Multinational Approaches To Limiting The Spread Of Sensitive Nuclear Fuel Cycle Capabilities

Final Report

Submitted to:

Ambassador Linton F. Brooks
Administrator, National Nuclear Security Administration
United States Department of Energy

Prepared by:

Stephen A. LaMontagne
John F. Kennedy School of Government, Harvard University

In partial fulfillment of the requirements for the degree of
Master in Public Policy

PAE Advisor: Dr. Ashton B. Carter
PAC Seminar Leader: Dr. Steven Miller

April 5, 2005

Contents

Memorandum

TO: Ambassador Linton F. Brooks
Administrator, National Nuclear Security Administration
United States Department of Energy

FROM: Stephen A. LaMontagne
John F. Kennedy School of Government, Harvard University

SUBJECT: Multinational Approaches to Limiting the Spread of
Sensitive Nuclear Fuel Cycle Capabilities

DATE: April 5, 2005

THE FUEL CYCLE PROLIFERATION THREAT

The international crises over the nuclear programs of Iran and North Korea have exposed a critical loophole in the nonproliferation regime. Under the 1968 Non-Proliferation Treaty (NPT), non-nuclear weapon states can acquire sensitive nuclear fuel cycle capabilities – uranium enrichment and spent fuel reprocessing – under the cover of peaceful nuclear power development. These states can subsequently divert fuel cycle capabilities to the production of nuclear weapons, sell sensitive technologies to third parties, or leave stockpiles of nuclear materials vulnerable to acquisition by terrorist groups.

The proliferation threat is especially alarming given the current global resurgence of interest in nuclear power. As states gradually turn to nuclear power to meet their domestic electricity needs, they may become increasingly interested in acquiring indigenous enrichment and reprocessing capabilities. The international community must therefore find a way to limit the spread of these capabilities while at the same time satisfying the legitimate fuel needs of states with civil nuclear power programs.

RESEARCH QUESTIONS

This report evaluates one potential approach to closing the loophole in the nonproliferation regime – creation of a multinational supply regime that would guarantee nuclear fuel cycle services to countries that agree to forego indigenous enrichment and reprocessing. In particular, this report evaluates various options for such a regime in the context of the following research questions:

- **Is a multinational supply regime economically viable?**

- **Is a multinational supply regime politically feasible?**

- **How should a multinational supply regime be structured and implemented?**

KEY FINDINGS: ECONOMIC VIABILITY

From the point of view of most potential recipient states, there is a compelling economic rationale for purchasing nuclear fuel cycle services from a multinational supplier instead of building and operating domestic uranium enrichment, reprocessing, and/or spent fuel storage facilities.

- **Indigenous enrichment is an order of magnitude more expensive than multinational supply at market-based prices.** Development of a completely indigenous nuclear fuel cycle is a capital-intensive undertaking that would cost several billion dollars, invite political isolation, and risk economic sanctions. In particular, a $1 billion enrichment plant would cost well over $100 million annually to build and operate. By contrast, at current market prices, it would cost approximately $13.7 million annually to purchase enrichment services from a multinational supplier to support operation of a single 1,000MW(e) light water reactor (LWR) for 40 years. Changes in the price of uranium, the price of enrichment, and the enrichment tails assay do not significantly affect the cost differential. Therefore, a recipient state's LWR program would have to exceed 10,000MW(e) before construction of an indigenous enrichment plant would become economically viable.

- **Spent fuel removal guarantees would provide an economically and politically attractive alternative to domestic spent fuel storage and/or reprocessing**. Whereas construction and operation of either a reprocessing facility or a spent fuel repository would likely cost tens of millions of dollars annually, spent fuel removal surcharges would total approximately $5 million per year for a single 1,000MW(e) LWR. Surcharge revenues can be pooled to finance international spent fuel storage options.

- **The uranium enrichment market possesses sufficient existing and planned capacity to meet global demand for the foreseeable future**. USEC, Urenco, and Eurodif all plan to build new commercial enrichment plants over the next several years. In addition, Russia's state-owned nuclear joint stock company, Techsnabexport (TENEX), plans to increase enrichment capacity by approximately 0.5 million separative work units (SWU) per year through 2010-2011. Even if a multinational supply regime generates an unanticipated spike in demand for enrichment, the modular nature of centrifuge enrichment plants would enable enrichers to further ramp up capacity.

- **Antitrust concerns are a potential obstacle, but are not intractable**. To some states, a multinational supply regime might represent little more than a euphemism for establishment of a nuclear fuel cycle cartel. However, one can make a strong case that the inherently dual-use nature of fuel cycle technologies justifies their exemption from anti-trust laws. Such laws are moreover ambiguous in their applicability.

KEY FINDINGS: POLITICAL FEASIBILITY

Government officials among potential supplier states expressed near universal interest in a multinational supply regime. However, the majority of subjects interviewed believed that insufficient political will exists to resolve difficult questions about how to structure and implement such a regime. In particular, a multinational supply regime must confront the following obstacles:

- **Credibility of Supply Assurances –** If potential recipient states believe that the market will be unable to satisfy their demand for nuclear fuel, or that policy changes in supplier state governments will jeopardize multinational fuel deliveries and spent fuel removal, then they will be reluctant to forego domestic enrichment and reprocessing programs.

- **States with Hidden Agendas –** Even if a multinational supply regime offered compelling economic advantages and credible supply assurances, some potential recipient states might nevertheless continue to pursue indigenous fuel cycle capabilities. Possible ulterior motives include nuclear weapons ambitions, naval nuclear propulsion, commercial gain, energy independence, and national pride. While a multinational supply regime can help expose these non-economic motivations, it may be unable to discourage them.

- **NPT Rights and Access to Technology –** Many non-nuclear weapon states party to the NPT, including potential supplier states, believe that their "inalienable right" to develop peaceful nuclear power under Article IV of the treaty includes the right to acquire national enrichment and reprocessing capabilities, a view that the United States does not share. A multinational supply regime must sidestep a paralyzing NPT debate by respecting Article IV rights while simultaneously reducing incentives for states to exercise those rights.

- **Spent Fuel Management –** For potential recipient states that face political, technological, or environmental obstacles to spent fuel storage and disposal, spent fuel removal guarantees can provide a major incentive to participate in a multinational supply regime. However, spent fuel takeback may prove equally problematic for many potential supplier states. International spent fuel storage options are a potential way forward, but prior consent issues pose a major obstacle.

- **Supplier State Participation and Coordination –** Any option for a multinational supply regime involves balancing the interests of multiple governments on multiple issues. In particular, supplier state governments must coordinate a common set of criteria governing nuclear exports, with a consistent set of nonproliferation obligations for recipient states. The IAEA can play an important role in legitimizing and facilitating the regime, but can do little without specific direction and funding from its member states.

CONCLUSIONS AND RECOMMENDATIONS

Although a multinational supply regime offers compelling economic advantages, it will be extremely difficult for supplier states to coordinate and implement an arrangement that attracts broad recipient state participation while simultaneously strengthening nonproliferation. Moreover, a multinational supply regime can do little to prevent states that are determined to acquire enrichment and reprocessing facilities for reasons that are fundamentally non-economic in nature.

However, a multinational supply regime can help pre-empt the longer-term proliferation dangers inherent in a global expansion of nuclear power by locking states into an arrangement in which they have every incentive to behave as responsible clients. Such a regime offers both economic and nonproliferation advantages that are mutually reinforcing, and therefore merits serious consideration. The following recommendations present the best path forward for an effective multinational supply regime.

RECOMMENDATION 1

IAEA member states should request that the agency facilitate the creation of a commercial supply consortium comprised of major uranium producers and enrichment providers. In particular, the IAEA would bring together the governments of Australia, Canada, France, Russia, and the United States to negotiate an intergovernmental agreement that would establish a political framework for commercial entities, acting as the executive agents of their respective governments, to cooperate in meeting global nuclear fuel cycle needs. The agreement would include a model safeguards agreement that would apply to all transactions between any member (or combination of members) of the supply consortium and any recipient state. Recipient states would undertake a common set of nonproliferation obligations, including a 10-year, renewable commitment to abstain from domestic enrichment and reprocessing.

RECOMMENDATION 2

To provide an additional layer of supply assurance, supplier state governments should create a "strategic uranium reserve" by financing the downblending of additional Russian weapons-origin HEU into LEU fuel for power reactors. Supplier states would pay Russia to blend down specific quantities of weapons-origin HEU into LEU fuel. The material would be held off the market and stored either entirely in Russia or distributed among the supplier states in proportion to their initial contributions. In the event that a supplier state is unable to meet its fuel supply obligations (for reasons other than suspicions of proliferation activity), the affected recipient state would be able to draw upon the strategic reserve to meet its fuel needs.

RECOMMENDATION 3

Construct an international spent fuel storage facility in Russia. Russia would own and operate the spent fuel storage facility, and would subject it to IAEA safeguards and inspections. Supplier states would contract with Russia to store spent fuel from recipient states at the facility. However, states from which spent fuel originated would retain prior consent rights over the fate of the fuel, and Russia would agree not to reprocess spent fuel for a specific period of time, perhaps 20 or more years.

RECOMMENDATION 4

Strengthen other options in the nonproliferation "toolkit". A multinational supply regime is not a silver bullet solution to the proliferation problem. Rather, it constitutes one strategy among a series of interdependent and mutually reinforcing policies for combating proliferation. As a result, the success of the commercial supply consortium will depend on the effectiveness of parallel efforts to strengthen export controls, improve nuclear intelligence and detection capabilities, and expand interdiction programs.

CONCLUSION

The four recommendations outlined above can help slow the spread of enrichment and reprocessing capabilities by providing an economically attractive alternative to an indigenous nuclear fuel cycle. They can also cast increased suspicion upon the intentions of determined proliferators by exposing any purported economic or commercial justifications for their nuclear programs as illegitimate. In so doing, they can remove political barriers to building international coalitions to confront proliferators with diplomatic pressure, economic sanctions, or military force if necessary.

Background and Methodology

THE FUEL CYCLE PROLIFERATION THREAT

The international crises over the nuclear programs of Iran and North Korea have exposed a critical loophole in the nonproliferation regime. Under the 1968 Non-Proliferation Treaty (NPT), non-nuclear weapon states can acquire sensitive nuclear fuel cycle capabilities – uranium enrichment and spent fuel reprocessing – under the cover of peaceful nuclear power development. Even if these capabilities are initially intended to support peaceful nuclear power generation, their diversion to a nuclear weapons program would require only a political decision. Factors that could lead to such a decision include unexpected changes to a state's security environment, political pressure from a domestic scientific bureaucracy or other interest groups, or a change in leadership.

Once a state enriches uranium to weapons-grade levels or reprocesses spent fuel to recover plutonium, the resulting fissile materials pose a threat for tens of thousands of years, a timeframe during which governments (and their intentions) will change, wars may break out, and materials may fall into the wrong hands. In particular, if states do not provide adequate physical security for fissile material stockpiles, sub-national terrorist groups or criminal organizations could steal the material and use it to attack the United States, its armed forces, its citizens, or its allies with a crude nuclear or radiological bomb. In addition, states that do not observe and enforce strict national and international guidelines governing nuclear exports could sell or transfer sensitive materials and technologies to states with nuclear weapons ambitions.

The loophole in the nonproliferation regime is especially alarming given that nuclear power may be on the verge of a renaissance. Nuclear power presents an attractive option for reducing carbon dioxide emissions and could potentially play a major role in long-term sustainable energy development. According to International Atomic Energy Agency (IAEA) data, a total of 441 nuclear power plants are operating in 30 countries, with another 25 plants under construction.[1] Nuclear generating capacity in East Asia could increase 75-100 percent by 2020, with China planning to commission two new nuclear reactors per year through 2020.[2] Significant nuclear generating capacity increases are also expected in South and Southeast Asia, Central and Eastern Europe, the Middle East, Central and South America, and Africa.[3] Countries planning to build commercial nuclear power plants in the next decade include Egypt, Indonesia, and Vietnam. As states gradually turn to nuclear power to meet their domestic electricity needs, they may become increasingly interested in pursuing their own enrichment and reprocessing capabilities.

The international community must therefore find a way to limit the spread of sensitive fuel cycle capabilities while at the same time satisfying the legitimate fuel needs of states with civil nuclear power programs. One option is to offer a multinational alternative to the indigenous fuel cycle. The general format of such an approach involves creating a multinational supply regime that would guarantee the timely supply of fresh reactor fuel to recipient states that renounce national enrichment and reprocessing programs, submit to strict safeguards (such as those stipulated in the IAEA Additional Protocol), and re-affirm their intention not to pursue nuclear weapons.

The concept of multinational nuclear fuel cycle controls is not new. Since the dawn of the nuclear age, several high-profile proposals have been advanced and rejected:

- **The Baruch Plan** – In a 1946 speech to the United Nations Atomic Energy Commission (UNAEC), Bernard Baruch (appointed by President Truman to be the U.S. representative to the UNAEC) proposed the creation of an International Atomic Development Authority that would assume control of all global uranium deposits, manage all fissile material production facilities, license and inspect all nuclear reactors, and conduct nuclear explosive research

---

[1] International Atomic Energy Agency Power Reactor Information System, http://www.iaea.org/programmes/a2/index.html
[2] French, Howard, "China Promotes Another Boom: Nuclear Power," *New York Times*, January 15, 2005; *Uranium 2003: Resources, Production, and Demand*, International Atomic Energy Agency and OECD Nuclear Energy Agency, 2004, p. 48.
[3] Ibid.

activities.[4] However, the Soviet Union blocked the proposal, arguing that it constituted an attempt by the United States to preserve its monopoly over nuclear weapons.

- **International Nuclear Fuel Cycle Evaluation** – In 1977, the IAEA, in part motivated by concerns over rising oil prices and India's 1974 nuclear test, launched the International Nuclear Fuel Cycle Evaluation (INFCE) project to study technological options for reducing the proliferation risks associated with nuclear power. In addition to concluding that technological solutions alone were insufficient to prevent proliferation, the INFCE participants failed to reach any consensus on institutional strategies for creating multinational nuclear fuel cycle controls.

- **Committee on Assurances of Supply** – In 1980, the IAEA convened a Committee on Assurances of Supply (CAS) to explore avenues of international cooperation with respect to the supply of nuclear materials, equipment, and technology. The Committee also considered proposals to establish regional or multinational fuel cycle centers, but never achieved any consensus recommendations.[5]

Despite these failures, high-level interest in multinational approaches has resurfaced, both in the United States and internationally.

- **Bush Initiative** – In his February 11, 2004 speech at National Defense University, President Bush proposed that "the world's leading nuclear exporters should ensure that states have reliable access at reasonable cost to fuel for civilian reactors, so long as those states renounce enrichment and reprocessing."[6] Addressing the importance of supply-side controls, President Bush continued, "The 40 nations of the Nuclear Suppliers Group should refuse to

---

[4] The Text of the Baruch Speech is Available at http://www.nuclearfiles.org/redocuments/1946/460614-baruch.html.

[5] "Multilateral Approaches to the Nuclear Fuel Cycle: Preliminary Views of the IAEA Secretariat for the Proposed Study," IAEA Office of External Relations and Policy Coordination, June 2004.

[6] The Text of President Bush's Speech is Available at http://www.whitehouse.gov/news/releases/2004/02/20040211-4.html.

sell enrichment and reprocessing equipment and technologies to any state that does not already possess full-scale, functioning enrichment and reprocessing plants."[7]

- **IAEA Experts Group** – IAEA Director-General Mohamed El-Baradei offered a more ambitious proposal in his September 2003 address to the IAEA General Conference, suggesting that enrichment, reprocessing, and spent fuel disposal be limited to international centers.[8] In June 2004, El-Baradei announced the creation of an *ad hoc* IAEA Experts Group to explore this and other multinational approaches to the nuclear fuel cycle.

The IAEA Experts Group reported its findings in February 2005, highlighting five options for multinational approaches to the nuclear fuel cycle.[9] These five options (**excerpted in Annex 1**) can be further distilled into three general approaches that vary according to the required degree of international cooperation.

- **Commercial Supply Consortium** – Major commercial uranium producers and enrichment providers, backed by intergovernmental agreements, would band together to guarantee supply of fresh fuel to, and spent fuel removal from, recipient states that agree to forego indigenous enrichment and reprocessing. John Deutch, Arnold Kanter, Ernest Moniz, and Daniel Poneman have proposed one such arrangement, which they call the "Assured Nuclear Fuel Services Initiative."[10] The IAEA Experts Group report suggests a variation of the commercial consortium that would involve the IAEA acting as guarantor of fuel supply agreements, possibly as the administrator of a nuclear "fuel bank."[11]

- **Regional Partnerships** – States in a given region would form joint partnerships in which they pool their resources and expertise to develop enrichment and possibly other fuel cycle

---

[7] Ibid.
[8] The Text of Director-General El-Baradei's Speech is Available at http://www.iaea.org/NewsCenter/Statements/2003/ebsp2003n020.shtml.
[9] "Multilateral Approaches to the Nuclear Fuel Cycle: Expert Group Report submitted to the Director General of the International Atomic Energy Agency," International Atomic Energy Agency INFCIRC/640, February 22, 2005, http://www.iaea.org/Publications/Documents/Infcircs/2005/infcirc640.pdf.
[10] Deutch, John et al, "Making the World Safe For Nuclear Energy."
[11] IAEA INFCIRC/640, p. 16.

capabilities to support their civil nuclear power programs. Joint ventures would involve either co-option of existing fuel cycle facilities or construction of new facilities, and can follow the model of either Urenco or Eurodif. The Urenco model would allow technology sharing among participating partners, but not outside the group. The Eurodif model would designate one country as the proprietary holder of technology, but allow partners to take an equity stake in fuel cycle facilities, enjoy priority access to nuclear fuel, and participate in facility management and administration.

- **International Nuclear Fuel Cycle Centers** – Managed and operated by the IAEA or another qualified international organization, these centers would provide "cradle-to-grave" nuclear fuel cycle services for all states with civil nuclear power programs. Again, creation of such centers would involve either construction of new enrichment and reprocessing facilities or conversion of existing facilities to international control.

RESEARCH QUESTIONS

This report builds on the IAEA Experts Group report by evaluating the above options in the context of the following research questions.

- **Is a multinational supply regime economically viable?** Specifically, what are the costs associated with indigenous nuclear fuel cycle development? How do those costs compare to the costs of purchasing fuel cycle services from a multinational supplier? What impact would a multinational supply regime have on the current market for uranium production and enrichment?

- **Is a multinational supply regime politically feasible?** In particular, what are the primary interests at stake for both potential supplier states and recipient states in a multinational supply regime? Given these interests, what are the principal obstacles to implementing such a regime? Can they be overcome?

- **How should a multinational supply regime be structured and implemented?** Among the various options for a multinational supply regime, which option best balances the interests of all potential stakeholders? What steps are necessary to implement this option?

METHODOLOGY

The section on economic viability compares, from the point of view of a potential recipient state, the costs of indigenous nuclear fuel cycle development against the costs of purchasing fuel cycle services from a multinational supplier at market-based prices, including payment of a spent fuel removal surcharge. Assumptions and data are drawn from official reports by the IAEA, the OECD Nuclear Energy Agency (NEA), the National Academy of Sciences (NAS), and other institutions; trade publications, in particular the *Ux Weekly*; and interviews with industry officials and analysts.

The section on political feasibility draws on extensive interviews, historical analysis, and relevant literature in order to identify key considerations affecting the implementation of various multinational approaches. Subjects interviewed for this report include high-level officials at the U.S. Departments of Energy and State; key officials from the governments of Australia, Brazil, Canada, France, Japan, and Russia; executives from the United States Enrichment Corporation (USEC); IAEA officials; a senior advisor to the IAEA Experts Group; and non-government experts. A complete list of subjects interviewed for this report is included in Annex 3. In some cases, officials requested that their identities be withheld.

Findings: Economic Viability

From the point of view of most potential recipient states, there is a compelling economic rationale for purchasing nuclear fuel cycle services from a multinational supplier instead of building and operating domestic uranium enrichment and reprocessing or spent fuel storage facilities. Due to economies of scale, indigenous enrichment and spent fuel disposal/reprocessing are both an order of magnitude more expensive than the multinational supply option.

COST OF INDIGENOUS FUEL CYCLE DEVELOPMENT

A complete indigenous fuel cycle is a capital-intensive undertaking that would involve the licensing, construction, operation, and decommissioning of facilities to convert uranium oxide (U_3O_8) to uranium hexafluoride (UF_6), enrich UF_6 to the desired level of U-235 (in the case of LWR, approximately 4.5%), fabricate fuel assemblies, and store (or reprocess and recycle) spent fuel. It is impossible to make a precise, generalized estimate of the aggregate discounted life-cycle costs of these facilities. States differ according to their licensing procedures, the availability of suitable facility sites, their costs for labor and materials, and their level of technical expertise. Exchange rate fluctuations add another layer of uncertainty. However, total discounted life-cycle costs would almost certainly amount to several billion dollars.

This report assume that, for states interested in developing civil nuclear power programs, the once-through LWR fuel cycle currently represents the most attractive technological option in terms of cost, safety, and proliferation-resistance.[12] Although closed-cycle options (that involve reprocessing spent fuel to recover un-irradiated uranium and plutonium) reduce the amount of long-term waste, they are much more expensive to implement and would only become economically attractive if the prices of uranium and enrichment were to dramatically increase. Even if uranium prices do increase, it would be less expensive for countries to reduce enrichment tails assays and increase LWR fuel burnup than to reprocess and recycle.

[12] *The Future of Nuclear Power: An Interdisciplinary MIT Study*, Massachusetts Institute of Technology, 2003, p. 31.

Enrichment Plant Costs – The cost of constructing a commercial-scale enrichment facility would likely exceed $1 billion. USEC estimates that construction of its planned American Centrifuge enrichment plant in Piketon, OH, with an initial nameplate capacity of 3.5 million SWU, will cost $1.5 billion.[13] A new Urenco plant under construction in New Mexico is projected to cost approximately $1.2 billion for an initial capacity of 3 million SWU.[14]

Construction of a $1 billion enrichment plant, amortized over 40 years at an interest rate of 5%, would cost approximately $58 million annually.[15] In addition, operation of a uranium enrichment plant requires a substantial amount of electricity, and would potentially entail construction of a small, dedicated power plant. For example, a gas centrifuge enrichment plant with a capacity of 1 million SWU would require approximately 5MW of electricity, assuming a requirement of 50kWh/SWU.[16] Adding the costs of plant operation, maintenance, security, and contingency expenses would likely inflate total plant costs to well over $100 million annually.

On the other hand, a country with a small civil nuclear power program need not build a commercial-scale enrichment plant to meet domestic enrichment needs. Rather, a small-scale "strategic" enrichment facility with an annual capacity of a few hundred thousand SWU would be sufficient to support a small LWR program. However, according to USEC officials, high capital costs would make even a strategic enrichment facility economically unattractive.[17] The fact that data related to enrichment economies of scale are such closely-held industry secrets seems to support this conclusion.

Moreover, total costs would likely run much higher for proliferators seeking to acquire sensitive centrifuge technologies from rogue sources, procure highly specialized equipment and materials through clandestine supply networks, conceal facility construction from IAEA inspectors and foreign intelligence assets, and guard the facility from attack or infiltration. If

---

[13] 2003 Annual Report (Financials), USEC, Inc., p. 22.
[14] Telephone interview with Charles B. Yulish, Vice President, Corporate Communications, USEC, Inc., March 4, 2005.
[15] The annual cost of enrichment plant construction is equal to the initial investment multiplied by the Capital Recovery Factor, where CRF = $[r(1+r)^t / (1+r)^{(t-1)}]$ In this equation, r is the interest rate and t is the plant lifetime in years. An investment amortized at 5 percent over 40 years results in a CRF = 0.058.
[16] 1 million SWU x 50kWh/SWU divided by 8,760h/yr = 5.7MW
[17] Telephone Interview with Charles B. Yulish, March 4, 2005.

detected, suspected proliferators might be forced to bear the additional costs of political and economic isolation.

Spent Fuel Repository Costs – There is no operational spent fuel repository anywhere in the world. As a result, there is little reliable information on the cost of building and operating such a facility. Factors affecting cost include specific waste characteristics; type of waste packaging; and the repository's design, scale, depth, and geology. However, the case of Finland provides a useful benchmark for approximating the costs that a recipient state might incur if it decided to build an indigenous spent fuel repository. Finland possesses a small civil nuclear power program (4 LWR with a total capacity of approximately 2,600MWe) and relatively mature plans for direct disposal of spent fuel in a geologic repository. In June 2004, the World Nuclear Association estimated the total cost of Finland's planned repository to be approximately 818 million Euros ($1 billion at current exchange rates).[18] This figure does not include the cost of interim storage as well as substantial research, development, design, and pilot-scale laboratory testing costs that Finland has already incurred. Based on this information, the levelized annual cost of domestic spent fuel disposal in a recipient state would likely amount to tens of millions of dollars annually over the lifetime of a repository.

However, some states may wish to retain the option of reprocessing and recycle, even if they have no obvious nuclear weapons ambitions. Others may care little about spent fuel storage and disposition altogether, opting only to build dry-cask interim storage facilities at their reactor sites. The costs of such facilities are roughly $10 million, regardless of scale,[19] and may be economically more attractive than paying a spent fuel removal surcharge.

COST OF MULTINATIONAL SUPPLY

Total Fuel Costs – Assuming current market prices for uranium, conversion, enrichment, and fuel fabrication, the total overnight cost of fuel needed to power a single 1,000MW(e) LWR for

---

[18] "Nuclear Energy in Finland," World Nuclear Association Issue Brief, June 2004, http://www.world-nuclear.org/info/inf76.htm.
[19] Bunn, Matthew et al, *The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel*, Final Report, Project on Managing the Atom, John F. Kennedy School of Government, December 2003, p. 52.

40 years at a 90 percent capacity factor is approximately $1.5 billion. This estimate includes a "spent fuel removal" charge of $260 per kilogram of heavy metal in fresh fuel, equivalent to the $0.001 per kWh that DOE charges public utilities for spent fuel storage and disposition. Assuming a 5 percent real discount rate over a 40-year reactor lifetime, the total cost of fuel in present value terms is approximately $635 million. The levelized annual cost of fuel amounts to approximately $37.0 million. Cost assumptions and data are summarized in Tables 1 and 2 below. **Detailed explanations of these data and assumptions are provided in Annex 2**.

Table 1: Base Case Assumptions for Multinational Supply[20]

Parameter	Unit of Measurement	Assumed Value
Uranium Oxide (U_3O_8) Requirement	kgU/kgHM in fresh fuel	10.15
Unit Cost of U_3O_8	$/kgU in U_3O_8	55.00
Unit Cost of Conversion	$/kgU in U_3O_8 converted to UF_6	10.00
Loss During Conversion	Fraction Lost	0.005
Uranium Into Enrichment	kgU in UF_6/kgHM of fresh fuel	10.10
Cost of Enrichment	$/SWU	110.00
Enrichment Requirement	SWU/kgHM in fresh fuel	6.26
Enrichment Level	Fraction U-235	0.045
Tails Assay	Fraction U-235	0.0030
Unit Cost of Fuel Fabrication	$/kgHM in fresh fuel	250.00
Loss During Fuel Fabrication	Fraction Lost	0.01
Spent Fuel Removal Charge	$/kgHM in fresh fuel	260.00
Unit Cost of Fuel		
Uranium Acquisition	$/kgHM in fresh fuel	558.28
Conversion	$/kgHM in fresh fuel	101.51
Enrichment	$/kgHM in fresh fuel	688.41
Fuel Fabrication	$/kgHM in fresh fuel	250.00
Spent Fuel Removal Charge	$/kgHM in fresh fuel	260.00
TOTAL UNIT COST	$/kgHM in fresh fuel	**$1858.20**

20 The expression $/kgHM can be read as "Dollars per kilogram of heavy metal in fresh fuel."

Table 2: Cost of Multinational Supply (Base Case)

Recipient Country Reactor Specifications	
Reactor Type	Light Water Reactor (LWR)
Number of Operational LWR	1
Capacity (MWe)	1,000
Capacity Factor	0.9
Burnup (MWd/kgHM in fresh fuel)	50
Thermal Efficiency	0.33
Operational Lifetime (years)	40
Total Output over Reactor Lifetime (MWd-thermal)	39,818,182
Quantity of Fuel Required to Produce Total Output (kgHM)	796,364
Total Unit Cost of Fuel ($/kgHM)	1858.20
TOTAL OVERNIGHT COST OF FUEL($millions)	**1,480**
PRESENT VALUE OF OVERNIGHT COST ($millions)	**635**
LEVELIZED ANNUAL COST ($millions)	**37.00**

These costs are fairly sensitive to the level of fuel burnup. Holding all other base case assumptions constant, reducing LWR burnup from 50MWd/kgHM to 30MWd/kgHM causes the levelized annual cost of fuel to increase from $37 million to nearly $62 million. However, the costs are only modestly sensitive to changes in the prices of uranium and enrichment. If the price of uranium were to double from its current level of approximately $55 per kilogram, the levelized annual cost of fuel would increase to approximately $48.1 million. If, in addition, states reduce their tails assays to 0.25% U-235 and the cost of enrichment doubles from its current long-term contract price of $110/SWU, the levelized annual cost of fuel would increase to approximately $62.3 million per year. Cost sensitivities are presented in Table 3.

Table 3: Cost Sensitivities for Multinational Supply

	Base Case	Scenario 1: Base Case w/ Low Burnup	Scenario 2: Price of Uranium Doubles	Scenario 3: States Reduce Tails Assay	Scenario 4: Price of Enrichment Doubles
Price of Uranium ($/kg U_3O_8)	55.00	55.00	110.00	110.00	110.00
Cost of Enrichment ($/SWU)	110.00	110.00	110.00	110.00	220.00
Enrichment Tails Assay (fraction U-235)	0.0030	0.0030	0.0030	0.0025	0.0025
Burnup (MWd/kgHM)	50	30	50	50	50
Annual Costs ($millions)					
Uranium Acquisition	11.11	18.52	22.23	20.10	20.10
Conversion	2.02	3.37	2.02	1.83	1.83
Enrichment	13.71	22.84	13.71	15.11	30.22
Fuel Fabrication	4.98	8.30	4.98	4.98	4.98
Spent Fuel Removal	5.18	8.63	5.18	5.18	5.18
TOTAL LEVELIZED ANNUAL COST ($millions)	**37.00**	**61.66**	**48.12**	**47.20**	**62.31**
TOTAL OVERNIGHT COST OF FUEL ($millions)	**1,480**	**2,466**	**1,925**	**1,888**	**2,492**
PRESENT VALUE OF OVERNIGHT COST ($millions) (r = 0.05)	**635**	**1,058**	**826**	**810**	**1,069**

Enrichment Costs – Under base case assumptions for multinational supply, the cost of enrichment accounts for approximately 37% of the annual cost of fuel, or $13.71 million. **Therefore, the nuclear power program of a recipient state would have to be fairly large (approximately 10 operational 1,000MW(e) LWR) to justify an indigenous enrichment facility on strictly economic grounds**. If recipient states reduce their tails assays and the price of enrichment doubles (**Scenario 4**), annual enrichment costs would increase to approximately $30 million, still well below the estimated $100+ million annual costs associated with enrichment plant construction and operation.

In short, multinational supply offers significant economies of scale. Just as it makes little sense for every state to operate its own national airline, it makes little sense for every state to develop its own nuclear fuel cycle. Fuel cycle facilities involve a substantial amount of fixed costs before they can produce even one kilogram of nuclear fuel. Thus, a large, commercial-scale enrichment facility can produce one kilogram of heavy metal in fresh fuel at a far lower cost than a small-scale national facility intended to support the domestic electricity needs of a state with a modest civil nuclear power program. Although the state in question could spend more to build a commercial-scale facility with substantial excess capacity, it would make little sense to do so without clear evidence that sufficient market demand exists for such additional capacity and that existing enrichment providers could not satisfy additional demand at less expense.

However, regardless of economies of scale, indigenous enrichment may become an economically attractive option for a select group of states with vast uranium reserves, potentially large commercial markets, and heavy reliance on nuclear power. Brazil, home to the world's sixth-largest uranium reserves, has argued that its Resende enrichment plant will save $10-12 million per year.[21] Iranian officials also argue that the costs of indigenous enrichment do not vastly exceed the costs of purchasing LEU through the market.[22] However, Iran's uranium reserves are of dubious size and quality, and its cost projections very likely do not reflect the substantial sunk costs of its 18 year clandestine acquisition program or the less quantifiable costs of economic sanctions and international isolation.

Spent Fuel Removal Costs – The cost of spent fuel removal translates into an annual expense of approximately $8.6 million under the low burnup scenario and $5 million for all other multinational supply scenarios. In any case, the amount is but a small fraction of the likely total annual costs associated with construction and operation of either a spent fuel repository or a reprocessing facility.

As is the case with enrichment, a recipient state's nuclear program would have to consist of dozens of reactors before domestic reprocessing or spent fuel disposal would become economically viable. For recipient states that are reluctant to deal with the political, environmental, financial, and logistical headaches associated with permanent disposal of spent fuel, multinational supply arrangements with spent fuel removal provisions might be especially

---

[21] Slevin, Peter, "Brazil Shielding Uranium Facility: Nation Seeks to Keep Its Proprietary Data From U.N. Inspectors," *Washington Post*, April 4, 2004.
[22] Conversation with Dr. Steven Miller, Harvard University, March 17, 2005. Dr. Miller had recently returned from a conference in Teheran during which he had the opportunity to discuss Iran's nuclear program with Iranian officials.

attractive. Rather than build a repository, recipient states need only pay a small surcharge, part of which can be passed off onto consumers in the form of higher electricity prices. Revenues from recipient state surcharges can be pooled in order to finance international spent fuel storage options. On the other hand, some states may demand to be compensated for the value of the energy content present in spent fuel.

MARKET CONSIDERATIONS

Sufficient uranium enrichment capacity exists to satisfy demand for the foreseeable future. Currently, eight countries possess operational, commercial-scale uranium enrichment facilities: China, France (Eurodif-Areva), Germany (Urenco), Japan, the Netherlands (Urenco), Russia (TENEX), the United Kingdom (Urenco), and the United States (USEC). Of this group, TENEX, Urenco, Eurodif, and USEC account for approximately 83 percent of world commercial enrichment capacity and 80 percent of world production (an estimated 44.3 million SWU for 2005).[23] Downblended Russian weapons-origin HEU accounts for another 12.5 percent of world production.

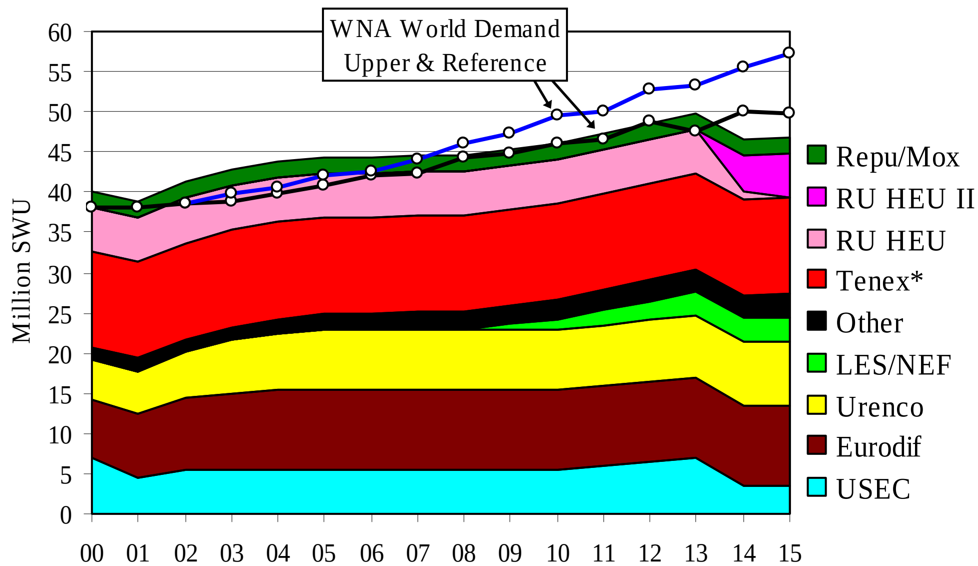
Although demand for SWU is projected to surpass production in 2014, enrichment capacity is expected to expand over the next decade, to approximately 52 million SWU. As mentioned above, USEC is planning to build a new centrifuge facility in Portsmouth, OH with an initial nameplate capacity of 3.5 million SWU. In addition, Urenco, through Louisiana Energy Services (a partnership with utilities including Exelon, Duke Power, Entergy, and Westinghouse), is planning to build a new 3 million SWU facility in New Mexico by 2013, and Eurodif is planning to install 7.5 million SWU of new capacity by 2016.[24] Russia's state-owned enrichment conglomerate, Techsnabexport (TENEX) plans to install 6 million SWU of new capacity by 2010-2011.[25]

---

[23] Data supplied by Ux Consulting, LLC
[24] McCormick, Tony, Urenco Enrichment Company, Ltd, Presentation to the World Nuclear Fuel Market, 2004 Annual Meeting, May 2004, http://www.wnfm.com/2004AnnualMeeting/Proceedings/McCormick.pdf.
[25] Ibid.

These planned capacity increases should be able to satisfy projected demand increases far into the future. Even if a multinational supply regime generates an unanticipated spike in demand for enrichment, the modular nature of centrifuge enrichment plants would enable existing enrichment companies to further ramp up capacity.

Figure 1: World SWU Production and Demand through 2015
Source: Ux Consulting, LLC



* Tenex production does not include tails re-enrichment.

Increases in the prices of uranium and enrichment would not undermine the economic appeal of multinational supply. SWU prices climbed in 2004 and will likely continue to increase over the long-term, especially if states reduce their enrichment tails assays. However, the OECD Nuclear Energy Agency reported in 2001 that planned new facilities based on advanced technology could eventually lower the cost of enrichment to as little as $50/SWU.[26]

Uranium prices are likewise a relatively unimportant factor in determining the economic appeal of multinational supply. A state without significant uranium reserves would be forced to pay the market price for uranium regardless of whether it enriches the fuel domestically or purchases enrichment from a foreign provider. Although high uranium prices could indirectly

[26] *Trends in the Nuclear Fuel Cycle: Economic, Environmental, and Social Aspects*, OECD Nuclear Energy Agency, Paris: NEA (2001), p. 83.

drive up SWU prices as states decrease their tails assays, they should cause states to reconsider nuclear power development altogether, not where to procure enrichment services.

Market-based prices are essential to the viability of any multinational supply regime. If a multinational supplier charges above going market rates for fuel cycle services, then recipient states will have little incentive to participate. On the other hand, pricing multinational fuel cycle services below market rates would interfere with well-functioning uranium production and enrichment markets and punish states that have thus far behaved as responsible users of nuclear power.

Anti-Trust Concerns are a potential obstacle, but are not intractable. To some states, a multinational supply regime might represent little more than a euphemism for establishment of a nuclear fuel cycle cartel. In particular, the commercial supply consortium option could conflict with anti-trust laws because it would involve coordinating the actions of governments that control a large fraction of global uranium reserves and enrichment capacity. Options that involve U.S. participation in construction of new enrichment plants would require an anti-trust review by the Nuclear Regulatory Commission, as stipulated in U.S. law.[27] Canadian officials were especially wary of creating the impression of a supply cartel, citing the backlash over the uranium price-fixing cartel formed in the early 1970s as a response to the U.S. embargo on foreign uranium imports. [28]

Despite these concerns, the applicability of anti-trust law is ambiguous. U.S. law also holds that the United States should "provide a reliable supply of nuclear fuel to those nations and groups of nations which adhere to policies designed to prevent proliferation."[29] In addition, the control of inherently dual-use technologies such as enrichment and reprocessing should not be relegated to perfectly competitive markets. The goal of the multinational supply regime is not to fix prices above market rates. To do so would only invite the proliferation of sensitive fuel cycle capabilities that the regime seeks to prevent.

---

[27] United States Code, Title 42, Chapter 23, Subchapter IX, Section 2135.
[28] Telephone interview with Anonymous Official, Government of Canada, January 25, 2005.
[29] United States Code, Title 22, Chapter 47, Subchapter I, Section 3221. This language was part of the Nuclear Nonproliferation Act of 1978.

Findings: Political Feasibility

Government officials among potential supplier states expressed near universal interest in a multinational supply regime. However, the majority of subjects interviewed believed that insufficient political will exists to resolve difficult questions about how to structure and implement such a regime. In particular, a multinational supply regime must balance recipient state concerns about supply assurance and perceived NPT rights against supplier state concerns about proliferation and protection of commercial interests.

ASSURANCE OF SUPPLY

The viability of any multinational approach to the nuclear fuel cycle will depend on the *credibility* of nuclear fuel supply assurances. If potential recipient states believe that the market will be unable to satisfy their demand for nuclear fuel, or that policy changes in supplier state governments will jeopardize fuel deliveries and spent fuel removal, then they will be reluctant to forego domestic enrichment and reprocessing programs.

If the nuclear fuel cycle were not inherently dual-use, then the market would provide sufficient assurance of supply. As discussed above, current and planned uranium enrichment capacity will be sufficient to meet demand for the foreseeable future. In the event that unanticipated technical complications or accidents at one particular enrichment facility threaten to disrupt the timely supply of nuclear fuel to a recipient state, the typical 12 month lead time for procurement of enrichment services would allow the state sufficient time to locate an alternate supplier. Moreover, there is little reason to believe that the probability of such "acts of God" is high enough to warrant an indigenous enrichment program.

Rather, supply assurance concerns stem primarily from the possibility that policy changes in the governments of one or more supplier states will jeopardize the timely delivery of fresh fuel. Such was the case during the 1970s, when the United States was beginning to lose its virtual monopoly over uranium enrichment. In an effort to preserve U.S. market dominance, the Nixon administration launched a multilateralization initiative in 1971, offering unclassified gaseous diffusion technology to partner governments provided that new enrichment plants be placed under multinational control and made accessible to Atomic Energy Commission (AEC) personnel.

The initiative backfired because European governments found the technology restrictions overly burdensome and were moreover upset at being denied access to new centrifuge technology. As a result, the initiative actually accelerated the development of foreign enrichment plants, including France's Eurodif plant.[30] The U.S. Nuclear Non-Proliferation Act of 1978, which offered fuel supply assurances to countries that agreed to stringent nonproliferation conditions, instead raised further doubts about the reliability of the United States as a fuel supplier, and may have further driven foreign countries to acquire independent enrichment capabilities.[31]

Therefore, from the perspective of potential recipient states, the credibility of supply assurances varies directly with the number and "mix" of states that would control fuel supply decisions in a multinational regime. Given that four major suppliers occupy the current enrichment market, one can argue that potential recipient states would have greater protection against politically and commercially motivated supply disruptions than France and other European powers enjoyed during the 1970s. On the other hand, commercial suppliers must operate within the boundaries set by their respective governments, which often adopt like-minded policies. This is the principal drawback of the commercial supply consortium option. If the United States refused to allow fuel exports to a recipient state in order to protest the policies and actions of that state's government, then the United States would likely also pressure other potential supplier states (i.e. Australia, Canada, France, and Russia) to join in the nuclear embargo.

By contrast, the international nuclear fuel cycle center option would ostensibly provide the greatest degree of supply assurance. This option would place fuel supply decisions under the control of a multinational governing body (such as the IAEA) that would include

---

[30] See Wonder, Edward F., *Nuclear Fuel and American Foreign Policy: Multilateralization for Uranium Enrichment*, Atlantic Council Policy Paperback, Westview: Boulder (1977).
[31] See Neff, Thomas J. and Henry D. Jacoby, "Nonproliferation Strategy in a Changing Nuclear Fuel Market," *Foreign Affairs*, Summer 1979.

representatives from both supplier states and recipient states, decreasing the possibility that any one state could veto the supply of fuel to a recipient state for political reasons.

However, the international fuel cycle center option would clash with the commercial and national security interests of major nuclear supplier states upon whose participation fuel cycle centers would depend for their success. Supplier states would be unwilling to fund the construction of an international enrichment facility that would compete directly with domestic enrichers, and would likewise be unwilling to cede control of existing facilities to the IAEA. Moreover, as Dick Stratford noted, the United States would never turn title over nuclear material to the IAEA if there was a possibility that the IAEA would turn the material over to a suspected proliferator such as Iran.[32] Even if an international fuel cycle facility could overcome these hurdles, fuel supply would be vulnerable to interference by the "host" country.

HIDDEN AGENDAS

Even if a multinational supply regime offered compelling economic advantages and credible supply assurances, some potential recipient states might nevertheless continue to pursue indigenous fuel cycle capabilities. These states may cite assurance of supply as a convenient excuse to hide the fact that they are interested in acquiring sensitive nuclear fuel cycle capabilities for other reasons.

- **Nuclear Weapons Ambitions** – As explained above, some states may pursue enrichment and reprocessing capabilities in order to develop nuclear weapons, or at least a capability to rapidly produce such weapons upon a political decision to do so.

- **Naval Propulsion** – Naval nuclear reactors operate on uranium that is enriched to near-weapons-grade levels. States that are interested in naval nuclear propulsion (such as Brazil) may therefore seek domestic enrichment capabilities to support nuclear navies.

[32] Interview with Richard J. Stratford, Director, Nuclear Energy Affairs, U.S. Department of State, January 18, 2005.

- **Commercial Interests** – Some states may see an opportunity to earn considerable revenue by entering the commercial enrichment and reprocessing markets. In addition, enrichment and reprocessing technologies could offer commercially valuable technological spin-offs.

- **National Pride** – Nationalism often motivates states to take actions that would, to the rational outside observer, seem to lack justification on economic and strategic grounds. For this group of states, acquisition of the complete fuel cycle might constitute a symbolic step towards energy independence and technological prowess that justifies the additional cost

It is unclear whether a multinational supply regime can address these non-economic motivations. Clearly, no degree of supply assurance will dissuade countries that are determined to proliferate. However, a multinational supply regime can cast further suspicion on the intentions of suspected proliferators, thereby making it easier for the international community to coordinate diplomatic, economic, and military responses.

In addition, a multinational regime could include certain punitive measures against holdout states. For example, the regime could make certain benefits, such as reactor-related assistance, available only to participating recipient states. The NSG could adopt a presumption of denial of all nuclear exports to holdout states. Enrichment suppliers could deny such states the opportunity to invest in future enrichment facilities, and the IAEA could deny them spots on its Board of Governors. However, it may be unreasonable to rate a multinational supply regime exclusively in terms of its ability to solve the most intractable cases. The regime's goal is not to guarantee nuclear fuel to suspected proliferators, but to accommodate states that undertake additional obligations *not* to proliferate.

NPT RIGHTS AND ACCESS TO TECHNOLOGY

The Nuclear Non-Proliferation Treaty (NPT) was designed to promote the peaceful use of nuclear power while at the same time limiting the spread of nuclear weapons. Article IV of the NPT recognizes the "inalienable right of all Parties to the Treaty to develop research, production, and use of nuclear energy for peaceful purposes."[33] Many non-nuclear weapon

[33] The Text of the NPT is available at http://www.state.gov/t/np/trty/16281.htm#treaty.

states party to the NPT, including potential supplier states, believe that this "inalienable right" includes the right to acquire national enrichment and reprocessing capabilities, subject to IAEA safeguards.

The United States does not share this interpretation of the treaty. Rather, Article IV guarantees non-nuclear weapon states an "inalienable right" to nuclear power for peaceful purposes only in conformity with the nonproliferation obligations stated in Articles I and II of the treaty. According to the U.S. interpretation, acquisition of enrichment and reprocessing technologies should constitute a *de facto* violation of these nonproliferation obligations. However, unless the United States can convince the international community to accept this more restrictive interpretation of Article IV, any multinational approach that entails permanent renunciation of access to enrichment and reprocessing capabilities by non-nuclear weapon states will fail to win broad international support.

Past efforts to establish multinational fuel cycle controls have stumbled over the issues of access to sensitive technologies. The 1971 Nixon administration multilateralization initiative failed to win international support because the United States refused to share state-of-the-art centrifuge technology, sparking accusations that the United States was only interested in limiting commercial competition.[34] A 1974 initiative spearheaded by Henry Kissinger, unlike the 1971 initiative, encouraged private sector enrichers to share centrifuge technology and ownership of production with prospective foreign partners. This initiative failed because industry was reluctant to share proprietary technology.[35]

In particular, the issue of access to technology creates deep divisions over proposals to establish regional fuel cycle partnerships. Potential supplier states, including the United States and France, prefer the Eurodif model, which would allow recipient states to take an equity stake in an enrichment facility, enjoy priority access to nuclear fuel, and participate in facility administration, but would not allow any access to sensitive technology.

---

[34] Wonder, Edward F., *Nuclear Fuel and American Foreign Policy: Multilateralization for Uranium Enrichment*, pp. 23-25.
[35] Ibid., pp. 48-49.

However, it is unclear whether a Eurodif-style arrangement offers sufficient incentives to potential recipient states to forego access to technology. Lawrence Scheinman suggested that, for recipient states without hidden agendas, it would make little sense to compete with a business arrangement that gives them an equity stake in a fuel cycle facility and guarantees priority access to fuel that it would be more costly to produce otherwise.[36] On the other hand, fuel deliveries to recipient states could be held ransom to policy changes in the state holding the technology. Moreover, recipient state participation would depend on domestic political developments. As one of the original Eurodif partners, Iran invested $1 billion in the construction of the first Georges Besse enrichment plant in France. After the 1979 revolution, Iran withdrew its investment, sparking a protracted legal dispute with France.

By contrast, potential recipient states prefer the Urenco model because it allows members to share resources and technological expertise with other members of the partnership. However, the United States regards access to technology as a deal-breaker for any multinational supply regime, and therefore opposes the Urenco model. As Stratford noted, the Urenco option could facilitate the very problem that the United States is trying to prevent: the spread of sensitive technologies to a handful of new countries that could then use them to develop indigenous fuel cycle capabilities or sell them to potential proliferators.[37]

Moreover, if a multinational supply regime can offer credible supply assurances, it is unclear whether recipient can demonstrate a compelling need for access to sensitive technology. As Dr. Ashton B. Carter notes, just as every country that uses computers does not need a capability to make computer chips, every country that relies on nuclear power does not need the capability to enrich uranium or reprocess spent fuel.[38]

SPENT FUEL MANAGEMENT

For potential recipient states that face political, technological, or environmental obstacles to spent fuel storage and disposal, spent fuel removal guarantees can provide a major incentive to

---

[36] Interview with Dr. Lawrence Scheinman, Distinguished Professor, Monterey Institute of International Studies, January 26, 2005.
[37] Interview with Richard J. Stratford, January 18, 2005.
[38] Conversation with Dr. Ashton B. Carter, Ford Foundation Professor of Science and International Affairs, John F. Kennedy School of Government, Harvard University, February 23, 2005.

participate in a multinational supply regime. Stratford remarked that most states and utilities would be willing to pay in order to have their spent fuel removed, even if they eventually had to eventually take back the high-level waste.[39] However, spent fuel takeback may prove equally problematic for many potential supplier states. In the case of the United States, for example, it would be difficult to convince Congress to authorize storage and disposal of foreign spent fuel on U.S. territory, especially given the uncertain future for storage of U.S. nuclear waste at the Yucca Mountain repository.

Given these political and environmental concerns, the IAEA Experts Group found considerable interest in multinational options for storage and geologic disposal of spent fuel.[40] In particular, proposals for an international spent fuel storage facility are attracting widespread interest. Russia is currently the only realistic candidate for an international spent fuel storage facility. In 2001, the Russian Duma passed legislation that would allow Russia to import spent nuclear fuel from foreign countries. Russian government officials interviewed for this study confirmed that Russia remains interested in hosting an international spent fuel storage facility.[41]

However, prior consent rights represent a major stumbling block. Given the size of current world stockpiles of separated plutonium, the United States currently opposes the reprocessing of U.S.-origin spent fuel. Although Russian officials stated that Russia has no immediate plans to reprocess, they refused to rule out the option. As Stratford noted, it would be difficult to convince Congress to help fund Russia's plutonium disposition program while at the same time asking for its permission to allow Russia to profit by producing more plutonium.[42]

SUPPLIER STATE PARTICIPATION AND COORDINATION

Many subjects interviewed for this report expressed concern that a multinational supply regime would be too difficult to coordinate. In particular, many felt that the international fuel cycle center option would involve balancing the interests and demands of so many governments, on

---

[39] Interview with Richard J. Stratford, Director, Nuclear Energy Affairs, U.S. Department of States, January 18, 2005.
[40] Ibid.
[41] Interview with Anonymous Russian Officials, January 19, 2005.
[42] Ibid.

so many issues, that it would be impossible to achieve any sort of political consensus on how to proceed.

On the other hand, some foreign government officials, including officials from France and Canada, endorsed the commercial supply consortium option. This option would require supplier state governments to coordinate a common set of criteria governing nuclear exports, with a consistent set of nonproliferation obligations for recipient states. Although the Nuclear Suppliers Group guidelines were intended to foster such coordination, each supplier state currently implements its own version of the NSG guidelines, and some states have adopted additional restrictions beyond those called for by the NSG.

Australia[43] – Australia possesses the world's largest uranium reserves and is the world's second largest uranium producer and exporter. It is also a staunch U.S. ally and would therefore be a desirable partner in a multinational supply regime. Although one Australian official remarked that Australia is currently "agnostic" about the likely effectiveness of such a regime, he commented that the commercial supply consortium option might present an interesting path forward. Such a consortium could allow Australia to manage the emergence of nuclear power programs in Indonesia and elsewhere in Southeast Asia, a front-line region in the war on terror and thus a region of primary importance to Australian national security.

Australian nonproliferation policy requires a bilateral safeguards agreement with any country that receives or handles Australian-origin uranium. Each bilateral agreement requires coverage of uranium exports by IAEA safeguards over the lifetime of the material, fallback safeguards in the event that IAEA safeguards fail to apply, prior Australian consent for the transfer of Australian-origin material to a third party, prior consent for reprocessing of Australian-origin material, and strict physical security requirements.[44] Although Australia currently has concluded bilateral agreements with all potential consortium supplier states, including Russia, it currently does not allow Russia to enrich Australian uranium due to concerns surrounding

[43] Unless otherwise noted, comments are based on a telephone interview with Anonymous Official, Government of Australia, February 22, 2005.
[44] "Australia's Uranium Exports Policy," Department of Foreign Affairs and Trade, Government of Australia, http://www.dfat.gov.au/security/aus_uran_exp_policy.html

Russia's material accounting practices. For the same reason, Australia is hesitant to allow storage of Australian-origin spent fuel in Russia, although it is interested in exploring proposals for international spent fuel storage.

Brazil[45] – Brazilian government officials expressed support for the general concept of a multinational consortium of nuclear fuel suppliers, but stated that Brazil would only participate as a supplier state, and not as a recipient state. They explained that Brazil was interested developing its sizable uranium reserves (the sixth largest reserves in the world) in order to provide for its domestic nuclear electricity needs and to eventually compete in the commercial market. National pride may also be a driving force behind Brazil's nuclear program. However, some U.S. officials remarked that Brazil's primary motivation for acquiring a domestic enrichment capability is to produce HEU for naval nuclear propulsion. Brazil may therefore represent one of the few cases in which non-economic motives may overwhelm the economic appeal of multinational supply.

Canada[46] – Officials from Canada, the world's largest producer and exporter of uranium, expressed interest in exploring proposals for multinational control over enrichment and reprocessing. In particular, they favored a variation of the commercial consortium option involving a small group of countries (such as the G-8) and IAEA participation (but not IAEA control). One official suggested an arrangement whereby uranium would be mined and converted in Canada, enriched in France or the United States, and delivered to the recipient country, with the spent fuel removed to Russia for long-term storage. The official also suggested that an international uranium bank could provide additional supply assurance, provided that it did not interfere with the market.

However, the official noted that the arrangement must be consistent with both the Article IV rights of non-nuclear weapon states and Canada's nonproliferation policies and prior consent laws. Canada currently does not allow Russia to enrich Canadian-origin uranium. Canada also opposes the removal of Canadian-origin spent fuel to a country that intends to reprocess it. In addition, Canada is still embarrassed by its role in supporting India's nuclear weapons

45 Telephone interview with Anonymous Official, Government of Brazil, January 27, 2005.
46 Telephone Interview with Anonymous Official, Government of Canada, January 25, 2005.

program, and, as mentioned above, is wary of creating the impression of a cartel among uranium producers and enrichers, citing the backlash Canada suffered as a result of its participation in the uranium price-fixing cartel during the 1970s.

Finally, Canadian officials stated that, although Canada currently possesses no enrichment or reprocessing facilities, it wants to retain the option to develop such facilities in the future. They further suggested that Canada's next generation of nuclear reactors, which it may seek to export, may not run on natural uranium.

France[47] – French officials favored a regional partnership option modeled after Eurodif, one of the world's major commercial enrichment providers. While they were also open to proposals for a commercial supply consortium, they reiterated that all countries participating in the consortium must subscribe to the same set of policies and criteria governing the supply of fresh fuel. Whereas Canada opposed reprocessing of Canadian-origin spent fuel, French officials expressed interest in the closed fuel cycle and opposed permanent storage of French-origin spent fuel in a repository.

At the 2004 Preparatory Committee meeting for the 2005 NPT Review Conference, France proposed a number of criteria to govern transfers of sensitive enrichment and reprocessing technologies. The criteria included traditional nonproliferation obligations such as adoption of the IAEA Additional Protocol, effective export controls and physical security standards, and a commitment to non-weapons use, as well as more subjective criteria such as a demonstrated energy requirement in the recipient state, a credible nuclear power generation program, and an economic justification for sensitive fuel cycle facilities.[48] However, Stratford remarked that the United States does not support any criteria-based approach that could plausibly allow countries such as Iran to legitimately acquire enrichment and reprocessing technologies.[49]

---

[47] Unless otherwise noted, comments are based on telephone interview with Anonymous Official, Atomic Energy Commission of France, January 31, 2005.
[48] "Strengthening the Nuclear Non-Proliferation Regime," Working Paper Submitted by the Government of France to the Preparatory Committee for the 2005 Review Conference of the Parties to the Treaty on the Non-Proliferation of Nuclear Weapons, May 4, 2004.
[49] Interview with Richard J. Stratford, January 18, 2005.

Japan[50] – Japanese officials viewed a multinational supply regime as a potential complement to strengthened efforts in the area of safeguards and export controls, but were skeptical of how the regime would directly support nonproliferation objectives. One official expressed concern about the impact of a multinational supply regime on Japan's own fuel cycle program. With few domestic energy resources, Japan is especially sensitive to the threat of supply disruption.

Russia[51] – Russian participation is essential to the success of any multinational supply regime. In addition to its vast uranium reserves, Russia possesses large military stockpiles of HEU and provides a large fraction of global enrichment capacity. Most important, Russia is the only realistic candidate for international spent fuel storage. However, Russian officials expressed only lukewarm interest in a multinational supply regime, citing concerns that the regime might require controversial changes in the legal understanding of the NPT. They added that the regime should be demonstrated on a small, pilot-scale before attempting to secure the participation of a large number of governments.

A multinational supply regime might also involve the downblending of additional Russian weapons-origin HEU, another important U.S. nonproliferation objective. Additional downblending need not be conducted under the auspices of a mammoth follow-on deal to the current U.S.-Russian HEU Purchase Agreement. The prospects for a follow-on deal are uncertain. Rather, supplier states can contract with Russia to blend down small quantities of HEU in order to create a safety net against market disruption. Although Russian officials did not dismiss the idea, they implied that Russia had more pressing concerns and that the international community would have to do more than simply cover the costs of additional downblending.

United States – Although the United States agreed to provide constructive advice to the IAEA Experts Group, Energy and State Department officials generally felt that a multinational supply regime would be too problematic to implement, and thus not worth the trouble. Jon Phillips added that any approach based on the open, once-through fuel cycle would not be viable over

---

50 Interview with Anonymous Official, Government of Japan, January 28, 2005; "Comment by Ambassador Tetsuya Endo (Japan) Prepared for Third Meeting of MNAs," January 10, 2005.
51 Interview with 2 Anonymous Officials, Embassy of Russia, January 19, 2005.

the long term, and that technical solutions involving advanced closed fuel cycle technologies might ultimately be necessary.[52] However, Stratford indicated that a multinational supply regime could help reduce the long-term proliferation dangers associated with the expansion of nuclear power.

Industry officials expressed enthusiastic support for the commercial consortium option. Lisa Gordon-Hagerty of USEC stated that for any such consortium to be effective, it should be limited to a small number of suppliers, rely on market-based pricing, and minimize government interference.[53] For example, she suggested an arrangement in which USEC acts either as the sole supplier of enrichment services or forms a small partnership with Eurodif and/or TENEX. She noted that such an arrangement, if offered to Iran, could both improve U.S.-Iranian relations and improve U.S. intelligence on and control over Iran's nuclear program. However, she noted that Congress would have to relax current U.S. restrictions on doing business with Iran.

IAEA – The IAEA must play a visible, important role in any multinational supply regime. First, its participation can lend legitimacy. Without IAEA involvement, non-nuclear states might view a multinational supply regime as little more than an attempt by the United States and other nuclear fuel cycle states to deny access to technology and prevent market entry. Second, the IAEA would assume primary responsibility for safeguarding and inspecting nuclear facilities in potential recipient states.

Poneman, Scheinman, and Stratford all added that the IAEA could help add credibility to multinational supply assurances by brokering safety-net arrangements in the event that recipient states experience a disruption in their supply of nuclear fuel. According to its statute, the IAEA has the authority to act as a repository for nuclear fuel, a fact that led INFCE to propose establishing a nuclear fuel bank in the late 1970s. The proposal faltered, but could be revived in the form of a "Strategic Uranium Reserve," in which the IAEA secures commitments

---

[52] Interview with Jon Phillips, Program Director, Policy and Treaty Implementation, Office of International Safeguards, National Nuclear Security Administration, January 18, 2005.
[53] Telephone interview with Lisa Gordon-Hagerty, Executive Vice President and Chief Operating Officer, USEC, Inc., January 24, 2005.

from supplier states to transfer specific quantities of nuclear fuel in the event of a supply disruption.

The IAEA Experts Group report also identified several potential roles for the IAEA in a multinational supply regime, including as guarantor of fuel supply arrangements, administrator of a nuclear fuel bank, or as a key partner in "stronger multilateral arrangements – by region or by continent."[54] However, according to IAEA officials, the agency has yet to think through the specific details of how it would fulfill these responsibilities. Instead, the IAEA is waiting for its member states, including the United States, to provide feedback on the Experts Group report and to take the lead in forging a consensus on how to proceed.[55] As Dr. Tariq Rauf, Head of Verification and Security Policy Coordination at the IAEA, noted, the agency has no power to force a course of action upon its member states, and its role in any multinational supply regime will depend on member state direction and funding.[56]

The likelihood of such direction and funding is uncertain. Many subjects interviewed for this report expressed little confidence in the ability of the IAEA to play an effective administrative or managerial role as a fuel supply guarantor. There is also no guarantee that suppliers will ultimately deliver on their commitments. Stratford noted that the United States would not turn title over uranium to the IAEA without maintaining the right to veto the final destination of fuel deliveries.

---

[54] INFCIRC/640, p. 16.

[55] Telephone Interview with Dr. Fiona Simpson, Office of External Relations and Policy Coordination, International Atomic Energy Agency, March 30, 2005.

[56] Telephone Interview with Dr. Tariq Rauf, Head of Verification and Security Policy Coordination, International Atomic Energy Agency, April 1, 2005.

Conclusions and Recommendations

Although a multinational supply regime offers compelling economic advantages, it will be extremely difficult for supplier states to coordinate and implement an arrangement that attracts broad recipient state participation while simultaneously strengthening nonproliferation.

Moreover, a multinational supply regime may not solve the most difficult cases involving countries such as Iran whose motivations for acquiring sensitive fuel cycle technologies are fundamentally non-economic in nature. If one believes, as Thomas Neff does, that Iran is the *only* instance in which a state has attempted to develop a nuclear weapons program under the cover of civil nuclear power development, then one might conclude that a multinational supply regime is unnecessary.[57]

However, Iran is only one symptom of a much larger potential problem – the danger that the expansion of nuclear power will facilitate the proliferation of enrichment and reprocessing capabilities, and therefore multiply the risk that future states will follow in Iran's footsteps. The United States and the international community have a clear interest in developing a multinational supply regime that can preempt this long-term problem. Such a regime offers economic and nonproliferation advantages that are mutually reinforcing. The following four recommendations present the best option for an effective multinational supply regime.

RECOMMENDATION 1

IAEA member states should request that the agency facilitate the creation of a commercial supply consortium comprised of major uranium producers and enrichment providers.

In the near term, the most feasible option for creating an effective multinational supply regime is to create a commercial supply consortium that would include major uranium producers, such as Australia and Canada, and commercial enrichment companies from France (Eurodif-Areva),

[57] Neff, Thomas L., "The Nuclear Fuel Cycle and the Bush Nonproliferation Initiative," Paper submitted to the 2004 World Nuclear Fuel Cycle Conference, pp. 10-11.

Russia (TENEX), and the United States (USEC). The consortium would encourage widespread adoption of the once-through LWR fuel cycle with high burnup.

Table 4: Potential Supply Consortium Participants

Country	Company	Activity
Australia	Rio Tinto, Ltd.	Uranium Production
Canada	Cameco Corporation	Uranium Production / Conversion
France	Areva (Eurodif)	Conversion / Enrichment
Russia	PPGHO	Uranium Production
	TENEX	Conversion / Enrichment
United States	USEC, Inc.	Enrichment

In order to foster the perception of international legitimacy, the United States and other supplier states should allow the IAEA to facilitate the creation of the consortium. In particular, the IAEA would bring together willing supplier state governments to negotiate an intergovernmental agreement that would establish a political framework for industry, acting as the executive agents of their respective governments, to cooperate in meeting global nuclear fuel needs.

The agreement would include a pledge guaranteeing the safe and timely supply of LEU fuel to states with civil nuclear power programs. If one supplier state is unable to deliver on its commitments (for reasons not related to suspicions of proliferation), the agreement would obligate the rest of the supplier states to meet the affected recipient state's needs from existing inventories. The defaulting supplier state would either have to restock those inventories or provide financial compensation to the other supplier states.

Supplier states should also negotiate, with IAEA assistance, a model safeguards agreement that would apply to all transactions between any member (or combination of members) of the supply consortium and any recipient state. As such, it would require Canada and Australia to modify their current bilateral safeguards agreements with Russia to allow for Russian enrichment of Canadian and Australian uranium. It would also require the five supplier states to forge a common position on re-transfer of sensitive material and technology as well as spent fuel management.

The model safeguards agreement would specify a common set of nonproliferation obligations applicable to recipient states. At a minimum, recipient state obligations should include:

- Membership of the NPT as a non-nuclear weapon state;
- A pledge not to develop nuclear energy for explosive purposes;
- Submission to IAEA safeguards and adoption of the Additional Protocol;
- A pledge not to re-sell or transfer nuclear fuel or spent fuel to third parties without prior consent of the supplier;
- Adherence to strict standards for the physical protection of nuclear materials during transport, storage, and use; and
- A **temporary** commitment to forego development of indigenous enrichment and reprocessing capabilities, **renewable every 10 years**.

The requirement for temporary renunciation of indigenous enrichment and reprocessing is especially important as it attempts to sidestep any paralyzing arguments over Article IV of the NPT. Theoretically, recipient states should find a 10-year abstention politically more acceptable than a permanent renunciation. If the multinational approach proves effective over the initial 10 years, recipient states might be willing to voluntarily agree to further, possibly indefinite abstention.

Over the long-term, supplier states could also offer additional incentives exclusively to recipient states, provided that they establish a track record of good behavior. When it becomes necessary to add capacity to the enrichment market, supplier states could offer recipient states the opportunity to take an equity and managerial stake in the construction and operation of new enrichment plants. As with the original Eurodif model, recipient states would also enjoy priority access to enrichment plant output. In addition, supplier states could provide recipient states with assistance building new LWR or opportunities to cooperate in developing advanced reactor concepts. States that refuse to participate would be denied all of these benefits.

The commercial supply consortium offers incentives to all potential stakeholders. Industry participants would enjoy preferential access to new markets and an opportunity to prevent the emergence of commercial competition. Supplier state governments would achieve nonproliferation benefits by slowing the spread of enrichment and reprocessing technologies. Recipient states would avoid the capital costs associated with the indigenous nuclear fuel cycle as well as the political, financial, and environmental hassles associated with spent fuel management. Simply put, recipient states would receive benefits for not engaging in activities in which they have no compelling justification to engage in the first place.

RECOMMENDATION 2

To provide an additional layer of supply assurance, supplier state governments should create a "strategic uranium reserve" by financing the downblending of additional Russian weapons-origin HEU into LEU fuel for power reactors.

Creation of a strategic uranium reserve would further ease the long-term supply concerns of recipient states. It would also link efforts to control the spread of sensitive fuel cycle technologies with another important U.S. nonproliferation objective – the elimination of Russia's vast stockpile of weapons-usable highly enriched uranium.

Supplier states would pay Russia to downblend specific quantities of weapons-origin HEU into LEU. The material would then be held off the market, and stored either entirely in Russia or distributed among the supplier states in proportion to their initial contributions. The uranium strategic reserve would be administered by a joint committee comprised of representatives from supplier states, the IAEA, and participating recipient states.

In the event that a supplier state is unable to meet its fuel supply obligations (for reasons other than suspicions of proliferation activity), the affected recipient state would petition the joint committee for permission to draw upon the strategic reserve to meet its fuel needs. The supplier state would then be responsible for replenishing the reserve.

Supplier states could count their contributions to the strategic reserve towards their commitments under the G-8 Global Partnership Against the Spread of Weapons and Materials of Mass Destruction. Although the G-8 initiative pledged a total of $20 billion through 2012, only $10 billion is expected to be committed by the end of 2007.[58] Much of this amount finances a wide range of diverse projects, including submarine dismantlement, environmental clean-up, and chemical weapons destruction. By contrast, the concept of a uranium strategic reserve can provide a broad, unifying goal for the G-8 initiative as member countries consider how best to fulfill their remaining commitments. Participation would also serve the economic interests of certain G-8 members, such as Japan, that are heavily dependent on foreign sources of enrichment. These states might even be willing to pay a small premium for access rights to the reserve.

The primary obstacle to the uranium strategic reserve will be willingness to participate on the part of Russia. Although Russian officials did not oppose the concept, they stated that Russia had many other competing priorities. In particular, Laura Holgate noted that Russia may be planning to use its remaining surplus HEU to support its own domestic nuclear power expansion.[59] She added that additional HEU downblending might strain Russia's enrichment capacity because Russia must use uranium enriched to 1.5% as blendstock in order to meet reactor operating specifications.[60] Although Russia will likely not consent to additional downblending unless it receives a heavy premium, the United States and the rest of the G-8 should theoretically be willing to pay such a premium to achieve mutual nonproliferation goals.

RECOMMENDATION 3

Construct an international spent fuel storage facility in Russia.

Spent fuel removal guarantees can provide a major incentive for recipient states purchase services from the commercial supply consortium instead of pursuing indigenous spent fuel storage. Such guarantees would also ensure that recipient states do not reprocess spent fuel to

---

[58] "Global Partnership Update: January 2005," Center for Strategic and International Studies, http://sgpproject.org/publications/GPUpdates/GPUpdateJan2005.pdf.

[59] Interview with Laura Holgate, Vice President for Russia/NIS Programs, Nuclear Threat Initiative, February 16, 2005.

[60] Ibid.

recover weapons-usable plutonium. The United States should therefore work closely with foreign governments, industry, the IAEA, and Russia to move ahead with plans to construct an international spent fuel storage facility in Russia.

Russia would own and operate the spent fuel storage facility, and would subject it to IAEA safeguards and inspections. However, states from which spent fuel originated would retain prior consent rights over the fate of their fuel. In addition, Russia would agree not to reprocess spent fuel for a specific period of time, perhaps 20 or more years. Given that Russian officials indicated that Russia does not plan to reprocess in the near future, Russia should not be unwilling to make such a commitment.

Utilities and governments for whom domestic spent fuel storage is either financially or politically infeasible should be willing to pay to have their spent fuel removed to the Russian facility. U.S. utilities already pay a small surcharge to support licensing and construction of the Yucca Mountain repository. Similarly, recipient states participating in a multinational supply regime would pay a per-kilogram spent fuel removal charge that would help cover Russia's costs. The charge would depend on the number of contributing states and the size of the storage facility.

RECOMMENDATION 4

Strengthen other options in the nonproliferation "toolkit".

The multinational approach outlined above is not a magic bullet solution to the proliferation problem. Rather, a multinational supply regime constitutes one strategy among a series of interdependent and mutually reinforcing policies for combating proliferation. Commercial supply assurances backed by a uranium strategic reserve and international spent fuel storage will provide few nonproliferation benefits without parallel efforts to strengthen other options for nonproliferation and counter-proliferation. In particular, the United States and the international community should continue to strengthen international export control regimes by encouraging greater NSG coordination; improve nuclear intelligence and detection capabilities per the recommendations of the recent WMD commission; and expand interdiction programs such as the Proliferation Security Initiative.

CONCLUSION

It may ultimately prove impossible to completely stem the dissemination of sensitive fuel cycle technologies. However, as nuclear power continues to expand, the four recommendations outlined above can help slow the spread of enrichment and reprocessing capabilities by providing an economically attractive alternative to an indigenous nuclear fuel cycle. Although a multinational supply regime may not stop determined proliferators such as Iran from pursuing nuclear weapons, it can cast increased suspicion upon their intentions by exposing any purported economic or commercial justifications for their nuclear programs as illegitimate. In so doing, the multinational supply regime can remove political barriers to building international coalitions to confront proliferators with diplomatic pressure, economic sanctions, or military force if necessary.

Annex 1

IAEA EXPERTS GROUP REPORT: FIVE SUGGESTED MULTINATIONAL APPROACHES
(Excerpted from "Multilateral Approaches to the Nuclear Fuel Cycle," INFCIRC/640, p.16)

INFCIRC/640 - 22 February 2005

Five Suggested Approaches

The objective of increasing non-proliferation assurances associated with the civilian nuclear fuel cycle, while preserving assurances of supply and services around the world could be achieved through a set of gradually introduced multilateral nuclear approaches (MNA):

1. Reinforcing **existing commercial market mechanisms** on a case-by-case basis through long-term contracts and transparent suppliers' arrangements with government backing. Examples would be: fuel leasing and fuel take-back offers, commercial offers to store and dispose of spent fuel, as well as commercial fuel banks.

2. Developing and implementing **international supply guarantees** with IAEA participation. Different models should be investigated, notably with the **IAEA as guarantor** of service supplies, e.g. as administrator of a fuel bank.

3. Promoting voluntary conversion of **existing facilities to MNAs**, and pursuing them as **confidence-building measures**, with the participation of NPT non-nuclear-weapon States and nuclear-weapon States, and non-NPT States.

4. Creating, through voluntary agreements and contracts, **multinational, and in particular regional, MNAs for new facilities** based on joint ownership, drawing rights or co-management for front-end and back-end nuclear facilities, such as uranium enrichment; fuel reprocessing; disposal and storage of spent fuel (and combinations thereof). Integrated nuclear power parks would also serve this objective.

5. The scenario of a further expansion of nuclear energy around the world might call for the development of a **nuclear fuel cycle with stronger multilateral arrangements** – by region or by continent - **and for broader cooperation**, involving the IAEA and the international community.

Annex 2

Base Case Assumptions For Multinational Supply

Parameter	Unit of Measurement	Assumed Value
Uranium Oxide (U_3O_8) Requirement	kgU/kgHM in fresh fuel	10.15
Unit Cost of U_3O_8	\$/kgU in U_3O_8	55.00
Unit Cost of Conversion	\$/kgU in U_3O_8 converted to UF_6	10.00
Loss During Conversion	Fraction Lost	0.005
Uranium Into Enrichment	kgU in UF_6/kgHM of fresh fuel	10.10
Cost of Enrichment	\$/SWU	110.00
Enrichment Requirement	SWU/kgHM in fresh fuel	6.26
Enrichment Level	Fraction U-235	0.045
Tails Assay	Fraction U-235	0.0030
Unit Cost of Fuel Fabrication	\$/kgHM in fresh fuel	250.00
Loss During Fuel Fabrication	Fraction Lost	0.01
Spent Fuel Removal Charge	\$/kgHM in fresh fuel	260.00
Unit Cost of Fuel		
Uranium Acquisition	\$/kgHM in fresh fuel	558.28
Conversion	\$/kgHM in fresh fuel	101.51
Enrichment	\$/kgHM in fresh fuel	688.41
Fuel Fabrication	\$/kgHM in fresh fuel	250.00
Spent Fuel Removal Charge	\$/kgHM in fresh fuel	260.00
TOTAL UNIT COST	\$/kgHM in fresh fuel	**\$1858.20**

Uranium Oxide (U_3O_8) Requirement

The uranium oxide requirement is the amount of uranium in U_3O_8 necessary to produce 1kg of heavy metal in fresh fuel. It can be calculated as follows:

$$U_3O_8 \text{ Requirement} = \text{Uranium into enrichment x (1 + Loss During Conversion)}$$

Cost of U_3O_8

The Cost of U_3O_8 is the long-term contract price as of December 27, 2004, converted from $/lb to $/kg.[61]

61 *The Ux Weekly*, January 24, 2005.

Unit Cost of Conversion

The cost of conversion (from U_3O_8 to uranium hexafluoride, or UF_6) is the EU conversion price as of December 27, 2004.[62]

Loss During Conversion

The fraction of uranium lost during conversion is assumed to be 0.005, the value assumed in the 1994 OECD-NEA report on the *Economics of the Nuclear Fuel Cycle*.

Uranium Into Enrichment

The quantity of uranium feed into enrichment is given by the equation:

Feed = (Xp-Xt) / (Xf-Xt) * (1 + Fraction Lost During Fuel Fabrication)

where Xp is the fraction U-235 in the enriched product, Xt is the fraction U-235 in the enrichment tails, and Xf is the fraction U-235 of the feed material (natural uranium).

In addition, according to the OECD Nuclear Energy Agency, this amount must be adjusted to account for loss of uranium during the fuel fabrication stage. Losses during other stages are considered negligible.[63]

Cost of Enrichment

The cost of enrichment is the long-term contract price per separative work unit (SWU) as of December 27, 2004.[64]

Enrichment Requirement

The Enrichment Requirement is expressed in terms of "Separative Work Units" (SWU), given by the equation:

SWU = V(Xp) + (F-1)*V(Xt) - F*V(Xf)

where the "separation potential", V(X) = (2X-1)ln[X / (1-X)]

SWU Calculation		
	Fraction U-235 (X)	V(X)
Product	0.0450	2.7801
Tails	0.0030	5.7713
Feed	0.0072	4.8555

---

62 Ibid.

63 *Management and Disposition of Excess Weapons Plutonium*, National Academy of Sciences, 1995; Economics of the Nuclear Fuel Cycle, OECD-NEA, 1994.

64 *The Ux Weekly*, January 24, 2005.

Enrichment Level

An enrichment level of 4.5% U-235 is typical for most LWR.

Tails Assay

The tails assay refers to the fraction U-235 in the enrichment tails, the depleted "wastes" of the enrichment process. Given that uranium prices are rising, this report assumes a tails assay of 0.3%.

Unit Cost of Fuel Fabrication

The unit cost of fuel fabrication is assumed to be $250/kg of initial heavy metal in fresh fuel, a central estimate based on previous estimates made by the OECD Nuclear Energy Agency, the National Academy of Sciences, and Harvard University.[65]

Loss During Fuel Fabrication

The fraction of enriched uranium product lost during fuel fabrication is assumed to be 0.01, the value assumed in the 1994 OECD-NEA report on the *Economics of the Nuclear Fuel Cycle*.

Spent Fuel Removal Surcharge

The assumed value of the spent fuel removal surcharge reflects the $0.001 / kWh that the Department of Energy charges U.S. utilities to fund the Yucca Mountain repository. According to the 1995 National Academy of Sciences report on *Management and Disposition of Excess Weapons Plutonium*, this surcharge translates to approximately $260 per kilogram of heavy metal in fresh fuel.

Unit Cost of Fuel ($/kgHM in fresh fuel)

Cost of Uranium Acquisition ($/kgHM) = Uranium Oxide Requirement (kgU/kgHM) x
Cost of U_3O_8($/kgU in U_3O_8)

Cost of Conversion ($/kgHM) = Uranium Oxide Requirement (kgU/kgHM) x
Unit Cost of Conversion ($kgU in U_3O_8 converted to UF6)

Cost of Enrichment ($/kgHM) = SWU Requirement (SWU/kgHM) x SWU Cost ($/SWU)

Cost of Fuel Fabrication ($250/kgHM) and Spent Fuel Removal Charge ($260/kgHM) are given.

---

[65] Bunn, Matthew, et al, *Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel*, pp. 55-56.

Cost of Multinational Supply (Base Case)

Recipient Country Reactor Specifications	
Reactor Type	Light Water Reactor (LWR)
Number of Operational LWR	1
Capacity (MWe)	1,000
Capacity Factor	0.9
Burnup (MWd/kgHM in fresh fuel)	50
Thermal Efficiency	0.33
Operational Lifetime (years)	40
Total Output over Reactor Lifetime (MWd-thermal)	39,818,182
Quantity of Fuel Required to Produce Total Output (kgHM)	796,364
Total Unit Cost of Fuel ($kgHM)	1858.20
TOTAL OVERNIGHT COST ($millions)	**1,480**

Reactor Type

Given that the once-through LWR fuel cycle possesses advantages in terms of cost, safety, and proliferation resistance, this report assumes that a multinational supply regime will encourage recipient states to rely on LWR for civil nuclear power generation.

Capacity

A typical LWR has a nameplate capacity of 1,000MW(e).

Capacity Factor

Reactors rarely operate at full capacity, and must occasionally be shut down to unload spent fuel and load fresh fuel. The capacity factor refers to the ratio of actual reactor power generation to power generation at full capacity. According to the Nuclear Regulatory Commission, the U.S. nuclear industry operates at an average capacity factor of 0.9, the value assumed in this report.

Burnup

LWR burnup typically varies between 30MWd/kgHM and 50MWd/kgHM. Given that countries will likely move gradually to higher burnup levels as uranium prices increase, this report assumes a burnup level of 50MWd/kgHM, the upper end of the range.

Thermal Efficiency

Thermal efficiency (or conversion efficiency) refers to the fraction of reactor power generation that is actually converted into electricity. A typical nuclear power reactor has a conversion efficiency of approximately one-third. Thus, a 1,000MW(electric) reactor has an actual generation capacity of 3,000MW(thermal). This report assumes a thermal efficiency of 0.33.

Operational Lifetime

This report assumes a typical 40 year operational lifetime for LWR.

Total Output Over Reactor Lifetime

Total reactor output (in MWd-thermal) is equal to:

$$\frac{\text{Capacity (MWe)}}{\text{Thermal Efficiency}} \times \text{Capacity Factor} \times 40\text{yrs} \times 365\text{days/yr}$$

Quantity of Fuel Required to Produce Total Output

The total quantity of fuel (kgHM) required to produce total thermal output over a 40 year reactor lifetime is equal to:

Total Output (MWd-thermal) / Burnup (MWd/kgHM)

Total Overnight Cost of Fuel Lease

The overnight cost of sufficient fuel to power a 1,000MW(e) LWR over its lifetime is equal to:

Fuel Required to Produce Total Output (kgHM) x Unit Cost of Fuel ($/kgHM)

Discounted Present Value and Levelized Annual Cost of Multinational Supply (Base Case)

Assumed Discount Rate: r = 0.05

Year	Uranium Acquisition	Conversion	Enrichment	Fuel Fabrication	Spent Fuel Removal	Total Levelized Annual Cost	Discount Factor	PV of LAC Payments
1	11.11	2.02	13.71	4.98	5.18	**37.00**	0.95	35.23
2	11.11	2.02	13.71	4.98	5.18	**37.00**	0.91	33.56
3	11.11	2.02	13.71	4.98	5.18	**37.00**	0.86	31.96
4	11.11	2.02	13.71	4.98	5.18	**37.00**	0.82	30.44
5	11.11	2.02	13.71	4.98	5.18	**37.00**	0.78	28.99
6	11.11	2.02	13.71	4.98	5.18	**37.00**	0.75	27.61
7	11.11	2.02	13.71	4.98	5.18	**37.00**	0.71	26.29
8	11.11	2.02	13.71	4.98	5.18	**37.00**	0.68	25.04
9	11.11	2.02	13.71	4.98	5.18	**37.00**	0.64	23.85
10	11.11	2.02	13.71	4.98	5.18	**37.00**	0.61	22.71
11	11.11	2.02	13.71	4.98	5.18	**37.00**	0.58	21.63
12	11.11	2.02	13.71	4.98	5.18	**37.00**	0.56	20.60
13	11.11	2.02	13.71	4.98	5.18	**37.00**	0.53	19.62
14	11.11	2.02	13.71	4.98	5.18	**37.00**	0.51	18.68
15	11.11	2.02	13.71	4.98	5.18	**37.00**	0.48	17.80
16	11.11	2.02	13.71	4.98	5.18	**37.00**	0.46	16.95
17	11.11	2.02	13.71	4.98	5.18	**37.00**	0.44	16.14
18	11.11	2.02	13.71	4.98	5.18	**37.00**	0.42	15.37
19	11.11	2.02	13.71	4.98	5.18	**37.00**	0.40	14.64
20	11.11	2.02	13.71	4.98	5.18	**37.00**	0.38	13.94
21	11.11	2.02	13.71	4.98	5.18	**37.00**	0.36	13.28
22	11.11	2.02	13.71	4.98	5.18	**37.00**	0.34	12.65
23	11.11	2.02	13.71	4.98	5.18	**37.00**	0.33	12.04
24	11.11	2.02	13.71	4.98	5.18	**37.00**	0.31	11.47
25	11.11	2.02	13.71	4.98	5.18	**37.00**	0.30	10.92
26	11.11	2.02	13.71	4.98	5.18	**37.00**	0.28	10.40
27	11.11	2.02	13.71	4.98	5.18	**37.00**	0.27	9.91
28	11.11	2.02	13.71	4.98	5.18	**37.00**	0.26	9.44
29	11.11	2.02	13.71	4.98	5.18	**37.00**	0.24	8.99
30	11.11	2.02	13.71	4.98	5.18	**37.00**	0.23	8.56
31	11.11	2.02	13.71	4.98	5.18	**37.00**	0.22	8.15
32	11.11	2.02	13.71	4.98	5.18	**37.00**	0.21	7.76
33	11.11	2.02	13.71	4.98	5.18	**37.00**	0.20	7.39
34	11.11	2.02	13.71	4.98	5.18	**37.00**	0.19	7.04
35	11.11	2.02	13.71	4.98	5.18	**37.00**	0.18	6.71
36	11.11	2.02	13.71	4.98	5.18	**37.00**	0.17	6.39
37	11.11	2.02	13.71	4.98	5.18	**37.00**	0.16	6.08
38	11.11	2.02	13.71	4.98	5.18	**37.00**	0.16	5.79
39	11.11	2.02	13.71	4.98	5.18	**37.00**	0.15	5.52
40	11.11	2.02	13.71	4.98	5.18	**37.00**	0.14	5.25
TOTAL	**444.59**	**80.83**	**548.23**	**199.09**	**207.05**	**1479.80**		**634.80**

Annex 3

Subjects interviewed for this report are listed below. In some cases, subjects requested that their identities be withheld.

Steven Aoki
Acting Deputy Under Secretary for Counterterrorism
U.S. Department of Energy

Robert J. Einhorn
Senior Advisor, International Security Program
Center for Strategic and International Studies

Lisa Gordon-Hagerty
Executive Vice President and Chief Operating Officer
USEC, Inc.

Dr. John Holdren
Director, Science, Technology, and Public Policy Program
Belfer Center for Science and International Affairs
John F. Kennedy School of Government

Laura Holgate
Vice President for Russia/NIS Programs
Nuclear Threat Initiative

Dr. Jon Phillips
Program Director, Policy and Trade Implementation, Office of International Safeguards
National Nuclear Security Administration
U.S. Department of Energy

Daniel Poneman
Principal
The Scowcroft Group

Dr. Tariq Rauf
Head of Verification and Security Policy Coordination
International Atomic Energy Agency

Dr. Lawrence Scheinman
Director, Washington Office
Center for Nonproliferation Studies

Dr. Fiona Simpson
Officer, External Relations and Policy Coordination
International Atomic Energy Agency

Richard J. Stratford
Director, Nuclear Energy Affairs
U.S. Department of State

Eric Webb
Vice President, Information Technology
Ux Consulting, LLC

Charles B. Yulish
Vice President, Corporate Communications
USEC, Inc.

Anonymous Officials

Atomic Energy Commission of France

Government of Australia

Government of Brazil

Government of Canada

Government of Japan

Government of Russia

Annex 4: Bibliography

2003 Annual Report (Financials), USEC, Inc., Available at http://www.corporate-ir.net/ireye/ir_site.zhtml?ticker=USU&script=700&layout=7

"Australia's Uranium Exports Policy," Department of Foreign Affairs and Trade, Government of Australia, http://www.dfat.gov.au/security/aus_uran_exp_policy.html

The Baruch Plan, http://www.nuclearfiles.org/redocuments/1946/460614-baruch.html

Bunn, Matthew, et al, "The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel," Project on Managing the Atom, Belfer Center for Science and International Affairs, John F. Kennedy School of Government, December 2003.

Chayes, Abram and W. Bennett Lewis, eds., *International Arrangements for Nuclear Fuel Reprocessing*, Cambridge: Ballinger (1977).

"The Cost of High-Level Waste Disposal in Geological Repositories: An Analysis of Factors Affecting Cost Estimates," Nuclear Energy Agency, Organization for Economic Cooperation and Development, 1993.

Deutch, John, et al, "Making the World Safe for Nuclear Energy," Massachusetts Institute of Technology and the Scowcroft Group.

French, Howard, "China Promotes Another Boom: Nuclear Power," *New York Times*, January 15, 2005.

"The Future of Nuclear Power: An Interdisciplinary MIT Study," Massachusetts Institute of Technology, 2003.

"Global Partnership Update: January 2005," Center for Strategic and International Studies, http://sgpproject.org/publications/GPUpdates/GPUpdateJan2005.pdf.

Goldschmidt, Pierre, "The Proliferation Challenge of the Nuclear Fuel Cycle in Non-Nuclear Weapon States," Paper submitted to the Institut Francais des Relations Internationales, April 26, 2004, http://www.iaea.org/NewsCenter/Statements/DDGs/2004/goldschmidt26042004.html

International Atomic Energy Agency Power Reactor Information System, http://www.iaea.org/programmes/a2/index.html

International Nuclear Fuel Cycle Evaluation, "INFCE Summary Volume", International Atomic Energy Agency, Vienna, 1980.

International Nuclear Fuel Cycle Evaluation, "Enrichment Availability: Report of INFCE Working Group 2," International Atomic Energy Agency, Vienna, 1980.

International Nuclear Fuel Cycle Evaluation, "Assurances of Long-Term Supply of Technology, Fuel, and Heavy Water and Services in the Interests of National Needs Consistent with Non-Proliferation: Report of INFCE Working Group 3," International Atomic Energy Agency, Vienna, 1980.

Management and Disposition of Excess Weapons Plutonium: Reactor-Related Options, Committee on International Security and Arms Control, National Academy of Sciences, National Academy Press, Washington D.C., 1995.

McCormick, Tony, Urenco Enrichment Company, Ltd, Presentation to the World Nuclear Fuel Market, 2004 Annual Meeting, May 2004, http://www.wnfm.com/2004AnnualMeeting/Proceedings/McCormick.pdf.

"Multilateral Approaches to the Nuclear Fuel Cycle: Expert Group Report submitted to the Director General of the International Atomic Energy Agency," International Atomic Energy Agency INFCIRC/640, February 22, 2005, http://www.iaea.org/Publications/Documents/Infcircs/2005/infcirc640.pdf

"Multilateral Approaches to the Nuclear Fuel Cycle: Preliminary Views of the IAEA Secretariat for the Proposed Study," IAEA Office of External Relations and Policy Coordination, June 2004.

Neff, Thomas L., "The Nuclear Fuel Cycle and the Bush Nonproliferation Initiative," Paper submitted to the 2004 World Nuclear Fuel Cycle Conference.

Neff, Thomas L. and Henry D. Jacoby, "Nonproliferation Strategy in a Changing Nuclear Fuel Market," *Foreign Affairs*, Summer 1979, 1123-43.

"Nuclear Energy in Finland," World Nuclear Association Issue Brief, June 2004, http://www.world-nuclear.org/info/inf76.htm

"President Announces New Measures to Counter the Threat of WMD," Remarks by President George W. Bush at National Defense University, February 11, 2004, http://www.whitehouse.gov/news/releases/2004/02/20040211-4.html

Scheinman, Lawrence, "The Nuclear Fuel Cycle: A Challenge for Nonproliferation," Disarmament Diplomacy, March/April 2004, http://www.acronym.org.uk/dd/dd76/76ls.htm

Slevin, Peter, "Brazil Shielding Uranium Facility: Nation Seeks to Keep Its Proprietary Data From U.N. Inspectors," *Washington Post*, April 4, 2004.

Statement of IAEA Director General Mohamed El-Baradei to the Forty-Seventh Regular Session of the IAEA General Conference, September 15, 2003, http://www.iaea.org/NewsCenter/Statements/2003/ebsp2003n020.shtml

"Strengthening the Nuclear Non-Proliferation Regime," Working Paper Submitted by the Government of France to the Preparatory Committee for the 2005 Review Conference of the Parties to the Treaty on the Non-Proliferation of Nuclear Weapons, May 4, 2004.

Treaty on the Non-Proliferation of Nuclear Weapons (1968), http://www.state.gov/t/np/trty/16281.htm#treaty

Trends in the Nuclear Fuel Cycle: Economic, Environmental, and Social Aspects, OECD Nuclear Energy Agency, Paris: NEA (2001).

United States Code, Title 22, Chapter 47, Subchapter I, Section 3221.

United States Code, Title 42, Chapter 23, Subchapter IX, Section 2135.

Uranium 2003: Resources, Production, and Demand, Joint Report by the OECD Nuclear Energy Agency and the International Atomic Energy Agency, 2004.

The Ux Weekly, Volume 19, Issues 1-4, January 3, 10, 17, and 24, 2005.

Wonder, Edward F., *Nuclear Fuel and American Foreign Policy: Multilateralization for Uranium Enrichment*, Atlantic Council Policy Paperback, Westview: Boulder (1977).

Annex 5: Acknowledgements

The author wishes to thank the following individuals for their contributions to this report: My client, Ambassador Linton F. Brooks, for his active involvement and detailed feedback; my advisor, Dr. Ashton B. Carter, for his careful guidance and tireless support; Dr. Steven Miller, for his comments on the draft report; Matthew Bunn, for his expert insight; and the interview subjects listed in Annex 2, for their generous time and candid remarks.