LA-UR- 99-517

Approved for public release; distribution is unlimited.

Title: An Architecture for Nuclear Energy in the 21st Century

Author(s): Edward D. Arthur
Paul T. Cunningham
Richard L. Wagner, Jr.

RECEIVED
AUG 19 1999
OSTI

Submitted to: The 1999 JNC International Forum on the Peaceful Use of Nuclear Energy - The Nuclear Fuel Cycle and Nuclear Non-Proliferation Technology

Los Alamos
NATIONAL LABORATORY

Los Alamos National Laboratory, an affirmative action/equal opportunity employer, is operated by the University of California for the U.S. Department of Energy under contract W-7405-ENG-36. By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes. Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy. Los Alamos National Laboratory strongly supports academic freedom and a researcher's right to publish; as an institution, however, the Laboratory does not endorse the viewpoint of a publication or guarantee its technical correctness.

Form 836 (10/96)

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, make any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

AN ARCHITECTURE FOR NUCLEAR ENERGY IN THE 21ST CENTURY

Edward D. Arthur, Paul T. Cunningham, and Richard L. Wagner, Jr.
Los Alamos National Laboratory, Los Alamos, USA

ABSTRACT

Global and regional scenarios for future energy demand have been assessed from the perspectives of nuclear materials management. From these we propose creation of a nuclear fuel cycle architecture which maximizes inherent protection of plutonium and other nuclear materials. The concept also provides technical and institutional flexibility for transition into other fuel cycle systems, particularly those involving breeder reactors. The system, its implementation timeline, and overall impact are described in the paper.

Nuclear power generates a significant portion of the electricity consumed in the United States and other major industrial nations. Its future is a matter of debate. Its use could expand to help meet the energy needs of developing economies, it could be needed more under fossil energy use constraints imposed by future environmental needs, or if fossil fuel supplies are threatened. These prospects are clouded, however, by problems inherent in some of the current technologies and practices of nuclear power, and by public perception of its risks. One confluence of those problems and perceptions is in what to do with the fuel discharged from nuclear power reactors — the "back end" of the nuclear fuel cycle. Discharged fuel is highly radioactive and contains plutonium, which has energy value but is a key material used in nuclear weapons.

In the on-going debate of nuclear energy's future, proponents and critics both appear to assume that its technologies, practices, and institutions will continue over the long term to look much as they do today. In contrast, we propose a nuclear fuel-cycle architecture that consumes plutonium in a "once-through" process. Use of this architecture could extract much of the energy-value of the plutonium in discharged fuel, reduce proliferation risks of the nuclear power fuel cycle, and substantially ease final disposition of residual radioactive waste.

Today: Increasing Global Inventories of Discharged Fuel and Plutonium

Operation of the world's four-hundred-plus power reactors creates a discharged product containing plutonium, other actinide isotopes, and highly radioactive fission products. Early in the nuclear era, recovering the substantial energy value remaining in the discharged fuel seemed essential to the economics of the technology. It was widely assumed that this "closed cycle" would be implemented essentially everywhere. This approach to resource conservation was based on conservative assumptions about the long-term availability and cost of uranium fuel and on optimistic assumptions about the growth of electricity demand and nuclear power production.

In 1977, the United States abandoned planning for the closed cycle out of concern that, if it were widely implemented internationally, the plutonium separated could be diverted for use in nuclear weapons, and because the demand for nuclear energy, at least in the U.S., did not seem to require reprocessing plutonium for a very long time. The U. S. adopted instead a "once-through" approach: discharged fuel, including plutonium, and uranium would be directly and permanently isolated in geologic repositories and its energy value abandoned. In adopting this "open cycle" approach for its domestic nuclear fuel cycle, the U. S. urged others to do the same. Sweden and a few other nations later did so, but a majority of countries continue to plan to reprocess discharged fuel or to retain the option to do so.

As practice has actually developed, open and closed fuel cycles both lead to increasing inventories of plutonium. Most discharged fuel has simply accumulated, often at reactor sites; it has not been reprocessed to recover plutonium or placed in geologic isolation. This accumulation has occurred in the U. S. because development of a permanent geologic repository has been long delayed. Nations that have planned to recycle plutonium have also accumulated discharged fuel because the relatively low cost of new, low-enriched uranium fuel has justified its continued use, although some plutonium has been separated. A portion of that plutonium has been fabricated into mixed oxide (MOX) fuel, principally for use in light-water power reactors. The number of times MOX fuel can be recycled in standard reactors is limited by physics constraints and possibly by the cost of multiple reprocessing. Ultimately it is assumed that breeder reactors would be used to extract all energy remaining in discharged fuel, plus produce other energy from plutonium breeding. However several recent studies[1,2] (results from Ref. 1 are described in more detail in the next section) using relatively robust scenarios of future nuclear-energy demand indicate that significant breeder implementation will not occur *globally* until well past the middle of the twenty-first century).

Thus, discharged fuel and its plutonium will probably continue to accumulate. The inventory of plutonium in discharged fuel worldwide presently amounts to about 1000 tonnes. By 2030, based on recent analyses[1] of global energy demand which show growth in nuclear-energy generation, particularly in industrializing countries, that volume will increase to about 5000 tonnes. If nuclear-energy generation remains at present levels, the accumulation by 2030 will total about 3000 tonnes.

Plutonium and proliferation from commercial nuclear power elicit widely disparate views. Plutonium in a reactor or present in freshly discharged fuel is guarded by the intense radiation field that the fission products mixed with it produce. This "radiation barrier" increases the difficulty of diverting plutonium for use in weapon[3]. Plutonium separated from spent fuel by reprocessing, and thus not protected by a radiation barrier, could be an easier target theft or diversion. Many experts believe that current International Atomic Energy Agency (IAEA) safeguards are sufficient to prevent theft or diversion of separated plutonium, or that extensions of them, coupled with stronger security measures, could make them so. Others believe that, despite safeguards, the inherent risks of theft or diversion of separated plutonium are too great to rely on safeguards, especially if plutonium were made more easily accessible through widespread commerce. Some believe, further, that open-cycle geologic repositories, accumulating large quantities of discharged fuel, could eventually become plutonium mines as the radiation barrier protecting the fuel matrix weakened over time.

Nuclear Scenarios

Assessments of the nuclear fuel cycle are tied to differing assumptions of future world security environments and their associated proliferation risks, and to scenarios for nuclear energy demand both globally and regionally. Although prediction of the future is impossible, *scenarios* can be developed using forecasting models built around assumptions of a "surprise-free future". Work at Los Alamos National Laboratory has produced a number of energy and nuclear energy demand scenarios through use of the Edmonds, Reilly, Barnes supply-demand equilibrium[1] economic

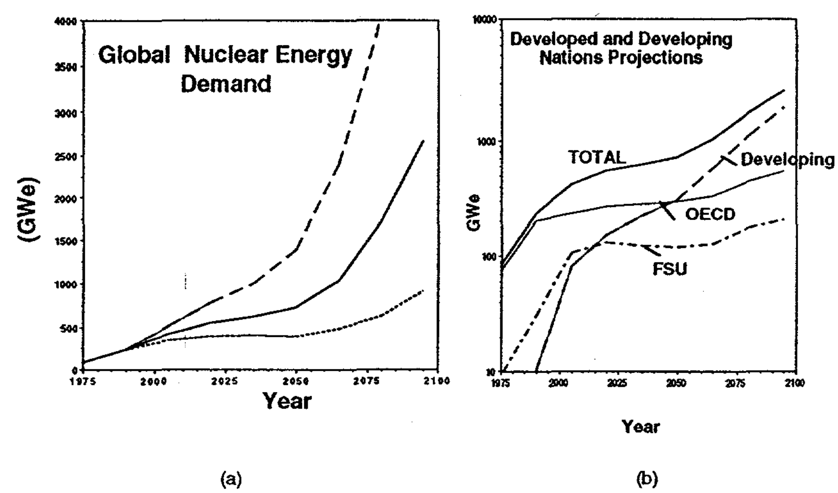

Figure 1 - Nuclear energy demand scenarios determined from analyses using the Edmonds, Reilly, Barnes model. (a) Total nuclear demand scenarios. (b) For a "business as usual" demand scenario, a breakout into developed, developing, and FSU country types.

model. A range of possible scenarios can be constructed using such a model that indicates expected demand sensitivities to input assumptions based upon population growth, productivity, energy efficiency, resource availability, and other constraints such as those associated with negative environmental impact mitigation. Results from Los Alamos analyses are shown in Figure 1. In Fig 1-a, an indication of nuclear energy demand scenarios and the resulting range of global demand is indicated. In Fig 1-b, scenarios for future nuclear energy demand are shown broken out in terms of developed country (OECD), developing countries, and former Soviet Union (FSU) trends.

Conclusions from Los Alamos analyses are

1) No general, global phase out of nuclear energy. This result arises from general overall energy demand growth projected for the 21st century, and the role of nuclear energy as one part of a mix of energy sources needed to meet future demand.

2) A shift from nuclear growth from developed to developing countries, a result that mirrors that occurring in total energy demand.
3) As indicated previously, no significant breeder reactor penetration is projected until the latter quarter or half of the 21st Century, even for the high demand scenario of Fig 1-a, based upon *global* considerations of economics and uranium resource availability.

Consuming Plutonium in a Once-Through Process
A better fuel cycle would fulfill several long-term goals by having the following features. It would: greatly reduce inventories of discharged fuel while recovering a portion of their energy value; keep as much plutonium as possible protected by a high radiation barrier during all fuel-cycle operations; reduce the amount of plutonium in waste that must go to a geologic repository; and eventually reduce the global inventory of plutonium in all forms.

We propose a nuclear fuel-cycle architecture to achieve these goals that has the following back-end components.
Interim storage facilities. Facilities for consolidated, secure, interim storage of discharged fuel should be built in several locations around the world. The facilities would accept fuel newly discharged from reactors, as well as discharged fuel now stored at utilities, and store it for periods ranging from decades (at first) to a few years (later.) These facilities could be similar to the Internationally Monitored Retrievable Storage System (IMRSS) concept that is currently being discussed in the United States and elsewhere.
Plutonium conversion facilities. A new type of facility--the Integrated Actinide Conversion System (IACS)--would process fuel discharged from power reactors into fresh fuel of a new type, consume it in its own fissioning systm, and generate electricity for use by utilities. This facility would discharge a much smaller volume of waste that is nearly free of plutonium. Its integrated process would operate in such a way that the plutonium is continuously guarded by a radiation barrier. All discharged fuel that exists now or will exist—whether just generated, in the interim storage facilities, or in utility stockpiles—would eventually pass through an IACS. Each IACS could process fuel from 5 to 10 reactors on a steady basis. Though no such facility has yet been designed, a variety of past and current R&D can serve as starting points for its development.
Waste repositories. Waste finally exiting an IACS would be ready for final disposal. Because it would be smaller in volume than the initial amount of fuel discharged from power reactors, and have greatly reduced levels of plutonium and other long-lived isotopes, this waste could be deposited in permanent geologic repositories that could be less expensive than the repositories required for the current waste stream. There would also be greater confidence that the material could be isolated from the environment. Furthermore, because the material's radioactivity would decay in hundreds of years rather than thousands, a wider range of repository designs and sites could be considered.

In this architecture, most of the power is generated by light water reactors whose designs are optimized for safety and economics. These could evolve from current designs, or they could be new. Some new designs, such as the high temperature gas reactor, could reduce the number of IACS needed for the fuel cycle architecture.

Together, power reactors, consolidated interim storage facilities, transportation, IACS, and final waste repositories would comprise an integrated, international fuel-cycle management system. Figure 2 illustrates the concept and its major components and material flows.

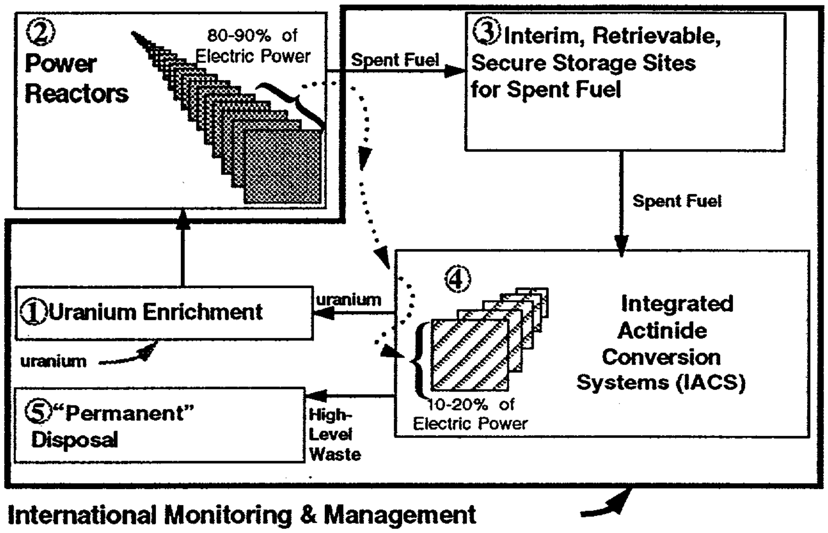

Figure 2: Major components of the proposed nuclear architecture as described in the text. In terms of nuclear energy, power reactors produce eighty to ninety percent of the total electricity amount, while Integrated Actinide Conversion Systems (IACS), whose main purpose is back-end materials management, produce ten to twenty percent.

Individual facilities might be owned and operated by nations or by national or transnational companies, but the system as a whole would be monitored and managed internationally. Although this approach reduces the global plutonium inventory, it allows for introduction of breeder reactors in the farther future if world energy demand requires it, making possible agreement on the fuel-cycle architecture between countries with different views on breeder reactors.

A Possible Timetable

This architecture might be built, and its use evolved, over several coming decades. Figure 3 provides a top-level view of a roadmap for implementation of such an architecture. An immediate step would be to begin converting existing and near-future inventories of separated plutonium into MOX fuel for power reactors, continuing until such stocks of material have been drawn down to zero and all stores of separated plutonium have been eliminated. At that point, all plutonium would be guarded by high radiation barriers in situ in power reactors, in secure interim storage or short-term storage awaiting consumption in IACS, and during consumption in IACS. Based on reasonable assumptions about capacities and lifetimes of existing reprocessing and MOX fuel-fabrication facilities and construction of new facilities, completing this phase might take thirty years.

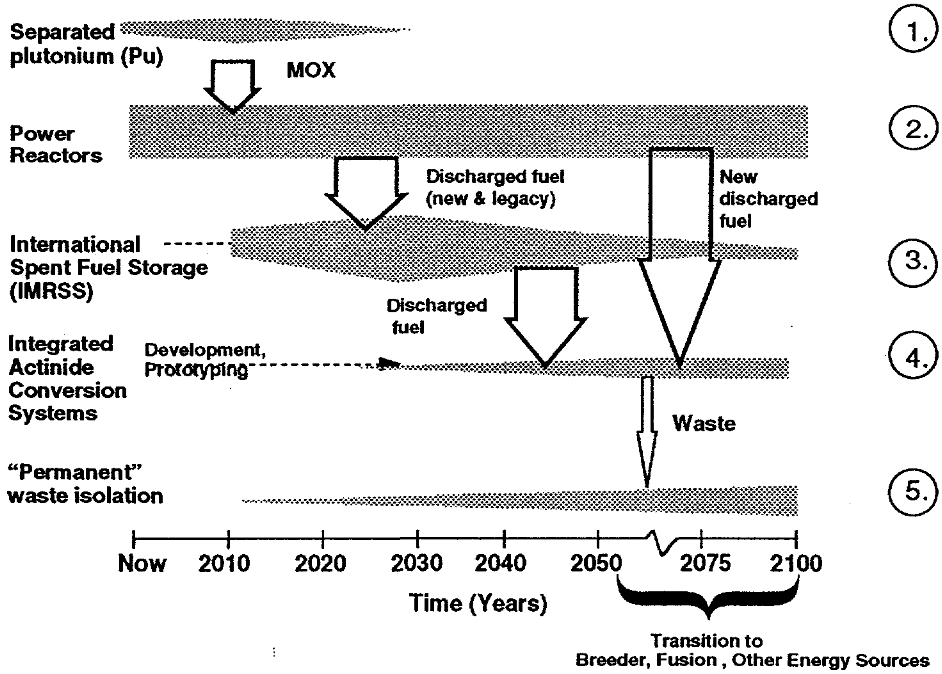

Figure 3: Top-level view of a proposed global nuclear materials management strategy. Objectives associated with each major component are 1) minimization of existing and near-future separated plutonium stocks by fabrication of them into mixed oxide or non-fertile fuels followed by use in light water reactors; 2) continued improvement of power reactors; 3) concurrent development and implementation of secure storage centers (to be managed or operated by international and/or transnational groups) so that all discharged fuel is consolidated in secure, monitored storage; 4) research, development, demonstration, and implementation of IACS systems to stabilize inventories by plutonium and other actinide consumption in secure environments devoid of separated plutonium; and 5) permanent disposal of waste that is greatly reduced in volume and in plutonium and other long-lived radioisotopes.

Concurrently, development of the system of IMRSS sites could begin. As each was completed, it would begin receiving existing inventories of discharged fuel currently in storage, as well as newly discharged fuel of both low-enriched uranium and MOX origin.

Research and development of IACS would also begin concurrently. Prototyping and pilot-plant demonstration might require two decades, after which IACS units would be built up over a few more decades to a total sufficient to process backlogged inventories plus fuel newly discharged from power-reactor operation. Later still, after backlogged inventories had been processed and converted, IACS would then keep pace with on-going fuel discharge so that only relatively small inventories of discharged fuel would need to be kept in short-term storage.

Over the several decades at the beginning of the evolution of this architecture, a smooth transition could be made from the current global nuclear energy posture to the integrated international fuel cycle management system mentioned above. With this transition, properly managed, investments in most current fuel cycle facilities need not be wasted, and R&D and investment in new facilities can be provided for. As this strategy is implemented across several decades, global inventories of plutonium would decline several-fold compared to projections based on present practices. Important qualitative changes would accompany this quantitative reduction, marked by key milestones:
1) when all separated plutonium stocks have been fabricated into MOX fuel and used in power reactors, and all plutonium resident in the global fuel cycle is protected at all stages by radiation barriers at or above the spent fuel standard suggested for weapons plutonium; 2) when all previously accumulated spent fuel has been processed and introduced into IACS for conversion; and 3) when equilibrium is reached between current fuel discharge from power reactors and IACS consumption.

At point 3, which would probably arrive sometime after 2050, nuclear materials inventories would be under control and positioned for the next phase of fission energy development: transition to a following generation of fission systems (breeder reactors if demand and uranium cost/availability require them) or phaseout and eventual replacement by other advanced energy sources, possibly including nuclear fusion. Figure 4 compares the impact of implementation of the architecture and technologies proposed here on global plutonium inventories with that obtained by simply extrapolating extensions of today's systems.

Technologies

Integrated Actinide Conversion Systems are central to this architecture and strategy. Each IACS would integrate two functions in a self-contained, unitary system: 1) processing spent fuel into new fuel for 2) a fission system which consumes plutonium and other actinides, and generates electricity much as a power reactor does. IACS would process both discharged fuel received from power reactors and fuel internally recycled from the IACS' own fission system. Processing technologies used would protect all plutonium with a high radiation barrier all the way through.

A system for improved back-end materials management and use should minimize negative cost impacts on nuclear energy. For this reason the proposed architecture assumes the vast majority of the global nuclear energy system is built around efficient and cost-effective nuclear power stations. Backend materials management would represent a perturbation on the global nuclear energy system, rather than a driver. For these reasons a key goal of IACS development would aim towards minimizing the capital and operating costs impact of IACS systems, This would be done by maximizing the number of power reactors which an IACS could service at equilibrium. This "support ratio" might range from five to ten depending on the amount of plutonium produced *in situ* within IACS and the plutonium inventory characteristics associated with power reactors, as they evolve. Minimizing in situ production is a key design- and technology-development goal for IACS. Minimizing power-reactor plutonium inventories might require greater fuel burnup or a change in fuel design. Development and use of "non-fertile" fuels would result in the production of much less plutonium in power reactors than do today's low-enriched uranium fuels.

Technology advancements that might contribute to IACS design include "dry processing" methods currently under development in the U.S. at the Argonne and Los Alamos National Laboratories as well as in Russia and Japan. These technologies can be adapted to materials processing which continuously maintains high in-situ radiation barriers. Integrating these with the fission system to achieve the largest possible support would require optimizing reactor designs or use of accelerator-based systems. In such systems, use of new coolants such as liquid lead also appears promising for safety and other operational reasons.

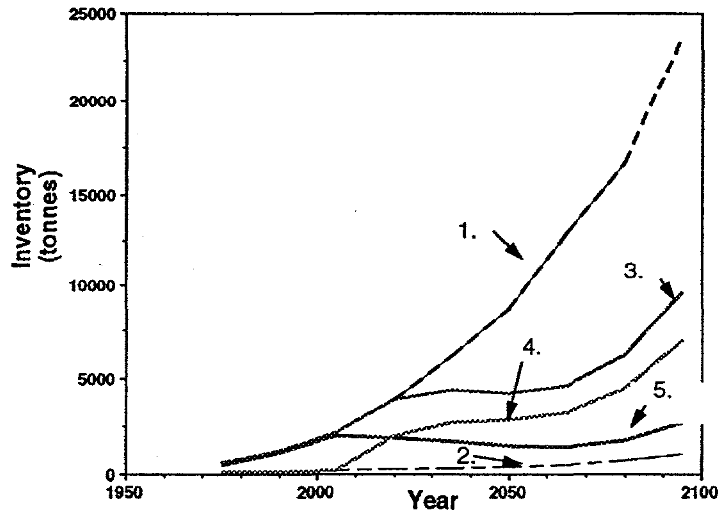

Figure 4: Comparison of the impacts of the proposed strategy on global plutonium inventories with that of a business-as-usual approach to the back end of the nuclear fuel cycle. The proposed strategy places all plutonium in an environment equivalent to the spent fuel standard and effects reduction in overall global plutonium inventories. Ultimate amounts of plutonium requiring geologic disposal would be minimized. (Curve 1 indicates plutonium (and spent fuel) inventory growth associated with current practices where most is in temporary, dispersed storage requiring long-term disposal. Curve 2 indicates plutonium amounts in reactors under an extrapolation of current approaches. Curves 3,4 and 5 respectively indicate total plutonium, plutonium in high-radiation environments, and plutonium in secure storage under the proposed architecture.)

IACS will require substantial development, but points of departure exist, and R&D underway at modest levels in the U.S., Japan, Russia and elsewhere can be expanded and adapted to the IACS concept. One point of departure is the Integral Fast Reactor (IFR), developed to the prototype stage in the U.S. between about 1970 and 1992, which integrated material processing with a power producing and plutonium breeding reactor. IACS is intended to consume spent fuel from other reactors while maintaining the radiation barrier throughout the process, so the particular technologies in IACS could be different from that developed for the IFR.

The array of relevant technologies from which we have selected these examples is rich, which indicates significant promise of success. But they are only current examples; the back end of the fuel cycle should be thought of as open territory for invention.

Conclusions

We believe that a new strategy is needed for managing the back of the nuclear fuel cycle. The accumulation of plutonium-laden discharged fuel is likely to continue under either current approach, challenging materials and waste management and increasing proliferation risk. We describe one particular alternative; there are others.

It will be difficult to implement this or any new strategy for the fuel cycle. Market forces will not drive such changes. Governments, industries, and the various institutions of nuclear power will have to take concerted action. A change in the architecture of nuclear power of this magnitude will require sustained commitment based on workable international consensus among the parties involved. Most of them understand that the back end of the fuel cycle needs to be fixed, but disagree on why, how, and when. If this disagreement persists, it will seriously hinder the necessary collective action.

Stronger and more constructive U.S. engagement will be needed. The U.S. policy community will have to rethink its position on the risk/benefit balance of nuclear power, and its strategy for dealing with the proliferation risks of the global nuclear fuel cycle; the international nuclear power community will have to acknowledge that structural changes in the architecture of the fuel cycle are needed on broad prudential grounds. A significant first step would be for the U.S. Department of Energy to actively embrace efforts for expanded international cooperation on nuclear materials management everywhere, including technologies for new fuel cycle architectures. More than that will be needed, and none of it will be easy, but we believe it can be done. And now is the time to start.

References

1. R. A Krakowski, J. W. Davidson, C. G.Bathke, E. D. Arthur, and R. L. Wagner, Jr. "Nuclear Energy and materials in the 21st Century", IAEA International Symposium on Nuclear Fuel Cycle and Reactor Strategies: Adjusting to New Realities, Vienna, June 1997, IAEA-SM-346/101

2. W. Burch, E. Rodwell, I. Taylor, M. Thompson, "A Review of the Economic Potential of Plutonium in Spent Nuclear Fuel", Electric Power research Institute report, EPRI TR-106072, February, 1996.

3. J. P. Holdren et al., *Management and Disposition of Excess Weapons Plutonium,* National Academy of Sciences, National Academy Press, Washington, D. C., 1994.