



Stemming the Spread of Enrichment Technology

Fuel-Supply Guarantees and the
Development of Objective Criteria for
Restricting Enrichment

Babur Habib

Sunil Jain

Richard Johnson

Ilan Jonas

R. Scott Kemp

Andrew Kovacs

David Malkin

Darya Nachinkina

Bart Szewczyk

Pei Tsai

Table of Contents

Executive Summary	1
Introduction.....	3
The Initiative.....	4
1. The Forum.....	6
<i>Potential Criterion #1: Threshold Nuclear Capacity</i>	8
<i>Potential Criterion #2: Black-box Technology</i>	10
<i>Potential Criterion #3: Multinational Arrangements</i>	11
<i>Long-Term Fuel-supply guarantees</i>	12
2. The De-facto moratorium	13
3. Fuel-supply guarantees.....	14
<i>U.S.-Gifted LEU</i>	16
<i>Additional Sources of LEU</i>	17
<i>Conditions for the Release of LEU</i>	18
After the Forum.....	18
The Initiative’s Impact on Special Cases	19
Conclusion	20
Appendix A: Details of the Fuel-supply guarantee	21
Appendix B: National vs. Purchased Enrichment: Cost Comparison.....	23
Appendix C: Experts Interviewed for the Workshop	26
Appendix D: Research Topics of Workshop Members.....	29

This paper was written for Princeton University’s Woodrow Wilson School of Public and International Affairs Fall 2005 Workshop on Stemming the Proliferation of Enrichment Plants. The authors thank gratefully the many people who shared their time, energy, and insights over the semester. Most of all they thank Robert Einhorn and Frank von Hippel, whose knowledge, guidance, and patience led them to do their best work.

Executive Summary

This report proposes an initiative to establish a new internationally-accepted norm against the proliferation of uranium-enrichment technology. The initiative has three linked components:

1. *Objective Criteria:* An international forum, supported by a system of intermediate fuel-supply guarantees, would be established to develop objective criteria for legitimate enrichment.
2. *Forum Participation:* States could participate in the forum if they do not engage in enrichment activities (“de-facto moratorium”). States that do not meet the de-facto moratorium condition at any point during the forum would be able to participate by contributing significant funds to a physical reserve of low-enriched uranium (LEU).
3. *Fuel-Supply Guarantees:* The fuel-supply arrangement would guarantee, over a ten-year period, the fuel supply to states that do not engage in enrichment activities.

The forum would develop a set of objective criteria to determine when a state’s pursuit of enrichment capabilities is legitimate. For example, one possible criterion is that a state should possess a minimum level of installed nuclear-power capacity before domestic enrichment is justified. We suggest that 10 GWe of installed light-water-reactor capacity is a reasonable threshold for states. This proposal offers several other suggested criteria, and the forum process could also develop its own criteria. Criteria could be adopted independently or in some combination.

A secure supply of enriched uranium is essential if states are to forgo the development of domestic enrichment facilities. To that end, the forum would also develop long-term fuel-supply guarantees.

In the meantime, an intermediate fuel-supply guarantee arrangement would be offered to states that do not engage in enrichment activities. Physical reserves of LEU, owned and managed by the International Atomic Energy Agency (IAEA), would back up the current enrichment market to help ensure the uninterrupted supply of fuel to recipient states. These reserves, located at various commercial enrichment facilities, would house the equivalent of twenty annual reloads for 1 GWe reactors.

Finally, the objective criteria and long-term fuel-supply guarantees developed during the forum could provide the basis for a permanent arrangement for controlling the proliferation of enrichment plants. A critical mass of states could agree to a new arrangement by adopting a new framework for assessing the

legitimacy of enrichment. A subsequent endorsement by the IAEA Board of Governors or the United Nations Security Council would make the new framework more acceptable and politically consequential. We concede that many non-nuclear-weapon states without enrichment technology may be initially reluctant to make additional concessions from the status quo. Nevertheless, we believe our proposal may help the international community move beyond a norm that legitimizes unrestricted enrichment to a more restrictive norm that balances energy needs with nonproliferation.

Taken together, objective criteria for the development of enrichment facilities and long-term fuel-supply guarantees could support states that do not intend to pursue the technology and de-legitimize the states that seek the capability without adequate justification.

Introduction

The ongoing international crisis over Iran's pursuit of uranium enrichment capacity has refocused the attention of the international community on the dangers posed by the proliferation of enrichment technology. Uranium-enrichment facilities, which are used to make fuel for nuclear power plants, could also be used to produce highly-enriched uranium (HEU) for nuclear weapons. An expansion of the number of states possessing enrichment plants—even if they are intended for peaceful use—is therefore also an increase in the number of states with ready access to the means to produce nuclear weapons. We propose an initiative to limit this expansion.

Although the dual-use nature of uranium enrichment has long been a concern, the emergence of gas-centrifuge enrichment has exacerbated the problem. Centrifuge plants are particularly susceptible to adaptation to the production of weapons-grade uranium, and the technology is becoming easier to obtain.¹ The slow but steady maturation of states' technological bases and the openness of world markets have reduced barriers to acquisition of what was once a fairly-arcaic technology.

The lowering of the technical threshold coincides with newly-exposed instances of state interest in acquiring a clandestine nuclear-weapons option. Iran, which has catalyzed much of the recent concern over latent proliferation, is only the most recent state to have acquired centrifuges. Iraq had three parallel programs, including functional centrifuges, to enrich uranium for weapon purposes, and Libya purchased ready-made centrifuges from the A.Q. Khan proliferation network. As latent proliferation becomes increasingly possible, more states could adopt commercial pretexts for building domestic enrichment plants.

The problem is not so much the current actions of particular states, but the inherently-incomplete nonproliferation regime institutionalized by the Treaty on the Nonproliferation of Nuclear Weapons (NPT). Article IV of the NPT states, "Nothing in this Treaty shall be interpreted as affecting the inalienable right of all the Parties to develop research, production and use of nuclear energy for peaceful purposes," provided it is in accordance with the nonproliferation requirements of Articles I and II. Since even a peaceful enrichment facility offers a state a latent-weapons capability, the goals of Articles I and II are undermined by Article IV. This inherent conflict is exacerbated by the difficulty in establishing a state's true motivations for exercising its Article IV rights.

¹ Centrifuges are well-suited to clandestine operation and have small uranium inventories. The first quality means that a state operating a declared facility for peaceful purposes could in parallel deploy the same technology at a secret facility dedicated to weapons production. The second quality means that a state could quickly convert a civilian-purposed facility into a weapon-producing facility, possibly acquiring enough fissile material for a bomb before the international community has time to respond.

The subjectivity introduced by Article IV has made it difficult for the nonproliferation community to respond to possible acts of latent proliferation because those acts arguably are sanctioned by the NPT. States developing such programs may claim that their efforts are intended to strengthen their nuclear-energy infrastructure. Under Article IV, such a claim would, at least in principle, be legitimate. To stem the spread of enrichment plants as part of fulfilling a broader nonproliferation goal, we must change this permissive norm and minimize its subjectivity.

Unfortunately, the NPT cannot evolve to address the Article IV problem because of political disagreements in interpreting the treaty's obligations. According to the NPT, nuclear-weapon states are obliged to reduce and ultimately eliminate their nuclear arsenals, and to facilitate non-weapon states' acquisition of peaceful nuclear technology. Non-nuclear-weapon states argue that the weapon states have failed to meet either obligation, and are unjustly enjoying the strategic benefits conferred to them by the discriminatory regime. If both sides of this debate remain intransigent, then the NPT is indeed deadlocked. The most recent NPT review conference in May 2005 illustrated these irresolvable divisions.

Finally, as global energy demand continues to increase and with nuclear power considered as an alternative to carbon-based energy, demand for enrichment services may increase beyond current capacity, providing further impetus for states to acquire their own enrichment capabilities. Hence, now is the time to address the threat to international security posed by the proliferation of nuclear fuel-cycle facilities.

The Initiative

There is a need to establish a new internationally-accepted norm against the further unrestrained proliferation of national uranium-enrichment capabilities. We offer here a path for moving from the current norm, under which the acquisition of national enrichment capability is legitimate, provided it is placed under safeguards, to a new norm where national enrichment capability is viewed as illegitimate unless judged to be in accordance with internationally-accepted criteria.

The initiative has three linked components:

1. *Objective Criteria:* An international forum, supported by a system of intermediate fuel-supply guarantees, would be established with a goal to develop objective criteria for assessing the legitimacy of enrichment.
2. *Forum Participation:* States could participate in the forum if they do not engage in enrichment activities² (“de-facto moratorium”). States that do not meet this de-facto moratorium condition at any point during the forum would be able to participate by contributing significant funds to a physical reserve of low-enriched uranium (LEU).
3. *Fuel-supply guarantees:* The fuel supply arrangement would guarantee, over a ten-year period, fuel supply for states that do not engage in enrichment activities.

Central to our proposal is a forum of state representatives established by the IAEA Board of Governors and chaired by an appointee of the Board. This forum would be charged with developing objective criteria for judging whether a state’s pursuit of enrichment is legitimate and necessary, as well as with developing a system of long-term fuel-supply guarantees.

If a large majority of states agree upon one set of criteria for evaluation of enrichment need, then those criteria would constitute an international norm. A norm is useful because it can influence states that may not have agreed with the criteria otherwise. Hence, widespread acceptance is an important element of this plan.

Although the de-facto moratorium would not require most states to take any actions, it would serve as a way for them to acknowledge explicitly the dangers posed by the spread of enrichment technology and to demonstrate their willingness to take concrete steps to address the problem. If the few states with developing enrichment programs, such as Brazil, were to join the moratorium, it would also serve as a way for the international community to buy time to allow the forum to arrive at relevant and effective criteria. The de-facto moratorium would be complemented by a commitment among all participants in the forum not to make new contracts for the transfer of enrichment facilities or technology for the five-year period in which the forum is in session.

A state that joins the forum through the de-facto moratorium track should receive a credible guarantee of uninterrupted supply of fuel for its domestic nuclear power plants. Therefore, the third component of the initiative is a system of fuel-

² Enrichment activities consist of operating centrifuges or gas-diffusion plants to enrich uranium, acquiring materials for such purposes, or building any isotope separation device that can be extended to enriching uranium.

supply guarantees for states taking part in the forum. These fuel-supply guarantees could also form the basis for long-term guarantees to be developed by the forum's participants.

The de-facto moratorium and the intermediate fuel-supply guarantees would encourage progress in the forum, prevent near-term actions from prejudicing long-term arrangements, and form a basis for constructing follow-up arrangements.

Finally, the objective criteria and long-term fuel-supply guarantees developed in the forum, as well as the broad consensus for action that may be achieved through confidence-building measures like the de-facto moratorium, would set the stage for creating a permanent arrangement for controlling the proliferation of enrichment technology. This arrangement would effectively change the meaning of the NPT Article IV rights without altering the text itself.

This proposal is not a short-term solution for current problem countries like Iran, although it could play a helpful role in solving such issues if implemented soon. Likewise, this proposal is not designed to satisfy or frustrate the aims of any one state. Rather, it provides a path around the political roadblocks that hold back progress on the fuel-cycle problem. The strength of this plan lies in its attempt to bring all states into agreement on a strategy to strengthen the nonproliferation mechanisms.

The initiative augments efforts to limit the spread of enrichment capabilities in the several ways. First, it minimizes the subjectivity of Article IV of the NPT and does not permanently divide the world into "haves" and "have-nots" based on which states currently have full fuel-cycle capabilities. Second, by developing long-term fuel-supply guarantees, it seeks to provide states with the assurances that they need to safely defer domestic enrichment. Third, it raises considerably the political cost for would-be proliferators. By taking into account the economics of enrichment and by providing fuel-supply guarantees in support of an already efficient enrichment market, the initiative addresses the economic and political arguments for developing fuel-cycle capabilities and serves to help spotlight those states that may have nuclear weapons ambitions.

1. The Forum

Many current efforts to discourage domestic enrichment seek to grandfather existing capabilities while preventing additional states from acquiring them. However, the extent to which any arrangement restricting states is successful depends foremost on the willingness of states to abide by that arrangement. The resentment created by the unwillingness of the "haves" of the NPT to move more rapidly toward joining the "have-nots" through disarmament suggests that an

attempt to divide states permanently into a new set of permanent “haves” and “have-nots” could face serious opposition.

On the other hand, more states might view as more legitimate and fair an approach that allows a transition from “have-not” to “have” status when certain criteria are met. Though we would prefer that no new states acquire enrichment capability, we concede that this goal may be too ambitious. Thus, we propose a medium-term and more realistic solution, which would permit only those states with a demonstrated need for domestic enrichment to acquire it. Objective criteria should determine such need. Based on the expected time that most states would need to reach such criteria, this solution would delay the problem of enrichment proliferation for about 10–25 years—similar to the initial NPT time-frame.

The first element of the initiative is an international forum to recommend objective criteria for the acquisition of enrichment plants. The forum would also discuss long-term fuel-supply guarantees. It would operate under the auspices of the IAEA Board, and be comprised of representatives from states eligible for participation in the forum. The Board’s appointee would chair the forum, which would meet regularly for a period of up to five years.

To join the forum, states would have to demonstrate their commitment to addressing the fuel-cycle problem. Most states would do so by not engaging in enrichment activities. Functionally, this de-facto moratorium would help prevent near-term actions from influencing the long-term decisions of the forum. Alternatively, states could make a significant contribution to a fuel bank that would form the basis of a fuel-supply guarantee, as detailed later in the report. Such contributions would be in the form of cash funds, enrichment services used to produce LEU for the bank, or LEU itself.

The forum’s first task would be to debate and recommend a set of objective criteria to determine when a states’ pursuit of enrichment capabilities is legitimate. Objectivity suggests that criteria should be based on the size and characteristics of the state’s civilian nuclear program and its need for domestic enrichment in support of that program.

A secure supply of enriched uranium is essential if states are to forgo the development of domestic enrichment facilities. To that end, the forum would also develop long-term fuel-supply guarantees.

In the end, as explained further, the IAEA Board of Governors or the UN Security Council could pass a resolution endorsing the forum’s recommendations as nonbinding yet politically consequential international guidelines. These recommendations could also become binding on states through a new multilateral agreement.

To demonstrate the forum's potential, we propose three possible criteria that member states may wish to consider:

1. threshold nuclear capacity,
2. black-box technology, and
3. multinational arrangements.

If adopted, each of the criteria listed above would help limit the spread of enrichment technology. These criteria could be adopted independently or in some combination. The forum could explore other criteria.³ As a precondition for acquisition of enrichment facilities, states would also need an acceptable track record of compliance with IAEA safeguards and intent to put into force the Additional Protocol.⁴

Potential Criterion #1: Threshold Nuclear Capacity

One possible criterion is that states should only be entitled to enrichment once they possess at least 10 GWe of installed light-water-reactor capacity. The threshold nuclear capacity criterion is based on the economics of enrichment. Currently, enrichment services are available at about \$100/SWU, which amounts to \$11 million for a year's fuel supply for a 1 GWe light-water reactor.⁵ We compare this price with the cost of operating a national enrichment plant in order to determine the scale at which a national enrichment plant becomes cost-competitive.

A state building its own centrifuge plant has two options: develop the technology itself, or buy the technology from Urenco or Russia. A state deciding to develop its own technology can expect to spend billions of dollars on research and development for decades before reaching a competitive design.⁶ This finding is consistent with the previous efforts of states that have developed domestic enrichment capabilities (e.g. the United States, Japan, and Brazil).

³ For example, states could be required to have a good track record of nonproliferation and not pose a security risk to their region through aggressive behavior or rhetoric.

⁴ Under our definition, states can demonstrate "intent" by having applied for and received the IAEA Board of Governors approval for entry into force of the Additional Protocol.

⁵ A modern power reactor has a design burn-up of about 53Mwd/kg and uses 4.4% enriched fuel. About one third of the thermal energy is successfully converted to electricity. $53\text{Mwd/kg}/3=17.7\text{MWe-days/kg}$. At 90% capacity factor, a 1 GWe reactor would use $(1000\text{ MWe} \times 365\text{days} \times 90\% / 17.7\text{ MW(e)d/kg}) = 18.6$ tons. A less modern reactors operating at lower burn-ups (say, 41Mwd/kg) would require about 24 metric tons. The separative work required to produce enriched fuel is based on a value function: $V(e)=(2e-1)\ln[e/(1-e)]$. The total SWUs required per kilogram is $V(e_p)-V(e_f)-F \times [V(e_t)-V(e_f)]$, where the subscripts p,f,t represent product, feed, and tails respectively; and F is the mass of feed per kilogram, given by $(e_p-e_t)/(e_f-e_t)$. For a kilogram of 4.5% product, assuming natural uranium feed ($e_f=0.00711$), 0.32% tails ($e_t=0.0032$), 10.7kg of feed is required, and 6.0 SWUs. For 18.6 metric tons, this is 110,000 SWUs. At \$100/SWU, this amounts to \$11 million.

⁶ See Appendix B.

The U.S. Department of Energy spent nearly \$3 billion over two decades on the development of its centrifuges.⁷ Japan started its program two decades ago, and although it has a commercial enrichment plant, it enriches uranium at twice the market price and has a high rate of centrifuge failure.⁸ As one representative of a Western enrichment firm said, “During the last twenty years, Japan put together a gold-plated centrifuge program whose costs were not under control and which produced SWUs at a price Japanese utilities couldn’t bear.”⁹ Similarly the Brazilian program that started in the early eighties has so far cost about \$1.1 billion since its inception.¹⁰ Although it claims a functioning technology, Brazil is still in the process of establishing a plant with a substantial SWU capacity.

The second option is for a state to buy an enrichment facility from one of the two technology suppliers, Urenco or Russia. Above a certain-size threshold, this option would give the state enrichment services at competitive rates immediately. However, Urenco experts report that it is not economically sensible to build a plant with less than about 1 million-SWU capacity using their technology.¹¹ For Urenco technology, this constraint sets the minimum-scale size at which their technology can compete in the marketplace.¹² One million SWUs equates to 10 GWe at a rate of 110,000 SWU/GWe per year; hence a state motivated by economic incentives would rely on the market until it has sufficient capacity to justify its own enrichment plant. We suggest taking this conclusion and making it a criterion, so that states seeking enrichment plants for non-peaceful reasons could not use economics to cloak their motivations.

Some may reason that instead of stemming enrichment facilities, this criterion could encourage states to pursue enrichment once they meet the 10 GWe criterion. We believe such action is unlikely. Compared to the current status quo, which sanctions the pursuit of enrichment as an inalienable right at any level of nuclear capacity, our suggested criterion is very restrictive. Furthermore, there is nothing to compel states to pursue enrichment once they have met the 10 GWe criteria. Indeed, those states with more than 10 GWe that choose not to build an enrichment plant could continue to enjoy the benefit of fuel-supply guarantees.

⁷ Van Namen, Robert. “American Centrifuge – The Road to Market.” Presented at the Nuclear Fuel Institute in April 2003.

⁸ For example, see *Nuclear Fuel* from 21 April 1997, 4 May 1998, and 2 November 1998.

⁹ Ibid.

¹⁰ Private communication with Jose Goldemberg, former Minister of Science and Technology, Brazil. This estimate includes all of the research and development investments so far made into the Brazilian enrichment program.

¹¹ Private communication with Dr. Pat Upson, Managing Director, ETC group, Urenco.

¹² Appendix B discusses how the cost of a Urenco black-box scales with SWU capacity and how it compares with the costs of purchasing enrichment services in the market.

It may also be argued that the 10 GWe threshold criterion would encourage states to build nuclear reactors so they can meet the criterion and obtain their own enrichment facility. This too is unlikely. A 1 GWe nuclear plant requires five years to construct and costs on the order of \$2 billion to build.¹³ A state that is just starting to build its first nuclear power plant would then incur costs of approximately \$20 billion to reach the 10 GWe capacity. Moreover, most states would take 10–25 years to build this amount of capacity. Consequently, our solution at the very least delays the problem of enrichment proliferation for a substantial amount of time.

Table 1 illustrates the impact of the 10 GWe criterion. The figures given show installed nuclear power that requires enriched uranium for fuel as of 2005.¹⁴ The states marked in blue already have 10 GWe of installed power. Out of these, South Korea and Ukraine do not have enrichment plants. Note that Canada, although it has over 10 GWe of capacity, does not need an enrichment plant because its reactors are fueled with natural uranium. Note also that Brazil, Argentina, Iran, South Africa, China and Pakistan have enrichment facilities but not 10 GWe of installed nuclear power. United Kingdom and the Netherlands, shown in green, meet the criterion based on the multinational-facility criterion discussed below.

Potential Criterion #2: Black-box Technology

Providing the enrichment technology in a so-called black-box arrangement may help prevent centrifuge technology from being copied for weapon-production purposes. A black-box enrichment facility refers to an arrangement where the state in physical possession of the plant has the

Table 1: Worldwide Installed Nuclear Power Requiring Enriched Uranium

States with nuclear power	GWe requiring enrichment
USA	97.8
France	63.5
Japan	47.7
Russia	21.7
Germany	20.3
South Korea	14.3
Ukraine	13.2
United Kingdom	9.6
Sweden	8.9
Spain	7.6
Belgium	5.7
China	5.3
China (Taiwan)	4.9
Czech Republic	3.5
Switzerland	3.2
Bulgaria	2.7
Finland	2.7
Slovak Republic	2.5
Brazil	1.9
South Africa	1.8
Hungary	1.8
Mexico	1.3
Lithuania	1.2
Slovenia	0.7
Netherlands	0.5
Armenia	0.4
India	0.3
Pakistan	0.3

Blue: more than 10 GWe installed
Green: part of multinational consortium with >10 GWe total

¹³ Bertel, E. and A. Morrison. "Nuclear Energy Economics in a Sustainable Development Perspective." NEA News 2001. 19:1. <http://www.nea.fr/html/pub/newsletter/2001/nuclear-economics19-1.pdf>.

¹⁴ IAEA Power Reactor Information System (PRIS). www.iaea.org.

ability to operate the plant without ready access to the centrifuge technology per se. This arrangement is feasible because the centrifuges require very little or no maintenance, and they therefore can be effectively sealed off from the technical staff of the host state.

A black-box arrangement avoids providing the host state with the ability to build and operate clandestine facilities, as they would lack access to the technical details required to duplicate the technology. While the adoption of this criterion by itself will limit the spread of enrichment technology, we support its adoption in conjunction with the first criterion. In other words, only states possessing 10 GWe of installed light-water-reactor capacity will be allowed to acquire black-box facilities.

Urenco and Russia are the two current exporters of centrifuge enrichment technology. Both have sold their centrifuges to be operated in a black-box mode. Russia built a black-box centrifuge plant for China in 1995. Urenco/ETC (Urenco's centrifuge-development subsidiary) has similar arrangements with the NEF/LES Consortium in the USA, Areva in France, and Urenco's enrichment-services subsidiary Urenco/UEC.

It should be noted that, although a black-box facility reduces the ability of states to replicate a plant clandestinely, the state could still produce weapons-grade HEU via a breakout scenario in which the host state takes over the facility. The state then removes IAEA monitoring arrangements and reconfigures the cascade for HEU production. This could be done in several ways. One involves reconfiguring header pipes, which according to one technology expert could take as little as two weeks with advance preparation.¹⁵ A worst-case scenario involves repeatedly recycling the partly enriched uranium through the cascade until a weapon-usable enrichment is achieved. This could take only a few hours.¹⁶ However, because the facility was taken over in a hostile manner, the state's intentions would at least be obvious to the world and appropriate consequences would follow.

Potential Criterion #3: Multinational Arrangements

Multinational enrichment plants provide another way to both reduce proliferation risks and improve states' fuel supply security, and so should be considered as a possible criterion.¹⁷ A state jointly owning and operating an enrichment plant

¹⁵ Private communication with Alex Glaser, Researcher with the Program on Science and Nuclear Security, Princeton University.

¹⁶ Ibid.

¹⁷ For a listing of multinational approaches, see "Multinational Approaches to the Nuclear Fuel Cycle," IAEA INFCIRC/640 from 22 February 2005.

with other trusted partners would have reason to feel more secure in its fuel supply. At the same time, the fact that a number of states are involved in the operation of the plant makes it more difficult for any one state to conduct a breakout scenario.

As mentioned before, the adoption of this criterion by itself will limit the spread of enrichment technology, yet we believe that it should be adopted together with the previous criteria. One option could be that a consortium of states could jointly meet the 10 GWe criterion, provided each of the members has a civilian nuclear power plant.

The workshop believes that criteria one and three together have the most promise of success in terms of acceptance in the forum. Combining them with the second criterion—which will restrict states to acquiring only black-box technology after meeting the threshold criteria—will be a challenge since it will be hard to convince states to give up the right to develop their own technology for good. An argument can also be made that developing a working technology on its own could take a state decades and a considerable financial investment. This would be an additional time period on top of the 10–25 years for most states to reach 10 GWe of installed nuclear capacity.

Long-Term Fuel-supply guarantees

In addition to developing the criteria, the forum would also establish long-term fuel-supply guarantees. The interim guarantees could be modified and extended to support those states that accept restrictions under any new agreement. A long-term fuel-supply guarantee protects those states from potential supply interruptions. Such guarantees make it more difficult for states to abrogate their obligations on a fuel security basis.

Provisions to deal with other fuel-cycle concerns, such as spent-fuel management, should also be incorporated to address proliferation risks and to incentivize participation in the forum and its outcome. Spent fuel contains weapon-usable plutonium, and its storage and disposal are problematic for many states.¹⁸ Reprocessing, a costly option that some states use to delay the disposal issue, separates the weapons-usable plutonium from the high-level radioactive waste that normally protects against diversion.¹⁹ Establishing

¹⁸ Reactor-grade plutonium is not ideal for nuclear weapons but it can be used. See J. Carson Mark, “Explosive Properties of Reactor-Grade Plutonium.” *Science and Global Security*. 1993. Vol. 4. 111–128.

¹⁹ So far, there is no proliferation-resistant reprocessing technology, despite efforts by U.S. laboratory scientists. See Kang, J. and Frank von Hippel. “Limited Proliferation Resistance from Recycling Unseparated Transuranics and Lanthanides from Light-Water Reactor Spent Fuel.” *Science and Global Security*. 2005. Vol. 13. 169–181.

mechanisms to help states deal with spent fuel could help reduce the number of states seeking a reprocessing option.

Russia has in recent years expressed an interest in hosting an international spent-fuel storage facility. Though a spent-fuel option that relies solely on one state is less than ideal, it is still useful. The Russian proposal is not likely to reach fruition unless the United States first negotiates an Agreement for Peaceful Nuclear Cooperation with Moscow. Given that 80 percent of the world's spent fuel is subject to U.S. consent rights,²⁰ Russia's inability to import this material all but ensures that a Russian-hosted, international spent fuel storage facility cannot be profitable. Hence, it is important that the United States negotiate the Agreement with Russia—a policy that might require de-linking the Agreement from Russia's stance on Iran.

2. The De-Facto Moratorium

We believe that the forum should be as inclusive as possible in order to maximize the legitimacy of its recommendations. At the same time, we believe that, as a condition for participation in the forum, states should acknowledge that there is a problem with the proliferation of enrichment plants and take preliminary but concrete steps towards resolving the problem.

The optimal way to deal with the problem is to refrain from building any new enrichment facilities. To this end, IAEA Director General Mohamed ElBaradei proposed in 2005 a five-year universal moratorium on the construction of any new facility for uranium enrichment (or plutonium separation).²¹ However, this proposal would compromise sustainable supply of nuclear fuel worldwide, interfere with existing expansion plans,²² and be politically impossible. Additionally, even states with no medium-term interest in constructing enrichment facilities will find it difficult to commit publicly to even a temporary moratorium on the exercise of their existing rights.

An alternative solution would be to exempt states with enrichment capacity from such a declared moratorium. However, determining such exemptions could pose problems. One proposal could allow states with 1 million SWU/yr of capacity to maintain their enrichment activities. Nevertheless, any such exemption could appear arbitrary and political, regardless of what terms are used to define the

²⁰ Burkhart, Alex and Janet Gorn. "International Storage of Commercial Spent Fuel and High-Level Waste." Prepared Remarks to the Conference. Bureau of Nonproliferation, U.S. Department of State. 18 July 2005. <http://www.state.gov/t/np/rls/rm/49749.htm>.

²¹ IAEA website. <http://www.iaea.org/NewsCenter/Statements/2005/ebsp2005n001.html>.

²² Urenco, Areva, and the NEF/LES consortium in the United States have current expansion plans.

exempted group. Moreover, definitions are likely to be over- or under-inclusive.²³ Finally, as with the first option, even states with no medium-term interest in constructing enrichment facilities will find it difficult to commit publicly to a moratorium on the exercise of their existing rights.

Therefore, we recommend a third alternative that is both feasible and favorable from the perspective of nonproliferation: allowing states to participate in the forum by either (1) not engaging in enrichment activities or (2) contributing significant funds to a fuel supply arrangement.²⁴ Most states will continue their current status quo and simply not pursue any enrichment activities. Since they would not have to commit publicly to any formal moratorium, they would not receive any domestic opposition to participation in the forum. Some states with current enrichment facilities would choose to contribute significant funds, which they would need to do in any event to establish a credible fuel supply arrangement. This second option would also technically allow states such as Iran and Brazil to contribute funds, maintain their enrichment activities, and participate in the forum. However, we view the downsides of this possibility as limited. First, both states would most likely engage in enrichment in any event. Participation in the forum does not give them (or anyone else for that matter) any additional rights, other than having a voice in the forum. Neither does it exempt them from fulfilling their international obligations, including NPT obligations. Second, their participation enhances the forum's legitimacy without changing the substance of its decisions.

Since we propose that the outcome of the forum should be an internationally-accepted norm, we believe that the eligibility criteria for joining the forum should be non-discriminatory. Therefore, we recommend that any state wishing to engage in enrichment activities should be eligible to opt for the second option. Moreover, during the five-year period of the forum, states can switch their conditions of participation if circumstances change.

3. Intermediate Fuel-supply guarantees

A state that does not engage in enrichment activities should be assured that it will not suffer fuel cut-offs during this period and in the immediate aftermath. A ten-year fuel-supply guarantee can provide much of that assurance, while also forming the basis for a long-term guarantee as an element of the post-forum arrangements.

²³ For example, this approach would not exempt India or Pakistan, which are important for negotiations within the forum but might be unlikely to commit to a *de jure* moratorium due to their military programs.

²⁴ Contributing states could stipulate that contributed funds be used to purchase their own enrichment services or their own stock of LEU.

The concept of fuel-supply guarantees is not new. In 1980, for example, the IAEA established the Committee on Assurances of Supply to reach consensus between suppliers and recipients on a guaranteed supply of fuel. Early efforts also sought to convince states with small nuclear capacities that domestic enrichment plants are an unnecessary investment. More recently, separate proposals for a system of fuel-supply guarantees have been tabled by the United States and Dr. Pierre Goldschmidt, former Deputy Director General of the IAEA. Offered in response to the situation in Iran, these proposals seek to prevent the proliferation of enrichment technology by trading a promise of guaranteed supply against a state's right to enrichment.

Unfortunately, fuel-supply guarantees cannot on their own convince states with an interest in domestic enrichment not to exercise their right to enrichment. For those states seeking security of supply, an external fuel assurance is inherently less reliable than a domestic fuel assurance. Thus, if a state is willing to bear the cost of domestic enrichment in the name of energy security, then a fuel-supply guarantee will be regarded as insufficient.²⁵ Moreover, some states pursue domestic enrichment for reasons other than energy security, including technological development, regional or international status, latent nuclear weapons option, or national pride. There is little reason to suspect that fuel-supply guarantees, on their own, can provide an incentive great enough to offset these motivations. A third challenge is that the market effectively meets demand for enrichment services and is expected to do so for the foreseeable future. The marginal benefit of such assurances is therefore limited, except in the unlikely event of an unjustified cut-off.

Recognizing these challenges, our proposal integrates fuel-supply guarantees into the greater mission of the forum, rather than simply treating such guarantees as a tool unto themselves. By agreeing to the de-facto moratorium in exchange for fuel-supply guarantees, states become eligible for participation in the forum. This modest trade-off will thus offer states a voice in the development of new objective criteria to guide future trends in the spread of enrichment technology. We regard this approach as a significant departure from previous proposals, whereby states were asked to accept a long-term freeze on the enrichment status quo in exchange for a guaranteed supply of fuel. While the prospect of forum participation may not bring about a change of heart in those states determined to acquire domestic enrichment, this added incentive may be sufficient to persuade other states to forgo, at least temporarily, plans for the construction of domestic facilities. At the very least, fuel-supply guarantees will

²⁵ To support this point, we note that states already have the right to build a domestic stockpile of fuel. By our reasoning, most states would consider such a stockpile to be more secure than a fuel-supply guarantee based on an external stockpile of LEU. If a state is willing to take on the cost of a domestic enrichment plant because it is the only option that would provide sufficient fuel security, then it must be dissatisfied with the domestic stockpile option, and by extension, would be dissatisfied with the external fuel-supply guarantee.

mitigate any threat to a state's energy security associated with the de-facto moratorium and possible restrictions created by the post-forum arrangements.

Based on the recent U.S. and Goldschmidt proposals, we have developed a model fuel-supply guarantee, the details of which are provided in Appendix A. Our guarantee relies on a physical reserve of LEU sufficient to provide twenty annual reloads for 1 GWe reactors, or 480 metric tons of 4.5%-enriched fuel. The LEU would be owned by the IAEA and stored at the sites of various commercial enrichment firms.

Those states not subject to the de-facto moratorium can demonstrate their resolve to work cooperatively towards progress in both the forum and the post-forum arrangement by contributing to the physical fuel bank. We suggest that ten annual reloads be provided by the United States, and an additional ten annual reloads be acquired through a combination of LEU, cash, or SWU donations from the other state participants. In essence, the contributions will serve as the price of admission to be paid by states with enrichment facilities that desire to participate in the forum.

U.S.-Gifted LEU²⁶

The U.S. contribution could come from the 17.4 tons of excess HEU recently offered by Secretary of Energy Samuel Bodman. However, it would need to be blended down and gifted to the IAEA in order to be considered a contribution to the fuel bank.

We recognize that there are legal restrictions on the transfer and final disposition of any U.S.-obligated material. Under our proposal, U.S. consent rights would remain intact for the life of the material. Retransfer would therefore be limited to those countries with which the United States has concluded an Agreement for Peaceful Nuclear Cooperation (Section 123 Agreement²⁷), and which are eligible for a Nuclear Regulatory Commission-approved export.

To ensure credibly that the fuel will be available when required, we recommend that the Executive Branch provide advance consent to the IAEA on the retransfer of LEU to countries with Agreements of Cooperation with the United

²⁶ The authors wish to acknowledge the contribution of Fred McGoldrick, former State Department Director of Nonproliferation and Export Policy, in helping us analyze the various challenges involved in the gifting of U.S.-origin fuel to the IAEA. Specifically, Mr. McGoldrick explained the legal and political challenges, as well as possible approaches for overcoming them.

²⁷ Section 123 Agreement refers to a part of the Atomic Energy Act of 1954. The full text of the Act can be found at <http://epw.senate.gov/atomic54.pdf>.

States²⁸ Advance consent would be restricted to claims made on the fuel bank in fulfilling the fuel-supply guarantee, and to those countries that meet the criteria of eligibility. Advance consent would not allow the recipient to reprocess, further enrich, or transfer to a third country U.S.-origin material. Although politically challenging, we believe that advance consent is essential in creating a credible guarantee of supply. Such rights have been granted before, and we suggest two possible approaches to this issue.²⁹

The United States could amend its Agreement for Peaceful Nuclear Cooperation with the IAEA in order to grant advance consent over the retransfer of U.S.-origin material. The amendment would specify that advance consent is limited to the countries meeting the conditions identified above. As this approach would entail a renegotiation of the Agreement, it would need to be submitted to Congress for review. Additionally, the Executive Branch would request from the Nuclear Regulatory Commission a long-term export license for those countries that are eligible for such licenses and are recipients of fuel-supply guarantees.

Alternatively, the Executive Branch could request that the Department of Energy grant advance consent to the IAEA over the retransfer of U.S.-origin material. In addition, the Executive Branch would need to procure from the Nuclear Regulatory Commission long-term export licenses as described above. This approach would avoid the formal process of renegotiating the Agreement for Peaceful Nuclear Cooperation, yet the Executive Branch would still need to consult with Congress to see whether it could gain tacit approval.

Additional Sources of LEU

Under this proposal, an additional ten annual reloads of LEU would be provided by other supplier states in the form of LEU, services to enrich natural uranium, or cash for the purchase of natural uranium and the requisite enrichment services. The total value of these donations would be approximately \$330 million.³⁰ To promote the effective and efficient operation of the LEU bank, the IAEA should seek to acquire this LEU free from consent rights.³¹

²⁸ Advance consent would be limited to fuel bank-designated LEU and would not pertain to other U.S.-origin fuel that might come into IAEA possession in the future.

²⁹ The United States has already granted advance consent for retransfer or reprocessing to a handful of entities, including Japan, EURATOM, Sweden, and Switzerland. In addition, Fred McGoldrick notes that many of the U.S.' agreements for cooperation contain advance consent for the enrichment of U.S.-obligated material up to 20 percent U-235.

³⁰ Assuming 18.6Mt of 4.5% LEU per reactor reload and ten annual reloads, this equates to 1.1 million SWUs and 2,000 tons of natural-uranium feedstock. At \$100/SWU and \$110/kgU in UF₆, this sums to \$330 million. See footnote 5 for more details. For estimates of the current spot price, see http://www.uxc.com/review/uxc_g_ind-s.html.

³¹ The largest suppliers of natural uranium, Canada and Australia, both maintain consent rights over their uranium. However, these countries have in the past granted programmatic consent over the

Conditions for the Release of LEU

If the supply of fuel to a state is terminated unexpectedly and that state is unable to fulfill its needs through the market, it may elect to draw fuel from the LEU bank. The sale of LEU from the bank would be subject to the approval of the Director General. Specifically, the Director General would be mandated to release the fuel upon judging that the cutoff is genuine, that it pertains to a contract registered with the IAEA, and that the state that bought the LEU is not in violation of any condition for eligibility as detailed in Appendix A. The Board of Governors would have the right to override the Director General's decision by a majority vote.

After the Forum

We anticipate three possible outcomes from the forum: (1) a critical mass of states agree to a new framework for assessing the legitimacy of enrichment; (2) states continue the deliberation process of the forum under the same conditions towards an agreement if the five-year period is insufficient; or (3) states return to the status quo of the NPT.

Under the first option, a critical mass of the forum's participants would adopt a new framework. The IAEA Board of Governors or the UN Security Council could then endorse the new framework to make it more acceptable and politically consequential. The proposal could at least serve as guidelines both for the acquisition and transfer of enrichment technology. Beyond this nonbinding commitment, the new framework could form the cornerstone for a binding multilateral treaty. For example, the agreement could limit legitimate acquisition of enrichment facilities to states above the 10 GWe threshold as well as require that signatory parties refrain from transferring enrichment technologies to states that do not meet the proposed criteria. Failing sufficient support for a treaty, states could endorse the new proposal in a nonbinding manner.

In the event that there is insufficient time to reach agreement, states could decide to continue deliberating under the previous conditions. With the extension of the forum, the de-facto moratorium and intermediate fuel-supply guarantees would be maintained. At the very least, this option could entrench certain patterns of state behavior against proliferation of enrichment.

retransfer or reprocessing of obligated materials. If it is not possible for the IAEA to source obligation-free uranium from these countries, it could go to a supplier like Kazakhstan. For more information about consent rights, see "Swaps in the International Fuel Market," prepared by the Uranium Institute's Trade Issues Working Group for the Committee on Supply, Demand and Trade from February 2000. http://www.world-nuclear.org/trade_issues/reports/swapsreport.pdf.

Finally, if no agreement is reached and there is no interest in extending the forum, states will maintain the NPT status quo. Even under this scenario, states' decisions regarding enrichment will be made in light of arguments debated in the forum.

We concede that many non-nuclear-weapon states without enrichment technology may be initially reluctant to make additional concessions from the status quo. Nevertheless, we believe our proposal may help the international community move beyond a norm that legitimizes unrestricted enrichment to a more restrictive norm that balances energy needs with nonproliferation.

The Initiative's Impact on Special Cases

This initiative is not a short-term solution to the current problem cases of the international nonproliferation regime. In particular, we recognize that Iran may not be willing to join the de-facto moratorium or rely upon fuel-supply guarantees, at least in the short run. However, through establishing objective criteria for legitimate enrichment, the proposed structure would raise additional doubts about Iran's motivations as well as reduce Iran's perceptions of being singled out by the United States. This framework could thus increase long-term pressure on Iran while also providing it with a face-saving option for ending enrichment, should it later be compelled to do so.³²

Similarly, it is unlikely that Brazil would be willing to accept the de-facto moratorium.³³ Although Brazil, like Iran, has an internal debate about the sensibility of the state's enrichment program, the current government might be unwilling to accept a de-facto moratorium, especially in light of the recent investments into the Resende enrichment facility.³⁴ However, in the long run, objective criteria developed in an inclusive manner could raise doubts concerning Brazil's rationales for domestic enrichment, thus perhaps compelling it to incorporate its program in a multinational arrangement.

Objective criteria that would be perceived as more legitimate by a greater number of states could make the emergence of similarly problematic cases in

³² In the short run, constructive compromise solutions to Iran's problem might include Russia's provision of enrichment services to Iran on Russia's territory or the establishment of a black-box facility in Iran.

³³ Brazil currently has a small civilian enrichment facility at Resende and is planning on expanding this facility. Sources: Personal communication with Goldemberg; IAEA 2003 Country Profile: Brazil; "Resende Nuclear Fuel Factory"; www.globalsecurity.org/wmd/world/brazil/resende.htm; Cirincione, Joseph, et al., eds. *Deadly Arsenals*. Carnegie Endowment. 2005.

³⁴ Although fuel-supply guarantees should provide Brazil with sufficient energy security, it cannot satisfy Brazil's underlying quest for "international prestige" that it believes comes with such capability. Moreover, reliance on fuel-supply guarantees, if it also meant the shutdown of the Brazilian Navy's enrichment plant, would disrupt Brazil's Nuclear Navy program.

the future less likely. For example, states such as Argentina and South Africa, which have shut down their enrichment facilities, may be willing to accept a de-facto moratorium and the forum, especially given their *relatively* small demand for nuclear services. In the long run, if the fuel-supply guarantees prove reliable, these states might be less likely to consider re-establishing national enrichment programs.³⁵ Finally, the fuel-supply guarantees could potentially dissuade such states as South Korea and Ukraine from developing enrichment capabilities, despite the fact that both already have over 10 GWe capacity.³⁶

Conclusion

The NPT is the critical but imperfect foundation of the international nonproliferation regime. In the coming years, as demand for energy grows and more states strive for technological independence, controlling the spread of enrichment technologies will be particularly difficult. In its current form, the NPT cannot effectively meet this challenge.

Recently, tools designed to complement the NPT, such as the Bush Administration's Proliferation Security Initiative, have been successful in addressing some issues that the Treaty cannot. The initiative proposed here could play a similar role in support of the NPT. It provides the means both to limit access to nuclear weapons and to define when uranium enrichment is permissible. In doing so, it strikes a fair balance between proliferation risks and the rights of individual states.

³⁵ At least in Argentina, there has been an internal discussion about the development of an advanced, proliferation-resistant national enrichment facility. *Nuclear Fuel*. 2000.

³⁶ South Korea (ROK): Although ROK imports enrichment services from several suppliers including the United States, UK, and Russia, it is heavily dependent on U.S. supplies. At this time, some within the ROK nuclear-establishment circle are tentatively considering national enrichment as a long-term possibility (in 10–20 years).

Ukraine: Like South Korea, Ukraine is worried about its heavy reliance on one supplier (Russia) for enrichment imports. Given Kiev's rocky relationship with Moscow and that Moscow has used the price and availability of enrichment services as leverage against Kiev, the supply-assurances arrangement would offer Ukraine greater energy security than the status quo. Sources: "Nuclear Power in Ukraine. Briefing Paper #63. August 2005. Uranium Information Centre. Melbourne, Australia. www.uic.com.au/nip63.htm (also available on the World Nuclear Association's website); "Ukraine: Country Profile and Reactor List." *International Nuclear Safety*. http://insp.pnl.gov/-profiles-ukraine-ukraine_intro.htm). Similarly, a potential spent fuel add-on could reduce Ukraine's dependence on Russia for back-end services, assuming it is possible to find alternative suppliers of spent-fuel services in addition to Russia.

Appendix A: Details of the Fuel-supply guarantee

Recipient states would be eligible for participation in a system of fuel-supply guarantees provided they meet the following conditions:³⁷

- Recipient is not engaging in any enrichment activities (“de-facto moratorium”).
- Recipient state is a member of the NPT and has not issued a notice of withdrawal from the NPT.
- Recipient state has the Comprehensive Safeguards Agreement in force.
- Recipient state has received IAEA Board of Governors approval for entry into force of the Additional Protocol.
- Any anomalies or inconsistencies concerning the state’s nuclear program discovered by the IAEA are resolved within 12 months.
- No fresh fuel or spent fuel has been removed from the nuclear power plant(s) except in accordance with safeguarded disposal arrangements.
- The nuclear power plants, for which the guarantee is in force, meet IAEA standards for safety and physical protection.

IAEA Authority to Manage Fuel Banks

The IAEA would manage the fuel-supply guarantee. The legal basis for this is established within the Statute of the IAEA.³⁸

Registration of Fuel Supply Contracts

Under this system of fuel-supply guarantees, a state seeking to protect a fuel supply arrangement would have to register a completed contract with the IAEA. The contract would be made with a recognized supplier. The IAEA, upon

³⁷ These conditions were derived primarily from Dr. Pierre Goldschmidt’s presentation to the November 2005 Carnegie International Nonproliferation Conference, titled “Mechanisms to Increase Nuclear Fuel-supply guarantees.”

³⁸ Specifically, Article III (A.1) authorizes the IAEA “to act as an intermediary for the purposes of...the supplying of materials, equipment, or facilities by one member of the Agency for another.” Article IX (A) authorizes the IAEA to take receipt of “special fissionable materials” to include LEU, and paragraph (J) establishes that “the materials made available pursuant to this article shall be used as determined by the Board of Governors in accordance with the provisions of this Statute.” Lastly, under Article XI, “Any member or group of members of the Agency desiring to set up any project for...practical application of...atomic energy for peaceful purposes may request the assistance of the Agency in securing special fissionable and other materials, services, equipment, and facilities necessary for this purpose.” The Statutes of the IAEA are available at: http://www.iaea.org/About/statute_text.html#A1.3.

certifying the contract, would issue a note of guarantee for the contract contingent upon the recipient state's continued eligibility.

Physical Fuel Banks versus Virtual Fuel Banks

The current proposals put forward by the United States and Dr. Goldschmidt both contain references to the concept of a "virtual fuel bank." Such a bank would consist of a pledge by enrichment providers to reserve a portion of their capacity for use by the IAEA as a guarantee for recipient states. Because a virtual fuel bank ultimately relies on the willingness of supplier states to act upon their pledges, we regard this approach as an insufficient guarantee to recipient states. If a system of fuel-supply guarantees is to be more than a symbolic gesture, it must contain a credible mechanism to facilitate the uninterrupted supply of fuel. In our proposal, credibility is achieved by establishing physical fuel banks owned and administered by the IAEA. This construct would effectively prevent the supplier states from dictating the functioning of the fuel-supply guarantees, thereby offering recipient state a sufficient assurance of uninterrupted supply.

Sale Price of Fuel Bank LEU

The price at which the IAEA sells LEU from the fuel bank is an important consideration for recipient states. In the event of an unexpected cut-off, we recommend that fuel bank LEU be sold at the original contract price until the recipient state successfully negotiates a new long-term contract with an alternate supplier state. Fuel would be available at the original contract price for a period equal to the time remaining in the now-defunct contract. Thereafter, the IAEA would charge a price comparable to prevailing long-term contract prices. This condition is intended to prevent states from relying exclusively upon the IAEA to meet fuel needs, thereby minimizing the impact of fuel-supply guarantees on the enrichment services market.

If the market experiences an upward trend in uranium or enrichment prices, then the revenues from the sale of fuel bank LEU will likely be insufficient for the restocking of the bank. To offset these additional costs, the IAEA might solicit additional monetary contributions from states with enrichment services not subject to the de-facto moratorium. These funds would be diverted to an escrow account dedicated to covering the additional costs of restocking the fuel banks. Given that a fuel cut-off is highly unlikely under the current market, however, we expect a stockpile of twenty annual reloads to serve as a sufficient guarantee until the forum develops longer-term fuel-supply guarantees, including specific conditions for the restocking of the fuel bank.

Appendix B: National vs. Enrichment Purchases Cost Comparison

The following spreadsheet shows a comparison between the cost of buying enrichment in the international market and the cost of owning a Urenco black-box enrichment plant. The comparison is done by breaking down the cost of owning a plant into production costs, financing costs, and the fixed cost of constructing a new plant. The various costs of building an enrichment facility and producing enriched uranium are summarized in the first figure. The green line gives the total cost of producing enriched uranium from a black box plant per SWU per year. At 10 GWe this number comes to about \$80 which is the estimated cost of enrichment for Urenco. The number of employees needed for a plant smaller than 3 million SWUs is fixed and according to Urenco's estimate will cost \$10 million/year for their facility in New Mexico. The sources for each number are listed below in the notes section. The second figure shows the cost of buying enriched uranium for twenty years from the international market at \$100/SWU versus producing the enrichment with Urenco's black-box technology. This is admittedly a rough estimate of the cost differences but they do convey the economies of scale argument and show that at approximately 10 GWe nuclear power capacity, it makes economical sense for a state to acquire enrichment technology.

Figure 1: National Enrichment

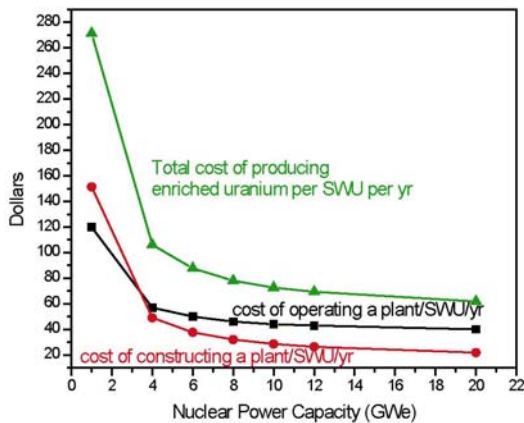
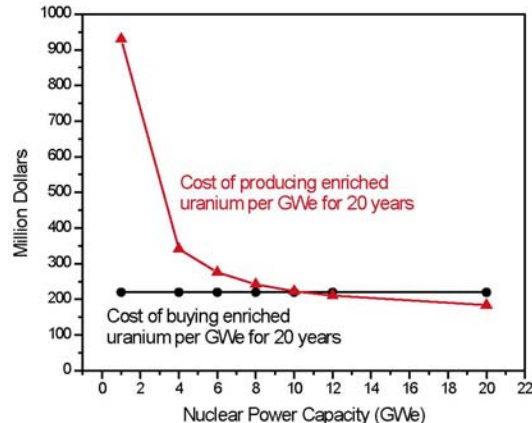


Figure 2: Enrichment Purchases



Market price/SWU	\$100.00						
SWU requirement/GWe/year	110,000see A4 in notes						
Fixed cost of building a plant (Million \$)	\$300.00See A6 in notes						
Number of 1 GWe reactors	1	4	6	8	10	12	20
SWU requirement/year	110000	440000	660000	880000	1100000	1320000	2200000
Cost of buying the SWU's from the market (Million \$)	\$11.00	\$44.00	\$66.00	\$88.00	\$110.00	\$132.00	\$220.00
Cost of building a black box cascade /SWU (see A13)	\$300.00	\$300.00	\$300.00	\$300.00	\$300.00	\$300.00	\$300.00
Cost of building a plant (Million \$)	\$333.00	\$432.00	\$498.00	\$564.00	\$630.00	\$696.00	\$960.00
Cost of operating a plant/SWU (see A14 in notes)	\$120.00	\$57.00	\$50.00	\$46.00	\$44.00	\$43.00	\$40.00
Cost of operating a plant/yr (Million \$)	\$13.20	\$25.08	\$33.00	\$40.48	\$48.40	\$56.76	\$88.00
Cost of financing a plant/yr (Million \$) (see A16)	\$16.65	\$21.60	\$24.90	\$28.20	\$31.50	\$34.80	\$48.00
Cost of buying for 20 years (Million \$)	\$220.00	\$880.00	\$1,320.00	\$1,760.00	\$2,200.00	\$2,640.00	\$4,400.00
Cost of producing for 20 years (Million \$)	\$930.00	\$1,365.60	\$1,656.00	\$1,937.60	\$2,228.00	\$2,527.20	\$3,680.00
Difference (Million \$) for twenty years	\$710.00	\$485.60	\$336.00	\$177.60	\$28.00	\$112.80	\$720.00

Notes

A4: 1GWe plant requires 18.6 MT of 4.5% enriched U which needs 110,000 SWUs. See footnote 3 in the main text for details.

A6: The new LES plant is being built for \$1.2 billion with a 3 million SWU capacity (NF, September 1, 2003). Assuming \$300/SWU for the cascade cost, the rest of the money is the fixed cost, i.e., \$300 million.

A13: This is taken to be \$300/SWU for any sized cascade. The reason for a constant number here is that for Urenco the costs are the same no matter what the size of the plant, since they are making so many centrifuges anyway for different projects.

A14: Power requirement of a Urenco Centrifuge is 50–200kWh/SWU (from a presentation by Executive Director, Commercial, Urenco Limited 2001)

The power requirement for older Urenco centrifuges were about 3% of the production cost (Nuclear Fuel June 8th 1992).

For the newer design it is assumed to be about 6%. The labor cost is taken separately in this number and is obtained from private communication with Dr. Pat Upson (ETC, Urenco) and the estimates for the New Mexico plant (<http://pearce.house.gov/news>)

A16: Assuming an interest rate of 8% and the loan is to be paid in 20 years. This means that the borrower will end up paying about 100% of the original amount in interest

Appendix C: Experts Interviewed for the Workshop

Name	Professional Affiliation, Place of Meeting
Liudmila Andreeva-Andrievskaya	Expert, Russian Atomic Energy Agency, Moscow
Alexey Arbatov	Co-Chair, Program in Nuclear Nonproliferation at the Carnegie Center, Moscow
Susan Bauer	Nuclear Nonproliferation Officer, U.S. Embassy in the Russian Federation, Moscow
Marina Belyaeva	Expert, Russian Atomic Energy Agency, Moscow
Grigoriy Berdennikov	Ambassador, Permanent Mission of the Russian Federation to International Organizations, Vienna
Terry Beven	Counselor, Australian Permanent Mission to the United Nations, Vienna
William Burns	U.S. Ambassador to the Russian Federation, Moscow
Oliver Caron	Atomic Energy Commission, Paris
Jean Cazalet	Deputy Director, Nuclear Energy Division of the Atomic Energy Commission, Paris
Aleksey Davydov	Expert on Issues of Nonproliferation and Safety, U.S. Embassy in the Russian Federation, Moscow
France Philippe Delaune	Director of International Relations, Atomic Energy Commission, Paris
Francois-Xavier Deniau	Ambassador, Permanent Mission of France to the United Nations and to International Organizations, Vienna
Philip Durst	Safeguards Technical Specialist, Office of the Deputy Director General, IAEA Department of Safeguards, Vienna
Gennadiy Evstafiev	Expert, PIR Center, Moscow
Denis Flory	Nuclear Counselor, French Embassy in the Russian Federation, Moscow

Jose Goldemberg	Former Secretary of State for Science and Technology in Brazil, Princeton, NJ
Pierre Goldschmidt	Former IAEA Deputy Director General for Safeguards, Princeton, NJ
Edward Ivanian	Professor, USA and Canada Institute, Moscow
Valentin Ivanov	Deputy of the Russian State Duma and Expert on Nonproliferation Issues, Moscow
Peter Jenkins	Ambassador, UK Mission to the United Nations, Vienna
Vitaly Keondjian	President, Group "Alliance," Moscow
Sergei Kislyak	Deputy Minister, Russian Ministry of Foreign Affairs, Moscow
Mikhail Kondratenkov	Second Secretary, Department for Security Affairs and Disarmament of the Nuclear Security and Nonproliferation Division, Russian Ministry of Foreign Affairs, Moscow
Vladimir Kuchinov	Senior Official, Russian Atomic Energy Agency, Moscow
Alexei Lebedev	Deputy General Director – Director, Department of Spent Nuclear Fuel Management, TENEX, Moscow
Jan Alexander Lodding	External Relations and Policy Officer, IAEA Office of External Relations and Policy Coordination, Vienna
Alan McDonald	Program Liaison Officer, IAEA Department of Nuclear Energy, Vienna
Fred McGoldrick	Former State Department Director of Nonproliferation and Export Policy, Bengelsdorf, McGoldrick, and Associates LLC, Phone Conference (Princeton to Boston)
Israel Michaeli	Ambassador, Permanent Mission of Israel to the IAEA, Vienna
David Noble	Counselor for Nuclear Policy, U.S. Mission to International Organizations, Vienna
Vadim Mikerin	Director, Department of Intergovernmental Programs and Pan-American Operations, TENEX, Moscow

Bruno Pellaud	Former IAEA Deputy Director General for Safeguards, Princeton, NJ
Douglas Scott Proudfoot	Alternative Permanent Representative, Permanent Mission of Canada to the IAEA, Vienna
Eric Pujol	Nuclear Attaché, Permanent Mission of France to the IAEA, Vienna
Bernardo Gratien Poli Ribeiro	External Relations Officer, Verification and Security Policy Coordination Section, IAEA Office of External Relations and Policy Coordination, Vienna
François Richier	French Foreign Ministry, Paris
Laura Rockwood	Principal Officer, IAEA Office of Legal Affairs, Vienna
Sergey Ruchkin	Deputy Director, Department of Strategic Analysis, TENEX, Moscow
Kirk Schnoebelen	Marketing Manager, URENCO Inc., Princeton, NJ
Greg Schulte	Ambassador, U.S. Mission to International Organizations, Vienna
Philip Sewell	Senior Vice President for Corporate Development at USEC, Princeton, NJ
Deborah Stokes	Ambassador, Australian Embassy and Permanent Mission to the United Nations, Vienna
Richard Stratford	Director, Office of Nuclear Energy Affairs, Bureau of Nonproliferation, U.S. Department of State, Princeton, NJ
James Timbie	Senior Adviser, Office of Under Secretary for Arms Control and International Security, U.S. Department of State, Video conference (Princeton to DC)
Roland Timerbaev	Expert at the PIR Center, Former NPT Negotiator for the Soviet Union, Moscow
Pat Upson	Managing Director, URENCO Enrichment Technology Company, Almelo (Netherlands)
Javad Zarif	Permanent Representative of the Islamic Republic of Iran to the Secretary-General of the United Nations, Princeton, NJ

Appendix D: Research Topics of Workshop Members

- Habib, Babur. “Multinational operation and ownership of fuel-cycle facilities.” bhabib@princeton.edu
 - Jain, Sunil. “Various approaches to fuel supply assurance.” sunilj@princeton.edu
 - Johnson, Richard. “Global enrichment and reprocessing supply and demand, and justifications for national plants.” rcjohnso@princeton.edu
 - Jonas, Ilan. “IAEA ability to detect diversions and clandestine plants.” ijonas@princeton.edu
 - Kemp, R. Scott. “Fuel-cycle industry constraints and preferences.” rskemp@princeton.edu
 - Kovacs, Andrew. “Effectiveness of technology denial efforts.” akovacs@princeton.edu
 - Malkin, David. “Russia as fuel-cycle service supplier, including spent-fuel storage.” dmalkin@princeton.edu
 - Nachinkina, Darya. “Brazil’s enrichment program, including naval-reactor program.” dnachink@princeton.edu
 - Szewczyk, Bart. “Iran’s fuel-cycle program and prospects for stopping it.” bszewczy@princeton.edu
 - Tsai, Pei. “Japan case study, including reprocessing program.” ptsai@princeton.edu
-