GT). The direct cycle only uses one loop, helium flows from the core exit, through the turbine, is circulated using a compressor, and then pumped back to the reactor. The direct cycle design significantly reduces the overall plant complexity, increases modularity, and can be viewed as the ultimate gas power plant.

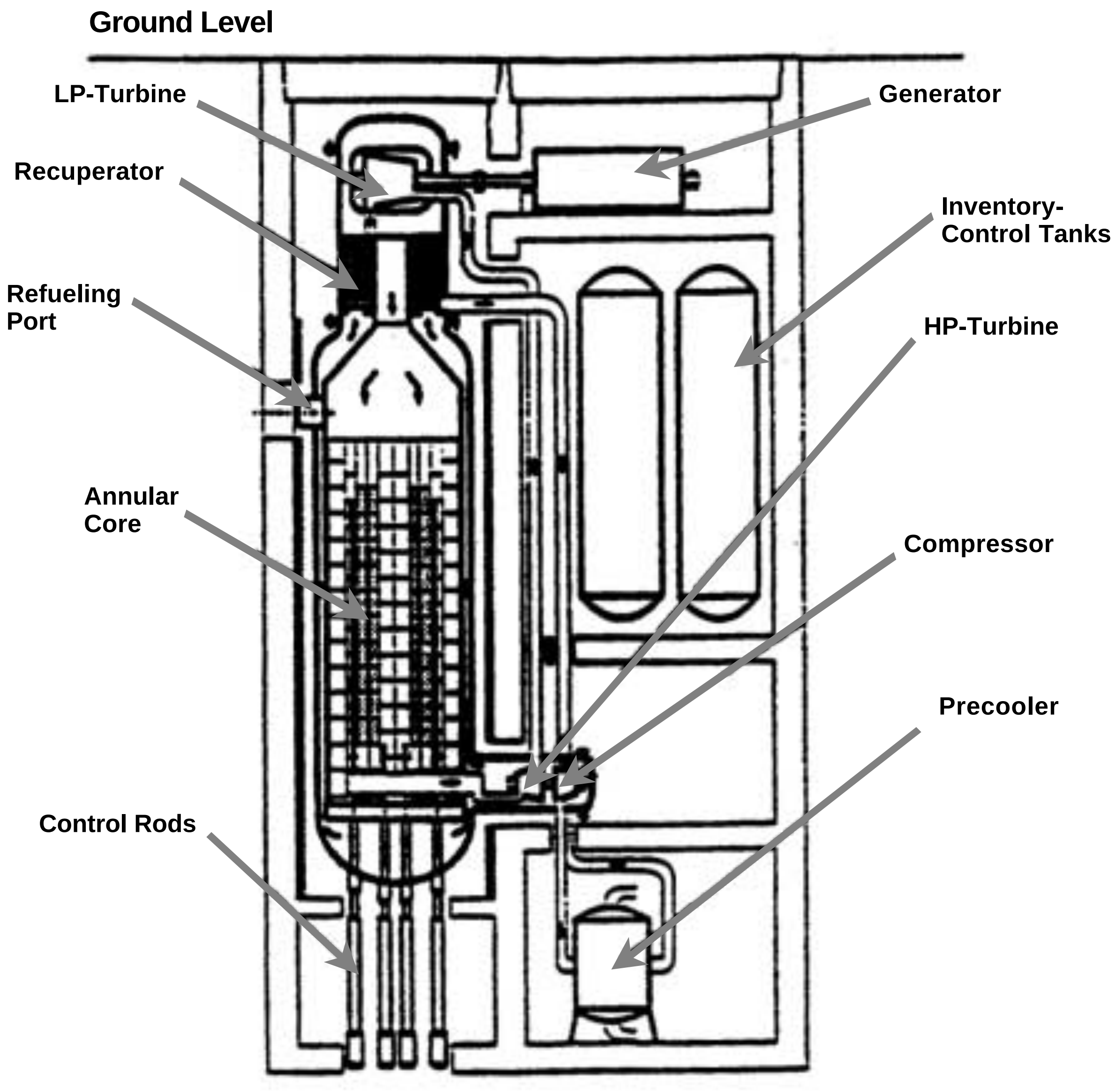

Figure 6.4 Direct Cycle

6.4 "Naturally Safe" By Fuel Design

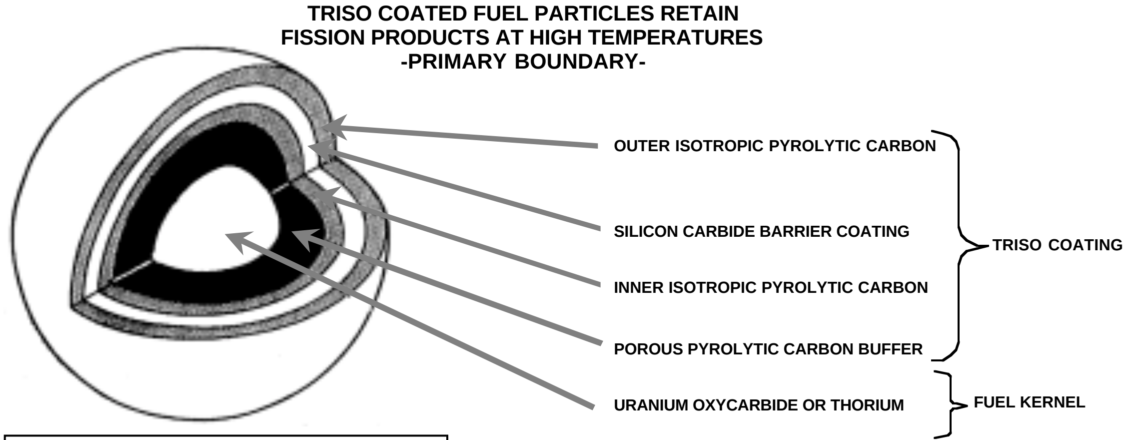

Figure 6.5 Pebble Bed Fuel

Both the direct and indirect reactor designs are "naturally safe" due to the inherent safety the fuel design offers. A pebble bed of triso-coated spherical fuel particles, such as the fuel pebble shown in Figure 6.5, comprise the core with control rods located around the outer perimeter of the fuel bed. Approximately 380,000 spheres are loaded in the core. Each fuel sphere contains: the uranium oxycarbide or thorium core, a porous pyrolytic carbon buffer, a inner isotropic pyrolytic carbon layer, a silicon carbide barrier coating, and an outer isotropic pyrolytic carbon layer; the total sphere is approximately the size of a racquet ball.

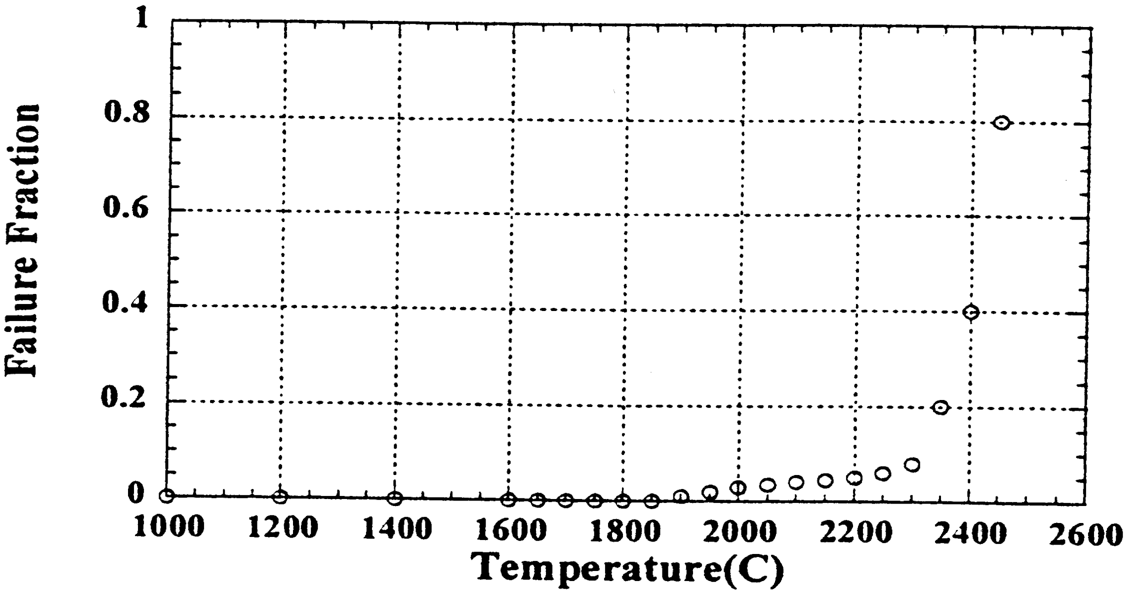

Figure 6.6 Fuel Failure

The inherent safety is derived from the sphere because it takes temperatures of approximately 2000°C in order for the ball to begin to break down. Figure 6.6 shows the fuel failure fraction as a function of fuel temperature. Safety is ensured against the worse case accident (loss of coolant with all rods out), by limiting the power density to approximately 6 MW/m^3 and the overall core size (resulting in an overall thermal power of ~ 200 MW). Based on these design parameters, the highest temperature the fuel would achieve is approximately 1600°C and it would take approximately 3 days to reach that peak fuel temperature before the fuel starts to naturally cool. Cooling to the core with a complete loss of coolant is achieved via natural conduction from the core to the surroundings.

Not only does the fuel offer a "naturally-safe" feature, but also easily facilitates online fueling. The fuel pebbles can be cycled through the core as necessary and discharged when fully burned out. Another advantage of having the fuel in pebble form is waste removal and storage. The spent fuel is inherently contained by the carbon material; therefore no spent fuel pool is needed and the storage facilities can be a lot less complex.

6.5 Modularity and Construction

Due to limitations placed on the size of the reactor for safety concerns, the total electric output per reactor will be small, possibly as low as 100 MWe per plant. Several plants could be combined to satisfy the electrical requirements of the utility. The smaller design allows for all components to be factory made and tested. This will significantly reduce the cost and construction time of the facility, plus it will increase the quality assurance of all components.

The reduced complexity of the gas cycle plant will reduce operating and maintenance requirements. Plant control will be simpler, therefore requiring fewer operators. Fewer components are present, therefore reducing component service requirements. Having the entire facility comprised of smaller units allows for online maintenance. A portion of the plant can be taken out of service without requiring a full shutdown; this will increase the overall capacity factor of the facility.

7 ECONOMIC ANALYSIS

7.1 Introduction

Initial economic projections were developed for the 10 x 250 MWt direct circle Modular High Temperature Gas Cooled Reactor (MHTGR) power plant, and comparisons were made with the competing nuclear and gas plants.

The basic information for the evaluation was mainly from an analysis performed by Gas-Cooled Reactor Associates[13].

7.2 Cost Estimate Ground Rules

The MHTGR cost estimates were developed according to the methodologies and guidelines in Cost Estimate Guidelines for Advanced Nuclear Power Technology[14] and Nuclear Energy Cost Data Base[15] developed by Oak Ridge National Laboratory for the U.S. Department of Energy (DOE). The purpose of using these cost ground rules was to provide the basis for a comparable and consistent advance reactor cost analysis. The cost estimates were calculated in terms of January 1992 dollars, in order to make the comparison with the other competing models analyzed previously[16].

Major changes to the ground rules have taken place since the prior MHTGR cost estimate including the establishment of the EPRI reference nuclear site. With the change in site, there were changes in labor costs, labor productivity, material costs, site conditions and ambient temperatures. The MHTGR design was optimized on the basis of a siting envelope consistent with the standardized design and deployment philosophy for the MHTGR.

The cost estimates are expected to be comparable with the USCEA[12], which gives the latest analysis of the cost of electricity from coal, gas and nuclear power plants.

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[13] Modular High Temperature Gas-Cooled Reactor Commercialization and Generation Cost Estimates, Gas-Cooled Reactor Associates, 1993.

[14] Cost Estimate Guidelines for Advanced Nuclear Power Technologies, ORNL/TM-10071/R3, Oak Ridge, TN, March 1993.

[15] Nuclear Energy Cost Data Base, U.S. Department of Energy, Washington, D.C., September 1988.

[16] Advanced Design Nuclear Power Plants: Competitive, Economical Electricity, U. S. Council for Energy Awareness, Washington, D.C., June 1992.

7.3 Cost Estimates

The cost of generating power from the MHTGR consists of four components: the capital cost, the operation and maintenance cost, the fuel cost and decommissioning cost. The two major factors are capital cost to construct the plant itself and the production cost associated with plant operation.

7.3.1 Capital Cost

The target nuclear island consists of ten 250 MWth units with common facilities. In this MHTGR concept design, structure costs dominate field labor and construction costs. The MHTGR has less piping and electrical construction when compared to other nuclear concepts due to the elimination of active safety systems and reliance on the inherent characteristics of the MHTGR. The direct circle model, through elimination of the steam and feedwater systems and their auxiliaries, has significantly less piping and electrical system requirements. The base construction cost for this 1125 MWe power plant is expected to be $2,006 million.

Compared to a nuclear island composed of a large single unit, the MHTGR has three major advantages to compensate for the theoretical capital economy of the large size of the single unit. These are:

> Cost saving from passive plant technology and a modular and simple design,
>
> Cost reduction due to common facilities used by ten units,
>
> Cost reductions from shorter construction schedules (36 months) and realization of the revenues from the power generated by the early finished units.

The updated MHTGR cost estimates presented herein have increased relative to prior estimates, due to a combination of design changes and cost estimate guideline changes. The cost estimates are expected to be more conservative than prior estimates and incorporate more design definition.

A contingency of 24% is applied to the cost estimate for the direct cycle MHTGR, and AFUDC adds 12.3% interest to the total capital cost. The MHTGR is evaluated to have the total capital cost at $2,006 million and the unit capital cost at $1,588 million before AFUDC.

7.3.2 Operating and Maintenance Costs

The MHTGR operating and maintenance costs have been estimated on a basis of its natural safety and simple system design. The more simplified, compact plant design requires the least number of systems and components to operate and maintain, thus significantly reduces the cost of maintenance and the number of the on-site staff which is expected to be 150 personnel.

The capacity factor of the plant is expected to range from 90% to 95% because of following factors:

> The high capacity factor of the single unit MHTGR (app. 84%) due to its online refueling method, and
>
> In the ten units plant, one unit shutdown will only reduce the output power of the plant instead of stopping the whole plant.

The MHTGR plant O&M costs were estimated to be $31.5 million per year, and the busbar cost were estimated to be 3.6 mills/kWh at 90% capacity factor.

7.3.3 Fuel Cost

The fuel costs presented are based on 30-year operation with 18 month operating periods between refueling for the ALWRs. Costs for periodic reflector block replacement for the gas reactor and control rod replacement costs are included in the operations and maintenance expenses for all plants.

In accordance with the requirements of the ground rules, the nuclear fuel cycle cost input assumptions used in the fuel cycle cost evaluation include uranium at $25/LB U_3O_8, conversion at $10/kgU, and enrichment at $125/kg-SWU under 10.5% and $925/kg-SWU over 10.5%. The higher efficiency (low heat rate) of the MHTGR concepts increases the $/MMBTU spent fuel disposal cost based on the 1 mill/kWh Waste Act assessment.

The fuel costs of MHTGR were estimated to be $1.28/MMBTU, and levelized busbar costs at 8.5 mills/kWh.

7.3.4 Decommissioning Cost

A specific decommissioning cost estimate was developed for the MHTGR using quantities and commodities from the detailed cost estimate for a decommissioning scenario defined to remove all radioactive waste from the site and all construction material to a level of 1m (3 ft) below grade. Based on the quantity takeoffs, the cost of decommissioning was estimated to be $199 million. Since the levelized busbar decommissioning costs are less than 0.6 mill/kWh, the decommissioning method will have minor impact on total busbar costs.

7.3.5 Total Generation Cost

Table 7-1 presents the 30-year levelized busbar generation costs for the MHTGR concepts, which were estimated at 3.4 cents/kWh.

Table 7-1
MHTGR Busbar Generation Costs ('92$)

Reactor Thermal Power (MWth)	10 x 250
Net Efficiency (%)	45%
Net Electrical Rating (MWe)	1125
Capacity Factor (%)	90%
Total Overnight Cost (M$)	1,786
Levelized Capital Cost ($/kWe)	1,588
Fixed Charge Rate (%)	9.47%
Total Capital Cost (M$)	***2,006***
30 year level cost per year (M$/YR):	
Levelized Capital Cost	190
Annual O&M Cost	31.5
Level Fuel Cycle Cost	75
Level Decommissioning Cost	5.4
Annual Revenue Requirements (millions)	***302***
Busbar Cost (mills/kWh):	
Capital	21.4
O&M	3.6
FUEL	8.5
DECOMM	0
Total Cost (mills/kWh)	***34.1***

7.4 Comparison with Alternatives

Table 7-2 provides a comparison of the MHTGR concept with the AP600 model of Westinghouse, the evolutionary ALWR1200 model and the natural gas combined cycle combustion turbine (CCCT).

Table 7-2
Summary Generation Cost Comparison ('92$)

	ALWR1200	AP600	CCCT	HTGR
Net Electrical Rating (MWe)	1x1200	2x600	2x500	10x112.5
Net Heat Rate (BTU/kWh)	10,200	10,400	7,514	7,070
Capacity Factor (%)	80	80	84	90
Levelized Generating Cost(cents/kWh)	3.8	3.62	4.2	3.4
Total Overnight Cost (before AFUDC) ($/kWe)	1,359	1,420	500	1,588
Fixed O&M ($/kWe/year)	42	35	7.5	28
Initial Fuel Cost (cents/million Btu)	70	63	214	128
Real Fuel Escalation Rate (%/year)	0	0	3.5	0
Construction Time (months)	72	60	36	36

8 Financing Construction

The construction of an MHTGR will demand a significant amount of capital. The fact remains though, that the customers for the service eventually pay for it, and the price includes not only operating costs but also the cost of capital. This section discusses the financial parameters and cost of capital involved in the construction of an MHTGR. The financing options will focus on the construction of 10, 112.5 MWe plants, at a total cost of $ 2,006,000 (from Table 7-1). This is approximately the size of the large light water reactors presently being offered.

8.1 The Concept of Cost of Capital

The revenues generated are used to service the capital supplied by investors to the utility. The aggregate return required by these investors is called "cost of capital." The cost of capital is the opportunity cost, expressed in percentage terms, of the total pool of capital employed by the utility. It is the composite weighted cost of the various classes of capital (bonds, preferred stock, common stock) used by the utility, with the weights reflecting the proportions of the total that each class of capital represents.

While utilities prior to deregulation enjoyed varying degrees of monopoly in the sale of public utility services, they now must compete with every one else in the free open market for the input factors of production, whether it be labor, materials, machines, or capital. The prices of these inputs are set in the competitive marketplace by supply and demand, and it is these input prices that are incorporated in the cost of service computation. This is just as true for capital as for any other factor of production. Since utilities must go to the open capital market and sell their securities in competition with every other issuer, there is obviously a market price to pay for the capital they require, for example, the interest on debt capital, or the expected return on equity.

The cost of capital is the compensation required by investors for postponing consumption and exposing capital to risk. While the market price of labor, materials, and machines is easily verifiable, the price of the capital input is more complex to determine. When investors supply funds to a utility by buying its stocks or bonds, not only are they postponing consumption, giving up the alternative of spending their dollars in some other way, but they are also exposing their funds to risk. Investors are willing to incur this double penalty only if they are adequately compensated. The compensation is the price of capital. If there are differences in the risk of the investments, competition among firms for a limited supply of capital will bring different prices. These differences in risk are translated into price differences by the capital markets in much the same way that commodities that differ in characteristics will trade at different prices.

The important point is that the prices of debt capital and equity capital are set by supply and demand, and both are influenced by the relationship between the risk and return expected for those securities and the risks expected from the overall menu of available securities.

8.2 Financial Parameters

There is an opportunity cost associated with the funds that capital suppliers provide a utility. That cost is the expected return foregone by not investing in other enterprises of corresponding risks. Thus, the expected rate of return on MHTGR's debt and equity capital should equal the expected rate of return on the debt and equity of other projects having comparable risks. Moreover, a power company is entitled to a return that will allow it to maintain its credit so that it continues to have access to the capital markets to raise the funds required for investment. The allowed return should therefore be sufficient to assure confidence in its financial health so it is able to maintain its credit and continue to attract funds on reasonable terms. This form of financing may also be applied to ALWRs and may be necessary for them to compete in the market.

Three examples are used to determine total revenue requirements and rate of return. In the first two examples, the allowed return of 10% to debt holders, 9% to preferred equity holders, and 16% to common equity holders are based on previous financing history of nuclear reactors. In the last example, the consortium approach is used whereby major suppliers of materials and major contractors to MHTGR's agree to provide equity but at a lower rate of return than the market in consideration for obtaining work on the project.

8.2.1 Analysis of Annual Revenue Requirements

An important and pivotal step is to determine the dollars necessary to service the capital invested. As shown below, earnings of $246.738 million are required to service both the debt (interest only) and equity capital of the company. This latter figure is calculated by multiplying the rate of return of 12.3% by the total capital cost $2.006 billion.

Calculations to Determine the Rate of Return

$K_d = 10\%$, $D = 50\%$, $K_{pe} = 9\%$, $\%PE = 10\%$, $K_{ce} = 16\%$, $\%E = 40\%$

$K_d \times D/C = 5\% + K_{pe} \times PE/C = .9\% + K_{ce} \times E/C = 6.4\%$ = Rate of Return

Rate of Return 12.3% X Capital Base ($2,006,000,000) = Return $246,738,000

Where K_d = interest rate on debt capital

K_{pe} = return of preferred equity

K_{ce} = return on common equity

D = debt

PE = preferred equity

E = common equity

C = total capital = D + PE + E

K_d X D/C = weighted average cost of debt

K_{pe} X PE/C = weighted average cost of preferred equity

K_{ce} X E/C = weighted average cost of common equity

The rate of 12.3% is the weighted average return on the pool of funds assembled by the utility in the proportions assumed as follows:

Type of Capital	Amount of Capital	Allowed Return	% Proportion	Weighted Return
Debt	$1,003,000,000	10%	.50	5.0%
Preferred Equity	$ 200,600,000	9%	.10	9%
Common Equity	$ 802,400,000	16%	.40	6.4%

12.3% - Total Weighted Cost of Capital

8.2.1.1 Calculation of 15 Year Amortization Annual Revenue Requirements

Calculations to Determine Total Revenue Requirements Based on 15 Year Amortization of Debt.

Assume:	Debt	$1,003,000,000	50%
	Preferred Equity	$200,600,000	10%
	Common Equity	$802,400,000	40%
	Total Capital	$2,006,000,000	100%

Return on Preferred Equity (9% X $200,600,000)	$18,054,000
Return on Common Equity (16% X $802,400,000)	$128,384,000
+ Income Taxes (40% of Profit Before Taxes)	$ 97,625,333
Required Profit Before Taxes	$244,063,333
+ Principal and Interest ($1,003,000,000@ 10%, 15 year amortization)	$129,339,470
Required Profit Before Interest and Taxes	$373,402,803
+ Operating Expenses (including depreciation, assumed)	$112,000,000
= ***Total Annual Required Revenue***	***$485,402,803***

8.2.1.2 Calculation of 30 Year Amortization Annual Revenue Requirements

Calculations to Determine Total Revenue Requirements Based on 30 Year Amortization of Debt

Assume:	Debt	$1,003,000,000	50%
	Preferred Equity	$ 200,600,000	10%
	Common Equity	$ 802,400,000	40%
	Total Capital	$2,006,000,000	100%

Return on Preferred Equity (9% X $200,600,000)	$ 18,054,000
Return on Common Equity (16% X $802,400,000)	$128,384,000
+ Income Taxes (40% of Profit Before Taxes)	$ 97,625,333
Required Profit Before Taxes	$244,063,333
+ Principal and Interest ($1,003,000,000 @ 10%, 30 year amortization)	$105,624,518
Required Profit Before Interest and Taxes	$349,687,851
+ Operating Expenses (including depreciation, assumed)	$112,000,000
= ***Total Annual Required Revenue***	***$461,687,851***

8.2.1.3 Consortium Approach

To share the huge cost of developing and manufacturing a new plant, it might be more attractive to create a consortia or joint venture. Since the development of nuclear power plants is a particularly cost-intensive business, it may be attractive for suppliers to form a consortium to share the risk. If these suppliers become investors, it is conceivable that they would in consideration for the business, require a lower return on their investment than a more traditional investor. A consortium can also enhance the competitiveness of the members by offering a turnkey solution to the customer.

The rate of 9.7% is the weighed average return on the pool of funds assembled by the utility in the proportions assumed as follows:

Type of Capital	Amount of Capital	Allowed Return	% Proportion	Weighted Return
Debt	$1,003,000,000	10%	.50	5.0%
Preferred Equity	$200,600,000	7%	.10	0.7%
Common Equity	$802,400,000	10%	.40	4.0%

9.7% - Total Weighted Cost of Capital

Calculations to Determine Total Revenue Requirements Based on Consortium Approach

Assume:

Debt	$1,003,000,000	50%
Preferred Equity	$200,600,000	10%
Common Equity	$802,400,000	40%
Total Capital	$2,006,000,000	100%

Return on Preferred Equity (7% X $200,600,000)	$14,042,000
Return on Common Equity (10% X $802,400,000)	$80,240,000
+ Income Taxes (40% of Profit Before Taxes)	$ 62,854,667
Required Profit Before Taxes	$157,136,667
+ Principal and Interest ($1,003,000,000 @ 10%, 30 year amortization)	$105,624,518
Required Profit Before Interest and Taxes	$262,761,185
+ Operating Expenses (including depreciation, assumed)	$112,000,000
= ***Total Annual Required Revenue***	***$374,761,185***

8.3 Generation of Revenues to Cover Debt Service

When fully operated, the total output generated over 30 years = (30 years) (8,760 hours per year) (1,125,000 kWh) (.90) = 266,085,000,000 kWh or 8,869,500,000 kWh per year
If one assumes a real cost of electricity (not levelized) of $.05-$.06 per kWh.
Total revenue: $443,475,000-$532,170,000 per year.

Total revenue required to service equity and 15 year amortization debt is $459,708,157 per year.

Debt service coverage: $443,475,000/$485,402,803; $532,170,000/$485,402,803 =
.91X debt service coverage-1.09X debt service coverage.

Total revenue required to service equity and 30 year amortization debt is $461,687,851 per year.

Debt service coverage: $443,475,000/$461,687,851; $532,170,000/$461,687,851 =
.96X debt service coverage-1.15X debt service coverage.

Under the consortium scenario total revenue required to service equity and 30 year amortization debt is $374,761,185 per year. Debt service coverage: $443,475,000/$374,761,185; $532,170,000/$374,761,185 = 1.18X debt service coverage-1.42X debt service coverage.

Debt service coverage represents the protection of assets or the number of times earnings are greater than fixed contractual charges or interest costs. Maintaining a consistent earnings level sufficient to provide a minimum post-tax interest coverage of a certain amount is considered necessary to retain a given current bond rating.

The equity ratio and coverage ratios are the most important quantitative determinants of bond ratings, followed by internal cash generation. Thus, all else remaining constant, the higher the level of internal cash flow generation through retained earnings and the higher debt service coverage, the higher the credit quality. Therefore the consortium approach is more attractive because of the higher debt service coverage.

8.4 Optimal Capital Structure

The benefits and costs of using debt, including taxes, agency costs, and distress costs can be identified and quantified by various models of capital structure. Both the cost of debt and equity can be seen to increase steadily with each increment in financial leverage. Despite the rise of both debt and equity costs, with increases in the debt ratio, the Weighted Average Cost of Capital reaches a minimum as the weight of low-cost debt in the average increases. Beyond this optimal point, the low-cost and tax advantages of debt are outweighed by the rising distress costs, agency costs, personal tax disadvantages, and the overall cost of capital increases rapidly at higher debt ratios.

Despite the intuitive and conceptual appeal of this “trade-off” view of the optimal capital structure, it is difficult to quantify precisely the costs/benefits of various debt levels and to establish the optimal level of debt. Moreover, the optimal capital structure shifts over time with changes in capital market conditions and changes in business risk. Finally, one should know from the signaling framework that utilities should maintain a borrowing reserve, using less debt in normal times so as to build reserve debt capacity when needed.

In the final analysis, finance theory provides limited guidance on what a company's capital structure should be precisely. Capital structure decisions must be determined by managerial judgment and market data in contrast to the exact mathematical formulas resulting from theories. Financial theory provides benchmarks and useful data to assist management in capital structure decisions. Capital structure decisions depend critically on each company's own situation and level of business risk as well. The higher the business risk, the lower the debt ratio.

8.5 Concerns Associated with Investments and Financing in Maturing Technologies

In relationship to other energy and non-energy technologies, nuclear power is still in the maturing phase. Although the commercial nuclear power technology has been in existence for more than 40 years, a number of unsettled questions still exist. Consequently, a number of investor concerns common to many other maturing technologies must be taken into account. In a narrow technical sense, risk refers to the variability in the perceived returns from an investment. Thus, the investment with the larger variability in perceived outcomes is said to be the riskier investment. With this rather loose notion of risk in mind, there appear to be three categories of concerns about investments in nuclear technologies:

> Concern that the commercial operation of the technology will not be as efficient as expected, and that investors will be penalized as a result,
>
> Concern about the safety of the technology. A safety-related mishap could range from a very small one to a major accident, which could prove ruinous to investors, and
>
> Concern that new construction of nuclear power plants will not be completed, due to changing economic conditions, changing regulations, and/or public pressure.

8.6 Less-Than-Expected Efficiency of Commercial Operation

One very general concern about any maturing technology is that its commercial operation may not be as effective as was planned. At one extreme, some maturing technologies have proved to be highly successful after being introduced; several developments in the field of electronics are good examples of this. At the other extreme, there are many cases (such as the ill-fated attempt by the Pennsylvania Railroad to develop a high-speed train in the 1950's) where the commercial implementation of a new technology has simply failed. In cases where a technology fails the test of the marketplace, investors face the prospect of substantial financial losses.

8.7 The Issue of Safety

Another general concern about any maturing technology relates to both the actual safety of the technology and the public's perception of its safety. In particular, there appear to be issues dealing with both the actual degree of safety and whether this level is "acceptable." In some cases, experience has indicated that the associated danger is too great, and as a result, the technology has disappeared from the market. In other cases, history has shown that the commercial implementation of a technology could result in serious or even catastrophic accidents. Examples of this type range from ocean and air transportation to large dams; in these cases, both society at large and the financial market appear to have accepted the risks of serious accidents. Nuclear power appears to fall in the category where the publics' perception of its safety is at issue.

8.8 Project Non-Completions

A final concern about investments in maturing technologies is that changing conditions will render a project uneconomical before it is completed, and the project will therefore be cancelled. Indeed, there are many examples of this kind, ranging from private synfuel projects to public transportation, in which changing economic conditions have led to project cancellations. In many cases, shareholders may be forced to bear the loss of substantial sunken investment costs when projects are cancelled.

8.9 Conclusions

Investors appear to have a number of general concerns about maturing technologies, including nuclear power. The effect of these concerns has been to increase investors' perceptions of the possibility of large, perhaps ruinous, financial losses. In addition to investor concerns about serious accidents, other factors that may influence investment decisions include the possibilities that projects already undertaken will be halted before they are finished, and that the operating efficiency of the commercial technology will be less than expected.

Because of the high cost and high stakes in financing turnkey projects (a plant, system, or project in which the buyer acquires a complete solution so that the entire operation can commence at the turn of a key), there is an incentive for companies and suppliers to band together to form a consortium. Joining together in a consortium can help share the risk and can enhance the competitiveness of the members by offering a turnkey solution to the customer. The selection of appropriate partners is important, and the chances for overseas orders may be improved if the foreign firms participating in the consortium understand the foreign buying environment.

One of the key criteria in selecting the small modular gas cooled reactor is to reduce many of these uncertainties and eliminate the concerns to the greatest degree possible. The small size, "naturally safe" with regulatory transparency should go a long way to reduce the level of concern.

9 HAS THE CHALLENGE BEEN MET ?

At the beginning of this project, the problems were identified with the existing nuclear power plants. These challenges were to have been met by the new nuclear energy power plant. The following brief summary outlines how the small modular Pebble Bed gas reactor plant meets those challenges from technical, political and economic considerations.

9.1 Unique Features of Design That Will Make The Pebble Bed HTGR Desirable

Existing Challenges for Current	***The Solution Offered by Our Proposed***
Nuclear Plants	***Modular Gas-Cooled Design***
Engineered Safety - Current designs depend heavily on engineered, active safety systems. Redundant sources of power, core cooling, and control systems are required.	No such defense-in-depth systems are required. The design is inherently “naturally safe." Operators or automated safety systems are not required to perform any reactor safety functions.
Regulatory Compliance – Prescriptive regulation has resulted in numerous expensive plant modifications and forced shutdowns.	The simplicity and inherent safety of our design will allow for risk-informed regulation. Regulatory requirements will be much less complex and conformance will be much less expensive. It is proposed that the plant be licensed by test of the as built facility.
Proliferation - Security forces and security devices intended to prevent sabotage or theft of nuclear material constitute a significant part of plant capital and operating costs.	The inherent safety of our design significantly reduces the potential consequences of any attempted sabotage. And the pebble-type fuel our design uses is stable, difficult to reprocess, and achieves such a high burn-up that it is not a practical source for nuclear material.
Construction Time - The large amount of time it takes to build a plant (between 5 and 15 years) results in huge expense due to interest payments on construction capital.	Our design is completely modular. Parallel construction of all components can take place, so only final assembly is performed on-site. As a result, total time from decision to build until power generation is 36 months for the first unit to be online, with subsequent units being completed every three months.
Plant Capacity - Current design choices require potential buyers to choose between very large (>1200 MWe) or small (600 MWe) plants. This forces the buyer to try to predict energy demand at least forty years in the future. Will they be able to sell 1200 MWe if they by the large plant? Or if opt for the small unit and then future demand increases, will they be	Our design allows buyers to build only the capacity they need. If they feel confident that they can sell 600 MWe for the next ten years but are uncertain beyond that time, they can build a six-unit site. The rapid assembly characteristic of our design allows for easy future increases in plant capacity. Therefore, the customer does not have to invest capital in building a large capacity plant until they are confident in the market demand. The design is also perfectly suited for export. The greatest demand for new generating capacity is coming from developing nations. Unlike the US, they do not have the electrical distribution infrastructure to effectively transmit 1200 MWe. Instead, they need a plant that can meet the needs of the

saddled with an under-sized unit?	immediate area without wasted excess capacity. Our design can be tailored to each individual need and small enough to ship by barge or even possibly by train.
Replacing Major Components **-** The high temperature water and steam used in LWRs creates a constant hostile environment for equipment. Commercial PWRs are faced with steam generator inspections and replacements, and BWRs have equally expensive condenser replacements. Both experience steam turbine blade erosion	Our design completely eliminates the corrosive aqueous environment from all but a few components. By using an inert gas as the cooling medium, major components will last much longer and chemistry control will not be a constant concern.
Refueling Outages **-** Current plants are required to shut down for approximately 40 days every 18-24 months in order to load more fuel. As a result, even if the plant operates perfectly, it can only achieve a capacity factor no better than 90 percent.	Our design allows for continuous refueling while the plant remains at full power, thus eliminating the need to shut down before adding more fuel. Not only will this will result in significant improvements in plant capacity factor, it also avoids the cyclic stresses placed on the plant by start-ups and shutdowns.
Online Maintenance **-** The requirement to have safety systems available during power operation requires the plant to be shutdown for a large number of maintenance activities.	Because there are no active safety systems, there are no similar requirements to shut down for maintenance. Additionally, because the typical station will have between four and 12 units, any unit can be taken off-line for maintenance without an appreciable impact on total plant generation.
Fuel Disposal **-** Spent fuel requires storage in cooling pools for several years before it can be permanently stored. Permanent disposal may as spent fuel will require extensive analysis to assure no long-term degradation in the repository and packaging. It may require expensive vitrification to make it stable enough for long-term disposal.	The pebble-type fuel is effectively ready for disposal the moment it comes out of the core. There are no requirements for pool cooling. The unique carbide-coated particle fuel is completely stable up to 1600°C, so it requires no additional processing before geologic disposal.
Staff Size **-** Salaries constitute the largest component of O&M. Most LWRs in the US employ about one person for every MWe generated	Our design offers two distinct features that significantly reduce required staffing. First, the simplicity of the design makes it amenable to automation. The absence of complex safety and support systems reduces the number of operators and maintenance workers. Second, because of the modular nature of the equipment, any significant maintenance can be performed by removing the equipment and sending it to the factory for refurbishment. Total estimated staff for a 10-unit station is between 150 and 200 people, resulting in a requirement of only one person for every 5 MWe generated.

Operating Efficiency **-** The Rankine steam cycle is limited to a maximum efficiency of approximately 33%	The Brayton cycle employed by our gas turbine power conversion system exceeds 45%
Waste Heat **-** The Rankine steam cycle in use requires the discharge of large amounts of waste heat, resulting in lost potential energy and significant environmental impact. The need for a large heat sink requires the construction of expensive cooling towers or geographic siting near a large body of water.	Our design uses the Brayton cycle, and less heat energy is rejected. In fact, no expensive water-based cooling systems are required, so there are less significant environmental impact or siting limitations. Additionally, because the waste heat is removed by dry air, the hot air is perfectly suited as a heating source for other commercial applications. This "free" source of energy for other commercial applications has the potential to make the design even more economically advantageous.
Decommissioning **-** The large size of many components makes final disposal difficult. High levels of contamination in equipment, as well as the large size of RCAs also make decommissioning very expensive. Decommissioning of existing plants has required many of the large components to be cut apart to allow shipment for disposal, which requires expensive contamination controls and the generation of additional radioactive waste that must also eventually be disposed of.	The durability of the coated fuel particle design makes it more resistant to fuel damage so lower contamination levels can be expected, resulting in lower decontamination costs. Our design is much smaller and the modular primary components can be easily disassembled and shipped for disposal. Our reactor vessel, for example, is small enough to be transported intact , and has been designed to eventually serve as its own shipping (with shield plates) and disposal container. The small size of other components will allow them to fit in standard sized shipping and disposal containers. Because there are no active safety (and therefore potentially contaminated) systems and far less other systems in general, the total amount of material that will require disposal is significantly less than for existing designs.

10 CONCLUSIONS

The issue of the use and production of energy is a critical question under normal circumstances. Past discussions focused on the availability of sufficient resources to allow nations to improve their quality of life. The concerns centered about the supply of oil, coal, gas, and the availability of additional hydroelectric sites capable of being harnessed. Today, it is not so much the supply of resources but the consequences of their use on the environment that is further complicating an already difficult problem.

The continued depletion of non-renewable resources coupled with the environmental consequences of their burning has reopened the discussion of the use of nuclear energy to help reduce the environmental burden of fossil fuels. While existing nuclear plants continue to provide reliable and safe electricity, there is resistance to their use in the future despite new designs now undergoing licensing reviews.

This project took a fresh look at the reasons for nuclear power's present problems and evaluated what criteria for a new plant are required to overcome these obstacles. Having established the needs for a new plant, the project then evaluated new reactor plants presently on the drawing boards to determine which best met the criteria. The most important factor was demonstrable safety for public acceptance followed closely by being competitive with natural gas at today's prices. A conceptual design was proposed based on a small modular pebble bed gas cooled reactor with direct cycle gas turbines producing the electricity. This "new" approach has been demonstrated in Germany for over 20 years. The safety and simplicity of the design is capable of being factory built and field assembled. The staff size is small due to its inherent safety design not requiring complicated safety systems installation to be tested and maintained.

The next challenge for this project is to confirm the design assumptions, cost estimates, the financial models and to gauge public and political support for the concept. This plant has the potential to provide electricity on a worldwide basis meeting the global climate change challenge in a manner that reduces the risk of nuclear proliferation.

Appendix A

Guest Lecturers

Name	Affiliation	Subject
Andrew C. Kadak	MIT	Issues with Current Nuclear Plants
Edward Rodwell	EPRI	EPRI ALWR Program
Michael Driscoll	MIT	Options for the Future
Neil Todreas	MIT	Advances in LWRs
Larry Lidsky	MIT	Gas Reactor Options
Chaim Braun	Bechtel	Economics of Nuclear Power
George Apostolakis	MIT	Risk Informed Performance
Ted Feigenbaum	NAEC	Seabrook Experience
Kory Sylvester	MIT	Proliferation
Walter Simon	General Atomics	Modular Gas Reactor Status