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

	ECONOMICS	WASTE	PROLIFERATION	SAFETY		REACTOR TYPES	EXAMPLES OF NEW FEATURES
				REACTOR	FUEL CYCLE		
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 p lus 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.

Chapter 10 — Recommended Measures to Resolve Uncertainties about the Economics of Nuclear Power

The analysis of Chapter 5 concludes that at the present time nuclear power is widely perceived by potential investors to be more costly than coal and gas alternatives. While segments of the nuclear industry argue that nuclear plants could be built much more cheaply than is widely perceived, investors in what has become a competitive electricity market in many countries do not believe this is so. Chapter 5 also discusses what must happen for nuclear energy to be competitive with these electricity supply alternatives: credible significant reduction in the perceived level and uncertainty associated with capital and operation and maintenance (O&M) costs of new nuclear plants; resolution of regulatory uncertainties regarding siting, construction time to completion, and costly redesign requirements; higher real acquisition cost for natural gas; and a significant value placed on the reduction in carbon emissions resulting from displacement of fossil-generation resources with nuclear power.[1] In this section we address what measures the government should take to improve nuclear power economics.

We note that a variety of reasons are put forward to justify government support for energy supply and energy efficiency technologies. They all reflect an argument that one or more social costs or benefits associated with the use of a particular technology are not properly reflected in investor and consumer decisions. Thus policies are designed, directly or indirectly, to internalize these social costs and benefits or to compensate for market imperfections more generally. Externalities that are considered include:

- internalizing costs of threats to national security;
- internalizing social benefits of favorable learning curve effects;
- compensating for the costs of regulatory uncertainty that may confront and be resolved by "first movers" in a regulatory process;
- internalizing the benefits of R&D spillovers that accrue to society at large but cannot be fully captured by investors in R&D;
- correcting other market imperfections, including imperfect information, capital market imperfections, and other decision making imperfections;
- internalizing costs of damages to the environment.

These are arguments for government support that are not unique to nuclear power and indeed are marshaled by advocates of many energy technologies, in order to justify government subsidies of one kind or another. The result is that at one extreme, skeptics argue the government should do nothing to support technologies, and at the other extreme, enthusiasts argue the government should manage key aspects of the innovation process. Indeed there is nothing in theory or experience to suggest that, in general, the government is better able to manage technical development in a manner that leads to its wide adoption in the private sector. Credible arguments for government support for R&D all turn on compensating for some type of market failure that leads to underinvestment in the particular technologies at issue. Government actions should be carefully targeted to a clearly defined market failure. In addition, questions of how much money should be spent, how it should be spent, and when it should be spent must all reflect well defined goals that permit measurement of progress.

Nor is the government in a better position than the private sector to judge the future price and availability of fuels. On the other hand, the consequences of *rapidly changing* higher (or lower) than expected fuel prices may be different for the private sector than for the government. If natural gas prices move sharply higher than expected, individual firms will be winners or losers, but the government, as a practical matter, will be called upon to take measures to compensate for significant adverse economic impacts resulting from these higher prices.

Massive research, development, and demonstrations of nuclear power projects were supported by the Department of Energy (DOE) and predecessor agencies in the 1960s and 1970s. These projects advanced costly new technologies too rapidly, e.g. commercial reprocessing and liquid metal fast breeder reactors. They misestimated the cost of electricity from first generation light water reactors; they paid insufficient attention to the critical issues of safety, waste management, and proliferation that have proven to be of concern to the public. Ironically, the lessons of the unintended bad consequences of past government involvement in the nuclear industry are contradictory: first, the government bears some responsibility for reviving this important energy option, but second, we should advance new proposals for government support with special clarity about their purpose and realistic expectations about success.

Our position is that the prospect of global climate change from greenhouse gas emissions and the adverse consequences that flow from these emissions is the principal justification for government support of the nuclear energy option. The environmental externality of carbon dioxide (CO_2) emissions means that price of carbon based fuel and electricity produced from it are too low. In an ideal world, this externality would be internalized either with a carbon tax or an emissions cap and trade program[2]. A carbon tax places a price on carbon emissions directly. A cap and trade program would establish a national CO_2 emissions cap, issue tradeable emissions permits equal to the cap, and require all emissions sources (at an appropriate place in the vertical chain from fossil fuel production to fossil fuel use) to hold permits to cover their emissions. The market price for these emissions permits then defines the price for CO_2, in much the same way as would a tax. Hybrid programs (e.g., cap and trade with an elastic supply of permits at a specified price) are also feasible and under consideration.

In practice we are unlikely to see the United States adopt any carbon emissions tax; proposing energy taxes, or what appear to be like energy taxes, has not proven to be career enhancing for elected officials. An essentially equivalent "cap and trade" policy that has proven successful in minimizing the social cost of reducing SO_2 emissions produced from coal-fired power plants is uncertain, at least in the near term, although legislation has been proposed for such a program. Instead we are likely to continue to see "second best" surrogate measures designed to reduce CO_2 emissions from power generation. These measures will include renewable energy portfolio standards, tax credits and production subsidies for a range of renewable energy supply and conservation technologies, and direct federal support for energy supply and conservation R&D programs. At the present time, nuclear power has generally been excluded from these programs and this undermines its ability to compete fairly to provide carbon-free electricity.

Our first principle is that all external costs associated with each electricity generating technology should be included in the price of electricity. For carbon emissions this means that all options for reducing carbon emissions should be treated equally. We should seek to lower carbon emissions at the lowest overall social cost and not adopt arbitrary rules for which technologies are 'in' and which technologies are 'out' of consideration for achieving lower emissions. The energy bill almost passed by Congress in the fall of 2002 contained a renewable energy portfolio standard mandating the use of specified percentages of renewable energy technologies by all retail electricity suppliers. Several states have already adopted similar renewable energy portfolio standards. The existing and proposed portfolio standards do not include incremental nuclear power as an alternative qualifying supply technology. *We recommend that incremental nuclear power be eligible for all "carbon free" federal portfolio standards programs.* Specifically, if tax or production credits are extended to a renewable technology, such as wind, photovoltaics, hydropower, and geothermal because they do not produce CO_2 in conjunction with the production of electricity, then incremental nuclear energy should be included.

It follows that the external costs unique to nuclear energy – notably waste disposal, safety, and proliferation resistance – should also be internalized in the cost and price of nuclear energy. The already established federally mandated nuclear waste disposal fee for nuclear power is a proper step in this direction, as are the costs of security needed to meet Nuclear Regulatory Commission requirements.

Our principal justification for federal action is avoiding the external cost of CO_2 emission. We also see merit in other arguments for federal intervention, but we are mindful of the need to craft measures that least distort private market forces, do not offer perverse incentives to industry, and conserve taxpayer dollars. For example, we are impressed by the widespread perception that uncertain regulation – affecting both licensing and siting of nuclear plants – is a major barrier to investment. There are two effects: a direct effect of lengthening project construction time due to the unpredictable time required to obtain regulatory approval, and the indirect effect of concern about the possibility of the retroactive application of a regulatory standard after a project has been launched. Regulation always creates uncertainty for investors. But the first to pass through the regulatory process will establish "learning by doing." First movers will effectively develop a set of new regulatory procedures that will then be applicable to follow-on applicants. Thus, the first movers incur costs but create benefits for others that they cannot (necessarily) capture.

The federal government cannot remove all the regulatory uncertainty, and indeed, other major energy facilities e.g. coal plants, electrical transmission lines, LNG terminals, face similar regulatory uncertainty. But, the government should take action to reduce this regulatory uncertainty as much as possible, without introducing perverse incentives for nuclear power and other energy facilities.

GOVERNMENT ACTIONS

We recommend three government actions. First, the government can review existing federal regulations to assure that the procedures in place, primarily at the NRC, but at other regulatory agencies as well (EPA and DOT), strike the correct balance between protecting the public interest and encouraging commerce. The Nuclear Regulatory certification of generic nuclear plant designs and adoption of a procedure for granting combined construction and operating licenses (COL) is a step in the right direction. *We believe that consideration should be given to the federal government paying a portion of the administrative costs for:*

1. *site banking for an envelope of plants*, i.e. obtaining approval for sites that might be used for construction of new plants. (In many cases the site for prospective new units will be at the location of existing plants);
2. *certifying a new plant design by the NRC.* Currently the Westinghouse AP600 and the GE System 80 advanced boiling water reactors are certified. Limited government financial assistance for certification of the Westinghouse AP1000, an HTGR design, and the Heavy Water Reactor (HWR) designed by the Atomic Energy of Canada (AECL) would

add valuable options to those considering relatively near term deployment of nuclear plants;

3. *sharing in the costs of applying for a COL license at the NRC*, in circumstances when the license would be used or banked.

The size of government subvention in each instance could be less than $20 million and 10-15 projects over a number of years would go a long way to reducing some of the outstanding uncertainty with regard to early deployment of nuclear power in the United States.

The next stage of government involvement might be sharing of some of the costs of one or more commercial demonstration projects. We distinguish between two types of "demonstration" projects. The first, and most common, type is the government sharing the costs of demonstrating a new technology in terms of its technical performance, environmental impacts, and cost. Examples include past DOE efforts to demonstrate synthetic fuel technologies, to encourage liquid metal fast breeder reactors, advanced photovoltaic and large wind energy systems. Candidate nuclear technology demonstration projects of this type might be demonstrating pyroprocessing technology or developing a modular High Temperature Gas Cooled reactor. For nuclear power, each technology demonstration of this type is likely to cost in excess of $1 billion. *We do not recommend that the government undertake any such large scale demonstration project of this type at the present time*. Such projects might be justified in the future, when it becomes clear that there is a need and economic basis for moving to alternative systems or, eventually, to a closed fuel cycle.

The second type of "demonstration" project is a first nuclear project carried out by industry, whose success would demonstrate to other private generators that the risks associated with nuclear power are manageable and the cost of new nuclear power is acceptable. Evidently, this type of demonstration is credible only if the government is *not* involved in design and construction or involved in an indirect manner. Otherwise the project has no "demonstration" value to practical investors considering future investments. The purpose of this demonstration is not to demonstrate a new technology but rather to demonstrate the cost of practical realization of a technology selected by private investors.

But a first project bears a risk that subsequent projects do not bear. Investors in subsequent projects have the knowledge that the first of a kind project has been successful (in which case they proceed with greater confidence) or that it has failed (in which case they do not proceed).[3] Yet, if the plant successfully meets its cost targets, a large number of additional plants will be built by the industry, taking advantage of the resolution of risk accomplished by the first project were it to proceed.

The initial project backers cannot capture the value of the information they provide to subsequent projects. Clearly there is a value to going second and a rational reason to share the risk of the first plant among an entire industry. Such sharing of risk is a matter of bargaining and difficult to achieve in practice. So it may well be in the government's interest to step in to assure that the demonstration occurs and the uncertainty is resolved. Given the circumstances of nuclear power today, this government interest in the demonstration of actual cost is justified, even when the technology selected is known and plants have been built in the past (although at a cost that today would be considered unaffordable). There must, of course, be a credible basis for believing that technology and industry practices have changed so that a lower capital cost outcome is a reasonable possibility. If the demonstration project results are to be credible to the private sector, the government's involvement must not be intrusive.

We believe the government should step in and increase the likelihood of practical demonstration of nuclear power by providing financial incentive to first movers.[4] We propose a production tax credit of up to $200 per kWe of the construction cost of up to ten "first mover" plants. This benefit might be paid out at 1.7 cents per kWe-hr, over a year and a half of full-power plant operation, since the annual value of this production credit for a 1000 MWe plant operating at 90% capacity factor is $134 million. The $200 per kWe government subsidy would provide $200 million for a 1000 MWe nuclear plant, about 10% of the historically-based total construction cost estimate; accordingly the total outlay for the program could be up to $2 billion paid out over several years.

We prefer the production tax credit mechanism because it offers the greatest incentives for projects to be completed and because it can be extended to other carbon free electricity technologies, for example renewables (such as wind which 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 come from coal plants, (or $160 from natural gas plants). Of course the carbon emission reduction would continue after the public assistance ended for the plant life (perhaps 60 years for nuclear). Even with this "first mover" incentive, private industry may not choose to proceed with new nuclear plant investment until some carbon free benefit is firmly established. If no new nuclear plant is built, the government will not pay any subsidy and the production tax credit will remain available as an incentive to future investment decisions.

These actions address regulatory and startup-cost issues identified by the nuclear industry as barriers to moving forward with a new generation of commercial nuclear plants. The actions will be effective in stimulating additional investments in nuclear generating capacity only if the industry can live up to its own expectations of being able to reduce considerably overnight capital costs for new plants far below historical experience. With these barriers removed, it is then up to the industry to demonstrate through its own investments in new nuclear power plants, that its cost projections can in fact be realized in practice, and that nuclear power can be competitive with fossil-fuel and renewable energy alternatives.

The government should also continue a vigorous R&D program for nuclear energy. In this section we are focused on the measures the government should take to lower the cost of nuclear power. An R&D effort focused on lowering the capital cost and the O&M cost of nuclear power is also important. But the nuclear R&D effort should also address a range of other matters: proliferation resistance, waste management, and fuel cycle research. The recommended R&D program is addressed in Chapter 12.

PRICE-ANDERSON INSURANCE

Originally enacted in 1957, the Price-Anderson Act establishes a framework defining the terms and conditions of payments to the public for damages caused by a nuclear accident. The Act has been amended several times, with the most recent major changes reflected in the 1988 amendments.[5] The act covers nuclear power plants, other nuclear facilities, and DOE contractors working on nuclear energy projects. The Act does not provide payments for the costs of any damages to a nuclear facility caused by an accident. We focus here on the provisions for nuclear power plants.

The Act requires that nuclear power plant licensees must purchase the maximum amount of commercial liability insurance available in the private market at a reasonable price. This is currently $200 million per plant. In addition, all nuclear power plant licensees must participate in what is effectively a joint-insurance pool. In the case of a nuclear accident whose costs exceed the first layer of private insurance coverage, each nuclear plant is obligated to make payments of up to $88 million[6] to cover any additional costs up to about $9.3 billion at the present time. The compensation provision of both the first and the second layers of insurance are "no fault" and not subject to civil liability litigation. If the cost of a nuclear accident exceeds

$9.5 billion, there are no further financial obligations placed on the nuclear plant owners. Since the Price-Anderson Act went into effect, $202 million has been paid in claims, all of it from the nuclear insurance pools. The largest single claim was $70 million in connection with the Three Mile Island accident.

Perhaps the most controversial aspect of Price Anderson is the current $9.5 billion limit on the civil liability of a licensee where the accident has occurred. Critics argue that this represents a significant subsidy to nuclear power. Estimates vary from about $3.5 million per plant per year to $30 million per plant per year ($2001). Critics of Price- Anderson often cite a 1990 study by economists Jeffrey Dubin and Geoffrey Rothwell that estimated the cost of the subsidy at about $30 million per year per plant or over $3 billion per year for the entire industry.[7] However, these calculations contain several errors that are now widely recognized, except perhaps by those who find it convenient to argue that Price Anderson represents a large subsidy. Heyes and Liston-Heyes show that errors in the original calculation reduce the level of the "subsidy" by a factor of between four and ten.[8] A subsequent paper by Rothwell argues that further corrections would reduce the value of the subsidy by as much as a factor of one million.[9] The correct value of the "subsidy" that would arise from the appropriate application of these methods is very small.

There have been arguments about whether Price-Anderson is or is not a "subsidy" to nuclear power. In some sense it is a subsidy, since it places a current $9.5 billion limit on the private liability payment obligations of nuclear plant licensees. Damages in excess of $9.5 billion would be absorbed by some combination of federal, state and local governments and by the individuals and businesses suffering damages from the accident. However, it is not at all obvious that this is the proper comparison. There is no obligation placed on businesses to carry full insurance against damages caused by an accident. Indeed, full insurance would be quite unusual. While a business would still be liable for damages in excess of its insurance coverage, any corporation effectively has limited liability, since a very large accident could exceed the financial resources of the company, and it would seek protection under the bankruptcy laws. So, for example, the collapse of a dam or the explosion of an oil tanker could cause substantial damages and these damages could exceed both the firm's liability insurance coverage and the value of the equity in the business. U.S. law does **not** require firms generally to carry any liability insurance, and the limited liability corporation places a limit on the damages that any company would pay as a result of an accident.

From this perspective, Price Anderson *requires* nuclear power plant licensees to carry substantial amounts of insurance coverage to provide compensation to the public in the case of a nuclear accident. It creates a second layer of pooled insurance coverage over and above what is available in the private market, and this insurance pool is feasible only because all licensees are required to participate in it. Moreover, the $9.5 billion coverage limit exceeds the equity values of many companies that operate nuclear power plants. Absent Price-Anderson, nuclear plant owners could decide to carry much less insurance and default to bankruptcy protection in the case of a catastrophic accident. In the end, if there were a catastrophic accident, the Price-Anderson framework may very well cost the government and damaged parties less than would be the case without it.

This being said, we would have no objection to assessing a fee to nuclear plants for the expected fair actuarial value of this third layer of insurance coverage. The estimates appear to suggest a cost of no higher than about $3 million per year per plant.

We have suggested five different roles for the federal government in promoting nuclear energy; these are:

1. assuring that nuclear energy is considered on the same basis as other technologies that reduce carbon emissions;
2. taking steps to reduce regulatory uncertainty;
3. providing partial support for industry projects that demonstrates the economic competitiveness of nuclear energy;
4. nuclear technology R&D;
5. reauthorizing Price-Andersen nuclear accident insurance.

This package of government actions is appropriate for nuclear technology in its present circumstances. We stress that our intention is not to advocate support for nuclear power at the expense of the other major alternatives — renewable energy, carbon sequestration, energy efficiency — that also can reduce greenhouse gas emissions. Of course the appropriate package of government incentives for each alternative must be tailored to the particular circumstance of that technology. In order to be confident that at least one option emerges as an attractive economic choice, the federal government should support programs on all these alternatives.

NOTES

1. We modeled this as a carbon tax in Chapter 5 to show how alternative carbon emissions valuations would affect the relative *social value* of nuclear power. However, a variety of other policies (e.g., cap and trade) might be used to internalize the social cost of carbon emissions.
2. A.D. Ellerman, P.L. Joskow, and D.A. Harrison, *Emissions Trading in the United States*, Pew Center for Global Climate Change, May 2003.
3. The large uncertain capital cost of a first plant is a critical barrier to nuclear power. This uncertainty is one aspect of "first mover" costs. A simple example illustrates the justification for government action. Assume that there is a probability p that the first plant will have a $1500/KWe overnight cost and a probability (1-p) that the plant will have an overnight capital cost of $2500/kWe,

   Expected capital cost per kWe = $1500p +$2500(1-p).

   For a realistic probability p, a prospective investor may judge the expected cost of the first plant to be too large to justify proceeding. If the government pays a portion of the difference between the two outcomes , (in this case $1000/kWe), an initial plant will be built and all future investors will have the benefit of knowing the answer — either the plant cost $1500/kWe and many plants will follow, or the plant costs $2500/kWe and no additional plants will be built.
4. It might be argued that with about 350 GWe of nuclear generating capacity world wide that the "first- time" costs are behind us. However, given the long hiatus in construction of new nuclear plants, the retirement of significant infrastructure needed to restart the program, the lack of experience with new licensing regulations, and the planned use of new reactor designs and construction management techniques, it is appropriate to think of a future program as having many of the characteristics of a new program. We have been building (and subsidizing) the construction of wind generating technologies for 25 years and prospects for "moving down the learning curve" still are used to justify continuing subsidies and other valuable preference for wind generation.
5. The provisions of the Act were extended to December 31, 2003 in the consolidated appropriations bill passed by Congress and signed by the President in early 2003. A longer extension is included in the House and Senate energy bills now being considered in Congress.
6. As of 2002. The value of this obligation is indexed to inflation.
7. J.A. Dubin and G.S. Rothwell, "Subsidy to Nuclear Power Through Price-Anderson Liability Limit," *Contemporary Policy Issues,* p 3, 7 (1990).
8. A. Heyes and C. Liston-Heyes, "Subsidy for Nuclear Power Through the Price-Anderson Liability Limit," *Contemporary Economic Policy*, January 1998, pp. 122-124.
9. Geoffrey Rothwell, "Further Comments on Subsidy to Nuclear Power through the Price Anderson Liability Limit," mimeo, August 2001.

Chapter 11 — Recommendations Bearing on Safety, Waste Management, and Proliferation

SAFETY

Our study has not been able to address each aspect of concern as thoroughly as deserved. One example is safety of nuclear operations. Accordingly, we report here views of our group that we believe to be sound but that are not supported by adequate analysis. We have four observations to make about the safety of nuclear operations:

- Public and governmental attention is understandably focused on reactor accidents because of Three Mile Island and Chernoybl. But all aspects of the nuclear fuel cycle present safety risks, as with other major industrial enterprises, and these risks need to be assessed in an objective and quantitative fashion, in order to establish standards for design, construction, and operations.
- There is an important body of informed technical opinion that believes a nuclear reactor technology can be made with negligible possibility of a severe reactor accident. HTGR reactors are often put forward as an example, because of the very large heat capacity of the power plant and the fuel design.
- Reactor safety depends on a strong safety culture involving management and the entire work force.
- The implied level of risk of serious nuclear accidents based on the existing level of worldwide deployment and number of serious accidents (2) that have been experienced is about 1 accident per 10^4 reactor-years of operation. If nuclear power is to expand to the mid-century benchmark of our global growth scenario, and if we assume the public's tolerance for nuclear accidents is unchanged, then the safety level that must be met should progressively improve by about one order of magnitude to 1 accident per 10^5 reactor-years. Advanced light water reactors are believed to achieve this improvement.
- We have given some thought but reached no conclusion about the regulatory regime that provides the best incentive for safe operation of the nuclear enterprise. The U.S. Nuclear Regulatory Commission (NRC) regime is based on prescriptive regulation, accompanied by inspection and enforcement of rules administered by an independent regulatory commission governed by strict procedural rules. Moreover the NRC is asked to address more than issues of safety, for example proliferation and antitrust concerns. This is not the only regulatory model that can be imagined. Indeed, the Environmental Protection Agency and Federal Aviation Administration each present a very different regulatory approach.

  Aside from technical safety considerations, the NRC procedures offer a very important opportunity for public involvement in the decision making process that leads to the decision to operate a nuclear plant. If a different regulatory process is adopted the interveners who seek a voice in the decision will not go away. They will demand, and legitimately so, another avenue to make their views known. So changing the rules for safety decisions should not be used as a device for stifling the legitimate expression of different views about the benefits and costs of nuclear power.

In sum, redesign of the nuclear safety regime must address two separate and important concerns: assuring safety and providing opportunity for public involvement.

We recommend: *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*. We propose $50 million per year for this purpose.

WASTE MANAGEMENT

The management and disposal of high-level radioactive waste continues to be one of the primary obstacles to the development of the nuclear power industry around the world. We concur with the many independent expert reviews that have concluded that the geologic disposal approach is capable of safely isolating the waste from the biosphere for as long as it poses significant risks. Successful implementation of this approach has yet to be demonstrated, however. Within the next 10-20 years, it is likely that one or two full-scale high-level waste repositories will be commissioned in the United States and elsewhere. Public opposition will continue to be a major obstacle to repository siting in many countries, however, and progress towards establishing operating repositories will be slow.

For fifteen years, the scientific and technical focus of the U.S. high-level waste management program has been directed almost exclusively on the investigation and development of the Yucca Mountain site. The focus on Yucca Mountain will continue as design and licensing activities gain momentum over the next few years. The successful commissioning and operation of Yucca Mountain would be a significant step towards the secure disposal of nuclear waste. However, a broader focus for the U.S. nuclear waste program is needed to provide a foundation for a possible expansion of the nuclear power industry in the U.S. and overseas.

Our assessment of advanced technical strategies for waste management and disposal in Chapter 7 led to the following key conclusions:

- Replacing the current ad hoc approach to spent fuel storage with an explicit strategy to store spent fuel for a period of several decades, prior to reprocessing and/or geologic disposal, will create additional flexibility and robustness in the waste management system and, if organized internationally, can also provide significant non-proliferation benefits.
- We do not believe that a convincing case can be made, on the basis of waste management considerations alone, that advanced fuel cycle schemes featuring waste partitioning and transmutation will yield long-term benefits that outweigh the attendant short term risks and costs.

  We recognize that future technology developments could change the balance of costs, risks, and benefits. But for our basic conclusion to change, 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.
- Technical modifications to waste management strategies in the once-through fuel cycle are potentially available that could yield benefits at least as great as those claimed for advanced fuel cycles featuring waste partitioning and transmutation, and with fewer short-term risks and lower costs of development and deployment.

In light of these conclusions, we believe that the following actions would both benefit current waste management efforts and help to lay the foundation for a possible future expansion of the nuclear power industry. *First, the U.S.*

Department of Energy should augment its current focus on Yucca Mountain with a balanced, long-term waste management R&D program. The broad goals of this program should be to investigate and develop waste management and disposal technologies that would offer improved short and/or long term performance. The program should encompass a balanced portfolio of technologies, including both incremental improvements to the current mainstream approach and more far-reaching innovations. *The program should include the characterization and investigation of alternative engineered barriers and geochemical and hydrological environments for waste repositories, as well as alternatives to the repository concept itself.*

Among alternatives to mined repositories, the deep borehole disposal approach has the potential to reduce significantly the already low risk of long-term radiation exposure and merits a significant research and development program, with the goal of determining operational, safety, and regulatory viability within a decade. This program should investigate methods for detailed site characterization at depth, mechanisms for possible radionuclide transport to the surface, alternative approaches to monitoring and retrieval of emplaced material, plugging and sealing techniques, site suitability criteria, and overall system optimization. Parallel investigations by regulatory and standard-setting bodies should also be undertaken.

The DOE high-level waste R&D program should be separated organizationally from waste management operations. A clear organizational separation will be necessary to resist pressures to narrow the scope of the R&D program. A stable source of funding will also be essential to the success of the R&D program.

The tenth of a cent per kilowatt hour waste management fee should be re-evaluated with a view to creating economic incentives for waste generators and others to develop and implement technologies that would reduce the risks and/or costs of waste disposal while ensuring the financial viability of the overall waste management program.

A period of many decades of interim spent fuel storage should be incorporated into the design of the waste management system as an integral part of the system architecture. A network of centralized facilities for storing spent fuel for several decades should be established in the U.S. and internationally.

The U.S. should actively pursue closer international coordination of standards and regulations for waste transportation, storage and disposal.

PROLIFERATION

The nonproliferation concerns associated with the global growth scenario discussed in Chapter 8 call for an international response that:

- strengthens the institutional underpinnings of the safeguards regime now, preparatory to a period of expanded nuclear power deployment; and
- guides nuclear fuel cycle development in ways that reinforce shared nonproliferation objectives.

Strengthening international norms for fuel cycle fissile material security and facility monitoring

The IAEA, functioning under the United Nations, is the key organization for implementing the international safeguards regime among NPT signatories. It also has the role of promoter of peaceful uses of atomic energy. The IAEA has built a foundation of bilateral safeguards agreements that, in effect, codify a compromise between national sovereignty, with respect to fuel cycle facility reporting and inspection, in the interests of an international regime that diminishes the threat of nuclear proliferation and provides access to civilian nuclear technology. Several steps to strengthen this regime should be pursued promptly:

1. *The IAEA should focus overwhelmingly on safety and safeguards,* for which it is uniquely positioned by reason of its bilateral agreements and U.N. affiliation. This is consistent with the spirit of separating regulatory/security functions and nuclear power development, as has been done in the United States and many other countries. The process already initiated for strengthening physical protection standards needs to be accelerated.

   Inspection resources should be allocated by a risk-based approach and in turn, the industrialized nations should increase their financial support for the safeguards function.

   The U.N. Security Council should develop guidelines for multilateral sanctions in the event of serious violations of safeguards agreements.

2. *The IAEA needs the authority to carry out inspections beyond declared facilities,* spurred by information developed by or reported to the agency. The restriction of inspections to declared facilities will undermine confidence in the global growth scenario. Thus, the Additional Protocol of the IAEA needs to be implemented uniformly across non-weapons states.

3. *Greater attention should be placed on the proliferation risks of the front end of the fuel cycle.* While we have emphasized the back end of the fuel cycle as a potential source of weapons-usable plutonium, the front end also deserves attention, especially in the context of undeclared facilities. Clandestine uranium enrichment programs, as have appeared in Iraq, Iran, North Korea and elsewhere, may present a dramatically increasing threat. Uneconomic technologies may in some cases be utilized for "batch scale" enrichment sufficient to produce HEU for a small number of nuclear weapons.

   For commercial scale enrichment, the economic choice today lies with centrifuges. Centrifuge design information was not adequately controlled in the past, so further diffusion of the technology requires tracking and transfer constraints on the specialized materials and components used to build centrifuges. This has proved to be difficult. There are also nonproliferation risks associated with both older technologies (gaseous diffusion, electromagnetic separators) that have been used on a significant scale and newer technologies (laser separation, chemical exchange) that have not yet gone beyond bench/prototype scale. Some of these technologies have very small "footprints" for tracking, detection, and control and may rely on many increasingly ubiquitous dual-use technologies.

   A concerted effort should be devoted to ongoing evaluation of isotope separation technologies, development of associated control mechanisms, and appropriate information sharing with the IAEA. Specifically the U.S. and other industrialized nations should strengthen intelligence collection and dual-use export control regimes with respect to isotope separation technology.

4. The IAEA safeguards framework should move from an approach based on accounting/reporting and periodic inspection to an approach based on continuous surveillance/-containment/security. This is crucial for PUREX/MOX fuel cycle facilities. For example, the Rokkasho PUREX plant nearing completion in Japan will process 800 tonnes of material annually, separating plutonium in amounts where accounting uncertainties will easily exceed a significant quantity (8 kg). An effective safeguard system should be integrated in the plant and process design, with a "real time" measurement/communications system. This system should be benchmarked by use of modeling/simulation for the process flows. Such a safeguards paradigm goes well beyond that currently followed by the agency, including the requirement for extensive information sharing.

   Additional important measures needed to safeguard the fuel cycle are highlighted by the PUREX/MOX case. Secure transportation of separated plutonium from separations to fuel fabrication plants is a concern to all nations, irrespective of the transportation route. A design basis threat, appropriate to the increasing capabilities of terrorist or criminal organizations with international reach, needs to be adopted and reliably implemented (this is currently only recommended by the IAEA). A broader set of IAEA standards for physical protection, associated with appropriate inspections, should be institutionalized and become part of an enforcement mandate.

Facilities should be co-located to eliminate vulnerable transportation links and to reduce separated plutonium inventories to the minimum needed for fuel cycle operation. The accumulated Pu inventory of 200 tonnes should be recognized as an important shortcoming of current fuel cycle operation, and reduction to minimum working inventories should be a near term priority, including for the weapons states.

Internationally supervised, integrated fuel cycle facilities are amenable to implementation of continuous surveillance/containment/security and should be encouraged where appropriate. In the near term, creation of international spent fuel storage facilities should be pursued, with no reprocessing allowed, at least until final disposition is resolved. For the longer term, internationally monitored fuel cycle centers could be the locus for advanced actinide recycling, should it prove attractive.

Fuel cycle analysis, research, development, and demonstration (ARD&D) must characterize and explore measures to minimize proliferation risks

Our global growth scenario envisions an open fuel cycle architecture at least until mid-century, with the advanced closed fuel cycles possibly deployed later and then only if significant improvements can be demonstrated. The principal driver for this conclusion is the clear economic advantage of the open fuel cycle, with proliferation resistance an important additional feature.

The PUREX/MOX fuel cycle remains a particularly poor choice since it costs more, produces weapons-usable separated plutonium in normal operations, and has unimpressive benefits with respect to uranium resource extension (for at least fifty years) and waste management. Nevertheless, several countries have made a substantial commitment to this fuel cycle over the past quarter century. Accordingly, advanced fuel cycle development will continue to be of interest to a number of countries and a subject of discussion for international collaboration.

The ARD&D program advanced later in Chapter 12 takes into account the need to reduce proliferation risks at every stage of the growth and evolution of nuclear power around the world. International analysis and research on advanced fuel cycles should focus only on technology pathways that do not produce weapons usable material during operation (for example, by leaving some uranium, fission products and/or minor actinides with the recycled plutonium, which in turn can achieve very high burnup to degrade the plutonium isotopics).

There are advanced fuel cycle combinations of reactor, fuel form, and separations technology that satisfy these conditions and, with appropriate stringent institutional arrangements, can have significantly better proliferation resistance than the PUREX/MOX fuel cycle – and perhaps approaching that of the open fuel cycle. In that light, the PUREX/MOX fuel cycle should be recognized as not being on the technology pathway to such advanced fuel cycles, and thus not a focus for further development or deployment.

The United States is engaged in the still relatively early stages of an international collaboration, called the Generation IV Forum, mapping out an R&D agenda for advanced reactors and perhaps, eventually, fuel cycles. The nuclear nonproliferation offices in the Department of Energy, Department of State, and National Security Council should play a much more active role along with the DOE Office of Nuclear Energy, Science, and Technology in guiding U.S. participation and leadership in Generation IV and especially in an international advanced fuel cycle initiative. We stress that such collaborative R&D can inadvertently facilitate proliferation through transfer of know-how and requirements for new nuclear infrastructure.

The recommendations put forward on nonproliferation represent a considerable change in the way of "doing business" under the NPT regime. The underlying basis of the NPT/Atoms for Peace framework and treaty structure is to permit all countries to have access to nuclear electricity production benefits and to support nuclear technologies, while implementing IAEA safeguards agreements to avoid the proliferation risk of supporting fuel cycle facilities (both enrichment and reprocessing) that can produce weapons-usable material. Commercial nuclear reactors are not intrinsically a proliferation risk.

We suggest a new approach that retains this framework and is based on technical assessment of risk, but politically non-discriminatory. This approach centers on classifying states as "privileged" of nuclear reactors or as "fuel cycle states." Declared "privileged states" would operate nuclear reactors according to their internal economic decisions about nuclear power versus alternatives, with international support for reactor construction, operational training and technical assistance, lifetime fresh fuel, and removal of spent fuel. Privileged states would not be eligible for fuel cycle assistance (enrichment, fuel fabrication, reprocessing). Thus "privileged" states would be low risk for proliferation and would gain several benefits: absence of intrusive safeguards and inspections, relief from expensive fuel cycle infrastructure development costs, and in particular elimination of nuclear spent fuel/waste management challenges. This approach is feasible under our global growth scenario — for example, in the balanced fast reactor/closed fuel cycle analyzed in Chapter 4, 55% of the reactors are once-through thermal reactors suitable for deployment in "privileged" states with their spent fuel sent to "fuel cycle" states for separation and transmutation.

On the other hand, the "fuel cycle states" would be subject to a new level of safeguards and security requirements, along the line of those recommended above. Both groups of states would be subject to the Additional Protocol with respect to undeclared facilities. Such an arrangement is a technology- and risk-based approach in the spirit of Article IV of the NPT, offering considerable benefits for those who restrict their nuclear activities while benefiting from nuclear power[1]. In addition, a stringent sanctions regime under the United Nations Security Council would be put in place for violations of the nonproliferation regime, and more stringent restrictions placed on those who choose to be outside the framework.

Clearly this new risk based approach is one that would take many years to formulate in detail and negotiate. Its very difficulty — an enhanced safeguards regime, international spent fuel management, stringent sanctions — highlights its importance for the global growth scenario. The new approach is most easily advanced while the once-through fuel cycle dominates and before nuclear power experiences dramatic growth in capacity and in geographical distribution.

A strengthened nonproliferation regime is a necessary condition for responsibly expanding nuclear power globally on a significant scale. *We recommend the U.S. government actively pursue the technical risk based approach to strengthening the non-proliferation regime outlined above.*

NOTE

1. Many of these elements (fresh fuel supply, spent fuel return, reactor construction assistance, Additional Protocol) have been discussed intensively over several years between the United States and Russia as a means of resolving differences with respect to Russian-Iran nuclear cooperation.

Chapter 12 — Recommended Analysis, Research, Development, and Demonstration (ARD&D) Program

The government R&D program should support technology required for the global growth scenario. The R&D activity should include diverse activities that balance risk of failure to achieve desired technical advances and the time that such technical advances are needed. Accordingly, *the highest priority in fuel cycle ARD&D, deserving first call on available funds, lies with efforts that enable, for both technical and public acceptance reasons, robust deployment of the open, once-through fuel cycle.*

We give priority to two tasks that are not presently part of the DOE program:

First, we call for a global uranium resource evaluation program to include geological exploration studies to determine with greater confidence the uranium resource base around the world. Our global growth scenario and technology plan are based on the judgment that natural uranium ore is available at reasonable prices to support the open cycle at least until late in the century. We propose $50 million per year for this purpose.

Second, we have been struck throughout our study about the absence of models and simulation that permit quantitative trade-off analysis between different reactor and fuel cycle choices. The analysis we have seen is based on point designs and does not incorporate information about the cost and performance of real nuclear facility operations. Such modeling and analysis, under a wide variety of scenarios, will be useful to the industry and investors, and to international discussions that take place about the desirability of different fuel cycle paths. 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. Changes in one feature of a design for the sake of, say, safety may affect other aspects of the design, the overall performance of the system, and the cost of operation. U.S. industries, for example, the chemical processing and commercial aircraft industries, have developed complex analytical models based on extensive engineering and economic information for the purpose of evaluation of alternative courses of action. The DOE nuclear R&D program seems focused on providing information about the operation of a single process, set up in one way. While this program produces knowledge, it does not allow for transferring information to new, related situations and thus provides no 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 resistant characteristics.

We call on DOE, perhaps in collaboration with other countries, to establish *a major project for the modeling, analysis, and simulation of commercial nuclear energy systems.* Evidently, the models and analysis should be based on real engineering data, wherever possible, and practical experience. The project should support assessment of reactor concepts and fuel cycles, and acquisition of engineering data on principal technology questions associated with the design of these concepts. This project is technically demanding and will require many years and considerable resources to carry out successfully. To have coherence, the project should have a single program plan and several performers who bring differing ideas and experience to the effort. The project should *not* be given to a single DOE lab or divided into equal shares for all interested DOE labs. We propose $100 million per year for ten years for this purpose.

We believe that development of advanced nuclear technologies — either advanced reactors[1] or advanced fuel cycles[2] — should await the results of the *Nuclear System Modeling Project* we have proposed, (with the exception of advanced design LWRs or R&D on the HTGR, as discussed below). Our analysis makes clear that there is ample time to compile the necessary engineering and economic analysis before undertaking expensive development programs, even if the project should take a decade to complete. A *development and demonstration* program on advanced fuel cycles and advanced reactors is simply not justified on the basis of cost, the unproven safety and waste properties of a closed cycle compared to the open cycle, and proliferation risk. Since deployment of the advanced alternatives is quite far off, efforts should focus on analysis and basic research only, as opposed to development and demonstration, for a considerable period. Costly development projects too far in advance of any credible deployment opportunity can be counterproductive both for optimizing the technology and for supporting the global growth scenario.

On the other hand, we support modest laboratory scale research and analysis on *new* separation methods with the objective to learn about separation methods that are less costly and more proliferation resistant. There has been little exploration in the United States of alternatives to PUREX and pyro-processing since their invention decades ago with entirely different purposes in mind: obtaining weapons usable material and reprocessing metal fuel, respectively. We note however that there is considerable skepticism for even this modest approach, because some see *any* U.S. work on reprocessing sending the wrong signal to other nations about the credibility of our expressed attitude toward the proliferation risks of reprocessing, and the concern that DOE will move from analysis and research to development before the technical basis for such action has been developed. We propose that this program begin at a modest scale, reaching $10 million per year in about five years.

The project's research and analysis effort should stress low cost, safety, and technology pathways that do not produce weapons usable material during operation (for example, by leaving some uranium, fission products and/or minor actinides with the recycled plutonium, which in turn can achieve very high burnup). There are advanced closed fuel cycle concepts[3] of combinations of reactor, fuel form, and separations technology that satisfy these conditions and, with appropriate institutional arrangements, can have proliferation resistance approaching that of the open fuel cycle.

Third, the DOE should, in parallel with the Nuclear System Modeling Project, support R&D on advanced design LWRs and on development of the HTGR that will operate in the open fuel cycle. LWRs will be the main reactor type in a mid-century scenario. The DOE should focus LWR R&D efforts on reducing the capital and operating costs of these reactors, moving to higher burnup fuel, and assuring achievement of improved safety standards. We believe that this program should begin at level of $50 million per year.

The HTGR has certain potential unique safety characteristics and, because of its high efficiency compared to LWRs, the HTGR will use less uranium resource and produce less fission products and actinides than other thermal reactors that produce the same amount of electricity. In addition, the HTGR may have some proliferation resistance advantage, because of the greater difficulty of processing its pellet fuel, although this is, as yet, unproven. The modular nature of the HTGR, with plants designed in the 110 to 300 MWe range, can be a significant advantage for deployment, especially in developing countries using the once-through fuel cycle. However, past operating experience with HTGR plants, at Peachbottom, at Fort St. Vrain, and in Germany is mixed and there is no reliable basis on which to estimate the economics of HTGR plants relative to LWR plants.

We believe the potential advantages of the HTGR justify DOE's support for research and limited development activity, for example measurement and characterization of fuel form behavior and confirmation of performance characteristics of gas power conversion components and suggest a R&D program for this purpose at a level of $30 million per year. The focus should be on moving to the stage where the HTGR can be demonstrated as a potential major contributor for electricity production in the global growth scenario. History suggests a demonstration plant built by the DOE on a DOE facility will not serve to establish the cost of electricity with credibility for investors. Instead, "first mover" assistance to the private sector would be more effective, if further R&D indicates that the HTGR is attractive for electricity production. Establishing the cost of building and operating an HTGR for electricity production is an important milestone for gauging its competitiveness for any application.

The DOE is considering the very high temperature gas reactor (VHTGR) for the purpose of hydrogen production by thermal cracking of water. Moving to very high temperatures will open up the need for still more R&D. With respect to hydrogen production, a major uncertainty lies with the chemical process of thermal cracking of water on an industrial scale and not with the production of high temperature steam, whether from a VHTGR, or any other source.

The *fourth area* that calls for a significant and redirected ARD&D program is waste management. We have emphasized that the DOE waste program has been singularly focused for the past several years on the Yucca Mountain project. As a result much analysis and R&D needed to enable the mid- century scenario has not been undertaken. As discussed in Chapter 11, DOE must broaden its waste R&D effort, or it runs the risk of being unable to rigorously defend its choices for waste disposal sites. Several important programs are required. Characterization of waste forms and engineered barriers, followed by development and testing of engineered barrier systems, is needed. We believe deep boreholes, as an alternative to mined repositories should be aggressively pursued. Reliance on central spent fuel storage facilities will require engineering and development activities on casks, facility design, and transportation.

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 world wide materials protection, control, and accounting tracking system. Cooperation on fuel cycle research will be more sensitive because, as we have stressed, the PUREX/MOX fuel cycle that is currently being pursued in France, Russia, and Japan is *not*, in our view, on the technology pathway to any future desirable closed fuel cycle. Thus, this international collaboration calls for a new international organization for the collaborative research, one that develops and enforces strict guidelines for participation. There currently is no suitable international organization for this task. A possible approach lies with the G-8 as a guiding body. The G-8 has already formed an umbrella structure for dealing with nuclear materials security — the G-8 Global Partnership Against the Spread of Weapons and Materials of Mass Destruction created at the 2002 summit in Canada.

The recommended program is summarized in Table 12.1 with a suggested budget for each category.

Table 12.1 Recommended Federal Analysis, Research, Development, and Demonstration Program (ARD&D) by Priority

RECOMMENDATION #	ECONOMICS	PROLIFERATION	WASTE MANAGEMENT	SAFETY	RESOURCE BASE	NEXT 5 YEARS	5 TO 10 YEARS	LONGER TERM — MAYBE BEYOND 10 YEARS	INCREMENTAL ANNUAL BUDGET $ MILLIONS 0–5 YEARS/5–10 YEARS
	R & D TIME PERIOD								
1	■				■	Global U ore resource assessment		Unconventional U recovery	50/0
2*	■	■	■	■	■	Fuel cycle modeling, simulation and analysis project	Fuel cycle modeling, simulation and analysis project		100/100
3*			■			Engineered barrier/waste form characterization	Engineered barrier development		50/100
4			■			Deep borehole disposal			50/?
5*		■	■				Central spent fuel/ high level waste storage		10/50
6	■	■				Lower once-through reactor capital cost	Thermal reactor high burn up fuel	Rarely refueld reactor	50/100
7		■		■			HTGR reactor development ❖		30/30
8				■		Analysis of LWR and fuel cycle safety	Reduce safety risk of LWR and fuel cycle		50/50
9			■				New separations analysis and research ❖	Revisit need for fuel cycle pilot plants †	10/40
10			■		■			Revisit need for fast reactor development †	—
11*		■				World wide M,P,C,&A tracking system	Containment, surveillance, and security systems		50/50

* Designates special international significance

❖ Could start in earlier period

† Development project starts await outcome of fuel cycle modeling project

NOTES

1. The study of Generation IV reactor concepts would, of course, be part of the assessment project we propose. Government support for reactor development, however, should not be contemplated until after conclusion of the project.

2. The DOE's Advanced Fuel Cycle Initiative calls for the development today of two pilot separation facilities, UREX (a PUREX derivative) and PYROX (an electrometallurgical method), of about 20MTHM/yr capacity in order to make a decision by the year 2007 on a 2000 MTHM/yr plant that would initially operate in 2015. We disagree with the assumptions on which this program is based, in particular that a separation and transmutation approach is needed before Yucca Mountain runs out of its nominal capacity for waste disposal, and that the advanced fuel cycle path will be politically more acceptable, despite its much higher cost, unproved safety and waste properties, and appreciable proliferation risks.

3. There are many reactor concepts. With clear criteria regarding cost, waste, safety, and proliferation resistance, promising concepts are sure to emerge. We mention only two: extremely high burn-up LWRs that can perform a good deal of transmutation in the core, and breed and burn fast reactors that never reprocess.