A. CRITERIA EVALUATION

Criterion 1: Regulatory Acceptance

Summary of PBMR Pty. Response

The Part 52 licensing process for the licensing and construction of PBMR plants will be utilized. An application for ESP is projected for the first of these sites to the NRC in mid-2002. In parallel with ESP review by the NRC, preparation and submittal of an application for construction and operation (COL) of a number of PBMR modules will be pursued for the first site in late 2002/early 2003.

Obtaining the COL prior to design certification will shorten the time to first plant construction and operation because the reviews and hearings associated with the design and site-specific issues can be combined and completed well in advance of the Republic of South Africa (RSA) demonstration plant completion. The US COL application would be submitted after the completion of the detailed design in South Africa; therefore, it will contain complete design and safety analysis information including ITAAC. As the design in the US is anticipated to be identical to the RSA design, it is not expected to have design features that are not demonstrated in the RSA demonstration program. There is potential that the RSA demonstration test plan can be influenced to include those tests required by the NRC. Exelon expects the PBMR to receive design certification after the demonstration unit in RSA and the first US unit have operated successfully.

Technical areas that present a challenge to meeting the licensing schedule have been identified and include: licensing review framework; licensing basis event selection; source term; containment; role of the operator; emergency planning; equipment classification; and prototype testing. In addition, code verification is an important activity that requires timely completion.

NTDG Assessment

The overall strategy is credible, but the time line is extremely aggressive. The strategy relies on the use of the design and safety analysis developed for an identical unit in the RSA, which serves as a demonstration unit. It uses an early submission of the ESP and COL in parallel without design certification (DC) in order to save time. Because the design is being developed for the RSA demonstration unit, it is anticipated that the COL will contain a comprehensive safety analysis, including a complete plant PRA, that equals or exceeds that necessary for an application for DC. Also it will contain proposed Inspections, Tests, Analyses and Acceptance Criteria (ITAAC).

This strategy is very challenging, with only two and a half years allotted for completion of the COL, including hearings. That is short based on past experience with safety reviews and the complex and difficult Exelon-identified list of issues to be resolved with the NRC. It is presumed that the regulatory infrastructure issues and the technology expertise within the NRC will be largely resolved before the COL application is submitted. If these are not resolved then delays in the schedule will be likely. In this regard, cooperation with GA (for licensing the GT-MHR) on the regulatory infrastructure issue is desirable.

Of particular concern for maintaining the schedule is the testing program required to qualify the fuel and the approval of a low pressure, vented containment. Insufficient time is allowed from startup of the fuel facility in South Africa to conduct shake-down tests and properly prepare fuel for irradiation testing before the irradiation tests would presumably begin. Since fuel qualification to standards consistent with the specified source term, EPZ boundary and containment is critical to plant operation, there is a limit to how much one can "rush" the program. Also, there must be sufficient time in the schedule for NRC review of the final results. Since the proposed containment design is a low-pressure citadel type structure with filtered vents for pressure release, this means the fuel is the primary containment barrier, and the fuel testing must demonstrate that this is satisfactory. In addition, there will be licensing issues that must be resolved with the NRC related to using a foreign supplier of fuel.

There is also concern about the timing of completion of the code qualification program. The accident scenarios that must be evaluated, and the NRC requirements for code verification and validation have yet to be worked out with the NRC. Many of the accidents and transients can be anticipated, such as air and water ingress, loss of heat sink, turbine overspeed, seismic events, and rod ejection. The status of this effort within PBMY Pty. Ltd. as it relates to the RSA Demonstration has not been identified to the NTDG. The NRC has some codes in development for independent safety evaluation, but it is not clear whether there is sufficient independent code capability to evaluate all the codes required, for example in core physics.

The non-fuels testing program also presents a schedule concern. This includes qualifying the graphite that is used in both fuel and in the reflector, and evaluating absorber materials such as boron carbide that would be used to limit neutron streaming. The time to complete this program and submit a topical report to the NRC seems to allow very little review time for the NRC before the decision is made regarding the COL application. Another licensing area that resulted in lengthy LWR negotiations with the NRC is control room design, and the number of operators needed to operate a plant. This problem is currently being addressed for the RSA plant, but its resolution for the U.S. plant is uncertain. The instrumentation and control design will also be of strong interest to the NRC, although the review should be different from the LWRs because of the different nature of the reactor safety response. In addition, the schedule provides essentially no overlap between the RSA Demonstration unit startup and the issuance of the COL. This would not present a problem as long as prototype testing is not required to resolve any safety issue. In the document "Preliminary Staff Views on PBMR Licensing Plan" (letter of August 23, 2001 from Samuel J. Collins, Director, Office of Nuclear Regulation, NRC, to James A. Muntz, VP of Exelon Generation), it states "Exelon's licensing plan should not assume that the NRC will issue a combined license prior to completion of all testing that is determined to be necessary to demonstrate the acceptability of a commercial PBMR." If prototype testing is required to resolve any issue this could delay the issuance of the COL Finally, it is noted that the use of the COL without Design Certification has less finality to it. Since there is no rulemaking involved, there is the possibility of design changes that could result in the first commercial unit differing from the RSA demonstration unit, and there is greater risk of post-construction intervention.

The schedule presented in Table 1 (Criterion 3) calls for loading fuel in September 2007. The NTDG believes that some delay in this schedule is probable. While a slippage in schedule for licensing delays, construction delays, fuel qualification or technical reasons has financial implications that could impact decisions to proceed, it is possible to tolerate some delay in regulatory acceptance and still have the first commercial unit in operation by the end of 2010. Since the critical path is determined by fuel qualification, and may well extend six to twelve months beyond the schedule presented to the NTDG, even a six-month delay on the COL could be accommodated.

The NTDG believes the PBMR can meet the criterion provided that several challenging technical issues (including fuel issues) can be resolved and demonstrated to NRC satisfaction in the time frame needed for 2010 deployment. U.S. licensing submittal information must be adapted from the German/South African design and test work. Pre-application steps with NRC are in progress.

Criterion 2: Industrial Infrastructure

Summary of PBMR Pty. Response

The industrial infrastructure needed to support the commercialization is already in place internationally with the exception of the fuel manufacturing facility. PBMR Pty. Ltd., which consists of ESKOM, the utility owned by the Republic of South Africa, IDC, BNFL, and Exelon, will provide this capability as well as support the plant development with their own resources and talent, as well as that of consultants. Contracts are in place for detailed design of all major components with credible industrial suppliers and preliminary design of these components is now complete. The suppliers would be capable of producing components for multiple units in a year. PBMR Pty Ltd. has also obtained full access to the German base of high temperature reactor (HTR) technology, experience, and know-how. Key technical specialists have been incorporated into the PBMR team to assure effective technology transfer.

The turbine generator, the fuel, and the pressure vessels are all on the critical path for the first plant. The systems requiring the largest extent of development are judged to be the turbomachinery, the magnetic bearings/auxiliary bearings, and the recuperator. Negotiations are currently underway with several suppliers for the turbine generator and the pressure vessels. The fuel will be produced in a plant in South Africa that is currently under design. It is anticipated that the longest lead-time component is approximately 24 months.

The PBMR will require unique operator training. PBMR is currently designing a control room simulator for this purpose and ESKOM is developing the operator training courses modeled on the INPO systematic training development format. INPO and Exelon will advise ESKOM on the training and procedure development, which would then be used in the US.

NTDG Assessment

The manufacture of major components should be able to meet the criteria for 2010 deployment if the RSA program moves forward according to schedule. The responses state that design contracts with suppliers of all major components are in place and that one or multiple (up to three) units could be built by 2010. The longest lead component, the pressure vessel, was identified as 18 months to two years. While this seems like a short time, it is based on quotes from the suppliers involved. Ordering of long lead-time materials and components is taking place on a schedule that could achieve fuel loading in late 2005. This is somewhat optimistic for a first plant, even with a construction schedule provided by a reputable architect-engineering firm that supports such a schedule. On the positive side, since the lead-plant in South Africa is identical to the U.S. plant, the major component manufacturers will have experience before producing the U.S. plant components.

One concern regarding PBMR is the lack of an experienced vendor organization with a strong management structure and a depth of technical knowledge in fuels and design. Much of the fuels expertise is provided by consultants from Germany. This provides valuable insights and information, but is not the basis for a long-term commercialization organization. It is important that the partners involved in the PBMR development, including ESKOM, BNFL, IDC and Exelon, put together a suitable vendor organization in the near future with strength in reactor design, safety analysis, and plant licensing.

One of the biggest technology risks is likely to be in the operation of the power conversion system. While components operating individually have operated under similar conditions, there appears to be little or no experience for such a system operating with its high temperatures and vertical mounting of the turbines within the context of a Brayton cycle. The RSA prototype, with two to three years of operation before the startup of the first commercial unit in the U.S., will be critical in providing a demonstration of this new technology.

The NTDG believes the PBMR can meet the criterion. An international team is being assembled. Design contracts are in place for major equipment. There is a need, in the near future, to develop a strong vendor organization that can support both the design and licensing.

Criterion 3: Commercialization Plan

Summary of PBMR Pty. Response

The commercialization of the PBMR will be accomplished by the construction and operation of a full size demonstration plant in South Africa with concurrent licensing in the US by Exelon. ESKOM and Exelon will place the first orders of commercial units during the demonstration plant construction and startup phases.

Institutional issues that need to be resolved for commercialization include insurance cost per unit under Price-Anderson legislation, and the funding formula related to the Decommissioning Trust Fund.

The table below lists key events and the earliest potential dates for their completion.

Table 1 – Potential PBMR Timeline

Earliest Possible Date	Event	Acting Party
Oct. 2001	Completion of RSA SAR, submittal to NNR	PBMR
Mar. 2002	SAR Rev 0 Approval – permission to construct	NNR
1Q, 2002	Decision to proceed with construction	PBMR
4Q, 2002	Start construction – RSA PBMR Demo Unit	PBMR, Eskom
4Q, 2005	Start non-nuclear testing, RSA Demo Unit	PBMR, Eskom
May, 2005	Load Fuel, RSA PBMR Demo Unit	PBMR, Eskom
May, 2007	Complete nuclear testing, start com. operation	Eskom
Aug. 2002	Submit ESP Application	Exelon
Mar. 2003	Submit COL Application	Exelon
Sept. 2004	Receive ESP	NRC
Sept. 2005	Receive COL	NRC
Sept. 2005	Start approved construction	Exelon
Sept. 2007	Load Fuel	Exelon
Sept. 2008	Complete Nuclear Testing	Exelon
May 2007	Submit Design Certification Application	PBMR
2010	Issue Design Certification	NRC

NTDG Assessment

The PBMR has a credible and detailed plan for commercialization if the commitment by Exelon, ESKOM and the other partners to keep the schedule is maintained. The actual construction and testing of the design in RSA, assuming it goes forward on schedule, will confirm the economic viability of the design, or at least provide the ability to project ahead to acceptable nth of a kind costs, with fabrication infrastructure in place and operating efficiently on a continuous production schedule.

The success is heavily dependent on the success of the RSA program for design, technology development, operating experience and fuel production. While experience gained from the RSA program impacts all aspects of U.S. commercialization it cannot assure that all problems in licensing in the U.S. and use of new technology will be satisfactorily resolved for commercial use of the PBMR in the U.S. Additional financial issues specific to the U.S. related to insuring nuclear units and in providing for the decommissioning fund also must be resolved to make the small sized units like the PBMR commercially viable. Licensing issues, as described under Criterion 1, could also influence a decision to proceed in the U.S. Thus, while the commercialization plan is strong it does not assure that commercialization of the PBMR in the U.S. will be achieved by 2010.

The NTDG believes the PBMR can meet the criterion since there is already a potential U.S. customer (Exelon) with substantial – albeit conditional – commitment. Presuming successful continuation of the South African project and an Exelon decision to proceed with a U.S. project, the PBMR commercialization plan is credible.

Criterion 4: Cost Sharing Plan:

Summary of PBMR Pty. Response

PBMR Pty Ltd. does not request any U.S. Government funding for the design and manufacture of the prototype PBMR module in the RSA, or for the design and manufacture of any PBMR units in the U.S. The recommended use of government funding is for the U.S. Government's fees associated with review of the ESP and COL applications, PBMR design and system education programs, improved gas reactor regulatory framework, code verification, fuel confirmatory testing, and material testing to demonstrate long term reliability.

PBMR Pty Ltd. will spend on the order of $200 million in the development and $300 million in the demonstration of the PBMR design. In contrast, the recommended government funding to support the PBMR aggregates to approximately 7.5 percent of this amount during FY 2002 and FY 2003.

NTDG Assessment

The PBMR has a workable approach to cost sharing between industry and Government, primarily by virtue of the indicated commitment of PBMR Pty. Ltd. to cover the costs of development (estimated $500 M, including construction of the first RSA unit) while seeking only minimal U.S. Government funding for costs related to licensing activities, including the NRC confirmatory fuel characterization and test programs. This represents an effective leveraging of U.S. Government funding against industry investment.

The NTDG believes the PBMR meets this criterion.

Criterion 5: Economic Competitiveness:

Summary of PBMR Pty. Response

The PBMR would be deployed in increments of 110 MWe, allowing for an improved match to demand growth and utilization of capacity. The owner/investor financial risk is reduced relative to intermediate or large capacity plants. Construction times are short, reducing cost and matching market demand. The PBMR would break-even with a Combined Cycle Gas turbine (CCGT) plant with gas at about $4.00/ MMBTU.

The table below indicates key economic parameters for the PBMR as currently designed. The costs for major components embedded in this estimate are based on quotations received from commercial suppliers of that equipment.

Table 3 - Approximate Cost Evaluation

	Value
PBMR Module Thermal Rating	268 MWth
PBMR Module Electrical Rating	110 MWe
PBMR Module power conversion efficiency	~40 percent
Modules per Plant	7 to 20
FOAK Development, including Fuel and Demonstration Module (FOAK)	~$500 M
Mature Plant PBMR Capital Cost Target (NOAK)	~$1250/kWe
Mature Operation and Maintenance Cost Target	2-3 mills/kWh
Mature Fuel Cycle Cost Target	4-6 mills/kWh
Total Mature Generating Cost Target	~3-3.5¢/kWh

These costs do not include government fees associated with the ESP, COL, or certification process for the PBMR in the US since these are proposed for government support.

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The economic competitiveness of multiple small units vs. a larger unit is a highly controversial topic. Exelon presents the case for use of smaller units, which includes short construction time that gets the electricity on line more quickly with less interest cost; more closely matching electricity production to demand so as not to depress the market with oversupply; and the financing advantages of sequentially building smaller units. This advantage is both through the learning process and the discount that comes with multiple component orders. In addition, the inherent passive safety potentially reduces the cost of safety systems and containment. They have higher fuel utilization than LWRs, and this improves fuel cycle economics. On the other hand, to reach the same power output as a large LWR they require 10 pressure vessels that are the same size as one LWR, and 10 structures. It will be a considerable challenge to have the beneficial cost factors compensate for the added costs. The PBMR projected busbar costs look favorable, but the economic uncertainties of using a new technology are much greater than using technology that has a stronger experience base. Also, the plant design and system costs such as the Power Conversion System (PCS) are not finalized so a realistic cost basis for the FOAK is not yet possible. Exelon indicated an installed cost in the range $1000/Kwe to $1700/Kwe, with an “expected value” of $1250/KWe. The economic competitiveness of the resulting busbar cost is quite different for these cases. As with all new reactor designs the initial units will have higher generation cost, so one should not be surprised by a value that exceeds the “expected
uence, in both gas-cooled reactor designs, of sacrificing economy of scale in the interest of safety, but achieving economics through efficiency and multiplicity. Multiple unit orders, consistent with the commercialization strategy, will be required to bring the cost down to more competitive levels. The NTDG cautions against over optimism in projecting the electricity cost of relatively untested technology. It is still premature to be confident of the final outcome.

The NTDG believes the PBMR can meet this criterion. However, projected economics are preliminary and have high uncertainty. Satisfactory economics rely on deployment of multiple modules and successful development of the design.

Criterion 6: Fuel Cycle Industrial Structure:

Summary of PBMR Pty. Response

The PBMR uses TRISO coated fuel kernels embedded into graphite spheres of racket-ball size. The kernels contain UO_2 enriched to between 8 percent and 9 percent U-235. Individual spheres pass through the core from 5 to 10 times during their useful life, and are then placed in long-term storage, without any reprocessing. The PBMR design accommodates the dry storage of spent fuel within the citadel over the lifetime of each module.

PBMR Pty. has selected the reference fuel design from the German AVR 21-2 pebble fuel with UO2 TRISO coated particles that was developed and tested in the AVR reactor. This fuel was produced over a period of several years and underwent testing at the Julich Research Center in Germany. In the German program, relevant irradiation testing of more than 2E5 particles was performed without a single coated particle failure during irradiation. Statistically, that corresponds to a 95 percent confidence level that the coating failure fraction of the reference design fuel is less than 2E-5. Fuel spheres were also subjected post-irradiation to high temperatures to simulate loss of cooling and loss of pressure events. The performance of the fuel under these conditions was well documented and forms the basis for the determination that the selected reference fuel design will be acceptable for use in the PBMR. The manufacturing specifications and test data for this fuel which was manufactured by NUKEM in Germany have been obtained by PBMR and are being used by a team from NUKEM, BNFL and PBMR to design the fuel manufacturing plant and its processes.

PBMR Pty Ltd. has obtained the licenses, fuel design specifications, tooling design specifications, and procedures used by Nukem in the manufacture of fuel for the AVR and THTR plants as well as test capsules for the German modular HTR designs. PBMR fuel will be manufactured in the RSA, by PBMR Pty Ltd. The PBMR manufacturing facility is being developed within the physical plant used for the BEVA LWR fuel manufacturing facility at Pelindaba, RSA. This facility adapts the Nukem base fuel process technology, however, key system aspects such as process automation, quality monitoring, and data management will be updated to current standards. Sources for the enriched feedstock have been identified and negotiations for supply are in progress. A pilot plant startup is scheduled for 2003 with full production by 2005. The initial core and reload fuel for the initial reactor modules proposed for construction in the US by Exelon will be manufactured in the RSA, at the fuel facility to be constructed at Pelindaba, RSA.

The manufacturing processes and Quality Control (QC) parameters used in Germany will be reproduced, in order to ensure that PBMR fuel elements will be equivalent to German fuel elements, and that testing performed on AVR fuel can be incorporated into the body of data supporting the PBMR safety case. The proof of equivalence consists of showing that the qualified PBMR fuel manufacturing process, based on the German fuel manufacturing process, produces fuel that complies with German fuel performance. Compliance will be demonstrated by using QC techniques and statistical sampling equivalent to those used during manufacture of German fuel.

NTDG Assessment

The PBMR probably can meet the criteria for 2010 deployment although the proposed schedule for U.S. operation calls for fuel loading in September 2007. This date is questionable, based on the expected length of the fuel qualification program. The current schedule calls for PBMR Pty. Ltd. to have a pilot fuel plant in operation in late 2003. Assuming fuel tests begin in mid-2004, fuel qualification is unlikely before mid to late 2008. Of course, there are still uncertainties in meeting this schedule related to successful operation of the fuel production facilities in South Africa and in the resolution with the NRC of fuel testing requirements and QA requirements to meet fuel acceptance criteria for fuel use in the U.S. The relationship of the licensing rationale for the low pressure containment to an acceptable upper limit for fuel failure fraction will need to be resolved with the NRC in the near future. Nonetheless, the schedule has sufficient margin for tuning the fuel production process and for fuel testing to allow U.S. operation of the reactor prior to 2010. In addition to fuel testing it will also be necessary to deal with licensing issues related to having a foreign fuel supplier. The mechanisms for NRC oversight of the QA program will have to be developed.

It is known that certain radioactive fission decay products, especially Ag-110, can diffuse through the SiC layer at operating temperatures. This might lead to contamination of the power conversion system, especially the turbine blades. The presence of Ag-110 was previously seen at Ft. St. Vrain, but was found to be of little consequence. However, the PBMR operates at a higher temperature than Ft. St. Vrain does, so the potential exists that the problem may be worse than found previously. The possible cost consequences are uncertain. It is the view of GA and Exelon that this is primarily a maintenance issue and not a safety issue, and it is being treated as such.

Storage of used fuel for the 60-year plant life is satisfactorily addressed in the PBMR design. Disposal of used fuel in a once-through fuel cycle is facilitated by the SiC coating that provides a fission product barrier not present in LWR fuel. Design features of this system, from both a system and worker safety viewpoint, would be included in the NRC review. However, there is no reason to believe that this would cause any delay.

The NTDG believes the PBMR can meet the criterion. PBMR safety and reliability hinge on a successful fuel test program and high quality fuel manufacture. The current plan includes a program to replicate German fuel design, perform confirmatory testing, obtain NRC license, and produce PBMR fuel. It is noted that the fuel for the initial U.S. unit is to be procured from a foreign supplier, so that licensing concerns regarding such a supplier will need to be addressed.

B. GAP ANALYSIS

The design specific gaps are the tasks that need to be done if this technology is to be brought to the marketplace by 2010. They relate to licensing, fuel and materials testing, and computer code verification. Below these gaps are presented along with the closure actions needed and the estimated cost (in $ million) of achieving closure. Cost sharing specifically related licensing and to confirmatory testing, which is also considered regulatory driven, is requested at a higher rate than 50-50 cost share with industry.

Numerous technical gaps exist as discussed under Criterion 1. Among these are instrumentation and control design, safety analyses, and the power conversion system. These and other FOAK design issues are being addressed by PBMR Pty. Ltd. during their design of the RSA demonstration unit and are being funded by industry. It is estimated that the cost of these efforts is approximately $200 M. They are not included below.

Regulatory Framework

Gap: No gas reactor regulatory framework exists against which to license the PBMR.

Closure: This gap can be resolved by developing a top-down risk-informed gas reactor regulatory framework. This would shorten the Part 52 licensing process and reduce regulatory uncertainty that could prevent the commitment to construction.

Year Source	FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	TOTAL
DOE		$3.5M	$3.5M							$7.0M
Industry	$0.5M	$0.5M	$0.5M							$1.5M
TOTAL	$0.5M	$4.0M	$4M							$8.5M

Fuel Performance and Testing

Gap: Regulator concurrence is needed on coated particle fuel performance characteristics that impact PBMR safety, source term, containment design and length of time to obtain a license.

Closure: To close the gap, it is proposed to perform a particle fuel characterization and test program that allows the PBMR to demonstrate to regulators that its fuel meets specified performance characteristics for safe operation. Testing would be performed on fuel from different countries as well as South Africa to benchmark fuel performance of known high quality fuel.

Year Source	FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	TOTAL
DOE		$10M	$11M	$11M	$8M					$40M
Industry	$1M	$2M	$3M	$3M	$3M					$12M
TOTAL	$1M	$12M	$14M	$14M	$11M					$52M

NTDG comment: While the total dollar value for fuel testing is reasonable, the funding profile needs to be stretched into FY08 to complete the program.

Computer Codes

Gap: PBMR computer codes used for design and safety analysis need to be verified and validated (V&V) to US standards.

Closure: To close this gap, develop the process by which these safety critical computer codes will be V&V'd and perform the benchmarking required by that process.

Year Source	FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	TOTAL
DOE	$0.6M	$2M	$2M	$1M						$5.6M
Industry	$0.6M	$2M	$2M	$1M						$5.6M
TOTAL	$1.2M	$4M	$4M	$2M						$11.2M

Materials Research

Gap: Data are lacking on high temperature and high radiation level performance of some materials to be used in the reactor cavity.

Closure: To close this gap, perform testing on selected materials at temperatures and radiation levels that represent the operating environment in the PBMR.

Year Source	FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	TOTAL
DOE	$1.4M	$3M	$2M							$6.4M
Industry	$2.5M	$3M	$2M							$7.5M
TOTAL	$3.9M	$6M	$4M							$13.9M

Total Resource Requirements to Close All Technical Gaps

Year Source	FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY 10	TOTAL
DOE	$2.0M	$18.5M	$18.5M	$12M	$8M					$59M
Industry	$4.6M	$7.5M	$7.5M	$4M	$3M					$26.6M
TOTAL	$6.6M	$26M	$26M	$16M	$11M					$85.6M

C. OVERALL ASSESSMENT

The schedule put forth by Exelon is very aggressive, including a demonstration unit to be completed in South Africa for fuel loading in 2005, a simultaneous ESP and COL application to the NRC with the ESP in 2002 and the COL in 2003, and two and a half years to complete the COL from its submission with the complete safety documentation. Based on this schedule the first unit would start up in 2007 and begin commercial operation in 2008. All the gaps identified for the PBMR, except for the engineering and technical gaps discussed earlier, relate to the licensing process, and include: (a) the development of a gas reactor regulatory framework; (b) safety and design code verification; (c) fuel testing and qualification; and (d) confirmatory material testing. Concurrence by the NRC with the containment design is also needed. In addition, licensing issues related to having a foreign fuel supplier will need to be addressed. The NTDG considers it unlikely that all these issues can be resolved in two and a half years, even with pre-applications meetings. In addition, a startup by 2007 is unlikely because of the length of time for the fuel testing program and fuel qualification. This is the most critical safety issue that exists for gas reactors since the fuel is proposed to be the final containment barrier, and justifies the use of a low pressure vented containment structure and potentially an evacuation zone at the site boundary. Finally, a construction schedule of only 24 months may be realistic for later units, but it is unlikely to occur on the first unit. It will include startup of a modular manufacturing facility and first time assembly and construction at the site. The NTDG believes that a first unit is likely to take three years to complete. While these factors may lead to a delay of 18 to 24 months, the unit should still be operational before 2010.

Design certification will be sought later, after the COL is issued and the RSA demonstration unit begins operation. The demonstration unit in RSA serves as a prototype. Other technologies are pursuing design certification first in order to potentially shorten the licensing time since safety issues would already be resolved before seeking the COL. While this approach has a higher risk for achieving the goal of operation by 2010, for the PBMR it has the potential to succeed because of the strong commitment of Exelon Corporation who would be the first customer in the United States. Exelon is a partner in PBMR Pty Ltd., the company that is developing the PBMR for commercial application, with the first unit to be built in South Africa if the design study shows the economic efficacy of the PBMR and the partners agree by early 2002 to go forward.

There are many uncertainties in the early use of a new technology. Cost estimates are limited by the lack of a complete design and by experience with building and operating a commercial application of the PBMR. Even though a 15 MW experimental reactor operated for 20 years in Germany, the commercial PBMR uses an untested power conversion system based on the Brayton cycle, a direct cycle with gas turbines, one of which is a vertically mounted power turbine on magnetic bearings that drives the generator. Modular construction would be incorporated to minimize construction time.

PBMR probably can be deployed in the U.S. by 2010.

PBMR is unique among the NTDG candidates in that it has an active customer, currently pursuing this design for U.S. application. Nonetheless, deployment by 2010 would require that:

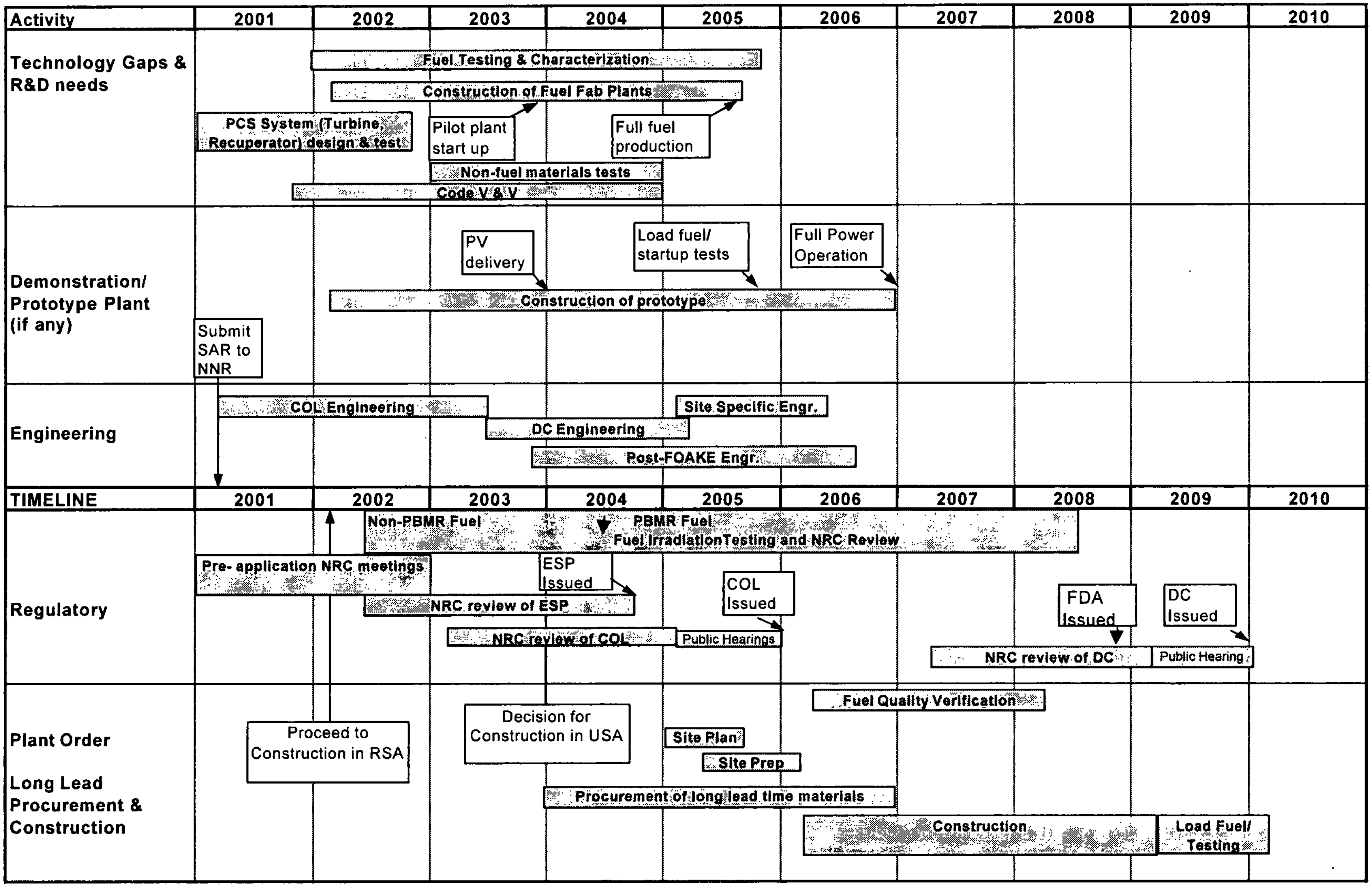
- The South African project continues successfully
- Exelon decides to proceed with a U.S. PBMR project, and commits to early (prior to COL) procurement of long lead-time plant components.
- A successful, expedited ESP/COL schedule
- Resolution of several challenging technical issues, including those related to fuel reliability and the energy conversion system.

Subsequent to the NTDG evaluation, Exelon announced that it intends to delay its decision to proceed with the PBMR by a year, and that one or two technical issues that create uncertainty with regard to PBMR licensability will need to be resolved for Exelon to proceed. The South African demonstration plant has also been delayed by one year. Exelon advises that it still plans to proceed with its ESP application in 2002, but will be delay the COL schedule. This recent development is an example of the uncertainty inherent in the proposed PBMR project schedule which led to the cautious NTDG judgments regarding deployment potential.

Timeline for the PBMR

The roadmap reflects the schedule shown in Criterion 3 but with adjustments based on NTDG judgments. It shows the interconnection of the various tasks necessary to support the schedule, including the gaps and when they are closed. The development of the power conversion system (including design and testing) is shown as being completed by the end of 2002. Non-fuel materials testing and code validation and verification is estimated to be completed in two years and three years, respectively. The relatively short time for code V & V is based on having a simple single-phase system, much simpler than LWRs. Fuel testing and characterization was anticipated by the vendor to be a four-year task, with two years for fuel quality verification. The date for issuing the COL is slightly extended to allow additional NRC review time for materials testing results and code verification results. The NTDG has adjusted the schedule for the fuel test start date. It also notes that additional time for review of the tests may be needed before the NRC qualifies the fuel. The demonstration unit in RSA has allowed extensive time for reactor testing. The times anticipated for regulatory actions and for ordering components and constructing a first plant in the U.S. are also shown. Two critical points are highlighted, the decision on whether to proceed to construction in RSA, which is in early 2002; and the decision, if the first decision is positive, on whether to proceed to construction in the US. This one comes at the end of 2003.

PBMR Near Term Deployment Roadmap



GENERAL ATOMICS GT-MHR DESIGN

The Gas Turbine – Modular Helium Reactor (GT-MHR) is a graphite moderated helium cooled reactor. Heat generated by nuclear fission in the reactor is transferred to the coolant gas (helium) and converted into electrical energy in a gas turbo-generator via a Brayton direct cycle. The fuel is made up of spherical fuel particles encapsulated in multiple coating layers, including an impermeable coating that contains fission products to temperatures up to 1600° C. These particles are formed into cylindrical fuel compacts and loaded into fuel channels in graphite blocks that are 0.79 meters in height. These blocks are stacked horizontally and vertically to make up an annular core. The core is contained within three boundaries, the primary system boundary, which contains the helium coolant, a chamber that houses the reactor, and the containment/confinement building.

The containment concept for high temperature gas reactors (both GT-MHR and PBMR) is distinctly different from high-pressure containment for light water reactors. For HTGRs there is an additional level of radionuclide containment in the TRISO coated fuel particles used in these reactors. A SiC coating that is presumed to contain the fission radionuclides during normal operation and during all accident scenarios provides this containment. A primary system boundary rupture during operation would lead to an initial pressure buildup. The building containment design allows this pressure to be released through filtered vents, which would then close. Analyses suggest to the designers that release of radioactivity for any accident scenario is sufficiently small that the emergency planning zone (EPZ) could be set at the plant boundary.

The fundamental concept is aimed at building a plant that has high thermal efficiency (48 percent), yet has no physical process that can cause a radiation hazard beyond the site boundary. This is to be achieved by demonstrating that passive heat removal from the reactor vessel through conduction, convection and radiation exceeds the decay heat production in the post accident conditions, and that the peak temperature reached in the core during the transient is below the demonstrated fuel degradation temperature and far below the temperature at which the physical structure is affected. This effectively would preclude the possibility of a core melt accident.

The GT-MHR module generates approximately 286 MWe and can be used to generate power in a stand-alone mode or as part of a power plant that consists of up to 4 modules.

A. CRITERIA EVALUATION

Criterion 1: Regulatory Acceptance

Summary of General Atomics Response

The General Atomics plan for licensing the commercial version of the GT-MHR is aimed at gaining design certification of the GT-MHR. However, the first and potentially one or more subsequent modules would be licensed through a combination of early site permitting (ESP) and combined construction / operating licenses (COL).

Consistent with the schedule outlined in Criterion 3, at or about the time of a letter of intent for a plant order (end of 2002) a pre-application safety document will be submitted to the NRC to allow for an early identification and resolution of issues and to minimize the time required for review of an application for COL. Prior to this submittal, the regulatory requirements for the GT-MHR will have been established through early interaction with the NRC. An ESP application will be submitted shortly after the pre-application safety document. It is anticipated that a potential customer for the GT-MHR will prepare the application for an ESP and will submit it to the NRC prior to or at the time of providing a letter of intent for a plant order. An application for a COL and DC would be submitted along with submittal of a SAR and risk assessment in mid 2004. Receipt of a COL is anticipated approximately 36 months later. Also aiding the review schedule would be the establishment of the acceptance testing (ITAAC) that would be performed. It is expected that design certification will be issued after startup of the first module.

NTDG Assessment

The licensing strategy makes use of the design and safety analysis developed for a plutonium burning unit in Russia, which serves as a prototype and makes possible an early submission of a pre-application safety document. Application for a DC made at the same time as the COL application should avoid duplication of NRC review efforts. Because the design is being developed first for the Russian prototype and the relevant aspects are being transferred (Gap 1) to the U.S. for the commercial unit, the COL will contain the same level of safety analysis, including a complete plant PRA, as the application for DC. Also it will contain proposed Inspections, Tests, Analyses and Acceptance Criteria (ITAAC). To meet their schedule, it will be necessary to have a letter of intent from a first-plant customer by no later than mid- 2003 for the COL application, but the intent letter is desired by the end of 2002 for customer support of the pre-application safety document. According to the GA schedule, there would be one and a half years for pre-COL submission safety review, and two years allotted for NRC review and approval of the COL, up to the hearing stage and 1 year for a hearing following completion of the NRC review.

This strategy is credible but very challenging. The time for review is short based on past LWR experience with safety reviews. Of particular concern for maintaining the schedule are the early identification of a customer, the testing program required to qualify the fuel, the approval of a low pressure, vented containment (features shared in common with the PBMR), and the development schedule in Russia for the power conversion system. The GT-MHR power conversion schedule is somewhat longer than the development schedule in South Africa for the PBMR power conversion system. In addition, the schedule provides one-year overlap between the Russian Prototype unit startup and the startup of the commercial unit, so there is some, albeit limited, opportunity for transfer of operating experience. However, the prototype cannot be used to resolve any safety related issue if a COL is issued. If prototype testing were required to resolve any issue this would delay the issuance of the COL (Letter of August 23, 2001 from Samuel J. Collins, Director, Office of Nuclear Regulation, NRC, to James A. Muntz, V.P. of Exelon Generation regarding NRC Staff view of PBMR licensing plan.) Finally, it is noted that the use of the COL without Design Certification has less finality to it. Since there is no rulemaking involved, there is greater risk of post-construction intervention.

General Atomics has the advantage of significant experience from the pre-application review of its prior MHGTR design, as well as experience from Ft. St. Vrain licensing activities. Significant GT-MHR engineering development has been completed in several related programs. These include DOE funding of the MHGTR; DOE funding of the GT-MHR up until 1995 for the gas-cooled option for a tritium production reactor; as well as efforts toward the joint initiative with Russia for a gas-cooled reactor focused on burning excess weapons plutonium. The latter program is particularly important, for the design, development and safety analysis that would be transferred to the commercial program is estimated to have a significant value. If this work were performed in the US, the cost is estimated to be $945 million, but will be done for about one-third this cost in Russia. The design information to be transferred (Gap 1) would be in final design detail. The design must be upgraded to Western standards for licensing purposes. In addition, either joint NRC review of common issues with PBMR or follow-on learning from an earlier PBMR submission would help speed the review process.

There are several issues that need to be resolved to accomplish the NRC review in the scheduled two year time period. Licensing issues shared with the PBMR include: lack of regulatory framework unique to gas reactors; selection of and acceptance by NRC of design basis accidents; policy issues regarding containment, resolution of source term and emergency planning; determination of fuel acceptance criteria with the NRC, establishment of fuel performance requirement in terms of testing, repeatability and QA. Cooperation with PBMR, especially on the regulatory framework issue, but possibly also on others, could potentially benefit both designs. Issues unique to the GT-MHR include: completion of final design documentation that requires the International Program maintain its schedule; and significant cost-sharing funds must be available from DOE for commercial plant design, analysis and fuel fabrication facility development. Based on the gap analysis it does not appear that the COL could be submitted earlier because the design documentation and analyses from both the Russian program and the additional work required by GA will not be ready for the final design before mid 2004. In this context, a listing of some of the technical tasks that are to be completed in the International Program by 2004 but currently represent technology gaps are the following:

- Reactor physics tests to validate the reactor physics codes.
- Thermal hydraulic tests to provide the data needed for flow distributions and core components pressure drops, thermal mixing at the core outlet, core column flow induced vibrations, and verification of core dynamic stability.
- Materials tests on reactor metals and ceramics to obtain supplemental data on material properties.
- Vessel materials tests, particularly on heavy section and welds.
- Reactor core graphite material tests on irradiated and unirradiated graphite specimens.
- Shutdown Heat Exchanger tests for flow behavior and to ISI with an eddy current probe.
- Reactor Cavity Cooling System component and integrated tests for RCCS properties and performance.
- Fuel handling system component and integrated tests.

- Turbomachine tests to verify key performance characteristics including surface coating tests where materials are in contact and subject to movement; flow distribution tests to characterize flow distributions in the compressor and turbine inlet and outlet ducts; and rotor dynamics tests.
- Turbomachine bearing tests to verify the performance of journal and thrust magnetic and catcher bearings.
- Seal tests related to the interface of the turbomachine and interfacing assemblies.
- Recuperator tests to verify the performance characteristics of this counterflow gas-to gas recuperator.
- Handling equipment tests for the turbomachine and generator.
- Precooler/intercooler tests to verify performance and inspectability of these heat exchangers.

This list enumerates the extensive design and testing effort being performed in Russia. Maintaining the schedule so all these efforts can be completed and transferred to the U.S. by 2004 represents a substantial challenge. It is a challenge not only to complete the large number of tasks to acceptable U.S. standards, but also to translate the design, testing, and analysis documents from Russian to English and prepare them in suitable form to be submitted to the NRC for the COL license application.

The NTDG believes the GT-MHR can meet the criterion, provided that several challenging technical issues (including fuel issues) can be resolved and demonstrated to NRC satisfaction in the time frame needed for 2010 deployment. U.S. licensing submittal information must be adapted from the Russian design and test work.

Criterion 2: Industrial Infrastructure

Summary of General Atomics Response

The GT-MHR is currently under development in an International program being performed in Russia for the disposition of surplus weapons plutonium. Both government and industrial organizations from the United States, Russia, France and Japan are sponsoring the development work. The lead Russian organization for the GT-MHR design and development work is the Experimental Machine Building Design Bureau (OKBM); General Atomics (GA) has the lead responsibility for providing technical support from the United States; Framatome from France and Fuji Electric from Japan have also provided support.

A commercialization program (see Criterion 3) has been developed for commercial deployment of the GT-MHR system in the United States and its markets based on utilizing the GT-MHR technology developed in Russia. The organization for commercial supply of GT-MHR plants in the United States is planned to be a consortium consisting of GA, OKBM, one or more domestic Architect-Engineer/ Constructor companies, and other potential organizations participating in development of the GT-MHR. For the first commercial plant in the United States, the commercialization program is based on using equipment suppliers that meet U.S. qualification requirements. These suppliers will also supply the equipment for the first prototype plant in Russia. However, the commercial plant will be fueled with uranium and a domestic fuel supplier is planned.

NTDG Assessment

The initial commercial GT-MHR units would utilize international suppliers for the major components, especially the Russian companies that are participating in the gas-cooled reactor program for plutonium burning. Meeting U.S. equipment standards will be an on-going challenge and concern for GA. The Russians are likely to have limited experience in meeting the ASME requirements. The development and testing of the technology for the Russian prototype, especially the power conversion equipment, is tied closely in schedule to the commercial program in the U.S. On the one hand, this allows for rapid technology transfer of evolving technology. On the other hand, full scale testing on the power conversion system will be limited because the prototype isn't scheduled to operate until one year before the first commercial unit. A degree of uncertainty in schedule is introduced related to funding uncertainties in the DOE funded International Program. The GT-MHR program may also experience complex relationships with the Russian Government that could result in commercial impediments, e.g. import-export rules. Even without these uncertainties there is a technology risk because of the complexity and lack of operating experience with the power conversion system, especially for a design with the turbocompressors and the power turbine-generator on a single shaft. The primary supplier of the power conversion system, OKBM, has a reputation for quality engineering, but lacks experience in the commercial market, especially in qualification as a commercial supplier in the U.S. Achieving equipment qualification for U.S. use in the time frame for 2010 deployment will be a challenging issue. On top of this, the vendor, GA, has not built a power reactor since Ft. St. Vrain in the 1970s, and they no longer have a strong vendor organization for reactor and system design. This will require that, in addition to obtaining a plant customer, GA must find a partner who can add this strength and experience to their organization, as well as financial resources.

The NTDG believes the GT-MHR can meet the criterion, provided that the Russian industrial infrastructure can be qualified as a commercial supplier in the U.S. This may be difficult to achieve in the time frame required for deployment by 2010. In addition, it must find a partner in the near future to strengthen the engineering and system design, provide an enhanced level of experience in building plants, and to provide industry match resources.

Criterion 3: Commercialization Plan

Summary of General Atomics Response

The GT-MHR is an effective nuclear power electric generation plant for commercial deployment when fueled with uranium. Because of this, a program has been implemented for commercial deployment in the United States and its foreign markets of the technology being developed in Russia. Schedule-wise, the commercial program closely follows the International program. Key milestones for the International program and the Commercial program are as follows:

GT-MHR INTERNATIONAL PROGRAM

Complete design and development	By end of 2004
Obtain prototype construction license	By end of 2005
Complete prototype construction	By end of 2009
Complete prototype demonstration testing	By end of 2010
Start prototype full power operations	By end of 2010

GT-MHR COMMERCIAL PROGRAM

Complete regulatory framework	By end of 2002
Submit pre-application safety analysis	By end of 2002
Submit COL and DC applications	By mid 2004
Complete NRC COL review	By mid 2006
Complete COL hearing	By mid 2007
Obtain COL	By mid 2007
Obtain letter of intent for plant order	Desired by end of 2002 (Needed by 4th Q of 2003)
Plant order	By mid 2006
Submit application for ESP	Early 2003
Obtain ESP	Early 2005
Complete fuel fabrication pilot plant	End of 2005
Complete fuel proof tests	End of 2009
Start plant site work	By mid 2006
Start plant construction	By mid 2007
Complete construction, begin fuel load	By end 2010

The engineering tasks necessary for adapting the technology developed in Russia for commercial plant deployment in the US consists of:

- GT-MHR technology transfer (e.g., drawings, specifications, reports)
- Performance of Incremental Design Items (e.g., uranium core, commercial BOP)
- Establishment of uranium fuel fabrication facility
- Plant safety and licensing
- Plant level design and analysis (e.g., utility/user requirements, performance analyses)

This engineering work is to be performed by team members of the GT-MHR supplier consortium. It is anticipated that no new R&D will be needed. All of the necessary development and test work, except for fuel supply proof testing covered under criterion 6, will be performed in Russia as part of the International program.

NTDG Assessment

GA has established a utility advisory group with a goal of identifying a first U.S. customer. It is critical to their schedule that they succeed by third quarter of 2003. Their big advantages are leveraging work from the International Program to reduce design and development cost, and their experience from earlier reactor design development and licensing. Nonetheless, there are significant uncertainties in the commercialization plan related to the licensing schedule; the heavy dependence on DOE funding and schedule adherence for the International Program in Russia; the U.S. funding for the commercial program; and the technology risks related to fuel and to first-of-a-kind power conversion system technology. The time period to successfully develop the commercial plan is rather short in order to have the first plant operating in the U.S. by 2010.

The NTDG believes the GT-MHR can meet the criterion. However, this presumes continued U.S. Government support to the Russian project, timely identification of a U.S. customer and industry partners who will strengthen the engineering organization and provide resources, and technical success with the Russian project.

Criterion 4: Cost Sharing Plan:

Summary of General Atomics Response

A table of cost categories and expected cost sharing between Government(s) and private industry for initial development of the GT-MHR for plutonium disposition and subsequent deployment of the GT-MHR for commercial power generation using uranium fuel is as follows:

Cost Category	Government Cost Share	Private Industry Cost Share
GT-MHR Conceptual design	30 percent	70 percent
GT-MHR Design & Development for Pu Disposition	95 percent	5 percent
GT-MHR Prototype Construction for Pu Disposition	95 percent	5 percent
Commercial Plant Design and Analysis	50 percent	50 percent
Technology Transfer for Commercial Deployment	50 percent	50 percent
Commercial Plant Incremental Design Items	50 percent	50 percent
Commercial Plant Safety and Licensing	50 percent	50 percent
Commercial Fuel Development	50 percent	50 percent
Commercial Fuel Fabrication Facility	5 percent	95 percent

The rational behind the planned cost sharing percentages is based on expenditures to date, DOE nuclear energy cost sharing precedents, and nuclear industry investment practices.

NTDG Assessment

The commercial program relies on U.S. Government cost sharing for licensing, transfer of technology and design from the Russian program, plant design not covered by the Russian program, and fuel development. The rationale for the proposed cost sharing percentages is based on expenditures to date, DOE nuclear energy cost sharing precedents, and nuclear industry investment practices. The GT-MHR has benefited from having its basic engineering development tied to the plutonium disposition program, which is almost fully government funded as a national security issue. This does not, by itself, negate the rationale for cost sharing for developing a commercial unit. Indeed, this has enabled GT-MHR to reduce its requested government support from DOE by transferring the technology from Russia rather than performing the first-of-a-kind engineering for the commercial reactor.

The major uncertainties include the availability of funds to continue the past government cost sharing precedents, and the identification of the necessary additional industrial participants who will provide the industry cost share. At this time the industry cost share participation is not all identified.

The NTDG believes the GT-MHR meets the criterion. The cost share proposal is predicated on continued U.S. Government support to the Russian project and presumes substantial private sector participation for commercialization.

Criterion 5: Economic Competitiveness:

Summary of General Atomics Response

The data provided to evaluate the economic competitiveness of the GT-MHR is summarized in the following table:

GT-MHR Data for Economic Competitiveness Evaluation

Plant Configuration & Capacity Data	
Number of modules/plant	4
Thermal power/module [MWth]	600
Thermal efficiency [percent]	~48
Net module capacity [MWe]	288
Net plant capacity, [MWe]	1150
Plant Construction Cost	
Site Engineering Cost [M$]	60
Procurement Cost [M$]	630
Construction Cost [M$]	260
Plant Base Cost [M$]	950
Contingency [M$]	190
Owners Cost [M$]	150
Overnight Cost [M$]	1,290
Overnight Unit Cost [$/kWe]	1122
NOAK/FOAK Cost	~0.75
Other Plant Costs	
Fixed O&M Costs [M$/yr.]	30.44
Variable O&M Costs [$/MWh]	0.64
Fuel Cost [$/MBTU]	1.27
Expected Plant Lifetime [Yrs.]	60
Nominal Capacity Factor [percent]	90
Decommissioning Cost [M$/Yr.]	1.1

As with all new reactor designs the initial units will have higher generation cost. This is a direct consequence, in both gas-cooled reactor designs, of sacrificing economy of scale in the interest of safety, but achieving economics through efficiency and multiplicity. Multiple unit orders, consistent with the commercialization strategy, will bring the cost down to more competitive levels.

NTDG Assessment

The short construction time, estimated to be three years after the four-year construction for the initial unit, is favorable to economic competitiveness since there would be smaller interest costs. In addition, the relatively small cost of the individual reactor modules should make financing easier than for large plants. Other features of the GT-MHR also favor good economics, including high thermal efficiency and high fuel burnup. On the other hand, it will take four pressure vessels and four structures to have the same power output as a large LWR. It will be a considerable challenge to have the beneficial cost factors compensate for the added costs. The projected busbar power cost looks favorable, particularly for the NOAK plants, but the uncertainties are significant. This is based on the lack of a complete design and the lack of experience with the power conversion equipment and the fuel manufacturing production facility. Much of the detailed design work and component technology development and testing will be funded through the International Program. Even with this, and cost-shared funding with DOE to transfer the technology to the commercial program, the initial four-unit plant is estimated to have a nominal capital cost of 1,576 $/kWe. This not surprising for FOAK technology, but it clearly identifies the need for multiple unit orders to reach a more competitive cost basis.

The NTDG believes the GT-MHR can meet the criterion. However, projected economics are preliminary and have a high uncertainty. Satisfactory economics rely on deployment of multiple modules and successful development of the design.

Criterion 6: Fuel Cycle Industrial Structure

Summary of General Atomics Response

The GT-MHR uses TRISO coated particle fuel. The reference fuel is TRISO particles containing uranium oxycarbide (UCO) with 19.8 percent enrichment. Test specimens for the reference fuel need to be manufactured for qualification testing.

No coated particle fuel fabrication facilities currently exist in the United States. An automated fuel fabrication pilot plant will be designed and constructed. It is scheduled to begin operation by the end of 2005. Proof test specimens will be fabricated in the pilot plant to qualify the automated fuel fabrication process.

For the first GT-MHR plant(s), the required GT-MHR uranium enrichment can be produced by blending highly enriched uranium down to 19.8 percent enrichment level. Once the demand has been established for these enrichment levels, supply capability for the required enrichments is expected to be established. There are no unique conversion requirements for the GT-MHR. Worldwide conversion capacity is sufficient to satisfy GT-MHR conversion needs.

Immediately after discharge from the reactor, spent GT-MHR fuel elements are stored dry, in an array of storage tubes externally cooled by water, for an approximate one-year cooling period. After 1 year of cooling, the spent fuel elements are removed from the storage tubes and placed in dry spent fuel storage casks. Loaded spent fuel storage casks are moved to an on-site spent fuel storage yard sized to contain all of the spent fuel storage casks required for the life of the plant.

NTDG Assessment

The fuel supply strategy is to qualify TRISO particle fuel containing uranium oxycarbide (UCO). The fuel supply will come from HEU that is blended down to 19.8 percent enrichment. GA will need to give attention to assuring that a long term, reliable fuel supply is available. The UCO fuel results in high fuel utilization and good fuel cycle economics. Simultaneous with the testing program with existing fuel, an automated fuel production pilot plant would be built in the U.S. by General Atomics that, when qualified for production, would be expanded into a fuel fabrication facility.

The critical issue that is not resolved is the determination, with the NRC approval, of fuel acceptance criteria and a demonstration that the fuel produced and tested meets those criteria. While GA previously used TRISO particle fuel at Ft. St. Vrain, which had a low-pressure containment, the type of containment is quite different from previously approved LWR power plants. Although a body of evidence on radionuclide release from irradiated TRISO particle fuels already exists, the licensing process has not proceeded far enough to make a reasonable determination whether the cost and effort is consistent for use of a low pressure containment for the GT-MHR operating conditions.

In any event, a full fuel-testing program is planned and required using fuel fabricated in the pilot plant. This fuel-testing program is required for NRC to qualify the fuel. This will take approximately four years including the NRC review of the topical report. Such a testing program is critical to the plant operation since the fuel is the main containment for fission products and the barrier to radionuclide release in the event of an accident. The testing program must show that the fuel meets the fuel acceptance criteria. If a low pressure, vented containment is used, then the risk is being taken in building the plant that the acceptance criteria for that type of containment will be met. This risk is necessary to achieve 2010 operation since the fuel testing isn't completed until early to mid 2010.

It is known that certain radioactive fission decay products, especially Ag-110, can diffuse through the SiC layer at operating temperatures. This might lead to contamination of the power conversion system, especially the turbine blades. The presence of Ag-110 was previously seen at Ft. St. Vrain, but was found to be of little consequence. However, the GT-MHR operates at a higher temperature than Ft. St. Vrain does, so the potential exists that the problem may be worse than found previously. The possible cost consequences are uncertain. It is the view of GA that this is a maintenance problem, not a safety problem, and it will be treated as such.

The NTDG believes the GT-MHR can meet the criterion. The GT-MHR safety and reliability hinge on successful fuel development and high quality fuel manufacture. The current plan includes an ambitious program to develop, test, license and produce GT-MHR fuel.

B. GAP ANALYSIS

The design specific gaps are the tasks that need to be done if this technology is to be brought to the marketplace by 2010. They relate to licensing, fuel fabrication and testing, safety analyses, and technology transfer for plant design plus additional plant design and analysis. Below these gaps are presented along with the closure actions needed and the estimated cost (in $ million) of achieving closure. Cost sharing on a per task basis is requested at a 50-50 cost sharing rate between industry and the U.S. Government.

The technology gaps that are to be filled in the International Program are identified under criterion 1 and represent much of the technical develop effort, FOAK engineering and safety analysis. GA has estimated that the cost of that effort at approximately $300 M. It is not singled out here, but the results are included in the technology transfer gap.

Technology Transfer

Gap: GT-MHR technology developed in Russia in the International Program needs to be transferred to the United States for the commercial program. A complete detailed design of a GT-MHR plant for plutonium disposition is being prepared in the International program and all of the necessary R&D to validate the design will be performed. For commercial deployment of this technology in the US, a transfer of the technology needs to take place.

Closure: To close this gap, the following activities are required:

- Preparation of System Design Descriptions (SDDs) for the commercial plant systems based on the equivalent documents developed in the International program but incorporating the use of US codes and standards.
- Adaptation of Drawings and Specifications by changing from the use of Russian codes and standards to the use of US codes and standards and any associated design consequences.
- Adaptation of Design and Technology Reports by verification of compliance to US codes and standards.

Year Source	FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	TOTAL
DOE		$3M	$4M	$3M	$2M					$12M
Industry		$1M	$2M	$3M	$3M	$2M	$1M			$12M
TOTAL		$4M	$6M	$6M	$5M	$2M	$1M			$24M

Systems Design

Gap: Design of plant systems for commercial deployment of the GT-MHR technology using uranium fuel.

Closure: To close this gap, the design of the following incremental systems is required for the commercial GT-MHR:

- A uranium core design,
- A low pressure, vented (LPV) containment system,
- A reactor cavity cooling system (RCCS) for the LPV containment,
- Conversion from 50 hertz to 60 hertz ac power generation,
- BOP structures and systems for the commercial plant design.

Year Source	FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	TOTAL
DOE		$5M	$4M	$4M	$4M					$17M
Industry		$1M	$4M	$4M	$4M	$3M	$1M			$17M
TOTAL		$6M	$8M	$8M	$8M	$3M	$1M			$34M

Obtaining a COL

Gap: Safety and licensing of the commercial GT-MHR aimed at gaining a positive Safety Evaluation Report (SER) for the GT-MHR, approval to start construction of the first plant and a design certification of the standard plant.

Closure: The major items that need to be completed to close this gap are as follows:

- Preparation of a licensing plan
- Performance of safety analyses and risk assessment
- Preparation of SAR for COL
- Interaction with NRC through completion of SAR review, SER preparation, and public hearings.

Year Source	FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	TOTAL
DOE	$1M	$3M	$2M	$2M	$2M					$10M
Industry	$.2M	$1.2M	$1.6M	$2.5M	$2.5M	$1.5M	$.5M			$10M
TOTAL	$1.2M	$4.2M	$3.6M	$4.5M	$4.5M	$1.5M	$.5M			$20M

Fuel Fabrication and Testing

Gap: No GT-MHR uranium fuel fabrication facility currently exists in the United States. The gap includes the design, construction and qualification of a GT-MHR fuel fabrication process.

Closure: The following activities are required to close this gap:

- Irradiation testing of GT-MHR fuel compacts to proof test TRISO coated particle fuel compacts for GT-MHR performance requirements
- Fuel fabrication QC process improvement
- Fuel fabrication process automation and qualification (pilot plant scale)
- Design and construct a fuel fabrication facility.

Year Source	FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	TOTAL
DOE	$1M	$4M	$4M	$5M	$5M					$19M
Industry		$2M	$3M	$5M	$5M	$3M	$3M			$21M
TOTAL	$1M	$6M	$7M	$10M	$10M	$3M	$3M			$40M

NTDG comment: It is unlikely that the fuel-testing program will be completed by the end of FY08. It is likely that additional funds will be required since $42M may be on the low side. (PBMR indicated that an equivalent program would take $52M, and a fuels-testing expert supported the higher number.)

Design Analysis

Gap: Commercial GT-MHR plant level design and analysis activities including a plant requirements document to be satisfied by the GT-MHR commercial plant and performance of plant level assessments such as economic performance (safety assessments are included in a separate safety and licensing gap).

Closure: The following items are required to close this gap:

- A plant requirements document to be used for preparation of the commercial plant design.
- Plant level economic, proliferation resistance, and spent fuel waste assessments.

Year Source	FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	TOTAL
DOE		$4M	$4M	$4M	$2M					$14M
Industry	$0.2M	$1.6M	$3M	$3M	$2.2M	$2M	$2M			$14M

TOTAL	$0.2M	$5.6M	$7M	$7M	$4.2M	$2M	$2M			$28M

Total Resource Requirements to Close All Gaps

Year Source	FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	TOTAL
DOE	$2M	$19M	$18M	$18M	$15M					$72M
Industry	$0.4M	$6.8M	$13.6M	$17.5M	$16.7M	$11.5M	$7.5M			$74M
TOTAL	$2.4M	$25.8M	$31.6M	$35.5M	$31.7M	$11.5M	$7.5M			$146M

The overall development cost is relatively low for development of a new reactor concept, with anticipated total development cost on the order of $400 M. Most of the remainder is being developed as part of the International Program for a plutonium disposition reactor in Russia.

C. OVERALL ASSESSMENT

The GT-MHR is a promising design being developed in Russia as a plutonium burner. This is an International Program with joint funding and/or participation from DOE and Russia, and companies in Japan and France. This approach has the advantage that much of the design and development effort for the commercial unit can be leveraged from the work being supported in Russia. However, it also means that the U.S. commercial schedule is tied to both the funding and schedule for the International Program, as well as the quality of the work performed and the ability of the Russian equipment suppliers to meet U.S. qualification standards. This introduces a significant schedule risk for the commercial program. Gaps that need to be filled on a cost-shared basis with industry include: (a) technology transfer from Russia for design work and technology development; (b) design of all aspects of the reactor not covered by the Russian design, including the core, containment and balance of plant structures and systems; (c) obtaining a COL; and (d) fuel fabrication and testing. A gap for code verification and validation is not identified on the basis that past work from the MHTGR and the NPR programs, and further physics code tests and safety analyses in Russia, will be sufficient to qualify their codes with little additional effort. Nonetheless, it is important that completion of this task be explicitly built into their schedule to assure the work is completed well before a decision is expected from the NRC on the COL application.

The GT-MHR has chosen a commercialization plan that involves seeking a combined construction and operating license (COL) in parallel with an ESP. Design certification will be sought later, after the first plant serves as a demonstration but an application for DC will be submitted at the same time as the application for COL. The COL schedule is aggressive, with 36 months allotted from submission of the COL application to issuance of the license. Approximately 18 months prior to submission of the COL application, a Pre-Application Safety Document will be submitted. In this time period, the main safety issues such as the fuel qualification and acceptability criteria, acceptability of a low-pressure containment, and an EPZ at the site boundary are planned to be resolved. During the 36 months following submittal of the

COL application, NRC review can focus on the adequacy of the final design, the ITAAC, and a public hearing. Some licensing benefits could accrue to the GT-MHR if the PBMR makes an earlier COL application. (The projected schedules have the PBMR submitting their COL application 18 months earlier than the GT-MHR, coincident with the GT-MHR pre-application submittal). This schedule would seem to fall within the minimum time requirements NRC has indicated for issuing the COL. It would be desirable to have the COL submitted earlier. However, this is unlikely because the documentation required for the COL application is tied to the International Program and to additional DOE funding.

A successful commercialization will require a strong vendor organization with experience in design, engineering and licensing, and who can provide the necessary financial resources for industry match in cost sharing. GA currently does not these capabilities and it will be necessary to find a partner by the time a customer expresses interest – by mid-2003 – if they are to keep even close to the proposed schedule.

Current cost estimates for an NOAK plant are encouraging. However, there are many uncertainties in the early use of a new technology. Cost estimates are limited by the lack of a complete design and by experience with a building and operating a commercial application of the GT-MHR. Even though a commercial demonstration plant with a steam cycle operated at Ft. St. Vrain in the 1980s, the current design uses an untested power conversion system based on the Brayton cycle with vertically mounted turbines on a single shaft. The Russian prototype will not provide any operating experience because the prototype won't operate until 2009, at the earliest.

Fuel performance under irradiation and safety tests that meets the fuel acceptance criteria remains a central requirement for operation. Because the tests will not be completed until construction is essentially complete, the customer and partners must accept the risk that the fuel will meet the acceptance criteria on schedule.

While the NTDG indicated that each of the criteria could be met, many of them were met marginally. As an overall assessment, the NTDG believes that the GT-MHR "possibly can be deployed in the U.S. by 2010".

For deployment by 2010, the following will be required:

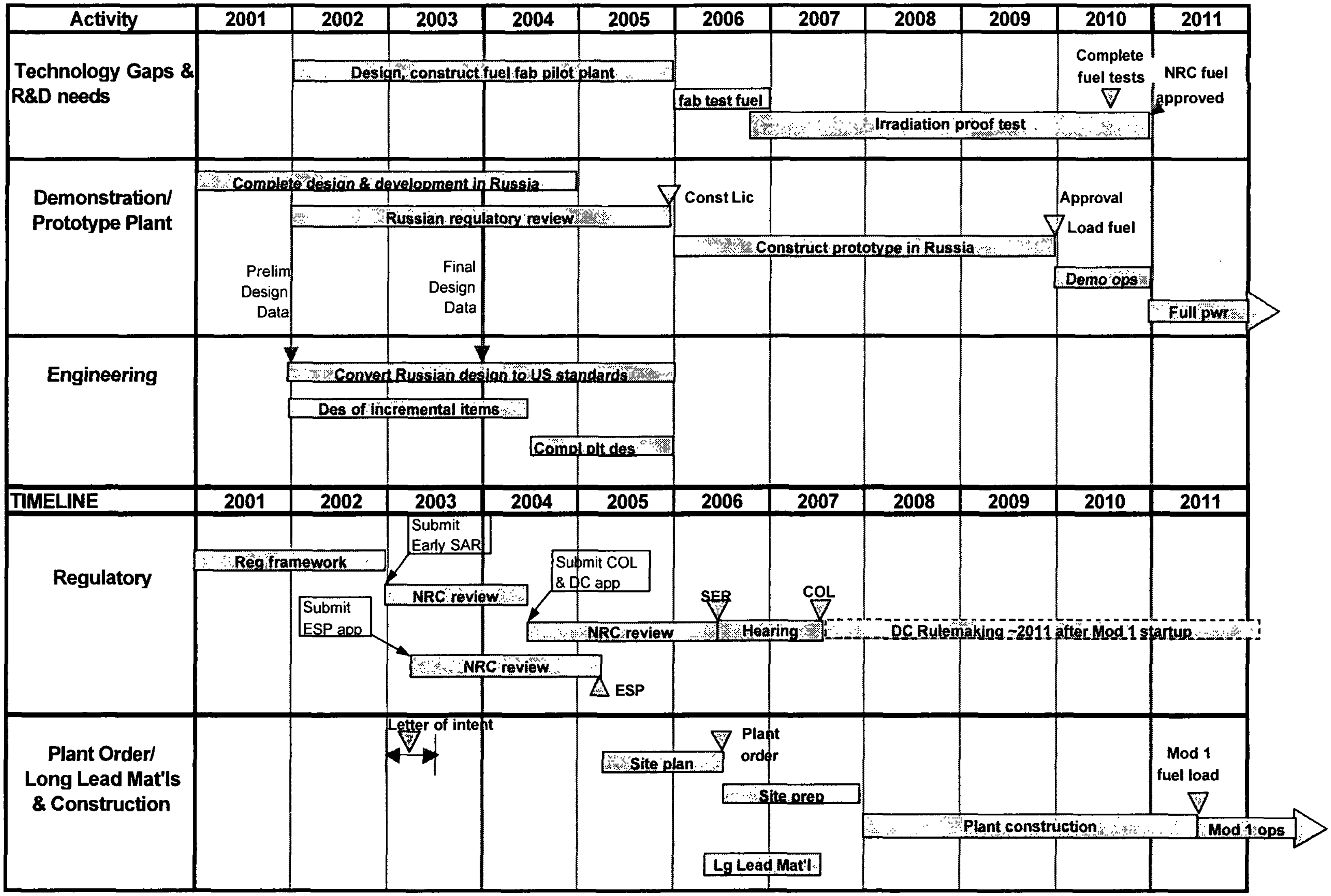
- Success in the Russian GT-MHR project (in turn, requiring continued U.S. Government support).
- GA must secure, in the near future, adequate investment from prospective customer(s) to fund engineering and licensing applications for the U.S. plant.
- A successful, expedited ESP/COL schedule
- Resolution of several challenging technical issues, including those related to fuel reliability and the energy conversion system.

Deployment could be achieved, however, if a currently interested customer commits to a GT-MHR by 2003, and it finds a partner in the near future to strengthen the engineering and system design, provide an enhanced level of experience in building plants, and provide industry match resources.

Timeline for the GT-MHR

The roadmap reflects the schedule shown in Criterion 3 but shows the interconnection of the various tasks necessary to support the schedule, including the gaps and when they are closed. The development of the power conversion system (including design and testing) is performed as part of the Russian development program and is not identified separately. It will be completed by the end of 2004. Gap closure is particularly emphasized in the "Engineering" block, where technology transfer from the Russian program is identified, and where the additional design work for a commercial uranium-fueled reactor is identified. Code verification and validation is not called out because GA believes the codes developed for the MHTGR and NPR programs are largely applicable, although new safety analyses must be performed for the SAR and COL submission, and new reactor physics tests will be performed in Russia. Fuel fabrication and testing gaps are identified and the time for closure is shown. If the fuel meets the acceptance criteria, it allows for full loading by the middle of 2011. A time of three years is shown for NRC review and hearings to obtain a COL. A full 3.5 years is allowed for the initial plant construction. Two critical points are highlighted: receiving a letter of intent to purchase a plant from a plant owner/operator, which is needed by the end of the second quarter of 2003; and the plant order decision by mid-2006. Even with these, the most probable time for fuel loading is mid-2011; however, if an order and partnering with a strong vendor should occur earlier, the schedule could be moved forward to make a late 2010 fuel load.

GT-MHR Near Term Deployment Roadmap



II-6: CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

The following is a summary of the most significant conclusions drawn by the NTDG in the course of their assessment, and as described in this report:

1. New nuclear plants can be deployed in the U.S. in this decade, provided that there is sufficient and timely private-sector financial investment.

2. To have any new nuclear plants operating in the U.S. by 2010, it will be necessary for generating companies to commit to new plant orders by the end of 2003, in order to proceed with preparation of COL applications. This will require very near term action by prospective new plant owner/operators and strong support from the Government.

3. Although conditions are currently more favorable for new nuclear plants than in many years, economic competitiveness in a deregulated electricity supply structure remains a key area of uncertainty with respect to near term deployment potential. The other gaps to near term deployment require attention; in particular, implementing an efficient and effective regulatory approval process for siting and licensing of new plants is an urgent matter, and will require use of new processes in 10 CFR Part 52, that have not been demonstrated in actual practice.

4. There are excellent new nuclear plant candidates that build on the experience of existing reactors in the U.S. and around the world, and that could be deployed in the U.S. in this decade. Readiness for deployment varies from design to design, based primarily on degree of design completion and status of regulatory approval. Those that are the most advanced in terms of design completion and approval status appear to be economically competitive in some scenarios, but not all. Other new nuclear plant designs, which still require licensing and engineering, show promise for improved economic competitiveness.

   The design-specific gaps that must be overcome by the gas-cooled candidates to achieve near term deployment are somewhat greater than those facing most of the water-cooled candidates.

5. Achieving near term deployment will require continuing close collaboration between Government and industry. Selections of new projects must be market-driven and supported primarily by private sector investment, but government support is essential, in the form of leadership, effective policy, efficient regulatory approvals, and cost sharing of generic and design-specific one-time costs.

RECOMMENDATIONS

This Chapter provides specific recommendations in both generic and design-specific categories. Generic recommendations are initially organized to coincide with the Gaps and Issues presented in Chapter II-3. Design-specific recommendations are derived from actions presented in Chapter

II-5. These recommendations are then reorganized and presented in a Phased Action Plan, which is an integrated, success-oriented approach to closing the gaps while taking concrete steps to get new plants under construction. The Phased Action Plan provides a logical and manageable approach to achieving the goals of this Roadmap – multiple plants on line by 2010.

Appendix J to this Roadmap provides a "roll-up" of the resource requirements needed to close site-specific, generic and design-specific gaps that present obstacles to near term deployment. These resource requirements are taken from Chapters II-3 and II-5. The design-specific funding needs in that table are for those designs that the NTDG judges should be candidates for industry-government cost sharing for near term deployment. However, the table does not represent NTDG funding recommendations, since actual government funding levels will be contingent on industry's ability to assemble the specified cost-share, as explained later in this Chapter.

The electricity shortages that are beginning to appear around the country are creating a sense of urgency. It is appropriate for the U.S. to take the necessary steps to see that nuclear energy options are available in time to support a likely surge in the need for new power plants over the next decade. The United States should be seeking to identify and support opportunities to immediately begin implementation of projects that will lead to the commercial operation of new nuclear plants by 2010. This near term imperative will complement the long-term development of new reactor technologies and fuel cycles via the Generation IV Roadmap.

Building new nuclear plants in the U.S. requires certainty and stability. Government can play a key role in encouraging market interest in new plants, and supporting public private partnerships. New nuclear capacity can and will be built when it makes sense to take the financial risk. Investors must see manageable risks equal or better than alternative sources of power, in the following areas:

- Capital and life-cycle operating costs of new plants
- Regulatory processes for new plants
- Time required to build a new plant, minimizing "time to market"
- Federal policy and technology support commitment

GENERIC GAP RECOMMENDATIONS

Following are recommendations to support resolution of the five generic gaps confronting near term deployment in the U.S., as discussed in Chapter II-3. These recommendations are viewed as very important to successful deployment of new plants by 2010. Because of the urgency of encouraging new orders in the next two years to support deployment by 2010, these recommendations focus on the near term horizon, and on strategic steps that must be taken now to enable near term deployment goals to be realized.

In general, the industry should have the overall responsibility for most of the actions described below. However, government assistance is needed for many of these recommendations to be successful. More important, increased government leadership is needed to help establish the policy, economic and regulatory environment that will allow nuclear energy to compete on a level playing field in a deregulated electricity marketplace with other energy supply options.

Gap 1: Nuclear Plant Economic Competitiveness

Recommendations to address the economic competitiveness of new nuclear plants fall into three categories:

- Design-specific recommendations: the major actions to ensure one or more designs are clearly economically competitive this decade are ones that individual vendors must take. These are covered in Chapter II-5 and in Appendix J.
- Generic recommendations that focus on technological advances of value to all applicants. There are a number of technologies that can reduce capital costs and construction times, and that can be made available in the short term that can be applied to certified designs without modifying the design itself, thus ensuring that the DC remains valid. These include enhanced information management systems, virtual construction technologies, advanced instrumentation, controls, and on-line diagnostic monitoring. These technologies may also help reduce capital and operating costs for uncertified designs. Details are discussed in Chapter II-3, with resource needs summarized in Appendix J.
- Generic recommendations that focus on business arrangements, federal treatment of energy investments and regulatory efficiencies that benefit all applicants. These are covered in the next gap related to deregulation, and in later sections in this Chapter.

Gap 2: Business Challenges of the Deregulated Electricity Marketplace

The industry needs to develop the business plans and models to facilitate the financing arrangements that will be required to build new plants in a deregulated electricity marketplace. This is a responsibility of industry, and NEI is facilitating this process through its development of an "Integrated Plan for New Nuclear Plants." (See Attachment 4.)

Execution will need help from Federal and State Governments, who can assist by taking actions in three general areas:

1) Establish vehicles for business risk reduction that can be taken to reduce the risks of capital-intensive new baseload generation investment, including nuclear energy. These vehicles should focus on one time costs and market-based incentives, and could include:

    - Provisions for accelerated depreciation to allow quicker recovery of capital investment
    - Negotiated long-term power purchase agreements (e.g., 20 years)
    - Tax credits for investments in new plant design, development, licensing and construction
    - Tax incentives for diversity in fuel supply and/or emission-free generation

    All of these measures can be considered for federal action; some can also be implemented at the regional, state, or even local level to provide incentives to address more specific market needs. Both federal and state/local entities have an interest in incentives that support strategic energy and environmental goals and that encourage competition among a mix of generating options. Many of these incentives can be put in place on a temporary basis – until the investment community has confidence that these plants can be built on schedule and within projected cost.

2) Take actions to reduce "time to market" for new capital-intensive projects. In a deregulated market, business decisions to invest in new baseload generation require many years of lead-time prior to construction of the plant. To remain competitive when placed in commercial operation, both pre-construction lead-time and actual plant construction time must be minimized. This requires concerted action by industry to plan and execute new plant projects efficiently, and requires NRC to execute licensing applications for new sites and designs as efficiently as possible, consistent with safety requirements.
3) Take actions to ensure energy and environmental policies and regulations are balanced among energy supply options, based on good science, through consistent tax and investment incentive treatment.

Industry and DOE should work together to investigate the costs and benefits of each of the above-recommended provisions, and seek implementation of those deemed appropriate. There are a number of other regulatory and statutory issues that industry has stated need to be addressed that are not directly within the purview of DOE or this NTD Roadmap. These were discussed at the end of Chapter II-3, where some actions, generally encouraged by industry, were presented. No recommendations are provided here. This list of issues included:

- Renewal of the Price-Anderson Act;
- Legislative and regulatory reforms, including changes to the Atomic Energy Act
- Dual or conflicting regulation (e.g., federal radiation protection policy)

Gap 3: Efficient Implementation of 10CFR Part 52

As discussed in Chapter II-3, there are four focus areas associated with this gap. Each is addressed by a separate set of recommendations below. These are consistent with and complement the President's recommendations in the National Energy Policy: "...expedite applications for licensing new advanced technology nuclear reactors," as summarized in Chapter II-2. DOE and industry should encourage a process that expedites resolution of open issues with the NRC, standardizes processes prior to applicant submittals, and tests these processes as soon as possible for effectiveness and efficiency. To fulfill the recommendations of the National Energy Policy, the NRC must continue regulatory modernization, including both the creation of risk-informed, performance-based regulations and regulatory guidance, and the assurance of regulatory stability for licensing of new plants. This effort is urgent and important to success.

The first three focus areas described below require essentially complete resolution to achieve near term deployment. The fourth focus area is not an obstacle to near term deployment, but deserves significant attention because of the opportunity it presents for major improvements toward more efficient and safety-focused regulation. This last focus area is included here for consistency and because it should be treated urgently.

A. The DC process must be expedited to help resolve the "time to market" obstacle to nuclear plant orders in a deregulated market.

NRC should work with industry to expedite the DC process so that any near term design could reasonably expect to complete the process in three years, including the rulemaking phase, assuming a quality submittal covering all required topics required by the regulations (e.g., full scope PRA for the design). For DC applications that rely significantly on design information from a previously reviewed and/or certified design, the goal should be to complete the process in less than two years.

DOE should cost share the costs of DC with any near-term applicant capable of producing a quality DC submittal and capable of assembling the financing for the industry share.

B. ESP and COL processes must be demonstrated successfully for new plants to be built. They must be shown to be stable and predictable processes that can be completed efficiently, in no more than 2 years for ESP and no more than 1 year for a COL that references an ESP and DC rule (i.e., for a certified design).

DOE should cooperate with industry and NRC to achieve these timing goals in a manner that encourages utility investment and development of applications for submittal to NRC as quickly as possible. In order to achieve that response by multiple utilities for multiple nuclear projects, DOE and Congress should agree to provide cost-share support for a sufficient number of ESP and COL applications to demonstrate and establish confidence in these processes for a range of likely scenarios.

The level of Federal commitment to a cost-shared program that is needed to create a sustained and self-supporting industry process of utility applications for new plant licensing should be as follows:

- Demonstrate NRC's ESP process for a range of likely siting scenarios by providing DOE cost share support for at least two "lead site" applications, and up to two additional ESP applications (total of four) that demonstrate the ESP process for differing siting scenarios, e.g., existing nuclear sites, a possible "greenfield site," an existing non-nuclear industrial site or a site with an existing nuclear construction permit but no operating nuclear plant. Joint industry-DOE funding for up to four sites is detailed in Chapter II-3 and Appendix J.
- Demonstrate NRC's COL process for a range of likely licensing scenarios by providing DOE cost share for the first COL application for each near term design that is supported in Phases 2 and 3, including both the first COL application for each certified design, and the first COL application for each uncertified design where the applicant chooses to submit an early COL application. DOE funding would only be requested for those NTD designs that actually garner sufficient market interest to proceed with adequate industry resources to complete the COL process.

C. Generic guidance must be developed to ensure efficient, safety-focused implementation of key Part 52 processes, including ESP, COL and ITAAC verification

The industry and NRC should work to provide generic guidance to COL applicants on COL application form and content, COL review processes, and the ITAAC verification process. NRC should also work with industry to ensure that process guidelines are reflected in the NRC's revised Construction Inspection Program. These efforts should ensure safety focused and efficient processes.

D. In parallel with the above, an overall risk-informed, performance-based regulatory framework should be established for future plants as the basis for NRC design review, licensing and oversight of future plants.

To increase investor confidence in predictable licensing and stable, efficient regulation, progress is needed toward a new regulatory framework for future plants. This effort would go beyond the ongoing efforts to risk-inform 10 CFR Part 50 for current plants to establish a new regulatory framework that is fully risk-informed and performance-based. This effort promises to enhance the protection of the public health and safety by maximizing the safety focus and efficiency of future plant licensing and regulation. This will be a long term effort, with benefits accruing as various parts of the framework are completed and judged "ready for use" by applicants. Equally important is that progress toward a new regulatory framework will increase the confidence of prospective applicants in the regulatory environment for new plants and encourage business decisions to proceed with new nuclear projects

For all the above efforts addressing Gap #4, the lead responsibility for resolution should be NEI, representing the industry and working with prospective applicants and the NRC. Support should be provided by DOE, individual applicants, and EPRI, per the resource requirements listed in Chapter II-3.

Gap 4: Nuclear Industry Infrastructure

Industry and Government should focus attention on both aspects of nuclear energy infrastructure that require reinvigoration:

- Fabrication and manufacturing infrastructure, including major components such as reactor vessels and steam generators, as well as smaller components such as pumps and valves.
- Next generation of scientists, engineers and technicians required to design, build and operate nuclear power plants.

Although these areas are not prepared today to support a large expansion of nuclear energy, they will likely grow as the expansion grows, through the natural process of supply and demand. So to a significant degree, most infrastructure gaps today will take care of themselves. However, longer lead-time issues related to qualified personnel and U.S. fabrication capacity warrant examination to see if anticipatory initiatives are needed to expedite preparation for a significant expansion of nuclear energy. It is likely that the most urgent infrastructure gap that must be addressed will be adequate qualified construction crews to support multiple plant projects.

Key initiatives dealing with human resources are already underway at DOE, ANS, and NEI. The DOE/Industry NEER Program for University Nuclear Engineering Departments should be maintained and strengthened. This program has had a major impact in improving the educational infrastructure for supplying nuclear engineers and has allowed the departments to enhance the quality of their programs. NERAC has made recommendations on strengthening educational infrastructure in its Long-Term Nuclear Energy R&D Plan and based on the Blue Ribbon Panel on University nuclear program infrastructure needs. Additionally, the ANS Task Force on Nuclear Workforce has identified human infrastructure needs. Important NEI initiatives on infrastructure are described in Attachment 4.

Industry and Government should cooperate on a study of manufacturing and infrastructure capacity, to determine if foreign suppliers can adequately meet U.S. needs in advance of market-driven domestic expansion of these capabilities.

Gap 5: National Nuclear Energy Strategy

It is vital to the future of nuclear energy and in particular to near term deployment of nuclear energy plants, that the Federal Government take a strong, sustained, and results-oriented stance on nuclear energy as a key component of our energy strategy. The President's National Energy Policy was an important step in that direction, but should be expanded to a more comprehensive National Nuclear Energy Strategy, backed up by specific actions and resources.

A National Nuclear Energy Strategy should:

- Clearly explain to Americans why our national security, economic strength, and environmental quality require – and will benefit from – greater reliance on nuclear energy as a primary source of energy in this country.
- Commit the Federal Government to embracing the nuclear energy industry's Vision 2020, which has as its goal the addition of 50,000 MWe of new nuclear generation by 2020, and the addition of 10,000 additional MWe of nuclear generation from efficiency improvements to current plants. This commitment should engage the Federal Government in assuming responsibility for all actions it could take to make this goal a reality, working closely with industry. Note that many of the specific actions that Government should take were listed above as recommendations to close other gaps.
- In the near term, commit the Federal Government to a nuclear energy supply R&D investment strategy that is in balance with that for other energy supply options. This R&D investment should focus on successful demonstration of untested regulatory processes and cost-sharing generic gap closure and the one-time costs associated with design completion.
- Reaffirm the commitment of the Administration to expedite applications for new plants through the NRC, consistent with safety regulations, as called for in the National Energy Policy.

- Commit DOE to enter into market-driven, public-private partnerships to execute those activities that garner the necessary industry support for cost sharing with DOE. This should include jointly funded efforts with NEI, EPRI, or any industry-wide consortium that is created to advance work of generic benefit to all new plant applicants, as well as design-specific consortia established to complete engineering work on a particular design and share the risks of new plant projects.
- Commit DOE to undertake a stronger leadership role in forging a strong consensus among the relevant DOE Offices, scientific and energy policy leaders, and government contractors, toward an integrated and effective national policy on nuclear fuel cycle issues, focused initially on establishing centralized used fuel management. This consensus should include a feasibility and cost-benefit assessment and subsequent prioritization of the various proposals for longer-term technologies that could further improve the management regime.
- Develop a plan of action to expand this Vision 2020 milestone to greater reliance on nuclear energy in the 2030 to 2050 timeframe, based on further advances in nuclear technology, developed under DOE leadership in partnership with industry.
- Seek broad support from Congress for this National Nuclear Energy Strategy.

At its heart, the case for DOE leadership, including a commitment to action and resources, rests on the premise that the Government has an interest in securing the supply of new emission free electrical generation and should be willing to pay part of the cost of expediting it. The importance of nuclear energy to clean air and carbon abatement has been historically unvalued. Without government support, the new capacity would probably be added eventually, but at a much slower pace that would be consistent with market forces and private financing. This could result in shortages of electricity, and reduced economic growth that would attend the shortages. A delay in deploying economically competitive nuclear plants will lead to substantially increased construction of fossil burning power plants, which will lead to increased emissions of air pollutants and greenhouse gases, as well as increased short-term electricity costs to consumers.

Necessary actions by Government are not limited to those recommended above as elements of a National Nuclear Energy Strategy. All recommendations above to close other gaps involve actions that Government should take on its own or in concert with industry.

Appendix J provides a complete "roll-up" of the funding needs identified in Chapter II-3 for site specific and generic gap closure, and Chapter II-5 for design-specific gap closure. It is important to recognize that the NTDG is not recommending full funding of every design-specific item in that table. Rather, the table should be viewed as a Roadmap for successful deployment of those designs the NTDG recommends be considered for public-private cost sharing as near term deployment options. Not all the designs listed in that table will be able to muster the industry cost-share proposed, and thus would not qualify for the full level of federal funding proposed.

The approach being recommended here is thus a market-driven one – proposing that the federal government support those plant project initiatives that are capable of showing sufficient private sector funding to make the initiative viable and capable of facilitating the deployment goal.

DESIGN-SPECIFIC RECOMMENDATIONS: NEED FOR A DUAL-TRACK STRATEGY

As described in the NTD Action Paper prepared for DOE in May 2001, the NTDG recommends a dual track approach that encourages public-private investment in both of the following tracks:

- ALWRs, including already certified designs and 1000+ MWe passively cooled designs that are power uprates of already certified designs (or substantially complete passive ALWR designs). This approach offers a substantial near-term opportunity to build new plants with low technological and licensing risk.
- Direct cycle high temperature helium-cooled reactors. Besides the ALWR options, there are other advanced reactor designs with near term potential, including designs currently being developed overseas. This NTD Roadmap identifies designs that have the potential to meet U.S. regulatory and U.S. utility requirements for safety and economic performance, and that have clear potential for near term deployment. By collaborating with other interested parties, it should be possible for U.S. companies to invest in these designs and for the NRC to review and certify these designs with a reduced effort. However, it may be necessary for NRC to follow a more flexible regulatory approach – especially, when reactor technologies with less operating or testing experience are being licensed. Such new designs, especially ones requiring prototype demonstration, might first be licensed by a Combined License for the first units, with the Design Certification coming later.

In order to meet the objectives of this Roadmap, both, not just one of these tracks, must be followed. ALWRs are the most likely options for achieving commercial operation in the shortest amount of time. They involve a lower level of investor risk than gas reactors because the technology is largely proven and the licensing path is more predictable. On the other hand, the gas reactors offer significant potential to improve safety and fuel-cycle objectives, and possibly to overcome the economies of scale with their higher efficiency, and improve on nuclear energy economic competitiveness for the future. However, the technology and market risks are considerably higher, suggesting a more aggressive role for the Government in demonstrating the promise of gas-cooled reactor technology.

The primary reason why both tracks are needed to proceed in parallel relates to the marketplace. Both of these tracks support a robust national energy portfolio, i.e., to ensure a secure energy future under a range of market scenarios. Neither industry nor Government can accurately predict the competitive price of electricity a decade or more into the future, or the demand growth, or the degree to which new environmental regulations will shape the power generation business. Perhaps large baseload plants will offer the best match to future markets because of their economies of scale and ability to service large industrial and commercial regions with significant projected demand growth; or perhaps smaller, modular plants will offer the best match to future markets because of their quicker time to market and ability to match load growth in more manageable increments. Because of the uneven progress by individual states toward electricity deregulation, and because of the large variations in regional demand growth in a country as large as the U.S., it is virtually guaranteed that both large and small nuclear options will be needed to match the markets that will exist in different regions of the country. Smaller plants are more likely to be needed for deregulated markets, whereas larger plants might better serve markets that have not been substantially deregulated.

The investment strategy required for these two tracks are different, since the technological and licensing risks are much higher for the two gas-cooled reactors evaluated in this Roadmap, i.e., the PBMR and the GT-MHR. In the case of ALWRs, the key needs are improved economics and going through 10CFR52 process; in the case of PBMR and GT-MHR the key needs are in separate effects tests, fuel and material development to satisfy regulatory and investor needs. Therefore, the NTD Roadmap proposes different approaches for these two tracks:

- For ALWRs that are either certified by NRC now or could complete certification on an expedited basis, the need is for an aggressive strategy to support expedited licensing, project decision, and commercial operation. This approach would consist of industry-led initiatives with government cost-share focused on one-time costs.
- For gas-cooled reactors, the NTDG recommends a similar strategy that could support expedited deployment if regulatory issues are resolved in the near term. If regulatory and/or technical issues emerge that require more study before deployment, then industry and DOE should evaluate the option for a demonstration project. Such a project would have major industry input, but might rely more extensively on government support.

Industry and Government should avoid the temptation to make a premature decision to pick one of these two tracks. There is not enough information to judge whether the second track is capable of delivering on its promise, and new plant deployment cannot be delayed for the amount of time required to determine the technological viability and economic competitiveness potential of gas reactors. Therefore, both tracks should be pursued until the relative merits of both tracks are clear. It may turn out that one track proves superior to the other. A much more likely outcome will be that both tracks prove out well and both have an important place in the marketplace because of their respective advantages in different markets.

This dual track approach is more focused than the design selection process of the 1960s and 70s. In that era, five or six vendors offered a variety of designs that were customized to meet the individual preferences of each utility investor. That process helped explore the advantages and disadvantages of a wide range of designs and design features, but it also led to unnecessary complex and costly engineering, operations, training, and regulatory oversight. In the 1990s, the nation's utilities committed to a strong policy of standardization, in order to optimize design, construction, operations and maintenance. That commitment also benefits the NRC, because it allows standardized processes, reduces the number of unique regulatory analyses and licensing actions, and simplifies the training of NRC staff. This commitment remains in effect today, and will facilitate the formation of consortia of owner-operators that order and construct a given standardized design. The benefits of such consortia include leveraging of initial investments, sharing information to improve performance and safety, and sharing engineering/training costs.

RECOMMENDATIONS FOR A PHASED ACTION PLAN

The recommendations above and the design-specific needs from Chapter II-5 are structured below into a phased approach to better plan and execute those urgent activities that must be undertaken in the next 2-3 years, in order to achieve deployment of new plants by 2010. This phased approach also presents the necessary implementing actions and resource requirements in a manner that better supports industry and Government planning. The basic purpose of phasing is to permit measurement of progress to confirm the value of continued commitment of resources and increasing degrees of industry and DOE investment to achieve deployment.

Three phases are identified below that should be developed further by industry and DOE, as a public-private partnership, into a comprehensive Plan of Action for Near Term Deployment. These phases, particularly Phases 1 and 2 are staggered, i.e., they require significant overlap in order to expedite processes and make most efficient use of resources:

- Phase 1: Regulatory Approvals
- Phase 2: Design Completion
- Phase 3: Construction and Startup

Phase 1 lays the foundation for Phases 2 and 3. It is intentionally structured to ensure a strong basis for realizing the NTD goal of "... making available a range competitive, NRC-certified and/or ready to construct nuclear energy generation options in a range of sizes to meet variations in market need." Since it is not yet clear which NTD options will best match market conditions and regional needs later this decade, it is imperative that generic regulatory process issues are resolved and that regulatory approvals are obtained for an optimum range of siting scenarios and reactor design options. Once this foundation is laid, the market place will judge which options are ready, and which ones best match business plans and investment criteria as they exist 2-3 years from now. Phase 1 is less resource intensive than Phases 2 and 3. However, it must be completed on an expedited basis, and must also be sufficiently robust to support the expected range of market conditions and needs.

Phases 2 and 3 will require substantial investment. Because the one-time costs of design completion are so high, it is likely that industry consortia will form behind those designs that best meet owner/operator specifications, in order to conserve and leverage resources. Federal cost sharing of these focused efforts to complete engineering work will be essential to success.

To deploy these nuclear plant candidates by 2010, a phased plan of action by industry and Government is proposed. This plan completes both the generic regulatory and technical work applicable to and needed by all applicants, and the design specific work needed to deploy NTD designs by 2010, on an industry/DOE cost-shared basis. This phased action plan is focused on the primary gaps to near term deployment: ensuring nuclear plant economic competitiveness and ensuring early and efficient implementation of 10CFR Part 52.

For design specific work, the NTDG believes that a dual track strategy, comprised of public-private investment in both 1000+ MWe ALWRs and 100-300 MWe gas cooled reactors, is essential. The needs of and investment strategy required for these two tracks are different, since the technological and licensing risks are much higher for the gas-cooled reactors evaluated in this

Roadmap. In order to meet the objectives of this Roadmap, it is imperative that both, not just one of these two tracks, be followed.

Phase I: Regulatory Approvals

Objective: Demonstrate and implement the regulatory requirements under 10 CFR 52 that are necessary and urgent prerequisites for NTD applicants, with the following objectives:

- Demonstrate the ESP process for a range of siting scenarios and obtain sufficient early site permits to support industry business plans for new plant orders and construction.
- Obtain design certifications (or FDAs for gas reactors) as needed for those NTD designs to be supported in Phases 2 and 3.
- Develop the necessary generic guidance to ensure the processes to obtain a combined construction and operating license are stable and predictable and efficient. This includes establishing guidance on the form and content of a COL application, developing review guidance, and guidance for the Inspections, Tests, Analyses and Acceptance Criteria (ITAAC) verification and construction inspection programs.
- Obtain on an expedited basis an initial COL for each NTD design to be supported in Phases 2 and 3, in order to demonstrate the process.

Also important to proceed on a best-effort basis, as opportunities to enhance the process and improve investor confidence, are two additional focus areas:

- On a generic basis, make more risk-informed and performance-based the operational requirements within the scope of the COL.
- Establish a risk-informed, performance-based regulatory framework for the above processes.

Schedule: This objective should be met by 2005. Work on the last two items above may take a year or so longer. Since the specific course of action to obtain all necessary regulatory approvals will differ among various sites and designs per industry business plans, it is imperative that the above objectives be developed in greater detail to ensure proper timing and adequate resources. Many of the above objectives must be achieved in 2002 or early 2003 to ensure success. The exception is the new plant regulatory framework, which can proceed as a continuing parallel activity.

Funding: Most of the above activities are to be cost-shared equally by industry and DOE. The total resource requirements (irrespective of funding source) over a four-year period are estimated as follows:

- Generic regulatory tasks (e.g., resolution of generic issues and guidance development for ESP, COL, ITAAC verification, construction inspection, risk-informed regulatory framework): $13M
- ESP Demonstrations for an adequate range of siting scenarios: $30M
- DC completion for designs based on previously certified or NRC-reviewed designs: $30M per design

- COL completion for approved sites and designs: $10M to $15M per application (estimate)
- COL completion for designs that defer design certification and seek NRC design approval via COL (e.g., gas reactors): $100M to $150M (estimate). Note that because this regulatory approval involves substantial engineering work, this funding estimate bridges into Phase 2 activities and could extend beyond the Phase 1 completion schedule above.

Phase II: Design Completion

Objective: Complete the detailed testing, engineering, and planning necessary to permit start of construction, including:

- Detailed design and evaluation, including first-of-a-kind engineering
- Nuclear and component and plant system testing
- Plant materials testing, if needed
- Fuel development and testing, if needed
- Balance of plant/power conversion system testing, if needed

The focus of this phase is on design specific work in support of those designs with sufficient market interest to obtain the necessary private sector investment, contingent on DOE cost-sharing, to proceed to successful completion and deployment.

In order to achieve the NTD goals discussed above, Phase 2 requires a dual track strategy comprised of both ALWR and gas reactor design options, as follows:

ALWR: At least one design must proceed on an expedited basis through design completion sufficient to support plant order and construction, probably on the basis of multiple projects supported by a consortia of owner-operators and other investors for a family of plants. If the resources permit, the ALWR track should consist of both a currently certified design and a design not yet certified but capable of accelerated DC completion based on prior design engineering and NRC review. If resources do not permit both a certified and a non-certified design project, then a market-driven selection should be made by private sector investors.

Gas Reactor: One or both gas reactor designs must proceed through design completion, depending on market interest and available private sector investment to match DOE cost-sharing. Given the level of testing required to confirm regulatory compliance and commercial performance, it is likely that the best path to success would involve a demonstration project, perhaps at a federal facility. DOE and potential private sector investors should evaluate the feasibility, practicality, and desirability of such a project and develop the commercial objectives that should be achieved by such a project. The evaluation should include consideration of siting such a demonstration project on federal land.

Schedule: This objective should be met for both the ALWR and gas reactor tracks by the end of the year 2007, although earlier completion is possible for some design options. The content and cost of the effort differs among the various designs.

Funding: The funding requirements for Phase 2 vary widely, depending on design-specific needs. This work has been completed for one certified design, and significant work has already been completed for some of the uncertified NTD designs. The cost to complete NTD designs that are not yet certified range from roughly $150M to roughly $300M per design. In some cases, private sector investors may be willing to fund design completion at a funding rate significantly above the 50 percent/50 percent-cost share formula applied to Phase 1.

Phase III: Construction and Startup

Objective: Construct, startup, and operate the plants to be economically competitive with alternative power generation options.

Schedule: The plants are to be in commercial operation no later than year-end 2010.

Funding: The private sector will raise the investment necessary to build and operate the plants with the help of environmental credits and other financial incentives of the kind already being applied to alternative generating systems, as discussed below.

Executing the Phased Approach: Aggressive Schedules

This phased approach will be implemented on an aggressive schedule, taking maximum advantage of coordinated efforts by industry consortia (or "family of plant" entities) working together and with Government to achieve earliest possible deployment of each design with sufficient market support to achieve commercial operation.

Measures to achieve aggressive project schedules will include:

- Parallel efforts on regulatory approvals for siting, design approval, and combined license. All of the timelines for NTD designs shown in Chapter II-5 propose significant overlapping of these activities. In many cases, the optimum schedules have been discussed with NEI and/or NRC for feasibility.
- Parallel efforts on Phases 1 and 2, such that detailed engineering work is completed concurrently with (or very soon after) regulatory approvals, in order to support construction start shortly after site permits and COL approvals are in hand. Again, all of the timelines for NTD designs shown in Chapter II-5 propose significant overlapping of these Phase 1 and Phase 2 activities
- Early procurement of many plant components, to ensue timely delivery of long lead-time items (e.g., large vessels), to support completion of detailed engineering, and to support early construction start soon after COL approval.
- Early actions to secure all necessary state and local approvals from all entities as needed. These actions include environmental and other investigations, and preparation and submittal of permit applications.

These aggressive project schedules necessarily require more up-front investment than would be required with more methodical, sequential project planning and execution. As such, projects implemented on aggressive schedules will require innovative business arrangements, such as consortia among designers, constructors, NSSS and major equipment suppliers, and plant owner/operators, with strong and common incentives to successfully build and operate new plants. Such consortia, to be successful, would include multiple future owner/operators, each willing to build one or more plants, which pool resources and expertise behind a chosen design. This enables cost and risk sharing between a broader investor base, and greater benefits from standardization of common engineering and programmatic efforts, state-of-art construction and operational management systems and equipment to optimize the cost and schedule of multiple plant projects. These teams of owner/operators form what industry refers to as "family of plant" organizations.

The government's role in making such projects succeed is very important, and includes the critically important step of cost-sharing the one-time costs associated with the phased approach, as well as providing economic incentives (e.g., federal tax credits) as discussed below, to encourage industry investment.

Alternate Scenarios and Contingencies

It is quite possible that the general assumptions taken in developing this Roadmap, which generally follow the standard assumptions that industry and Government (i.e., Energy Information Agency) use for energy planning, could vary widely. For example, the recent attack on the U.S. by terrorists and the subsequent war on terrorism could place energy resources in the Middle East at risk.

An energy crisis, brought about by problems in the Middle East or elsewhere could stress our fossil energy resources and create increased pressure on U.S. energy consumers to achieve greater energy independence and a higher level of electrification of our nation's commercial, industrial, and transportation infrastructure. Specifically, it is very likely that the nation would shift to higher reliance on electricity and natural gas in the transportation sector, and place greater reliance on coal and nuclear energy in power generation. To accelerate such a shift in energy strategy, the Federal Government might create incentives to support such shifts on an expedited schedule.

If such an need for accelerated nuclear energy plant construction occurred, the NRC would be asked to accelerate licensing procedures as much as possible, consistent with safety requirements. Investment incentives would focus on rapid market response. Design choices for new plants would trend more toward proven technology and choices with very high assurance of rapid deployment with minimum chance of project delays. In such situations, it is likely that designs that are already certified or are near completion of NRC certification would be built. It is also likely that existing nuclear sites would be used for new plant siting, preferably one previously evaluated for the addition of one or more nuclear plants. These strategies would take optimum advantage of existing infrastructure, transmission access, and more rapid site approvals.

Other scenarios should be considered and planned for. They might include wider variations in fossil fuel prices than generally projected, severe delays in NRC licensing of new designs, major shifts in national or global economic conditions, significant changes in trends toward economic deregulation of electricity, and greater prominence of health and safety issues related to fossil fuel consumption. Each of these scenarios present challenges to a national nuclear energy strategy that must remain flexible and ready to respond with a range of options in both design choices and business approaches to building new plants.

PUBLIC-PRIVATE PARTNERSHIPS: IMPLEMENTING A MARKET-DRIVEN APPROACH

Recent events suggest that a more proactive approach to encouraging new nuclear plant projects is in order. First, the National Energy Policy (NEP) was issued in May 2001 under the direction of Vice President Cheney. The NEP seeks a much more active role for nuclear power than previous government positions. Second, President Bush commissioned a National Climate Change Technology Initiative (NCCTI) in June 2001 to seek technological alternatives for addressing possible global climate changes. In particular, Bush directed that nuclear power be considered as one of the NCCTI alternatives for mitigating carbon emissions. A report addressing the capability of nuclear power (and other alternatives) to provide this carbon emission mitigation is due to the President by the end of 2001. Third, the Congress is becoming more aware of the need to pursue a balanced energy strategy that includes new power generation, in addition to conservation, and is generally supportive of the important role nuclear energy can play. These Federal Government directions suggest that national policies may be emerging that could change the driving forces for new nuclear power, at the same time that marketplace forces suggest increasing private sector interest and investment in nuclear energy.

Examples of such national policy considerations are:

- Maintaining or increasing the share of nuclear power in the nation's energy mix to ensure a reliable future energy supply for the US through diversification of energy sources. Maintaining or increasing the share of nuclear power would seem to require a significant increase in the Government's role compared to current or presently planned actions in stimulating the deployment of new nuclear plants at a faster rate than would normally occur from market-driven forces only.
- Achieving energy independence from foreign sources.
- Providing a sure, technologically proven basis for reducing carbon emissions without incurring serious national economic penalties.
- Support of national defense issues such as utilization of the GT-MHR to burn excess weapons grade plutonium as currently being supported by the U.S. Government.
- Maintenance of the lead role of the US in the international nuclear power community to support a strong voice in the future directions of this technology.

In light of these strategic incentives, the Federal Government should encourage investment in new power plant construction. This should be accomplished by federal funding, on a cost-shared basis with industry, the first time costs of new plants that are generic to the entire industry or generic to families of NTD plants.

The one-time costs that DOE and industry should cost share in the design-specific category fall into two overlapping categories:

- One-time costs of Design Certification for near term deployment capable designs (or equivalent costs for licensing application preparation and review for designs that seek NRC approval via COL without a pre-approved DC), along with a small number of design-specific aspects of the COL application that are also site specific (e.g., ultimate heat sink design).
- One-time costs associated with first-time engineering that is generally beyond the scope of DC but essential to completing a firm cost and schedule estimate, essential for investor decisions.

These one-time costs include those needed to close technology gaps identified in Chapter II-5, and summarized in Appendix J.

There is no single, simple strategy for an early start of nuclear construction. Many different activities need to come together with the right timing and resource priority. Broad-based investment on the industry side will be necessary, and Government willingness and commitment to support a market-driven decision process will be required. For these reasons, a phased approach that relies heavily on industry-Government cooperation is proposed.

The Cooperative Agreement

DOE and industry should create a Government/industry partnership to pursue these objectives. Full exercise of this initiative would cover, on a cost-shared basis, most of the one-time generic costs for each family of plants for each design clearly capable of near term deployment, as well as representative siting situations of generic value to the industry. This initiative will require a modest additional federal investment in nuclear energy research and development.

The challenge is to determine how to best structure this initiative in a deregulated marketplace. Ultimately, the industry should establish a partnership with DOE that shares one-time costs in a manner that is responsive to the marketplace. Experience with the ALWR program suggests that the Federal Government, particularly OMB and Congress, will expect some degree of real, hard-dollar private sector cost sharing as an indication of market interest. Exploiting this desire for industry cost-share is the best way to create the market incentives to encourage the designs most likely to be competitive in the marketplace to come forward for DOE cost-share support. In spite of the pressures of deregulation that limit private sector cost-sharing, the closer industry can come to demonstrating its ability to bring together meaningful private sector investment funds, the more likely the Federal Government should be willing to leverage public funds for success.

Again, based on experience with the ALWR program, the NTDG proposes that DOE and industry use a process similar to that used in the early 1990s to select designs for joint funding under the ALWR FOAKE program. Other processes that could facilitate market-driven resource allocation should also be considered. The ALWR process relied upon broad utility participation in a process that identified the necessary R&D, analyses, process development tasks, and engineering work, and sought broad utility participation on a collaborative basis, to cost-share the costs with DOE under a Cooperative Agreement. That process also relied on industry to select those designs most worthy of joint development with DOE through a utility-managed, market-driven voting process among the utility funders, which ensured the best designs proceeded. In the case of the ALWR FOAKE program about 15 utilities participated in selecting the designs for cost-shared R&D. In today's marketplace, the likely utility participants would be less than ten. However, this number is still high enough to obtain multiple independent assessments of the merits of each candidate NTD design, and to obtain the benefits of standardization among owner-operators.

This collaborative model could also be used to select representative siting demonstrations of value to the industry, achieve consensus on strategies for resolution of regulatory process issues, and achieve consensus on operational programs for NRC concurrence, on an industry-wide basis. It could then be used as a springboard to create more design-specific consortia of future owner/operators, suppliers, and other investors to proceed ahead on one or more specific construction projects.

This process would provide DOE with the same high integrity competitive decision process that it did in the early 90s, which satisfied its mandate for unbiased contracting decisions. DOE's Cooperative Agreement stipulated a partnership with an organization that exercised a market-driven voting procedure acceptable to DOE.

Gas Reactor Demonstration Project

The gas reactor track discussed above within the Phased Plan of Action introduces the idea of a gas reactor demonstration project. The need for such a project is not yet clear. If gas reactor regulatory issues are resolved expeditiously, and if technical obstacles are resolved quickly to investor satisfaction, then gas reactors could proceed on a phased approach similar to ALWRs. However, if technical or regulatory issues emerge that require more testing than anticipated today, then an approach that better supports such testing via demonstration should be considered.

The needs of the gas reactor options are different than those of the ALWR options. They need all the industry and Government coordination discussed above, e.g., to facilitate closing generic gaps and to establish consortia and public private partnerships to complete first time engineering. They also need a great deal more development of regulatory criteria and licensing processes to deal with new and unresolved questions, some of which are fundamental to the safety case of the gas reactor (e.g., reliance on unique and highly resilient fuel that could obviate the need for traditional defense-in-depth features like the large pressure-tight containment that surround water reactors). Finally, they will need much more first time and confirmatory testing to benchmark analysis codes and verify licensing assumptions.

These additional needs represent a higher level of project risk and a larger R&D component to deployment, in turn suggesting a greater federal role. More federal resources may be required. More reliance on federal test facilities, such as those located at some national laboratories may be required. If a prototype demonstration is deemed necessary for either licensing or commercial reasons, there may be a benefit to siting that demonstration at a federal site (e.g., national laboratory, native Indian reservation). Most national laboratories already have some facilities to support nuclear operations and could expand those facilities to support a demonstration initiative.

Federal sites also present challenges. For licensing purposes, most federal sites are essentially "greenfield sites" or "industrial sites", which require more extensive analysis and licensing work than existing commercial nuclear plant sites. Existing sites already have a complete safety analysis of the site and full emergency planning and security measures in place to NRC standards, as well as transmission right-of-way, switchyard, maintenance and training facilities, and other supporting infrastructure already in place. Further, many federal siting options are not in a region of heavy and growing electricity demand, and thus are not amenable to siting a large plant such as an ALWR. However, since the gas reactors are smaller, they might well fit within the regional electricity market needs of many federal sites. Finally, Federal siting would raise significant legal issues such as jurisdiction and licensing responsibility.

Siting is only one of many questions that must be resolved to proceed with such a demonstration. Even more urgent are regulatory considerations, especially ones that might require an extensive test program (e.g., for fuel performance) that will take years to plan and execute.

Even though greater federal involvement and support may be required for a gas reactor demonstration project relative to an ALWR project, the importance and value of commercial entities leading the effort and ultimately taking responsibility for owning and operating the facility should be recognized. Establishing project objectives that ensure commercial viability is demonstrated, along with technical viability, are also critical to success. For example, demonstration on a federal site should be done under NRC safety and environmental regulations to facilitate commercial application.

Whatever special considerations might be required to facilitate obtaining the commitments to support a gas reactor demonstration, should be provided on a non-discriminatory basis to commercial sites as well. Ultimately the decision on where to site a plant should be made by the primary investors in the project who will operate the plant on a commercial basis, after the demonstration is completed. The Federal Government should consider offering a federal site but should not require it as a condition for proceeding. DOE and industry should make every effort to structure the arrangements for a gas reactor demonstration in a manner that is highly scrutable. Siting decisions should be based on their merits as they relate to licensability, availability of infrastructure, need for power, and many other factors that could effect the success of the project (see industry's recently updated Siting Selection Guide).

DESCRIPTION OF APPENDICES AND ATTACHMENTS

This NTD Roadmap includes twelve Appendices and four Attachments:

Appendices:

A. Design Description, Advanced Boiling Water Reactor (ABWR)
B. Design Description, ESBWR
C. Design Description, SWR 1000
D. Design Description, AP 1000
E. Design Description, AP 600
F. Design Description, International Reactor Innovative and Secure (IRIS)
G. Design Description, Pebble Bed Modular Reactor (PBMR)
H. Design Description, Gas Turbine Modular Helium Reactor (GT-MHR)
I. Cost Sharing Rationale. This appendix provides a more complete rationale for the imperative for a public-private partnership approach to attacking the many challenges facing this nation's energy security in the decade ahead, and specifically the many challenges to facilitating an important role for nuclear energy.
J. Near Term Deployment Roadmap Resource Needs. This table displays proposed tasks and annual funding requirements, along with a short discussion or justification for each task. This table is broken down into broad categories, such as site-specific tasks, generic regulatory and technical needs, and design-specific tasks, and proposes how costs should be allocated between industry and Government.
K. Background and Source Documents. This appendix provides a high level summary of seven key DOE and industry strategic planning documents related to building new plants. It focuses on goals established by these recent documents.
L. Reference List
M. Acronyms

Attachments:

1. Near Term Deployment Group Mission
2. Near Term Deployment Group Request for Information
3. NEI's "Vision 2020" – Strategic Objectives for Nuclear Energy's Future
4. NEI's "Integrated Plan for New Nuclear Plants"

APPENDIX A: DESIGN DESCRIPTION, ADVANCED BOILING WATER REACTOR (ABWR)

ABWR DEVELOPMENT

The ABWR was developed in cooperation with the Tokyo Electric Power Company and Hitachi and Toshiba, GE's long time partners in the development of advanced nuclear technology. The stated purpose of the development effort was to design a BWR plant that included a careful blend of (1) the best features of worldwide operating BWRs, (2) available new technologies, and (3) new modular construction techniques. Safety improvements were the top priority. Anticipating the economic challenges that lay ahead, special attention was paid to systematically reducing the capital cost and incorporating features into the plant design that would make maintenance significantly easier and more efficient.

After more than a decade of test and development the first two ABWRs went into commercial operation in Japan in 1996 and 1997, known as Kashiwazaki-Kariwa Units 6 and 7. They are currently in their fifth cycle of operation.

The ABWR was the first design reviewed and certified by the U.S. Nuclear Regulatory Commission (NRC) under the provisions of Title 10 of the Code of Federal Regulations Part 52 (10CFR52). More recently, the ABWR received regulatory approval in Taiwan and a construction permit for two ABWR units at the Lungmen site was issued in March 1999. The two Taiwan units are currently under construction.

PLANT OVERVIEW

The key design objectives for the ABWR were established during the development program. The key goals, all of which were achieved, are as follows:

- Design life of 60 years.
- Plant availability factor of 87 percent or greater.
- Less than one unplanned scram per year.
- 18 to 24-month refueling interval.
- Reduced calculated core damage frequency by at least a factor of 10 over previous BWRs (goal $<10^{-6}$/yr).
- Radwaste generation <100 m^3/yr.
- 48-month construction schedule.
- 20 percent reduction in capital cost ($/kWh) vs. previous 1100 MWe class BWRs.

SUMMARY OF THE ABWR KEY FEATURES

A comparison of key features of the ABWR to the previous model, known as BWR/6, is shown in Table 1.

Table 1
Comparison of Key ABWR Features to a BWR/6

Feature	ABWR	BWR/6
Recirculation	Vessel mounted reactor internal pumps	Two external loop recirculation system with jet pumps inside RPV
Control Rod Drives	Fine-motion CRDs	Locking piston CRDs
ECCS	3 division ECCS	2 division ECCS plus HPCS
Reactor Vessel	Extensive use of forged rings	Welded plate
Primary Containment	Advanced – compact, inerted	Mark III – large, low pressure, not inerted
Secondary Containment	Reactor Building	Shield, fuel, auxiliary & DG buildings
Control & Instrumentation	Digital, multiplexed, fiber optics, multiple channel	Analog, hardwired, single channel
Control Room	Operator task-based	System-based
Severe Accident Mitigation	Inerting, drywell flooding, containment venting	Not specifically addressed
Reactor Water Cleanup	2 percent, sealless pumps in cold leg	1 percent, pumps in hot leg
Offgas	Passive Offgas with room-temperature charcoal	Active Offgas with chilled charcoal filters

The cutaway rendering of the ABWR plant (Figure 1) illustrates the general configuration of the plant for a single unit site in the U.S.

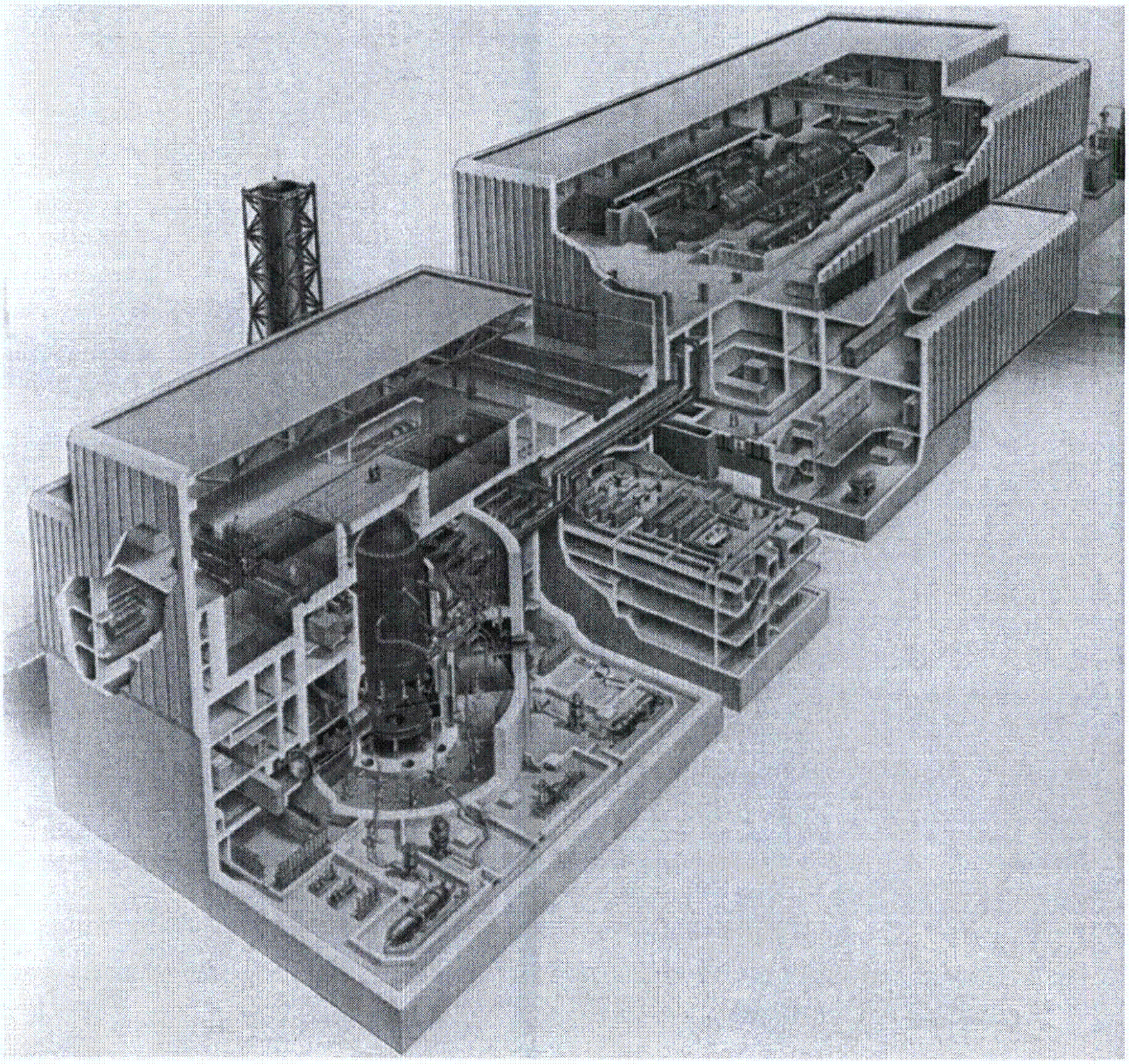


Figure 1

ABWR BUILDING CUTAWAY

Shown in the foreground is the Reactor Building, and in the background is the Turbine Building. Between them is located the Control Building.

An artist's rendering of the major systems and how they are inter-connected is shown in Figure 2. This shows the reactor, ECCS, containment, turbine equipment and the key auxiliary mechanical systems.

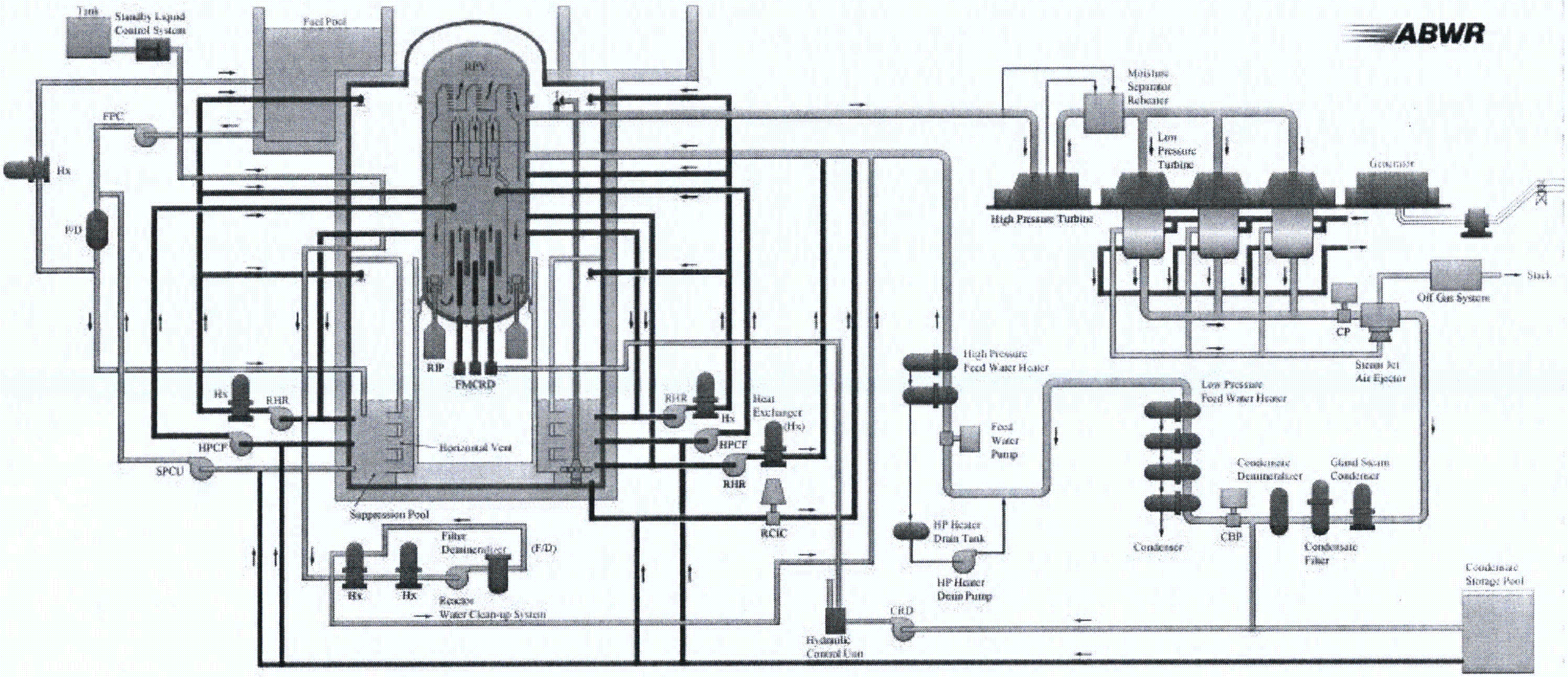


Figure 2. ABWR Major Systems

Safety Enhancement

Recognizing the desire for the continuous enhancement of safety, one of GE's goals for the ABWR was to reduce calculated core damage frequency by an order of magnitude relative to currently operating plants. The most important design feature contributing to this goal is the adoption of reactor internal pumps (RIPs). These vessel-mounted pumps eliminate large, recirculation piping on the vessel, particularly involving penetrations below the top of the core elevation, and make possible a smaller Emergency Core Cooling System (ECCS) network to maintain core coverage during postulated loss-of-coolant events.

The ABWR ECCS network was designed as a full three-division system, with both a high and low pressure injection pump and heat removal capability in each division. For diversity, one of the systems, the Reactor Core Isolation Cooling (RCIC) System, includes a steam-driven, high pressure pump. Transient response was improved by designing three available high-pressure injection systems in addition to feedwater. The adoption of three on-site emergency diesel-generators to support core cooling and heat removal, as well as the addition of an on-site gas turbine-generator, reduces the potential for "station blackout" (SBO). The balanced ECCS system has less reliance on the Automatic Depressurization System (ADS) function, since a single, motor-driven high pressure core flooder (HPCF) can maintain core safety for any postulated pipe break.

Response to anticipated transients without scram (ATWS) is improved by the adoption of fine-motion control rod drives (FMCRDs), which allow reactor shutdown either by hydraulic or electric insertion. In addition, the need for rapid operator action to mitigate an ATWS is avoided by automation of emergency procedures such as feedwater runback and Standby Liquid Control System (SLCS) injection.

Calculated core damage frequency is reduced by more than a factor of ten relative to the BWR/6 design. Furthermore, the ABWR also improved the capability to mitigate severe accidents, even though such events are extremely unlikely. Through nitrogen inerting, containment integrity threats from hydrogen generation were eliminated. Sufficient spreading area in the lower drywell, together with a drywell flooding system, assures coolability of postulated core debris. Manual connections make it possible to use onsite or offsite water systems to maintain core cooling. Finally, to reduce potential offsite consequences, a passive, hard-piped wetwell vent, controlled by rupture disks, is designed to prevent catastrophic containment failure and provide maximum fission product "scrubbing". The result of this design effort is that in the event of a severe accident, the whole body dose consequence at the calculated site boundary is less than 25 Rem. The probability of such an occurrence is calculated at the very low level of 10^{-9}/year.

Improvements to Operation and Maintenance

With the goal of simplifying the utility's burden of operation and maintenance (O&M) tasks, the design of every ABWR electrical and mechanical system, as well as the layout of equipment in the plant, is focused on improved O&M.

The reactor vessel is made of forged rings rather than welded plates. This eliminates 30 percent of the welds from the core beltline region, for which periodic in-service inspection is required. Since there are ten RIPs on four power buses, the ABWR's recirculation system is quite robust. Pump speed is controlled by solid-state adjustable speed drives, eliminating the requirement for flow control valves and low-speed motor-generator sets. The wet motor design also eliminates rotating seals.

The FMCRDs permit a number of simplifications. First, scram discharge piping and scram discharge volumes (SDVs) were eliminated, since the hydraulic scram water is discharged into the reactor vessel. By supporting the drives directly from the core plate, shootout steel located below the reactor vessel to mitigate the rod ejection accident was eliminated. The number of hydraulic control units (HCUs) was reduced by connecting two drives to each HCU. The number of rods per gang was increased up to 26 rods, greatly improving reactor startup times. Finally, since there are no organic seals, only two or three drives will be inspected per outage, rather than the 30 specified in most current plants.

It was possible to significantly downsize ECCS equipment as a result of eliminating large vessel nozzles below the top of the core. Capacity requirements are sized based on operating requirements—transient response and shutdown cooling—rather than on the need for large reflood capability. Inside the reactor vessel, core spray spargers were eliminated, since no postulated LOCA would lead to core uncovery. For transient response, the initiation water levels for RCIC and HPCF were separated so that there is reduced duty on the equipment relative to earlier BWRs. There are three complete shutdown cooling loops, including dedicated vessel nozzles. Complex operating modes of the Residual Heat Removal (RHR) Systems, such as steam condensing, were eliminated. Finally, heat removal, in addition to core injection, was automated so that the operator no longer needs to choose which mode to perform during transients and accidents.

Lessons learned from operating experience were applied to the selection of ABWR materials. Stainless steel materials which qualified as resistant to intergranular stress corrosion cracking (IGSCC) were used. In areas of high neutron flux, materials were also specially selected for resistance to irradiation-assisted stress corrosion cracking (IASCC). Hydrogen Water Chemistry (HWC) is recommended for normal operation to further mitigate any potential for stress corrosion cracking. The use of material producing radioactive cobalt was minimized. The condenser uses titanium tubing at sea water sites and stainless steel tubing for cooling tower sites. The use of stainless steel in applications that currently use carbon steel was expanded. These materials choices reduce plant-wide radiation levels and radwaste and will accommodate more stringent water chemistry requirements.

Also contributing to good reactor water chemistry is the increase of the Reactor Water Cleanup System (RWCU) capacity to two percent.

The Offgas System was simplified, reflecting lessons learned from operating experience. The charcoal beds are maintained at ambient temperature rather than refrigerated. The desiccant drier was eliminated.

The ABWR Reactor Building (including containment) was configured to simplify and reduce the O&M burden. The containment itself is a reinforced concrete containment vessel (RCCV). Within the containment itself, no equipment requires servicing during plant operation. The containment is significantly smaller than that of the preceding BWR/6. However, primarily due to the elimination of the external recirculation system, there is actually more room to conduct maintenance operations. To simplify maintenance and surveillance during scheduled outages, permanently installed monorails and platforms permit 360° access, and both the upper and lower drywells have separate personnel and equipment hatches. To simplify RIP and FMCRD maintenance, a rotating platform is permanently installed in the lower drywell, and semi-automated equipment was specially designed to remove and install that equipment. The wetwell area is compact and isolated from the rest of containment, thus minimizing the chance for suppression pool contamination with foreign material.

A new Reactor Building design surrounds the containment and incorporates the same functions as the BWR/6 auxiliary, fuel and diesel-generator buildings. Its volume (including containment) is about 30 percent less than that of the BWR/6 and requires substantially lower construction quantities. Its layout is integrated with the containment, providing 360° access with servicing areas located as close as practical to the equipment requiring regular service. Clean and contaminated zones are well defined and kept separate by limited controlled access. The fuel pool is sized to store at least ten years of spent fuel plus a full core. Therefore, the BWR/6-type fuel transfer system has been eliminated.

Controls and instrumentation were enhanced through incorporation of digital technologies with automated, self-diagnostic features. The use of multiplexing and fiber optic cable has eliminated 1.3 million feet of cabling. Within the safety systems, the adoption of a two-out-of-four trip logic and the fiber optic data links have significantly reduced the number of required nuclear boiler safety system related transmitters. In addition, a three-channel controller architecture was adopted for the primary process control systems to provide system failure tolerance and on-line repair capability. A number of improvements were made to the Neutron Monitoring System (NMS). Fixed wide-range neutron detectors have replaced retractable source and intermediate range monitors. In addition, an automatic, period-based protection system replaced the manual range switches used during startup. The man-machine interface was significantly improved and simplified for the ABWR using advanced technologies such as large, flat-panel displays, touch-screen CRTs and function-oriented keyboards. The number of alarm tiles was reduced by almost a factor of ten. Many operating processes and procedures are automated, with the control room operator performing a confirmatory function.

The plant features discussed above, while simplifying the operator's burden, have an ancillary benefit of increased failure tolerance and/or reduced error rates. Studies show that less than one unplanned scram per year will be experienced with the ABWR. Increased system redundancies will also permit on-line maintenance. Thus, both forced outages and planned maintenance outages will be significantly reduced.

Table 2 provides a summary of the ABWR design parameters.

TABLE 2
ABWR DESIGN PARAMETER SUMMARY

Design Parameter	
Thermal Power	3926 MWt
Electrical Power	1350 MWe (nominal)
Reactor Coolant Pressure	7.17 MPa (1040 psia)
Reactor Coolant Temperature	287° C (549°)
Core Flow Rate	52.2×10^6 kg/hr (115.1×10^6 lb/hr)
Active Fuel Length	3.7 m
Reactor Pressure Vessel Inner Diameter	7.1 m
Number of Fuel Assemblies	872
Number of Control Rod Drives	205

APPENDIX B: DESIGN DESCRIPTION, ESBWR

ESBWR Development

In 1992, GE along with its sponsors at the US Department of Energy (DOE) and several international utilities, designers and research organizations, undertook to design and obtain USNRC design approval for a natural circulation power reactor featuring passive plant safety-systems technology. This effort produced a Standard Safety Analysis Report (SSAR) describing a 670 MWe predecessor to the current ESBWR. Work undertaken by GE with the support of many European nuclear power design firms, nuclear research labs, utility companies and universities in the period since 1994 has taken this predecessor, SBWR-670 nuclear power plant design, to new uprated power levels.

ESBWR Features

The ESBWR plant design relies on the use of natural circulation for the recirculation system and passive safety features to enhance the plant performance and simplify the design. The use of natural circulation has allowed the elimination of several systems. Table 1 shows a comparison of some key plant features for several BWR designs. It shows that the full benefit of natural circulation has been achieved in the ESBWR, allowing the reduction of the number of control blades and control rod drives (CRD's).

Table 1. Comparison of Key Features

Parameter	ABWR	SBWR	ESBWR
Power (MWt)	3926	2000	4000
Power (MWe)	1350	670	1380
Vessel height (m)	21.1	24.5	27.7
Vessel inner diameter (m)	7.1	6.0	7.1
Fuel bundles, number	872	732	1020
Active fuel height (m)	3.7	2.7	3.1
Power density (kw/l)	51	41.5	53.7
Number of CRDs	205	177	121

The ESBWR has evolved over the last seven years from the original 670 MWe SBWR taking advantage of the economies of scale, enhancing the natural circulation core flow, retaining the original passive safety features, but adding to the simplification with enhanced safety and economics in mind. The approach to improving the commercial attractiveness of the ESBWR compared to the SBWR was to follow a multi-pronged approach by:

1) Enhancing the overall plant performance
2) Taking advantage of the modular design of the passive safety systems, and
3) Reducing overall material quantities.

The ESBWR design has achieved a major plant simplification by eliminating the recirculation pumps. The use of natural circulation, along with the desire to maintain the same or better plant performance margins, resulted in the following key design features:

1) Opening the flow path between the downcomer and lower plenum
2) Use of shorter fuel - resulting in a reduced core pressure drop
3) Use of an improved steam separator to reduce pressure drops
4) Use of a 5m chimney to enhance the driving head for natural circulation flow

The selection of the optimum power level was based on the desire to utilize the synergism between the ABWR and the ESBWR and to utilize existing design and technology from the ABWR - like using the same diameter pressure vessel. With this constraint, the SBWR core circumscribed diameter was increased, using the ABWR vessel diameter and leaving approximately the same size annulus as the earlier SBWR. The ESBWR core was then increased in size by adding fuel bundles to accommodate this increased diameter. The core was increased from 732 fuel assemblies, in the SBWR, to 1020 fuel assemblies, resulting in an optimum thermal power rating of 4000 MWt. The selected power for the ESBWR would have required the addition of 400 fuel assemblies and 92 control rod drives (CRD) compared to the SBWR. However, the use of a new core lattice design reduced the number of CRDs from 269 to 121, better than a 50 percent reduction and 56 fewer drives than the original SBWR.

Plant Safety Systems

The ESBWR safety system design was extended to a higher power level by taking advantage of the modular design approach of the safety systems. The isolation condensers and the passive containment decay heat removal system, utilize simple heat exchangers. Any increase in power level only requires additional heat exchangers or tubes. The Gravity Driven Cooling System (GDCS), is not sensitive to power level and its capacity is primarily determined by containment geometrical considerations.

High and Low Pressure Inventory Control

The ESBWR uses isolation condensers for high pressure inventory control and decay heat removal under isolated conditions. The isolation condenser system has four independent high pressure loops, each containing a heat exchanger that condenses steam on the tube side. The tubes are in a large pool, outside the containment. The steam line connected to the vessel is normally open and the condensate return line is normally closed. The four units are the same size as those previously tested for the SBWR.

The reactor vessel is depressurized rapidly to allow multiple sources of safety and non-safety systems to provide water makeup. Typically in a BWR, rapid depressurization only results in the loss of half the reactor inventory, allowing the core to remain covered. Consequently, any makeup system has only to provide a slow water makeup to account for loss of inventory resulting from boil-off by decay heat. For the ESBWR, the makeup water flows into the vessel by gravity (GDCS), instead of relying on pumps and their associated support systems. The ESBWR uses the Automatic Depressurization System (ADS) to depressurize the vessel. The GDCS pool capacity is primarily determined by containment geometrical considerations. The vessel diameter was increased to 7.1m resulting in an increase of the lower drywell volume, consequently the GDCS pool volume increased by approximately 200 m^3.

Containment Heat Removal

Containment heat removal is provided by the Passive Containment Cooling System (PCCS), consisting of four safety-related low-pressure loops. Each loop consists of a heat exchanger open to the containment, a condensate drain line and a vent discharge line submerged in the suppression pool. The four heat exchangers, similar in design to the isolation condensers, are located in cooling pools external to the containment. The heat exchanger unit is only about 35 percent larger than the as-tested PCCS unit. Figure 1 shows a combined sketch of the safety systems.

BUILDINGS AND STRUCTURES

The ESBWR Reactor Building has been considerably simplified and reduced in volume, through use of passive systems. The primary safety-grade inventory control system - the isolation condenser - is a simple heat exchanger. The backup low-pressure inventory control system - the gravity driven cooling system (GDCS) - is a fairly small pool of water. The passive containment decay heat removal system consists of modular heat exchangers, requiring no moving parts or valves. Most of the safety systems are now either in the containment or directly above it.

Any other systems in the plant are either non-safety grade or fairly small. This allows a significant reduction of the overall building volumes, especially for the expensive safety category buildings. A reduction of the reactor building volume and footprint has the added benefit of reducing the size of the building which is on the critical path for construction.

The plant design has some added features that allow it to be very flexible in siting at different locations. The design is reasonably robust to account for evolving severe accident requirements by different safety authorities. The design of the plant structures allows application to different seismic requirements. The main access to the building and fuel cask transfer hatch, allow different building embedments - for different site conditions and seismic levels. The main control building location is flexible enough to accommodate differing requirements.

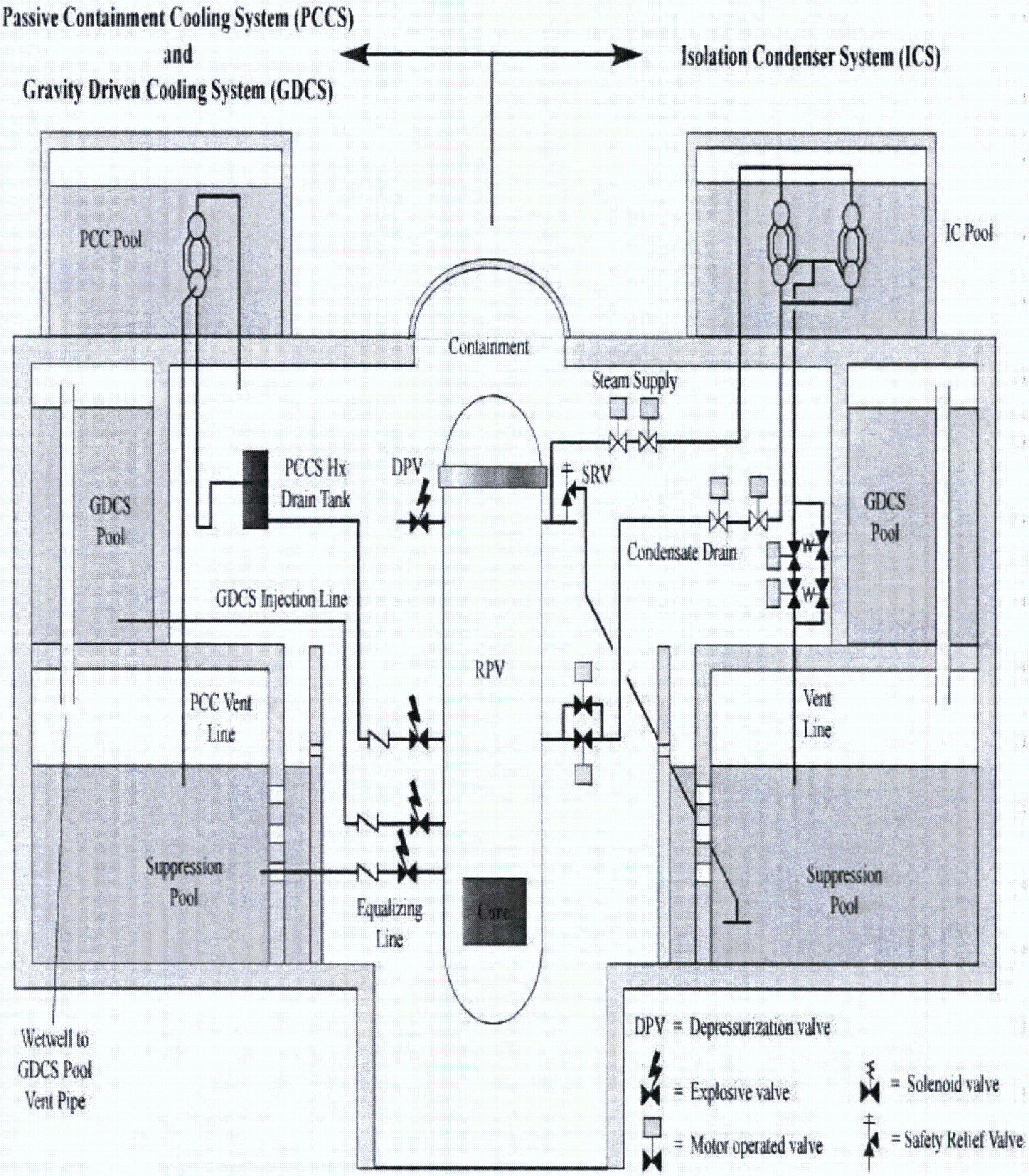


Figure 1. Schematic Diagram of ESBWR Safety Systems

PLANT PERFORMANCE

The key design features described above, along with the use of the latest fuel designs, result in a substantial enhancement of the overall plant performance, as summarized in Table 2.

Table 2
Comparison of Performance for Various BWRs

Performance Parameter	Typical BWRs	SBWR	ESBWR
Average natural circulation flow per bundle [kg/s]	3.5 - 5.0	8.5	12.0
Power/Flow ratio at rated conditions [MW/(kg/s)]	0.25	0.31	0.26
Pressurization rate during fast transients [MPa/s]	0.8	0.4	0.4
Margin to SRV set point during fast isolation event [MPa]	SRV opens	0.52	0.32
Minimum water level following accident [m above fuel]	0.0 *	1.5	2.8
Post accident containment pressure margin [kPa below design]	40	100	160

* For internal pump plant, for jet pump plant value is -2m

This table shows that the use of natural circulation significantly improved several key performance parameters, while keeping others within the same range as those for forced circulation plants. Additionally, certain design changes made for the ESBWR, allowed the increase in power level from the SBWR without a decrease in margins - in some cases margins actually increased.

a. The higher average flow per bundle in the SBWR and ESBWR, is due to the unrestricted downcomer and shorter core. The increased flow from SBWR to ESBWR is due to a longer chimney and improved separator configuration.

b. In general, a reactor is more stable with a lower power/flow ratio. The ESBWR power/flow ratio is comparable to the operating BWRs at rated conditions. This is because the power per bundle is lower for the ESBWR and the natural circulation flow has been enhanced, as described above.

c. Slower pressurization rates in ESBWR and SBWR, are due to the large steam volume in the chimney and the use of Isolation Condensers (IC). Because of the slower pressurization rate and the use of IC's, there is adequate margin to prevent any Safety Relief Valves (SRV) from opening.

d. Due to larger vessels for the ESBWR and SBWR, the water level always covers the core following an accident.

e. The increase in containment pressure margin from SBWR to ESBWR is due to the relocation of the GDCS pool from the drywell to the wetwell.

The major advantage of the increased margins is the added flexibility the plant design gives the plant operator. These margins can be utilized to optimize fuel management or to modify plant features for individual utility needs without an increase in costs.

Figure 2 shows the major systems for the overall ESBWR plant.

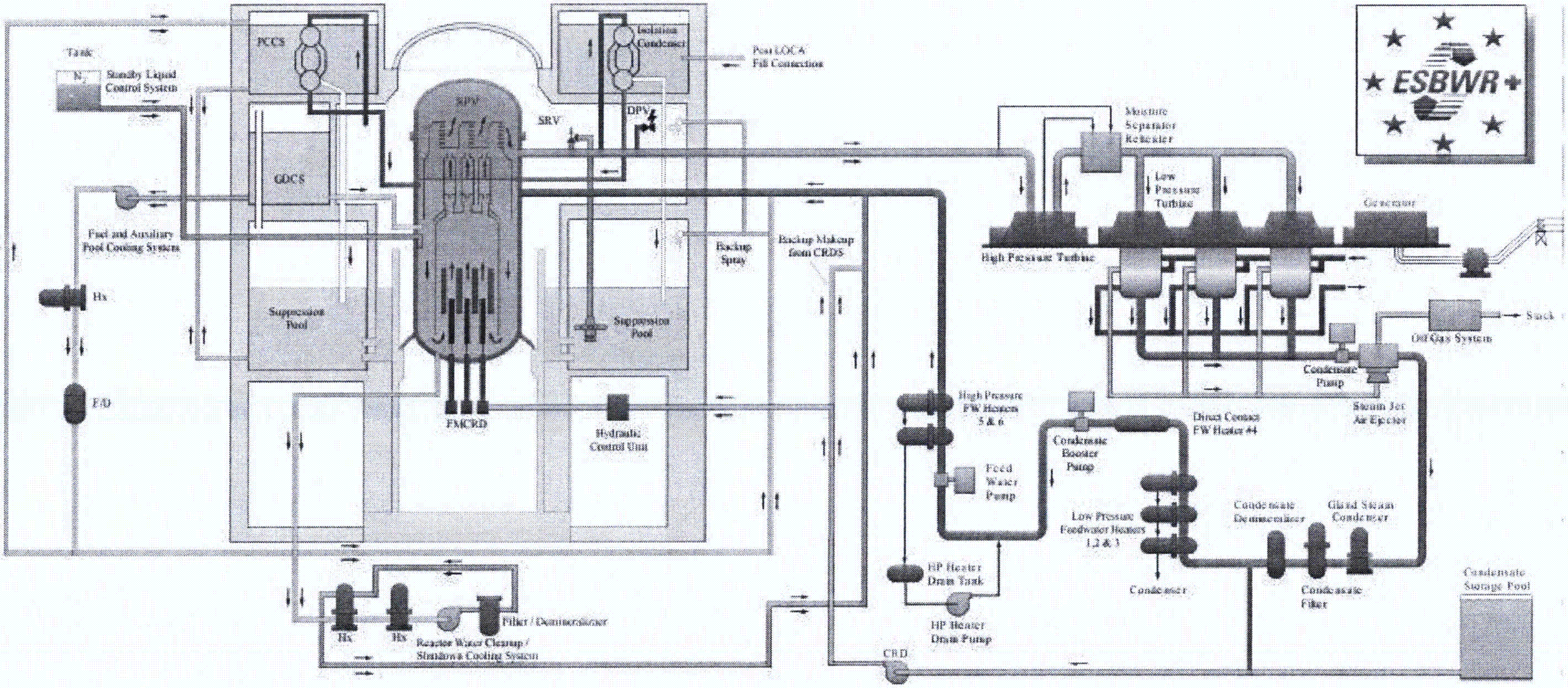


Figure2. ESBWR Major Systems

APPENDIX C: DESIGN DESCRIPTION, SWR 1000

INTRODUCTION

Framatome Advanced Nuclear Power (F-ANP) has developed a medium-capacity (approximately 1000 MW_e) boiling water reactor (SWR 1000) in conjunction with German electric utilities, with the support of European partners. This project is based on experience gained from the operation of proven BWR plants. However, evolutionary development is supplemented by an innovative approach, which entails partly replacing the active safety systems with passive safety features. The passive safety systems utilize basic laws of physics such as gravity, for example, enabling these systems to function without electrical power supply or actuation by instrumentation and control (I&C) systems. In this way, evolutionary developments are supplemented by innovative concepts, which provide enhanced safety benefits.

The SWR 1000 was developed on the basis of the relevant requirements set forth in Germany's nuclear codes and standards, while taking into consideration the recommendations proposed by the French and German reactor safety commissions for the EPR (European Pressurized Water Reactor).

Development at Siemens (now F-ANP) of a new BWR plant concept with an approximate capacity rating of 650 MW began in early 1992. This concept phase was completed in the fall of 1993, while the subsequent consolidation phase reached completion by mid-1995. The following four-year design phase of the SWR 1000, carried out in consultation with the German Reactor Safety Commission (RSK), was completed in 1999. The design phase was concluded with the release of a site-independent safety analyses report, a probabilistic safety analysis report and an analysis of projected erection costs.

In parallel with the design phase, an experimental testing program was conducted at F-ANP's own testing facilities and at other German and European research centers to provide verification of the function and effectiveness of the SWR 1000's passive safety systems.

DESIGN GOALS

a.) High Safety Standards

The high safety standard of current nuclear power plants is based, among other factors, on a very reliable and correspondingly complex system of redundant active safety equipment. However, achieving this safety standard entails high investment costs and considerable expenditure for operation and maintenance in terms of both personnel and equipment.

The driving force behind this further development was therefore the search for alternative concepts for enhancing the safety of future nuclear power plants by simpler means.

To achieve this goal, the following requirements were defined for the safety concept:

- Clear and simple systems engineering through consistent use of passive safety equipment
- Increased safety margins
- Good accident control behavior through slower reaction to off-normal conditions
- Increased grace periods (up to several days) after the onset of accident conditions before active intervention by operating personnel is required
- Effect of human error on reactor safety is minimized or avoided entirely
- Much lower probabilities of occurrence for serious accidents with core melt than in present designs
- Compliance with the requirements governing the control of core melt accidents set forth in the July 1994 amendment to the German Atomic Energy Act. This means limiting the effects of a core melt accident to the plant itself, i.e. eliminating the need for emergency-response actions with far-reaching effects such as temporary evacuation or permanent relocation of the local population.
- Optimum Availability
- Application of the wide range of experience gained from plants currently in service by making extensive use of systems and components that have proven themselves in operation.
- Optimization of these systems on the basis of well established operating experience.
- Economic Competitiveness

Future nuclear power plants can only be economically competitive if power-generation costs (i.e. investment costs plus operating, maintenance and decommissioning costs) are no higher than those for BWR and PWR plants of evolutionary designs or for fossil-fired power plants (e.g. coal- or gas-fired units).

Cost reductions are achieved by introducing passive safety equipment and cost savings to almost all plant areas (e.g. systems, components, electrical and I&C equipment and civil structures) are feasible by utilizing one type of component for multiple tasks. This allows equipment standardization. As a result the need to comply with more stringent safety requirements is achieved while competitive electrical generating costs are obtained.

d.) Public Acceptance

- Improvement of public acceptance of nuclear power generation through the use of simple, understandable safety technology and verification of control of serious accidents.

SWR 1000 BASIC DESIGN FEATURES

The key design features of the concept are as follows:

- Reactor core with low power density
- Large water inventory inside the reactor pressure vessel (RPV) to ensure good thermal-hydraulic behavior in the event of an accident, i.e. excellent slow-acting accident control capabilities
- Control of transients without coolant makeup in the RPV from an external source
- Large heat storage capacity inside the containment thanks to large water inventories in the core flooding pool and the pressure suppression pool
- Passive equipment for heat removal from the RPV and containment
- Large flooding water inventory available inside the containment for discharge by gravity flow into the RPV following depressurization
- Passive actuation of key safety functions such as reactor scram, pressure relief and depressurization as a diverse means to actuation by the safety I&C
- Passive accident control without power supply, actuation by I&C systems or intervention by operating personnel in the initial days following the onset of accident conditions, and subsequent unlimited heat removal via simple active measures
- Nitrogen-inerted containment atmosphere to preclude hydrogen combustion and hydrogen reactions inside the containment in the event of a serious core melt accident
- Extended containment pressure load-bearing capacity to accommodate the quantity of hydrogen arising from 100 percent zirconium oxidation in the event of a serious accident
- Passive cooling of the RPV exterior in the event of core melt scenarios to ensure retention of the core melt inside the RPV
- Flexible operating cycle length (1 to 2 years) with a mean discharge burnup of up to 65 GWd/t
- High plant availability (> 87 percent/a) thanks to short plant downtimes for refueling, maintenance and servicing
- 48-month plant construction period
- 60-year plant service life.

PLANT DESCRIPTION

The systems and components are arranged inside the various plant buildings and structures (Fig. 1), creating three delineated structural complexes, which enables the buildings to be constructed in a parallel time frame. The structural complex at the center of the plant comprises the reactor building, the turbine building and the reactor auxiliary building. The second complex contains the switchgear equipment, the systems for radioactive waste treatment and storage, the hot workshop, staff amenities and the entrance to the controlled access area. The third structural complex consists of the plant service systems such as the circulating water supply systems, the emergency diesel generators, the workshops and the demineralized water system, etc. The first complex is fixed together while the other buildings and systems can be adapted to a specific site.

The plant (Fig. 2) is equipped with a boiling water reactor to generate steam at a thermal output of 2778 MW. The saturated steam produced, which has a pressure of 71 bar, is used to drive a steam turbine which in turn drives a generator, supplying a gross electrical output of 1013 MWe. The steam leaving the low pressure turbine sections is condensed into water in the turbine condensers. This condensate is returned to the reactor by condensate and feedwater pumps via a reactor water cleanup system and a feedwater heating train.

Figure 1 – Site Layout and View into the SWR 1000 Reactor Building

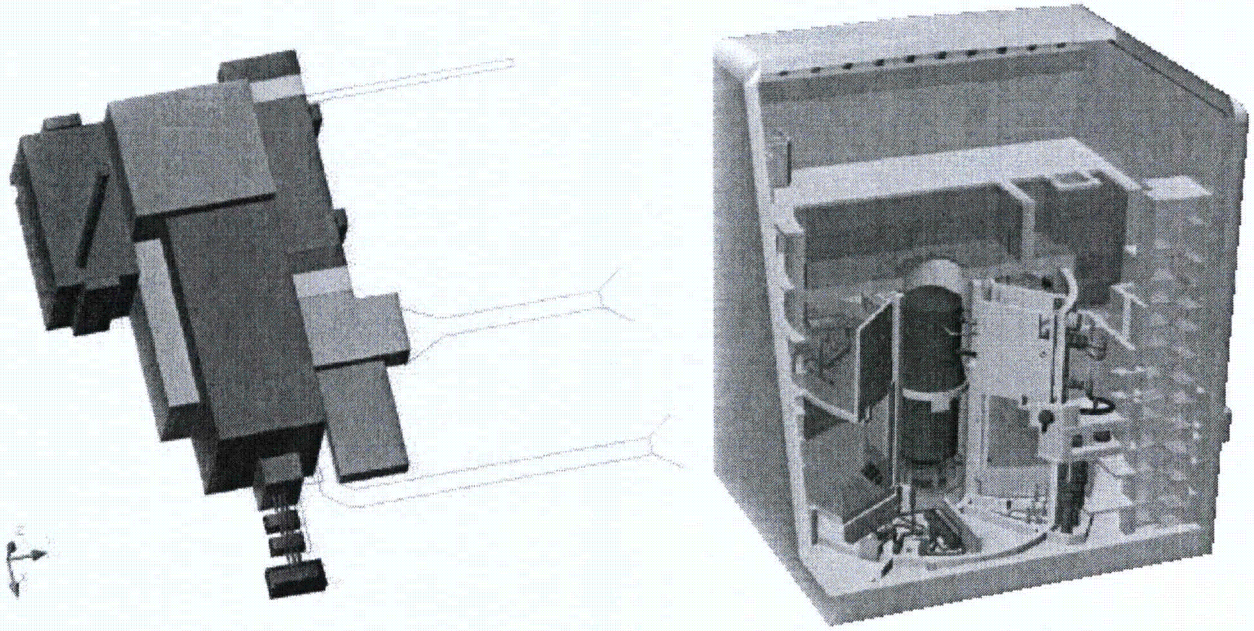


Figure 2 - Power Generation Cycle

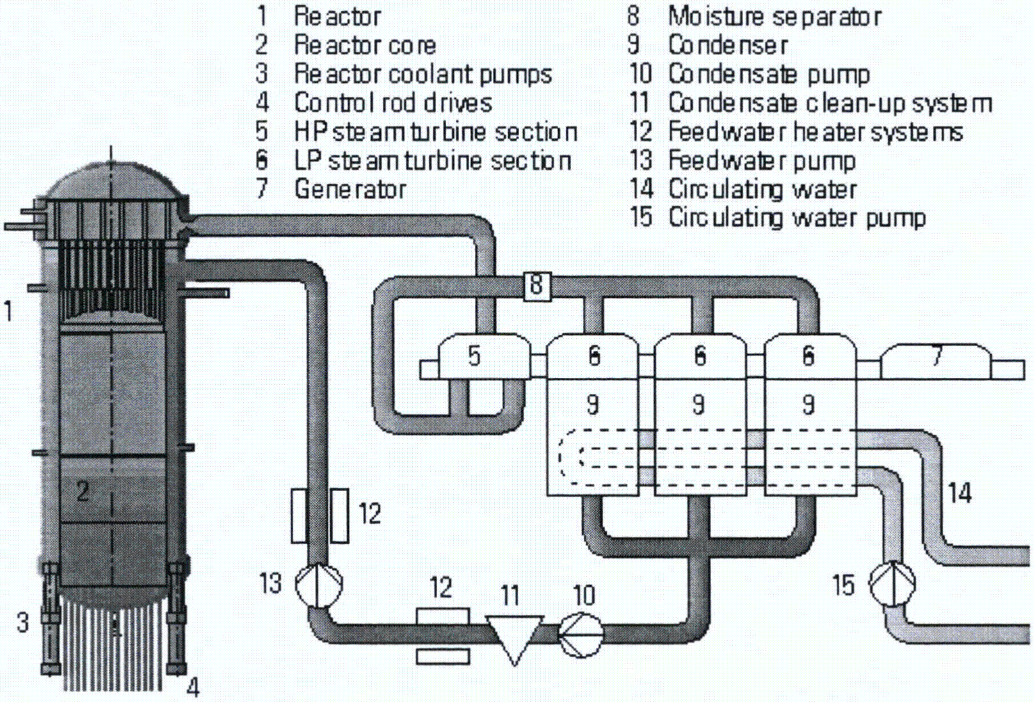


Table 1 – Design Parameters

Data		SWR 1000
Overall plant		
- thermal output	MW	2778
- gross electric output	MW	1013
- net electric output	MW	977
- net efficiency	percent	35.2
Reactor core		
- No. of fuel assemblies	-	624 (12x12)
- Total uranium weight	t	119
- Active height of core	m	2.80
- Average power density	kW/l	48.8
- Average discharge burnup	GWd/t	65
- Core throughput	gpm	200000
- Coolant Pressure	psi	1030
- Coolant Temperature	°F	547
Reactor pressure vessel		
- Inside height	ft	76
- Inside diameter	ft	23
- Design pressure	psi	1276
- No. of recirculation pumps	-	6

Data		SWR 1000
Turbine		
- Number	-	1
- Speed	rpm	1800/3600
- No. of HP/LP casings	-	1/3
Containment		
- Inside diameter	ft	105
- Inside height	ft	94
- Design pressure (abs.)	psi	109
- Drywell volume + gas volume of core flooding pool	ft^3	201000
- Water volume of pressure suppression pool	ft^3	102000
- Gas volume of pressure suppression pool	ft^3	194000
- Water volume of core flooding pool	ft^3	109000
- Plant design life	years	60
- Plant construction period	months	48

APPENDIX D: DESIGN DESCRIPTION, AP 1000

The AP1000 is a two-loop, 1000 MWe pressurized water reactor (PWR) with passive safety features and extensive plant simplifications to enhance the construction, operation, and maintenance. The AP1000 design is derived directly from the AP600, a two-loop, 600 MWe PWR. The AP600 uses proven technology, which builds on the over 30 years of operating PWR experience. The AP600 design received Final Design Approval from the U.S. NRC in September 1998 and Design Certification in December 1999. The AP600 meets all of the U.S. electric utility requirements including their cost goals. Although the AP600 is the most cost-effective plant ready for deployment, it is still more expensive than the $1000/kw needed to compete in the United States today. In order to develop a cost competitive nuclear power plant Westinghouse has completed design studies which demonstrate that it is feasible to increase the power output of the AP600 to at least 1000 MWe, maintaining its current design configuration, use of proven components and licensing basis. In order to achieve these objectives the AP1000 has been designed within the space constraints of the AP600, while retaining the credibility of proven components and substantial safety margins. This paper describes the changes made to uprate the AP600 and gives an overview of the plant design. It also summarizes the basis for the AP600 testing program and computer codes being sufficient for the AP1000.

The United States Nuclear Regulatory Commission issued Design Certification of the AP600 standard nuclear reactor design in December of 1999. This culminated a 7-year, 110 man-year, and review of the AP600 design, safety analysis and probabilistic risk assessment. The AP600 is a 600 MWe reactor that utilizes passive safety features that, once actuated, depend only on natural forces such as gravity and natural circulation to perform all required safety functions. These passive safety systems result in increased plant safety and have also significantly simplified plant systems and equipment, resulting in simplified plant operation and maintenance. The AP600 meets NRC deterministic safety criteria and probabilistic risk criteria with large margins. The Westinghouse computer codes used to analyze the AP600 were validated against the extensive AP600 test program in accordance with U.S. NRC procedures.

The AP600 meets the EPRI ALWR Utility Requirements including the cost goals. The overnight capital cost for the first AP600 plant is calculated to be between 1300-1500 $/kW depending on the site selected. Although the AP600 is the most cost effective nuclear power plant ready for deployment, it is still more expensive than the $1000/kw needed to compete in the United States today. In order to develop a cost competitive nuclear power plant Westinghouse has completed design studies which demonstrate that it is feasible to increase the power output of the AP600 to at least 1000 MWe, maintaining its current design configuration, use of proven components and licensing basis.

The approach to achieving these objectives is to design the AP1000 within the space constraints of the AP600, while retaining the credibility of proven components and substantial safety margins. The arrangement of the reactor, the passive safety systems and the auxiliary systems is the same as the AP600. To increase the output of the reactor, the core, reactor coolant pumps and steam generators have been increased in size. The design of these larger reactor components are based on components that are used in operating PWRs or have been developed / tested for new PWRs. In order to maintain adequate safety margins, the capacity of the passive safety features have been selectively increased based on insights from the AP600 test and analysis results. Figure 1 shows a section view of the AP1000 and AP600 containments; Figure 2 shows a plan view.

The AP1000 is being designed to meet NRC regulatory criteria in a similar manner to that found to be acceptable for the AP600. The AP1000 is being designed to meet NRC deterministic safety criteria and probabilistic risk criteria with large margins. Westinghouse intends to certify the AP1000 standard plant design under the provisions of 10 CFR Part 52. Preliminary pre-application discussions with the NRC began in 2000.

Some of the high level design characteristics of the AP1000 are as follows:

- Net electrical power is 1090 MWe and nuclear steam supply thermal power is 3415 MWe.
- Rated plant performance is achieved with 10 percent of the SG tubes plugged and with a maximum hot leg temperature of 610°F.
- Safety systems are passive; they provide core and containment cooling for a protracted time without ac power and require no operator actions for 72 hours.
- PRA performance is predicted to be similar to AP600 and well within NRC goals. Core damage frequency of AP600 is 1.7E-7/yr vs. NRC goal 1E-4/yr and large release frequency is 1.8E-8/yr vs. NRC goal of 1E-6/yr.
- Occupational radiation exposure is expected to be below 0.7 man-Sv/yr.
- Overall plant availability is expected to be greater than 93 percent, including forced and planned outages. Less than 1 reactor trip is expected per year.
- The plant is designed to accept a 100 percent load rejection without reactor trip.
- The plant is designed to be simple to construct, operate and maintain with significantly fewer safety and non-safety components, simpler components, and better materials than a currently operating PWR.
- The plant design life is 60 years without the replacement of the reactor vessel. The design provides for the replaceability of other major components, including the SG.
- The design of the major components used for power generation (fuel, internals, SG, reactor coolant pumps, turbine, etc) is based on equipment that has successfully operated in power plants. Modifications to these proven designs were based on similar equipment that had successful operating experience in similar or more severe conditions.

AP1000 Major Reactor Components

The major differences in the AP1000 core design compared to the AP600 core design are the addition of 12 fuel assemblies, an increase in the length of the fuel assemblies, and additional control assemblies. The extra assemblies and increase in length along with an increase in the linear power density in the core enabled the core power rating to be increased from 1,933 MWt to 3,400 MWt within the same diameter reactor vessel. The number of rod control cluster was increased to 53 in the AP1000 compared to 45 in the AP600. The AP1000 core also incorporates the Westinghouse ROBUST fuel assembly design compared to the Vantage 5-H design of the AP600. The ROBUST design includes guide tubes with increased wall thickness.

The AP1000 core is based on core designs in operation today. The core active fuel length is 14 feet, similar to the XL core designs in operation in South Texas, Doel4 and Tihange3. The linear power density of the AP1000 core is approximately the same as the operating fleet of 3-loop Westinghouse plants. The AP1000 reactor vessel has the same overall diameter and number and size of nozzles as the AP600 vessel. The overall length of the AP1000 vessel has been increased to accommodate the increase in core length to 14 feet. The AP1000 reactor vessel internals are of the same design as the AP600 vessel internals except that the length of the lower internals has increased because of the longer core design. Also, the thickness of the lower support plate has increased to accommodate the heavier AP1000 core which has both additional fuel assemblies (12) and heavier assemblies due to the longer length.

The AP1000 integrated head package design is the same as that of the AP600 except that the overall height has increased to accommodate the longer control rod drives and incore components required for the 14-foot AP1000 core. Internally, the AP1000 integrated head package also accommodates an additional eight control rod assemblies.

The AP1000 steam generators incorporate very similar features. Both units are vertical-shell U-tube evaporators with a triangular pitch tube bundle and integral moisture separating equipment. They both use Inconel-690 thermally treated tube material. To accommodate the higher thermal output of the AP1000 more heat transfer surface is required, thus increasing the shell diameter and height to enclose the larger tube bundle and larger moisture separation equipment required for the higher steam flow. The mass of water stored in the secondary side AP1000 SG has been increased such that it is about 36 percent larger, on a per MWt basis, than that of the AP600 SG. This increased water mass results in a greater heat transfer capability from the reactor coolant system during transients and improves safety margins. Westinghouse has successful experience in building and operating steam generators as large as the AP1000 in a number of plants including Arkansas, San Onofre and Waterford.

The same basic canned-motor pump design is employed in the AP1000 as in the AP600 including the use of a uranium flywheel to provide rotating inertia to extend the flow coastdown. However, the higher thermal power and core power density of the AP1000 requires higher flow and longer coastdown from the AP1000 pumps compared to the AP600 pumps. A variable speed controller was added to the AP1000 pumps to reduce the motor power required when pumping cold reactor coolant. To provide the larger flow rates, the

AP1000 pumps include higher efficiency hydraulics which were scaled down from the Westinghouse APWR reactor coolant pump design. A longer coastdown is obtained in the AP1000 pumps through increased inertia in the flywheel.

The AP1000 pressurizer volume was increased compared to the AP600 to accommodate the larger reactor coolant system volume in the AP1000. This was accomplished by making the AP1000 pressurizer taller while maintaining the same diameter pressurizer as in the AP600. The total volume of the AP1000 pressurizer is 2,100 ft^3 compared to 1,600 ft^3 for the AP600.

The sizes of the AP1000 reactor coolant loop piping are the same as those for the AP600. The elevations of the AP1000 hot and cold legs are also maintained the same as those in the AP600. Table 1 provides a summary comparison of the key design parameters of the AP1000 with those of the AP600.

AP1000 Passive Safety Features

The AP1000 is being designed to meet NRC regulatory criteria in a similar manner to that found to be acceptable for the AP600. The AP1000 is being designed to meet NRC deterministic safety criteria and probabilistic risk criteria with large margins. Westinghouse intends to certify the AP1000 standard plant design under the provisions of 10 CFR Part 52.

The AP1000 passive safety features use the same design approach and arrangement as the AP600. The capacities of the AP1000 passive safety features have been selectively increased using insights from the AP600 design, testing, analysis and licensing activities. Two key factors in these insights are the uncertainty in the computer analysis tools and the margin between the calculated results and the licensing limits. These insights indicate that some passive safety features should be increased at least as much as the increase in core power. These insights also indicate that other features do not need to be increased as much.

A summary comparison of key passive safety system design features is provided in Table 2. These key features are discussed due to their importance in affecting the key thermal-hydraulic phenomenon exhibited by the passive safety systems in critical areas.

COSTS AND CONSTRUCTION

In the United States, the Utility Requirements Document for advanced light water reactor plants included a cost goal that was based on the cost of coal generated electricity at the time the document was written. The overnight capital cost for the first AP600 plant is calculated to be much less that the Utility Requirements Document cost goal, between 1300-1500 $/kW depending on the site selection. It also places the AP600 as the most cost effective nuclear power option available for deployment in the world today. This low cost demonstrates the benefits of the use of passive safety systems and other plant simplifications (Table 3).

However, since that time, the cost of new generating capacity and the overall operating cost of generating electricity has gone down. This is a result of low natural gas prices, more efficient plants in general and the current record breaking reductions in outage times and operating costs for nuclear plants. As a result, the cost of the AP600, is more expensive than the $1000/kw needed to compete in the United States today.

The affect of the changes that are required to uprate the AP600 to the AP1000 is small on the plants overnight cost. A detailed estimate of each difference from AP600 was applied to the already extensive and validated AP600 cost estimate. This overall cost addition is on the order of 11 percent. The overall power increase however is over 66 percent. The overnight cost per megawatt is greatly reduced.

Westinghouse has designed the AP600 using 3D computer models which allows very detailed quantity calculations. A detailed construction schedule has been developed for the AP600 over eight years using input from a number of design participants. This schedule shows that the AP600 design simplifications and use of modular construction techniques allows for a 36 month duration from start of basemat concrete pour to the beginning of fuel load.

More recently the 3D model has been linked to construction schedule model to develop a 4D (3D plus time) representation of the plant construction and as used this model to review and optimize the construction sequence and schedule. As a result of using this model to study the initial portion of the 36 month construction schedule, that schedule has been reduced by over 4 months.

CONCLUSIONS

The AP1000 is derived directly from the AP600, which uses passive safety features and extensive simplifications to enhance construction, operation, and maintenance. This paper describes the design changes that are most important in uprating the AP600 to 1000 MWe. These design changes are being incorporated into the AP1000 standard plant design that Westinghouse intends to license in the U.S. under 10 CFR Part 52. The AP600 design has already been licensed with the NRC, receiving Design Certification in December 1999.

Preliminary safety evaluations and analysis results, performed on the AP1000, indicate that passive safety features can be successfully applied to a plant of a higher power rating while maintaining large safety margins. Scaling evaluations indicate that the AP600 test program and the analysis codes validated for AP600 should be sufficient to perform the accident analyses for Design Certification of the AP1000 without the need to perform additional testing.

The design evaluations performed on the AP1000 indicate that the design objectives of maintaining the AP600 design configuration, use of proven components and licensing basis can be met and that the AP1000 costs will be competitive in the U.S as well as other parts of the world.

Table 1 Comparison of Selected Parameters

	AP600	**AP1000**
Reactor Power, MWt	1933	3400
Hot Leg Temperature, °F	600	610
Number of Fuel Assemblies	145	157
Type of Fuel Assembly	17x17	17x17
Active Fuel Length, ft	12	14
R/V I.D., inches	157	157
Number Control Rod Assemblies	45	53
Hot Leg / Cold Leg Pipe ID, in	31/22	31/22
Steam Generator Heat Transfer Area, ft^2	75,000	125,000
Reactor Coolant Pump Flow, gpm	51,000	75,000
Pressurizer Volume, ft^3	1600	2100

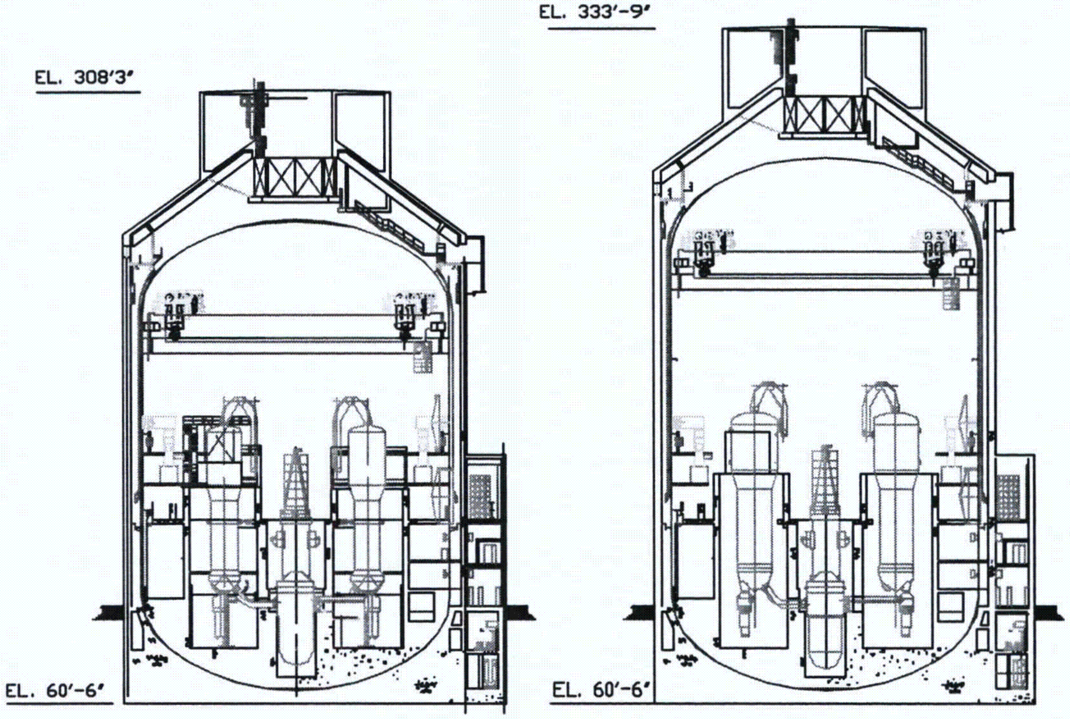
Table 2 Comparison of Passive Safety System Design Features

	AP600	AP1000	Comment
Passive RHR Heat Exchanger			The AP1000 PRHR HX retains the AP600 configuration and elevations. The heat transfer surface area is increased by extending the horizontal portion of the heat exchanger tubes. The inlet and outlet piping has been increased resulting in higher flow rates.
Type	C-Tube	C-Tube	
Surface Area, %	100 %	122 %	
Design Flow Rate, %	100 %	174 %	
Design Heat Transfer, %	100 %	172 %	
Core Makeup Tanks			Core makeup tank volume and flow rate is increased to provide additional safety injection flow. A flow control orifice is changed to increase the flow. CMT elevations are maintained at the AP600 level. The duration of CMT injection is maintained similar to AP600.
Number	2	2	
Volume, ft^3	2000	2500	
Line Resistance, %	100 %	64 %	
Design Flow Rate, %	100 %	125 %	
Accumulators			The accumulators are the same as AP600. Accumulator sizing is based on LBLOCA performance and is affected by reactor vessel volume and core power density. The AP600 and AP1000 employ the same diameter reactor vessel. Although the AP1000 has a higher core power density, there will still be large margins to the peak clad temperature limit of 1204C (2200F).
Number	2	2	
Volume, ft^3	2000	2000	
Pressure, psig	700	700	
IRWST			The IRWST normal water level is increased by using more accurate level instruments. The higher IRWST water level increases the driving head, which together with larger injection line piping, results in higher flow rates.
Volume, gallons	557,000	590,000	
Driving Head, %	100 %	108 %	
Line Resistance, %	100 %	32 %	
Design Flow Rate, %	100 %	184 %	
Containment Recirculation			The post accident containment flood up level has been increased by using a higher initial IRWST level and installing check valves in the refueling cavity drain line so that it does not flood. In addition, the RNS pumps are aligned to take suction from outside containment instead of from the IRWST; this change delays the start of recirculation which adds additional margin.
Line Resistance, %	100 %	39 %	
Driving Head, %	100 %	209 %	
Design Flow Rate, %	100 %	231 %	
Time of Recirculation, hr	2.10	2.67	

	AP600	AP1000	Comment
Automatic Depressurization			
Stages 1-3			The first three stages of ADS are the same as AP600. Their sizing basis is to reduce pressure to permit adequate injection from the accumulators and to permit transition to 4th stage ADS.
RCS connection	Top pzr	Top pzr	
Configuration	6 paths	6 paths	
Vent Area, %	100 %	100 %	
Stage 4			The 4th stage ADS vent capability is the most important design feature to allow for adequate IRWST/sump injection during long term core cooling. The 4th stage piping has been increased resulting in higher flows.
RCS connection	Hot Leg	Hot legs	
Configuration	4 paths	4 paths	
Vent Area, percent	100 %	176 %	
Line Resistance	100 %	28 %	
Capacity	100 %	189 %	
Containment			The AP1000 containment volume and design pressures are increased to accommodate higher mass and energy releases. Increasing the shell thickness to 1.75" and using higher strength steel allows for the higher design pressure.
Diameter, ft	130	130	
Overall Height, ft	189.83	215.33	
Design Pressure, psig	45	59	
Net Free Volume, ft^3	1.73 E06	2.07 E06	
Passive Containment Cooling			The PCS water storage tank was increased to accommodate higher flow rates. The PCS flow rates have been increased based on the increase in core power.
Storage Tank Volume, gal	580,000	800,000	

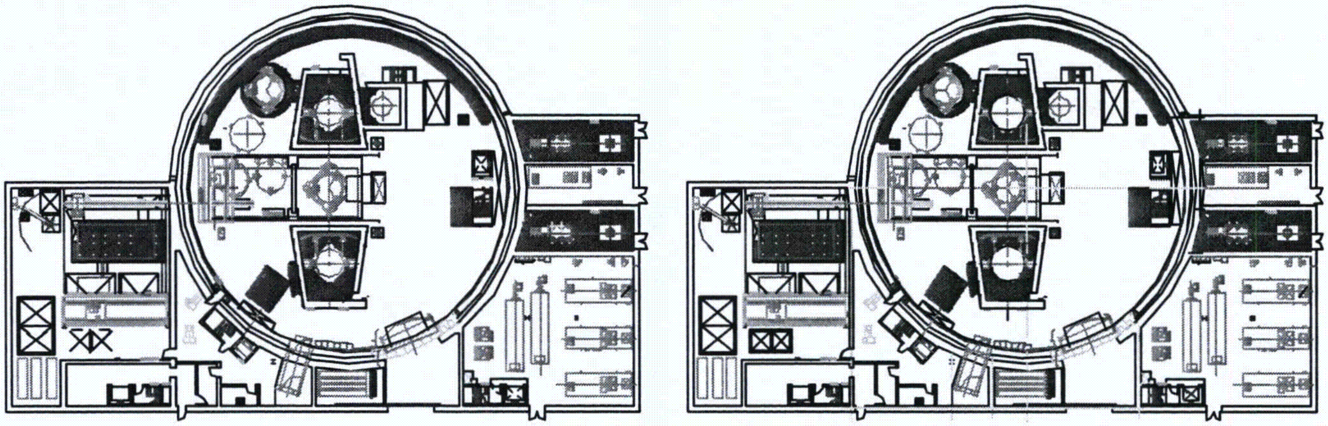
AP1000 Simplifications

	1000 MW Reference	AP1000	Reduction
Pumps	280	180	36 %
ASME Valves	2800	1400	50 %
ASME Piping, million m (ft)	33,500 (110,000)	5800 (19,000)	83 %
Cable, million m (ft)	2.77 (9.1)	0.37 (1.2)	87 %
Seismic Building Volume, million m^3 (ft^3)	0.36 (12.7)	0.16 (5.6)	56 %



AP600 **AP1000**

Figure 1 – Westinghouse AP1000 and AP600 Plants (Section)



AP600 **AP1000**

Figure 2 – Westinghouse AP1000 and AP600 Plants (Plan)

APPENDIX E: DESIGN DESCRIPTION, AP 600

The Westinghouse AP600 is a 600 MWe Pressurized Water Reactor (PWR) with advanced passive safety features and extensive plant simplifications to enhance the construction, operation, and maintenance of the plant. The plant design utilizes proven technology which builds on over 30 years of operating PWR experience. PWRs represent 76 percent of all Light Water Reactors around the world, and 67 percent of the PWRs are based on Westinghouse PWR technology.

The AP600 is designed to achieve a high safety and performance record. It is conservatively based on proven PWR technology, but with an emphasis on safety features that rely on natural forces. Safety systems maximize the use of natural driving forces such as pressurized gas, gravity flow and natural circulation flow. Safety systems do not use active components (such as pumps, fans or diesel generators) and are designed to function without safety-grade support systems (such as AC power, component cooling water, service water, HVAC). The number and complexity of operator actions required to control the safety systems are minimized; the approach is to eliminate a required operator action rather than to automate it. The net result is a design with significantly reduced complexity and improved operability.

The AP600 standard design complies with all applicable U.S. NRC criteria. Extensive safety analysis has been completed and documented in the Standard Safety Analysis Report (SSAR) and Probabilistic Risk Analysis (PRA) submittals to the NRC. An extensive testing program has been completed, and verifies that the innovative plant features will perform as designed and analyzed. PRA results show a very low core damage frequency which meets the goals established for advanced reactor designs and a low frequency of release due to improved containment isolation and cooling.

An important aspect of the AP600 design philosophy focuses on plant operability and maintainability. These factors have been incorporated into the design process. The AP600 design includes features such as simplified system design to improve operability while reducing the number of components and associated maintenance requirements. In particular, simplified safety systems reduce surveillance requirements by enabling significantly simplified technical specifications.

Selection of proven components has been emphasized to ensure a high degree of reliability with a low maintenance requirement. Component standardization reduces spare parts, minimizes maintenance training requirements, and allows shorter maintenance durations. Built-in testing capability is provided for critical components.

Plant layout ensures adequate access for inspection and maintenance. Laydown space for staging of equipment and personnel, equipment removal paths, and space to accommodate remotely operated service equipment and mobile units have been considered as part of the plant design. Access platforms and lifting devices are provided at key locations, as are service provisions such as electrical power, demineralized water, breathing and service air, ventilation and lighting.

The AP600 design also incorporates radiation exposure reduction principles to keep worker dose as low as reasonably achievable (ALARA). Exposure length, distance, shielding and source reduction are fundamental criteria that are incorporated into the design.

Reducing construction costs of commercial nuclear power plants is essential in order to expand the future use of nuclear energy. Two major components of plant construction cost are the cost of financing during construction and the cost of skilled craft labor needed on site during construction. Modular construction techniques, a design requirement for the AP600, significantly reduce these components of construction cost. Through the use of modular construction, our construction planning has shown that AP600 can be constructed in 36 months from pouring the first concrete to fuel load.

Various features have been incorporated in the design to minimize construction time and total cost by eliminating components and reducing bulk quantities and building volumes. Some of these features include the following:

- The flat, common basemat design selected for the nuclear island effectively minimizes the construction cost and schedule.
- Utilization of the integrated protection system, the advanced control room, the distributed logic cabinets, multiplexing, and fiber optics, significantly reduces the quantity of cables, cable trays, and conduits.
- A key feature of the AP600 plant configuration is the stacked arrangement of the Class 1E battery rooms, the dc switchgear rooms, the integrated protection system rooms, and the main control room. This stacked arrangement eliminates the need for the upper and lower cable spreading rooms that are required in the current generation of PWR plants.
- Application of the passive safeguards systems replaces and/or eliminates many of the conventional mechanical safeguards systems that are typically located in the Seismic Category I buildings in the current generation of PWR plants.

The AP600 is designed with environmental consideration as a priority. The safety of the public, the power plant workers, and the impact to the environment have all been addressed as specific design goals, as follows:

- Operational releases have been minimized by design features.
- Aggressive goals for worker radiation exposure have been set and satisfied.
- Total radwaste volumes have been minimized.
- Other hazardous waste (non-radioactive) have been minimized.

The AP600 Nuclear Power Plant has been designed by Westinghouse under the sponsorship of the U.S. Department of Energy (DOE) and the Electric Power Research Institute (EPRI). The design team includes a number of U.S. and foreign companies and organizations, such as Bechtel, Burns

& Roe, Initec (Spain), UTE (Spain), and Ansaldo (Italy) as architect engineers, Avondale Industries (module design), CBI Services, Inc. (containment vessel design), M-K Ferguson Co. (constructability, schedule, and cost estimation), Southern Electric International (turbine island buildings and systems), ENEA Energy Research Center of Italy (tests of the automatic depressurization system), SIET, SPES Facility in Italy (full-pressure integral passive safety system tests), and Oregon State University (low-pressure integral passive safety system tests).

The Electric Power Research Institute (EPRI) has, with a broad participation of numerous countries, developed a Utility Requirements Document (URD) for ALWRs, taking into account the wealth of information related to nuclear power plant safety and operations that has been generated worldwide with commercial nuclear power. The purpose of the URD is to delineate utility desires for their next generation of nuclear plants, and to this end, it consists of a comprehensive set of design requirements for future plants.

Incorporation of the ALWR URD has been a design goal for the AP600 from the design inception, and has continued to be so during the ongoing First-of-a-Kind Engineering (FOAKE) program. The AP600 has a well-defined design basis that is confirmed through thorough engineering analyses and testing and is in conformance with the URD. Some of the high-level design characteristics of the plant are:

- Net electrical power of at least 600 MWe; and a thermal power of 1940 MWt.
- Rated performance is achieved with up to 10 percent of the steam generator tubes plugged and with a maximum hot leg temperature of 600°F (315.6°C).
- Core design is robust with at least a 15 percent operating margin on core power parameters.
- Short lead time (five years from owner's commitment to commercial operation) and construction schedule (3 years).
- No plant prototype is needed since proven power generating system components are used.
- Major safety systems are passive; they require no operator action for 72 hours after an accident, and maintain core and containment cooling for a protracted time without ac power.
- Predicted core damage frequency of 1.7E-07/yr is well below the 1E-05/yr requirement, and frequency of significant release of 1E-08/yr is well below the 1E-06/yr requirement.
- Standard design is applicable to anticipated U.S. sites.
- Occupational radiation exposure expected to be below 0.7 man-Sv/yr (70 man-rem/yr).
- Core is designed for a 24-month fuel cycle assuming an 87 percent capacity factor; capable of a 18-month cycle.
- Refueling outages can be conducted in 17 days or less.

- Plant design life of 60 years without replacement of the reactor vessel.
- Overall plant availability greater than 90 percent, including forced and planned outages; the goal for unplanned reactor trips is less than one per year.

AP600 PLANT COMPARISON WITH SIMILAR FACILITIES

Systems - Components	AP600	Reference 2L	Reference 4L
Plant design objective	60 yrs	40 yrs	40 yrs
NSSS power	1,940 MWt	1,882 MWt	3,425 MWt
Core power	1,933 MWt	1,876 MWt	3,411 MWt
Net electrical output	600 MWe	620 MWe	1,120 MWe
Reactor operating pressure	2,250 psia	2,250 psia	2,250 psia
Hot leg temp	600°F	616°F	618°F
Steam Generator Design pressure	1200 psia	1100 and 1200 psia	1200 psia
Main feedwater temp	435°F	430°F	440°F
Core			
Number fuel assemblies	145	121	193
Active fuel length	144 in	144 in	144 in
Fuel assembly array	17 x 17	16 x 16	17 x 17
Fuel rod OD	0.374 in	0.374 in	0.360 in
Number control assemblies	45	33	53
- Absorber material	Ag-In-Cd	Ag-In-Cd	Ag-In-Cd
Number gray rod assemblies	16	---	---
- Absorber material	SS-304/Ag-In-Cd	---	---
Average linear power	4.10 kw/ft	5.37 kw/ft	5.44 kw/ft
Heat flux hot channel factor, FQ	2.60	2.34	2.32
Reactor Vessel			
Vessel ID	157 in	132 in	173 in
Construction	forged rings	welded plate	welded plate
Number hot leg nozzles	2	2	4
- ID	31.0 in	29.0 in	29.0 in

AP600 PLANT COMPARISON WITH SIMILAR FACILITIES

Systems - Components	AP600	Reference 2L	Reference 4L
Number cold leg nozzles	4	2	4
- ID	22.0 in	27.5 in	27.5 in
Number safety injection nozzles	2	2	0
Design fluence	2.0E+19 n/cm^2	5.0E+19 n/cm^2	3.0E+19 n/cm^2
Steam Generators			
Type	vertical U-tube recirc. design	Vertical U-tube Recirc. design	vertical U-tube recirc. design
Model	Delta-75	D Series/F	D5
Number	2	2	4
Heat transfer area/SG	75,180 ft^2	55,000 ft^2	48,300 ft^2
Number tubes/SG	6,307	5,626	4,568
Tube material	I 690 TT	I 600 TT	I 600 TT
Separate startup feedwater nozzle	Yes	Yes and No	Yes and No
Reactor Coolant Pumps			
Type	canned	Shaft seal	shaft seal
Number	4	2	4
Rated HP	• 3,500 hp/pump	7,000 hp/pump	7,000 hp/pump
Estimated flow/loop	102,000 gpm	102,000 gpm	100,200 gpm
Pressurizer			
Total volume	1,600 ft^3	1,000 ft^3	1,800 ft^3
Volume/MWt	0.825 ft^3/MWt	0.531 ft^3/MWt	0.526 ft^3/MW
Safety valves #/size	2 - 6"	2 - 6"	3 - 6"
PORV #/size	no	2 - 3"	3 - 3"
PRT volume	no	1,000 ft^3	1,800 ft^3
Auto depressurization	yes	no	no
Turbine Island			
Turbine - # HP cylinder	1	1	1
# LP cylinders	2	2	3

AP600 PLANT COMPARISON WITH SIMILAR FACILITIES

Systems - Components	AP600	Reference 2L	Reference 4L
Max blade length	47 in	44 in	44 in
Number reheat stages	1	2	2
Feedwater heating stages			
- # LP stages	4	5	5
- # HP stages	2	1	2
Deaerator	yes	no	no
Main feedwater pumps	2 motor driven	3 motor driven	3 turbine driven
Condensate pumps	3	3	3
Condenser tube material	Ti	SS	SS
Condensate polishing	33 percent	0-100 percent	0-100 percent
Containment			
Type	Steel	steel	pre-stressed concrete
Inside dia.	130 ft	105 ft	140 ft
Volume	1.76E+06 ft^3	1.44E + 06 ft^3	2.80E + 06 ft^3
Volume/MWt	910 ft^3/MWt	768 ft^3/MWt	821 ft^3/MWt
Post accident cooling	air and water on outside of steel containment vessel	Component cooling water cooled fan coolers	Service water cooled fan coolers
Safety Injection			
Accumulator - #/volume	2/2,000 ft^3	2/2,000 ft^3	4/1,350 ft^3
Core makeup tank - #/volume	2/2,000 ft^3	no	no
High head pumps - #	none	2	2
- runout flow	-	800 gpm	600 gpm
- shutoff head	-	2,000 psi	1,800 psi
Low head pumps - #	none	see RHR pumps	see RHR pumps
Refuel water storage tank - #	1	1	1
- location	in containment	ex-containment	ex-containment
- volume	530,000 gal	350,000 gal	350,000 gal
Boron inject tank #/vol	no	1/900 gal	1/900 gal

AP600 PLANT COMPARISON WITH SIMILAR FACILITIES

Systems - Components	AP600	Reference 2L	Reference 4L
Normal Residual Heat Removal (NRHR)			
Design pressure	900 psig	600 psig	600 psig
Normal RHR pumps - #/design flow	2/1,000 gpm per pump	2/2,200 gpm per pump	2/3,800 gpm per pump
Cooling Water Systems			
Safety-related	no	yes	yes
Component cooling water pumps	2	4	4
Service water pumps	2	4	4
Heat sink	separate mechanical draft cooling tower	separate mechanical draft cooling towers	separate mechanical draft cooling towers
Startup/Auxiliary Feedwater			
Motor pumps - #/flow per pump/safety-related	2/380 gpm/no	2/400 gpm/yes	2/600 gpm/yes
Turbine pumps - #/flow	none/-	1/800 gpm	1/1,200 gpm
Passive RHR HX - #/heat removal/safety-related	1/42 MW/Yes	None/-/-	None/-/-
Chemical and Volume Control			
Purification/Letdown flow - normal	100 gpm	60 gpm	75 gpm
- max	100 gpm	120 gpm	120 gpm
Purification location	IRC	ORC	ORC
RCP seal injection/pump	None	8 gpm	8 gpm
Charging pumps	2 @ 100 gpm	2 @ 160 gpm 1 @ 35 gpm	2 @ 150 gpm 1 @ 90 gpm
- SI use	No	no	yes
- safe shutdown use	no	yes	yes
- continuous oper.	no	yes	yes
Boron thermal regeneration	no	yes	yes
Boron recycle evaporator	no	15 gpm	15 gpm

AP600 PLANT COMPARISON WITH SIMILAR FACILITIES			
Systems - Components	**AP600**	**Reference 2L**	**Reference 4L**
Instrumentation and Control			
Type control room	work station	control boards	control boards
Electrical			
Diesels - #	2	2	2
- safety-related	no	yes	yes
- capacity	4,000 kw	4,600 kw	6,000 kw
1E batteries - total capacity	28,000 AMP-HR	5,700 AMP-HR	4,800 AMP-HR

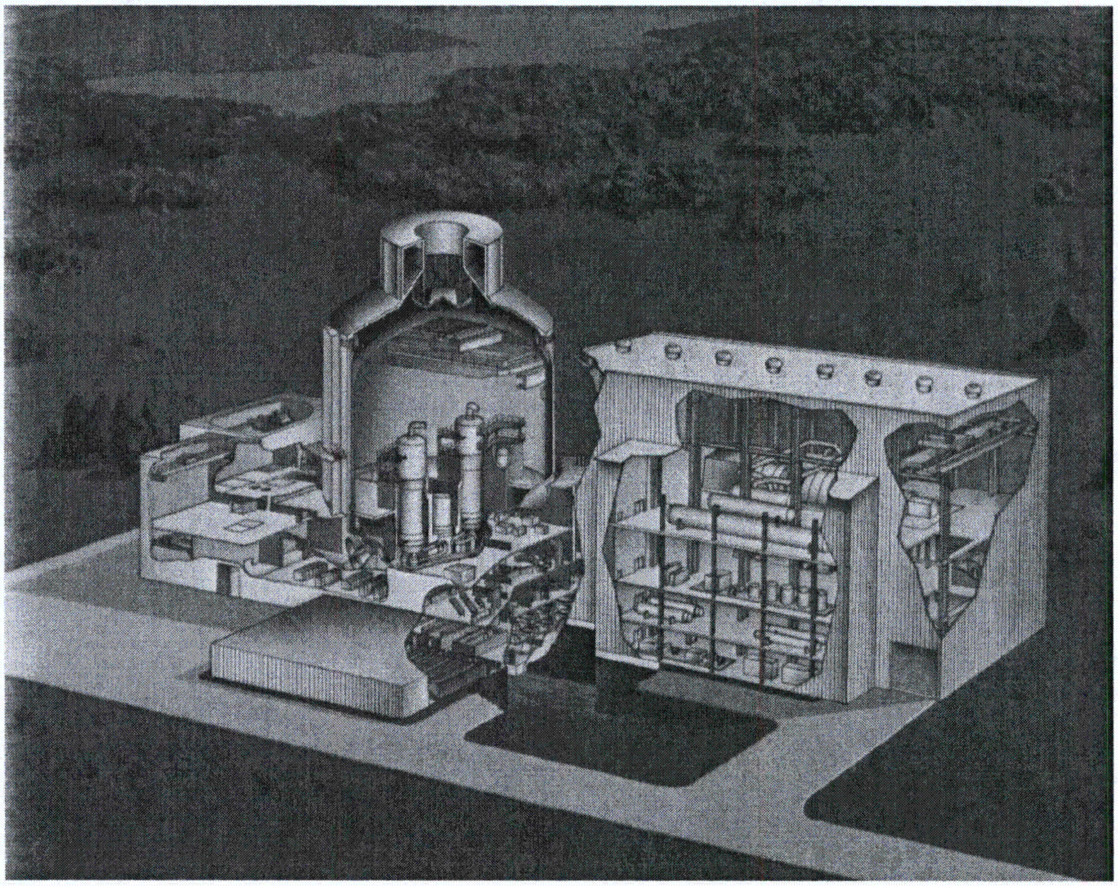


Figure 1 – The Westinghouse AP600 Standard Nuclear Plant received Design Certification from the U.S. NRC in 1999

Figure 2 – The AP600 Passive Core Cooling System

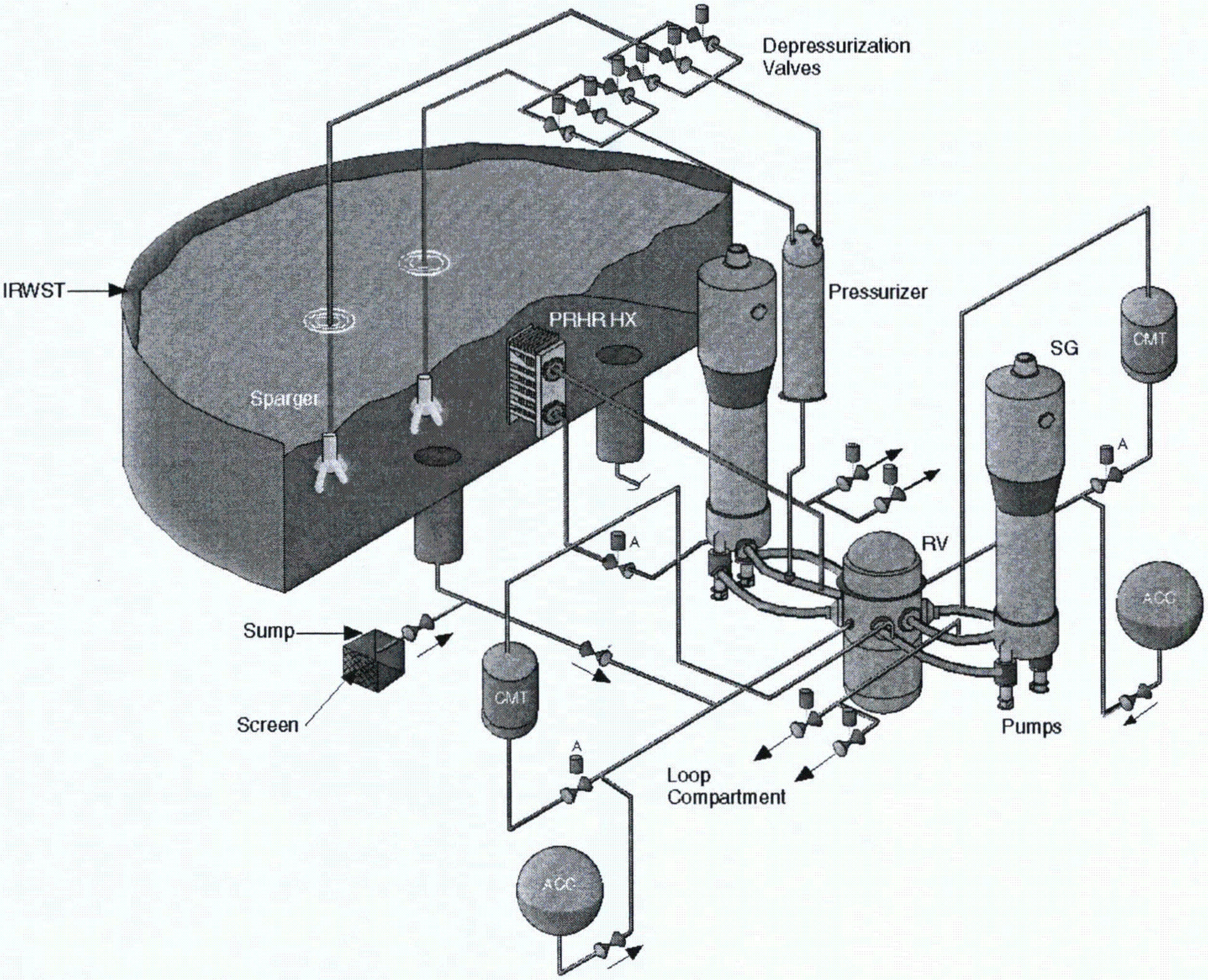
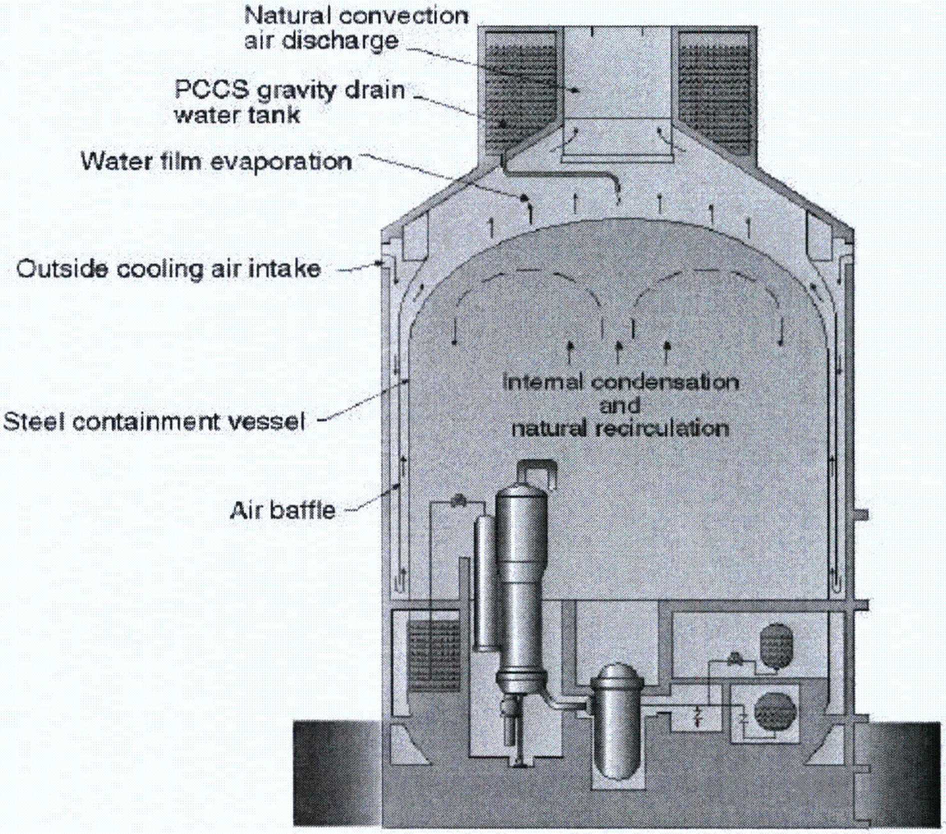


Figure 3 – AP600 Passive Containment Cooling



Appendix F: Design Description, International Reactor Innovative And Secure (IRIS)

IRIS (International Reactor Innovative and Secure) is a modular, integral, light water cooled, medium power (335 MWe) reactor which addresses the requirements defined by the US DOE for Generation IV reactors, i.e., proliferation resistance, enhanced safety, improved economics and fuel cycle sustainability. IRIS is being developed by an international team led by Westinghouse and including at present 18 organizations from 9 countries. Reactor vendors, component designers and manufacturers, architect-engineers, utilities, laboratories and academia are participating. IRIS relies on the proven technology of light water reactors but it features innovative engineering for improved performance.

The major unique features of the IRIS design are:

- five-year long straight burn fuel cycle without shuffling, or partial refueling
- integral primary coolant circuit,
- modular helical tube steam generators,
- internal radiation shields.
- immersed spool pumps,
- safety by design approach, where several accident initiators are eliminated by design
- maintenance shutdown interval no shorter than 4 years

The following represents a description of the major IRIS plant components and characteristics, while design and operation parameters are summarized in Table 1.

System Configuration

An integral vessel (23.52 m height and 6.45 m outside diameter) houses reactor core and support structures, core barrel, upper internals, control rod guides and drivelines, radiation shields, steam generators, pressurizer, and spool reactor coolant pumps (Figure 1). Such an arrangement eliminates separate steam generators and pressurizer, connecting pipes, and supports. Hot coolant rising from the reactor core to the top of the vessel is being pumped by eight immersed spool pumps into eight helical-tube, once-through steam generators. Currently, conventional out-of-vessel Control Rod Drive Mechanisms (CRDMs) are included in the reference design. However, internal CRDMs are envisioned for reducing the number of vessel penetrations, reducing the vessel height and eliminating some control rod ejection accidents.

Core and Fuel

In order to stay within the current licensing space, the first IRIS cores will employ standard <5 percent UO_2 fuel and standard PWR fuel assembly design. Reload cores might employ higher (about 9 percent) enriched fuel to achieve longer (8-10 yrs) fuel cycle and higher burnup.

The reference first core design uses UO_2 fuel, enriched to 4.95 w/o in U235, with axial blankets and with lower enrichment at the core periphery. Fuel pellet diameter is 0.366", similar to the Westinghouse 15x15 fuel assembly design. It incorporates 204 fuel rods, 20 guide thimbles for control rods, and 1 central instrumentation tube. Fuel rod diameter is 0.423". Use of soluble boron is reduced, or possibly eliminated. This makes the moderator temperature coefficient more negative, thus contributing to inherent safety. It also allows using a somewhat more open lattice than in current PWRs, with a lattice pitch-to-rod diameter ratio of 1.4. The average discharge burnup is about 40,000 MWd/tU, achieved in a straight burn mode. The active fuel length is 14 feet. The fission products gas plenum length is increased (roughly doubled) compared to current PWRs, thus eliminating potential concerns with internal overpressure. Because of the integral configuration, an increase in fuel assembly length does not impact the vessel height.

The core includes 89 fuel assemblies. To control relatively large beginning-of-life excess reactivity, which is needed to achieve extended core lifetime in straight burn, advanced burnable absorbers are employed, combined with an increased number of control rod assemblies. Control rods are arranged in banks of black and gray control rods, to address safety as well as operational reactivity control requirements. Current design focuses on use of thin B10 fuel pellet coating (Westinghouse type IFBA - Integral Fuel Burnable Absorber) combined with integral erbium or gadolinium, to tailor the reactivity depletion profile as required for a straight burn operation.

Reactor Safety

IRIS reactor safety relies on "safety by design" approach, which attempts to first eliminate the possibility of accident sequences from occurring, and second, to reduce the severity of consequences and/or the probability of occurrence. The table below summarizes how this is accomplished by engineering the IRIS design features.

Design Characteristic	Safety Implication	Related Accident	Disposition
Integral reactor configuration	No external loop piping	Large LOCAs	Eliminated
Tall vessel with elevated steam generators	Can accommodate internal control rod drives	Reactivity insertion due to control rod ejection	Can be eliminated
	High degree of natural circulation	LOFAs (e.g., pump seizure or shaft break)	Either eliminated (full natural circulation) or mitigated consequences (high partial natural circulation)
Low pressure drop flow path and multiple RCPs	N-1 pumps keep core flow above DNB limit, no core damage occurs		
High pressure steam generator system	Primary system cannot over-pressure secondary system	SGTR	Automatic isolation, accident terminates quickly

	No SG safety valves required	Steam and feed line breaks	Reduced probability Reduced consequences
Once through SG design	Low water inventory		
Long life core	No partial refueling	Refueling accidents	Reduced probability
Large water inventory inside vessel	Slows transient evolution Helps to keep core covered	Small-medium LOCAs	Core remains covered with no safety injection
Reduced size, higher pressure containment	Reduced driving force through primary opening		
Inside the vessel heat removal			

Initial evaluations indicate that out of the eight Class IV accidents considered for the AP-600 reactor design, seven are either eliminated or down-graded to Class III and the only remaining (refueling) accident has a much reduced probability of occurring.

The most innovative feature in terms of enhanced safety of the IRIS design is in the handling of small-to-medium LOCAs, historically the most troublesome accidents. The approach is to reduce the pressure differential between vessel and containment, thus reducing the driving force across the rupture and ultimately the coolant loss, through: a) a high pressure containment, which increases the pressure after the break, and b) an efficient heat removal inside the vessel through steam generators which reduces the pressure before the break. Also, the large water inventory inside the vessel acts as an accumulator. The ultimate result is that for the worst (in terms of size and location) hypothetical LOCA the core remains for several days safely under water without any core water makeup or safety injection.

Steam Generator

The 335 MWe IRIS unit features eight helical-coil tube bundle steam generator modules. This design is capable of accommodating thermal expansion without excessive mechanical stress, and has high resistance to flow-induced vibrations. The tube rupture event likelihood is significantly reduced due to the fact that the steam generator tubes are in compression (high pressure primary fluid outside the tubes); in addition, the feed and steam piping, isolation valves, and instrumentation are designed for full primary system pressure. Steam generator modules are located in the annular space between the core barrel and the reactor vessel. Each module consists of a central inner column which supports the tubes and the lower feed water header and the upper steam header. The tube coils are 1.64 m in diameter and there are 820 helical tubes (outside diameter 19.05 mm and wall thickness 2.26 mm) arranged in 20 annular rows. The tubes are connected to the vertical sides of the lower feedwater header and the upper steam header. The module headers are bolted to the vessel from the inside of the feed inlet and steam outlet pipe.

Coolant Pump

IRIS design features a "spool type" pump with the motor and pump consisting of two concentric cylinders, where the outer ring is the stationary stator and the inner ring is the rotor that carries high specific speed pump impellers. As opposed to conventional canned motor pumps, the spool type pump would be located entirely within the reactor vessel eliminating the need for large vessel openings and closure flanges; only small penetrations for the electrical power cables and for water cooling supply and return piping are required. It also provides high inertia/coastdown and high run-out capability, which will contribute to mitigate the consequences of LOFAs. Use of spool pumps is not possible in loop type PWRs because of the pump low developed head, a feature which is no longer limiting in the integral configuration IRIS.

Maintenance

A three-prong approach is used to overcome regulatory-based and investment protection barriers to achieve the current IRIS operating cycle length goal of at least four years without a maintenance shutdown, to match the long core life: a) if practical, defer inspection and maintenance until the end of the fuel cycle; b) when possible, perform on-line inspection and maintenance; and c) if the two preceding options are not available, redesign the corresponding systems and components to allow for longer operation intervals or online inspection and maintenance. For example, the IRIS team has developed a novel reactor vessel overpressure protection system using paired safety valves which permits on-line testing of one safety valve while the other valve of the pair provides the required overpressure protection. Furthermore, many of the known four-year operating cycle barriers in a typical pressurized water reactor plant, are eliminated due to the inherent IRIS design features. For example, all 18-month reactor coolant pump lubricating oil maintenance actions performed at existing PWRs have been eliminated in IRIS by use of internal spool pumps, which are lubricated by the reactor coolant

Internal Radiation Shields

The vessel surface activation is significantly reduced due to internal radiation shields located in a 1.5 m wide annular space between the core barrel and the vessel. Carbon steel annuli of 100 mm thickness, with a thin stainless steel cladding and including or not B_4C, were considered. Composite shields (made of 30 percent vol. carbon steel + 70 percent vol. water, or 20 percent vol. carbon steel with 10 percent boron carbide + 80 percent vol. water) are expected to result in dose of 10^{-6} Sv/h at the vessel outer surface, and vessel activation of 10 Bq/g several weeks after shutdown. This has positive implications on workers' exposure as well as on final disposal (the vessel can act as a sarcophagus, with no need for removing the reactor internals).

Generation Costs

For a site in North America, having three IRIS modules each rated at 335 MWe, Nth-of-a-kind plant cost projections including all lifetime costs and revenues indicate that IRIS is fully competitive with all power options. A staggered construction schedule (projected at 36 months for a first-of-a-kind and 24 months for a nth-of-a-kind) of the modules allows to produce positive case flow from electricity generation in the first module while proceeding with construction of the third module.

Table 1. IRIS Design Parameters Summary

BASIC COMPONENTS			
Reactor Vessel, OD, m (in)			6.45 (254)
Core			
	Number of Assemblies		89
	Rod Array, rods		15x15 square
	Rod OD, mm (in)		10.74 (0.423)
	Reactivity control with control rods, movable absorber rods, Integral Fuel Burnable Absorber coated fuel pellets		
	Number of Control Rods per Assembly		20
	No. of instrumentation tubes per assembly		1
	Fuel rods in a fuel assembly skeleton with grid support		204
	Number of Grids		12
	Total Fuel Assembly Length m (in)		5.18 (204)
	Fuel Assembly Loading, Kg U		542
	UO$_2$ fuel 4.95 percent (first core), approximately 9 percent (reload cores) enriched		
	Active Fuel Length, m (in.)		4.27 (168)
	Fuel Pellet Diameter, mm (in)		9.3 (0.366)
	Fuel rod average power		3.93 kw/ft
	Target burnup	First core:	40 to 50 GWd/MT-HM
		Reload core:	< 90 GWd/MT-HM

DESIGN PARAMETERS		
Reactor Thermal Power, MWt (10^8 BTU/hr)		1000 (3412)
Reactor Electric Power, MWe		335
Reactor Coolant Flow, kg/s (10^8 lb/hr)		4481 (35.53)
Reactor Coolant Pressure MPa (psia)		15.5 (2250)
Reactor Coolant Temperature, °C (°F)		
	Core Outlet	330 (626)
	Vessel Outlet	327.9 (622.2)
	Core Average	311 (591.8)
	Vessel Average	309.9 (589.9)
	Vessel/Core Inlet	292 (557.6)
	Steam Generator Outlet	292 (557.6)
Steam Generator		
	Model	Modular Helical Coil
	Number of Modules	8
	Reactor Coolant Pressure, MPa (psia)	15.5 (2250)

	Steam Temperature °C (°F)	310.8 (525.4) (superheated)
	Steam Pressure, MPa (psi)	7.0 (1015)
	Secondary Design Pressure, MPa (psi)	17.24 (2500)
	Steam Flow, kg/s (10^8 lb/hr) total	535.97 (4.25)
	Feed Temperature, °C (°F)	226.7 (440.1)
	Tube Plugging, percent	10 percent (max)
Reactor Coolant Pump		Submersed Spool Pump

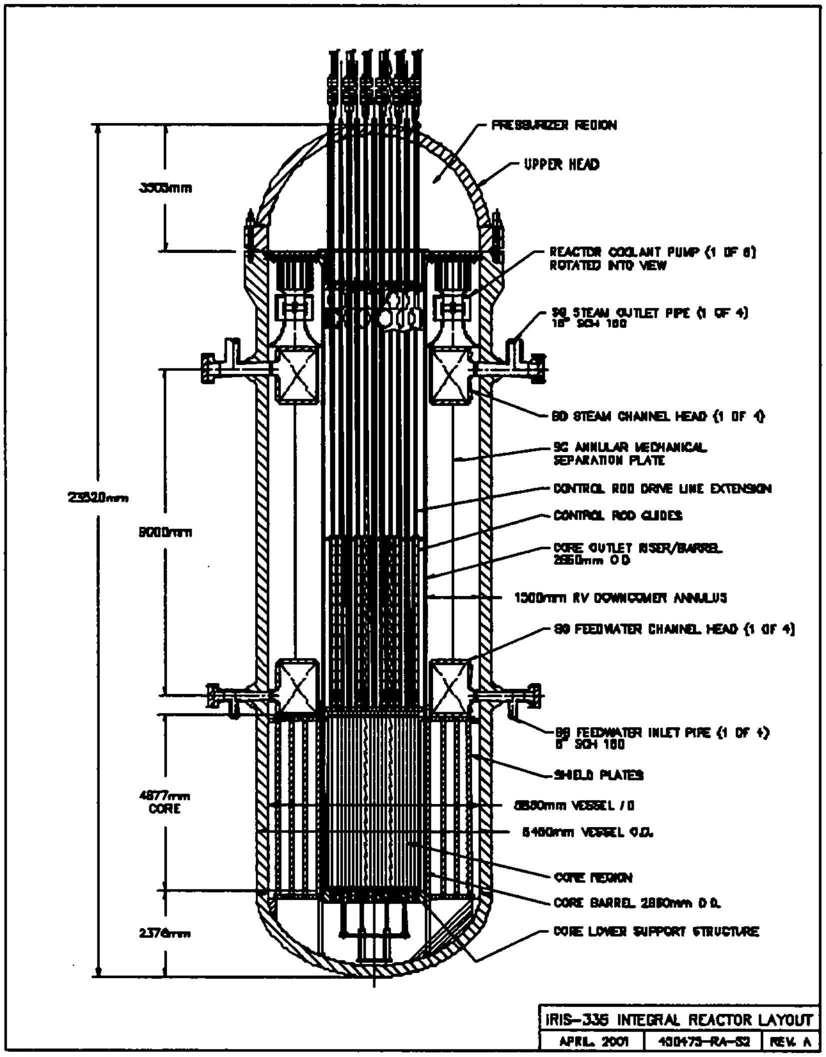


Figure 1. Vessel Layout for the 335 MWe IRIS Plant

APPENDIX G: DESIGN DESCRIPTION, PEBBLE BED MODULAR REACTOR (PBMR)

GENERAL DESCRIPTION

Technical Design Philosophy

The fundamental concept of the design of the PBMR is aimed at achieving a plant that has no physical process that could cause a radiation hazard beyond the site boundary. This is principally achieved in the PBMR by demonstrating that the integrated heat loss from the reactor vessel exceeds the decay heat production in the post accident condition, and that the peak temperature reached in the core during the transient is below the demonstrated fuel degradation point and far below the temperature at which the physical structure is affected. This is intended to preclude any prospect of a core melt accident. Heat removal from the vessel is achieved by passive means.

The PBMR module is the smallest standalone component of the PBMR power generation system. The module is a power station that can produce approximately 110 MW (or more) of electrical power. This module can be used to generate power in a standalone mode or as part of a power plant that consists of up to 10 units.

The Pebble Bed Modular Reactor (PBMR) is a graphite moderated helium cooled reactor which uses the Brayton direct gas cycle to convert the heat, which is generated in the core by nuclear fission. The heat is transferred to the coolant gas (helium), and converted into electrical energy by means of a gas turbo-generator. The PBMR core is based on the German high temperature gas cooled technology and uses spherical fuel elements.

Any concern of fire in the graphite core is avoided by showing that there is no method of introducing sufficient oxygen into a high temperature (>1000 C) core to achieve sustained oxidation. This is achieved primarily by the structural design of the reactor structure and building.

The use of helium as a coolant, which is both chemically and radiologically inert, combined with the high temperature integrity of the fuel and structural graphite, allows the use of high primary coolant temperatures (800 to 900 C), which yield high thermal efficiencies. With these high temperatures, the use of a closed cycle gas turbine is justified. This increases the efficiency over a steam plant (from ~35 percent to ~45 percent), thus reducing the unit capital cost. It also removes external sources of contamination of the nuclear circuit, as there is no system with a higher pressure than helium. Without the possibility of leakage into the helium circuit the need for on-line clean up systems to remove water vapor is largely reduced.

Normal Operation (Figure 1)

At nominal rated full power conditions helium enters the reactor at a temperature of about 500°C (932°F) and 70 bar (1015 PSIA) and moves downward between the hot fuel spheres. It picks up the heat from the fuel spheres, which have been heated by the nuclear reaction. The helium then leaves the reactor at a temperature of about 900°C (1652°F).

The helium then moves through the High Pressure Turbine and drives the High Pressure Compressor. Next the helium moves through the Low Pressure Turbine, which drives the Low Pressure Compressor.

The helium then moves through the Power Turbine, which drives the generator.

At this point, the helium is still at a high temperature (~520^0 C) . It passes through the recuperator in this state. Heat is transferred between the high temperature helium from the Power Turbine and the low temperature helium returning to the reactor.

The helium is now cooled by means of a pre–cooler. This increases the density of the helium and improves the efficiency of the compressor.

The helium is then compressed by the Low Pressure Compressor.

The helium is cooled in the inter–cooler. This process increases the density and improves the efficiency of the compressor.

The High Pressure Compressor then compresses the helium.

The cold, high-pressure helium passes through the recuperator where it is pre–heated. The helium then returns to the reactor.

Power output control is achieved by adding (or removing) helium to the circuit. This increases (or decreases) the pressures and mass flow rate without changing the gas temperatures or the pressure ratios of the system. The increased pressure and subsequent increased mass flow rate increases the heat transfer rate, thus increasing the power. Power reduction is achieved by removing gas from the circuit.
The power control system is supplied by a series of helium storage tanks ranging from low to high pressure to maintain the required gas pressure in the circuit. Adjustable stator blades on the turbo machinery and bypass flow are used to achieve short-term control.

During reactor shutdown, residual heat is removed by active and/or passive cooling of the system.

KEY FEATURES

Helium is radiologically inert. The radiation in the core does not activate the gas.

Helium is also chemically inert and can not react with any of the materials that are used in the construction of the PBMR.

The use of Helium in a direct cycle gas turbine based power conversion unit eliminates the requirement for a heat exchanger between a primary and secondary cycle. This improves the efficiency of the plant.

The PBMR fuel is based on a high quality German design of molded graphite spheres containing coated fuel particles. See Figure 2. The fuel particles (kernels) consist of uranium dioxide. Each kernel is coated with a layer of porous carbon, two high-density layers of pyrolytic carbon (a very dense form of heat-treated carbon) with a layer of silicon carbide in between. The porous carbon accommodates any mechanical deformation that the kernel may undergo during the lifetime of the fuel as well as accommodating gaseous fission products released from the kernel without over-pressuring the coated particle. The deformation of the kernel is due to the density changing, which is caused by fission products. The pyrolytic carbon and silicon carbide layers provide an impenetrable barrier; containing the fuel and the radioactive products that result from the nuclear reactions. These coated particles are embedded in a carbon matrix as a 50 mm sphere, called the fuel zone. Adding a 5 mm thick fuel free graphite zone makes up the fuel sphere with an outer diameter of 60 mm. The fuel zone contains approximately 15 000 coated particles which contain 9g uranium. A total of 330,000 fuel spheres and 110,000 pure graphite spheres are required for a single core loading.

SAFETY DESIGN PROVISIONS

Physical Barriers against the Release of Radionuclides

The coated particle is the primary physical barrier against radionuclide release.

Conservatism in Radionuclide Retention

Although the coated particle is the most important physical barrier against the release of radionuclides, other physical retention mechanisms do exist. These mechanisms introduce a high level of conservatism into the defense in depth approach from an engineering point of view and are mentioned from this perspective. The retention mechanisms are:

- Graphite
- Pressure Boundary
- Reactor Building

Many fuel particles are embedded in the graphite matrix of the spherical fuel elements. This graphite has a high capacity for retaining some fission products (i.e. Sr, Rb, Cs, Ba, and rare earths), but is virtually transparent to others (i.e. noble gases).

The primary gas envelope can also be considered a barrier against radionuclide release. However, for the short-lived fission gases, the dominant removal mechanism is radioactive decay. For the condensable fission products, the dominant removal mechanism is deposition or plate-out on the various helium wetted surfaces in the primary circuit.

The reactor building is a reinforced concrete, vented containment building. No leaktight requirement is necessary for this building. In the event of a break in the primary boundary, it is only the very slight gas-borne activity in the primary coolant and a portion of the activity deposited on the surfaces of the primary system that may be released into the reactor building.

Even if the vent opens, natural removal mechanisms (including radioactive decay, condensation, fallout, and plate-out) reduce the concentration of the radionuclides in the containment atmosphere, reducing off site releases.

Accident Prevention and Mitigation

Simplicity of the reliance on passive safety features and inherent characteristics allow a simple overall PBMR plant design. The PBMR modules are operated as independent units and interaction between them is minimized. The layout of the PBMR eliminates unnecessary components and systems, which simplifies normal and emergency operating procedures, inspection, testing, and maintenance. Reliance on control room and operating staff is minimized, since no operator actions are required to prevent fuel damage. Similarly, errors by the operating staff cannot upset the safety characteristics of the PBMR.

The continuous fuelling of the reactor implies that no excess reactivity is necessary in order to compensate for burn-up effects. Nevertheless, a certain margin is required for reactor control and to compensate for changes in the xenon concentration following changes in reactor power. A fast acting control rod system will serve to keep the reactor within normal operating limits.

Reactor cooling is accomplished by the power conversion unit or by the reactor cavity cooling system. The power conversion unit is an active system that operates during power generation and provides the primary shutdown cooling when available.

In the event active heat removal systems are unavailable, the core design ensures a passive residual heat removal capacity. The core geometry, limited core diameter, low thermal power rating, low power densities, high negative temperature coefficient, and the passive cavity cooling system limit the maximum core and fuel temperatures.

Under these conditions, heat is transferred through the reactor vessel wall by thermal radiation and natural convection to the cooling surfaces of the reactor cavity cooling system. The reactor vessel walls are uninsulated to facilitate this process.

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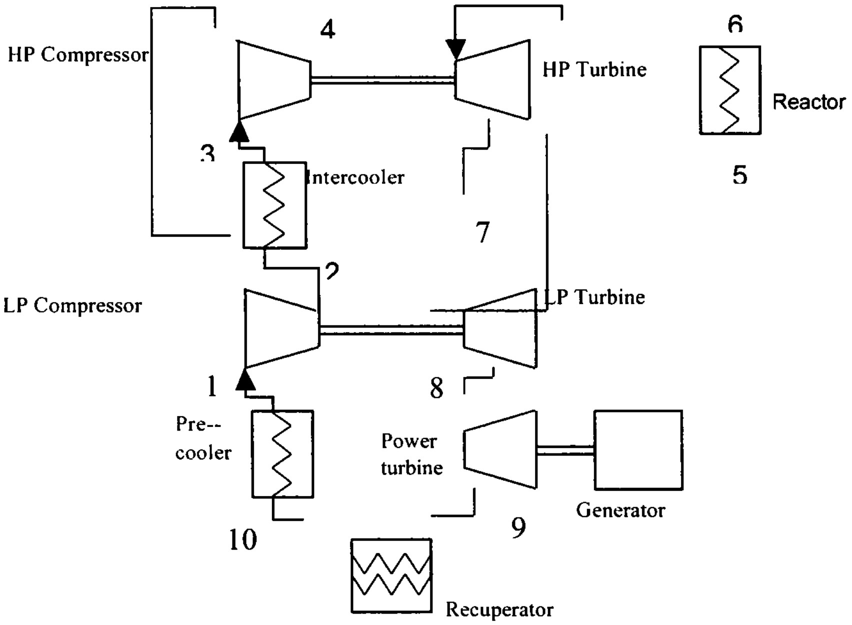


Location		Pressure		Temperature	
Schematic	Description	MPa	PSIG	C	F
1	Precooler outlet LP Compressor Inlet	2.6	377	33	91.4
2	LP Compressor Outlet Intercooler Inlet	4.7	682	130	266
3	Intercooler Outlet HP Compressor Inlet	4.7	682	33	91.4
4	HP Compressor Outlet Recuperator Inlet	7.0	1015	100	212
5	Recuperator Outlet Reactor Inlet	7.0	1015	500	932
6	Reactor Outlet HP Turbine Inlet	7.0	1015	900	1652
7	HP Turbine Outlet LP Turbine Inlet	5.7	827	800	1472
8	LP Turbine Outlet Power Turbine Inlet	4.3	624	690	1274
9	Power Turbine Outlet Recuperator Inlet	2.6	377	520	968
10	Recuperator Outlet Precooler Inlet	2.6	377	150	302

FIGURE 1 - SCHEMATIC / TEMPERATURE & PRESSURE (METRIC & ENGLISH)

KEY DESIGN PARAMETERS

Electrical Power Rating	110 MWe (or more)
Reactor Coolant	
Pressure & Temperature	See schematic (Brayton Cycle)
Fuel	
Active Length	NA (spherical design)
Core	3.5m Diameter, 8.5 m High
Average Enrichment	8 percent U-235
Burn-up	80,000 MWd/T
Reactor Vessel	6m Diameter, 20 m High

Appendix H: Design Description, Gas Turbine Modular Helium Reactor (GT-MHR)

General Description

The Gas Turbine – Modular Helium Reactor (GT-MHR) is an advanced nuclear power system designed to provide very high safety, high thermal efficiency, environmental advantages, and competitive electricity generation costs. The GT-MHR module, Figure 1, couples a gas-cooled modular helium reactor (MHR), contained in one vessel, with a high efficiency Brayton cycle gas turbine (GT) energy conversion system contained in an adjacent vessel. The reactor and power conversion vessels are interconnected with a short cross-vessel and are located in a below grade concrete silo.

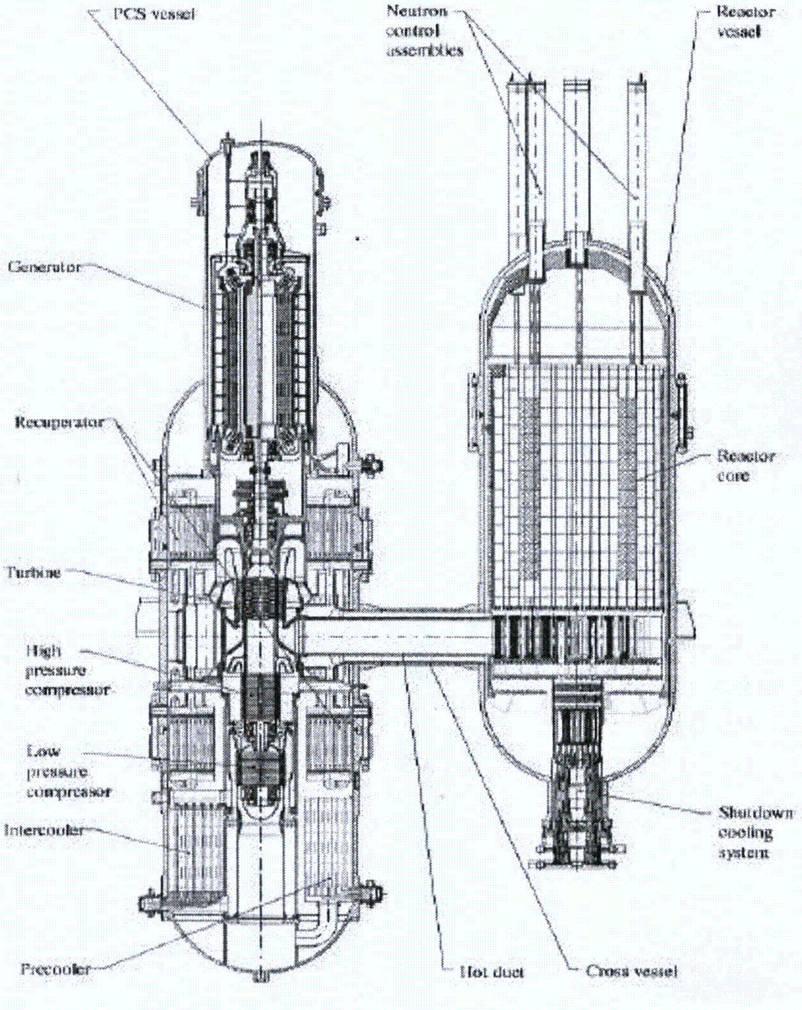


Figure 1. GT-MHR Module

Key design characteristics of the Modular Helium Reactor (MHR) are the use of helium coolant, graphite moderator, and refractory coated particle fuel. Helium coolant is heated in the reactor core by flowing through coolant channels in graphite fuel elements. The heated coolant flows through the cross-vessel to the power conversion system. The power conversion system consists of a gas turbine, electric generator, and gas compressors on a common vertically orientated shaft supported by magnetic bearings and recuperator, precooler and intercooler heat exchangers.

Figure 2 is a schematic of the coolant flow through the power conversion system. Heated helium from the reactor is expanded through the gas turbine to drive the generator and gas compressors. From the turbine exhaust, the helium flows through the hot side of the recuperator transferring residual heat energy to helium on the recuperator cold side returning to the reactor. From the recuperator, the helium flows through the precooler and then passes through low and high-pressure compressors with intercooling. From the high-pressure compressor outlet, the helium flows through the cold, high-pressure side of the recuperator where it is heated for return to the reactor. Nominal full power operating parameters are given in Table I.

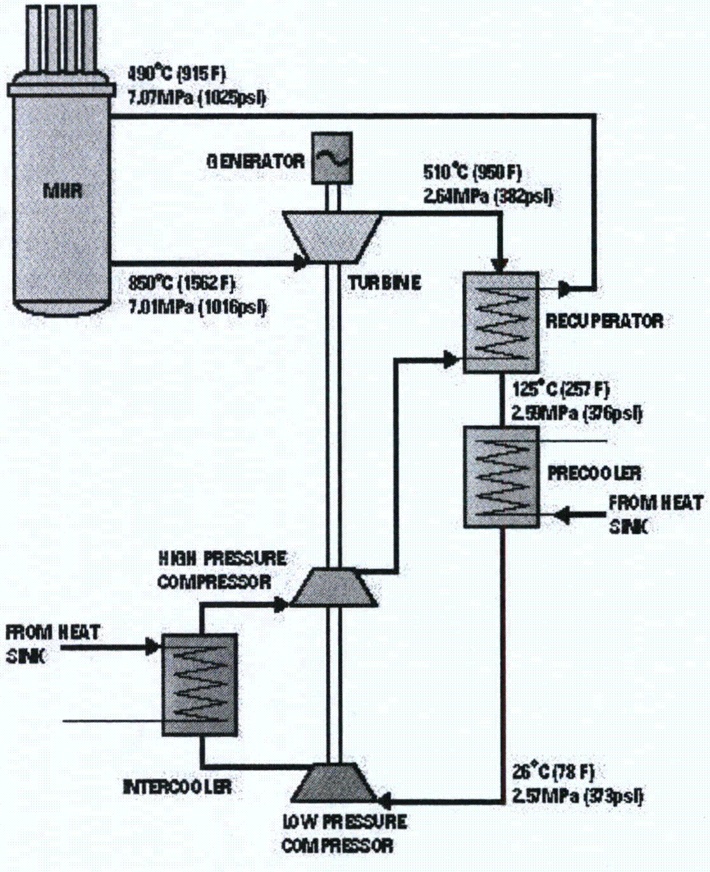


Figure 2. GT-MHR Coolant Flow Schematic

Table 1. GT-MHR Nominal Full Power Operating Parameters

Reactor Power, MWt	600
Core Inlet/Outlet Temperatures, °C	491/850
Core Inlet/Outlet Pressures, MPa	7.07/7.02
Helium Mass Flow Rate, Kg/s	320
Turbine Inlet/Outlet Temperatures, °C	848/511
Turbine Inlet/Outlet Pressures, MPa	7.01/2.64
Recuperator Hot Side Inlet/Outlet Temps, °C	511/125
Recuperator Cold Side Inlet/Outlet Temps, °C	105/491
Net Electrical Output, MWe	286
Net Plant Efficiency, percent	48

The gas turbine power conversion system has been made possible by key technology developments during the past several years in: large aircraft and industrial gas turbines; large active magnetic bearings; compact, highly effective gas-to-gas heat exchangers; and high strength, high temperature steel alloy vessels.

The MHR refractory coated particle fuel, identified as TRISO coated particle fuel, consists of a spherical kernel of fissile or fertile material, as appropriate for the application, encapsulated in multiple coating layers. The multiple coating layers form a miniature, highly corrosion resistant pressure vessel and an essentially impermeable barrier to the release of gaseous and metallic fission products. The coatings do not start to thermally degrade until temperatures approaching 2000°C are reached. Normal operating temperatures do not exceed about 1250°C and worst case accident temperatures are maintained below 1600°C. Extensive tests in the United States, Europe, and Japan have proven the excellent performance characteristics of this fuel.

The overall diameter of standard TRISO-coated particles varies from about 650 microns to about 850 microns. For the GT-MHR, TRISO coated particles are mixed with a matrix and formed into cylindrical fuel compacts, approximately 13 mm in diameter and 51 mm long. The fuel compacts are loaded into fuel channels in hexagonal graphite fuel elements, 793 mm long by 360 mm across flats. One hundred and two columns of the hexagonal fuel elements stacked 10 high are arranged in an annular core configuration as shown in Figure 3. Replaceable reflector graphite blocks are provided inside and outside of the active core.

GT-MHR Safety Characteristics

The GT-MHR safety is achieved through a combination of inherent safety characteristics and design selections that take maximum advantage of the inherent characteristics. These characteristics and design selections include:

1. Helium coolant, which is single phase, inert, and has no reactivity effects;
2. Graphite core, which provides high heat capacity and slow thermal response, and structural stability at very high temperatures;

3. Refractory coated particle fuel, which retains fission products at temperatures much higher than normal operation and postulated accident conditions;
4. Negative temperature coefficient of reactivity, which inherently shuts down the core above normal operating temperatures; and
5. An annular, low power density core in an uninsulated steel reactor vessel surrounded by a natural circulation reactor cavity cooling system (RCCS).

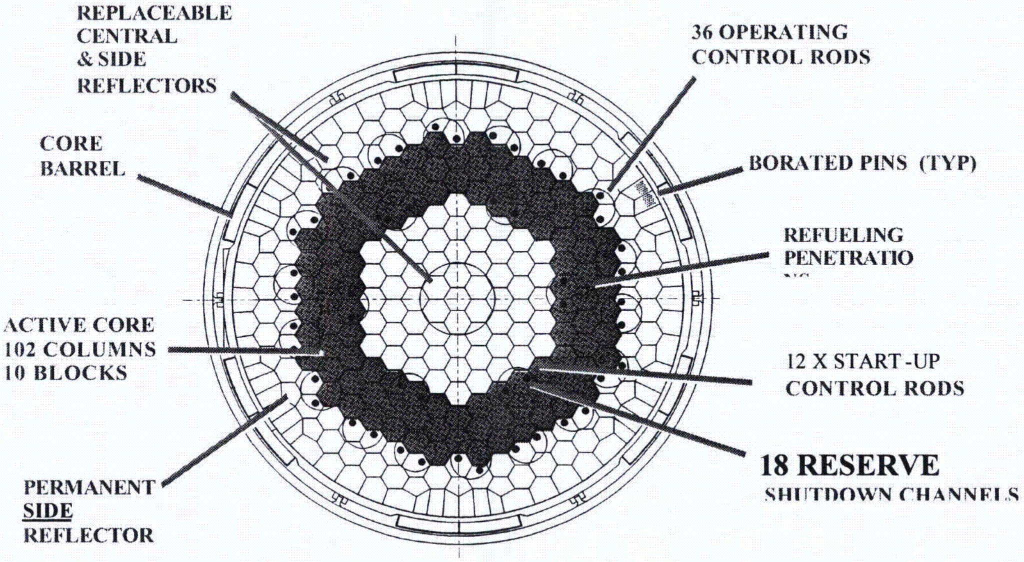


Figure 3. GT-MHR Reactor Cross Section

The GT-MHR has two active, diverse heat removal systems, the power conversion system and a shutdown cooling system that can be used for the removal of decay heat. In the event that neither of these active systems are available, an independent passive means is provided for the removal of core decay heat. This system surrounds the reactor vessel and is identified as the reactor cavity cooling system (RCCS). For passive removal of decay heat, the core power density and the annular core configuration have been designed such that the decay heat can be removed by heat conduction, thermal radiation and natural convection without exceeding the fuel particle temperature limit. Core decay heat is conducted to the pressure vessel and transferred by radiation from the vessel to the natural circulation RCCS. Even if the RCCS is assumed to fail, passive heat conduction from the core, thermal radiation from the vessel, and conduction into the silo walls and surrounding earth is sufficient to maintain peak core temperatures to below the design limit. Radionuclides are retained with the refractory coated fuel particles without the need for AC powered systems or operator action. These safety characteristics and design features result in a reactor that can withstand loss of coolant circulation or even loss of coolant inventory and maintain fuel temperatures below damage limits.

The large heat capacity of graphite core structure is an important inherent characteristic that significantly contributes to maintaining fuel temperatures below damage limits during loss of cooling, or coolant, events. The core graphite heat capacity is sufficiently large to cause any heatup, or cooldown, to take place slowly. A substantial time (on the order of days) is available to take corrective actions to mitigate abnormal events and to restore the reactor to normal operations.

GT-MHR ECONOMIC CHARACTERISTICS

The GT-MHR is projected to be economically competitive with alternative electricity generation technologies. The economic competitiveness of the GT-MHR is a consequence of:

1. The high operating temperature of the modular helium reactor,
2. The use of the Brayton cycle power conversion system,
3. Enhanced safety characteristics,
4. A fuel system highly compatible with automated production processes,
5. The use of a modest module power size and modular design features allowing for a factory fabrication with significant learning cost reductions,
6. Small plant foot print, even for a modular plant,
7. High fuel burnup (>100,000 MWd/MT), and
8. Low operation and maintenance requirements.

The high operating temperature of the GT-MHR coupled with the use of the direct Brayton cycle power conversion system results in a net thermal conversion efficiency of approximately 48 percent. The Brayton cycle gas turbine power conversion system eliminates extensive equipment required by the century-old Rankine steam cycle technology. The enhanced safety characteristics result in reduced needs for safety systems and their associated capital and O&M costs. The net effect of reduced power conversion equipment and fewer safety related systems is reduced overnight construction costs, construction times, and O&M costs and increased reliability, availability and capacity factors.

Economic evaluations of the GT-MHR in comparison to similarly sized alternative generation technologies indicate the GT-MHR to have economic advantages, in terms of cost of electricity generation, to both advanced light water reactor plants and fossil-fired steam power plants and to be competitive with gas turbine, combined cycle merchant plants.

Waste Management

The GT-MHR produces less heavy metal radioactive waste than other reactor options because of the plant's high thermal efficiency and high fuel burnup. Additionally, the refractory fuel coatings are superior barriers for containment of radionuclides. The TRISO fuel particle coating system for containment of fission products under reactor operating conditions, also provides an excellent barrier for containment of the radionuclides for storage and geologic disposal of spent fuel. Experimental studies have shown the corrosion rates of the TRISO coatings are very low under both dry and wet conditions. The measured corrosion rates indicate the TRISO coating system should maintain its integrity for a million years or more in a geologic repository environment.

APPENDIX I: COST SHARING RATIONALE

DOE has established six criteria for designs to be considered as Near-Term Deployment (NTD) options. Criterion 4 states "Cost-sharing between industry and Government – technology plans must include a clear delineation of the cost categories to be funded by Government and the categories to be funded by private industry. The private/Government funding split for each of these categories must be shown along with rationale for the proposed split." This criterion was considered in preparing this paper and in developing the proposed funding requirements.

The Federal Government has a long history of using public-private partnerships to leverage limited federal funds, to inject market forces into Government R&D prioritization, and to encourage technology transfer of federal R&D investments into the marketplace. DOE has used this strategy effectively in nuclear energy supply R&D, most recently in the ALWR Program.

Cost sharing by Government and industry is a means of accelerating the development of new nuclear plants, by channeling funds to make things happen sooner than they otherwise would by means of industry funding alone. There is incentive for industry to move ahead, but the time to recover investment from it would likely be longer than the crisis of electrical generation allows.

Nuclear generation is in a special category for several reasons. It is a viable candidate for supply of new capacity provided there would be sufficient time available for the nuclear industry to demonstrate the effectiveness of the NRC's untested Part 52 licensing process for new plants, get site approvals, and build the required new plants. The time and cost associated with resolving licensing issues and obtaining NRC approvals under Part 52 have been enormous, based on the experience of the 1990s. This experience also confirms the risks and uncertainties involved – issues of major concern to investors in today's deregulated electricity marketplace. These and other challenges prompted DOE to initiate the NTD Roadmap, to seek opportunities to help facilitate new orders through standardized generic issue resolutions, efficiency improvements, and direct assistance to applicants to defray regulatory costs and review fees.

There is another important reason for nuclear generation to play a major role in the required expansion of capacity. That is the potential environmental effect of conventional fossil fuel burning alternatives for new generation capacity: the production of huge quantities of air pollutants and greenhouse gases that nuclear generation avoids. Although the scientific case for global warming and its potential harmful effects has not been proven, the U.S. Government is considering alternatives to the U.N. Kyoto Accord that would support a balanced approach to addressing greenhouse gas emissions – one that does not create severe economic impacts. It is only appropriate that the U.S. aid in the expansion of U.S. nuclear capacity as a cost-effective way to facilitate a global response without serious negative impacts on national economies.

It follows from this analysis that the costs of new plant construction for the first plant in excess of the cost of later plants are candidates for government cost sharing. It is reasonable to expect the excess cost to disappear with plants that follow and if it doesn't that should be to industry's account. The better the management of the process, the sooner the excess cost will disappear.

Also, when it is clear that the crisis of generation shortage is under control, the need for government cost sharing disappears.

No.	TASK	DISCUSSION	FY 02	FY 03	FY 04	FY 05	FY 06	FY 07	FY 08	FY 09	Total Ind.	Total DOE	TOTAL
SITE-SPECIFIC REGULATORY-RELATED TASKS													
S-1	Early Site Permitting (Site Specific) Support of the First-of-a-Kind Demonstrations of Part 52 (Subpart A) at representative U.S. sites. Federal support to be provided on cost share basis, with industry entities providing ≥50 percent funding.	This task will demonstrate the ESP process at an appropriate number of representative U.S. sites with sufficiently unique circumstances so as to examine the more credible situations (e.g., green field sites, existing sites,) Funding estimates based on ½ of sum of each of the following: one green field, one existing non-nuclear site, and two unique variations on existing sites. Includes full NRC review fee reimbursement.	3	7	5						15	---	**30**
			3	7	5						---	15	
			6	**14**	**10**								
S-2	COL Application Support (Site Specific): DOE fund, on a cost-share basis, the expense of developing & submitting the first COL application for each NTD design (Limit: one demo per design). Federal support to be provided on cost share basis, with industry entities providing ≥50 percent funding.	Many aspects of a COL application are unique to the design and go beyond the design information approved in the DC (e.g., programmatic issues and programs tailored for each certified design). The first COL applicant for each design will bear the extra burden of gaining NRC approval for many first-of-a-kind licensing provisions that standardized plants of that design will follow. Planning assumptions: no COL applicants in 2002; two applications per year each year in 2003 and 2004; each application takes 2 years. Funding estimate based on ½ the estimated full cost to each applicant for developing and submitting the COL, including full NRC review fee reimbursement.		5	10	10	5				30	---	**60**
				5	10	10	5				---	30	
				10	**20**	**20**	**10**						
	TOTAL SITE SPECIFIC REQUIREMENTS		3	12	15	10	5				**45**	—	**90**
			3	12	15	10	5				—	**45**	
			6	**24**	**30**	**20**	**10**						

This section specifies complete resource needs to close all site-specific, generic, and design-specific gaps, but is contingent on industry agreement to provide the necessary cost-share funds to match potential government funding. As discussed in Chapter II-6, this is not a federal funding request.

No.	TASK	DISCUSSION	FY 02	FY 03	FY 04	FY 05	FY 06	FY 07	FY 08	FY 09	Total Ind.	Total DOE	TOTAL
GENERIC, INDUSTRY-WIDE COST SHARE PROGRAM WITH DOE													
[The following section is intended to address, on a cost-shared basis, the various expenses associated with generic activities of benefit to all NTD designs and all owner-operators investing in these designs. The types of tasks to be undertaken in this generic category include both generic regulatory activities and generic technical activities. The proposition behind this cost-shared category of work is that industry will cost-share this work with DOE on an industry-wide basis, (e.g., via EPRI) as <u>a single, integrated program</u> (similar to NEPO for current plants); and that industry will assume responsibility for prioritizing tasks based on their urgency and generic benefit to near term deployment (e.g., via NEI). The task descriptions listed below have been validated by industry as high priority needs. Many are prerequisites (or essential parallel initiatives) to other site-specific or design specific activities. The specific funding needs for each task listed below are less precise, because of the dynamic nature of each issue. It is possible that by the time Federal funding becomes available to this proposed program, a few tasks, as currently defined, may be near completion, based on unilateral industry efforts. However, experience shows that follow-on work in these areas will be needed, and new high priority generic tasks will be identified that need joint industry-DOE funding. Hence the U.S. needs an integrated, multi-year NTD generic issue resolution program with sufficient flexibility to target the most important activities each year in support of building new plants. It is currently envisioned that this program would start in 2003 at $6M ($3M DOE, $3M industry), and would continue each year for 3-4 years. Its continuation would depend on the opportunities for and value of <u>generic</u> activities in relation to site-specific projects.]													
GENERIC REGULATORY TASKS													
G-1	<u>Early Site Permitting (Generic)</u> Resolution of open generic issues with Early Site Permitting, e.g.: • Update the Guideline for Preparation of an ESP Application Submittal • Review of Part 52, Subpart A for necessary modifications • Develop guidance on Part 51 and EIS compliance • Review & update Site Selection Criteria Document	Most of this generic work is a prerequisite to site-specific projects (S-1 & S-2), or will proceed in parallel with site-specific applications and complete as S-1 and S-2 proceed. Much will be done by industry. Some of it is already underway at NEI, under an ESP Task Force, supported by EPRI. At the present time, no DOE funding assistance is needed.	0.5	1	0.5						2	---	**2**
											---	0	
			0.5	**1**	**0.5**								
G-2	Combined License (Generic) Resolution of open generic issues with COL process, e.g., COL form and content; procedures and guidelines to document how ITAAC review and verification will be conducted. Establish an efficient process for construction inspection and ITAAC sign-off.	NEI has the lead for industry work on the generic aspects of this issue. Resolving these issues generically is essential to executing ITAAC on a design-specific basis. A need for DOE assistance is not anticipated at this time.		1	1	1					3	---	**3**
											---	0	
				1	**1**	**1**							

No.	TASK	DISCUSSION	FY 02	FY 03	FY 04	FY 05	FY 06	FY 07	FY 08	FY 09	Total Ind.	Total DOE	TOTAL
G-3	<u>Generic Risk-Informed Regulatory Framework</u> Develop a new generic regulatory framework, using a risk-informed, performance-based approach that builds on the policies and cornerstones of the new NRC Oversight Process and utilizes the work underway on a risk-informed, performance based regulatory framework for the present nuclear plants. It will establish means to risk-inform new plant processes, and will provide both design requirements and operational/programmatic requirements for future plants. Operational requirements to be addressed include: security, QA, Radiation Protection, Emergency Planning. This is a "fresh sheet of paper" initiative. However, as progress is made, applicants may evaluate the potential for selective implementation of risk-informed regulations, in order to apply them to individual applications.	NEI has the lead for industry in developing this new framework. The DC-related effort is likely to be a new optional regulation (e.g., Part 53) to address the safety design and operating criteria for all design concepts (e.g., LWR, HTGR, LMR), to permit consistent specifications for each design, to be developed in separate Regulatory Guides. Part 53 would seek to develop risk-informed, performance-based requirements for each design concept. This will take about 3 years. Prior to completion, industry would proceed to license new plants based on existing regulations, with later DC / COL applications using this new rule. Progress on NRC's Option 2 and Option 3 in SECY-98-300 for risk-informing the regulations could be applied here (Option 2 for application of new special treatment requirements to new plants; Option 3 for application of LBLOCA and leak-before-break technology to new plants).	0.5	1	1	1	0.5				4	---	**8**
					2	2					---	4	
			0.5	**1**	**3**	**3**	**0.5**						

No.	TASK	DISCUSSION	FY 02	FY 03	FY 04	FY 05	FY 06	FY 07	FY 08	FY 09	Total Ind.	Total DOE	TOTAL
GENERIC TECHNICAL TASKS													
G-4	<u>Advanced information management and virtual construction technologies:</u> This task will develop, with industry on a cost-share basis, an integrated, open-architecture information management system that includes plant design and operating characteristics, as-built conditions, and licensing bases. This is a generic, cost-shared task, based on work already underway. The basic technology is available but it needs to be applied in a more integrated form and specifically to nuclear plants.	This task will construct an integrated, open architecture information management system to govern configuration control for the life of the plant. It will include 4-D virtual construction simulation (3-D plus time) of a plant's construction and module installation. It would be used to plan the construction process, to monitor actual construction, to optimize construction management processes, including ITAAC verification, NRC "sign-as-you-go (SAYGO)" ITAAC sign-offs.		1	2	2	1				6	---	**12**
				1	2	2	1				---	6	
				2	**4**	**4**	**2**						
G-5	Expand short term R&D on NPP enhancements. Many technologies currently under development for current plants can benefit new plants. This initiative will examine short-term technologies for rapid infusion into advanced plant applications, including: digital I&C, advanced sensors, fiber optics, self-diagnostics, and human performance products. This is a generic, cost-shared task, drawing on prior work done by DOE and industry.	This effort must be focused and limited to only those technology applications that are ready now or will be ready for application within the next several years. It will be limited to technology applications that can provide a direct and cost-beneficial benefit to NTD designs. It will only examine and apply technologies that can be implemented within existing DCs, and will focus primarily on supporting COL issue closure and FOAKE beyond DC and COL scope.	2	4	4	4	2				16	---	**30**
				4	4	4	2				---	14	
			2	**8**	**8**	**8**	**4**						
TOTAL GENERIC FUNDING REQUIREMENTS			3	8	8.5	8	3.5				31	---	**55**
				5	8	8	3				---	24	
			3	**13**	**16.5**	**16**	**6.5**						

No.	TASK	DISCUSSION	FY 02	FY 03	FY 04	FY 05	FY 06	FY 07	FY 08	FY 09	Total Ind.	Total DOE	TOTAL
DESIGN-SPECIFIC TECHNICAL TASKS (Note 1)													
D-1	ABWR	ABWR certified, design complete											
D-2a	ESBWR FDA/DC	GE intends to obtain a DC for ESBWR prior to seeking COL applicants and orders.		5	5	5					15	---	**30**
				5	5	5					---	15	
				10	**10**	**10**							
D-2b	ESBWR FOAKE	FOAKE costs for ESBWR are rough estimates.			10	40	50	40	10		150	---	**300**
					10	40	50	40	10		---	150	
					20	**80**	**100**	**80**	**20**				
D-3a	AP600/AP1000 FDA/DC	AP1000 DC will be based largely on AP600 DC, obtained from NRC in 1998. Expedited DC should be possible.	6	3	2	0.3					11.3	---	**30**
			3	6	6	3.7					---	18.7	
			9	**9**	**8**	**4**							
D-3b	AP600/AP1000 FOAKE	Includes all items from Chapter II-5 not specifically listed as DC		12	50	51.7	50				163.7	---	**273**
				9	31	36.3	33				---	109.3	
				21	**81**	**88**	**83**						
D-4a	PBMR pre-application & FDA (incl. fuel testing)	All PBMR reqts. from Chapter II-5 listed in this row	4.6	7.5	7.5	4	3				26.6	---	**85.6**
			2	18.5	18.5	12	8				---	59	
			6.6	**26**	**26**	**16**	**11**						
D-4b	PBMR FOAKE	PBMR PTY has provided initial rough estimates for FOAKE.			50	50	50	50			200	--	**200**

					50	**50**	**50**	**50**					
D-5a	GT-MHR pre-application & FDA (incl. fuel testing)	All GT-MHR reqts. from Chapter II-5 listed in this row	0.4	6.8	13.6	17.5	16.7	11.5	7.5		74	---	**146**
			2	19	18	18	15				---	72	
			2.4	**25.8**	**31.6**	**35.5**	**31.7**	**11.5**	**7.5**				
D-5b	GT-MHR FOAKE	GT-MHR FOAKE needs to be covered by joint US program with Russia for Pu-burning design (DOE-MD & Russian budgets)											
					(40)	(40)	(40)	(40)				(160)	
					(40)	**(40)**	**(40)**	**(40)**					

No.	TASK	DISCUSSION	FY 02	FY 03	FY 04	FY 05	FY 06	FY 07	FY 08	FY 09	Total Ind.	Total DOE	TOTAL
	TOTALS, DESIGN SPECIFIC TASKS **All numbers rounded off to closest $ million**		11	34	138	169	170	102	17		641	---	**1065**
			7	58	88	115	106	40	10		---	424	
			18	**92**	**226**	**284**	**276**	**142**	**27**				
	GRAND TOTAL, SITE-SPECIFIC PLUS GENERIC PLUS DESIGN-SPECIFIC FUNDING REQUIREMENTS **SUMMED IN ROWS FOR INDUSTRY FUNDING, DOE FUNDING, AND TOTAL FUNDING, BY YEAR.** **All numbers rounded off to closest $ million**		17	54	162	187	178	102	17		**717**	—	**1210**
			10	75	111	133	114	40	10		—	**493**	
			27	**129**	**273**	**320**	**292**	**142**	**27**				

All funding levels in $M.

APPENDIX K: BACKGROUND AND SOURCE DOCUMENTS

The following goals and objectives are quoted from other nuclear R&D planning documents for purposes of providing a basis for the goals of the DOE/NERAC Nuclear Technology Roadmap. For completeness, this listing includes both near term and longer-term goals, and thus provides a resource for both this portion of the Roadmap and other portions.

1. **DOE's Office of Nuclear Energy, Science and Technology developed a Strategic Plan for Nuclear Energy in August 2000.** It covered all aspects of DOE-NE's charter. The goal and objective related to nuclear energy supply R&D is as follows:

   > "GOAL 1 - RESEARCH AND DEVELOPMENT
   >
   > Promote the R&D necessary to advance applications of nuclear technologies that improve U.S. energy security, economic vitality, and quality of life.
   >
   > NE engages in a wide array of scientific, medical and engineering research. Our research is aimed at improving our products (isotopes and power systems), creating the next generation of products, and supporting the R&D community in the long-term exploration of innovative ideas. We have developed the following objectives for meeting this goal:
   >
   > OBJECTIVE 1: Conduct competitively selected research aimed at enabling the benefits of nuclear power to be available to future generations."

2. **The DOE "Long-Term Nuclear Technology R&D Plan,"** (July 2000) prepared by NERAC, contains the following goals.

   Related to nuclear energy supply R&D:

   - Advanced fuel cycle R&D: develop (1) improved performance and advanced fuel design for existing light water reactors (Generation II and III) and (2) advanced fuel designs and related fuel cycle requirements for advanced Generation IV reactor designs.
   - Plant operations and control R&D: develop instrumentation, controls, information management and decision making systems for use in nuclear power plants that employ or adapt the latest technological advances in digital instrumentation and controls, communications, and man-machine interface technology including micro-analytical devices and/or "smart" sensors, on-line signal validation, and condition monitoring.
   - Nuclear power R&D: develop advanced nuclear reactor technologies that will allow the deployment of highly safe and economical new nuclear power plants that would be a competitive electricity production alternative in the U.S. and foreign markets, while being responsive to environmental, waste management, and proliferation concerns.

   Related to supporting U.S. energy, environmental, and economic interests in global markets. (DOE Strategic Plan, September 1997, Objective # 4):

- Apply the U.S. technology used to address the above goals to foster increased international trade in U.S. nuclear technologies (Source: Nuclear Energy R&D Strategic Plan, EPRI, June 1997, Corollary Goal # 14).
- Cooperate with foreign Governments and international institutions to develop open energy markets, and facilitate the adoption and export of clean, safe, and efficient energy technologies and energy services. (DOE Strategic Plan, September 1997, Objective 4, Strategy 2). Specifically, support implementation of U.S. Government agreements with Asian-Pacific countries that open enhanced market opportunities for U.S. nuclear industrial suppliers, enabling them to exchange information and export U.S. light water reactor technology and services."

3. **The Joint DOE-EPRI Strategic R&D Plan to Optimize U.S. Nuclear Power Plants"** (November 2000) contains some long-term goals, as follows (note references to earlier DOE & EPRI reports in 1997-99 timeframe):

"Future goal: Provide competitive nuclear energy generation options to meet medium term (5 to 10 years) requirements for adequate and affordable baseload capacity.

R&D Objectives:

1. Maintain a viable nuclear option for future, carbon-free baseload electricity through cooperative technical development activities with U.S. electric industry that would facilitate a U.S. order of an advanced nuclear power plant by 2010 (Source: DOE Strategic Plan, September 1997, Objective 2, Strategy 8).
2. Provide technologies to enable an increasing nuclear share of U.S. generation by 2020.
3. Identify innovative techniques, approaches, and R&D needs to reduce the capital and operating costs of new nuclear plants and the time required to place them in service. (Source: A Strategic Direction for Nuclear Energy in the 21st Century, NEI, May '99)
4. Maintain effective, ongoing processes for transfer and application of technologies developed for advanced reactors to meet current plant needs, and for application of solutions developed for current plant issues to enhance future plant options (Source: Nuclear Energy R&D Strategic Plan, EPRI, June 1997, Corollary Goal #13).
5. Evaluate options for further advances in the ALWR designs in the current ALWR program, to meet future contingencies. Possible contingencies that could require a commitment to more advanced ALWR developments include:
    - Future market requirements for passive ALWRs with a smaller or larger than 600 MWe plant electrical output
    - Innovations to improve ALWR electrical production efficiencies.

(Note that longer term advanced reactor design goals and objectives are covered in DOE's Long Term Nuclear R&D Plan developed by NERAC, and by EPRI's Electricity Supply Roadmap.)

4. **The EPRI Electricity Technology Roadmap** (June 99) is a six-volume set:

- Volume 1: Summary and Synthesis
- Volume 2: Electricity Supply
- Volume 3: Electricity Delivery
- Volume 4: Economic Growth
- Volume 5: Environment
- Volume 6: Sustainability

Volume 2, covering all energy supply options, including nuclear, was completed in Jan. 1999. Volume 1, a strategic overview of the entire Technology Roadmap, was completed in July 1999. Both Volumes focus on long-term strategies, in the 2020 and 2050 time frames. Volume 1 calls for a major expansion of non-emitting generation technologies, including both renewable energy and nuclear energy. It proposes that the U.S achieve sustained annual funding levels of $600M per year by 2010 for nuclear energy R&D aimed at future generation nuclear plants. This figure is intended to represent both industry and government investments to reach roadmap destinations.

Detailed technology destinations and R&D objectives from the EPRI Energy Supply Roadmap (Volume 2) have been factored into the consolidated R&D agenda in this Roadmap.

The "Strategic Bridge Plan for the EPRI Nuclear Power Sector" is just getting underway. This document is intended to form the strategic planning "bridge" between the Energy Supply Roadmap, which looks out 20 – 50 years, and EPRI's Nuclear Power Sector RD&D Plan, which is a tactical plan that looks out 2-3 years. The Strategic Bridge Plan (SBP) will focus on roughly the 5-10-year timeframe and will form the basis for EPRI strategic funding investments in nuclear energy. It will address both strategic R&D needs for current plants (e.g., running existing plants reliably and cheaply for 60 years; achieving cost-risk-focused decision-making), as well as R&D needs for future plants (e.g., building next plants faster and cheaper; developing new nuclear plant designs). The SBP will be highly integrated with NEI and INPO strategic planning documents, as well as government (i.e., DOE, NRC) planning, in order to leverage public and private sector resources.

EPRI's Energy Supply Roadmap (Volume 2), (January 1999) contains the following priority R&D needs:

> "CIRCA-2020 -- Addressing current obstacles that constitute uncertainties that are prohibitive to potential investments in new nuclear plants:
>
> 1. Close residual embedded technology gaps, complete cost-effective designs of, and construct the facilities needed to implement the spent fuel management and low-level radioactive waste disposal systems.
> 2. Investigate and establish which of the many specific deterministic and prescriptive regulations and regulatory decisions applied to nuclear power plant design, construction, inspection, testing, operation, and maintenance are replaceable by

significantly more cost-effective risk-based regulations and decisions, develop technical bases for such risk-based replacements, and negotiate their acceptance for application to future nuclear power plants.

CIRCA 2020 -- essential to both new plants, and continuing and extended high performance of existing plants:

3. Continue the ongoing utility-sponsored technology development, and implement the planned industry/government technology development, designed to reduce the operational costs and enhance the capacity factors of the existing U.S. plants and extend their lives.

CIRCA 2020--most promising tasks to reduce costs of new plants:

4. Adapt advanced electronic information management technologies to create a plant information management system that seamlessly serves the life-cycle of future nuclear power plants.
5. Adapt and apply emerging advanced modular and construction technologies to future nuclear power plants.

CIRCA 2050:

6. Determine the most cost-effective choices for basic features of higher-fuel-utilization nuclear power plants options & their associated fuel cycles, such as fertile material, fuel form, reactor coolant, energy conversion equipment configuration, fuel cycle technology
7. Pursue breakthroughs in high-temperature helium cooled reactor technology that will support temperatures high enough for process-heat applications
8. Determine the most cost-effective & practicable features of the nuclear fusion option and establish and maintain a credible estimate of its economic potential, focusing on establishing viable approaches to materials and engineering challenges in transferring heat from fusion."

Finally, for historical completeness, the following fourteen ALWR Policies from the **ALWR Utility Requirements Document** (1991) are provided:

Simplification. Simplification is fundamental to the ALWR success. Simplification opportunities are to be pursued with very high priority and assigned greater importance in design decisions than has been done in recent, operating plants; simplification is to be assessed primarily from the standpoint of the plant operator.

Design Margin. Like simplification, design margin is considered to be of fundamental importance and is to be pursued with very high priority. It will be assigned greater importance in design decisions than has been done in recent, operating plants. Design margins that go beyond regulatory requirements are not to be traded off or eroded for regulatory purposes.

Human Factors. Human factors considerations will be incorporated into every step of the ALWR design process. Significantly improvements will be made in the main control room design.

Safety. The ALWR design will achieve excellence in safety for protection of the public, on-site personnel safety, and investment protection. It places primary emphasis on accident prevention as well as significant additional emphasis on mitigation. Containment performance during severe accidents will be evaluated to assure that adequate containment margin exists.

Design Basis vs. Safety Margin. The ALWR design will include both safety design and safety margin requirements. Safety design requirements (referred to as the Licensing Design Basis [LDB]) are necessary to meet the NRC's regulations with conservative, licensing-based methods. Safety margin requirements (referred to as the Safety Margin Basis [SMB]) are Plant Owner-initiated features, which address investment protection and severe accident prevention and mitigation on a best estimate basis.

Regulatory Stabilization. ALWR licensability is to be assured by resolving open licensing issues, appropriately updating regulatory requirements, establishing acceptable severe accident provisions, and achieving a design consistent with regulatory requirements.

Standardization. The ALWR requirements will form the technical foundation that leads the way to standardized, certified ALWR plant designs.

Proven Technology. Proven technology will be employed throughout the ALWR design in order to minimize investment risk to the plant owner, control costs, take advantage of existing LWR operating experience, and assure that a plant prototype is not required; proven technology is that which has successfully and clearly demonstrated in LWRs or other applicable industries such as fossil power and process industries.

Maintainability. The ALWR will be designed for ease of maintenance to reduce operations and maintenance costs, reduce occupational exposure, and to facilitate repair and replacement of equipment.

Constructibility. The ALWR construction schedule will be substantially improved over existing plants and must provide a basis for investor confidence through use of a design-for-construction approach, and completed engineering prior to initial construction.

Quality Assurance. The responsibility for high quality design and construction work rests with the line management and personnel of the Plant Design and Plant Constructor organizations.

Economics. The ALWR plant will be designed to have projected busbar costs that provide sufficient cost advantage over the competing baseload electricity generation technologies to offset higher capital investment risk associated with nuclear plant utilization.

Sabotage Protection. The design will provide inherent resistance to sabotage and additional sabotage protection through plant security and through integration of plant arrangements and system configuration with plant security design.

Good Neighbor. The ALWR plant will be designed to be a good neighbor to its surrounding environment and population by minimizing radioactive and chemical releases.

APPENDIX L: REFERENCES

Documents reviewed in the development of this Roadmap include:

1. "Strategic Plan for Nuclear Energy," DOE Office of Nuclear Energy Science and Technology, August 2000

2. "Long-Term Nuclear Technology R&D Plan," NERAC, July 2000

3. "Nuclear Energy Industry's Strategic Plan for Building New Nuclear Power Plants," eight revisions from Nov. 1990 to Nov. 1998.

4. "Strategic Direction for Nuclear Energy in the 21st Century," NEI, May 1999 – May 2000.

5. "Energy Supply Roadmap" (Volume 2) EPRI, January 1999, and an new complementary document, "Strategic Bridge Plan for the EPRI Nuclear Power Sector."

6. "ALWR Utility Requirements Document" EPRI, 1991

7. "Joint DOE-EPRI Strategic R&D Plan to Optimize U.S. Nuclear Power Plants," November 2000 (Note this Plan relates primarily to current plants, but does contain long term goals).

8. "National Energy Policy," Report of the National Energy Policy Development Group, May 2001

9. Congressional Testimony (R. Hutchinson, Entergy, March 27 and July 17, 2001; Joe Colvin (NEI), 8 May 2001; Oliver Kingsley (Exelon), 8 May 2001; Marv Fertel (NEI), 27 June and 12 July, 2001; Maurine Koetz (NEI), 10 July 2001.

Information on most of these reports can be found in Chapter II-2 or Appendix K.

Appendix M: Acronyms

ABWR	Advanced Boiling Water Reactor
AC	alternating current
ALWR	Advanced Light Water Reactor
ANS	American Nuclear Society
ASME	American Society of Mechanical Engineers
BNFL	British Nuclear Fuels, Limited
BTU	British Thermal Unit
BWR	Boiling Water Reactor
CAD	Computer Aided Drawing
CANDU	Canadian Deuterium (reactor)
CFR	Code of Federal Regulations
COL	Combined Operating License
CP/OL	Construction Permit/Operating License
CRD	Control Rod Drive
CRDM	Control Rod Drive Mechanism
DC	direct current
DNBR	Departure from Nucleate Boiling Ratio
DOE	U.S. Department of Energy
DOE-NE	DOE Office of Nuclear Energy, Science, and Technology
EDF	Electricite de France
EIA	Energy Information Agency (DOE)
EPA	Environmental Protection Agency
EPACT	Energy Policy Act
EPC	Engineering, Procurement and Construction
EPR	European Pressurized water Reactor
EPZ	Emergency Planning Zone
EPRI	Electric Power Research Institute
ESBWR	European Simplified Boiling Water Reactor
ESP	Early Site Permit
EUR	European Utility Requirements
FANP	Framatome ANP
FDA	Final Design Approval
FEMA	Federal Emergency Management Agency
FERC	Federal Energy Regulatory Commission
FMCRD	Fine Motion Control Rod Drive
FOAK	First of a Kind
FOAKE	First of a Kind Engineering
FTE	First Time Engineering
G&A	General and Administrative
GA	General Atomics
GE	General Electric
GE/NE	General Electric Nuclear Energy
GEN IV	Generation IV
GNF	Global Nuclear Fuels

GRNS	Generation IV Roadmap NERAC Subcommittee
GT-MHR	Gas Turbine-Modular Helium Reactor
HTGR	High Temperature Gas Reactor
IAEA	International Atomic Energy Agency
IDC	Interest during construction
INPO	Institute of Nuclear Power Operations
IPP	Independent Power Producer
IRIS	International Reactor Innovative and Secure
ISO	Integrated System Operator
ITAAC	Inspections, Tests, Analysis and Acceptance Criteria
kWe	kilo-Watt Electric
LEU	Low Enriched Uranium
LOCA	Loss of Coolant Accident
LTA	Lead Test Assembly
LWR	Light Water Reactor
MCP	Market Clearing Price
MHI	Mitsubishi Heavy Industries
MHTGR	Modular High Temperature Gas Reactor
MOU	Memorandum of Understanding
MOX	Mixed Oxide (fuel)
MWe	Mega Watt electric
MWH	Mega Watt Hour
MWth	Mega Watt thermal
NCCTI	National Climate Change Technology Initiative
NEER	Nuclear Engineering Educational Research
NEI	Nuclear Energy Institute
NEP	National Energy Policy
NEPO	Nuclear Energy Plant Optimization
NERAC	Nuclear Energy Research Advisory Committee
NERI	Nuclear Energy Research Initiative
NOAK	Nth of a Kind
NOX	Nitrous Oxides
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission
NSSS	Nuclear Steam Supply System
NTD	Near Term Deployment
NTDG	Near Term Deployment Group
O&M	Operations and Maintenance
OKBM	Experimental Machine Building Design Bureau (Russia)
O/O	Owner/Operator
OSHA	Occupational Safety and Health Administration
PBMR	Pebble Bed Modular Reactor
PCAST	President's Committee of Advisors on Science and Technology
PCT	Peak Centerline Temperature
PPA	Power Purchase Agreement
PRA	Probabilistic Risk Assessment

PUC	Public Utility Commission
PWR	Pressurized Water Reactor
QA	Quality Assurance
QC	Quality Control
RFI	Request for Information
RMR	Regulation Must Run
ROI	Return on Investment
RPV	Reactor Pressure Vessel
RSA	Republic of South Africa
RSK	Reactor Safety Commission (Germany)
RTO	Regional Transmission Organization
SBWR	Simplified Boiling Water Reactor
SECY	NRC Office of the Secretary
SER	Safety Evaluation Report
SNF	Spent Nuclear Fuel
SSAR	Standard Safety Analysis Report
SSC	Systems, Structures, and Components
STUK	Radiation and Nuclear Safety Authority (Finland)
T&D	Transmission and Distribution
TEPCO	Tokyo Electric Power Company
TMI-2	Three Mile Island (Unit 2)
TRAC	Transient Reactor Analysis Code
TWG	Technical Working Group
URD	Utility Requirements Document
USCEA	US Council for Energy Awareness
V&V	Validation and Verification
WANO	World Association of Nuclear Operators

ATTACHMENT 1: MISSION OF THE NEAR-TERM DEPLOYMENT GROUP

The Near-Term Deployment Group (NTDG) shall identify technological and institutional gaps between the current state of the art and the necessary conditions to deploy new nuclear plants in the United States before 2010. In order to meet U.S. near-term requirements for affordable baseload capacity additions by 2010, at least one competitive nuclear energy generation option, NRC-certified and/or ready to construct, must be available by 2005. By 2010, the U.S. needs a range of competitive, NRC-certified and/or ready to construct nuclear energy generation options of a range of sizes to meet variations in market need, supported by sufficient fabrication, construction and human infrastructure to enable simultaneous, large-scale deployment across the U.S. Multiple standardized nuclear power plants should be under construction this decade, with lead plants achieving operational status by EOY 2010.

The scope of the NTDG shall encompass those nuclear power plants technologies that meet the following six criteria:

1. Credible plan for gaining regulatory acceptance - Candidate technologies must show how they will be able to receive either a construction permit for a demonstration plant or a design certification by the U.S. NRC within the time frame required to permit plant operation by 2010 or earlier.
2. Existence of industrial infrastructure - Candidate technologies must be able to demonstrate that a credible set of component suppliers and engineering resources exist today, or a credible plan exists to assemble them, which would have the ability and the desire to supply the technology to a commercial market in the time frame leading to plant operation by 2010 or earlier.
3. Credible plan for commercialization - A credible plan must be prepared which clearly shows how the technology would be commercialized by 2010 or earlier, including market projections, supplier arrangements, fuel supply arrangements and industrial manufacturing capacity.
4. Cost-sharing between industry and Government - Technology plans must include a clear delineation of the cost categories to be funded by Government and the categories to be funded by private industry. The private/Government funding split for each of these categories must be shown along with rationale for the proposed split.
5. Demonstration of economic competitiveness - The economic competitiveness of candidate technologies must be clearly demonstrable. The expected all-in cost of power produced is to be determined and compared to existing competing technologies along with all relevant assumptions.
6. Reliance on existing fuel cycle industrial structure - Candidate technologies must show how they will operate within credible fuel cycle industrial structures, i.e., they must utilize a once-through fuel cycle with LEU fuel and demonstrate the existence of, or a credible plan for, an industrial infrastructure to supply the fuel being proposed.

The NTDG shall report directly to the Department of Energy Near Term Deployment (NTD) Manager and brief and receive advice from the Generation IV Roadmap NERAC Subcommittee as the NTD Manager directs. It shall also maintain a coordination relationship with the Nuclear Energy Institute (NEI) Executive Task Force on New Nuclear Power Plants, assuring close cooperation with ongoing industry activities.

Initial Work Product: The primary objective and initial work product of the NTDG is to develop an input to the overall Generation IV Roadmap that identifies all the institutional barriers and technological gaps that could prevent achieving the near term deployment needs discussed above. This input should be prepared on an urgent basis as a stand-alone document for use in spring 2001 to inform federal energy policy makers on urgent needs that could be included in developing national energy policy and energy appropriations. This input could also be used by NEI and industry leaders to prioritize their activities on behalf of a new energy policy, and to plan public-private partnership investment strategies.

This initial NTDG work product shall specifically include recommendations for funding priorities from FY2002 and FY2003. This initial roadmap input shall provide a systematic and defensible basis for future federal and industry investments.

Final Work Product: The NTDG will later expand this initial Roadmap input in support of spring 2001 needs, into a more complete document that provides a more direct and useful contribution to the overall Generation IV Roadmap effort. In order to develop this document, the NTDG will solicit and assess non-proprietary design-specific information from potential suppliers and/or potential customers of reactor technologies that meet the above screening criteria. This information should address how the subject technology meets each of the above criteria, what specific technological and institutional gaps exists which must be addressed to allow successful commercialization of the technology, and the cost, schedule and deliverables that would be required.

Based upon the initial mid-2001 Roadmap input and the design-specific information above, the working group shall also develop and include in this document complete estimates of the resources (schedule and funding levels) required to close the gaps in time to meet the deployment goals (achieving new nuclear plant orders by 2005 and a range of options with robust implementation infrastructure on or before 2010). The estimates will be included in the more complete roadmap for near-term deployment provided as a final report of this Group to the DOE Generation IV roadmapping effort. This document will be complete by 9/30/2001.

Liaison: The NTDG will work closely with other Working Groups in the broader Generation IV program to share information, exchange information and conclusions; and to ensure NTWG work products are useful as an input to longer term Roadmap development.

The NTDG shall be comprised of two co-chairmen from industry with representation from industry, vendors, national laboratories and academia.

ATTACHMENT 2: NTD REQUEST FOR INFORMATION

This attachment provides a copy of Sections 1 and 2a of the Near Term Deployment Request for Information, issued by DOE on March 31, 2001. These sections gave respondents the key content information and questions they needed that amplified on the six design criteria and generic gap discussion in Chapter II-1. Other portions of the RFI were administrative in nature and/or provided details on requested format and are not repeated here.

Section 1:

Request for Information on Specific Candidate Near Term Deployment Options

The primary audience for this section is the plant designer or design team (vendors, A/Es, etc.), although owner-operators and others are also invited to provide their inputs and perspectives (e.g., views on validity and priority of evaluation criteria).

Nuclear design companies or teams are asked to show how their nuclear plant designs (including nuclear systems and power conversion/balance-of-plant systems) satisfy the six screening criteria. The six evaluation criteria are provided below, with an expanded discussion of the specific types of information requested. Responses to each of these six criteria should be as brief as possible (e.g., 2-4 pages each).

For each criterion, the text below provides a description of the specific information requested and/or a series of questions to be answered. It is important that the respondent provide as much relevant information as possible, within the suggested limit above. However, if the specific questions or information requested are not directly applicable to the respondent's design, or the information is not yet available in the form or detail requested, please provide the best available input.

Criterion 1: Regulatory Acceptance:

"Credible plan for gaining regulatory acceptance - Candidate technologies must show how they will be able to receive either a construction permit for a demonstration plant or a design certification by the U.S. Nuclear Regulatory Commission (NRC) within the time frame required to permit plant operation by 2010 or earlier."

For already certified designs, this criterion requires that the respondent provide a credible plan to resolve any remaining design-specific COL issues and to show that any other regulatory considerations (e.g., construction inspection) can be managed so as to permit operation by 2010.

For designs that are not certified, this criterion requires that the respondent provide a credible plan for gaining regulatory approval for the design, to include obtaining a design certification or a construction permit and operating license for a first plant, as well as a credible plan for managing the regulatory aspects of construction, test and start up of the first unit by 2010.

In responding to this criterion, the plan for obtaining a construction permit or design certification should include (but is not limited to) answers to the following:

1. Describe how the technology will comply with current regulatory requirements or a proposed alternative regulatory approach, and summarize the scope of the documentation that will be submitted to the NRC.
2. Summarize the most significant issues expected in the review by the NRC.
3. Identify the most significant risks to completion of the NRC review on schedule, accompanied by explanations of how those risks will be managed, etc.
4. Provide a timeline and identify major milestones in the submittal and the review schedule for conducting the NRC review, including Inspections, Tests, Analysis, and Acceptance Criteria (ITAAC) implementation during construction.
5. Summarize interactions that have already taken place with the NRC concerning plans for review of the candidate technology.

Criterion 2: Industrial Infrastructure:

"Existence of industrial infrastructure - Candidate technologies must be able to demonstrate that a credible set of component suppliers and engineering resources exist today, or a credible plan exists to assemble them, which would have the ability and the desire to supply the technology to a commercial market in the time frame leading to plant operation by 2010 or earlier."

(Note: no discussion of fuel cycle infrastructure should be included here, since that is covered under Criterion 6.)

Please answer the following, addressing generic and design-specific issues as well as hardware and personnel issues.

1. Describe the industrial infrastructure in place today to construct one nuclear unit in the U.S. by 2010. If an element of infrastructure is not in place, please identify it and give anticipated dates for when the element is needed and will be in place.
2. Describe the industrial infrastructure in place today to construct multiple nuclear units in the U.S. by 2010. If not in place, please identify the missing element(s) and give the anticipated dates for when the element(s) are needed and will be in place.
3. Identify the top 3-5 generic areas where today's available infrastructure is not adequate to permit construction and startup of multiple units of your nuclear design. This question is intended to identify common infrastructure needs (e.g., n-stamp valve manufacturers, reactor core physics engineers) that many or most near term deployment options see as important gaps in the nuclear infrastructure. Prioritize if possible.
4. Describe the extent to which structures, systems and components can be constructed, manufactured, or procured according to commercial standards (as opposed to safety grade).
5. Identify the longest lead time component for your design and the time required to manufacture it.

Criterion 3: Commercialization Plan:

"Credible plan for commercialization - A credible plan must be prepared which clearly shows how the technology would be commercialized by 2010 or earlier, including market projections, supplier arrangements, fuel supply arrangements and industrial manufacturing capacity."

Commercialization requires bringing a nuclear power plant based on proven technology to the market with a predictable schedule and within the owner(s) targeted cost. Commercialization also entails meeting the established operating performance requirements so as to meet the shareholders expected return on investment (ROI).

Provide a realistic plan that clearly shows how your design would be commercialized. Include a general description of project responsibilities and financial participation by team members.

Criterion 4: Cost Sharing Plan:

"Cost-sharing between industry and Government - Technology plans must include a clear delineation of the cost categories to be funded by Government and the categories to be funded by private industry. The private/Government funding split for each of these categories must be shown along with rationale for the proposed split."

1. Delineate the cost categories (for all activities, including licensing, engineering, construction, etc.) that you believe should be funded, all or in part, by the Government, and those categories that should be funded by private industry or non-Government sponsors. Identify which private industry organizations (or, at least, types of organizations) would be expected to provide the funding. If funding is already being provided toward your particular design, identify the sources, to the extent possible.
2. For any of the above activities that you suggest receive any government funding, please describe the recommended funding split between Government and private industry and non-government partners, as well as the rationale for the proposed split. The rationale should identify the responsibilities of individual parties that would justify their expenditure.
3. Describe any non-direct cost-share provisions or incentives that you believe the Government should provide, e.g., loan guarantees, tax credits, etc. Identify whether any of these are viewed as necessary to assure success of your candidate technology.

Criterion 5: Economic Competitiveness:

"Demonstration of economic competitiveness - The economic competitiveness of candidate technologies must be clearly demonstrable. The expected all-in cost of power produced is to be determined and compared to existing competing technologies along with all relevant assumptions."

Respondents are requested to provide plant-specific cost data in order to compute the all-in total generation costs of near-term nuclear plants, likely to reach commercial operation by 2010.

Plant Capital Cost Data

The data requested should be provided in units of Million Dollars or $/kWe in year 2000 dollars. For all the data items requested please provide your nominal value as well as a high-low range around the nominal value. Information is requested here for:

1. Net plant electric capacity, (for modular plants, please specify the configuration and number of modules); plant engineering, procurement, construction (EPC) cost; project startup and development costs; owners costs and contingency; and post construction costs. Please indicate the particular site (or which NERC region) these cost estimates are based upon.
2. Project start date; project development period from order until construction starts; project construction time period; post-construction time period; and commercial operation date.
3. Cost escalation rate during construction, above inflation (inflation assumptions are not required if input is provided in constant year 2000 dollars).
4. For modular plants, if more than one module is expected to reach commercial operation before 2010, please provide the above information request for each module.
5. Please provide the above requested data for the first-of-a-kind (FOAK) plant expected to reach commercial operation by 2010, and for the subsequent Nth-of-a-kind (NOAK) plant. Please specify your definition for NOAK.

First Deployment Costs vs. Nth of a Kind (NOAK) Costs

Please provide your assessment and cost breakdown for the difference between the FOAK and the NOAK plants. The first plant deployment costs are defined as the incremental costs of specific activities that need to be completed to deploy the first nuclear plants in this decade. These would be costs above and beyond those included in the FOAK costs above. Typical costs could include estimates of the following:

- Completing the ESP licensing process,
- Resolving all NRC COL procedural issues and of obtaining the first COL from NRC,
- Resolving any remaining generic licensing issues,
- Reactivating domestic equipment components manufacturing infrastructure,
- Incremental costs of manufacturing long lead-time heavy components abroad,
- Hiring and training A/E and vendor nuclear manpower required for the plant construction and deployment process, and
- Covering any other incremental or contingency costs for the FOAK plant.

Other Plant Cost Components

Other cost components of the total life-cycle generation costs for the near-term plants. These costs can be expressed in cost accounting units such as $/MWh, $/Yr.-Yr., or M$/Yr., all reported in year 2000 dollars. Please provide information for the following cost components:

1. Annual O&M costs and breakdown of annual O&M costs into fixed and variable cost components.
2. Annual fuel costs, and full-load net heat rate.
3. Annual capital addition costs (if any).
4. Expected plant operating lifetime.

5. Projected availability and annual averaged capacity factors.
6. Decommissioning sinking-fund annual payment.
7. Other annual costs such as G&A, taxes

Please indicate if you expect escalation (above inflation) in any of the cost components mentioned above.

Criterion 6: Fuel Cycle Industrial Structure:

"Reliance on existing fuel cycle industrial structure - Candidate technologies must show how they will operate within credible fuel cycle industrial structures, i.e., they must utilize a once-through fuel cycle with LEU fuel and demonstrate the existence of, or a credible plan for, an industrial infrastructure to supply the fuel being proposed."

Respondents should provide answers to the following questions:

1. What fuel production facilities, including enrichment, conversion, and fabrication, now exist or will exist (with a time line for operation) to reliably supply the fuel for reactor operation? Your response should include a review of fuel manufacturing capacity for sufficiency and flexibility to handle unanticipated maintenance, QA problems and fuel design changes, while also meeting the plant requirements for an adequate fuel supply for the plant(s) life.
2. If required, what is the strategy for fuel qualification and licensing?
3. How will fuel reliability be assured (e.g., such that the production facilities will meet QA requirements necessary for the plant to operate reliably and within technical specifications)?
4. What assumptions are made regarding the on-site spent fuel storage capability?

Section 2:
Request for Information on Barriers to Near Term Deployment Options

This section identifies all the technical, institutional, and regulatory barriers and gaps that must be addressed to achieve near term deployment. The format for this section is structured for consistency and for assisting in the prioritization, planning, and resource management of actions designed to close these gaps. Respondents are requested to discuss each specific barrier or gap using the format provided below. Each gap analysis response should be limited to 2 pages.

The points addressed under each gap analysis are:

- Gap (short definition of issue)
- Solution or outcome required
- Resource requirements to close gap (total needs, irrespective of source, estimated on an annual basis, FY02-FY10. A simple table to fill-in this data is provided below.
- Responsibility (primary organization(s) and supporting organization(s))
- Anticipated benefits of gap closure in economic and/or schedule terms (e.g., reduction in busbar costs), if feasible. (Note: some gaps are prerequisites that cannot be quantified.)

This section is comprised of two sub-sections:

SECTION 2A: Generic Gaps and Barriers

The primary audiences for this section are owner/operators; although vendors, A/Es, energy policy experts, etc., are invited to provide their inputs and perspectives as well.

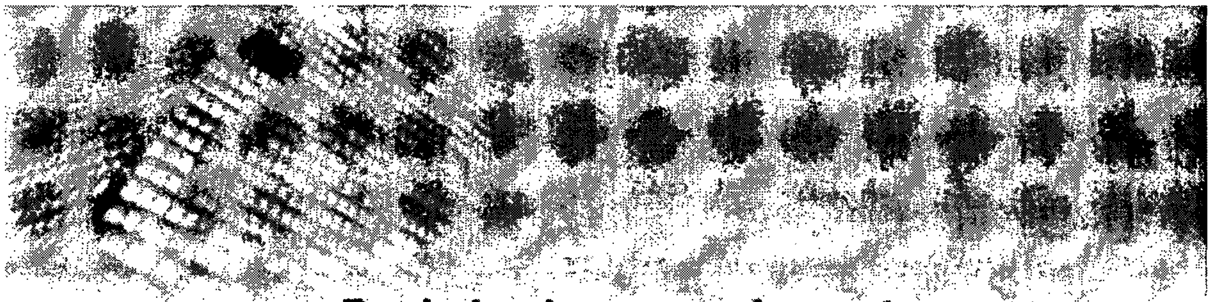
This subsection addresses generic gaps and barriers. These are primarily in the institutional and regulatory areas, but some crosscutting technical gaps (e.g., generic construction technologies) are also included. For this section, significant known gaps are pre-identified below. Respondents are requested to provide their views and add relevant details to the gap analysis (e.g., costs to close gap, responsibility, benefits, etc.). Respondents are requested to identify and analyze any generic gaps not already noted below. Also, respondents should identify instances, if any, where it is judged that an identified gap has been filled or partially filled by other past or ongoing activities, giving references to the work done in this respect.

This section summarizes six gaps and solutions or required outcomes for each. These gaps and solutions are then transcribed into "Gap Analysis for Near Term Deployment" forms later in this section. Respondents are requested to provide further discussion on each of these gaps and solutions on the forms provided. Respondents are also requested to assign a priority to each solution in the table below, using H for High, M for Medium, and L for Low.

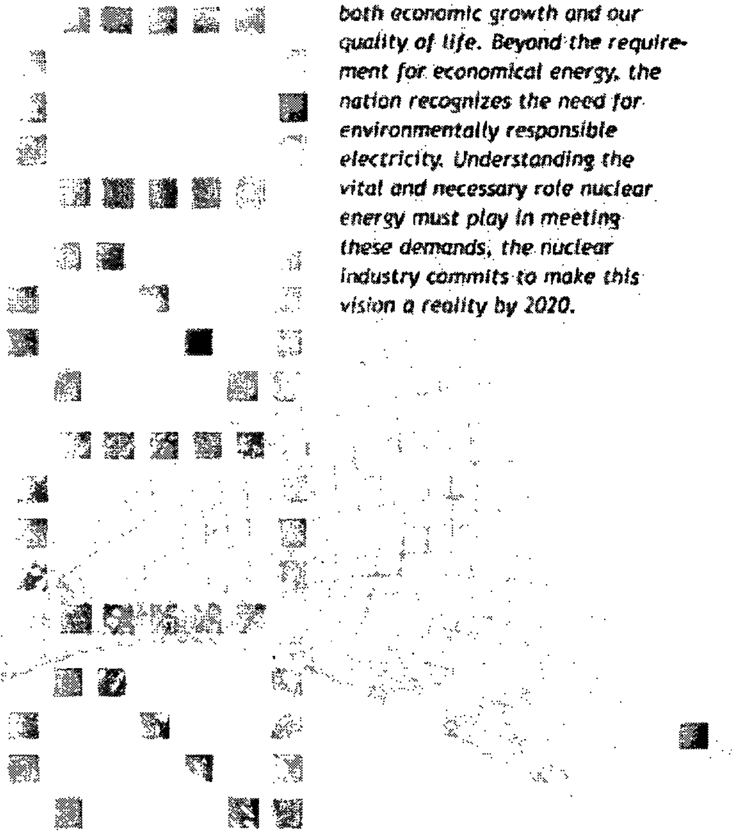
Note that spent fuel management and non-proliferation concerns are considered to be longer term global fuel cycle issues, and are being addressed by the Generation IV Roadmap. Adequate response exists today, or adequate progress is being made on these issues to allow near term new plant construction in the U.S. They are not appropriate issues for this near term gap analysis.

Gap	Solution or Required Outcome	Priority (H, M, L)
Lack of demonstrated process for obtaining an Early Site Permit	1. Develop generic guidance on all aspects of ESP and obtain NRC concurrence in advance of ESP filings	
	2. Demonstrate NRC's ESP process for each likely siting scenario	
Lack of demonstrated process for obtaining a Combined Construction and Operating License	1. Develop generic guidance on all aspects of COL and obtain NRC concurrence in advance of COL filings	
	2. Demonstrate NRC's COL process for each NTD design option	
Lack of an appropriate Risk-Informed, Performance-Based regulatory process for licensing decisions	1. Develop risk-informed performance-based regulatory framework for future design certifications of new plants	
	2. Develop a means for streamlined demonstration, regulatory approval, & infusion of new technologies	
Lack of closure with NRC on major COL issues that can affect construction schedule and cost-effective plant operation	1. Establish an efficient process for construction inspection and ITAAC sign-off	
	2. Develop a generic, risk-informed, and appropriate basis for new plant physical plant security.	
	3. Develop a generic, risk-informed regulatory basis for appropriate emergency planning.	
Lack of assurance that nuclear plants will be cost leader in new generation (with focus on generic solutions that will further reduce busbar costs relative to competing options)	1. Adapt advanced fabrication, modularization and construction technologies including time-sequenced virtual construction.	
	2. Adapt and standardize advanced information management system open architectures for life-cycle design, procurement, construction, maintenance, and engineering/licensing management	
	3. Develop standardized advanced man-machine interface systems for plant safety and control, including advanced sensors, programmable controllers, fiber optics, self-diagnostics, and human performance technologies	
	4. Systematically evaluate other opportunities (in addition to those above) to reduce plant construction time. Evaluate technologies, techniques, and human resource opportunities	
Lack of assurance that nuclear plants will be cost leader in new generation (design-specific)	Design-specific refinements – see Section 2 B	

ATTACHMENT 3: NUCLEAR ENERGY INSTITUTE'S VISION 2020



Positioning today's nuclear energy industry to meet tomorrow's energy challenges



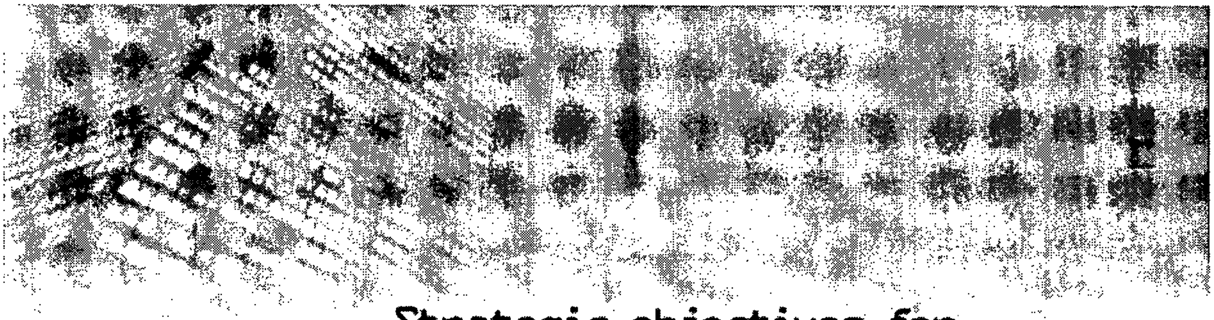
The Department of Energy projects the need for about 50 percent more electricity in the United States by 2020. Reasonably priced energy for consumers is the foundation for both economic growth and our quality of life. Beyond the requirement for economical energy, the nation recognizes the need for environmentally responsible electricity. Understanding the vital and necessary role nuclear energy must play in meeting these demands, the nuclear industry commits to make this vision a reality by 2020.

Vision 2020

Nuclear energy is widely recognized as a safe, reliable, competitive and environmentally sound source of electricity. In the two decades since the turn of the century, 50,000 megawatts of new nuclear generating capacity has been added to the grid. The domestic and international industry supporting the existing and new capacity is robust and competitive.

Policymakers and the public are demanding further increases in the share of sustainable nuclear energy to satisfy economic growth and environmental objectives.

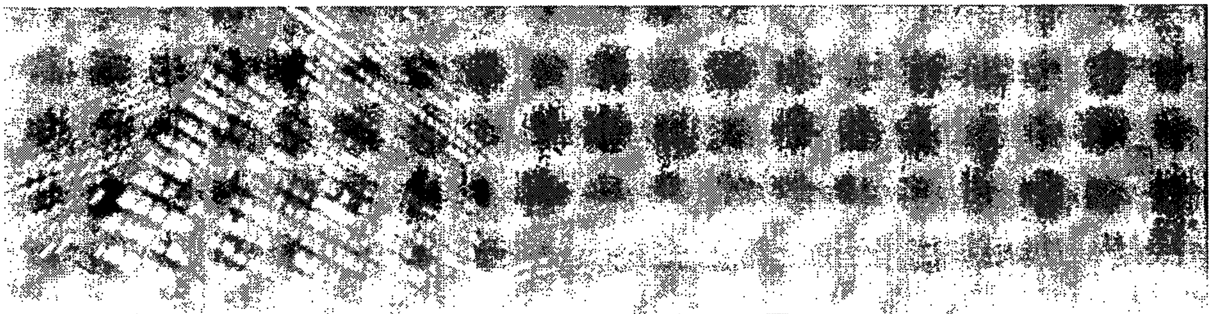
Nuclear technologies are widely used in medicine, food safety, water management and to produce complementary clean fuels such as hydrogen. U.S. leadership continues to be demonstrated in the deployment of nuclear technology on a global basis.



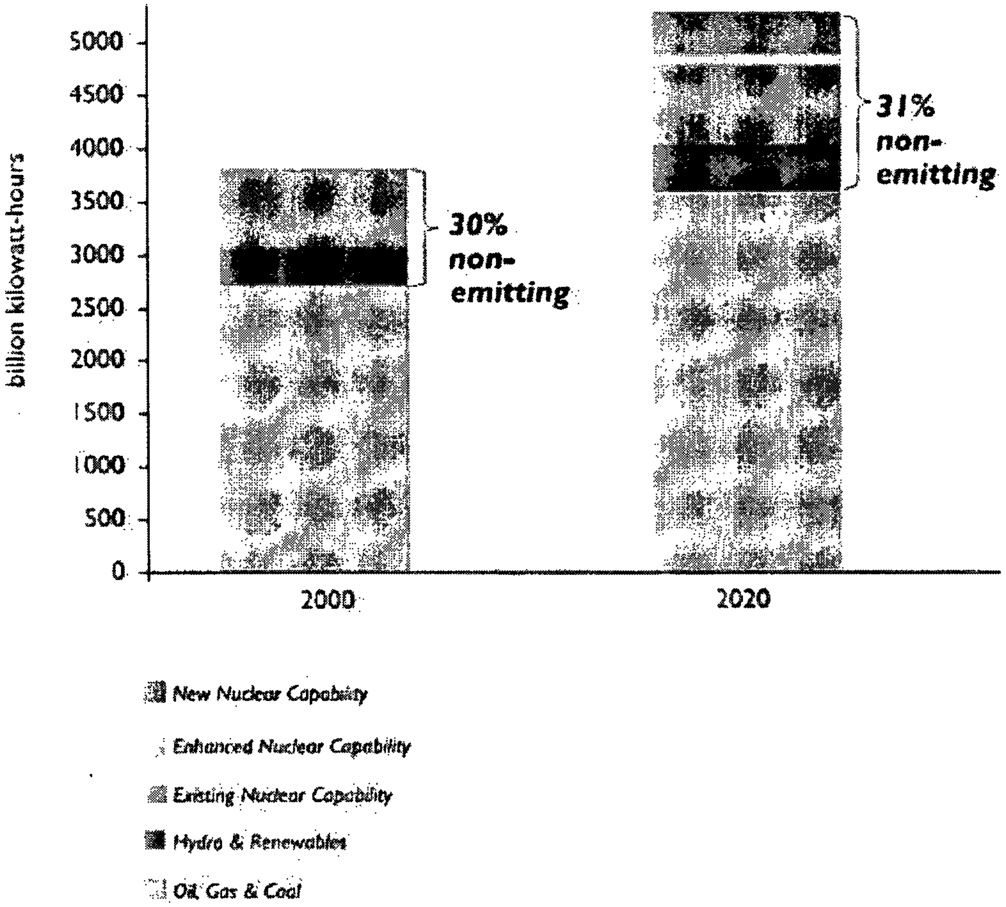
Strategic objectives for building nuclear energy's future

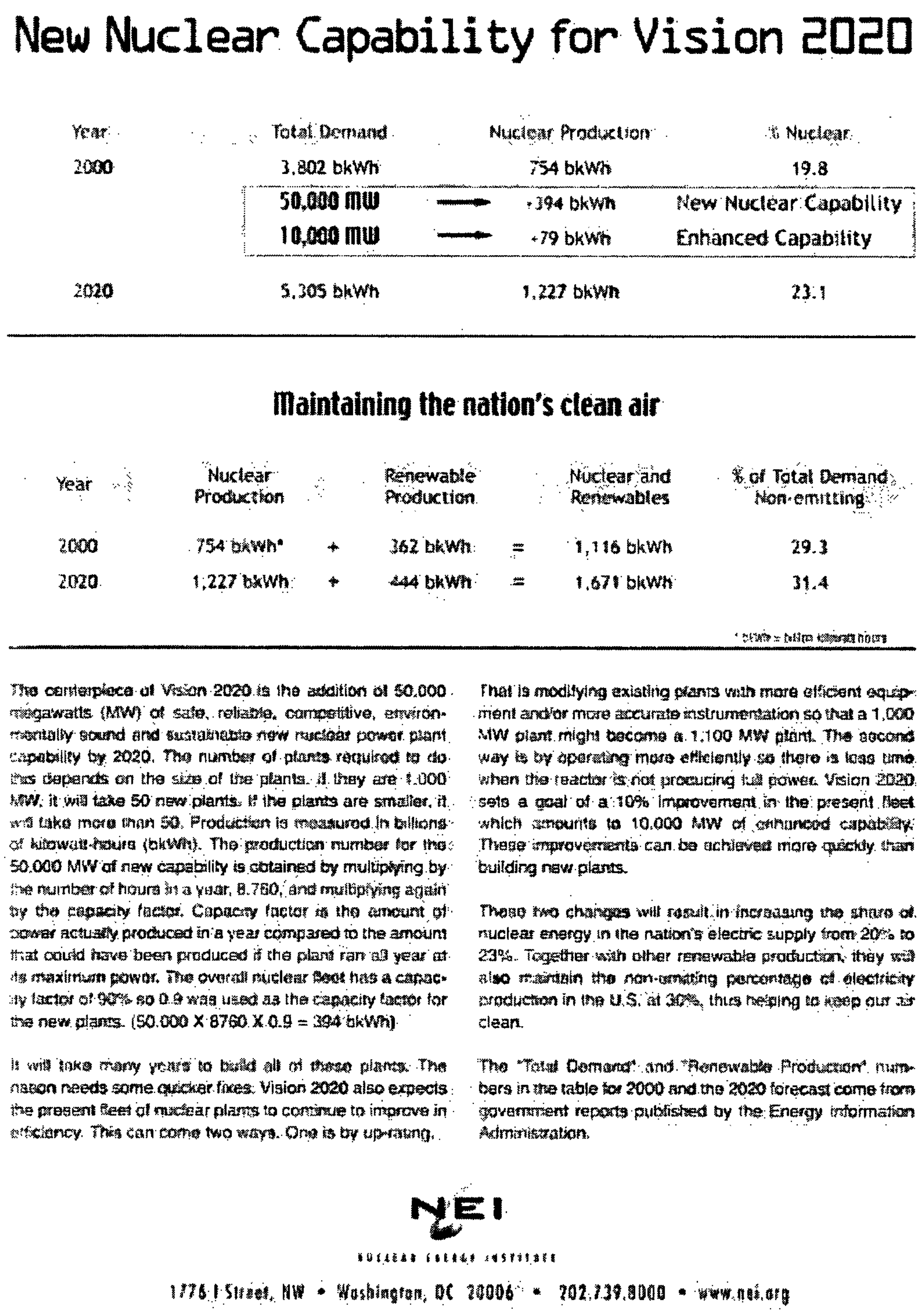
From Renaissance to Reality

- Attain prominent, equitable acknowledgement of nuclear energy in national and international energy and environmental policy.
- Maintain excellence in safe, reliable nuclear energy operations and consistent, predictable regulatory processes.
- Attain an integrated, robust nuclear fuel cycle.
- Maximize the value of nuclear energy assets.
- Increase public and policymaker support for nuclear energy and associated technologies.
- Develop the necessary infrastructure and qualified human resources for today and the future.



Preserving Emission-Free Electricity for Vision 2020





New Nuclear Capability for Vision 2020

Year	Total Demand		Nuclear Production	% Nuclear
2000	3,802 bkWh		754 bkWh	19.8
	50,000 MW	→	+394 bkWh	New Nuclear Capability
	10,000 MW	→	+79 bkWh	Enhanced Capability
2020	5,305 bkWh		1,227 bkWh	23.1

Maintaining the nation's clean air

Year	Nuclear Production		Renewable Production		Nuclear and Renewables	% of Total Demand Non-emitting
2000	754 bkWh*	+	362 bkWh	=	1,116 bkWh	29.3
2020	1,227 bkWh	+	444 bkWh	=	1,671 bkWh	31.4

* bkWh = billion kilowatt hours

The centerpiece of Vision 2020 is the addition of 50,000 megawatts (MW) of safe, reliable, competitive, environmentally sound and sustainable new nuclear power plant capability by 2020. The number of plants required to do this depends on the size of the plants. If they are 1,000 MW, it will take 50 new plants. If the plants are smaller, it will take more than 50. Production is measured in billions of kilowatt-hours (bkWh). The production number for the 50,000 MW of new capability is obtained by multiplying by the number of hours in a year, 8,760, and multiplying again by the capacity factor. Capacity factor is the amount of power actually produced in a year compared to the amount that could have been produced if the plant ran all year at its maximum power. The overall nuclear fleet has a capacity factor of 90% so 0.9 was used as the capacity factor for the new plants. (50,000 X 8760 X 0.9 = 394 bkWh)

It will take many years to build all of these plants. The nation needs some quicker fixes. Vision 2020 also expects the present fleet of nuclear plants to continue to improve in efficiency. This can come two ways. One is by up-rating. That is modifying existing plants with more efficient equipment and/or more accurate instrumentation so that a 1,000 MW plant might become a 1,100 MW plant. The second way is by operating more efficiently so there is less time when the reactor is not producing full power. Vision 2020 sets a goal of a 10% improvement in the present fleet which amounts to 10,000 MW of enhanced capability. These improvements can be achieved more quickly than building new plants.

These two changes will result in increasing the share of nuclear energy in the nation's electric supply from 20% to 23%. Together with other renewable production, they will also maintain the non-emitting percentage of electricity production in the U.S. at 30%, thus helping to keep our air clean.

The "Total Demand" and "Renewable Production" numbers in the table for 2000 and the 2020 forecast come from government reports published by the Energy Information Administration.

NEI

NUCLEAR ENERGY INSTITUTE

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ATTACHMENT 4: NEI'S INTEGRATED PLAN FOR NEW NUCLEAR PLANTS

Plan Overview

The purpose of this plan is to support the business decisions on new nuclear plant construction that are expected in the near future. The business entities making the decisions to build new nuclear plants will need sound estimates of costs and schedules. Many of the cost and schedule drivers are design/project specific and well understood; others are based upon external factors that are less certain and affect the confidence in project estimates. This plan is focused on reducing uncertainties related to these external factors to enable informed business decisions on new nuclear plant projects.

The plan to address these external uncertainties is organized into four broad areas of activity:

- **New Plant Economics and Project Structure** – Activities in this area are focused on enhancing the economics of new nuclear plants through energy policy initiatives, innovative project structures, improved capital cost and schedule estimates, and modernizing NRC financial-related requirements.
- **Predictable Licensing and Stable Regulation** – Activities in this area are focused on reducing the "time-to-market" for new nuclear plants by ensuring well understood processes are in place for predictable and efficient licensing, construction, start-up and operation of new nuclear plants. Reducing time-to-market is a key factor in business decisions to build new nuclear plants.
- **Policymaker and Public Support** – Activities in this area are focused on enhancing support for new nuclear plant construction among policymakers and opinion leaders.
- **Nuclear Industry Infrastructure** – Activities in this area are focused on maintaining a robust infrastructure – hardware, technical services and the people that provide them – to support both construction and operation of new plants and continued operation of the current nuclear fleet.

Outside of this plan, concerted, aggressive actions are also underway in other significant areas important to both future and current plants such as ensuring a robust, cost-effective fuel supply and a permanent repository for used nuclear fuel. The intent of this plan is to focus and coordinate industry actions that are uniquely focused on near term deployment of new nuclear plants in the U.S.

This overview identifies the plan objectives and the key supporting actions in progress or planned to achieve those objectives. The plan is dynamic and status reports are issued quarterly that highlight significant progress and developments, challenges ahead, and upcoming meetings.

Plan Objectives

Focus Area 1: New Plant Economics and Project Structure

1.1 Identify possible approaches to ownership; risk sharing; capital recovery and reduction of business risks associated with large, capital intensive projects.

1.2 Identify changes in policy or legislation that might be necessary or desirable to supplement market forces that influence energy supply choices, and work toward achieving those changes.

1.3 Identify ways to reduce engineering, procurement and construction costs, and implement a strategy to achieve those reductions.

1.4 Identify and achieve necessary changes to, or clarification of, NRC regulations that apply to new nuclear plants built by unregulated, merchant generating companies.

Focus Area 2: Predictable Licensing and Stable Regulation

2.1 Support NEI member applications for early site permits, combined licenses and design certifications for new nuclear plants.

2.2 Establish efficient and predictable processes for NRC review and issuance of combined construction and operating licenses under 10 CFR Part 52, verifying operational readiness of completed plants, and authorizing start-up and operation.

2.3 Establish an efficient and predictable process for NRC review and issuance of early site permits under 10 CFR Part 52.

2.4 Establish a risk informed, performance based regulatory framework for future nuclear power plants.

Focus Area 3: Policymaker and Public Support

3.1 Broaden the base of support for nuclear energy, and for new nuclear plant construction, within Congress and the Administration.

3.2 Broaden the base of support for nuclear energy, and for new nuclear plant construction, with private sector policy organizations, the financial community, the media and other key publics.

Focus Area 4: Nuclear Industry Infrastructure

4.1 Identify future needs and implement a strategy to ensure sufficient qualified personnel and skills to support renewed nuclear plant construction and continued operation of the current plants.

4.2 Identify future needs and implement a strategy to ensure sufficient manufacturing capability, engineering services, equipment suppliers, etc., to support renewed nuclear plant construction and continued operation of current plants.

Key Supporting Actions

Within each focus area, there is a range of specific activities underway or planned for achieving Plan objectives. These activities are identified below. Detailed schedules and work plans for each activity are maintained by cognizant NEI project managers.

Focus Area 1: New Plant Economics and Project Structure

Objective 1.1: Identify possible approaches to ownership; risk sharing; capital recovery and reduction of business risks associated with large, capital intensive projects.

Supporting Activities

1.1.1 Apply NEI's merchant plant project financing model and use it to help quantify the need for, and value of, new policy initiatives and economic incentives.

1.1.2 Examine approaches to risk-sharing and financing of capital-intensive projects that may be relevant for future nuclear power plant projects.

Objective 1.2: Identify changes in policy or legislation that might be necessary or desirable to supplement market forces that influence energy supply choices, and work toward achieving those changes.

Supporting Activities

1.2.1 Develop and implement a coordinated industry strategy for providing industry input to energy security legislation (e.g., bills from Senators Murkowski and Domenici, and the Administration).

1.2.2 Develop and implement a coordinated industry strategy to achieve renewal of Price Anderson legislation.

1.2.3 Identify any changes to the Tax Code for new nuclear plant projects, and implement a strategy to achieve the necessary changes.

1.2.4 Develop and implement a strategy to achieve DOE revisions to the Energy Policy Act 1605b program (voluntary carbon emission reductions) that recognize and include avoided emissions at both new and existing plants.

1.2.5 Develop and implement a strategy to include new nuclear plants in the electricity generating sources eligible for any economic incentives provided under revisions to the Clean Air Act.

Focus Area 1, continued

Objective 1.3: Identify ways to reduce engineering, procurement and construction costs, and implement a strategy to achieve those reductions.

Supporting Activities

1.3.1 Assess the potential for reduced engineering, procurement, construction, and O&M costs for future plants by applying risk-informed regulation concepts developed for current plants, e.g., risk-informing the scope of applicability of Part 50 special treatment requirements (such as EQ, QA, seismic, etc.).

1.3.2 Work with reactor vendors and A/Es to improve cost and schedule estimates for NRC-certified standard plant designs, both in terms of bottom line engineering, procurement and construction costs and certainty in them.

Objective 1.4: Identify and achieve necessary changes to, or clarification of, NRC regulations that apply to new nuclear plants built by unregulated, merchant generating companies.

Supporting Activities

1.4.1 Clarify and/or modify NRC requirements that apply to new nuclear plants built by unregulated, merchant generating companies.

1.4.2 Clarify and/or modify NRC requirements for advanced modular and/or non-light water cooled nuclear plants

1.4.3 Modify NRC regulations to accommodate plants consisting of a series of modular reactors.

Focus Area 2: Predictable Licensing and Stable Regulation

Objective 2.1: Support NEI member applications for early site permits, combined licenses and design certifications for new nuclear plants.

Supporting Activities

2.1.1 Maintain close coordination of the plan objectives and milestones with efforts to establish appropriate design and licensing bases for gas cooled reactors.

2.1.2 Maintain close coordination of the plan objectives and milestones with efforts to modify design and licensing bases for ALWR designs.

Objective 2.2: Establish efficient and predictable processes for NRC review and issuance of combined construction and operating licenses under 10 CFR Part 52, verifying operational readiness of completed plants, and authorizing start-up and operation.

Supporting Activities

2.2.1 Develop and achieve NRC endorsement of guidance on the scope of COL ITAAC, in particular, that no ITAAC on operational programs are required.

2.2.2 Provide coordinated industry comments on the Part 52 update rulemaking, and identify policy issues to the Commission as appropriate.

2.2.3 Achieve clear guidance for future licensees and NRC reviewers on implementation of the ITAAC verification process and NRC construction inspection program.

2.2.4 Develop a white paper that describes the interface between new Part 52 requirements and existing Part 50 requirements. Use this paper as the basis for comprehensive Part 52 implementation guidance.

2.2.5 Develop and achieve NRC endorsement of guidance on preparation of COL applications.

Focus Area 2, continued

Objective 2.3: Establish an efficient and predictable process for NRC review and issuance of early site permits under 10 CFR Part 52.

Supporting Activities

2.3.1 Identify and achieve necessary changes to Parts 51 and 52 to ensure NRC reviews of early site permit applications are safety-focused, predictable and efficient

2.3.2 Update the tools from the 1991-92 joint industry-DOE Early Site Permit Demonstration Project

2.3.3 Develop guidance that facilitates preparation of ESP applications for new and existing sites and promotes NRC reviews that safety-focused, predictable and efficient

2.3.4 Support NEI member ESP applications.

Objective 2.4: Establish a risk informed, performance based regulatory framework for future nuclear power plants.

Supporting Activities

2.4.1 Develop a risk informed, performance based framework for a top down approach to design and operating criteria for future plants, and petition NRC to issue an Advance Notice of Proposed Rulemaking.

2.4.2 Provide coordinated industry input to proposed and final rules leading to establishment of a risk informed regulatory framework for future plants

2.4.3 Support NEI member application of a risk informed regulatory framework and development of design-specific implementation guidance.

Focus Area 3: Policymaker and Public Support

Objective 3.1: Broaden the base of support for nuclear energy, and for new nuclear plant construction, within Congress and the Administration.

Supporting Activities

3.1.1 Implement a coordinated industry strategy for FY 2002 (and beyond) DOE and NRC appropriations.

3.1.2 Implement a strategy to gain support within the NRC and Congress for an appropriate level of NRC resources dedicated to assuring efficient licensing processes that meet the objectives of Part 52 and the Energy Policy Act of 1992.

3.1.3 Ensure coordination of industry and DOE activities related to near-term commercial deployment of advanced nuclear plant designs

3.1.4 Work with the DOE Energy Information Administration and provide input to the Annual Energy Outlook to ensure appropriate forecasts related to nuclear energy

3.1.5 Provide information to the House Nuclear Issues Group and Senate Nuclear Caucus on policy changes needed to facilitate new nuclear plant construction

Objective 3.2: Broaden the base of support for nuclear energy, and for new nuclear plant construction, with private sector policy organizations, the financial community, the media and other key publics.

Supporting Activities

3.2.1 Develop an integrated communications plan as the platform for all communications on the industry commitment to new plants and the need for legislative and policy changes.

3.2.2 Communicate to media, financial, state/local/federal, environmental and other key audiences on the benefits of and need for new nuclear plants – "the nuclear imperative" – as well as the business case for nuclear energy as the only competitive, long-haul source of clean, safe, reliable baseload generation

3.2.3 Develop community and coalition support for new nuclear plants in the U.S. through outreach to union groups, chambers of commerce, state and local officials, and others.

3.2.4 Support and leverage media coverage of comprehensive energy policy/legislation and nuclear renaissance.

Focus Area 4: Nuclear Industry Infrastructure

Objective 4.1: Identify future needs and implement a strategy to ensure sufficient qualified personnel and skills to support renewed nuclear plant construction and continued operation of the current plants.

Supporting Activities

4.1.1 Establish a credible estimate of current and projected staffing demand and supply for the nuclear power generation industry, including generating companies, NSSS designers, architect engineering firms, equipment suppliers, contractors, governmental agencies, and academic institutions.

4.1.2 Develop a comprehensive industry staffing plan with specific tasks, lead entities and responsibilities to address any existing or anticipated staffing gaps.

4.1.3 Implement a coordinated industry strategy to achieve policy maker support and action on a national and state level for nuclear workforce issues.

Objective 4.2: Identify future needs and implement a strategy to ensure sufficient manufacturing capability, engineering services, equipment suppliers, etc., to support renewed nuclear plant construction and continued operation of current plants.

Supporting Activities

4.2.1 Identify the structures, system and component (SSC) needs that will arise as the result of a decision to deploy a series of new nuclear plants in the US market.

4.2.2 Survey nuclear operating companies, NSSS designers, architect engineering firms and other segments of the nuclear industry to assess possible gaps in the ability to support renewed nuclear plant construction.

The Future of Nuclear Power

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Forward and Acknowledgments

We decided to study the future of nuclear power because we believe this technology, despite the challenges it faces, is an important option for the United States and the world to meet future energy needs without emitting carbon dioxide (CO_2) and other atmospheric pollutants. Other options include increased efficiency, renewables, and sequestration. We believe that all options should be preserved as nations develop strategies that provide energy while meeting important environmental challenges. The nuclear power option will only be exercised, however, if the technology demonstrates better economics, improved safety, successful waste management, and low proliferation risk, and if public policies place a significant value on electricity production that does not produce CO_2. Our study identifies the issues facing nuclear power and what might be done to overcome them.

Our audience is government, industry, and academic leaders with an interest in the management of the interrelated set of technical, economic, environmental, and political issues that must be addressed if large-scale deployment of new nuclear power generating facilities is to remain an option for providing a significant fraction of electricity supply in the middle of this century. We trust that our analysis and arguments will stimulate constructive dialogue about the way forward.

This study also reflects our conviction that the MIT community is well equipped to carry out interdisciplinary studies intended to shed light on complex socio-technical issues that will have a major impact on our economy and society. Nuclear power is but one example; we hope to encourage and participate in future studies with a similar purpose.

We acknowledge generous financial support from the Alfred P. Sloan Foundation and from MIT's Office of the Provost and Laboratory for Energy and the Environment.

Executive Summary

STUDY CONTEXT

Over the next 50 years, unless patterns change dramatically, energy production and use will contribute to global warming through large-scale greenhouse gas emissions — hundreds of billions of tonnes of carbon in the form of carbon dioxide. Nuclear power could be one option for reducing carbon emissions. At present, however, this is unlikely: nuclear power faces stagnation and decline.

This study analyzes what would be required to retain nuclear power as a significant option for reducing greenhouse gas emissions and meeting growing needs for electricity supply. Our analysis is guided by a global growth scenario that would expand current worldwide nuclear generating capacity almost threefold, to 1000 billion watts, by the year 2050. Such a deployment would avoid 1.8 billion tonnes of carbon emissions annually from coal plants, about 25% of the increment in carbon emissions otherwise expected in a business-as-usual scenario. This study also recommends changes in government policy and industrial practice needed in the relatively near term to retain an option for such an outcome.

We did not analyze other options for reducing carbon emissions — renewable energy sources, carbon sequestration, and increased energy efficiency — and therefore reach no conclusions about priorities among these efforts and nuclear power. In our judgment, it would be a mistake to exclude any of these four options at this time.

STUDY FINDINGS

For a large expansion of nuclear power to succeed, four critical problems must be overcome:

- ☐ Cost. In deregulated markets, nuclear power is not now cost competitive with coal and natural gas. However, plausible reductions by industry in capital cost, operation and maintenance costs, and construction time could reduce the gap. Carbon emission credits, if enacted by government, can give nuclear power a cost advantage.
- ☐ Safety. Modern reactor designs can achieve a very low risk of serious accidents, but "best practices" in construction and operation are essential. We know little about the safety of the overall fuel cycle, beyond reactor operation.
- ☐ Waste. Geological disposal is technically feasible but execution is yet to be demonstrated or certain. A convincing case has not been made that the long-term waste management benefits of advanced, closed fuel cycles involving reprocessing of spent fuel are outweighed by the short-term risks and costs. Improvement in the open, once through fuel cycle may offer waste management benefits as large as those claimed for the more expensive closed fuel cycles.
- ☐ Proliferation. The current international safeguards regime is inadequate to meet the security challenges of the expanded nuclear deployment contemplated in the global growth scenario. The reprocessing system now used in Europe, Japan, and Russia that involves separation and recycling of plutonium presents unwarranted proliferation risks.

We conclude that, over at least the next 50 years, the best choice to meet these challenges is the open, once-through fuel cycle. We judge that there are adequate uranium resources available at reasonable cost to support this choice under a global growth scenario.

Public acceptance will also be critical to expansion of nuclear power. Our survey results show that the public does not yet see nuclear power as a way to address global warming, suggesting that further public education may be necessary.

SELECTED RECOMMENDATIONS

- ☐ We support the Department of Energy (DOE) 2010 initiative to reduce costs through new design certification, site banking, and combined construction and operation licenses.
- ☐ The government should also share "first mover" costs for a limited number of power plants that represent safety-enhancing evolutionary reactor design. We propose a production tax credit for up to $200/kWe of the plant's construction cost. This mechanism creates a strong incentive to complete and operate the plant and the mechanism is extendable to other carbon-free technologies. The government actions we recommend aim to challenge the industry to demonstrate the cost reductions claimed for new reactor construction, with industry assuming the risks and benefits beyond first- mover costs.
- ☐ Federal or state portfolio standards should include incremental nuclear power capacity as a carbon free source.
- ☐ The DOE should broaden its long-term waste R&D program, to include improved engineered barriers, investigation of alternative geological environments, and deep bore hole disposal. A system of central facilities to store spent fuel for many decades prior to geologic disposal should be an integral part of the waste management strategy. The U.S. should encourage greater harmonization of international standards and regulations for waste transportation, storage, and disposal.
- ☐ The International Atomic Energy Agency should have authority to inspect all suspect facilities (implement the Additional Protocol) and should develop a worldwide system for materials protection, control, and accountability that goes beyond accounting, reporting, and periodic inspections. The U.S. should monitor and influence developments in a broad range of enrichment technologies.
- ☐ The DOE R&D program should be realigned to focus on the open, once-through fuel cycle. It should also conduct an international uranium resource assessment; establish a large *nuclear system analysis, modeling, and simulation project*, including collection of engineering data, to assess alternative nuclear fuel cycle deployments relative to the four critical challenges; and halt development and demonstration of advanced fuel cycles or reactors until the results of the nuclear system analysis project are available.

CHAPTER 1 — THE FUTURE OF NUCLEAR POWER — OVERVIEW AND CONCLUSIONS

The generation of electricity from fossil fuels, notably natural gas and coal, is a major and growing contributor to the emission of carbon dioxide – a greenhouse gas that contributes significantly to global warming. We share the scientific consensus that these emissions must be reduced and believe that the U.S. will eventually join with other nations in the effort to do so.

At least for the next few decades, there are only a few realistic options for reducing carbon dioxide emissions from electricity generation:

☐ increase efficiency in electricity generation and use;

☐ expand use of renewable energy sources such as wind, solar, biomass, and geothermal;

☐ capture carbon dioxide emissions at fossil-fueled (especially coal) electric generating plants and permanently sequester the carbon; and

☐ increase use of nuclear power.

The goal of this interdisciplinary MIT study is not to predict which of these options will prevail or to argue for their comparative advantages. In *our view, it is likely that we shall need all of these options and accordingly it would be a mistake at this time to exclude any of these four options from an overall carbon emissions management strategy.* Rather we seek to explore and evaluate actions that could be taken to maintain nuclear power as one of the significant options for meeting future world energy needs at low cost and in an environmentally acceptable manner.

In our view, it would be a mistake at this time to exclude any of these four options from an overall carbon emissions management strategy.

In 2002, nuclear power supplied 20% of United States and 17% of world electricity consumption. Experts project worldwide electricity consumption will increase substantially in the coming decades, especially in the developing world, accompanying economic growth and social progress. However, official forecasts call for a mere 5% increase in nuclear electricity generating capacity worldwide by 2020 (and even this is questionable), while electricity use could grow by as much as 75%. These projections entail little new nuclear plant construction and reflect both economic considerations and growing anti-nuclear sentiment in key countries. The limited prospects for nuclear power today are attributable, ultimately, to four unresolved problems:

☐ *Costs: nuclear power has higher overall lifetime costs* compared to natural gas with combined cycle turbine technology (CCGT) and coal, at least in the absence of a carbon tax or an equivalent "cap and trade" mechanism for reducing carbon emissions;

☐ *Safety: nuclear power has perceived adverse safety, environmental, and health effects*, heightened by the 1979 Three Mile Island and 1986 Chernobyl reactor accidents, but also by accidents at fuel cycle facilities in the United States, Russia, and Japan. There is also growing concern about the safe and secure transportation of nuclear materials and the security of nuclear facilities from terrorist attack;

☐ *Proliferation: nuclear power entails potential security risks*, notably the possible misuse of commercial or associated nuclear facilities and operations to acquire technology or materials as a precursor to the acquisition of a nuclear weapons capability. Fuel cycles that involve the chemical reprocessing of spent fuel to separate weapons-usable plutonium and uranium enrichment technologies are of special concern, especially as nuclear power spreads around the world;

☐ *Waste: nuclear power has unresolved challenges in long-term management of radioactive wastes.* The United States and other countries have yet to implement final disposition of spent fuel or high level radioactive waste streams created at various stages of the nuclear fuel cycle. Since these radioactive wastes present some danger to present and future generations, the public and its elected representatives, as well as prospective investors in nuclear power plants, properly expect continuing and substantial progress towards solution to the waste disposal problem. Successful operation of the planned disposal facility at Yucca Mountain would ease, but not solve, the waste issue for the U.S. and other countries if nuclear power expands substantially.

We believe the nuclear option should be retained, precisely because it is an important carbon-free source of power.

Today, nuclear power is not an economically competitive choice. Moreover, unlike other energy technologies, nuclear power requires significant government involvement because of safety, proliferation, and waste concerns. If in the future carbon dioxide emissions carry a significant "price," however, nuclear energy could be an important — indeed vital — option for generating electricity. We do not know whether this will occur. But *we believe the nuclear option should be retained, precisely because it is an important carbon-free source of power that can potentially make a significant contribution to future electricity supply.*

To preserve the nuclear option for the future requires overcoming the four challenges described above—costs, safety, proliferation, and wastes. These challenges will escalate if a significant number of new nuclear generating plants are built in a growing number of countries. The effort to overcome these challenges, however, is justified only if nuclear power can potentially contribute significantly to reducing global warming, which entails major expansion of nuclear power. In effect, preserving the nuclear option for the future means planning for growth, as well as for a future in which nuclear energy is a competitive, safer, and more secure source of power.

To explore these issues, our study postulates a *global growth scenario* that by mid-century would see 1000 to 1500 reactors of 1000 megawatt-electric (MWe) capacity each deployed worldwide, compared to a capacity equivalent to 366 such reactors now in service. Nuclear power expansion on this scale requires U.S. leadership, continued commitment by Japan, Korea, and Taiwan, a renewal of European activity, and wider deployment of nuclear power around the world. An illustrative deployment of 1000 reactors, each 1000 MWe in size, under this scenario is given in following table.

Global Growth Scenario

REGION	PROJECTED 2050 GWe CAPACITY	NUCLEAR ELECTRICITY MARKET SHARE 2000	NUCLEAR ELECTRICITY MARKET SHARE 2050
Total World	**1,000**	**17%**	**19%**
Developed world	625	23%	29%
U.S.	300		
Europe & Canada	210		
Developed East Asia	115		
FSU	50	16%	23%
Developing world	325	2%	11%
China, India, Pakistan	200		
Indonesia, Brazil, Mexico	75		
Other developing countries	50		

Projected capacity comes from the global electricity demand scenario in Appendix 2, which entails growth in global electricity consumption from 13.6 to 38.7 trillion kWhrs from 2000 to 2050 (2.1% annual growth). The market share in 2050 is predicated on 85% capacity factor for nuclear power reactors. Note that China, India, and Pakistan are nuclear weapons capable states. Other developing countries includes as leading contributors Iran, South Africa, Egypt, Thailand, Philippines, and Vietnam.

This scenario would displace a significant amount of carbon-emitting fossil fuel generation. In 2002, carbon equivalent emission from human activity was about 6,500 million tonnes per year; these emissions will probably more than double by 2050. The 1000 GWe of nuclear power postulated here would avoid annually about 800 million tonnes of carbon equivalent if the electricity generation displaced was gas-fired and 1,800 million tonnes if the generation was coal-fired, assuming no capture and sequestration of carbon dioxide from combustion sources.

FUEL CYCLE CHOICES

A critical factor for the future of an expanded nuclear power industry is the choice of the fuel cycle — what type of fuel is used, what types of reactors "burn" the fuel, and the method of disposal of the spent fuel. This choice affects all four key problems that confront nuclear power — costs, safety, proliferation risk, and waste disposal. For this study, we examined three representative nuclear fuel cycle deployments:

We believe that the world-wide supply of uranium ore is sufficient to fuel the deployment of 1,000 reactors over the next half century.

- ☐ *conventional thermal reactors operating in a "once-through" mode*, in which discharged spent fuel is sent directly to disposal;
- ☐ *thermal reactors with reprocessing in a "closed" fuel cycle*, which means that waste products are separated from unused fissionable material that is re-cycled as fuel into reactors. This includes the fuel cycle currently used in some countries in which plutonium is separated from spent fuel, fabricated into a mixed plutonium and uranium oxide fuel, and recycled to reactors for one pass[1];
- ☐ *fast reactors[2] with reprocessing in a balanced "closed" fuel cycle*, which means thermal reactors operated world-wide in "once-through" mode and a balanced number of fast reactors that destroy the actinides separated from thermal reactor spent fuel. The fast reactors, reprocessing, and fuel fabrication facilities would be co-located in secure nuclear energy "parks" in industrial countries.

Closed fuel cycles extend fuel supplies. The viability of the once-through alternative in a global growth scenario depends upon the amount of uranium resource that is available at economically attractive prices. *We believe that the world-wide supply of uranium ore is sufficient to fuel the deployment of 1000 reactors over the next half century* and to maintain this level of deployment over a 40 year lifetime of this fleet. This is an important foundation of our study, based upon currently available information and the history of natural resource supply.

The result of our detailed analysis of the relative merits of these representative fuel cycles with respect to key evaluation criteria can be summarized as follows: *The once through cycle has advantages in cost, proliferation, and fuel cycle safety*, and is disadvantageous only in respect to long-term waste disposal; the

[1] This fuel cycle is known as Plutonium Recycle Mixed Oxide, or PUREX/MOX.

[2] A fast reactor more readily breeds fissionable isotopes-potential fuel-because it utilizes higher energy neutrons that in turn create more neutrons when absorbed by fertile elements, e.g. fissile Pu^{239} is bred from neutron absorption of U^{238} followed by beta (electron) emission from the nucleus.

two closed cycles have clear advantages only in long-term aspects of waste disposal, and disadvantages in cost, short-term waste issues, proliferation risk, and fuel cycle safety. (See Table.) Cost and waste criteria are likely to be the most crucial for determining nuclear power's future.

We have not found, and based on current knowledge do not believe it is realistic to expect, that there are new reactor and fuel cycle technologies that simultaneously overcome the problems of cost, safety, waste, and proliferation.

Fuel Cycle Types and Ratings

				SAFETY	
	ECONOMICS	**WASTE**	**PROLIFERATION**	**Reactor**	**Fuel Cycle**
Once through	+	× short term − long term	+	×	+
Closed thermal	−	− short term + long term	−	×	−
Closed fast	−	− short term + long term	−	+ to −	−

+ means relatively advantageous; × means relatively neutral; − means relatively disadvantageous

This table indicates broadly the relative advantage and disadvantage among the different type of nuclear fuel cycles. It does not indicate relative standing with respect to other electricity-generating technologies, where the criteria might be quite different (for example, the nonproliferation criterion applies only to nuclear).

Our analysis leads to a significant conclusion: *The once-through fuel cycle best meets the criteria of low costs and proliferation resistance.* Closed fuel cycles may have an advantage from the point of view of long-term waste disposal and, if it ever becomes relevant, resource extension. But closed fuel cycles will be more expensive than once-through cycles, until ore resources become very scarce. This is unlikely to happen, even with significant growth in nuclear power, until at least the second half of this century, and probably considerably later still. Thus our most important recommendation is:

For the next decades, government and industry in the U.S. and elsewhere should give priority to the deployment of the once-through fuel cycle, rather than the development of more expensive closed fuel cycle technology involving reprocessing and new advanced thermal or fast reactor technologies.

This recommendation implies a major re-ordering of priorities of the U.S. Department of Energy nuclear R&D programs.

PUBLIC ATTITUDES TOWARD NUCLEAR POWER

Expanded deployment of nuclear power requires public acceptance of this energy source. Our review of survey results shows that a majority of Americans and Europeans oppose building new nuclear power plants to meet future energy needs. To understand why, we surveyed 1350 adults in the US about their attitudes toward energy in general and nuclear power in particular. Three important and unexpected results emerged from that survey:

☐ The U.S. public's attitudes are informed almost entirely by their perceptions of the technology, rather than by politics or by demographics such as income, education, and gender.

☐ The U.S. public's views on nuclear waste, safety, and costs are critical to their judgments about the future deployment of this technology. Technological improvements that lower costs and improve safety and waste problems can increase public support substantially.

☐ In the United States, people do not connect concern about global warming with carbon-free nuclear power. There is no difference in support for building more nuclear power plants between those who are very concerned about global warming and those who are not. Public education may help improve understanding about the link between global warming, fossil fuel usage, and the need for low-carbon energy sources.

There are two implications of these findings for our study: first, the U.S. public is unlikely to support nuclear power expansion without substantial improvements in costs and technology. Second, the carbon-free character of nuclear power, the major motivation for our study, does not appear to motivate the U.S. general public to prefer expansion of the nuclear option.

The U.S. public is unlikely to support nuclear power expansion without substantial improvements in costs and technology.

ECONOMICS

Nuclear power will succeed in the long run only if it has a lower cost than competing technologies. This is especially true as electricity markets become progressively less subject to economic regulation in many parts of the world. We constructed a model to evaluate the real cost of electricity from nuclear power versus pulverized coal plants and natural gas combined cycle plants (at various projected levels of real lifetime prices for natural gas), over their economic lives. These technologies are most widely used today and, absent a carbon tax or its equivalent, are less expensive than many renewable technologies. Our "merchant" cost model uses assumptions that commercial investors would be expected to use today, with parameters based on actual experience rather than engineering estimates of what might be achieved under ideal conditions; it compares the constant or "levelized" price of electricity over the life of a power plant that would be necessary to cover all operating expenses and taxes and provide an acceptable return to investors. The comparative figures given below assume 85% capacity factor and a 40-year economic life for the nuclear plant, reflect economic conditions in the U.S, and consider a range of projected improvements in nuclear cost factors. (See Table.)

Comparative Power Costs

CASE (Year 2002 $)	REAL LEVELIZED COST Cents/kWe-hr
Nuclear (LWR)	6.7
+ Reduce construction cost 25%	5.5
+ Reduce construction time 5 to 4 years	5.3
+ Further reduce O&M to 13 mills/kWe-hr	5.1
+ Reduce cost of capital to gas/coal	4.2
Pulverized Coal	4.2
CCGT[a] (low gas prices, $3.77/MCF)	3.8
CCGT (moderate gas prices, $4.42/MCF)	4.1
CCGT (high gas prices, $6.72/MCF)	5.6

a. Gas costs reflect real, levelized acquisition cost per thousand cubic feet (MCF) over the economic life of the project.

We judge the indicated cost improvements for nuclear power to be plausible, but not proven. The model results make clear why electricity produced from new nuclear power plants today is not competitive with electricity produced from coal or natural gas-fueled CCGT plants with low or moderate gas prices, unless *all* cost improvements for nuclear power are realized. The cost comparison becomes worse for nuclear if the capacity factor falls. It is also important to emphasize that the nuclear cost structure is driven by high up-front capital costs, while the natural gas cost driver is the fuel cost; coal lies in between nuclear and natural gas with respect to both fuel and capital costs.

Nuclear does become more competitive by comparison if the social cost of carbon emissions is internalized, for example through a carbon tax or an equivalent "cap and trade" system. Under the assumption that the costs of carbon emissions are imposed, the accompanying table illustrates the impact on the competitive costs for different power sources, for emission costs in the range of $50 to $200/tonne carbon. (See Table.) The ultimate cost will depend on both societal choices (such as how much carbon dioxide emission

Power Costs with Carbon Taxes

CARBON TAX CASES LEVELIZED ELECTRICITY COST cents/kWe-hr	$50/tonne C	$100/tonne C	$200/tonne C
Coal	5.4	6.6	9.0
Gas (low)	4.3	4.8	5.9
Gas (moderate)	4.7	5.2	6.2
Gas (high)	6.1	6.7	7.7

to permit) and technology developments, such as the cost and feasibility of large-scale carbon capture and long-term sequestration. Clearly, costs in the range of $100 to $200/tonne C would significantly affect the relative cost competitiveness of coal, natural gas, and nuclear electricity generation.

The carbon-free nature of nuclear power argues for government action to encourage maintenance of the nuclear option, particularly in light of the regulatory uncertainties facing the use of nuclear power and the unwillingness of investors to bear the risk of introducing a new generation of nuclear facilities with their high capital costs.

We recommend three actions to improve the economic viability of nuclear power:

The government should cost share for site banking for a number of plants, certification of new plant designs by the Nuclear Regulatory Commission, and combined construction and operating licenses for plants built immediately or in the future; we support U.S. Department of Energy initiatives on these subjects.

The government should recognize nuclear as carbon-free and include new nuclear plants as an eligible option in any federal or state mandatory renewable energy portfolio (i.e., a "carbon-free" portfolio) standard.

The government should provide a modest subsidy for a small set of "first mover" commercial nuclear plants to demonstrate cost and regulatory feasibility in the form of a production tax credit.

We propose a production tax credit of up to $200 per kWe of the construction cost of up to 10 "first mover" plants. This benefit might be paid out at about 1.7 cents per kWe-hr, over a year and a half of full-power plant operation. We prefer the production tax credit mechanism because it offers the greatest incentive for projects to be completed and because it can be extended to other carbon free electricity technologies, for example renewables, (wind currently enjoys a 1.7 cents per kWe-hr tax credit for ten years) and coal with carbon capture and sequestration. The credit of 1.7 cents per kWe- hr is equivalent to a credit of $70 per avoided metric ton of carbon if the electricity were to have come from coal plants (or $160 from natural gas plants). Of course, the carbon emission reduction would then continue without public assistance for the plant life (perhaps 60 years for nuclear). If no new nuclear plant is built, the government will not pay a subsidy.

These actions will be effective in stimulating additional investment in nuclear generating capacity if, and only if, the industry can live up to its own expectations of being able to reduce considerably capital costs for new plants.

Advanced fuel cycles add considerably to the cost of nuclear electricity. We considered reprocessing and one-pass fuel recycle with current technology, and found the fuel cost, including waste storage and disposal charges, to be about 4.5 times the fuel cost of the once-through cycle. Thus use of advanced fuel cycles imposes a significant economic penalty on nuclear power.

SAFETY

We believe the safety standard for the global growth scenario should maintain today's standard of less than one serious release of radioactivity accident for 50 years from all fuel cycle activity. This standard implies a ten-fold reduction in the expected frequency of serious reactor core accidents, from 10^{-4}/reactor year to 10^{-5}/reactor year. This reactor safety standard should be possible to achieve in new light water reactor plants that make use of advanced safety designs. International adherence to such a standard is important, because an accident in any country will influence public attitudes everywhere. The extent to which nuclear facilities should be hardened to possible terrorist attack has yet to be resolved.

We do not believe there is a nuclear plant design that is totally risk free. In part, this is due to technical possibilities; in part due to workforce issues. Safe operation requires effective regulation, a management committed to safety, and a skilled work force.

The high temperature gas-cooled reactor is an interesting candidate for reactor research and development because there is already some experience with this system, although not all of it is favorable. This reactor design offers safety advantages because the high heat capacity of the core and fuel offers longer response times and precludes excessive temperatures that might lead to release of fission products; it also has an advantage compared to light water reactors in terms of proliferation resistance.

These actions will be effective in stimulating additional investment in nuclear generating capacity if, and only if, the industry can live up to its own expectations of being able to reduce considerably overnight capital costs for new plants.

Because of the accidents at Three Mile Island in 1979 and Chernobyl in 1986, a great deal of attention has focused on reactor safety. However, the safety record of reprocessing plants is not good, and there has been little safety analysis of fuel cycle facilities using, for example, the probabilistic risk assessment method. More work is needed here.

Our principal recommendation on safety is:

The government should, as part of its near-term R&D program, develop more fully the capabilities to analyze life-cycle health and safety impacts of fuel cycle facilities and focus reactor development on options that can achieve enhanced safety standards and are deployable within a couple of decades.

WASTE MANAGEMENT

The management and disposal of high-level radioactive spent fuel from the nuclear fuel cycle is one of the most intractable problems facing the nuclear power industry throughout the world. No country has yet successfully implemented a system for disposing of this waste. We concur with the many independent expert reviews that have concluded that geologic repositories will be capable of safely isolating the waste from the biosphere. However, implementation of this method is a highly demanding task that will place great stress on operating, regulatory, and political institutions.

We do not believe a convincing case can be made, on the basis of waste management considerations alone, that the benefits of advanced, closed fuel cycles will outweigh the attendant safety, environmental, and security risks and economic costs.

For fifteen years the U.S. high-level waste management program has focused almost exclusively on the proposed repository site at Yucca Mountain in Nevada. Although the successful commissioning of the Yucca Mountain repository would be a significant step towards the secure disposal of nuclear waste, we believe that a broader, strategically balanced nuclear waste program is needed to prepare the way for a possible major expansion of the nuclear power sector in the U.S. and overseas.

The global growth scenario, based on the once-through fuel cycle, would require multiple disposal facilities by the year 2050. To dispose of the spent fuel from a steady state deployment of one thousand 1 GWe reactors of the light water type, new repository capacity equal to the nominal storage capacity of Yucca Mountain would have to be created somewhere in the world every three to four years. This requirement, along with the desire to reduce long-term risks from the waste, prompts interest in advanced, closed fuel cycles.

These schemes would separate or partition plutonium and other actinides — and possibly certain fission products — from the spent fuel and transmute them into shorter-lived and more benign species. The goals would be to reduce the thermal load from radioactive decay of the waste on the repository, thereby increasing its storage capacity, and to shorten the time for which the waste must be isolated from the biosphere.

We have analyzed the waste management implications of both once-through and closed fuel cycles, taking into account each stage of the fuel cycle and the risks of radiation exposure in both the short and long-term. *We do not believe that a convincing case can be made on the basis of waste management considerations alone that the benefits of partitioning and transmutation will outweigh the attendant safety, environmental, and security risks and economic costs.* Future technology developments could change the balance of expected costs, risks, and benefits. For our fundamental conclusion to change, however, not only would the expected long term risks from geologic repositories have to be significantly higher than those indicated in current assessments, but the incremental costs and short-term safety and environmental risks would have to be greatly reduced relative to current expectations and experience.

We further conclude that waste management strategies in the once-through fuel cycle are potentially available that could yield long-term risk reductions at least as great as those claimed for waste partitioning and transmutation, with fewer short-term risks and lower development and deployment costs. These include both incremental improvements to the current mainstream mined repositories approach and more far-reaching innovations such as deep borehole disposal. Finally, replacing the current ad hoc approach to spent fuel storage at reactor sites with an explicit strategy to store spent fuel for a period of several decades will create additional flexibility in the waste management system.

Our principal recommendations on waste management are:

The DOE should augment its current focus on Yucca Mountain with a balanced long-term waste management R&D program.

A research program should be launched to determine the viability of geologic disposal in deep boreholes within a decade.

A network of centralized facilities for storing spent fuel for several decades should be established in the U.S. and internationally.

NONPROLIFERATION

Nuclear power should not expand unless the risk of proliferation from operation of the commercial nuclear fuel cycle is made acceptably small. We believe that nuclear power can expand as envisioned in our global growth scenario with acceptable incremental proliferation risk, provided that reasonable safeguards are adopted and that deployment of reprocessing and enrichment are restricted. The international community must prevent the acquisition of weapons-usable material, either by diversion (in the case of plutonium) or by misuse of fuel cycle facilities (including related facilities, such as research reactors or hot cells). Responsible governments must control, to the extent possible, the know-how relevant to produce and process either highly enriched uranium (enrichment technology) or plutonium.

Three issues are of particular concern: existing stocks of *separated* plutonium around the world that are directly usable for weapons; nuclear facilities, for example in Russia, with inadequate controls; and transfer of technology, especially enrichment and reprocessing technology, that brings nations closer to a nuclear weapons capability. The proliferation risk of the global growth scenario is underlined by the likelihood that use of nuclear power would be introduced and expanded in many countries in different security circumstances.

Nuclear power should not expand unless the risk of proliferation from operation of the commercial nuclear fuel cycle is made acceptably small.

An international response is required to reduce the proliferation risk. The response should:

- ☐ re-appraise and strengthen the institutional underpinnings of the IAEA safeguards regime in the near term, including sanctions;
- ☐ guide nuclear fuel cycle development in ways that reinforce shared nonproliferation objectives.

Accordingly, we recommend:

The International Atomic Energy Agency (IAEA) should focus overwhelmingly on its safeguards function and should be given the authority to carry out inspections beyond declared facilities to suspected illicit facilities;

Greater attention must be given to the proliferation risks at the front end of the fuel cycle from enrichment technologies;

IAEA safeguards should move to an approach based on continuous materials protection, control and accounting using surveillance and containment systems, both in facilities and during transportation, and should implement safeguards in a risk-based framework keyed to fuel cycle activity;

Fuel cycle analysis, research, development, and demonstration efforts must include explicit analysis of proliferation risks and measures defined to minimize proliferation risks;

International spent fuel storage has significant nonproliferation benefits for the growth scenario and should be negotiated promptly and implemented over the next decade.

ANALYSIS, RESEARCH, DEVELOPMENT, AND DEMONSTRATION PROGRAM

The U.S. Department of Energy (DOE) analysis, research, development, and demonstration (ARD&D) program should support the technology path leading to the global growth scenario and include diverse activities that balance risk and time scales, in pursuit of the strategic objective of preserving the nuclear option. *For technical, economic, safety, and public acceptance reasons, the highest priority in fuel cycle ARD&D, deserving first call on available funds, lies with efforts that enable robust deployment of the once-through fuel cycle.* The current DOE program does not have this focus.

Every industry in the United States develops basic analytical models and tools such as spreadsheets that allow firms, investors, policy makers, and regulators to understand how changes in the parameters of a process will affect the performance and cost of that process. But we have been struck throughout our study by the absence of such models and simulation tools that permit in-depth, quantitative analysis of trade-offs between different reactor and fuel cycle choices, with respect to all key criteria. The analysis we have seen is based on point designs and does not incorporate information about the cost and performance of operating commercial nuclear facilities. Such modeling and analysis under a wide variety of scenarios, for both open and closed fuel cycles, will be useful to the industry and investors, as well as to international discussions about the desirability about different fuel cycle paths.

We call on the Department of Energy, perhaps in collaboration with other countries, to establish a major project for the modeling, analysis, and simulation of commercial nuclear power systems — The Nuclear System Modeling Project. This project should provide a foundation for the accumulation of information about how variations in the operation of plants and other parts of the fuel cycle affect costs, safety, waste, and proliferation resistance characteristics. The models and analysis should be based on real engineering data and, wherever possible, practical experience. This project is technically demanding and will require many years and considerable resources to be carried out successfully.

For technical, economic, safety, and public acceptance reasons, the highest priority in fuel cycle R&D, deserving first call on available funds, lies with efforts that enable robust deployment of the once-through fuel cycle.

We believe that development of advanced nuclear technologies — either fast reactors or advanced fuel cycles employing reprocessing – should await the results of the *Nuclear System Modeling Project* we have proposed above. Our analysis makes clear that there is ample time for the project to compile the necessary engineering and economic analyses and data before undertaking expensive development programs, even if the project should take a decade to complete. Expensive programs that plan for the development or deployment of commercial reprocessing based on any existing advanced fuel cycle technologies are simply not justified on the basis of cost, or the unproven safety, proliferation risk, and waste properties of a closed cycle compared to the once-through cycle. Reactor concept evaluation should be part of the Nuclear System Modeling Project.

On the other hand, we support a modest laboratory scale research and analysis program on *new* separation methods and associated fuel forms, with the objective of learning about approaches that emphasize lower cost and more proliferation resistance. These data can be important inputs to advanced fuel cycle analysis and simulation and thus help prioritize future development programs.

The modeling project's research and analysis effort should only encompass technology pathways that do not produce weapons-usable material during normal operation (for example, by leaving some uranium, fission products, and/or minor actinides with the recycled plutonium). *The closed fuel cycle currently practiced in Western Europe and Japan, known as PUREX/MOX, does not meet this criterion.* There are advanced closed fuel cycle concepts involving combinations of reactor, fuel form, and separations technology that satisfy these conditions and, with appropriate institutional arrangements, can have significantly better proliferation resistance than the PUREX/MOX fuel cycle, and perhaps approach that of the open fuel cycle. Accordingly, the governments of nuclear supplier countries should discourage other nations from developing and deploying the PUREX/MOX fuel cycle.

Government R&D support for advanced design LWRs and for the High Temperature Gas Reactor (HTGR) is justified because these are the two reactor types that are most likely to play a role in any nuclear expansion. R&D support for advanced design LWRs should focus on measures that reduce construction and operating cost. Because the High Temperature Gas Reactor (HTGR) has potential advantages with respect to safety, proliferation resistance, modularity and efficiency, government research and limited development support to resolve key uncertainties, for example, the performance of HTGR fuel forms in reactors and gas power conversion cycle components, is warranted.

Waste management also calls for a significant, and redirected, ARD&D program. The DOE waste program, understandably, has been singularly focused for the past several years on the Yucca Mountain project. We believe DOE must broaden its waste R&D effort or run the risk of being unable to rigorously defend its choices for waste disposal sites. More attention needs to be given to the characterization of waste forms and engineered barriers, followed by development and testing of engineered barrier systems. We believe deep boreholes, as an alternative to mined repositories, should be aggressively pursued. These issues are inherently of international interest in the growth scenario and should be pursued in such a context.

The closed fuel cycle currently practiced in Western Europe and Japan, known as PUREX/MOX, does not meet this nonproliferation criterion.

There is opportunity for international cooperation in this ARD&D program on safety, waste, and the Nuclear System Modeling Project. A particularly pertinent effort is the development, deployment, and operation of a word wide materials protection, control, and accounting tracking system. There is no currently suitable international organization for this development task. A possible approach lies with the G-8 as a guiding body.

Our global growth scenario envisions an open fuel cycle architecture at least until mid-century or so, with the advanced closed fuel cycles possibly deployed later, but only if significant improvements are realized through research. The principal driver of this conclusion is our judgment that natural uranium ore is available at reasonable prices to support the open cycle at least to late in the century in a scenario of substantial expansion. This gives the open cycle clear economic advantage with proliferation resistance an important additional feature. The DOE should undertake a global uranium resource evaluation program to determine with greater confidence the uranium resource base around the world.

Accordingly, we recommend:

The U.S. Department of Energy should focus its R&D program on the once-through fuel cycle;

The U.S. Department of Energy should establish a Nuclear System Modeling project to carryout the analysis, research, simulation, and collection of engineering data needed to evaluate all fuel cycles from the viewpoint of cost, safety, waste management, and proliferation resistance;

The U.S. Department of Energy should undertake an international uranium resource evaluation program;

The U.S. Department of Energy should broaden its waste management R&D program;

The U.S. Department of Energy should support R&D that reduces Light Water Reactor (LWR) costs and for development of the HTGR for electricity application.

We believe that the ARD&D program proposed here is aligned with the strategic objective of enabling a credible growth scenario over the next several decades. Such a ARD&D program requires incremental budgets of almost $400 million per year over the next 5 years, and at least $460 million per year for the 5-10 year period.

Chapter 2 — Background and Purpose of This Study

In 2000 nuclear power produced about 17% of the world's electricity from 442 commercial reactors in 31 countries. The United States has the largest deployment, with 104 operating reactors producing 20% of the country's electricity, followed by France, Japan, Germany, Russia, and South Korea. The reliability of these plants has improved considerably in recent years (for example, capacity factors of U.S. nuclear reactors have achieved 90%), and many will have their originally expected operating lives extended significantly. Nuclear power is clearly an important source of electricity in the United States and the world.

If current policies continue, however, nuclear power is likely to decline gradually and conceivably disappear in this century from the world's electricity supply portfolio. We believe removing nuclear power as a supply option would be a mistake at this time. The primary reason is that nuclear power is an important source of electricity that does not rely on fossil fuel and hence does not produce greenhouse gas emissions. This is the primary motivation for our examination for an inter-connected set of issues that will challenge nations individually and collectively over the next century. The issues are:

☐ reducing atmospheric pollution and emissions of greenhouse gases;

☐ meeting dramatically increased energy, and especially electricity, demand throughout the industrialized and developing world; and

☐ assuring security and minimizing conflict associated with energy supply.

Our study undertakes to:

☐ describe the characteristics of a nuclear power infrastructure that would make a significant contribution to reducing CO_2 emissions;

☐ identify the issues that must be addressed if nuclear power is to make a contribution on this scale; and

☐ outline the needed program of analysis, research, development, and demonstration.

GLOBAL WARMING

Most developed countries are in the early stages of implementing policies to stabilize and ultimately reduce greenhouse gas emissions and the attendant global warming. The scientific consensus about the risks of further significant increases in atmospheric greenhouse gas concentrations grows steadily stronger and more widely endorsed. This consensus underlies a strong impetus for governmental actions that prepare the ground for meeting possibly stringent CO_2 emission constraints in the decades ahead, specifically global emission levels comparable to or below those of today, despite a considerable increase in energy production and use. Developing countries will need to limit the growth of greenhouse gas emissions while their energy consumption increases dramatically. For example, if atmospheric concentration of CO_2 is not allowed to exceed twice its pre-industrial value, then CO_2 emissions in the 21st century will need to be held to half the cumulative total expected under a "business as usual" trajectory,[1] and the annual emission rate would eventually need to fall well below the 2000 value. While our focus is on global warming because of its overwhelming international implications, we recognize that reduction in other emissions from fossil fuel combustion would have important regional and local benefits for clean air.

We believe that the United States will eventually join with other developed countries in the effort to reduce greenhouse gas emissions, even if the mechanisms for doing so are uncertain for the moment. Developing countries – certainly the large ones, such as China, India, Pakistan, Brazil, and Indonesia – must ultimately be party to this effort if it is to succeed. Achieving the reductions in greenhouse gas emissions likely to be required will be a major technical and economic challenge to both developed and developing countries that will persist for many decades into the future.

The power sector contributes about a third of greenhouse gas emissions worldwide. The Energy Information Administration (EIA) of the U.S. Department of Energy projects that, in the absence of CO_2-control policies and technologies, electricity's share of global emissions of greenhouse gases (CO_2 and others) will climb to over 40% by 2020. In the United States, almost 90% of the carbon emissions from electricity generation come from coal-fired generation, even though this accounts for only 52% of the electricity. (About 29% of United States electricity comes from carbon-free nuclear and renewables-based generation; about 19% comes from natural-gas-fired and oil-fired generation, but both of these fuels release less carbon per kilowatt-hour than coal-fired generation does.)

There are few realistic options to reduce significantly carbon emissions from electricity generation (besides lowering standards of living):

- ☐ increased efficiency in electricity end-use and generation;
- ☐ increased use of renewable energy technologies (e.g., wind, solar, biomass, and geothermal);
- ☐ introduction of carbon capture and sequestration at fossil-fueled (especially coal) power plants on a massive scale; and
- ☐ increased use of nuclear fission power reactors (and possibly fusion at a later date).

As we have argued in Chapter 1, *our view is that it would be a mistake to exclude at this time any of these four basic options as a possibly important part of an overall carbon emissions management strategy*. Each of the options presents technical, economic, environmental, political, and human behavioral issues that make their ultimate market penetration uncertain.

Nuclear power is a special case, however. If current trends continue, nuclear power will gradually decrease and perhaps even disappear as part of the global energy portfolio, thus failing to make any long-term contribution to reducing greenhouse gas emissions. Few nuclear power plants are under construction worldwide, and of those, most are being built in a small number of developing countries or developed countries in East Asia.[2] In most developed countries, the use of nuclear power is not expected to expand and, in many of these countries, including the United States, nuclear power has been explicitly excluded from policies to stabilize and reduce carbon emissions (e.g., direct and tax subsidies for renewable energy and energy conservation, high mandated purchase prices for renewable energy, renewable energy portfolio standards). In Britain, nuclear power plants pay a "carbon tax," even though they have essentially no CO_2 emissions. We believe that a more objective approach will have a better chance at meeting the global warming challenge. Indeed, it is likely that our energy future will exploit *all* of the four options to one degree or another. This study addresses the issues associated with maintaining the nuclear power option.

ELECTRICITY DEMAND

The U.S. National Academy of Engineering named electrification as the premier engineering achievement of the twentieth century[3]. This is a remarkable statement for the century of lasers, computers, airplanes, and other ubiquitous and important technologies and is indicative of the extraordinary impact of electricity in improving the quality of people's lives. Accordingly, it should not be surprising that global electricity use is expected to increase dramatically in the years ahead, even taking into account improvements in end use efficiency. Growth in electricity use is expected especially in developing countries, as they strive to meet basic needs and to modernize and industrialize their economies.

The U.S. Department of Energy's EIA projects a 75% increase in global electricity use in two decades, from 2000 to 2020. By mid-century, a threefold increase or more is credible and, indeed, expected. Table 2.1 gives the growth rate for electricity use in different regions of the world as anticipated in the EIA "business-as-usual" projections to the year 2020.[4]

There is a strong correlation between electricity consumption per capita and the United Nations "human development index" (HDI), which combines indicators of health, education, and economic prosperity.[5] Industrialized countries have an HDI above 0.9 (on a scale of 0 to 1) and per capita energy consumption above 4000 kWe-hrs.

Large developing countries, such as China, India, Pakistan, and Indonesia, are well below the industrialized country HDI and aspire to advance by rapid economic growth. Overall, energy consumption per capita in the developing world is currently less than a fifth of that in the developed world. Unless provided with assistance or incentives, these developing nations are likely to seek the lowest cost supply alternatives that can meet their growing industrial and consumer demand for electricity. This prospect clearly raises the specter of substantially increased greenhouse gas emissions, since coal is likely to be an economic choice for many developing countries, e.g. China and India. *How these developing countries meet their electricity demand is of central interest to the discussion of global warming, since over time their choices will influence global emissions levels more than measures taken by the developed world.* Greater electricity consumption is desirable because it accompanies social and economic advance, but we want the electricity production to take place in an economic and environmentally acceptable manner.

Table 2.1 Anticipated Growth of Electricity (billion kWe-h)[4]

REGION (billion kWe-h)	1999	2020	GROWTH RATE %
Industrialized	7,500	10,900	1.8
(US)	3,200	4,800	1.9
FSU	1,500	2,100	1.8
Developing	3,900	9,200	4.2
Total World	12,800	22,200	2.7

The attractiveness of nuclear power as an option will be determined by many country-specific factors. To understand how much nuclear power would be needed to make a significant contribution to reducing CO_2 emissions by 2050, and where it might be deployed, we present, in Appendix 2, a simple scenario for electricity growth over the next fifty years. The scenario is not based on economic forecasting, but on a model of what electricity growth could be as countries attempt to raise individual living standards to acceptable levels within credible growth constraints. The model assumes a modest 1%/year annual growth in per capita electricity consumption for developed countries and a growth rate for developing countries that takes them to 4000 kWe-hrs/person/year in 2050 (i.e., we determine the growth rate as an outcome). Population projections are those currently provided by the United Nations. The one additional constraint in the scenario is that the annual growth rate in total electricity production for any country is capped at 4.7%; this is one half percent above EIA's projected electricity growth rate for the developing world overall up to 2020. Sustaining a 4.7%/year growth rate for fifty years yields a factor of ten increase; although within the realm of possibility with appropriate policies and sufficient resource investment, this cap on total growth represents a very ambitious target for any individual developing country. Within this scenario, global electricity production is slightly below the EIA reference in 2020 and about a factor of three greater in 2050 than it is today. The implications of this scenario for four categories of nations are described below.

Developed countries. Among the major developed countries, the United States is unique in having a projected large increase in population and a concomitant large increase in total electricity demand. If the global deployment of nuclear power is to grow substantially by mid-century, the United States almost certainly must be a major participant. Nuclear power growth is unlikely to be very large in other key developed countries, such as Japan (with an anticipated population decline) or France (with a stable population and a power sector already dominated by nuclear power).

More advanced developing countries. Countries such as China, Brazil, Mexico, and Iran can reach the 4000 kWe-hrs/person/year benchmark with annual growth rates of electricity consumption in the 2%-3% range. Although improved business, regulatory, financial, political, and other conditions may be needed, these countries would likely be very important for an expanded nuclear power scenario. By 2050, they will have large urban populations (above 85%), an important factor favoring the introduction of large base load plants. This model is, of course, subject to country-specific caveats; for example, Iran has abundant natural gas supplies, so its pursuit of nuclear power logically raises proliferation concerns. Collectively, countries in this group have relatively little nuclear power today but could turn to nuclear power to meet a fraction of their future electricity supply needs, as South Korea has done.

Less advanced developing countries. Countries such as India, Pakistan, Indonesia, Philippines, and Vietnam (with a combined projected population of 2.5 billion in 2050) may, with considerable progress in their political, legal, financial, and regulatory regimes and an associated increase in domestic and foreign investment in their energy sectors, reach 2000-3000 kWe-hrs/person/year by mid-century. This will be a tall order. Nuclear power may account for part of the dramatic increase in electricity supply called for in these countries (India is an exception in that it already has fourteen units), but pursuing such a capital- and management-intensive technology will prove challenging. In many cases, proliferation concern – the concern that the commercial nuclear fuel cycle will be used as a source of materials and/or technology that will lead to proliferation of nuclear weapons – will accompany development of substantial nuclear technology infrastructures.

Least advanced developing countries. Many large developing countries, with a particular concentration in Africa, cannot come close to the per capita benchmark within economically credible scenarios. These countries are not good candidates for nuclear power, barring an unforeseen breakthrough in technology and capital requirements.

In sum, electricity utilization is likely to increase significantly worldwide over the next half-century, requiring a major investment in both replacement and expansion of generating capacity. Much of the expansion will take place in the developing world. Selected developed countries will be central to a major increase in nuclear power, but large parts of the developing world are unlikely participants. If developing nations do adopt nuclear power, all nations of the world will have an interest in how these countries regulate their nuclear enterprise with respect to reactor and fuel cycle safety, transportation of nuclear materials, waste disposal, and especially proliferation safeguards.

SECURITY

Yet another reason for thinking about the nuclear option — national security — is not new. The dependence of the developed world on oil from the Middle East, an unstable region of the world, has long presented a risk to the economies of the United States and other countries that depend on imported oil, such as Japan, Germany, and France. The United States' dependence is linked principally to fuel for the transportation sector, but many other countries rely on oil for significant power generation. Nuclear power offers one option for reducing this dependence.

Within the time horizon addressed in this study, however, the national security implications of expanded nuclear power may be even more significant with respect to natural gas, which displays the same lack of geographic correlation between supply and demand that has defined the geopolitical landscape for oil. It is likely that many nations, including the United States, may import large quantities of LNG or liquids from gas, produced from stranded gas in diverse regions of the world.

There is another national security dimension to nuclear power. Combating nuclear proliferation is one of our most important foreign policy objectives. There is no doubt about the great risk to the security of the United States and the rest of the world that the spread of nuclear weapons to other states and perhaps non-state actors would bring. So there is a major security interest in how all aspects of nuclear commerce develop around the world. For example, the extensive U.S. "Cooperative Threat Reduction program,"[6] provides assistance to Russia for the purpose of improving their efforts to protect their nuclear weapons and nuclear explosive materials against theft.[7] On the other hand, there is considerable tension between the United States and Russia created by Russian assistance to Iran on commercial nuclear power, especially since Iran is awash in natural gas.

Indeed, it is worth recalling that the unresolved nuclear fuel cycle "schism" of the 1970s between the United States and its European and Japanese allies stemmed from nonproliferation concerns. In the Ford and Carter administrations, the United States stopped the recycling of plutonium in commercial reactors because of proliferation risks associated with a "plutonium economy." The hope that others would emulate this policy was not realized, as energy resource-poor countries, such as France and Japan, evaluated the balance of risks differently. As countries look to shape today's nuclear fuel cycle policy and R&D decisions in the context of the world environmental, economic development, and security needs of the next fifty years, finding a common path among the G-8 and others can itself contribute significantly to managing proliferation concerns. The expansion of nuclear power, should it occur, will raise proliferation concerns that call for ongoing American engagement in nuclear fuel cycle issues independent of nuclear power's level of contribution to domestic electricity generation.

THE CHALLENGES OF NUCLEAR POWER EXPANSION

Despite the strong rationale for reducing greenhouse gas emissions that contribute to global warming, for meeting increasing demand for electricity, and for improving the national security aspects of energy supply, the EIA's "business-as-usual" projection for nuclear power indicates a mere 5% increase in 2020, even as world electricity use increases by 75%. After 2020, if significant investments are not made, nuclear power supply would decline as existing reactors are retired. EIA projects significant increases in nuclear generated electricity in China, Japan, and South Korea, largely offsetting decreases in the United States and Western Europe. In the United States, the last nuclear plant order was in 1979. There is considerable anti-nuclear sentiment in Europe: Belgium, Germany, the Netherlands, and Sweden are officially committed to phasing out nuclear power gradually; and there is public opposition to nuclear power in Japan and Taiwan. To be sure, several countries are still on a path to construct new operating units — South Korea, Finland, India, and Russia are examples — and China may yet commit to substantial new nuclear plant construction.

There are several reasons why nuclear power has not met the expectations for capacity growth projected several decades ago. One factor is that the public perception of nuclear energy is unfavorable, in part due to concern about effects of radiation that the public associates with nuclear energy. More importantly, the adverse impression derives from real and unique problems presented by this technology. These problems are:

Unfavorable economics. Most operating nuclear plants are economical to operate when costs going forward are considered, i.e. when sunk capital and construction costs are ignored. However, new plants appear to be more expensive than alternate sources of base load generation, notably coal and natural gas fired electricity generation, when both capital and operating costs are taken into account.

Coal plants have capital costs intermediate between those of gas and nuclear. Even with SO_2 and NO_x controls that meet U.S. new source performance standards, new coal plants are widely perceived to be less costly than nuclear plants. However, if CO_2 emissions were in the future to become subject to control and a significant "price" placed on emissions, the relative economics could become much more favorable to nuclear power.

Perceived adverse safety, environmental, and health effects. After the 1979 accident at Three Mile Island in Harrisburg, Pennsylvania and the 1986 accident at Chernobyl in the Soviet Union, public concern about reactor safety increased substantially. The 1999 accident at the Tokai-

Mura plant underscored safety concerns about the nuclear fuel cycle outside of the reactor. There is also concern about transportation of nuclear materials, and waste management. The September 11, 2001 terrorist attack on the World Trade Center and the Pentagon have heightened concerns about the vulnerability of nuclear power stations and other facilities, especially spent fuel storage pools, to terrorist attack. There is concern about radiation exposure of citizens and workers from activities of the industry despite good regulation and health records. There are significant environmental impacts, ranging from long-term waste disposal to the handling and disposal of toxic chemical wastes associated with the nuclear fuel cycle.

Proliferation. The possibility exists that nations wishing to acquire or enhance a nuclear weapons capability will use commercial nuclear power as a source of technological know-how or nuclear weapons usable material, notably plutonium. Although this has not proved to be the preferred pathway to nuclear weapons capability, the possession of a complete nuclear fuel cycle, including enrichment, fuel fabrication, reactor operation, and reprocessing, certainly moves any nation closer to obtaining such a capability. The key step for achieving nuclear weapons capability is acquisition of sufficient weapons-usable fissionable material, either high-enriched uranium or plutonium. Unfortunately, reprocessing of spent fuel for the fuel cycle operation in Europe, Russia, and Japan has led to the accumulation of about 200 tonnes of separated plutonium. The associated risks have been viewed with increased alarm since the 9/11 events that demonstrated the reach of international terrorism. Radiation exposure from spent fuel that is not reprocessed is a strong, but not certain, barrier to theft and misuse.

Difficulty of waste management. There are many radioactive waste streams created in various parts of the nuclear fuel cycle. What deservedly receives the most attention is the high level waste containing the fission products and/or transuranic (TRU) elements created during energy generation. The spent fuel from nuclear reactors contains radioactive material that presents health and environmental risks that persist for tens of thousands of years. At present, no nation has successfully demonstrated a disposal system for these nuclear wastes. On the other hand, Finland has decided on a path to manage spent fuel, and the United States has decided to proceed with licensing of Yucca Mountain as a geological repository. At the same time, many of the discussions surrounding alternative reactors and fuel cycles are motivated by a desire to reduce high-level waste management challenges.

The potential impact on the public from safety or waste management failure and the link to nuclear explosives technology are unique to nuclear energy among energy supply options. These characteristics and the fact that nuclear is more costly, make it impossible today to make a credible case for the immediate expanded use of nuclear power.

Inevitably, there will be a high degree of government involvement in nuclear power, even in market economies, to regulate safety, waste, and proliferation risk. This is, in itself, another challenge for nuclear power. There is considerable variation in how different countries approach the issues of safety, proliferation, and waste management. This often complicates the role of governments in setting international rules – especially for preventing proliferation, but also for safety and waste management – that serve common interests. Poor safeguarding of nuclear materials or facilities in any nation could result in acquisition of nuclear explosives by a rogue state or terrorist group for use in another nation. The Chernobyl accident demonstrated the potential for radioactivity to spread across borders and thus the importance of uniformly high safety standards and advanced safety technologies (such as western reactor containment designs).

Nuclear power's value as a carbon-free electricity supply technology has also generally not been recognized in government policies. Government policies have focused on targeting renewable energy resources and end-use efficiency improvements through a combination of direct subsidies, tax subsidies, renewable energy portfolio standards, appliance efficiency standards, and other "second best" mechanisms to promote carbon-free supply technologies and to reduce electricity demand. Nuclear power has generally been excluded from these programs. While the European Union will introduce a carbon dioxide emissions trading system in a few years, countries have not yet turned to broad policies to internalize the social costs of carbon emissions that would provide incentives for investment in all carbon free electricity supply or energy efficiency technologies, including nuclear power. Thus nuclear power does not compete on a level playing field and, from this perspective, is presently being discriminated against in policies designed to respond to the challenge of reducing carbon dioxide emissions.

Given these difficulties, it is fair to ask whether nuclear energy can ever recapture its attractiveness as a major energy supply option. However, this is not the question we seek to address. The answer to such a question necessarily depends on how societies and technology evolve (economic growth, electricity demand, fuel prices, environmental constraints, premium attached to energy security, the cost of alternatives such as renewables, new technologies such as fusion).

The difficulties facing nuclear power should not, at this time, rule it out as one of a small number of options that may be attractive to exercise in the future, as countries develop responses to the energy and environmental challenges of this century. *We believe that it is important for governments to adopt policies that enable the full range of significant options available. Nuclear is one of those options.* Whether it is an option that will eventually be exercised will depend on many unknown contingencies.

Given the difficulties that confront nuclear power, the effort required to overcome them is justified only if nuclear power potentially can make a significant impact on the major challenges of global warming, electric supply, and security. That is, for nuclear power to merit strategic focus and sustaining actions on the part of government , there must also be a commitment to significant expansion of nuclear power that will sustain and perhaps modestly increase its share of global electricity generation, even as use of electricity multiplies.

NOTES

1. T.M.L. Wigley, "Stabilization of greenhouse gas concentrations," in *U.S. policy on climate change: What next,?* Aspen Institute, Washington D.C., 2002.
2. In 2003, five new units are expected to come into operation: one in the Czech Republic, two in China, and two in South Korea. An additional 18 plants are under construction worldwide, primarily in China, Taiwan, India, Japan, and South Korea.
3. National Academy of Engineering website http://www.greatachievments.org/
4. U.S. Department of Energy, Energy Information Administration (EIS) International Energy Outlook 2002.
5. S. G. Benka, "The Energy Challenges," Physics Today (April 2002) p. 38.
6. This is the Nunn-Lugar-Domenici program. See " DOE's non-proliferation programs with Russia," Co- chairs Howard Baker and Lloyd Cutler, January 10, 2001, The Secretary of Energy Advisory Board, U.S. DOE.
7. For a recent report card, see M. Bunn, A. Wier, and J.P. Holdren, *"Controlling nuclear warheads and materials,"* Nuclear Threat Initiative, Washington, D.C., March 2003.

Chapter 3 — Outline of the Study

Our study makes two assumptions: First, as discussed in Chapter 1, that *nuclear energy is an important energy supply option for the future, but that exercising the option for significant deployment requires that the four significant challenges — cost, safety, waste, and proliferation — must be addressed and overcome.* Second, as discussed in Chapter 2, *that the public and private sectors can justify devoting the resources necessary to overcome these four challenges only if there is some reasonable possibility for major benefit to society* from having this option available in the future.

Therefore, we must consider large-scale deployment of nuclear power as a possible outcome and understand fully the ramifications of turning to nuclear power to provide a significant source of non-carbon electricity supply. From a public policy perspective, the scenarios that merit analysis are either a large-scale deployment or a phase-out of nuclear power over the next half-century. We stress that our approach is to evaluate expansion of nuclear energy as an *option* possibly needed in the future to meet a significant fraction of world electricity demand while addressing global environmental challenges. We are *not* declaring a specific goal for a particular time. Our evaluation criteria are:

☐ favorable economics;

☐ effective waste disposal;

☐ high proliferation resistance; and

☐ safe operation of all aspects of the fuel cycle.

To undertake this evaluation we need to establish a point of reference for nuclear deployment that might be realized 50 years from now. To set this point of reference, we stipulate as the basis of a scenario that *nuclear energy will retain or increase its current share of electricity generation at mid-century.*[1] The projected growth rate of electricity over a half century period is uncertain. The average rate of growth will depend importantly on several variables, notably the rate of economic growth and the price of electricity. A range of possibilities[2] is presented in Table 3.1.

Table 3.1 Alternative Reference Points for Nuclear Deployment in 2050 in GWe for Different Assumptions about Electricity Growth Rates and Nuclear Market Share[a]

	ALTERNATIVE AVERAGE ELECTRICITY GROWTH RATES 2000–2050 %		
NUCLEAR GENERATION MARKET SHARE %	1.5	2.0	2.5
17	650	838	1,060
20	770	970	1,235
25	880	1,235	1,545

a. We assume the global average capacity factor increases from 75% to 85%.

We adopt 1000 to 1500 GWe as the mid-century reference point range for our study. This is large enough to reveal the challenges that need to be faced to enable the large-scale deployment of nuclear energy. Our analysis and conclusions concerning what we refer to as the global growth scenario, as described in Chapter 1, would not change significantly if this number of deployed reactors were somewhat higher, nor if the time period to reach full operational deployment were extended. We have examined the rate of deployment that would need to occur for a deployment in the range of 1000 to 1500 GWe and note that it is unlikely to proceed in a linear manner; for the next ten to fifteen years, deployment is likely to be slow, and therefore the rate would necessarily accelerate dur-

Table 3.2 Global Growth Scenario

REGION	PROJECTED 2050 GWe CAPACITY	NUCLEAR ELECTRICITY MARKET SHARE 2000	NUCLEAR ELECTRICITY MARKET SHARE 2050
Total World	1,000	17%	19%
Developed world	625	23%	29%
U.S.	300		
Europe and Canada	210		
Developed East Asia	115		
FSU	50	16%	23%
Developing world	325	2%	11%
China, India, Pakistan	200		
Indonesia, Brazil, Mexico	75		
Other developing countries	50		

Projected capacity comes from the global electricity demand scenario in Appendix 2, which entails growth in global electricity consumption from 13.6 to 38.7 trillion kWe-hrs from 2000 to 2050 (2.1% annual growth). The market share in 2050 is predicated on 85% capacity factor for nuclear power reactors. Note that China, India, and Pakistan are nuclear weapons capable states. Other developing countries includes as leading contributors Iran, South Africa, Egypt, Thailand, Philippines, and Vietnam.

ing the expansion period. The implied construction rate near the mid-century endpoint of the global growth scenario would be challenging and exceed any rate previously achieved.

The pattern of deployment of nuclear power around the world is also important, especially from the viewpoint of assessing the risks of proliferation. Table 3.2 indicates how 1000 1000MWe (or equivalent smaller reactors) might be distributed around the world in the time period 2030 to 2050. Although this illustrative deployment is highly speculative, it provides a concrete instance of how the global growth scenario might be realized.

Nuclear power expansion on this scale is not likely to happen without United States leadership. It also requires continued European commitment and the initiation or expansion of nuclear power programs in many developing countries around the world. If nuclear deployment on the scale of the global growth scenario were to occur, however, it would avoid a significant amount of carbon dioxide emissions, largely by displacing carbon emitting fossil fuel generation. Today, carbon equivalent emission from human activity totals about 6,500 million metric tonnes per year. This value will probably more than double by 2050, depending on the assumptions made. The 1000 GWe of nuclear power assumed in the global growth scenario would avoid about 800 million tonnes of carbon equivalent if the electricity generation displaced was gas-fired and 1,800 million tonnes of carbon equivalent, if the generation was coal-fired, (assuming no capture and sequestration of CO_2 combustion product). *Thus, the 1000 GWe nuclear program has the potential of displacing 15 - 25% of the anticipated growth in anthropogenic carbon emissions.* In 2050, deployment of 1000 Gwe of nuclear power would generate about 20% of worldwide electricity production, if electricity production grows at 2% per year. Evidently, the global growth scenario would have nuclear power generating significant amounts of electricity that would otherwise likely be generated by fossil fuels.

FUTURE STRUCTURE OF THE NUCLEAR INDUSTRY

Significant expansion of nuclear power has implications for the structure of its supporting nuclear industry infrastructure. In an unregulated economy comprised of private business firms competing in the marketplace, market forces determine the organization and structure of the firms that design, construct, and operate nuclear power plants and supporting fuel cycle facilities. However, because nuclear technology involves significant public issues of safety, waste management, and proliferation, the government has a responsibility to ensure that whatever industry structure develops will facilitate, rather than impede, attention to these issues. The intersection of these public issues and free market operations cannot be handled through minor government regulation, as is possible in some other industries. An additional layer of government involvement stems from the traditional structure of electric utilities as vertically integrated monopolies. Government intervention has been necessary to ensure that the operations of the electric utility industry are efficient and that other public objectives for electricity supply are achieved. We do not today know how the nuclear industry will evolve but we mention issues that we believe are an important determinant of the future success of nuclear power.

The tension between public responsibility and private market operation has been present since the beginning of commercial nuclear power. In the U.S., the assumption was that any private utility was in principle capable of owning and operating a nuclear power plant and should be allowed to do so under appropriate government supervision with regard to safety. Several other countries have followed this route, notably Japan and Germany. In other countries, such as Russia and China, nuclear power has been entirely the responsibility of the central government. Elsewhere the pattern has been mixed. In France, all nuclear plants have been operated by a single state-owned utility, Electricite de France. Similar arrangements have applied in South Korea and Taiwan. In Spain and Sweden a small number of investor-owned utilities have built and operated nuclear power plants.

No arrangement has proved free of tension. In many countries with state-owned electric power monopolies, there has been a move towards privatization and increased competition, while in the U.S. it is widely recognized that in the current environment, small investor-owned utilities operating a single nuclear power plant are more likely to encounter operational problems and to experience higher generating costs.

We do not believe that a single organizational model for nuclear power will be applicable throughout the world. We do believe that industrial organization is an important consideration for the future expansion of nuclear power. To oversimplify, too much government involvement is likely to make nuclear power expensive and uncompetitive, and too little government involvement risks safety, waste, and proliferation problems. International cooperation is also critical for the effective management of these public issues, especially proliferation. Thus, the industrial structure in each country must be compatible with whatever international norms are adopted

The structure of the nuclear industry is also important because of its influence on innovation, productivity, and performance. A necessary condition for the expanded nuclear deployment postulated in the global growth scenario is that nuclear power plants and other nuclear facilities be designed, built, and operated to expectation. This performance, in turn, depends upon sound technological choices, high quality design and construction, and the availability of competent construction project management teams, craft labor, and operating and maintenance personnel. Moreover, the growth of capability in all these categories must occur in the context of a deployment schedule that will be highly uncertain. These are all matters of industrial organization that are critical to the prospects for the expansion of nuclear power but do not happen automatically. Nor is it clear that governments are sufficiently agile or wise to adopt policies that will encourage the proper sequencing of industrial capabilities and needs.

OUTLINE OF THE STUDY

In conducting this study, our first step was to define the character of the global growth scenario, i.e., the nature and size of the fuel cycle necessary for it to function. The results are discussed in Chapter 4.

Our second step was to answer the question: "Is such a mid-century scenario technically, economically and politically credible?" We do this by evaluating how well the global growth scenario can meet the four challenges of cost, safety, waste disposal, and proliferation risk. This is undertaken in Chapters 5 through 8.

Our third step was to consider public attitudes to an expanded nuclear future. Chapter 9 reports on the result of an Internet-based poll that we conducted and its implications.

Our fourth step was to make recommendations that would retain the nuclear option. These recommendations, presented in Part 2 of the report, addresses both domestic and international issues and includes both technical and institutional measures. We identify organizational changes that we believe would increase the chance of success of the effort and decrease the cost. The technical measures involve a sustained and disciplined program of analysis, research, development, and demonstration of various aspects of the nuclear enterprise. We do not seek to establish rigid goals or a fixed timetable for the technical program. The pace of the program should be determined by its technical success in the context of the world energy and environmental outlook. We anticipate that the cost of the technical program would be borne by other countries, as well as by the United States.

This study approach is conditioned by the belief that the nuclear power option makes sense only if possible deployment is quite large, since no small deployment can make a significant contribution to dealing with the greenhouse gas problem. Support for keeping the nuclear power option open will therefore depend on convincing the public and their elected representatives that large-scale deployment can overcome the four challenges. *We believe that establishing a vision for a possible large- scale deployment of nuclear energy that is both technically and politically credible is a necessary condition for gaining public support.* Indeed it is misleading to focus on small increases in nuclear capacity justified by significant CO_2 reduction. Furthermore, small deployments ignore or do not face squarely the challenges that must be overcome for nuclear energy to become a significant contributor to controlling CO_2 emissions.

It will take sustained effort to accomplish the necessary technical and institutional steps needed to make nuclear an attractive energy option. Given the expected evolution of worldwide energy supply and demand, however, we believe there is time to undertake this work . We do not believe that nuclear energy will go forward without such a comprehensive approach. The construction of a few reactors in the short term and a technology driven R&D program is not sufficient. Although R&D is a vital ingredient, a comprehensive program should address all four of the key criteria in order to create a clear and sound vision of the energy future. A similarly broad approach should be applied to all energy supply and end-use efficiency technologies under consideration. A policy directed to a single solution is inadequate. We also recognize that the deployed nuclear fuel cycle will not simply "jump" to a new reality. But, we believe the evolution will be guided by a clear picture of where we are headed and how we will get there.

NOTES

1. Some advocate hydrogen production as an objective for nuclear power. To be economical hydrogen produced by electrolysis of water depends on low cost nuclear power. Hydrogen can also be produced by high temperature thermal cracking with heat provided by a nuclear reactor. This approach is presently highly speculative. Our belief is that if nuclear proves to be an economical choice for electricity production, it *may* prove to be interesting for hydrogen production, whether the production is through electrolysis or high temperature thermal splitting of water. However, if nuclear is not an economical choice for electricity production, it is most unlikely to be used for large-scale production of hydrogen.
2. For example, the EIA projects worldwide electricity growth rate of 2.7% for the period 2000-2020. If we project that this growth rate continues [See Table 3.1.] through mid-century and recognize that about 350 GWe nuclear capacity is currently deployed worldwide (in over 400 units), then the mid-century point of reference for nuclear maintaining its market share is 1325 GWe of deployment in 2050. This deployment might correspond to 1325 reactors, each with capacity of 1000 MWe or more units of smaller rated capacity. There are higher and lower projections of world electricity use.The MIT Emissions Prediction and Policy Analysis (EPPA) project projects an average growth rate between 1995 and 2004 of 1.8% that gives a nuclear deployment of 950 Gwe in 2050, assuming nuclear power retains its market share. If we assume the EIA 2.7% growth rate to 2020 and the lower MIT EPPA 1.8% growth rate between 2020 and 2050, the calculated number is 1164 GWe of nuclear power in 2050.

Chapter 4 — Fuel Cycles

The description of a possible global growth scenario for nuclear power with 1000 or so GWe deployed worldwide must begin with some specification of the nuclear fuel cycles that will be in operation. The nuclear fuel cycle refers to all activities that occur in the production of nuclear energy.

It is important to emphasize that producing nuclear energy requires more than a nuclear reactor steam supply system and the associated turbine-generator equipment required to produce electricity from the heat created by nuclear fission. The process includes ore mining, enrichment, fuel fabrication, waste management and disposal, and finally decontamination and decommissioning of facilities. All steps in the process must be specified, because each involves different technical, economic, safety, and environmental consequences. A vast number of different fuel cycles appear in the literature,[1] and many have been utilized to one degree or another. We review the operating characteristics of a number of these fuel cycles, summarized in Appendix 4.

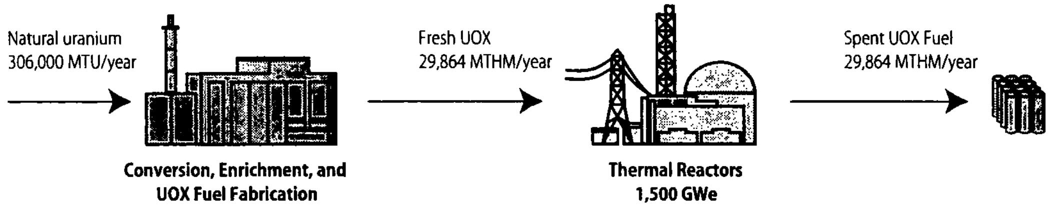
In this report, our concern is not with the description of the technical details of each fuel cycle. Rather, we stress the importance of aligning the different fuel cycle options with the global growth scenario criteria that we have specified in the last section: cost, safety, nonproliferation, and waste. This is by no means an easy task, because objective quantitative measures are not obvious, there are great uncertainties, and it is difficult to harmonize technical and institutional features. Moreover, different fuel cycles will meet the four different objectives differently, and therefore the selection of one over the other will inevitably be a matter of judgment. All too often, advocates of a particular reactor type or fuel cycle are selective in emphasizing criteria that have led them to propose a particular candidate. We believe that detailed and thorough analysis is needed to properly evaluate the many fuel cycle alternatives.

We do not believe that a new technical configuration exists that meets all the criteria we have set forth, e.g. there is not a technical 'silver bullet' that will satisfy each of the criteria. Accordingly, the choice of the best technical path requires a judgment balancing the characteristics of a particular fuel cycle against how well it meets the criteria we have adopted.

Our analysis separates fuel cycles into two classes: "open" and "closed." In the open or once-through fuel cycle, the spent fuel discharged from the reactor is treated as waste. See Figure 4.1. In the closed fuel cycle today, the spent fuel discharged from the reactor is *reprocessed*, and the products are partitioned into uranium (U) and plutonium (Pu) suitable for fabrication into oxide fuel or mixed oxide fuel (MOX) for recycle back into a reactor. See Figure 4.2. The rest of the spent fuel is treated as high-level waste (HLW). In the future, closed fuel cycles could include use of a dedicated reactor that would be used to transmute selected isotopes that have been separated from spent fuel. See Figure 4.3. The dedicated reactor also may be used as a breeder to produce new fissile fuel by neutron absorption at a rate that exceeds the consumption of fissile fuel by the neutron chain reaction.[2] In such fuel cycles the waste stream will contain less actinides,[3] which will signifi-

Figure 4.1 Open Fuel Cycle: Once-Through Fuel — Projected to 2050

Current Burnup: 50 GWD/MTIHM:



High Burnup: 100 GWD/MTIHM:

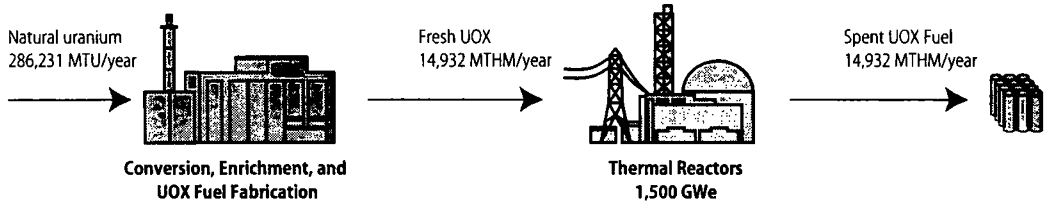


Figure 4.2 Closed Fuel Cycle: Plutonium Recycle (MOX option - one recycle) — Projected to 2050

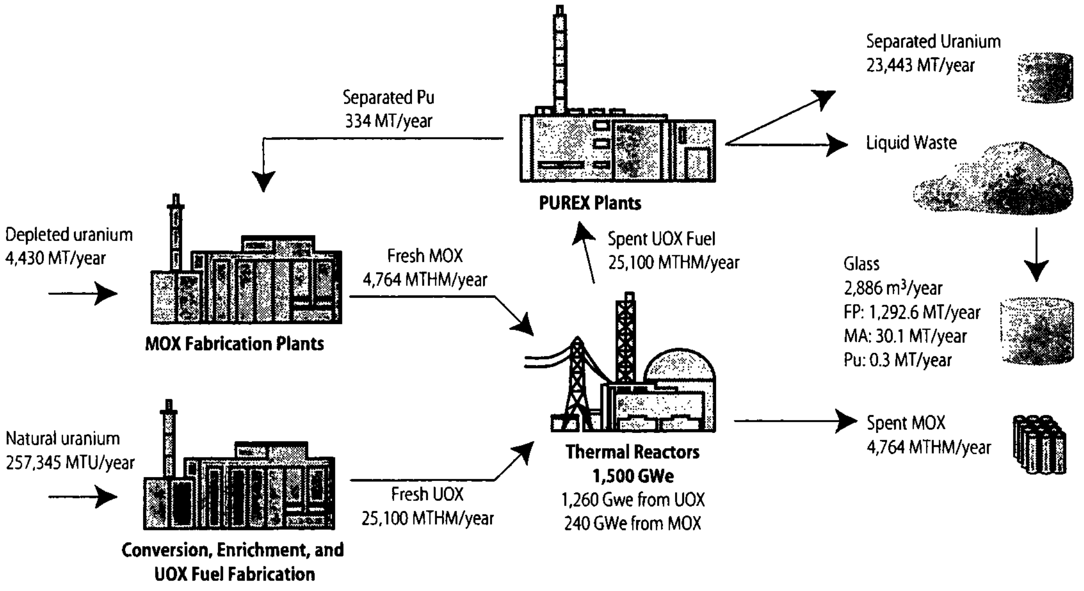
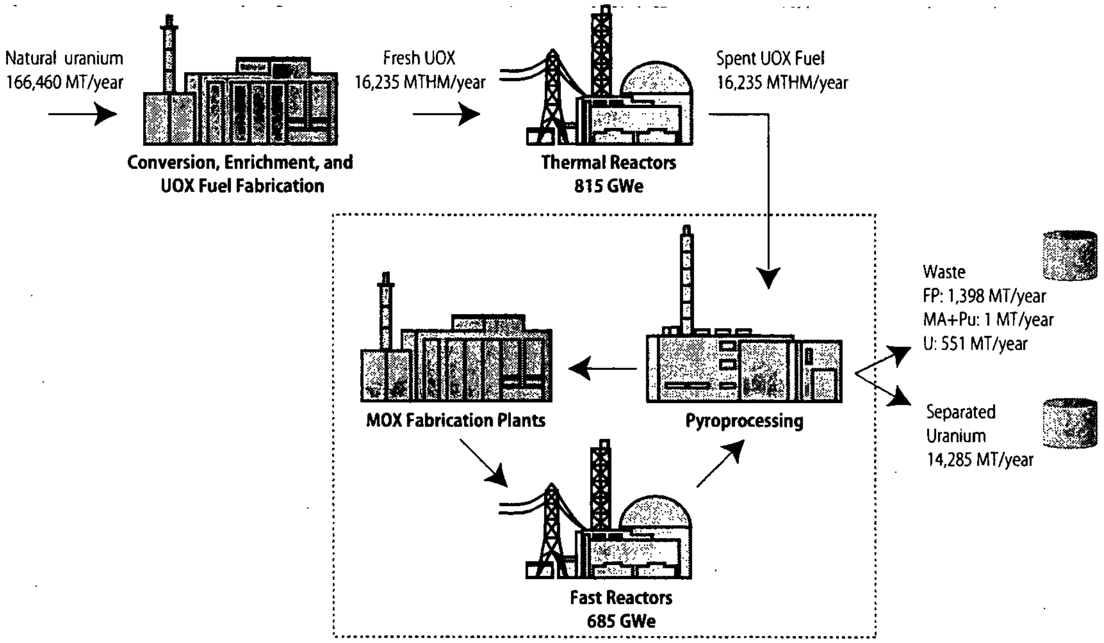


Figure 4.3 Closed Fuel Cycle: Full Actinide Recycle — Projected to 2050



cantly reduce the long-term radioactivity of the nuclear waste.[4]

In general, we expect the once-through fuel cycle to have an advantage in terms of cost and proliferation resistance (since there is no reprocessing and separation of actinides), compared to the closed cycle. Closed cycles have an advantage over the once-through cycle in terms of resource utilization (since the recycled actinides reduce the requirement for enriched uranium), which in the limit of very high ore prices would be more economical. Some argue that closed cycles also have an advantage for long-term waste disposal, since long-lived actinides can be separated from the fission products and transmuted in a reactor. Our analysis below focused on these key comparisons.

Both once-through and closed cycles can operate on U or Th fuel and can involve different reactor types, e.g., Light Water Reactors (LWRs), Heavy Water Reactors (HWRs), Supercritical water reactors (SCWRs), High Temperature and very High Temperature Gas Cooled Reactors (HTGRs), Liquid Metal and Gas Fast Reactors (LMFRs and GFRs), or Molten Salt Reactors (MSR) of various sizes. Today, almost all deployed reactors are of the LWR type. The introduction of new reactors or fuel cycles will require considerable development resources and some period of operating experience before initial deployment.

The fuel cycle characteristics of the current worldwide deployment of nuclear power (with the exception of three operating liquid metal fast breeder plants[5]) are summarized in Table 4.1. At present, plants employing the once-though enriched uranium oxide (UOX) fuel have a total capacity of about 325 GWe of electricity. In addition there are plants burning reprocessed mixed Pu and U oxide fuel (MOX) in reactors with a total capacity of about 27 GWe.[6] Current plans call for only one recycle of the fuel. Table 4.1 gives the annual material flows for the entire fleet of reactors.

The proposed mid-century deployment under the global growth scenario of this study is

Table 4.1 Fuel Cycle Characteristics of Current Plants[a]

	U FEED 10^3 MT/YR	HLW DISCHARGED YR^{-1}	Pu DISCHARGED MT/YR	SEPARATED Pu INVENTORY MT
UOX Plants 325 GWe	66.340	Spent UOX: 6471 MTIHM	Discharged: 89.7	—
MOX Plants 27 GWe	3.675	Spent MOX: 179 MTIHM Glass[b]: 109 m^3 Process Waste: 330 m^3	Consumed: 12.6 Discharged: 8.8	6.3[c]

a. Initial enrichment 4.5%, tails assay 0.3%, discharge burnup 50GWd/MTIHM, thermal efficiency 33%, capacity factor 90%. Values on a per GWe basis are given in appendix 4.

b. Requires reprocessing of 944 MTIHM spent UOX per year (0.6 La Hague equivalents). Borosilicate glass contains: 48.6 MT FP, 1.1 MT Pu+MA.

c. Separated Pu storage time is assumed to be 6 months. See Brogli, Krakowski, "Degree of Sustainability of Various Nuclear Fuel Cycles," Paul Scherrer Institut, August 2002.

achieved either by exclusive use of the once-through cycle with current LWRs (option one) or by plutonium recycle (where all the spent UOX but none of the spent MOX is reprocessed) with current LWRs (option two). Under both of these options, material flows increase significantly, as presented in Table 4.2.

The once-through fuel cycle is a technically credible option, assuming there is sufficient uranium ore available at reasonable cost to support a deployment of this size. Note that the single-pass[7] thermal reprocessing option uses almost as much U ore as the once-through system. Furthermore, if there is adequate ore supply at reasonable prices, then the single-pass recycle option will not be economically attractive compared to the once through option as Appendix 4.1 discusses.

As indicated in Table 4.2, the thermal recycle option does have an advantage in producing less material requiring permanent waste disposal, but this is balanced by greater transuranic (TRU)[8] waste produced during reprocessing. Furthermore, the fission product

Table 4.2 Fuel Cycle Characteristics Projected to Mid-Century

	1500 GWE FLEET PER YEAR IN 2051			
	U FEED 10^3 MT/YEAR	HLW DISCHARGED $YEAR^{-1}$	Pu DISCHARGED MT/YEAR	SEPARATED Pu INVENTORY MT
Scenario 1 Once-through 1500 GWe	306	Spent UOX: 29 864 MTIHM	Discharged: 397	—
Scenario 2 Thermal Recycle[d] UOX Plants: 780 GWe MOX Plants: 720 GWe	257	Glass a: 2886 m^3 Process Waste: 8785 m^3 Spent MOX: 4764 MTIHM	Discharged: 233	167[e]
	FLEET CUMULATIVE, FROM 352GWE IN 2002 TO 1500 GWE IN 2051			
	U FEED 10^6 MT	HLW DISCHARGED	Pu DISCHARGED 10^3 MT	—
Scenario 1 Once-through 1500 GWe	9.45	Spent UOX: 922·10^3 MTIHM (13.2 YMEs[c])	Discharged: 12.0	—
Scenario 2 Thermal Recycle[d] UOX Plants: 780 GWe MOX Plants: 720 GWe	8.18	Spent UOX: 147·10^3 MTIHM Spent MOX: 124·10^3 MTIHM Glass[b]: 75·103 m^3 Process Waste: 228·103 m^3	Discharged: 8.0	—

a. Requires reprocessing of 26 335 MTIHM spent UOX per year (14 La Hague equivalents). Borosilicate glass contains: 1292.6 MT FP, 30 MT MA, 0.3 MT Pu.

b. Requires reprocessing of 651·10^3 MTIHM spent UOX. Borosilicate glass contains: 33.5·10^3 MT FP, 781 MT MA, 8.7 MT Pu.

c. YME: Yucca Mountain Equivalent (70 000 MTIHM).

d. MOX Plants have 2/3 of the core loaded with UOX and 1/3 loaded with MOX. Hence, 540 GWe is generated from UOX, and 240 GWe is generated from MOX.

e. Separated Pu storage time is assumed to be 6 months. See Brogli, Krakowski, "Degree of Sustainability of Various Nuclear Fuel Cycles," Paul Scherrer Institut, August 2002.

Table 4.3 Global Growth Scenario — Fuel Cycle Parameter comparison. Annual Amounts for 1500 GWe Deployment[a]
See Appendix 4 for fuel cycle calculations.

	OPTION 1A ONCE THROUGH LOW BURN UP	OPTION 1B ONCE THROUGH HIGH BURN UP	OPTION 3 LWR + FAST REACTOR[b]	
			LWR	Fast reactor
Capacity, GWe	1,500	1,500	815	685
Enrichment, %	4.5	8.2	4.5	25
Burn up, GWd/MTIHM	50	100	50	120
Uranium ore				
per year, 10^3 MT/yr	306	286	166	
cumulative, 10^6 MT	9.45	8.76	5.96	
Spent or repr. Fuel				
per year, 10^3 MTIHM/yr	29.9	14.9	Repr.: 20.9 (12.3 LHE[c])	
cumulative, 10^3 MTIHM	922 (13.7 YME)	516 (7.4 YME)	Spent : 4.1 YMEs	
HLW, MT/yr	Not applicable	Not applicable	FP: 1398; MA+Pu: 1.0	
Pu, MT/yr	397	294	0.7 (repr. losses)	
Waste decay heat[d]				
W/GWeY (100 yrs)	$1.1 \cdot 10^4$	$1.1 \cdot 10^4$	$2.8 \cdot 10^3$	
Waste ingestion hazard				
m^3/GWeY (1,000 yrs)	$6.9 \cdot 10^{11}$	$5.3 \cdot 10^{11}$	$2.2 \cdot 10^7$	

a. Thermal efficiency 33% for LWRs and 40% for FRs, capacity factor 90%, enrichment tails assay 0.3%. Capacity is assumed to increase linearly. Fast reactors start deployment in 15 years.

b. Intended as generic fast reactor; data from ANL IFR.

c. LHE means La Hague equivalent (1,700 MTHM/year)

d. The decay heat and radiotoxicity are computed from and MCODE/ORIGEN run and expressed on a per GWe-y basis to establish a fair comparison between the various fuel cycles. The decay heat and radiotoxicity per unit mass can be obtained by dividing by the mass of spent fuel discharged per GWe-y. The spent fuel discharge for option 1A is 22.1 MTIHM/y, giving a decay heat at 100 years of 5.0·102 W/MTIHM and a radiotoxicity at 1000 years of 3,1·1010 m3/MTIHM, as shown in Figures 7.2 and 7.3.

inventory is essentially the same. Most important, the thermal recycle case has a large amount of Pu separated each year.[9] The separated plutonium inventory required for option two is 167 metric tons. A nuclear weapon of significant yield can comfortably be made with less than 10kg of Pu, so this amount represents the potential for thousands of nuclear weapons. Thus, the once-through thermal recycle scenario will not be a reasonable mid-century state, so long as U ore is available at reasonable prices. If ore prices were to become very high, the one-pass thermal recycle option would potentially be attractive, but under those conditions, a fuel cycle that includes reactors that transmute actinides must then be considered (option 3). Single-pass thermal recycle is not an attractive approach for nuclear energy for the next half century.

In option 3 we consider a *fully closed fuel cycle*. This fuel cycle is exactly balanced so the number of fast reactors deployed is sufficient to burn all the actinides produced in once through thermal reactors. Only the fast reactor fuel is reprocessed, presumably in a developed country and a 'secure' energy park; the thermal reactors operating on a once-through cycle, can be located anywhere. This configuration has proliferation advantage over the situation considered in option two, as discussed in Chapter 8. *It is important to note that this balanced closed fuel cycle is entirely different from breeder fast reactor fuel cycles where net plutonium produced in fast reactors is made into MOX fuel to be burned in thermal reactors.* In the closed fuel cycle we considered, the fast reactor burns plutonium and actinides created in the thermal reactor.

In Table 4.3, we describe three illustrative deployments of 1500 reactors each with rated capacity of 1000 MWe, in order to give a more concrete impression of what the global growth scenario might look like. Option one is expanded and option two is replaced by a fully closed fuel cycle. The three options are:

- ☐ *Base line.* 1000 MWe LWRs operating on a oncethrough fuel cycle with today's typical characteristics. (Option 1A);
- ☐ *Advanced once-through* LWRs , perhaps with some smaller, modular HTGR nuclear systems, with higher fuel burnup characteristics that better meet the four objectives. (Option 1B);
- ☐ *Fast reactors* deployed in developed countries with a balanced closed fuel cycle. Reprocessing, fuel fabrication, and fast reactor burners are co-located in secure nuclear energy "parks." In the developing world, the deployment is largely once-through LWR fuel cycle (Option 3).

AVAILABILITY OF URANIUM RESOURCES

How long will the uranium ore resource base be sufficient to support large-scale deployment of nuclear power without reprocessing and/or breeding?[10] Present data suggests the required resource base will be available at an affordable cost for a very long time. Estimates of both known and undiscovered uranium resources at various recovery costs are given in the NEA/IAEA "Red Book"[11]. For example, according to the latest edition of the Red Book, known resources[12] recoverable at costs < \$80/kgU and < \$130/kgU are approximately 3 and 4 million tonnes of uranium, respectively. However, the amount of known resources depends on the intensity of the exploration effort, mining costs, and the price of uranium. Thus, any predictions of the future availability of uranium that are based on current mining costs, prices and geological knowledge are likely to be extremely conservative.

For example, according to the Australian Uranium Information Center, a doubling of the uranium price from its current value of about \$30/kgU could be expected to create about a ten-fold increase in known resources recoverable at costs < \$80/kgU[13] i.e., from about 3 to 30 million tonnes. By comparison, a fleet of 1500 1000 MWe reactors operating for 50 years requires about 15 million tonnes of uranium (306,000 MTU/yr as indicated in Table 4.2), using conventional assumptions about burn-up and enrichment.

Moreover, there are good reasons to believe that even as demand increases the price of uranium will remain relatively low: the history of all extractive metal industries, e.g., copper, indicates that increasing demand stimulates the development of new mining technology that greatly decreases the cost of recovering additional ore. Finally, since the cost of uranium represents only a small fraction of the busbar cost of nuclear electricity, even large increases in the former — as may be required to recover the very large quantities of uranium contained at low concentrations in both terrestrial deposits and seawater — may not substantially increase the latter.[14] In sum, we conclude that resource utilization is not a pressing reason for proceeding to reprocessing and breeding for many years to come.

NOTES

1. See, for example, OECD Nuclear Energy Agency, Trends in the Nuclear Fuel Cycle ISBN 92-64-19664-1 (2001) and Nuclear Science Committee "Summary of the workshop on advanced reactors with innovative fuel," October 1998, NEA/NSC/DOC(99)2.
2. Several nations have explored breeder reactors, notably the U.S., France, Russia, Japan, and India.
3. Minor actinides are Americium (Am), Neptunium (Np), and Curium (Cm).
4. There are still other options, such as using an accelerator to produce neutrons in a sub-critical assembly.
5. The three surviving developmental breeder reactors are Phenix in France, Monju in Japan, and BN600 in Russia.
6. The MOX fueled plants are currently operating with only about a third of their core loaded as MOX fuel; the balance is UOX fuel. Hence only about 9 GWe are being generated in these reactors from the MOX fuel
7. Single pass recycle means that a discharged fuel batch is reprocessed once only.
8. TRU here refers to the U.S. definition: low-level waste contaminated with transuranic elements.
9. Due to process holding time, the actual amount of separated Pu inventory could be several or more years' worth of separations.
10. For additional details, see Appendix 5-E and Marvin Miller, *Uranium resources and the future of nuclear power*, Lecture notes, MIT, Spring 2001; for copies contact marvmiller@mit.edu.
11. Uranium resources, production, and demand ("The Red Book"), OECD Nuclear Energy Agency and International Atomic Energy Agency, 2001.
12. Such resources are also known as measured resources and reserves.
13. Uranium Information Center, "Nuclear Electricity", 6th edition, Chapter 3 (2000). Available on the web at http:www.uic.com.au/ne3.htm.
14. For example, recent research in Japan indicates that uranium in seawater — present in concentration of 3.3 ppb — might be recovered at costs in the range of $300–$500/kg.

Chapter 5 — Nuclear Power Economics

Investments in commercial nuclear generating facilities will only be forthcoming if investors expect the cost of producing electricity using nuclear power will be lower than the risk-adjusted costs associated with alternative electric generation technologies. Since nuclear power plants have relatively high capital costs and very low marginal operating costs, nuclear energy will compete with alternative electricity generation sources for "baseload" (high load factor) operation. We recognize that over the next 50 years some significant but uncertain fraction of incremental electricity supplies will come from renewable energy sources (e.g. wind) either because these sources are less costly than alternatives or because government policies (e.g. production tax credits, high mandated purchase prices, and renewable energy portfolio standards) or consumer choice favor renewable energy investments. Despite the efforts to promote renewable energy options, however, it is likely that a large fraction of the incremental and replacement investments in electric generating capacity needed to balance supply and demand over the next 50 years will, in the absence of a nuclear generation option, rely on fossil-fuels — primarily natural gas or coal. This is particularly likely in developing countries experiencing rapid growth in income and electricity consumption. Accordingly, we focus on the costs of nuclear power compared to these fossil fuel generating alternatives in base-load applications.

Any analysis of the costs of nuclear power must take into account a number of important considerations. First, all of the nuclear power plants operating today were developed by state-owned or regulated investor-owned vertically-integrated utility monopolies.[1] Many developed countries and an increasing number of developing countries are in the process of moving away from an electric industry structure built upon vertically integrated regulated monopolies to an industry structure that relies primarily on competitive generation power plant investors. We assume that in the future nuclear power will have to compete with alternative generating technologies in competitive wholesale markets — as merchant plants.[2] These changes in the structure of the electric power sector have important implications for investment in generating capacity. Under traditional industry and regulatory arrangements, many of the risks associated with construction costs, operating performance, fuel price changes, and other factors were borne by consumers rather than suppliers.[3] The insulation of investors from many of these risks necessarily had significant effects on the cost of capital they used to evaluate alternative generation options and on whether and how they took extreme contingencies into account. Specifically, the process reduced the cost of capital and led investors to give less weight to regulatory (e.g. construction and operating licenses) and construction cost uncertainty, operating performance uncertainties and uncertainties associated with future oil, gas and coal prices than if they had to bear these cost and performance risks.

In a competitive generation market it is investors rather than consumers who must bear the risk of uncertainties associated with obtaining construction and operating permits, construction costs and operating performance. While some of the risks associated with uncertainties about the future market value of electricity can be shifted to electricity marketers and consumers through forward contracts, some market risk and all construction cost, operating cost and performance risks will continue to be held by power plant investors.[4] Thus, the shift to a competitive electricity market regime necessarily leads investors to favor less capital-intensive and shorter construction lead-time investments, other things equal.[5] It may also lead investors to favor investments that have a natural "hedge" against market price volatility, other things equal.[6]

Second, the construction costs of nuclear plants completed during the 1980s and early 1990s in the United States and in most of Europe were very high — and much higher than predicted today by the few utilities now building nuclear plants and by the nuclear industry generally. The reasons for the poor historical construction cost experience are not well understood and have not been studied carefully. The realized historical construction costs reflected a combination of regulatory delays, redesign requirements, construction management and quality control problems. Moreover, construction on few new nuclear power plants has been started and completed anywhere in the world in the last decade. The information available about the true costs of building nuclear plants in recent years is also limited. Accordingly, the future construction costs of building a large fleet of nuclear power plants is necessarily uncertain, though the specter of high construction costs has been a major factor leading to very little credible commercial interest in investments in new nuclear plants. Finally, while average U.S. nuclear plant availability has increased steadily during the 1990s to a high of 90% in 2001, many nuclear plants struggled with low availabilities for many years and the life-cycle availability of the fleet of nuclear plants (especially taking account of plants that were closed early) is much less than 90%.[7] In addition, the average operation and maintenance costs of U.S. nuclear plants (including fuel) were over $20/MWh during the 1990s (though average O&M costs had fallen to about $18/MWe-hr and the lowest cost quartile of plants to about $13/MWe-hr by 2001)[8], rather than the $10/MWe-hr often assumed in many paper engineering cost studies.

Third, even if an investment in nuclear power looked attractive on a spreadsheet, investors must confront the regulatory and political challenges associated with obtaining a license to build and operate a plant on a specific site. In the past, disputes about licensing, local opposition, cooling water source and discharge requirements, etc., have delayed construction and completion of nuclear plants. Many planned plants, some of which had incurred considerable development costs, were cancelled. Delays and "dry-hole" costs are especially burdensome for investors in a competitive electricity market.

With these considerations in mind, we now proceed to examine the relative costs of new nuclear power plants, pulverized coal plants, and combined-cycle gas turbine (CCGT) plants in base-load operations in the United States.[9] The analysis is not designed to produce precise estimates, but rather a "reasonable" range of estimates under a number of different assumptions reflecting uncertainties about future construction and operating costs. Similar analysis for Europe and especially Japan and Korea would be somewhat more favorable to nuclear, since gas and coal costs are typically higher than in the United States.

We start with a "base case" that examines the levelized *real* life-cycle costs of nuclear, coal, and CCGT generating technology using assumptions that we believe commercial investors would be expected to use today to evaluate the costs of the alternative generation options. The levelized cost is the constant real wholesale price of electricity that meets a private investor's financing cost, debt repayment, income tax, and associated cash flow constraints.

The base case assumes that non-fuel O&M costs can be reduced by about 25% compared to the recent operating cost experience of the average nuclear plant operating in the U.S. in the last few years. This puts the total O&M costs (including fuel) at about 15 mills/kWe-hr. We include this reduction in O&M costs in the base case because we expect that operators of new nuclear plants in a competitive wholesale electricity market environment will have to demonstrate better than average performance to investors. The 15 mill O&M cost value is consistent with the performance of existing plants that fall in the second lowest cost quartile of operating nuclear plants.[10] (The assumptions underlying the base case are listed in Table 5.3 and illustrative cash flows produced by our financial model are provided in Appendix 5.)

We then examine how the real levelized cost of nuclear generated electricity changes as we allow for *additional* cost improvements. First, we assume that construction costs can be reduced by 25% from the base case levels to more closely match optimistic but plausible forecasts. Second, we examine how life-cycle costs are further reduced by a one-year reduction in construction time. Third, we examine the effects of reducing financing costs to a level comparable to what we assume for gas and coal generating units as a consequence of, for example, reducing regulatory risks and commercial risks associated with uncertainties about construction and operating costs that presently burden nuclear compared to fossil-fueled alternatives. This reduction in financial risk might result from an effective commercial demonstration program of the type that we discuss further in Part II. Finally, we examine how the relative costs of coal and CCGT generation are affected by placing a "price" on carbon emissions, through carbon taxes, the introduction of a carbon emissions cap and trade program, or equivalent mechanism to price carbon emissions to internalize their social costs into investment decisions in a way that treats all supply options on an equivalent basis. We consider carbon prices in a range that brackets current estimates of the costs of carbon sequestration (capture, transport and storage). The latter analysis provides a framework for assessing the option value of nuclear power if and when the United States adopts a program to stabilize and then reduce carbon emissions.

The levelized cost of electric generating plants has typically been calculated under the assumption that their regulated utility owners recover their costs using traditional regulated utility cost of service cost recovery rules. Investments were recovered over a 40 year period and debt and equity were repaid in equal proportions over this lengthy period at the utility's cost of capital, which reflected the risk reducing effects of regulation. Moreover, the calculations typically provided levelized *nominal* cost values rather than levelized *real* cost values, obscuring the effects of inflation and making capital intensive technologies look more costly relative to alternatives than they really were.

We do not believe that these traditional levelized cost models based on regulated utility cost recovery principles provide a good description of how merchant plants will be financed in the future by private investors. Accordingly, we have developed and utilized an alternative model that provides flexibility to specify more realistic debt repayment obligations and associated cash flow constraints, as well as the costs of debt and equity and income tax obligations that a private firm would assign to individual projects with specific risk attributes, while accounting for corporate income taxes, tax depreciation and the tax shield on interest payments. We refer to this as the Merchant Cash Flow model. We have relied primarily on simulation results using this model under assumptions of both a 25-year and 40-year capital recovery period and 85% and 75% lifetime capacity factors.

BASE CASE

The base case reflects reasonable estimates of the current perceived costs of building and operating the three generating alternatives in 2002 U.S. dollars. The overnight capital cost for nuclear in the base case is $2000/kWe. As discussed in Appendix 5, this value is consistent with estimates made by the U.S. Energy

Information Administration (EIA), estimates reported by other countries to the OECD, and recent nuclear plant construction experience abroad. We have not relied on construction cost data for U.S. plants completed in the late 1980s and early 1990s; if we had, the average overnight construction cost in 2002 U.S. dollars would have been much higher. We are aware that some vendors and some potential investors in new nuclear plants believe that they can achieve much lower construction costs. We consider significant construction cost reductions in our discussion of improvements in nuclear costs.[11]

As previously discussed, our base case assumes that O&M costs are 15 mills/kWe-hr, which is lower than the recent experience for the average nuclear plant and is consistent with the recent performance of plants in the second lowest cost quartile of operating nuclear plants in the U.S. The O&M costs of plants in the lowest cost quartile (best performers) are about 13 mills/kWe-hr. We consider this to represent the potential for further cost improvements for a fleet of new nuclear plants but we do not believe that investors will assume that all plants will achieve the O&M cost levels of the best performers.

The construction costs assumed for CCGT and coal plants are in line with experience and EIA estimates. The construction cost of the coal plant is assumed to reflect NOx and SO_2 controls as required to meet current New Source Performance Standards. There are four cases presented for the CCGT plants: (1) a low gas price case that starts with gas prices at \$3.50/MMBtu which rise at a real rate of 0.5% over 40 years (real levelized cost of \$3.77/MMbtu over 40 years); (2) a moderate gas price case with gas prices starting at \$3.50/MMBtu as well, but rising at a real rate of 1.5% per year over 40 years (real levelized cost of \$4.42 over 40 years); (3) high gas price case that starts at \$4.50/MMbtu and rises at a real rate of 2.5% per year (real levelized cost of \$6.72/Mmbtu over 40 years). (4) The fourth CCGT case reflects high gas prices and an advanced CCGT design with a (roughly) 10% improvement in its heat rate. The base case results for 25 and 40-year economic lives and 85% capacity factor are reported in Table 5.1 and the equivalent results for a 75% lifetime capacity factor are reported in Table 5.2. The assumptions for the cases are given in Table 5.3. The discussion that follows is based on the 85% capacity factor simulations since the basic results don't change very much when we assume the lower capacity factor.

The base case results suggest that nuclear power is much more costly than the coal and gas alternatives even in the high gas price cases. In the low gas price case, CCGT is cheaper than coal. In the moderate gas price case, total life-cycle coal and gas costs are quite close together, though we should recognize that there are regions of the country with below average coal costs where coal would be less costly than gas and vice versa. Under the high gas price assumption, coal beats gas by a significant amount. (We have not tried to account for the relative difficulties of siting coal and gas plants.) We discuss potential future carbon emissions regulations separately below.

This suggests that high natural gas prices will eventually lead investors to switch to coal rather than to nuclear under the base case assumptions as nuclear appears to be so much more costly than coal and U.S. coal supplies are very elastic in the long run so that significant increases in coal demand will not lead to significant increases in long term coal prices. In countries with less favorable access to coal, the gap would be smaller, but 2.5 cents/kWe-hr is too large a gap for nuclear to beat coal in many areas of the world under the base case assumptions (absent additional restrictions on emissions of carbon dioxide from coal plants which we examine separately below).

The bottom line is that with current expectations about nuclear power plant construction costs, operating cost and regulatory uncertainties, it is extremely unlikely that nuclear power will be the technology of choice for merchant plant investors in regions where suppliers have access to natural gas or coal resources. It is just too expensive. In countries that rely on state owned enterprises that are willing and able to shift cost risks to consumers to reduce the cost of capital, or to subsidize financing costs directly, and which face high gas and coal costs, it is possible that nuclear power could be perceived to be an economical choice.[12]

IMPROVEMENTS IN NUCLEAR COSTS

We next examine how the cost of electricity generated by nuclear power plants would change, if effective actions can be taken to reduce nuclear electric generation costs in several different ways. First, we assume that construction costs can be reduced by 25%. This brings the construction costs of a nuclear plant to a level more in line with what the nuclear industry believes is feasible in the medium term under the right conditions.[13] While this reduces the levelized cost of nuclear electricity considerably, it is still not competitive with gas or coal for any of the base cases. Reducing construction time from 5 years to 4 years reduces the levelized cost further, but not to a level that would make it competitive with fossil fuels. However, if regulatory, construction and operating cost uncertainties could be resolved, and the nuclear plant could be financed under the same terms and conditions (cost of capital) as a coal or gas plant, then the costs of nuclear power become very competitive with the costs of CCGTs in a high gas price world and only slightly more costly than pulverized coal plants, assuming that comparable improvements in the costs of building coal plants are not also achieved. If nuclear plant operators could reduce O&M costs by another 2 mills to 13 mills/kWe-hr, consistent with the best performers in the industry, nuclear's total cost would match the cost of coal and the cost of CCGT in the moderate and high gas price cases. However, nuclear does not have a meaningful economic advantage over coal.

These results suggest that with significant improvements in the costs of building, operating, and financing nuclear power plants, and continued excellent operating performance (85% capacity factor), nuclear power could be quite competitive with natural gas if gas prices turn out to be higher than what most analysts now appear to believe and would be only slightly more costly than coal within the range of assumptions identified.[14]

The cost improvements we project are plausible but unproven. It should be emphasized, that the cost improvements required to make nuclear power competitive with coal are significant: 25% reduction in construction costs; greater than a 25% reduction in non-fuel O&M costs compared to recent historical experience (reflected in the base case), reducing the construction time from 5 years (already optimistic) to 4 years, and achieving an investment environment in which nuclear power plants can be financed under the same terms and conditions as can coal plants. Moreover, under what we consider to be optimistic, but plausible assumptions, nuclear is never less costly than coal.

CARBON "TAXES"

From a societal cost perspective, all external social costs of electricity generation should be reflected in the price. Here we consider the cost of CO_2 emissions and not other externalities; for example we ignore the costs of other air pollutants from fossil fuel combustion and nuclear proliferation and waste issues (except for including the costs of new coal plants to meet new source performance standards). Nuclear looks more attractive when the cost of CO_2 emissions is taken into account. Unlike gas and coal-fired plants, nuclear plants produce no carbon dioxide during operation and do not contribute to global climate change. Accordingly, it is natural to explore what the comparative social cost of nuclear power would be, if carbon emissions were "priced" to reflect the marginal cost of achieving global carbon emissions stabilization and reduction targets.[15] Future United States policies regarding carbon emissions are uncertain at the present time.

Table 5.1 Costs of Electric Generation Alternatives
Real Levelized Cents/kWe-hr (85% capacity factor)

Base Case		25-YEAR	40-YEAR
Nuclear		7.0	6.7
Coal		4.4	4.2
Gas (low)		3.8	3.8
Gas (moderate)		4.1	4.1
Gas (high)		5.3	5.6
Gas (high) Advanced		4.9	5.1
Reduce Nuclear Costs Cases			
Reduce construction costs (25%)		5.8	5.5
Reduce construction time by 12 months		5.6	5.3
Reduce cost of capital to be equivalent to coal and gas		4.7	4.4
Carbon Tax Cases (25/40 year)			
	$50/tC	**$100/tC**	**$200/tC**
Coal	5.6/5.4	6.8/6.6	9.2/9.0
Gas (low)	4.3/4.3	4.9/4.8	5.9/5.9
Gas (moderate)	4.6/4.7	5.1/5.2	6.2/6.2
Gas (high)	5.8/6.1	6.4/6.7	7.4/7.7
Gas (high) advanced	5.3/5.6	5.8/6.0	6.7/7.0

Table 5.2 Costs of Electric Generation Alternatives
Real Levelized Cents/kWe-hr (75% capacity factor)

Base Case		25-YEAR	40-YEAR
Nuclear		7.9	7.5
Coal		4.8	4.6
Gas (low)		4.0	3.9
Gas (moderate)		4.2	4.3
Gas (high)		5.5	5.7
Gas (high) advanced		5.0	5.2
Reduce Nuclear Costs Cases			
Reduce construction costs (25%)		6.5	6.2
Reduce construction time by 12 months		6.2	6.0
Reduce cost of capital to be equivalent to coal and gas		5.2	4.9
Carbon Tax Cases (25/40 year)			
	$50/tC	**$100/tC**	**$200/tC**
Coal	6.0/5.8	7.2/7.0	9.6/9.4
Gas (low)	4.5/4.4	5.0/5.0	6.0/6.0
Gas (moderate)	4.7/4.8	5.3/5.3	6.3/6.4
Gas (high)	6.0/6.3	6.5/6.8	7.5/7.8
Gas (high) advanced	5.5/5.7	5.9/6.2	6.8/7.1

By examining the relative economics of nuclear power under different assumptions about future social valuations for reducing carbon emissions, we can get a feeling for the option value of nuclear generation in a world with carbon emissions restrictions of various severities.

To examine this question we have recalculated the costs of the fossil-fueled generation alternatives to reflect a carbon tax of \$50/tC, \$100/tC, and \$200/tC. The lower value is consistent with an EPA estimate of the cost of reducing U.S. CO_2 emissions by about 1 billion metric tons per year.[16] The \$100/tC and \$200/tC values bracket the range of values that appear in the literature regarding the costs of carbon sequestration, recognizing that there is enormous uncertainty about the costs of deploying CO_2 capture, transport, and storage on a large scale. These hypothetical taxes should be thought of as a range of "backstop" marginal costs for reducing carbon emissions to meet aggressive global emissions goals. These results are reported in Table 5.1 and 5.2, as well.

With carbon taxes in the \$50/tC range, nuclear is not economical under the base case assumptions. If nuclear costs can be reduced to reflect all of the cost-reduction specifications discussed earlier, nuclear would be less costly than coal and less costly than gas in the high gas price cases. It is roughly competitive with gas in the low and moderate price gas cases. With carbon taxes in the \$100/tC to \$200/tC range, nuclear power would be an economical base load option compared to coal under the base case assumptions, but would still be more costly than gas except in the high gas price case. However, nuclear would be significantly less costly than all of the alternatives with carbon prices at this level, if all of the cost reduction specifications discussed earlier could be achieved.

The last conclusion ignores one important consideration. With carbon taxes at these high levels, it could become economical to deploy a generating technology involving the gasification of coal, its combustion in a CCGT (IGCC), and the sequestration of carbon dioxide produced in the process. The potential cost savings from this technology compared to conventional pulverized coal plants arises from (a) the use of relatively inexpensive coal to produce syngas (mostly CO and H_2) (b) the higher thermal efficiency of CCGT, and more economical capture of CO_2. Depending on the economics of this technology, coal could play a larger competitive role in a world with high carbon taxes than might be suggested by Tables 5.1 and 5.2. We observe as well, that from an environmental perspective, the world looks very different if there are abundant supplies of cheap natural gas, than if natural gas supplies are scarcer and significantly more expensive than many recent projections imply.

INTERNATIONAL PERSPECTIVE ON COST OF ELECTRICITY

The methodology followed above is pertinent to an electricity generation market that is unregulated, a situation that the United States is moving toward, as are several other countries. An additional advantage to describing deregulated market situations is that the methodology properly focuses on the true economic cost of electricity generating alternatives. There are however many nations that do not enjoy an unregulated generating market and are unlikely to adopt deregulation for some time to come. In many of these countries electricity generation is run directly or indirectly by the government and significant subsidies are provided to generating facilities. The electricity "cost" in these countries is not transparent and leads to a different political attitude toward investment decisions because consumers enjoy subsidized prices. The result is a misallocation of resources and over the long-run one can expect that political and economic forces will call for change. These non-market situations are encountered in Europe, e.g. Electricite de France, although there is a strong move to deregulation in the EU and in developing countries that frequently have state run power companies. Importantly, the costs of advanced fuel cycle technologies

Table 5.3 Base Case Assumptions

Nuclear
- Overnight cost: $2000/kWe
- O&M cost: 1.5 cents/kWh (includes fuel)
- O&M real escalation rate: 1.0%/year
- Construction period: 5 years
- Capacity factor: 85%/75%
- Financing:
  - Equity: 15% nominal net of income taxes
  - Debt: 8% nominal
  - Inflation: 3%
  - Income Tax rate (applied after expenses, interest and tax depreciation): 38%
  - Equity: 50%
  - Debt: 50%
- Project economic life: 40 years/25 years

Coal
- Overnight cost: $1300/kWe
- Fuel Cost: $1.20/MMbtu
- Real fuel cost escalation: 0.5% per year
- Heat rate (bus bar): 9300 BTU/kWh
- Construction period: 4 years
- Capacity factor: 85%/75%
- Financing:
  - Equity: 12% nominal net of income taxes
  - Debt: 8% nominal
  - Inflation: 3%
  - Income Tax rate (applied after expenses, interest and tax depreciation): 38%
  - Equity: 40%
  - Debt: 60%
- Project economic life: 40 years/25 years

Gas CCGT
- Overnight cost: $500/kWe
- Initial fuel cost:
  - Low: $3.50/MMbtu ($3.77/MMbtu real levelized over 40 years)
  - Moderate: $3.50/MMbtu ($4.42/MMbtu real levelized over 40 years)
  - High: $4.50/MMbtu ($6.72/MMbtu real levelized over 40 years)
- Real fuel cost escalation:
  - Low: 0.5% per year
  - Moderate: 1.5% per year
  - High: 2.5% per year
- Heat rate: 7200 BTU/kWh
  - Advanced: 6400 BTU/kWh
- Construction period: 2 years
- Capacity factor: 85%/75%
- Financing:
  - Equity: 12% nominal net of income taxes
  - Debt: 8% nominal
  - Inflation: 3%
  - Income tax rate (applied after expenses, interest and tax depreciation): 38%
  - Equity: 40%
  - Debt: 60%
- Project economic life: 40 years/25 years

such as PUREX reprocessing and MOX fabrication are heavily subsidized reflecting political rather than economic decision making.

COST OF ADVANCED FUEL CYCLES.

We have not undertaken as complete analysis for the costs of advanced fuel cycles as we have for the open fuel cycle. We have however examined in some detail the cost of the closed fuel cycle with single pass PUREX/MOX relative to the open cycle. This analysis is reported in the Appendix 5.D.

The fuel cycle cost model presented in Appendix 5.D shows that the closed cycle PUREX/MOX option fuel costs are roughly 4 times greater than for the open cycle, using estimated costs under U.S. conditions. The closed cycle can be shown to be competitive with the once-through option only if the price of uranium is high and if optimistic assumptions are made regarding the cost of reprocessing, MOX fabrication, and high level waste disposal. As explained in Appendix 5.D, the effect of the increased MOX fuel cycle cost on the cost of electricity depends upon the percentage of MOX fuel in the entire fleet if fuel costs are blended.

The case is often advanced that disposing of reprocessed high level waste will be less expensive than disposing of spent fuel directly. But there can be little confidence today in any estimate of such cost savings, especially if disposal of non-high-level waste contaminated with significant quantities of long-lived transuranic radionuclides (TRU waste) associated with recycle facilities and operations is taken into account. Furthermore, our cost model shows that even if the cost of disposing of reprocessed high-level waste were zero, the basic conclusion that reprocessing is uneconomic would not change.

It should be noted that the cost increment associated with reprocessing and thermal recycle is small relative to the total cost of nuclear electricity generation. In addition, the uncertainty in any estimate of fuel cycle costs is extremely large.

NOTES

1. Though in the United States and the United Kingdom some nuclear plants were subsequently sold or transferred to merchant generating companies.
2. Merchant plants sell their output under short, medium and longer term supply contracts negotiated competitively with distribution companies, wholesale and retail marketers. The power plant developers take on permitting, development, construction cost and operating performance risks but may transfer some or all risks associated with market price volatility to buyers (for a price) through the terms of their contracts.
3. It is often assumed that regulated monopolies were subject to "cost-plus" regulation which insulated utilities from all of these risks. This is an extreme and inaccurate characterization of the regulatory process, at least in the United States. (P.L. Joskow and R. Schmalensee, "Incentive Regulation for Electric Utilities," *Yale Journal on Regulation*, 1986; P.L. Joskow, "Deregulation and Regulatory Reform in the U.S. Electric Power Sector," in *Deregulation of Network Industries: The Next Steps* (S. Peltzman and Clifford Winston, eds.), Brookings Press, 2000). Several U.S. utilities were faced with significant cost disallowances associated with nuclear power plants they completed or abandoned, a result inconsistent with pure cost-plus regulation. Nevertheless, it is clear that a large fraction of these cost and market risks were shifted to consumers from investors when the industry was governed by regulated monopolies.
4. The current state of electricity restructuring and competition in the United States and Europe has made it difficult for suppliers to obtain forward contracts for the power they produce. We believe that this chaotic situation is unsustainable and that a mature competitive power market will make it possible for power suppliers to enter into forward contracts with intermediaries. However, these contracts will not generally be like the 30-year contracts that emerged under regulation which obligated wholesale purchasers (e.g. municipal utilities) to pay for all of the costs of a power plant in return for any power it happened to produce. In a competitive market the contracts will be for specified delivery obligations at a specified price (or price formula), will tend to be much shorter (e.g. 5-year contract portfolios), and will place cost and operating performance risk on the generator not on the customer.

5. Oversimplifying, these effects can be thought of as an increase in the cost of capital faced by investors.

6. For example, in areas of the United States where the wholesale market tends to clear with conventional gas or oil-fired power plants on the margin, spot market clearing prices will move up and down with the price of natural gas and oil. A combined cycle gas turbine (CCGT) that also burns natural gas, but with a heat rate 35% lower on average than those of the marginal gas plants that clear the market (e.g. 11,000 BTU/kWh), will always run underneath the market clearing price of electricity. Whatever the price of gas, the CCGT is always in the money and will be economical to run under these circumstances. If gas prices go up, the CCGT will be more profitable, and if they go down it will be less profitable, but the volatility in profits with respect to changes in gas prices will be lower than that for coal or nuclear plants.

7. In 2000, the capacity factors for the nuclear plants in France were 76%, for those in Japan 79%, and for those in South Korea, 91%. Ideally, we would look at availability data, but except for France where nuclear accounts for such a large share of electricity supply that some plants must by cycled up and down, nuclear units are generally run full out when they are available (Source: Calculated from data on EIA web site.)

8. These numbers underestimate the true O&M costs of nuclear plants because they exclude administrative and general operating costs that are typically captured elsewhere in utility income statements. These overhead costs probably add another 20% to nuclear O&M costs. We do not consider these additional costs here because they are also excluded from the O&M costs for competing technologies. In a competitive power market, however, generating plants must earn enough revenues to cover these overhead costs as well as their direct capital and O&M costs.

9. That is, we are not considering competition between new nuclear plants and *existing* coal and gas plants (whose construction costs are now sunk costs). We recognize there may be economical opportunities to increase the capacity of some existing nuclear plants and to extend their commercial lives. We do not consider these opportunities here.

10. The reduced non-fuel O&M costs assumed are about 10 mills/kWh in the base case and compare favorably to 9 mills/kWh assumed by TVA (90% capacity factor) in its recent evaluation of the restart of Browns Ferry Unit #1.

11. Of course, in a competitive wholesale electricity market investors are free to act on such expectations by making financial commitments to build new nuclear plants. About 150,000 MWe of new generating capacity has been built in the U.S. in the last five years, most of it owned by merchant investors and most of it fueled by natural gas and none of it nuclear. See Paul L. Joskow, "The Difficult Transition to Competitive Electricity Markets in the U.S.," May 2003

12. We have seen some analyses that assume that nuclear plants will be financed with 100% government-backed debt, pay no income or property taxes, and have very long repayment schedules. One can make the costs of nuclear power look lower this way, but it simply hides the true costs and risks of the projects which have effectively been transferred to consumers and taxpayers.

13. This brings the nuclear plant cost down to $1500/kW. This is roughly the cost used in the analysis of the costs of a new nuclear power plant in Finland at current exchange rates. (However, the Finnish analysis assumes that the plant can be financed with 100% debt at a 5% real interest rate and would pay no income taxes). Note, however, that TVA estimates that the costs of *refurbishing* a mothballed unit at Browns Ferry will cost about $1300/kWe, and that recent Japanese experience is closer to the $2000/kWe base case assumption. TVA's analysis of the costs of refurbishing the Browns Ferry unit assume that the project can be financed with 100% debt at an interest rate 80 basis points above 10-year treasury notes and would pay no taxes.

14. Obviously, there is some set of assumptions that will make nuclear cheaper than coal. However, they basically require driving the construction costs and construction time profile to be roughly equivalent to those of a coal unit. We also have not assumed any improvements in construction costs or heat rates for coal units associated with advanced coal plant designs.

15. We have modeled the carbon "price" as a carbon dioxide emissions tax. However, the intention is to simulate any policies that give nuclear power "credit" relative to fossil fuel alternatives for producing no CO_2.

16. "Summary and Analysis of McCain-Leiberman 'Climate Stewardship Act of 2003'," William Pizer and Raymond Kopp, Resources for the Future, January 28, 2003.

Chapter 6 — Safety

Safe operations of the entire nuclear fuel cycle are a paramount concern. In this chapter we address reactor safety, the continuing availability of trained personnel for nuclear operations, the threat of terrorist attack, and nuclear fuel cycle safety, including nuclear fuel reprocessing plants.

There are about 100 nuclear power plants in the U. S., and over 400 in the world, mostly light water reactors (LWRs). With the benefit of experience and improved plant designs going into service, performance has improved over time to unit capacity factors[1] of 90% and higher in the U.S.[2] The means of improvement include independent peer review and the feedback of operating experience at reactor fleets worldwide, so that all operators become aware of mishaps that occur, and the commitment of plant owners and managements to the development of safety culture within the organizations that operate nuclear power plants. These actions and initiatives in training and qualification of reactor operators that have been implemented by organizations of plant owners[3] are major factors in the performance improvements. Experience also includes three serious reactor accidents[4] and several fuel cycle facility accidents.[5]

A number of events have occurred at reactors that were headed for an accident but stopped short. Such an event[6] came to light during an inspection of the Davis-Besse reactor vessel head in March, 2002, during reactor shutdown. The inspection disclosed a large cavity in the vessel head next to one of the reactor control rod drive mechanisms, caused by boric acid leakage and corrosion. The cavity seriously jeopardized reactor vessel integrity. Fortunately, the fault was discovered before restart of the reactor. This event discloses a failure on the part of the plant owners to respond to earlier indications of an issue and to look for problems in an early stage at their plant. It is still an open question whether the average performers in the industry have yet incorporated an effective safety culture into their conduct of business. The U.S. Nuclear Regulatory Commission shares responsibility in the matter, as it accepted delay of scheduled surveillance and inspection of vital primary system components. A major nuclear power initiative will not gain public confidence, if such failures occur.

With regard to the mandate of the Nuclear Regulatory Commission for safety of nuclear plants in the U. S., the Davis-Besse incident also raises questions about whether nuclear reactor safety goals are compatible with the transition to competitive electricity markets. On the one hand some observers suggest that unregulated generators will be more concerned with maximizing plant output and less willing to close plants for safety inspections and corrective actions where necessary. On the other hand, owners groups have long stated that nuclear plant operation conducted to ensure a high level of safety is also economically beneficial. Further, nuclear plant accident costs are not financially attractive for plant owners. While there may be some accident costs that are not fully internalized into decisions made by individual nuclear plant owners, the owner of a plant that has a serious accident would face very significant adverse financial consequences, as was the case of General Public Utilities after the accident at Three Mile Island Unit 2. We believe it is important to maintain the principle that the primary responsibility for safe operation of nuclear plants rests with the plant owners and operators, as the generation segment of the electric power industry is deregulated, and that the Nuclear Regulatory Commission should adapt its inspection activities, reporting requirements, and enforcement actions to reflect the new incentives created by competitive generation markets.

REACTOR SAFETY

The global growth scenario considered in this report is a three-fold increase in the world nuclear fleet capacity by 2050. The goal, of course, should be to carry out this large expansion without increasing the frequency of serious accidents. We believe this can be accomplished by means of both evolutionary and new technologies focused on LWRs.

Three major reasons for reducing the frequency of serious accidents are: first, and foremost, they are a threat to public health. Reactor core damage has the potential to release radioactivity to air and groundwater. Second, an accident destroys capital assets. Loss of a plant costs billions of dollars and could restrict electrical generating capacity in the locality until replacement, thereby adding to the economic loss. Third, a serious accident erodes public confidence in nuclear generation, with possible consequences of operating plant shutdowns, and/or moratoria on new construction.

What is the expected frequency of accidents today with the currently operating nuclear plants? There are two ways to determine the frequency of accidents: historical experience and Probabilistic Risk Assessment.[7] Since the beginning of commercial nuclear power in 1957, more than 100 LWR plants have been built and operated in the U.S., with a total experience of 2679 reactor-years through 2002. During this time, there has been one reactor core damage accident at Three Mile Island Unit 2. The core damage frequency of U.S. reactors is therefore 1 in 2679 reactor-years on average.

Probabilistic Risk Assessment (PRA) identifies possible failures that can occur in the reactor, e.g., pipe breaks or loss-of-reactor coolant flow, then traces the sequences of events that follow, and finally determines the likelihood of their leading to core damage. PRA includes both internal events and external events, i.e., natural disasters. Expert opinion using PRA considers the best estimate of core damage frequency to be about 1 in 10,000 reactor-years for nuclear plants in the United States. Although safety technology has improved greatly with experience, remaining uncertainties in PRA methods and data bases make it prudent to keep actual historical risk experience in mind when making judgments about safety.

With regard to implementation of the global growth scenario during the period 2005-2055, both the historical and the PRA data show an unacceptable accident frequency. The expected number of core damage accidents during the scenario with current technology[8] would be 4. We believe that the number of accidents expected during this period should be 1 or less, which would be comparable with the safety of the current world LWR fleet. A larger number poses potential significant public health risks and, as already noted, would destroy public confidence. We believe a ten-fold reduction in the likelihood of a serious reactor accident,[9] i.e., a core damage frequency of 1 in 100,000 reactor- years is a desirable goal and is also possible, based on claims of advanced LWR designers, that we believe plausible. In fact, advanced LWR designers claim that their plant designs already meet this goal, with even further reduction possible. If these claims and other plant improvements and cost reductions are verified, advanced LWRs will be in a very good position to drive a large share of the global growth scenario market.

For future LWR development, we recommend implementation of designs that use a combination of passive and active features in order to enhance reliability of plant safety systems. Passive systems utilize stored energy for pumping, either by means of pressurized tanks or by gravity acting on water in elevated tanks. They substitute for motor-driven pumps ultimately driven by emergency diesel generators, and can thereby remove the risk of failure of diesels to start when needed, i.e., during a station blackout.

Additional gains may come with the introduction of High-Temperature Gas Reactors (HTGRs). In principle the HTGR may be superior to the LWR in its ability to retain fission products in a loss-of- coolant accident, because of fuel form and because core temperatures can be kept sufficiently low due to low power density design and high heat capacity of the core, if RD&D validates this feature. Two HTGR plants of small capacity and modular design are under development for eventual commercial application.

We describe briefly deployment for the global growth scenario, first for LWRs, and then for HTGRs. Because of the experience base, construction of certified LWR designs at approved sites could begin within the year or two required for contractual arrangements, limited primarily by retooling of a dormant industry, and obtaining regulatory approvals under new licensing procedures. In order to build the global growth scenario capacity of 1000 GWe in 50 years, an average rate of construction of 20 to 25 plants[10] per year would be required, with greater numbers in later years. For historical comparison, LWR actual worldwide construction totaled about 400 plants over 25 years, for an average of 16 plants completed per year. Doubling the past rate of construction for this scenario is not an unreasonable projection, but remains a challenge, because plant construction time must also be reduced in order to reduce plant capital cost.

LWR experience does not exclude entry of the HTGR into the marketplace. However, it does focus attention on the lead times and costs associated with its development and the need for operating experience before commitment of capital investment and the large manufacturing expansion required to carry it out.

We believe that the lead time to carry out RD&D requirements for HTGR licensing, and at least several years of operation by one or more demonstration plants, will add up to 15 to 20 years before rapid, commercial deployment can be expected. Given this lead time, we expect that two thirds or more of the fleet through 2050 will be LWRs.

It is possible with success at every turn that HTGR deployment could make up as much as one third of the global growth scenario. The uncertainties in this projection are large, however, and a range of HTGR penetration from very small to a high of one third is realistic. We note that the plant capacity of the two HTGR concepts is in the range of 125-350 MWe, i.e., substantially smaller than LWR plants. This is a very attractive feature of HTGRs, if cost targets are met. Depending on the market shares of the two HTGR concepts, about 4 plants would be required to equal the output of a 1000 MWe LWR. If HTGR plants were to capture one third of the mid-century scenario, there would be about twice as many HTGRs as LWRs in 2050.

TRAINING AND QUALIFICATION OF PLANT MANAGEMENT AND STAFF

Realization of the mid-century scenario has important implications for safety, and especially in training and qualification of people competent to manage and operate the plants safely, including the supporting infrastructure necessary for maintenance, repair, refueling, and spent fuel management. Development of competent managers and identification of effective management processes is a critical element in achieving safe and economic nuclear power plant operations. For developed countries that now operate nuclear plants, these tasks require attention to the rejuvenation of the entire workforce.[11]

For developing countries, however, this challenge is much greater, because of the lack of workers in the many skills required in nuclear power plant construction, operations, and maintenance. The workforce must be trained and grow from a small or negligible base. There are two main models for realization of the necessary growth: first, "do it yourself," and second, the commercial mode of importing goods and services. The first takes time and is subject to error in the process of learning. The second is expensive in the long run and fails to create skills and provide jobs at home. The best path for most developing countries is likely to be some combination of the two models that yields both competence and jobs.

TERRORIST ATTACK ON NUCLEAR INSTALLATIONS

Terrorists have demonstrated their ability to inflict catastrophic damage. Nuclear facilities as potential targets have not escaped notice. On the one hand experts have concluded that civil works and security provisions make nuclear plants hard targets. On the other hand, the hazards are on a scale previously considered to be extremely rare in evaluation of severe reactor accidents. The question is what new security measures, if any, are appropriate? We believe there is no simple, one-size-fits-all answer. It depends on many factors including threat evaluation, plant location, facility design, and government security resources and practices.

Nuclear plant safety is a good starting point for the evaluation of security risk. What we conclude about plants also applies to other fuel cycle facilities. Nuclear plant safety has considered natural external events, such as earthquakes, tornadoes, floods, and hurricanes. Terrorist attack by fire or explosion is analogous to external natural events in its implication for damage and release of radioactivity. The strength of containment buildings and structures presents a major obstacle and hardened target for attack. The Electric Power Research Institute[12] carried out an evaluation of aircraft crash and NPP structural strength, concluding that U.S. containments would not be breached. The U.S. NRC is performing its own evaluation, including structural testing at Sandia National Laboratory, not yet complete.

A broad survey and evaluation of hazards and protective actions is in order to make decisions on adequate protection. Such a survey must begin by identifying possible modes of attack and vulnerabilities associated with designs and locations. It must also identify the cost effectiveness of a range of security options for new designs, old plants near decommissioning, and plants in mid-life. There is also a need for sharing information with governments of countries and supporting institutions that will undertake nuclear power programs in order to provide effective intelligence and security.

NUCLEAR FUEL CYCLE SAFETY

Realization of the global growth scenario entails construction and operation of many fuel cycle facilities around the world, such as those described in Chapter IV, and also the facilities and repositories associated with waste management. There are varying degrees of risk to public safety associated with these facilities, and therefore a need for systematic evaluation of risk on a consistent basis that takes into account evaluations performed heretofore on individual fuel cycle facilities.

The need for such an evaluation is especially important in the case of reprocessing plants. The United States does not have any commercial reprocessing plants. France, the United Kingdom and Japan have reprocessing plants in operation, based on aqueous PUREX separations technology and improvements to it over many years. Pyro-reprocessing and dry reprocessing R&D has been done with no commercial application as yet. Aqueous separation plants have high inventories of fission products, as well as fissile material of work in process, and many waste streams. Future improvements in separation technology may be capable of reducing radioactive material inventories, measured as a fraction of annual throughput, but inventories will continue to be large, because of the large annual product required, if and when reprocessing comes into wider commercial use many years in the future.

We are concerned about the safety of reprocessing plants,[13] because of large radioactive material inventories, and because the record of accidents, such as the waste tank explosion at Chelyabinsk in the FSU, the Hanford waste tank leakages in the United States and the discharges to the environment at the Sellafield plant in the United Kingdom. Releases due to explosion or fire can be sudden and widespread. Although releases due to leakage may take place slowly, they can have serious long-term public health consequences, if they are not promptly brought under control. Although the hazards of reprocessing plants differ from those of reactors, the concepts and methods and practices of reactor safety are broadly applicable to assuring the safety of reprocessing plants. We do not see the need for commercial reprocessing in the global growth scenario, but we believe the subject requires careful study,[14] and action, if and when reprocessing becomes necessary.

NOTES

1. Capacity factor is the ratio of actual annual plant electrical production and maximum annual production capability.
2. While worldwide capacity factors (around 75%) are lower than those recently achieved in the U.S., a similar trend of improved capacity factors is observed outside of the U.S. as well.
3. The Institute of Nuclear Power Operations in the U.S. and the World Association of Nuclear Operators worldwide.
4. Windscale, UK, gas-cooled reactor, graphite combustion due to graphite stored heat release, with limited release of radioactivity, 1952; TMI 2, PWR, loss-of-coolant, 20% core meltdown, and small release, 1979; Chernobyl, graphite-moderated, water-cooled reactor, reactivity accident with large external release of radioactivity and health effects, 1986.
5. Chelyabinsk, FSU, reprocessing waste explosion, (1957); Hanford, Washington State, waste storage tank leakage, (1970-); Sellafield, UK, reprocessing waste discharges into ocean, (1995-), Tokai-Mura, Japan, nuclear criticality incident in fuel fabrication, (1999). We know of no complete inventory of reprocessing accidents; such a survey is needed.
6. A similar event was discovered at a French nuclear power plant in 1991.
7. Three important references are: Reactor Safety Study, WASH 1400, U.S. Nuclear Regulatory Commission, October 1975; Severe Accident Risks, NUREG-1150, U.S. NRC, December 1990; and Individual Plant Examination Program, NUREG-1560, U.S. NRC, December 1997.
8. The number of core damage accidents expected is the product of the CDF and the reactor-years of experience. We assume a CDF of 10-4 and 40,000 reactor-years experience during the period of 2005 to 2055: the product is 4 accidents. The Safety Appendix 6 explains the relevant data in more detail.
9. Potentially large release of radioactivity from fuel accompanies core damage. Public health and safety depends on the ability of the reactor containment to prevent leakage of radioactivity to the environment. If containment fails, there would be a large, early release (LER) and exposure of people for some distance beyond the plant site boundary, with the amount of exposure depending on accident severity and weather conditions. The probability of containment failure, given core damage, is about 0.1. Hence the frequency of a LER is 1 in 1,000,000 years. LER is defined in U.S. NRC Regulatory Guide 1.174.
10. We expect individual plant capacities in the range of 600-1500 MWe. In developed countries the average plant capacity is expected to be about 1000 MWe, with a smaller average capacity in developing countries.
11. The workforce has been aging for more than ten years due to lack of new plant orders and decline of industrial activity.
12. Deterring Terrorism - Aircraft Crash Impact Analyses Demonstrate Nuclear Power Plant's Structural Strength; EPRI Study, Nuclear Energy Institute website, www.nei.org, December 2002.
13. A brief comparison of reprocessing plants with reactors shows that the historical accident frequency of reprocessing plants is much larger than reactors: three of the more significant accidents are cited in footnote 5. Furthermore, the number of reprocessing plant-years of operation is many fewer that in the case of reactors. Therefore the accident frequency of reprocessing plants is much higher.
14. We are not aware of PRA analyses of fuel cycle facilities; one exception is: *Status report on the EPRI fuel cycle accident risk assessment*, prepared by SAIC for EPRI report number NP-1128, July 1979.

Chapter 7 — Spent Fuel/High-Level Waste Management

The management and disposal of radioactive waste from the nuclear fuel cycle is one of the most difficult problems currently facing the nuclear power industry. Today, more than forty years after the first commercial nuclear power plant entered service, no country has yet succeeded in disposing of high-level nuclear waste – the longest-lived, most highly radioactive, and most technologically challenging of the waste streams generated by the nuclear industry.[1]

In most countries, the preferred technological approach is to dispose of the waste in repositories constructed in rock formations hundreds of meters below the earth's surface. Although several experimental and pilot facilities have been built, there are no operating high-level waste repositories, and all countries have encountered difficulties with their programs. The perceived lack of progress towards successful waste disposal clearly stands as one of the primary obstacles to the expansion of nuclear power around the world.[2]

THE GOALS OF NUCLEAR WASTE MANAGEMENT AND DISPOSAL

Spent nuclear fuel discharged from nuclear reactors will remain highly radioactive for many thousands of years. The primary goal of nuclear waste management is to ensure that the health risks of exposure to radiation from this material are reduced to an acceptably low level for as long as it poses a significant hazard. Protection against the risk of malevolent intervention and misuse of the material is also necessary.

Because of the very long toxic lifetime of the waste, the primary technical challenge is that of long- term isolation. However, shorter-term risks must also be addressed. Prior to final disposition, the waste will pass through several intermediate stages or operations, including temporary storage, transportation, conditioning, packaging, and, potentially, intermediate processing and treatment steps. There are several possible choices at each stage, and the design of the overall waste management system – including the specific technical characteristics and the physical location of each stage – will importantly affect the overall level of risk and its distribution over time. For example, waste management strategies involving the separation of individual radionuclides from the spent fuel could reduce long-term exposure risks, while elevating risks in the short term. Such interdependencies attest to the importance of an integrated approach to nuclear waste management decision-making, in which the system-wide impacts of individual decisions are fully considered.

What constitutes an acceptable level of exposure risk? The U.S. Environmental Protection Agency (EPA) has stipulated that the radiation dose from all potential exposure pathways to the maximally- exposed individual living close to a waste disposal site should not exceed 15 millirems per year for the first 10,000 years after final disposition. This is about twenty times less than the dose that individuals receive annually from natural background radiation on average. EPA has translated the 15 millirem per year standard into an annual risk of developing a fatal cancer of about 1 chance in 100,000.

Different radiation exposure standards apply to operating nuclear fuel cycle facilities.

The suitability of alternative waste management schemes must ultimately be judged in relation to these fundamental safety goals. Other measures of waste management system performance are frequently cited, such as the volume or mass of waste material generated, the total inventory of radioactivity in the waste, the amount of heat it emits, its radiotoxicity, and the solubility and mobility of specific radionuclides. Each of these metrics contains useful information about the technical requirements of individual components of the waste management system. But none of these metrics is an adequate proxy for the fundamental measure of waste management system performance — that is, the risk to human health from radiation exposure in the short and long term.

THE FEASIBILITY OF GEOLOGIC DISPOSAL

As already noted, most countries with nuclear power programs have stated their intention to dispose of their high-level waste in mined repositories, hundreds of meters below the earth's surface. The concept of deep geologic disposal has been studied extensively for several decades, and there is a high level of confidence within the expert scientific and technical community that this approach is capable of safely isolating the waste from the biosphere for as long as it poses significant risks.[3] This assessment is based on: (1) an understanding of the processes and events that could transport radionuclides from the repository to the biosphere; (2) mathematical models which, when combined with information about specific sites and repository designs, enable the long-term environmental impact of repositories to be quantified; and (3) natural analog studies which help to build confidence that the analytical models can be reliably extrapolated to the very long time-scales required for waste isolation.

We concur with the view that high-level waste can safely be disposed of in geologic repositories. As discussed below, we believe there are opportunities for advances in geologic and engineering system design that can provide additional assurance regarding the long-term performance of such repositories. We note, however, that among the general public, and even among some in the technical community, there is a lack of confidence in the prospects for successful technical and organizational implementation of the geologic disposal concept. Previous missteps and failures in the waste management programs of several countries have contributed to these doubts. Some members of the public – especially those living in the vicinity of proposed repository sites – also question the fairness and integrity of the site selection process.

MEASURES TO INCREASE THE LIKELIHOOD OF SUCCESSFUL IMPLEMENTATION OF WASTE MANAGEMENT AND DISPOSAL

We have examined several possible innovations that might facilitate the successful implementation of waste management and disposal. In order to make a difference, any such measure should have to contribute significantly to one or more of the following goals:

☐ reduction of the risks to public health and safety and the environment from waste management and disposal activities in the short and/or long term;

☐ reduction of the economic costs of achieving an acceptable level of performance with respect to short and long-term risk;

☐ increase of public confidence in the technical and organizational effectiveness of waste management and disposal activities.

The innovations we have considered can be grouped into three categories:

☐ technical modifications or improvements that could be incorporated into the once-through fuel cycle;

☐ technical modifications or improvements requiring a closed fuel cycle;

☐ institutional or organizational innovations.

It is important to emphasize that each innovation must be evaluated in terms of its impact on the entire waste management system, including not only final disposal but also pre-disposal processing, transportation, and storage operations. In the following paragraphs we summarize our findings concerning each category of innovations. More detailed discussions can be found in Appendix 7.

TECHNICAL MODIFICATIONS OR IMPROVEMENTS TO SPENT FUEL MANAGEMENT IN THE ONCE-THROUGH FUEL CYCLE

Extended interim storage of spent fuel Although most spent fuel destined for direct disposal will in practice be stored above ground for many years because of the protracted process of developing high level waste repositories, storage arrangements so far have mostly been ad hoc and incremental. We believe that a period of several decades of interim storage should be incorporated into the design of the spent fuel management system as an integral part of the system architecture.[4] Such a storage capability would:

☐ provide greater flexibility in the event of delays in repository development;

☐ allow a deliberate approach to disposal and create opportunities to benefit from future advances in relevant science and technology;

☐ provide greater logistical flexibility, with centralized buffer storage capacity facilitating the balancing of short and long-term storage requirements, and enabling the optimization of logistics, pre- processing, and packaging operations;

☐ allow countries that want to keep open the option to reprocess their spent fuel to do so without actually having to reprocess;

☐ create additional flexibility in repository design, since the spent fuel would be older and cooler at the time of emplacement in the repository; and

☐ potentially reduce the total number of repositories required.

At-reactor storage will be feasible for some spent fuel, even for several decades. For the remainder, centralized storage facilities will be required. Internationally, a network of safeguarded, well protected central storage facilities will also yield important non-proliferation benefits (see Chapter 8). The siting of temporary storage facilities will likely be difficult. Although the technical issues involved are more straightforward than for geologic repositories, the task of persuading affected communities to accept such facilities may be no less challenging. Nevertheless, making provision for several decades of temporary spent fuel storage would make for a more robust waste management system overall, and could be cost-effective too, if the result was to postpone the onset of major spending on repository construction and operation.

High burnup fuel The burnup of spent fuel – the amount of energy that has been extracted from a unit of fuel at the time of its discharge from the reactor – is a design choice for reactor operators. In the past, the burnup of LWR fuel averaged about 33 MWD/kg. An increase to 100 MWD/kg is within technical reach, and even greater increases are potentially achievable.

Increasing the burnup to 100 MWD/kg would yield a threefold reduction in the volume of spent fuel to be stored, conditioned, packaged, transported, and disposed of per unit of electricity generated. The corresponding reduction in the required repository storage volume would be more modest; the individual fuel assemblies, although there would be fewer of them, would generate more decay heat and would therefore have to be spaced farther apart in the repository. The amount of plutonium and other actinides, which are the dominant contributors to the radiotoxicity of the spent fuel after the first hundred years or so, would also be reduced somewhat per unit of electricity generated. A further benefit of higher burnup is that the isotopic composition of the discharged plutonium would make it less suitable for use in nuclear explosives.[5]

It is important to note, however, that the present pricing structure for nuclear waste management services in the United States – a standard fee of one-tenth of a cent payable to the government on each kilowatt hour of nuclear electricity generated — provides no economic incentive for nuclear generators to move in the direction of higher burnup. No discount is provided for the reduced volume of spent fuel and the safety, proliferation resistance, and economic benefits associated with higher burnup.[6]

Advances in geologic repository design A geologic repository must provide protection against every plausible scenario in which radionuclides might reach the biosphere and expose the human population to dangerous doses of radiation. Of all possible pathways, the one receiving most attention involves groundwater seeping into the repository, the corrosion of the waste containers, the leaching of radionuclides into the groundwater, and the migration of the contaminated groundwater towards locations where it might be used as drinking water or for agricultural purposes. Although the details differ, all proposed repository designs adopt a 'defense in depth' approach to protecting against this scenario, relying on a combination of engineered components and natural geologic, hydrologic, and geochemical barriers to contain the radionuclides.

The engineered barriers, broadly defined to include those physical and chemical features of the near- field environment that affect the containment behavior of the waste packages, have an important role to play in the overall performance of the repository. To date there has not been an adequate technical basis for the selection and development of the engineered barriers in the context of the overall multi- barrier system.

In siting a repository, it is important to select a geochemical and hydrological environment that will ensure the lowest possible solubility and mobility of the waste radionuclides. The geochemical conditions in the repository host rock and surrounding environment strongly affect radionuclide transport behavior. For example, several long-lived radionuclides that are potentially important contributors to long-term dose, including technetium-99 and neptunium-237, are orders of magnitude less soluble in groundwater in reducing environments than under oxidizing conditions.

Alternative disposal technologies: The deep borehole approach An alternative to building geologic repositories a few hundred meters below the earth's surface is to place waste canisters in boreholes drilled into stable crystalline rock several kilometers deep. Canisters containing spent fuel or high-level waste would be lowered into the bottom section of the borehole, and the upper section – several hundred meters or more in height – would be filled with sealant materials such as clay, asphalt, or concrete. At depths of several kilometers, vast areas of crystalline basement rock are known to be extremely stable, having experienced no tectonic, volcanic or seismic activity for billions of years.

The main advantages of the deep borehole concept relative to mined geologic repositories include: (a) a much longer migration pathway from the waste location to the biosphere; (b) the low water content, low porosity and low permeability of crystalline rock at multi-kilometer depths; (c) the typically very high salinity of any water that is present (because of its higher density, the saline water could not rise convectively into an overlying layer of fresh water even if heated); and (d) the ubiquity of potentially suitable sites.

An initial screening suggests that most of the countries that are likely to employ nuclear power in our global growth scenario may have geology appropriate for deep waste boreholes. Co-location of boreholes with reactor sites is a possibility. Suitable host rock also occurs beneath the sea floor. For this reason the concept may be particularly interesting for densely populated countries like Japan, Korea, and Taiwan. Since most of the power reactors in these countries (and indeed in most countries) are located on or close to the coast, the possibility arises of constructing artificial offshore islands which would be ideal sites from which to drill beneath the seabed and which could also serve as temporary storage venues for the spent fuel, obviating the need for on-land waste transportation and storage.

The overall system cost of deep borehole disposal using conventional drilling technology is uncertain, but according to one estimate would be comparable to that of mined geologic disposal.[7] Advances in technology could reduce the cost of drilling significantly. But since drilling alone accounts for only a relatively small fraction of the overall costs, the opportunities for savings are limited. A more important economic advantage may derive from the modularity of the deep borehole concept and the more flexible siting strategy that it allows.[8]

Implementing the deep borehole scheme would require the development of a new set of standards and regulations, a time-consuming and costly process. A major consideration would be the difficulty of retrieving waste from boreholes if a problem should develop (though the greater difficulty of recovering the plutonium in the waste might also be an advantage of the borehole scheme). Current U.S. regulatory guidelines for mined repositories require a period of several decades during which the high level waste should be retrievable. This would be difficult and expensive to ensure in the case of deep boreholes, though probably not impossible. Moreover, at the great depths involved, knowledge of in situ conditions (e.g., geochemistry, stress distributions, fracturing, water flow, and the corrosion behavior of different materials) will never be as comprehensive as in shallower mined repository environments. Recovery from accidents occurring during waste emplacement – for example, stuck canisters, or a collapse of the borehole wall – is also likely to be more difficult than for corresponding events in mined repositories. Finally, despite the order of magnitude increase in the depth of waste emplacement, it is difficult to predict the impact on public opinion of a shift in siting strategy from one large central repository to scores of widely dispersed boreholes.

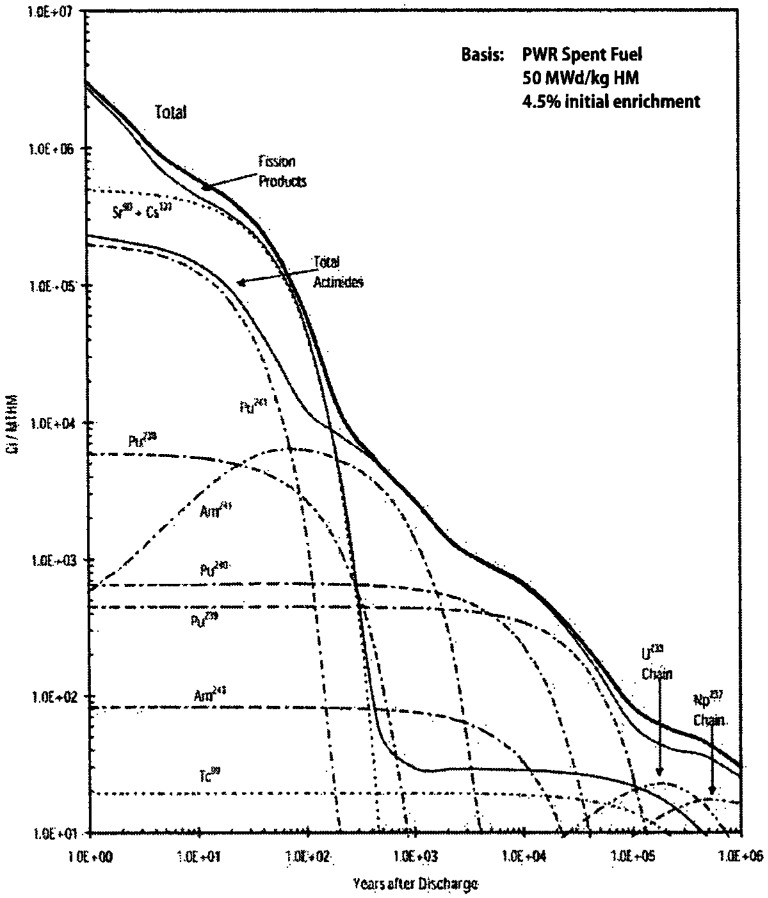
Despite these obstacles, we view the deep borehole disposal approach as a promising extension of geological disposal, with greater siting flexibility and the potential to reduce the already very low risk of long-term radiation exposure to still lower levels without incurring significant additional costs.

TECHNICAL MODIFICATIONS REQUIRING A CLOSED FUEL CYCLE

We next consider a set of waste management options involving the extraction of radionuclides from the spent fuel. The motivations for waste separation can be inferred from Figures 7.1, 7.2, and 7.3. At different times, different radionuclides are the dominant contributors to overall radioactivity and radiotoxicity and to the radioactive decay heat emitted by the fuel. Partitioning the spent fuel into separate radionuclide fractions and managing each fraction according to its particular characteristics could create additional flexibilities and new opportunities to optimize the overall waste management system. Partitioning also creates the opportunity to transmute the most troublesome radionuclides into more benign species. Thermal reactors, fast reactors, and accelerators have all been investigated as candidate transmutation devices, both individually and in combination.

Decisions about partitioning and transmutation must also consider the incremental economic costs and safety, environmental, and proliferation risks of introducing the additional fuel cycle stages and facilities necessary for the task.[9] These activities will be a source of additional risk to those working in the plants, as well as the general public, and will also generate con-

Figure 7.1 Radioactivity profile of spent fuel (curies/MTHM)



siderable volumes of non-high- level waste contaminated with significant quantities of transuranics. Much of this waste, because of its long toxic lifetime, will ultimately need to be disposed of in high-level waste repositories. Moreover, even the most economical partitioning and transmutation schemes are likely to add significantly to the cost of the once-through fuel cycle.[10]

We first consider the option of waste partitioning alone, and then the combination of partitioning and transmutation.

Waste partitioning Two fission products, strontium-90 and cesium-137, each with half-lives of about 30 years, account for the bulk of the radioactivity and decay heat in spent fuel starting a few years after discharge and for the next several decades. Thereafter, the actinides as a group become the dominant contributors to decay heat and radiotoxicity, with different actinides dominating at different times.

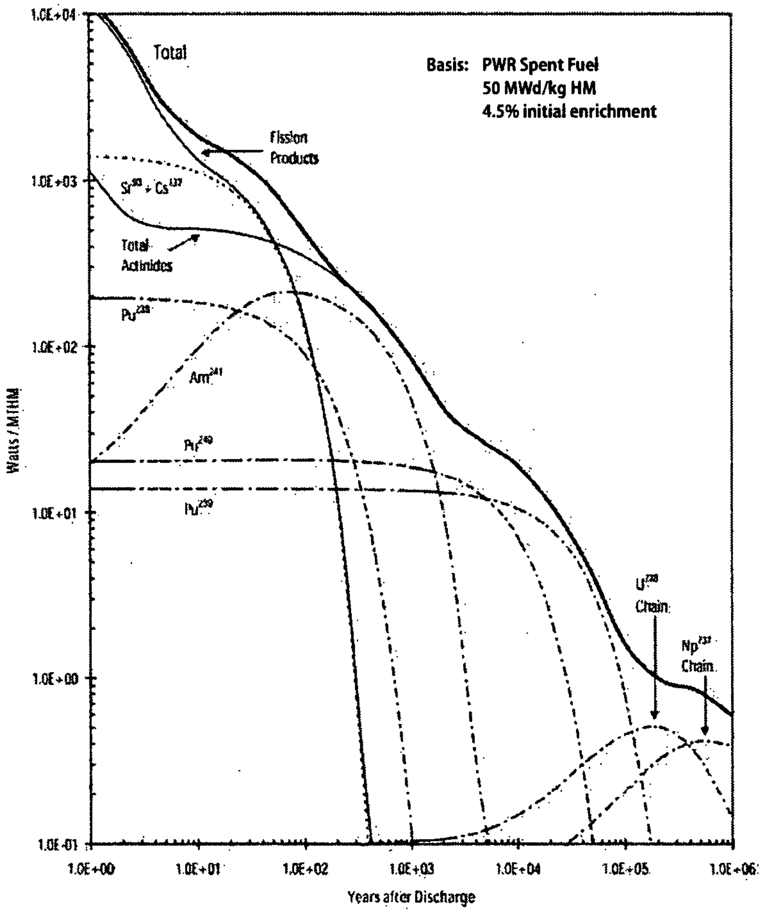
Extracting the high-heat-emitting fission product radionuclides from the spent fuel and storing them separately would allow the remainder of the radionuclides to occupy a more compact volume in a geologic repository, perhaps even reducing the total number of repositories required. It should be noted, however, that a similar result could be achieved without the need for separation by storing the spent fuel for several decades to allow the fission products to decay. In this case, moreover, there would be no need for a separate storage facility for the partitioned strontium-90 and cesium-137, which would have to be isolated from the biosphere for several hundred years before radioactive decay would render them harmless.

An alternative strategy would be to partition the uranium, plutonium and the other actinides from the spent fuel. If actinide partitioning were implemented in conjunction with interim waste storage for long enough to allow the strontium-90 and cesium-137 to decay significantly before repository emplacement, the effective storage capacity of a given repository could be increased many-fold. But the partitioned actinides would still have to be stored in a separate repository (or alternatively in deep boreholes). Moreover, by separating the actinides from the more radioactive fission products, the radiation barrier against unauthorized recovery of weapons-usable plutonium would be reduced relative to the case of intact spent fuel, at least for a century or so.

The case for partitioning the spent fuel and separately storing the different radionuclide fractions does not seem persuasive, especially given the additional costs and near-term environmental and safety risks associated with partitioning operations.

Waste partitioning and transmutation Waste partitioning strategies potentially become more attractive when combined with transmutation. There are three principal motivations for partitioning/transmutation schemes. First, if the long-lived isotopes in the waste could be extracted and destroyed, many more locations might become suitable candidates to host a repository for the remaining material. Indeed, if *all* of the long-lived radionuclides could be removed and destroyed, a disposal strategy relying solely on engineered structures for radionuclide containment might become feasible. The actinides, which as a group dominate the radiotoxicity of the spent fuel after about 100 years (see Figure 7.3), are usually cited as the prime candidates for partitioning and transmutation. However, performance assessments of the proposed repository sites at Yucca Mountain and at Olkiluoto in Finland show that long-lived fission products, such as technetium-99 and iodine-129, are more important than most actinides as sources of long-term exposure risk.[11] Partitioning and transmutation studies have yet to show that these fission products can be dealt with effectively. Even for the actinides, the technology is not yet available to remove these isotopes from all fuel cycle waste streams, and complete elimination of these isotopes from secondary, as well as primary waste streams, is unlikely ever to be attractive on economic grounds.

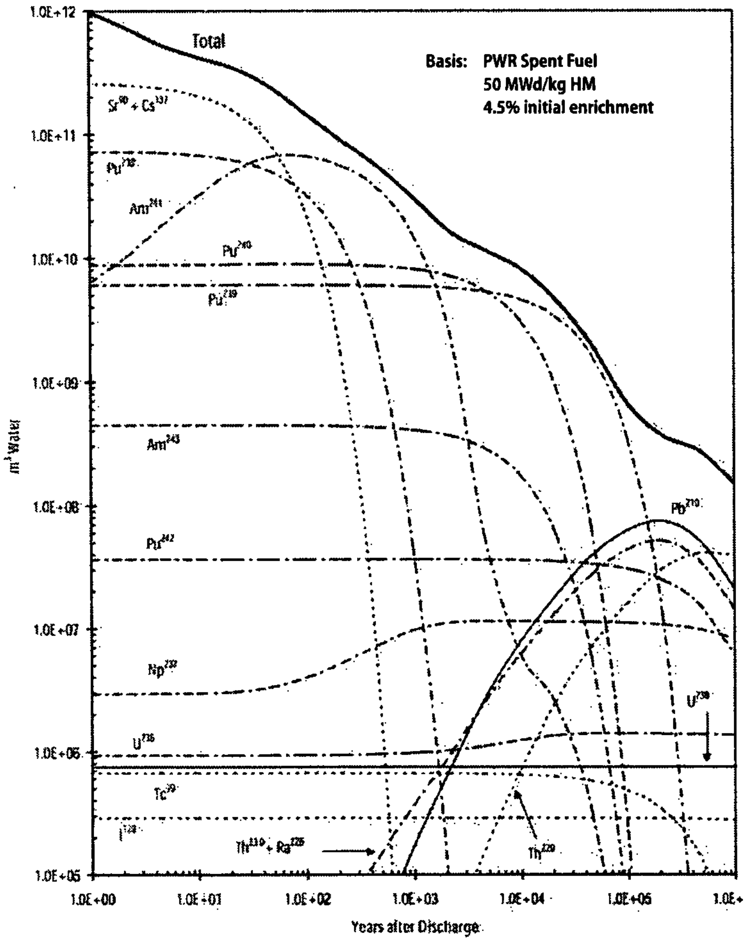
Figure 7.2 Decay Heat Profile of Spent Fuel



A second motivation for partitioning and transmutation is to reduce the thermal load on the repository, thereby increasing its storage capacity. As Figure 7.2 shows, after 60–70 years, the actinides are the dominant contributors to waste heating. As previously noted, actinide partitioning and transmutation, combined with a period of several decades of interim storage prior to final disposal of the residual waste, could increase the effective storage capacity of a given repository several-fold. Given the extreme difficulty of repository siting in most countries, any reduction in the required number of repositories must be counted as a significant gain, although this would be at least partly offset by the additional difficulty of siting the necessary waste partitioning and related fuel cycle facilities. As noted above, a less costly way to increase the effective storage capacity of repositories would simply be to defer waste emplacement until more of the heat-emitting radionuclides have decayed. In some countries, moreover, especially those with relatively small nuclear programs, a single repository is likely to be able to accommodate the entire national inventory of high-level waste even without actinide partitioning. [12]

A third motivation for partitioning and transmutation is to eliminate the risk that plutonium could later be recovered from a repository and used for weapons. It is difficult to assess the significance of this result. The value today of elim-

Figure 7.3 Radiotoxicity Index for 1MT of Spent Fuel



inating the technical means for one particular type of aggressive or malevolent human behavior centuries or millennia from now, out of all possible opportunities for such behavior that may exist at that time, is a question perhaps better addressed by philosophers than engineers, political scientists, or economists. From a narrowly technical perspective the best that can be said is that, without partitioning and transmutation, the feasibility of plutonium recovery from a repository will increase with time, as the radiation barrier created by the fission products in the waste decays away.

Against these putative long-term benefits of waste partitioning and transmutation must be weighed the increased short-term health, safety, environmental, and security risks involved. All actinide partitioning and transmutation schemes currently under consideration also seem likely to add significantly to the economic cost of the nuclear fuel cycle.

The trade-off between reduced risk over very long time scales and increased risk and cost in the short term is an issue on which reasonable people can disagree. The evaluation can furthermore be expected to vary by country, reflecting the different preferences and different constraints – geological, demographic, political, economic – of different societies. *Nevertheless, taking all these factors into account, we do not believe that a convincing case can be made on the basis of waste management considerations alone that the benefits of advanced fuel cycle schemes featuring waste partitioning and transmutation will outweigh the attendant risks and costs.* Future technology developments could change the balance of expected costs, risks, and benefits. For our fundamental conclusion to change, however, not only would the expected long-term risks from geologic repositories have to be significantly higher than those indicated in current risk assessments, but the incremental costs and short-term safety and environmental risks would have to be greatly reduced relative to current expectations and experience.

Some argue that partitioning and transmutation, by reducing the toxic lifetime of the waste, could change public attitudes towards the feasibility and acceptability of nuclear waste disposal. There is no empirical evidence of which we are aware to support this view. Our own judgment is that local opposition to waste repositories or waste transportation routes would not be much influenced, even if the toxic lifetime were reduced from hundreds of thousands to hundreds of years.

Our assessment of alternative waste management strategies leads to the following important conclusion: *technical improvements to the waste management strategies in the once-through fuel cycle are potentially available that could yield benefits at least as large as those claimed for advanced* *fuel cycles featuring waste partitioning and transmutation, and with fewer short-term risks.* The most that can reasonably be expected of partitioning and transmutation schemes is to reduce the inventory of actinides in geologic repositories by perhaps two orders of magnitude.[13] Reductions of two orders of magnitude or more in long-term radiation exposure risks could potentially be achieved by siting the repositories in host environments in which chemically reducing conditions could be ensured. Moreover, deep borehole technology offers a credible prospect of risk reductions of several orders of magnitude relative to mined repositories. Neither of these options is likely to cost as much or take as long to develop and deploy as waste partitioning and transmutation schemes.

INSTITUTIONAL INNOVATIONS

Technological advances can increase the likelihood that nuclear waste disposal will be successfully implemented. But an equally important consideration is the competence of the implementing authorities. A major challenge for these authorities under our global growth scenario will be to find suitable disposal sites. A worldwide deployment of one thousand 1000 megawatt LWRs operating on the once-through fuel-cycle with today's fuel management characteristics would generate roughly three times as much spent fuel annually as does today's nuclear power plant fleet.[14] If this fuel was disposed of directly, new repository storage capacity equal to the currently planned capacity of the Yucca Mountain facility would have to be created somewhere in the world roughly every three or four years. For the United States, a three-fold increase in nuclear generating capacity would create a requirement for a Yucca Mountain equivalent of storage capacity roughly every 12 years (or every 25 years if the physical rather than the legal capacity limit of Yucca Mountain is assumed.) Even if the technical strategies discussed above succeed in reducing the demand for repository capacity, the organizational and political challenges of siting will surely be formidable.

Today the political and legal mechanisms for balancing broad national policy goals against the concerns of affected local communities in the site selection process vary widely, even among the democratic societies of the West. This diversity of approaches will surely persist, although over time, as some nations achieve success in gaining local acceptance of repositories, some international diffusion of 'best siting practices' is probable. On present evidence, these best practices seem likely to include full access to information, opportunities for broad-based and continuing local community participation in consensus-building processes, the adoption of realistic and flexible schedules, and a willingness not merely to compensate local communities for hosting facilities, but also to find ways to make them actually better off.

Another important requirement for successful waste management implementation is the effective administration of a large-scale industrial operation involving the transportation, storage, processing, packaging, and emplacement of large quantities of radioactive waste. In the United States, as a matter of law and policy, the governance and management structure of the high-level waste program has been heavily focused on the development of the Yucca Mountain project. The scientific and engineering effort has also been almost exclusively focused on the investigation of the Yucca Mountain site and the development of a repository design for that site. However, the organizational and managerial demands of repository siting – a one-time project that is by definition exploratory, developmental, and, inevitably, highly politicized – are fundamentally different from the demands of a routine-based large-scale industrial processing and logistics operation. The intense focus on the Yucca Mountain project will continue as design and licensing activities gain momentum over the next few years. *In addition, the U.S. high level waste management program will require (1) a broadly-based, long-term R&D program, and (2) a separate organization for managing the operations of the waste management system.*

Finally, we note that international cooperation in the field of high-level waste management and disposal is presently under-developed. Stronger international coordination of standards and regulations for waste transportation, storage, and disposal will be necessary in order to strengthen public confidence in the safety of these activities. There is also considerable potential for international sharing of waste storage and disposal facilities. This might not only reduce proliferation risks from the fuel cycle (as discussed in the following chapter), but could also yield significant economic and safety benefits, although formidable political obstacles will have to be overcome first.

The authors of this study wish to acknowledge the valuable research support provided by our former students, Dr. Brett Mattingly and Dr. David Freed in the preparation of this chapter.

NOTES

1. In this study we focus on spent fuel and reprocessed high-level waste, since these waste types contain most of the radioactivity generated in the nuclear power fuel cycle and pose the greatest technical and political challenges for final disposal. We also include in the discussion so-called TRU waste — non-high-level waste contaminated with significant quantities of long-lived transuranic radionuclides — which because of its longevity will likely be disposed of in the same facilities as high-level waste. Other types of nuclear waste, including low-level waste and uranium mill tailings, are generated in larger volumes in the nuclear fuel cycle but pose fewer technical challenges for disposal, although localized opposition to disposal facilities for these materials has sometimes been intense.
2. In the opinion survey commissioned for this study, almost two-thirds of respondents did not believe that nuclear waste could be safely stored for long periods.
3. According to one recent international scientific assessment, "[I]n a generic way, it can be stated with confidence that deep geologic disposal is technically feasible and does not present any particularly novel rock engineering issues. The existence of numerous potentially suitable repository sites in a variety of host rocks is also well established." (International Atomic Energy Agency, "Scientific and Technical Basis for the Geologic Disposal of Radioactive Wastes", Technical Report No. 413, IAEA, Vienna, 2003.) Another expert group, convened by the OECD's Nuclear Energy Agency, found that, "[T]here is today a broad international consensus on the technical merits of the disposal of long-lived radioactive waste in deep and stable geologic formations.... Currently, geologic disposal can be shown to have the potential to provide the required level and duration of isolation." "The Environmental and Ethical Basis of Geologic Disposal of Long-Lived Radioactive Wastes: A Collective Opinion of the Radioactive Waste Management Committee of the OECD Nuclear Energy Agency," 1995 at http://www.nea.fr/html/rwm/reports/1995/geodisp.html . Yet another recent international assessment, this time under the auspices of the U.S. National Academy of Sciences, found that, "geological disposal remains the only scientifically and technically credible long-term solution available to meet the need for safety without reliance on active management...a well-designed repository represents, after closure, a passive system containing a succession of robust safety barriers. Our present civilization designs, builds, and lives with technological facilities of much greater complexity and higher hazard potential." See National Academy of Sciences, Board on Radioactive Waste Management, *Disposition of High Level Waste and Spent Nuclear Fuel: The Continuing Societal and Technical Challenges,* National Academy Press, Washington, D.C., 2001.
4. Because of the high heat generation, spent fuel must be stored for at least five years before it can be emplaced in a geologic repository. After another 30 years, the decay heat from the fission products Cs-137 and Sr-90, the leading sources of heat during this period, will have halved. After 100 years, the contribution from these isotopes will have declined by more than 90%. At that point, the fission product radiation barrier, which until then would complicate attempts by would-be proliferators to recover plutonium from the spent fuel, will have largely dissipated, and storage in relatively accessible surface or near-surface facilities thereafter would be less desirable on non-proliferation grounds.

5. As the burnup increases, the proportion of plutonium-239 in the plutonium declines, while the proportion of Pu-238 increases. For example, an increase in the burnup of PWR fuel from 33 MWD/kg to 100 MWD/kg would result in a decline in the Pu-239 content from 65% to 53%, while the Pu-238 content would increase from 1% to about 7%. (Zhiwen Xu, Ph.D. dissertation, Department of Nuclear Engineering, M.I.T., 2003). Pu-238 is a particularly undesirable isotope in nuclear explosives because of its relatively high emission rate of spontaneous fission neutrons and decay heat. According to some specialists, a Pu- 238 content above about 6% would make plutonium essentially unusable for weapons purposes. The denaturing effect of Pu-238 would be limited to a couple of centuries, however, because of its relatively short (87-year) half-life.
6. In recent years the average burnup of LWR fuel has risen from about 33 MWD/kg to about 45–50 MWD/kg. LWR operators have taken this step for economic reasons that are largely unrelated to waste disposal; the higher-burnup fuel cycle allows the reactors to operate for longer periods between refueling, thus increasing the reactor capacity factor.
7. Weng-Sheng Kuo, Michael J. Driscoll, and Jefferson W. Tester, "Re-evaluation of the deep drillhole concept for disposing of high-level nuclear wastes," *Nuclear Science Journal*, vol. 32, no. 3, pp. 229–248, June 1995.
8. According to one recent estimate, a full-scale 4-kilometer deep borehole could be drilled and cased in less than 5 months, at a cost of about $5 million. Tim Harrison, "Very Deep Borehole: Deutag's Opinion on Boring, Canister Emplacement and Retrievability", Swedish Nuclear Fuel and Waste Management Co., R- 00-35, May 2000.
9. See, for example, National Academy of Sciences, *Nuclear Wastes: Technologies for Separation and Transmutation, Committee on Separations Technology and Transmutation Systems*, National Research Council, Washington, D.C., 1996; B.Brogli and R. A. Krakowski, "Degree of sustainability of various nuclear fuel cycles," Paul Scherrer Institut Nuclear Energy and Safety Research Department, PSI Bericht No. 02-14, August 2002.
10. The PUREX/MOX fuel cycle currently practiced in several countries is one variant of the waste partitioning/transmutation option, in which uranium and plutonium isotopes are partitioned from the spent fuel, and the separated plutonium isotopes are partially transmuted into shorter-lived fission products in light water reactors. As shown in Appendix 5D, PUREX/MOX increases the fuel cycle cost to 4.5 times the once-through fuel cycle cost, depending on various assumptions.
11. To determine which radionuclides should be the principal targets of partitioning and transmutation, it is necessary to assess the likelihood that individual radionuclides will be transported from the repository to the biosphere. This in turn is a function of the particular geochemical and hydrological characteristics of the repository environment. In the oxidizing conditions characteristic of Yucca Mountain, the dominant contributors to long-term exposure risk are neptunium-237 and technetium-99. During the first 70,000 years, technetium-99 is the leading contributor, and between 100,000 years and 1 million years, the dominant isotope is Np-237. The peak dose of about 150 millirems/year (about half the background dose) occurs after about 400,000 years. (See: *Final Environmental Impact Statement for Yucca Mountain Repository*, February 2002) In contrast, a performance assessment of the proposed Finnish repository at Olkiluoto, in crystalline rock in a chemically reducing environment, concludes that the actinides would contribute very little to long-term dose, and that the dominant contributors would be a few long-lived fission products. The projected peak dose, moreover, is three orders of magnitude lower than that at Yucca Mountain (see Vieno and Nordman, "Safety Assessment of Spent Fuel Disposal in Hastholmen, Kivetty, Olkiluoto and Romuvaara - TILA-99," POSIVA 99-07, March 1999, ISBN 951-652-062-6).
12. For the repository at Yucca Mountain, operating in the so-called higher-temperature operating mode, the total subsurface area that would be required to accommodate the legal limit of 70,000 MT of spent fuel equivalent (including 7000 MT of defense high level waste) would be 1150 acres, equivalent to a square roughly 2 kilometers along a side. U.S. Department of Energy, "Yucca Mountain Science and Engineering Report, Rev. 1", DOE/RW-0539-1, February 2002, Executive Summary, at http://www.ymp.gov/documents/ser_b/. The current fleet of U.S. reactors is expected to discharge at least 105,000 MT of spent fuel and possibly considerably more, depending on reactor operating lifetimes. The 70,000 MTHM capacity limit at Yucca Mountain was politically determined, and according to some knowledgeable observers the physical storage capability of the site would be at least twice as large.
13. Nuclear Energy Agency, *Accelerator-Driven Systems and Fast Reactors in Advanced Fuel Cycles: A Comparative Study*, OECD, 2002 (available at http://www.nea.fr/html/ndd/reports/2002/nea3109.htm.
14. If each reactor has a burn-up of 50,000 MWth-d/MTHM, a capacity factor of 0.9, and a thermal efficiency of 33%, deployment of 1000 1 Gwe reactors would result in an annual spent fuel discharge of about 20,000 metric tons per year.

Chapter 8 — Nonproliferation

Nuclear weapons proliferation has been prominent in discussions about nuclear power since its earliest days. The birth of nuclear technology that began with production of the first weapons-usable fissionable material — plutonium production in nuclear reactors and high-enriched uranium by isotope enrichment — assured that this would be so. *Today, the objective is to minimize the proliferation risks of nuclear fuel cycle operation.* We must prevent the acquisition of weapons-usable material, either by diversion (in the case of plutonium) or by misuse of fuel cycle facilities (including related facilities, such as research reactors or hot cells) and control, to the extent possible, the know-how about how to produce and process either HEU (enrichment technology) or plutonium.

This proliferation concern has led, over the last half century, to an elaborate set of international institutions and agreements, none of which have proved entirely satisfactory. The Nuclear Nonproliferation Treaty (NPT) is the foundation of the control regime, since it embodies the renunciation of nuclear weapons by all signatories except for the declared nuclear weapons states – the P-5 (the United States, Russia, the United Kingdom, France, China) — and a commitment to collaborate on developing peaceful uses of nuclear energy. However, non-signatories India and Pakistan tested nuclear weapons in 1998, and signatories, such as South Africa and North Korea, have admitted to making nuclear weapons.

The International Atomic Energy Agency (IAEA) has responsibility for verifying NPT compliance with respect to fuel cycle facilities through its negotiated safeguards agreements with NPT signatories. The IAEA's safeguard efforts, however, are seriously constrained by the scope of their authorities (as evidenced in Iraq, Iran, and North Korea during the last decade), by their allocation of resources, and by the growing divergence between responsibilities and funding. The United Nations Security Council has not yet established a procedure or shown a willingness to impose sanctions when IAEA safeguards agreements are violated. A variety of multilateral agreements, such as the Nuclear Supplier Group guidelines for export control, aim to restrict the spread of proliferation-enabling nuclear and dual-use technology. European centrifuge enrichment technology, however, is known to have contributed to weapons development elsewhere, and the US and Russia have a continuing dispute over transfer of Russian fuel cycle technologies to Iran (a NPT signatory). This is not to say that the safeguards regime has failed to restrain the spread of nuclear weapons; it almost certainly has. Nevertheless, its shortcomings raise significant questions about the wisdom of a global growth scenario that envisions a major increase in the scale and geographical distribution of nuclear power.

In addition to the risk of nuclear weapons capability spreading to other nations, the threat of acquisition of a crude nuclear explosive by a sub-national group has arisen in the aftermath of the September 11, 2001 terrorist attacks. The report of interest in nuclear devices by the terrorist Al Qaeda network especially highlights this risk. Terrorist or organized crime groups are not expected to be able to produce nuclear weapons material themselves; the concern is their direct acquisition of nuclear materials by theft or through a state sponsor. This places the spotlight on the PUREX/MOX fuel cycle as currently practiced in several countries, since the fuel cycle produces during conventional operation nuclear material that is easily made usable for a weapon. The sub-national theft risk would be exacerbated by the spread of the PUREX/MOX fuel cycle, particularly to those countries without the infrastructure for assuring stringent control and accountability.

A separate concern is the dirty bomb threat in which radioactive material (from any source, such as nuclear spent fuel or cobalt sources used in medicine and industry) is dispersed in a conventional explosive as a weapon of mass disruption. The dirty bomb threat is a very serious security concern but is not specific to the nuclear fuel cycle and will not be discussed further in the proliferation context.

It is useful to set a scale for the proliferation risk that has emerged from nuclear power operation to date. Spent fuel discharged from power reactors worldwide contains well over 1000 tonnes of plutonium. While the plutonium is protected by the intense radioactivity of the spent fuel, the PUREX chemical process most commonly used to separate the plutonium with high purity, is well known and described in the open literature. With modest nuclear infrastructure, any nation could carry out the separation at the scale needed to acquire material for several weapons. Further, the MOX fuel cycle has led to an accumulation of about 200 tonnes of separated plutonium in several European countries, Russia and Japan. This is equivalent to 25,000 weapons using the IAEA definition of 8 kg/weapon. Separated plutonium is especially attractive for theft or diversion and is fairly easily convertible to weapons use, including by those sub-national groups that have significant technical and financial resources.

The nonproliferation issues arising from the global growth scenario are brought into sharp focus by examining a plausible scenario for the deployment of 1000 GWe nuclear capacity (see Table 3.2 and Appendix 2). An important characteristic of this scenario is that much of the deployment would be expected in industrialized countries that either already have nuclear weapons, thus making materials security against theft the principal issue, or are viewed today as minimal proliferation risks. The concern about these nations' ability to provide security for nuclear material is especially elevated for Russia, whose economic difficulties have limited its effort to adopt strong material security measures; the concern applies to materials from both the weapons program and the fuel cycle,[1] which have significant inventories of separated Pu. Moreover geopolitical change, for example, in East Asia, could change the interests of some nations in acquiring nuclear capability. Japan, South Korea, and Taiwan have advanced nuclear technology infrastructures and over several decades might adjust to the emergence of China as both a nuclear weapons state and a regionally dominant economic force by seeking nuclear capability. North Korea provides a further complication to this dynamic.

The developing world might plausibly account for about a third of deployed nuclear power in the mid-century scenario. An appreciable part of this will likely be in China and India, which already have nuclear weapons and dedicated stockpile facilities and thus are not viewed as the highest risks for fuel cycle diversion. Nevertheless, dramatic growth of nuclear power in the sub-continent could be a pathway for nuclear arsenal expansion in India and Pakistan. The security of their nuclear enterprises remains of concern.

On the other hand, a number of other nations with relatively little nuclear infrastructure today, such as the Southeast Asian countries Indonesia, Philippines, Vietnam, and Thailand (with a 2050 projected combined population over 600 million) are also likely candidates for nuclear power in the global growth scenario. Iran is actively pursuing nuclear power, with Russian assistance, even though it has vast unexploited reserves of natural gas and could clearly meet its electricity needs more economically and rapidly by using this domestic resource. The United States in particular has argued that this indicates Iranian interest in acquiring a nuclear weapons capability, even though Iran is an NPT signatory and has a safeguards agreement with the IAEA in place. Recent revelation of the spread of clandestine centrifuge enrichment and heavy water technology exacerbates this concern. Thus the U.S. is arguing that cooperation with Iran on nuclear power should cease irrespective of the NPT's call for cooperation in the peaceful use of nuclear energy (Article IV). This issue has been a significant irritant in U.S.-Russia relations. Such conflicts between an underlying principle of the NPT and the aims of specific countries could become more common in the growth scenario.

The rapid global spread of industrial capacity (such as chemicals, robotic manufacturing) and of new technologies (such as advanced materials, computer-based design and simulation tools, medical isotope separation) will increasingly facilitate proliferation in developing countries that have nuclear weapons ambitions. A fuel cycle infrastructure makes easier both the activity itself and the disguising of this activity. Indeed, even an extensive nuclear fuel cycle RD&D program and associated facilities could open up significant proliferation pathways well before commercial deployment of new technologies.

We conclude that the current non-proliferation regime must be strengthened by both technical and institutional measures with particular attention to the connection between fuel cycle technology and safeguardability. Indeed, if the nonproliferation regime is not strengthened, the option of significant global expansion of nuclear power may be impossible, as various governments react to real or potential threat of nuclear weapons proliferation facilitated by fuel cycle development. The U.S. in particular should recommit itself to strengthening the IAEA and the NPT regime.

The specific technical and institutional measures called for will depend upon the fuel cycle technologies that account for growth in the global growth scenario. We have considered several representative fuel cycles: light water reactors and more advanced thermal reactors and associated fuel forms, operated in an open, once-through fuel cycle; closed cycle with Pu recycling in the PUREX/MOX fuel cycle; and closed fuel cycles based on fast reactors and actinide burning. The priority concern is accounting and control of weapon-usable material during normal operation and detection/prevention of process modification or diversion to produce or acquire such material.[2]

The open fuel cycles seek to avoid the proliferation risk of separated plutonium by requiring that the highly radioactive spent fuel be accounted for until final disposition. This defines the baseline for adequate proliferation-resistance, assuming that spent fuel is emplaced in a geological repository less than a century or so following irradiation (i.e., before the self-protection barrier is lowered excessively). However, the open fuel cycle typically requires enriched uranium fuel, so the spread of enrichment technology remains a concern.

The advanced closed fuel cycles that keep the plutonium associated with some fission products and/or minor actinides also avoid "directly usable" weapons material in normal operation, since there is a chemical separation barrier analogous to that which exists with spent fuel. Nevertheless, closed fuel cycles need strong process safeguards against misuse or diversion. However, the development and eventual deployment of closed fuel cycles in non-nuclear weapons states is a particular risk both from the viewpoint of detecting misuse of fuel cycle facilities, and spreading practical know-how in actinide science and engineering.

Greater proliferation resistance will require the adoption of technical and institutional measures appropriate to the scale and spread of the global growth scenario and responsive to both national and sub-national threats. Proliferation concerns contributed significantly to our conclusion that the open, once-through fuel cycle best meets the global growth scenario objectives, since no fissile material easily usable in a nuclear weapon appears during normal operation, and the "back end" does not have plutonium separation facilities. Enrichment facilities that could be employed for HEU production represent a risk. A variety of measures can minimize the risk: strengthened IAEA technical means to monitor material flows and assays at declared facilities; reliable supply of fresh fuel (and perhaps return of spent fuel) from a relatively small set of suppliers under appropriate safeguards; implementation of IAEA prerogatives with respect to undeclared facilities (the "Additional Protocol"); strengthened export controls on enrichment technologies and associated dual-use technologies; and utilization of national intelligence means and appropriate information sharing with respect to clandestine facility construction and operation. This is a demanding agenda, both diplomatically and in its resource needs, and calls for active effort on the part of the U.S. and other leading nuclear countries. With such an effort, the level of proliferation risk inherent in the possible expansion to 1000 GWe nuclear power by mid-century appears to us to be manageable.

It is clear that international RD&D on closed fuel cycles will continue and indeed grow over the next years, with or without U.S. participation. We believe that such work should be restricted by proliferation considerations to those fuel cycles that do not produce "direct use" nuclear materials in their operation. Current R&D planning discussions in the U.S. reflect this concern. Such fuel cycles may also have manageable proliferation risks when coupled with improved technical and institutional safeguards. However, although advanced closed fuel cycles cannot realistically by deployed for many decades, the R&D program could itself assist and provide cover for proliferants unless structured carefully from the beginning. Today, the international discussions are carried out by those principally interested in developing advanced technologies, without the needed level of engagement from those whose primary responsibility is nonproliferation. The U.S. could play a crucial role in shaping these discussions properly before major efforts are underway.

In this context, the PUREX/MOX fuel cycle is a major issue. It is the current candidate, because of experience, for near-term deployment in nations determined to pursue closed fuel cycles. However, it should be stressed that the PUREX/MOX fuel cycle is not on the "technology pathway" to the advanced fuel cycles discussed earlier (typically, the advanced fuel cycles will involve different separations technology, fuel form, and reactor). The U.S. should work with France, Britain, Russia, Japan, and others to constrain more widespread deployment of this fuel cycle, while recognizing that development of more proliferation-resistant closed fuel cycle technologies is widely viewed as a legitimate aspiration for the distant future. The associated institutional issues encompass examination of the underlying international regime embedded in the NPT/Atoms for Peace framework. All of these issues confront the fundamental question of tradeoffs of national sovereignty in the context of access to nuclear materials and technology. Such issues are intrinsically difficult and time-consuming to resolve through diplomacy, but concomitantly important for realizing the global growth scenario, while preserving international commitment to and confidence in a strong nuclear nonproliferation regime.

In summary, the global growth scenario built primarily upon the once-through thermal reactor fuel cycle would sustain an acceptable level of proliferation resistance if combined with strong safeguards and security measures and timely implementation of long term geological isolation. The PUREX/MOX fuel cycle produces separated plutonium and, given the absence of compelling reasons for its pursuit, should be strongly discouraged in the growth scenario on nonproliferation grounds. Advanced fuel cycles may achieve a reasonable degree of proliferation resistance, but their development needs constant and careful evaluation so as to minimize risk. The somewhat frayed nonproliferation regime will require serious reexamination and strengthening to face the challenge of the global growth scenario, recognizing that fuel cycle-associated proliferation would greatly reduce the attraction of expanded nuclear power as an option for addressing global energy and environmental challenges.

NOTE

1. "DOE's Nonproliferation Programs with Russia, Howard Baker and Lloyd Cutler, co-chairs, Secretary of Energy Advisory Board report, January 2001; "Controlling Nuclear Warheads and Material", M. Bunn, M. Wier, and J. Holdren, Nuclear Threat Initiative report, March 2003.
2. E. Arthur, et. al., "Uranium enrichment technologies: workshop materials," Los Alamos Report — LA-CP-03-0233, (December, 2002).

Chapter 9 — Public Attitudes and Public Understanding

There is little question that the public in the United States and elsewhere is skeptical of nuclear power. A majority of Americans simultaneously approve of the use of nuclear power, but oppose building additional nuclear power plants to meet future energy needs. Since the accident at the Three Mile Island power plant in 1979, 60 percent of the American public has opposed and 35 percent have supported construction of new nuclear power plants, although the intensity of public opposition has lessened in recent years.[1] Large majorities strongly oppose the location of a nuclear power plant within 25 miles of their home.[2] In many European countries, large majorities now oppose the use of nuclear power. Recent Eurobarometer surveys show that 40 percent of Europeans feel that their country should abandon nuclear power because it poses unacceptable risks, compared with 16 percent who feel it is "worthwhile to develop nuclear power."[3]

Why does nuclear power, or for that matter any energy source, receive or lose public confidence? There is a surprising lack of survey data in the public domain that would allow us to understand why people oppose and support specific power sources. [4] To fill that void, we have conducted a survey[5] of 1350 adults in the United States. This internet survey[6] measures public opinion about future use of energy sources, including fossil fuels, nuclear power, hydroelectricity, and solar and wind power.

Our survey showed the same level of skepticism as other surveys. Respondents in our survey, on average, preferred that the United States reduce somewhat nuclear power usage in the future. The same, however, was true of coal, the nation's largest energy source, and oil. On average, respondents wanted to keep natural gas at its current level. And, respondents strongly support a significant expansion of wind and solar power.

On what do these attitudes depend? We explored this question this question two ways. First, we performed a statistical analysis to determine which factors explain who supports nuclear power and who does not. This analysis is presented in the Chapter 9 Appendix. The results are, briefly, as follows:

- ☐ Perceived environmental harms weigh most heavily. The average person responded that nuclear power is moderately harmful to the environment, and the difference between someone who perceives nuclear power as "somewhat harmful" and "moderately harmful" is the difference between wanting to expand and wanting to reduce nuclear power in the future.
- ☐ Safety and waste are also significant factors. Those who believe that waste can be stored safely for many years express higher levels of support for building additional nuclear power plants. Those who believe that a serious accident is unlikely in the next 10 years also express higher support for nuclear power. The problem is a majority of respondents do not believe that nuclear waste can be stored safely for many years, and the typical respondent believes that a serious reactor accident is somewhat likely in the next 10 years.
- ☐ Perceived costs of nuclear power are the third most important factor. Those who

believe nuclear power is uneconomical support it less.

☐ Surprisingly, concern about global warming, in our survey, does not predict preferences about future use of nuclear power. There is no difference in support for expanding nuclear power between those who are very concerned about global warming and those who are not.

☐ Political beliefs and demographics, such as age, gender, and income, mattered relatively little, if at all.

Second, we performed an experiment within the survey to measure sensitivity of attitudes to possible changes in cost, waste, and global warming. Half of the sample was provided no information; they are the control group. The remaining half was divided into four groups. These groups were provided with information about future energy prices or about toxic waste from fossil fuels or about global warming or about all three factors (economics, pollution, and global warming). Our aim was not to increase support for nuclear power, but to see how the mix of energy sources would change with accurate information about costs, toxic waste, and global warming.

Only nuclear power showed substantially more support between the control group and the others. Those who received all three pieces of information supported nuclear power and natural gas equally, and supported nuclear power much more than coal and oil.

Information about the relative prices of energy sources produced almost all of this shift. The public perceives solar and wind to be inexpensive. When informed that solar and wind are more expensive than fossil fuels or nuclear power, survey respondents showed substantially less support for expanding solar and wind and substantially more support for nuclear power and somewhat more support for coal and oil. Information about global warming again had no effect on public attitudes toward alternative energy sources.

In our view, these survey data reveal the fundamental importance of the technology itself for public support. American public opinion toward energy is not the product of political ideology or party politics. Rather, public opposition to nuclear power in the United States is due primarily to the public reaction to the concrete problems of the technology and the industry, notably concerns over safety, toxic waste, and poor economics. It is not surprising that the public is skeptical about a technology that has over promised.

Should there be a public campaign to change perceptions about nuclear power? The evidence suggests that such a campaign may have only modest effect. Most of the change would come through education about the high price of alternative energy sources, such as solar and wind. The other possible source of change in public attitudes is the connection between global warming and fossil fuels. The typical person expresses concern about global warming, but that concern does not in turn translate into higher support for carbon free electricity sources, such as nuclear power.

The surer way to cultivate public acceptance of nuclear power, though, is through the improvement of the technology itself and choosing carefully what nuclear technology to use. Developing and deploying technology that proves uneconomical and hazardous will make the global growth scenario infeasible. Technology choices and improvements that lower the cost of nuclear power, that improve waste management and safety, and that lessen any environmental impact will substantially increase support for this power source.

NOTES

1. Eugene A. Rosa & Riley E. Dunlap, "Poll Trends: Nuclear power — three decades of public opinion" Public Opinion Quarterly, *58*, 295-324 (1994). National Science Board, Science and Engineering Indicators 2000, volume 1, page 8–19. Washington DC: National Science Foundation. Survey results vary because researchers ask different questions and in different contexts. Recent surveys range from 60 percent opposed to "building new nuclear power plants" (AP/Washington Post) to 55 percent favoring "new nuclear power plants in the future" (Nuclear Energy Industry tracking survey questionnaire, October 2002, carried out by Bisconti Research Inc). For a discussion of some of these issues and the state of public opinion, see Steve Miller "Pragmatic Concerns Fuel Nuclear Support," IEEE Spectrum, http://www.spectrum.ieee.org/WEBONLY/publicfeature/nov01/natt.html. Because existing survey data do not directly address many of the issues that motivate our inquiry, we conducted our own survey.

2. Associated Press poll conducted by ICR March 12–16 1999, N = 1015 adults nationwide. MIT Energy Survey, June, 2002, N = 1350.

3. European and Energy Matters, 1997, EUROBAROMETER 46.0, Directorate General for Energy, European Commission, February 1997.

4. Studies of particular factors have been conducted. Accidents and waste loom large in public thinking. See, for example, Ellen Peters and Paul Slovic, Journal of Applied Social Psychology, *26*, 1427-1453, (1996). Connie de Boer and Ineke Catsburg, "A Report: The Impact of Nuclear Accidents on Attitudes Toward Nuclear Energy," Public Opinion Quarterly, 52, 254-261 (1988).

5. We surveyed the United States for reasons of cost. A reliable survey of a similar size in another country performed by a reputable survey research firm was too expensive. It is our hope that this survey offers a model for studies of public attitudes toward energy use and development in other countries. The responses might be quite different. For example, Europeans are more concerned with global warming which could influence their attitudes toward nuclear energy.

6. We performed an Internet based survey because of four design advantages over the alternative methods, phone or face-to-face. First, a face-to-face survey was prohibitively costly — at least 10 times the cost of the Internet survey. Second, Internet surveys have much higher response rates than phone surveys. Knowledge Networks, the firm we employed, recruits a pool of approximately 2 million people from which it draws a random sample. Approximately 80 percent of the people sampled responded to our survey within one week. The typical phone survey with a similar cost structure has a non-response rate of around 70 percent. Third, ensuring a higher response rate in a phone survey would have increased costs substantially (approximately double). Fourth, Internet surveys are ideal for the experimental manipulations we performed. We provided information in graphics and text format, which is superior to reading text over the phone.

   The drawback of the Internet survey is that Internet users are not necessarily representative of the population. Knowledge Networks recruits a pool of potential survey respondents from the general population and develops sample weights to allow us to extrapolate to the general population. So, a college educated, high income individual receives less weight than an individual without a bachelor's degree and with modest or low income, because individuals with college educations and above average income are more common in the pool than in the population. Data analyses are performed with appropriate sample weights and controlling for demographic factors.

PART 2

In Chapter 3 we outlined our study approach. We noted that nuclear energy is one important energy option for the future that avoids carbon emission, but that exercising the option for *significant* deployment requires overcoming four challenges — economics, safety, waste, and proliferation. We defined a global growth scenario with a range of future nuclear power deployment between 1000 to 1500 GWe. In Chapter 4, we analyzed three different fuel cycle scenarios and evaluated them against the significant challenges: economics (Chapter 5), safety (Chapter 6), waste management (Chapter 7), and proliferation (Chapter 8). In Chapter 9, we reported on survey results about attitudes of the U.S. public to the technologies we are studying.

This analysis leads us to a conclusion of great significance: the open, once-through fuel cycle best meets the criteria of economic attractiveness and proliferation resistance. Closed fuel cycles may have an advantage from the point of view of long-term waste disposal and, if it ever becomes relevant, resource extension. But closed fuel cycles will be more expensive than once through cycles, until ore resources become very scarce. This is unlikely to happen even with significant growth in nuclear power deployment until the end of this century. We also find that the long-term waste management benefits of separation are outweighed by the short-term risks and costs.

Thus our paramount recommendation is:

For the next decades, government and industry in the United States and elsewhere should give priority to deployment of the once-through fuel cycle, rather than development of the more expensive closed fuel cycle technology involving reprocessing and new advanced thermal or fast reactor technologies.

This recommendation implies a major re-ordering of priorities of the U.S. Department of Energy (DOE) nuclear R&D programs.

The following table indicates how well each of the fuel cycles considered matches the criteria we have used for each of the four objectives:

Fuel Cycle Types and Criteria Ratings

				SAFETY			
	ECONOMICS	WASTE	PROLIFERATION	REACTOR	FUEL CYCLE	REACTOR TYPES	EXAMPLES OF NEW FEATURES
Once through (1)	+	× short term – long term	+	×	+	LWRs CANDU HTGRs	High burn up fuel Thorium Lifetime core Modular Passive safety
Closed thermal (2)	–	– short term + long term	–	×	–	Same plus Molten Salt	
Closed fast (3)	–	– short term + long term	–	+ to –	–	Liquid sodium, lead Gas	Advanced PUREX Pyroprocessing Adv partitioning & transmutation Integrated energy parks

+ means relatively advantageous; × means relatively neutral; – means relatively disadvantageous

This table indicates broadly the relative advantage and disadvantage among the different type of fuel cycles. It does not indicate relative standing with respect to other electricity-generating technologies, where the criteria might be quite different (for example, the nonproliferation criterion applies only to nuclear). The economic and waste criteria are likely to be the most crucial for determining nuclear power's future.

We have not found and, based on current knowledge, do not believe it is realistic to expect that there are new reactor and fuel cycle technologies that simultaneously overcome the problems of cost, safety, waste, and proliferation.

In this second part of our report we present recommendations enabling a path that leads from today to the mid-century scenario. We do not establish a timetable or specific goals. Rather our purpose is to identify measures — both technical and institutional – that address the major barriers to nuclear power expansion. We present our recommendations in three chapters: Chapter 10, which addresses economic incentives; Chapter 11, which addresses measures bearing on waste management, safety, and proliferation; and Chapter 12, which presents a recommended government R&D program.