The Economics of Nuclear Energy Markets and the Future of International Security

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ABOUT THE AUTHORS

Erwann O. Michel-Kerjan is Managing Director of the Wharton School's Risk Management and Decision Processes Center, a center with more than 20 years of experience in the development of strategies and policies for dealing with extreme events.

As large-scale risks reshape the future of an increasingly interdependent world, Dr. Michel-Kerjan has worked over the past 10 years helping corporations and governments address this new landscape, develop appropriate solutions and create market opportunities. His current work focuses on terrorism risk insurance, climate change, mitigation and financing of natural disasters, energy interdependence and non-proliferation, the impact of information sharing on optimal risk sharing, and projects on national security and critical infrastructure protection in collaboration with Lockheed Martin and several federal agencies.

He has authored or coauthored over 40 publications and two books focusing on the intersection of financial management and global risks/opportunities, including *Seeds of Disaster, Roots of Response: How Private Action Can Reduce Public Vulnerability* (with P. Auerswald, L. Branscomb, and T. LaPorte, Cambridge University Press, 2006), which is the first attempt to analyze the private efficiency/public vulnerability trade-off in the context of national and international security. (See www.seedsofdisaster.com.)

From 2003 to 2005, he served on the OECD Terrorism Insurance Task Force, and in 2005, he co-led, with Howard Kunreuther, the Wharton initiative on the future of terrorism risk financing in the United States (TRIA and Beyond). He has studied and collaborated with several research institutions in North America (including McGill, Columbia and Harvard) and is also Faculty Research Associate at the Ecole Polytechnique in Paris, where he completed his doctoral studies in mathematics and economics before joining Wharton in 2002.

In 2007, Dr. Michel-Kerjan was named a Young Global Leader by the World Economic Forum, an honor bestowed to recognize and acknowledge the most extraordinary leaders of the world under the age of 40.

Debra K. Decker is a Research Associate with the Belfer Center for Science and International Affairs at the John F. Kennedy School of Government at Harvard University and has worked with the American Academy of Arts and Sciences' Global Nuclear Future project. Her research focuses on nuclear proliferation and proposals for reform.

Early in her career, Mrs. Decker worked on arms control and foreign aid for U.S. State Department–related agencies. Entering the private sector, she was manager of planning for Europe for Chase Manhattan Bank and then a consultant on strategic planning. Most recently, she has been a national award-winning journalist writing editorials and columns for the *Dallas Morning News* and other newspapers and journals.

She received an MBA from the Wharton School and an MPA from Harvard, where she was distinguished as a Littauer Fellow. Mrs. Decker is a member of the International Institute for Strategic Studies, the World Affairs Council and the Dallas Committee on Foreign Relations. In 2007, she also joined the consulting firm Booz Allen Hamilton as an advisor to government clients.

The Economics of Nuclear Energy Markets and the Future of International Security

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Abstract

This paper discusses the evolution of nuclear energy markets and key drivers of the growing "nuclear renaissance." We focus on uranium, the largest part of the nuclear fuel markets, and analyze market demand, supply, and prices since the 1970s. We review the forces impacting this market – historically and prospectively - and note proliferation concerns surrounding nuclear energy: i.e. the same facilities that enrich uranium for electricity generation can also enrich it further for nuclear weapons.

We discuss proposals currently being offered by the international community to counter this proliferation challenge and propose a complementary solution: the development of a market-based approach that relies on what has become the largest industry in the world, insurance and finance. We analyze the feasibility of such an "Insure to Assure" approach, developed in conjunction with the public sector, and its implications for international security and nuclear energy markets (including the possible commoditization of enriched uranium).

1. Introduction

Nuclear energy is likely to play a small but important role in satisfying rising energy needs as concerns grow over carbon-based energy's effect on global warming and countries look to fulfill their electricity needs through alternative sources (International Energy Agency, 2007). The U.S. Department of Energy estimates the world commercial nuclear generating gross capacity could increase from 2005 levels by 35 percent in 2015 and by 70 percent in 2030 (U.S. Department of Energy, 2006).

Until the end of the 1970s, nuclear reactors provided less than 5 percent of the world's electricity. Today they provide 16 percent of a much higher level of world electric production (Figures 1a and 1b). They contribute about 2,600 billion kilowatt-hours (kWh) each year to satisfy electricity needs, as much as from all sources of electricity worldwide in 1960 (U.S. Department of Energy, 2005).

Figures 1.a and 1.b.

World Electricity Generation by Fuel—As a Percentage of World Electricity Generation

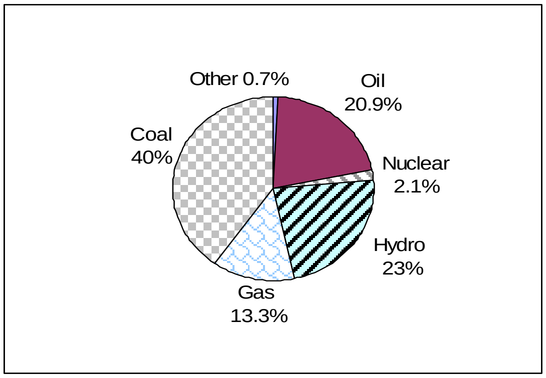

Figure 1.a. 1971 (total: 5,500 billion kWh)

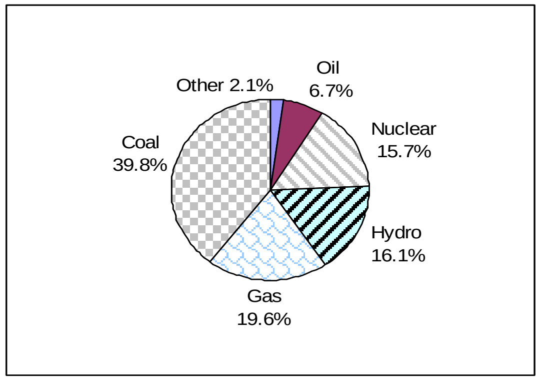

Figure 1.b. 2004 (total: 17,500 billion kWh)

Source: Data from OECD (2007)

Nuclear power is particularly important in parts of the industrialized world. Electricity from nuclear reactors typically represents a significant portion of the electricity consumed in most Organization for Economic Cooperation and Development (OECD) countries: about 20 percent in the United States, 25 percent in the United Kingdom, nearly 30 percent in Germany, and over 75 percent in France. Although about 439 nuclear power plants currently operate in thirty countries, the United States, France, and Japan operate about half of these. Five countries—the United States, France, Japan, Russia, and Germany—represent nearly 70 percent of the worldwide commercial nuclear generating gross capacity; the top fifteen countries represent over 90 percent (Table 1).

As energy needs increase disproportionately in developing countries, however, these figures are changing. Currently, an additional 33 plants are or are in the process of being constructed, with another 94 planned, and 222 proposed by countries ranging from China to South Africa (UIC, 2007b). These figures do not include potential nuclear electric production in Saudi Arabia and some other member states of the Gulf Cooperation Council, which have recently expressed interest in nuclear development. Thus, in accounting for future potential reactors, the relative importance of nuclear power will vary, with China becoming one of the leaders in nuclear power generation, and countries such as India, Brazil, South Africa, and Iran joining the top fifteen nuclear energy users. Overall, with the planned or proposed reactors, the world would go from thirty countries having commercial nuclear reactors to at least thirty-eight—more than a quarter increase.

This increase in the expected need for nuclear power and its wider geographic spread has led to new concerns over the security of nuclear power generation. Although concern over reactor safety—fueled dramatically by the Three Mile Island (1979) and Chernobyl (1986) accidents—have been allayed somewhat by new power designs, the problems of safe disposal of the waste and the potential for nuclear proliferation (that could both lead to use of nuclear weapons by terrorists and by states) have not been fully resolved. To understand these concerns and their relationship to nuclear energy markets, one must first become familiar with the entire nuclear fuel cycle, from the mining of uranium ore to the production of electricity—or of nuclear weapons.

Table 1. **World Commercial Nuclear Generating Gross Capacity, Nuclear Power Reactors, and Uranium Required, 2007**

Country	*Total commercial nuclear generating gross capacity (MWe)*[1]	*% of total*	*Reactors Operable*	*Uranium required* *(Pounds equivalent U_3O_8)*	*% of total*
USA	98,254	26.6%	103	52,964,958	30.1%
France	63,473	17.2%	59	27,388,563	15.6%
Japan	47,700	12.9%	55	23,436,664	13.3%
Russia	21,743	5.9%	31	9,977,489	5.7%
Germany	20,303	5.5%	17	9,208,770	5.2%
South Korea	17,533	4.8%	20	8,022,672	4.6%
Ukraine	13,168	3.6%	15	5,291,213	3.0%
Canada	12,595	3.4%	18	4,850,058	2.8%
United Kingdom	10,982	3.0%	19	5,338,762	3.0%
Sweden	8,975	2.4%	10	3,877,933	2.2%
China	7,587	2.1%	10	3,840,950	2.2%
Spain	7,442	2.0%	8	3,891,141	2.2%
Belgium	5,728	1.6%	7	2,850,334	1.6%
India	3,577	1.0%	16	1,297,047	0.7%
Switzerland	3,220	0.9%	5	1,518945	0.9%
Top 15	342,280	91.9%	393	163,755,499	93.2%
Others	26,580	8.1%	42	11,990,421	6.8%
World Total	368,860	100.0%	435	175,745,920	100.0%

Sources: Data from World Nuclear Association, International Atomic Energy Agency

[1] A typical 1,000 megawatt-electric (MWe) reactor can provide enough electricity for a city of about 600,000 people.

The next section of this article explains the nuclear fuel cycle. The article focuses specifically on the uranium market, which is the largest part of the nuclear fuel markets, and analyzes the demand, supply, and prices in this market. We then discuss some of the important forces that have impacted this market in the past 30 years as well as those which will determine its future. These forces include a large spectrum of possible effects worldwide, ranging from increasing demand for energy to growing concern about carbon dioxide emissions and their impact on global warming to the sunsetting of the Megatons to Megawatts program between the U.S. and Russia in 2012. We then review two critical forces which could have negative impacts: continuing safety issues related to nuclear technology and growing concern over nuclear proliferation. Throughout, we note the distinctive feature of this market: vigorous government involvement. The final section of this article discusses proposals currently being offered by the international community to counter one of the negative drivers –the nonproliferation challenge– and introduce our market-based proposal that relies on what has become the largest industry in the world, insurance and finance. We discuss the feasibility of such an approach, developed in conjunction with the public sector, and its implications for international security and nuclear energy markets (including the possible commoditization of enriched uranium).

2. THE NUCLEAR CYCLE: RELATING ELECTRICITY GENERATION AND EXTREME THREATS

The nuclear fuel cycle involves multiple steps. Uranium is first mined then milled to obtain uranium oxide concentrate (U_3O_8, or “yellowcake”). This is the form in which uranium is commonly contracted for sale.

For most nuclear reactors, the next step is purification and conversion of the uranium oxide into a gas, uranium hexafluoride (UF_6), which enables enrichment. Enrichment can occur in various ways, but the most economic today is the centrifuge process in which the difference in atomic weights allows the percentage of the fissile isotope U-235 to increase from the 0.7 percent typical in natural uranium to the 3–5 percent most reactors require to make the uranium fissile; i.e. made up of atoms that can be split in a self-sustaining chain reaction to release energy. After enrichment, the UF_6 gas is converted to uranium dioxide (UO_2), which forms fuel tablets that are typically placed inside tubes assembled in bundles to become the fabricated fuel elements for the core of the reactor that will produce electricity. The process from mining to fuel fabrication involves a variety of companies and countries to transform the uranium required into the fuel elements for a typical 1,000 MW(e) light-water reactor. These fuel elements ordinarily require a changeout every 12 to 36 months.

Six countries presently enrich for the commercial markets: France, Germany, the Netherlands, Russia, the United Kingdom, and the United States. Enrichment is or has recently occurred in Argentina, Brazil, China, Iran, North Korea, Pakistan, and South Africa (Australian House of Representatives, 2006). Many other states have demonstrated interest in enrichment capability.

The used fuel elements contain uranium residuals and other elements including plutonium. In an “open” fuel cycle, the used fuel is maintained on-site until its radioactivity decreases and it can be put into final storage. A “closed” fuel cycle involves reprocessing the used fuel into mixed oxide fuel (MOX) and reusing it. Some reactors, such as in France, are constructed to use MOX, while others may need to be converted to use such fuel. In the “closed” fuel cycle, the residual uranium is recovered and this depleted uranium reenriched. It is supplemented with the plutonium that had been formed in the fuel elements and subsequently chemically separated out.

Spent fuel is naturally proliferation-resistant because it possesses such high radioactivity that it cannot be safely handled or stolen. In reprocessing, the natural radioactivity of the residual fuel is reduced thereby making the material easier to handle and harder to detect; also the most fissile plutonium is separated out and could be diverted into weapons. Commercial reprocessing currently occurs in France, India, Japan, Russia, and the United Kingdom (UIC, 2007). The nuclear weapons states—China, France, India, North Korea, Pakistan, Russia, the United Kingdom, and the United States—have all reprocessed plutonium for bombmaking.

The controversial parts of the fuel cycle include enrichment and fuel reprocessing. Indeed, the same facilities that enrich uranium for electricity generation can also enrich it further for developing nuclear weapons. Highly enriched uranium is composed of at least 20 percent U-235, and weapons-grade uranium is typically 80 or 90 percent, although a less efficient weapon could use lower enrichment levels.[2] Nuclear weapons can be made from enriched uranium, plutonium, or a combination of each—and the materials can come from noncommercial nuclear reactors as well.[3] These include research reactors (currently about 100 research reactors worldwide use highly enriched uranium) and naval propulsion reactors on icebreakers, submarines, and other ships. For instance, the 2006 North Korean nuclear test is believed to have used plutonium reprocessed from its 5 MW(e) Yongbyon experimental nuclear reactor. States prefer plutonium-based weapons, which - for the same yield - weigh less than an enriched uranium warhead and thus more easily fit on a missile. Terrorists, on the other hand, might prefer enriched uranium, which they could more easily fashion into a nuclear weapon.

This duality of nuclear material usage—electricity versus bomb—is a peculiar feature of this energy source. For this reason, any economic analysis that examines the future of nuclear energy markets without integrating the international security aspect would paint a very incomplete picture and lead to inaccuracies. On the other hand, focusing exclusively on the security aspect, disregarding the increasing demand for energy in general—and carbon-free energy sources in particular—combined with more countries calling for their energy independence (whether for oil, gas, or enriched uranium), would be misleading as well. Not surprisingly, then, both energy and security forces have influenced this market and are likely to continue to do so.

We now turn to an analysis of demand for and supply of uranium, as well as of the evolution of prices, which, after 20 years of relative stability, have recently set record highs.

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[2] Working the opposite way, it is possible to produce low-enriched uranium by blending down highly enriched uranium (from existing weapons) with uranium with very low levels of isotope U-235. See our discussion of the "Megatons to Megawatts" program.

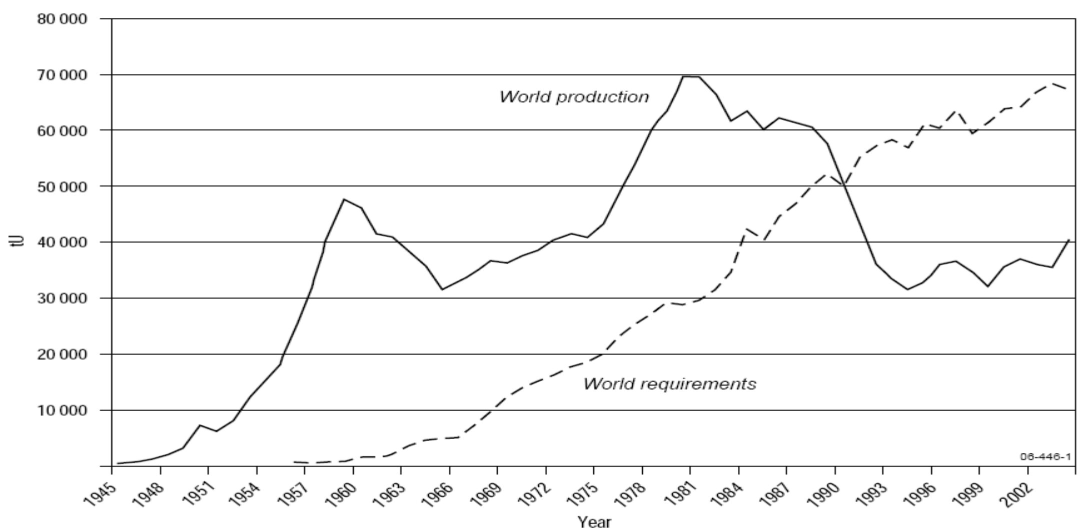
[3] The International Atomic Energy Agency considers 8 kilograms of plutonium and 25 kilograms of uranium enriched to 20% or more of uranium-235 to be quantities sufficient to make a nuclear weapon, although here again lower amounts can be used.

3. HISTORICAL PERSPECTIVE ON URANIUM MARKETS

3.1. Demand

Demand for uranium has been increasing since the 1950s. Figure 2 depicts the worldwide evolution of uranium requirements (dashed line) and production (solid line) since the development of nuclear technology. Although the first commercial reactors began to operate in the late 1950s, most of the uranium production was used to satisfy military demand in the 1950s and the 1960s, as the United States and Soviet Union increased their nuclear weapons stockpile (and also increased reliance on nuclear-powered ships[4]).

Figure 2. **World Uranium Reactor Requirements and Production from Mines, 1945–2004**



Sources: OECD and IAEA (2005)

As depicted in Figure 2, in 1969 the world annual uranium requirements for reactors were nearly 11,000 metric tons (t).[5] In 1976, requirements had almost doubled, and after

[4] Nuclear propulsion does not represent a large demand today. This demand is satisfied generally out of existing state reserves of enriched uranium—with the United States, for example, currently maintaining 50 years' worth of highly enriched uranium (HEU) naval propulsion reserves (D'Agostino, 2007). Space exploration with nuclear fuel is also considered a potential, however minor, demand.

[5] Measures that describe uranium markets vary: kilogram and metric ton of uranium (kgU and tU, respectively) or pound, kilogram, and metric ton of uranium oxide concentrate (U_3O_8). One ton (or tonne)

another 7 years had doubled again, to reach 40,000 tU in 1983. In addition to these direct reactor requirements, and the direct military uses already mentioned, much of the production went into commercial and military inventories—although military stocks are harder to estimate since data are often not publicly available.

In the 1970s with utilities building up large stockpiles that amounted to several times the actual annual consumption for electricity production, commercial stock also increased. That buildup was driven by both the oil crisis and a growing concern about a possible uranium supply shortfall induced by more orders for new nuclear reactors. Over time, however, civilian inventories have fallen. Utilities today typically have 1 to 2 years of stocks as strategic reserves or in the pipeline (although in Asia the levels may be higher) and producers have 1 year (OECD, 2007).

However, as nuclear power generation has increased and the number of operable reactors in the world continues to rise, so too have overall civilian uranium needs. As discussed in the introduction, as of January 2007, 435 reactors were operable worldwide and 92 others were under construction or planned (even though it is not clear at this point whether all the planned reactors will actually be constructed). Moreover, despite some aging reactors being decommissioned, many reactors are getting refurbished for larger capacities and are extending their operational lives. Thanks to better efficiency of fuel changeouts and reduced downtimes, many existing reactors now operate at a much higher capacity factor (output proportion of their nominal full-power capacity). In the United States, deregulation of electricity markets has increasingly pressured utilities to be even more cost efficient and to tighten inventory management. The United States operated its nuclear reactors at an average 54 percent of their capacity in 1980, at 68 percent by 1991, and at 90 percent by 2001 (AUA, 2007).

In 2005 world uranium requirements were nearly 66,000 tU (about 173 million pounds U_3O_8). To put this in perspective, one typical 1,000 megawatt electric nuclear power plant—enough to provide base power for a town of 600,000 people, as mentioned in footnote 1—typically uses 200 tons of natural uranium per annum. The United States remains the largest uranium consumer; its 103 nuclear reactors operating with an average

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of uranium oxide concentrate (U_3O_8) is made out of 1.17788 tU, and one pound uranium oxide (lb U_3O_8) contains approximately 0.38 kgU. One tU, therefore, can generate about 2,632 lb U_3O_8.

generation capacity of 950 MWe consumed over 20,000 tU in 2005, or nearly one-third of the world's uranium demand.[6] Together, the United States, France, and Japan represent nearly 60 percent of the worldwide demand today (see Table 1, "Uranium required").

Meanwhile, non-civilian demand for new uranium supplies has nearly disappeared in the established nuclear weapons states as bombmaking has generally subsided. Whereas only two nuclear bombs have been used in war to date (on Hiroshima and Nagasaki, Japan, in August 1945[7]), Russia and the United States together possess today around 26,000 nuclear weapons, and France, the United Kingdom, and China together possess about 1,000. These states' weapons are generally plutonium-based but have uranium components. As discussed above, India, Pakistan, and North Korea are also declared nuclear powers; Israel is presumed to have nuclear weapons; and Iran is suspected of planning to build them. These other states might have some demand for increasing weapon stockpiles (Cirincione, 2007).

3.2. Supply

Out of the 66,000 tU uranium requirements in 2005, only 41,600 tU (about 109 million pounds U_3O_8) came from mines—so-called primary markets (Figures 2 and 3). The shortfall between demand and supply—24,400 tons of uranium (about 64 million pounds U_3O_8) per year—came from secondary markets. These secondary markets are derived from inventories, the dismantling of warheads and conversion of the warheads' highly enriched uranium to a proper level for fuel, the reenrichment of depleted uranium tails, and the reprocessing of spent fuel.

Primary Markets: Mine Production

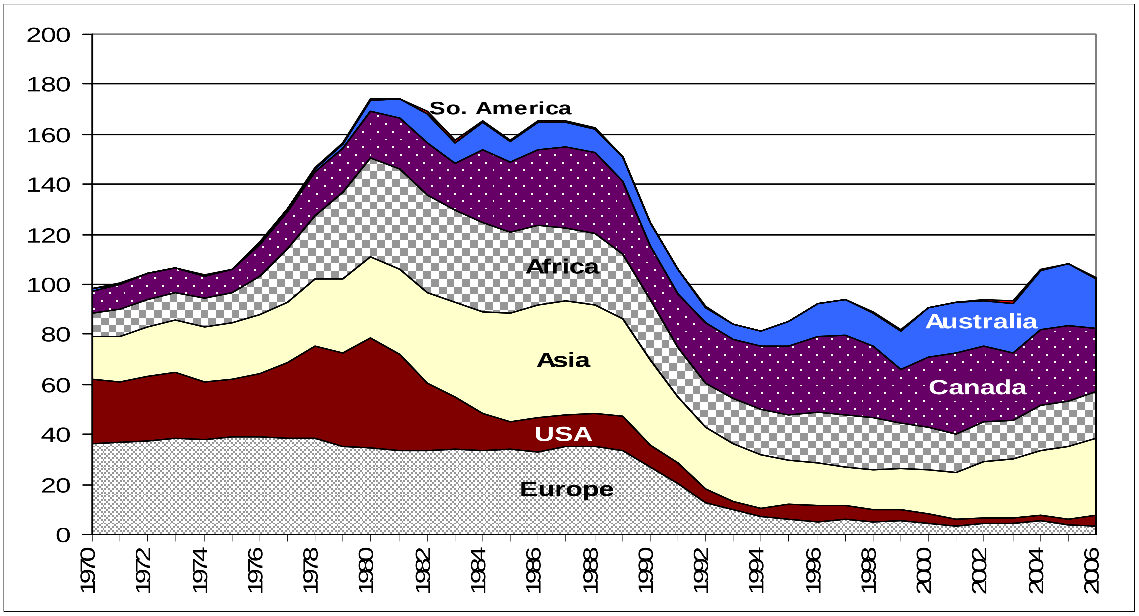
Thus, today, just 60 percent of uranium supplied for nuclear power comes from mines. Figure 3 below depicts the evolution of world uranium production from 1970 to 2006 as

[6] There are now 104 licensed nuclear plants in the United States. The 104th plant, TVA's Browns Ferry Unit 1, is undergoing refurbishment and is expected to restart later in 2007.

[7] The atomic bomb dropped on Hiroshima, although comprised of over 60 kg of highly enriched uranium, only fissioned less than a single kilogram.

well as the quantities of uranium extracted from mines by the major producers in terms of million pounds equivalent U_3O_8.

Figure 3. **World Uranium Production from Mines per Zones or Countries, 1970-2006**



Source: Data courtesy of TradeTech (in million pounds equivalent U_3O_8).

The overall pattern shows a significant increase in volume in the late 1970s up to nearly 175 million pounds U_3O_8 in 1980/81—mainly due to much higher prices of uranium that made mining projects more economically attractive—followed by a radical reduction in production starting at the end of the 1980s. Falling production continued for a few years to reach 88 million pounds U_3O_8 in 1999 but has reversed lately. At 102 million pounds U_3O_8 in 2006, however, the production from mines still remains much lower than what it was 20 or 25 years ago (Figure 3).

Today the biggest producers of uranium from mines are Canada (25 percent) and Australia (20 percent), followed by Kazakhstan (10 percent). U.S. mines produce only 4 percent of the world's uranium, a sharp decrease compared to the quarter of world-wide mine production the United States produced 25 years ago.

This global decrease over time, however, is not due to a lack of resources. Uranium is indeed a relatively common element found worldwide; it is as about as common as zinc and about 40 times as abundant as silver. Most of it is located in Australia (24 percent), Kazakhstan (17 percent), Canada (9 percent), the United States (7 percent), South Africa (7 percent), and Brazil (6 percent).

A joint study by the OECD and the UN International Atomic Energy Agency (IAEA) estimated that the total identified amount of conventional uranium stock, which can be mined for less than $50 per pound U_3O_8, was enough to generate electricity for 85 years (based on the 2004 nuclear electricity generation rate of demand) (OECD-IAEA, 2006). Moreover, while little effort has been devoted to producing new mines in the past, it does not mean this will remain the case in the future. New exploration has been undertaken as prices have risen since 2001 (see our discussion on prices below).

Production from Secondary Markets

The other 40 percent of uranium supplies currently comes from sources other than mine production.[8] The substitution of supplies in primary markets from secondary market sources makes uranium markets somewhat unique compared to markets for other products such as oil and gas.

The largest of these secondary sources are the stockpiles of natural and low-enriched uranium, held by electric energy producers. This secondary market accounts for 25 to 30 percent of total world supply for uranium. But this proportion is now decreasing as excess inventories have been seriously reduced. According to the world's largest uranium producer, Cameco Corporation, in 2005 some utilities actually started purchasing uranium again to build new strategic inventories (Cameco, 2005).

Another important source of nuclear fuel—about 10 to 13 percent of world supply—comes from the world's nuclear weapons stockpiles, which raises serious international security issues in the post–Cold War environment. The United States and countries of the former U.S.S.R. signed several disarmament treaties that aimed to significantly reduce their nuclear arsenals.[9] This made possible the 1993 U.S. and Russia Highly Enriched

[8] This proportion varies from year to year; over the past 10 years it has been between 35 and 45 percent.

[9] For instance, Ukraine agreed in the 1990s to sign the Nuclear Nonproliferation Treaty and received high payments from both the United States and Russia to dismantle its nuclear weapons. The first U.S. payment, pledged under the Nunn-Lugar legislation, was $175 million, making Ukraine, almost overnight, the fourth largest recipient of American aid at that time. In 1994 it received $350 million in economic aid and $350

Uranium Purchase Agreement, based on a commercially financed public-private partnership.[10] The main goal of this unique twenty-year program is to convert uranium enriched to over 90 percent U-235, taken from dismantled Russian nuclear weapons, into low-enriched uranium (LEU) (typically 3–5 percent) for nuclear fuel.

To implement this agreement, the United States set up the U.S. Enrichment Corporation (USEC)–at that time a government-owned corporation, before it was fully privatized in July 1998–while the Russian Federation created a commercial subsidiary of its Ministry of Atomic Energy, Techsnabexsport ("Tenex"). Tenex has facilities that convert warhead material to low-enriched uranium and sell it to USEC. USEC receives the fuel for shipment to the United States and sale to its customers.[11] This initiative, known as the *Megatons to Megawatts* program, had and continues to have an important impact on both uranium markets and international security (Garwin and Charpak, 2002). The first shipment from Russia arrived in the United States in 1995. By the time the program ends in 2013, it should have eliminated weapons-grade uranium equal to 20,000 nuclear warheads (for a total of 500 tons of HEU converted into over 14,500 tons of LEU).

The fuel purchased by the United States from Russia through this program generates on average 10 percent of all-source electricity consumed in America each year. By 2013, this commercial program supported by the U.S. and Russian governments will have produced fuel sufficient to power the United States for about 2 years. As nuclear power plants generate about 20 percent of all electricity consumed in the United States each year, the equivalent of 10 years of U.S. nuclear-generated electricity has come from this program, rather than from mine production. The total value of the LEU resulting from this agreement is $12 billion.

The United States has made also some of its military inventories available to the market but in much lower quantities than the Megatons to Megawatts program. Between 1999 and 2006, 50 tons of weapons-grade uranium was downblended to 660 tons of low-

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million towards dismantling nuclear weapons, besides an additional $200 million bestowed by President Clinton (Jehiel, Moldovanu and Stacchetti, 1996).

[10] The idea of the HEU Purchase Agreement was first publicly suggested by MIT's Thomas Neff in a 1991 op-ed in the *New York Times* (Neff, 1991).

[11] See http://www.usec.com for a more detailed description of the commercial arrangements.

enriched nuclear fuel (U.S. Department of Energy, 2006-b). An additional 37 tons is planned to be downblended (20 for sale and about another 17 reserved for an international fuel bank).

The last two secondary markets comprise the reenrichment of depleted uranium tails at enrichment plants (3–4 percent of world demand) and the reprocessing of used reactor fuel (about 1 percent).

3.3. Prices

Term Market

The economics of these demand and supply forces are reflected in the evolution of uranium prices over time. In most countries, nuclear power plants and electric utilities secure the most important part of their required uranium by signing medium-term and long-term contracts with foreign uranium producers and suppliers. These contracts call for deliveries to start about 3 years after contract signing and run for an average of 6 years, according to Ux Consulting, which tracks market activity. Prices for such contracts are established through negotiation between the buyer and the seller. Prices are typically based on a set of various pricing formulas such as reference prices (based on spot market; see below) with or without price ceilings or floors, fixed prices that are only adjusted for inflation depending on delivery time, and so on. As a result, it is difficult to establish a robust quantification of the evolution of this market because the transactions are typically confidential.

According to Ux and TradeTech which track most of these transactions though, in the last several years, the term market volume has more than tripled as buyers seek to lock in uranium supplies, if not the delivery price (contracts contain price floors and some ceilings). Contracts written in 2005 lasted much longer than before (several of them up to 10 years), leading to a higher volume of uranium under contract. According to these two companies, the average long-term price was $36 per pound at the end of 2005, up 45 percent from $25 per pound at the end of 2004. In December 2006, the long-term price had reached $69 per pound, and by March 2007 was as high as $85 (TradeTech, 2007).

That drastic increase in price makes some mining projects that were deemed uneconomic now look attractive.

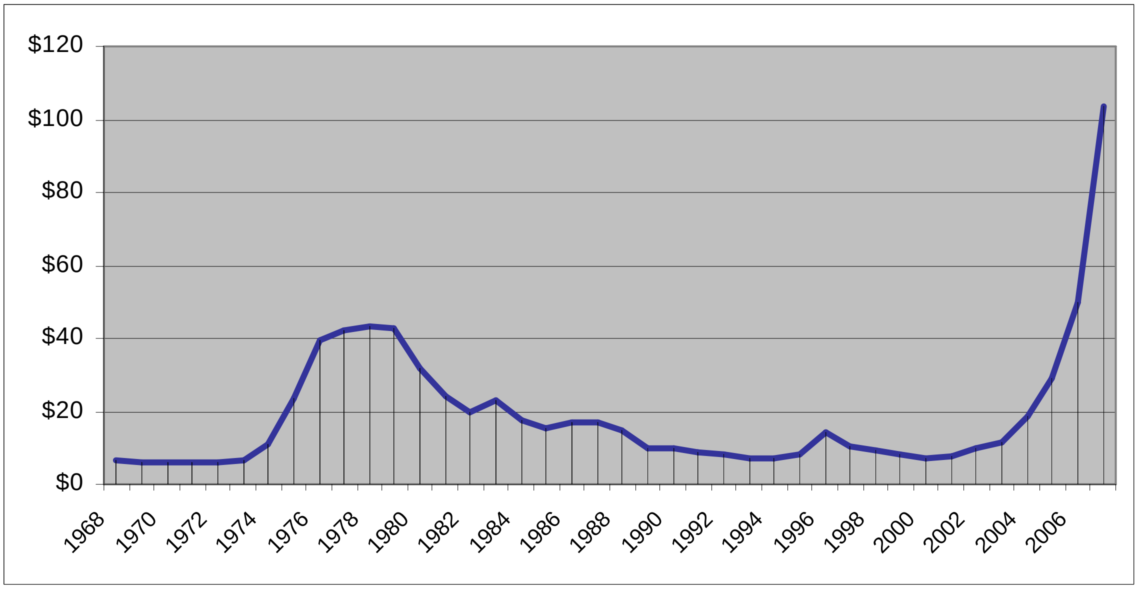
Spot Market

What is not purchased through the term market is purchased directly in the spot market, which is for quick sell (deliveries from a few weeks up to one year or so, after contract signing). For many years the spot market for uranium remained quite low, typically trading below $20 a pound between 1984 and 2004 (Figure 4). As previously discussed, the radical increase of the demand in the post-oil crisis of the 1970s, combined with growing concern about a possible uranium supply shortfall, pushed prices up during this period. After that, the spot price almost always continuously decreased for the following 25 years due to the availability of secondary sources of supply (including excess inventories and dismantled Russian nuclear weapon stockpiles). Uranium spot market reached a twenty-six-year low record in 2000 at the NUEXCO Exchange Value—the longest-running price indicator in the uranium market since 1968—at less than $7 per pound U_3O_8.

That has changed radically, however, in recent years. The price of uranium has grown since 2003, and in August 2006 it soared through the $50 level for the first time in its history, with a pound of U_3O_8 priced at $52. As Figure 4 depicts, only in the late 1970s was the Exchange value above $40 a pound (equivalent to nearly $110 in 2007 dollars). The price has continued to rise in the following months, however, reaching $75 in February 2007, up to an historic record high (even in real terms) at $140 in July 2007, before reaching the $75-$85 range again in September 2007.

The combination of at least four elements explains the recent trend, which we believe might reveal the beginning of more radical change in nuclear markets. First, the global demand for energy continues to increase. For example, China’s increased energy demand has impacted oil markets, indirectly affecting nuclear markets as well (Combs, 2006). Further, the recognition that some of the secondary uranium sources cannot be sustained at least in the short term and the increasing concern about finding non-carbon energy sources pushes the demand upward in primary markets. As discussed in the introduction, several countries have now revised their plans and are looking to build more reactors.

Figure 4. **Evolution of Uranium Spot Market Prices, 1968–2007 (in current prices)**



Source: Data from TradeTech. (Dollars per pound equivalent U_3O_8)

Note: We determine annual price by averaging monthly prices over the year; last point on the graph is the average spot price over the first 9 months of the year 2007, $104 per pound.

We believe this increasing primary demand constitutes one of the fundamental drivers of the recent evolution of prices on the uranium markets, and certainly represents a continuing driver in the future (see next section).

Second, while the impending disparity between supply and demand has been well-known for years, external shocks such as natural and man-made disasters increased awareness of the potential effects from disruptions of production. Examples are the second large fire at the 2001 Olympic Dam mines (South Australia) and the 2003 flooding of the McArthur River mine (Canada), the world's largest high-grade uranium mine, which closed for several weeks. Most recently, the October 2006 flooding of the new 18-million-pound Cigar Lake mine (Canada) has delayed production until 2010—three years later than planned (American Nuclear Society, 2007).

Third, a new way of buying uranium has emerged: uranium auctions. As long as active demand for spot uranium continues to outpace active supply several fold, buyers have to expect to compete aggressively for the product. While the total volume exchanged through auctions remained low compared with the total consumption worldwide, the spot price almost always systematically increased after each of the 13 fixed bid price uranium auctions that took place in 2006 (TradeTech, 2006).

Fourth, uranium is now seen as a very profitable investment for investors looking for portfolio diversification. According to Ux, investors/hedge funds entered the market strongly in 2005 and accounted for 25 percent of the transactions by volume (tons) that year—although only 107 transactions were recorded. These discretionary purchases (not for immediate consumption) accounted for about two-thirds of the 2005 spot volume (35 million pounds). In 2006 the investors/funds accounted for about 35 percent of the spot market (Davis, 2007). With a 500% increase in price between 2004 and 2007, uranium might have been one of the most profitable energy investments.

4. What Are The Positive Drivers of Future Uranium Markets?

What will the uranium markets look like in the short term (2 to 5 years) and long term (10 to 25 years)? There is no easy answer to this question because it depends on several complex dynamics involving market, political, and international security concerns.

In this section we discuss elements that, beyond the expected increase in energy demand discussed earlier, will also have a positive impact on the "nuclear renaissance" and further development of nuclear energy markets in the coming years. Here we focus on what we believe shall be two of the most important: (1) increasing concern about global warming and growing recognition by governments that nuclear energy can help address this issue; and (2) growing concern about energy independence. We end this section with a note on the status of nuclear energy development in the United States. In the following section we then turn to events that could negatively impact the future development of nuclear energy markets.

4.1. How Global Warming May Affect Nuclear Markets

Consensus has emerged that anthropogenic climate change is occurring. A few years back that might have been just a theoretical view, but the recent debate on global warming has reached new dimensions, with a clear call for concrete mitigating actions, including in the United States. While other greenhouse gases such as methane are believed to contribute to global warming, carbon dioxide is considered the most immediately problematic – which has led to an interest in non-carbon-based energy sources.

Increasing Pressure from National and International Communities

The World Economic Forum recently stated that global warming and climate change was one of the most important global risks that key decision makers will face in the years to come (World Economic Forum, 2007). New regulations to be implemented in the United States and Europe will certainly shift the demand toward alternative energy sources—nuclear being one of them. The European Council presidency recently reemphasized the European Union's commitment to developing a highly energy-efficient and low greenhouse-gas-emitting European economy and the need for a global and comprehensive agreement to reduce worldwide greenhouse gas emissions after 2012, when the Kyoto Protocol emission targets expire. In particular, the European Union has confirmed its commitment to reduce greenhouse gas emissions by at least 20 percent by 2020 compared to 1990 (Council of the European Union, 2007). European leaders agreed to increase the emissions reduction target to 30%, if other countries including the U.S., Russia, China and India follow suit. Although the Kyoto Protocol of the UN Framework Convention on Climate Change (UNFCCC) did not directly favor nuclear energy in project-based mechanisms to reduce greenhouse gas emissions, many forums do recognize the contribution of nuclear energy to meeting emission cap goals and discussed in the UNFCCC negotiation of greenhouse gas emission targets beyond 2012 (World Nuclear Association, 2007).

The Intergovernmental Panel on Climate Change (IPCC), which countries in the World Meteorological Association and the UN Environment Program formed in 1988 to assess climate change issues, issued its fourth series of reports in Spring 2007—and confirmed that nuclear power, including the commercialization of new nuclear technologies, has a role to play in stabilizing greenhouse gas emissions (IPCC, 2007). The 2007 G8 summit also stated "those of us who have or are considering plans relating to the use and/or development of safe and secure nuclear energy believe that its development will contribute to global energy security, while simultaneously reducing harmful air pollution and addressing the climate change challenge" (G8, 2007, p. 26).

The key here is whether or not at some point a carbon tax or current carbon caps and consequent emissions trading, which establishes in essence a price for carbon, will be more widely instituted (OECD-NEA, 2002). With the European Union's emissions trading scheme now launched, the market is developing internationally through voluntary participation by large companies (e.g., carbon emissions trading on the Chicago Climate Exchange) and is being further encouraged by other countries such as Japan. The global carbon trading market is already expected to reach $40 billion in 2007, and some predict huge long-term growth (Kennedy, 2007).

In the United States, several cities and states, such as California, have already started pushing hard to reduce carbon dioxide emissions. Moreover, the pressure to reduce emissions is increasing with some lawsuits that have already been filed against electrical companies for excessive carbon dioxide emissions. While none of them has actually received favorable support for any jury yet, the spectrum of series of costly lawsuits is becoming real. As noted recently, "while environmental litigation of this type is unprecedented, the cigarette cases were novel as well. The cigarette litigation did not establish legal precedents because the cases were settled without any court verdicts, but the threat of the suits was sufficiently real that it led to damages payments of close to $250 billion" (Hersch and Viscusi, in press). The fear of costly law suits might be sufficient to reorient investments in favor of green technologies.

Moreover, a recent important case was *Massachusetts vs. Environmental Protection Agency* (EPA), in which twelve states and several cities and organizations (plaintiffs) challenged the denial of a petition that asked the EPA to regulate CO_2 and other greenhouse gas emissions. The Supreme Court heard the case on November 29, 2006, and ruled in favor of the plaintiffs on April 2, 2007: the Clean Air Act does give EPA the authority to regulate emissions of greenhouse gases (Kunreuther and Michel-Kerjan, 2007). This decision is likely to seriously impact future U.S. regulations of energy sources generating carbon dioxide emissions (especially coal), and increase interest in other energy sources. Nuclear is a natural candidate.

Increasing Pressure from Investors

Increasing pressure comes from the financial community as well. In April 2004, a group of thirteen public pension funds managing over $800 billion in assets wrote a letter to then U.S. Securities and Exchange Commission (SEC) Chairman William Donaldson asking him to clarify that climate change is indeed a material risk requiring disclosure on SEC filings and to strengthen current disclosure requirements, for example, by providing interpretive guidance on the materiality of climate change risks. More recently, in June 2006 this now-enlarged group of investors—fifty members of the Investor Network on Climate Risk (INCR), representing nearly $3 trillion in assets—reiterated this demand to the new SEC chairman (Ceres, 2006).

In this context of growing pressure from investors themselves, any publicly traded company in the new Sarbanes-Oxley business environment will find it difficult not to consider how climate change will affect its operations and financial results, and report these as a part of environment liabilities in its annual SEC filings. A recent review of climate change reporting in the SEC filings of automobile, manufacturing, integrated oil and gas, insurance, petrochemicals, and utilities companies indicates that over the past 5 years, climate reporting has steadily increased in quality and has also doubled in number. According to the report, all twenty-six electric utilities in the United States reported on climate risk, whereas 5 years ago, only half disclosed climate risks to shareholders (Chan-Fishel, 2006).

Wall Street could actually enhance the future of nuclear energy markets by challenging investments in other sources of energy that produce large quantity of greenhouse gases.

4.2. How the Search for Energy Independence May Affect Nuclear Markets

Another element which is likely to enhance nuclear energy development relates to countries' looking for energy independence. Concern over energy independence is not new of course. When members of the Organization of Petroleum Exporting Countries issued an embargo in 1973, calls for energy self-sufficiency gained prominence in the West. The response of the members of the OECD, the primary targets of the embargo, was the formation of the International Energy Agency (IEA), whose members agree to cooperate in their own energy policies and maintain strategic oil reserves. Whether oil dependence should be a cause for concern can be argued but the fact remains that it is (Barsky and Killian, 2004; Council on Foreign Relations, 2006). In addition, the recent movement toward possible establishment of a gas cartel has further heightened fears over energy independence. Some European countries, for example, have clear concerns over their dependence on Russian gas.

The importance of nuclear energy to energy independence is two-fold. First, increased reliance on nuclear energy reduces the need to rely on gas and oil imports, which could become especially important in displacing oil for transportation as/if electric hybrid technology use increases or if nuclear power is used to generate hydrogen for fuel cells.[12] In addition, as all types of fuel costs have risen dramatically, nuclear power has been discussed as prices of nuclear fuel are of less concern than other energy sources. Despite recent high uranium prices, the cost of uranium ore is a negligible fraction of the cost of nuclear power generation, which makes nuclear energy generation extremely insensitive to "uranium price shocks" and thus an excellent candidate for independence.[13] This is a definite advantage of nuclear energy over electricity generated from gas, coal, and oil.

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[12] In the early 1970s, oil generated about 25 percent of electricity, but the desire to decrease dependence on oil imports and the electricity sector being one area where substitution could occur led to a reduced reliance on oil (see Figures 1.a and 1.b)—although in absolute terms the amount of oil used in electricity generation has not declined. See Toth and Rogner (2006).

[13] Nuclear plants are typically highly capital intensive. For instance, the new plant being built by Areva-Siemens in Finland—Olkiluoto III, the first in the West in several decades, and one of the world's largest at 1,600 megawatts—was the first "third generation" pressurized water reactor to be constructed. It cost over 3 billion euros ($5 billion). Several studies have considered nuclear electricity generation's commercial competitiveness on a kilowatt-hour basis compared with oil, coal, gas, and hydro. See MIT (2003); University of Chicago (2004); IEA (2006, Chapter 13), IPCC (2007). And the answer is "it depends." In this case, it all depends on several variables including costs of capital assumptions (including discount rate) construction times and associated cash flows, current and projected fuel costs, regulatory delays and whether carbon savings are included and at what price per ton of CO_2. Private investment in new nuclear builds might well not be viable without state support, given the uncertainties surrounding the cost of new nuclear builds and the correspondence of fuel costs possibly not providing a sufficient options return (Roques et al, 2006). For a comparison of some studies and of the actual delivered costs per kilowatt hour of U.S. nuclear plants, see Joskow (2006) and Hultman, Koomey, and Kammen (2007). Some suggest that the comparison calculation shall include not only the positive externalities of saved greenhouse gases, but also the negative—such as the added costs from increased safeguards; see Ferguson (2007).

As the impetus for nuclear energy increases, however, the general realization that energy can be cartelized and used both to control prices and delivery and to affect other's policies has spread to concern over nuclear energy independence. Curiously, in the case of uranium, the suppliers, rather than the users, raised the concerns. This is because the six countries that provide most of the enrichment capability as well as the IAEA, which promotes safe nuclear uses, have proliferation concerns and want to dissuade other countries from initiating enrichment activities.

However, several countries consider the in-essence oligopolistic organization of the enrichment facilities a real challenge to their nuclear energy independence and want to develop (or be able to develop) their own enrichment capacity.

4.3. Recent Movements in Favor of Nuclear Energy in the United States

Where does the United States, the largest consumer of nuclear fuel, stand? No nuclear plants had been ordered since 1978. But the political will to promote nuclear development rose with the Bush administration. In February 2002, then U.S. Secretary of Energy Spencer Abraham unveiled the Nuclear Power 2010 program. This program, which aims to address the expected need for new power plants, is a joint cost-sharing effort between industry and government to identify future sites, develop R&D, bring to market advanced nuclear plant technologies, and evaluate the economic value for industry to build new plants.

Three years later, Congress passed the U.S. Energy Policy Act, which the president signed on August 8, 2005. The act notably establishes "a production tax credit of 1.8 cents per kilowatt-hour for the first 6,000 megawatt-hours from new nuclear power plants for the first 8 years of their operation, subject to a $125 million annual limit. The production tax credit places nuclear energy on equal footing with other sources of emission-free power, including wind and closed-loop biomass." The act also authorizes cost-overrun support of up to $2 billion total for up to six new nuclear power plants and $1.25 billion for the Department of Energy to build a nuclear reactor to generate both electricity and hydrogen (U.S. Congress, 2005). These are clear incentives for first-movers and several companies have already responded and applied for new combined construction and operating licences in the US. Whether that will be enough to truly revitalize the US nuclear energy market remains to be seen (Joskow, 2006), especially given new deregulation and competition in power markets (Rothwell, 2006).

The combination of all these elements is likely to enhance the future of nuclear markets in the coming years. Nevertheless, other elements may counterbalance these.

5. What Could Be The Limitations to The Development of Uranium Markets?

We now turn to events that could have a serious—if not irreversible—negative impact on the future development of nuclear energy, namely (1) a nuclear accident in one of the world nuclear power plants, (2) an explosion of a nuclear device or nuclear plant sabotage by terrorist groups, and (3) the incapacity of the international community to develop a sustainable solution to assure safe nuclear uses while constraining the proliferation of nuclear weapons capabilities.

5.1. Safety Issues

Safety considerations deterred nuclear development as communities feared the long-term fallout effects from accidents and questions arose about the safety of workers (see Feinstein (1989) for a discussion of U.S. commercia1 nuclear power plants' compliance and non-compliance to Nuclear Regulatory Commission (NRC)'s safety regulation).

As a result of past accidents, however, efforts to improve nuclear safety grew. Nuclear supporters point out that the Chernobyl accident occurred in a graphite-moderated reactor that had design deficiencies, which inspired changes in other reactors of this type to improve their safety. The World Association of Nuclear Operators (WANO) was formed in 1989 to share best safety practices. Containment structures and passive control systems have reduced the likelihood of accidents. All states with nuclear power plants signed the Nuclear Safety Convention in 1996, which sets international safety benchmarks.

Nonetheless, some recent incidents noted on the International Nuclear Event Scale occurred in 1999 in Japan, 2005 in the United Kingdom, and 2006 in Sweden. Human error and the lack of a safety culture caused the most deadly incident in Tokaimura, Japan, where two workers died from radiation exposure as a result of accidentally starting a critical reaction in preparing fuel for an experimental reactor. The potential for disaster is the largest fear and one the industry recognizes it must continually address. Although supporters of nuclear technology believe safety is not a major issue, many in the public disagree—with several developed countries disavowing development of nuclear power and some saying that fast nuclear energy growth could by stymied by a lack not only of specialized building supplies but also of knowledgeable and experienced personnel, thereby further compromising safety.

In addition to accidents, the other safety issue is spent fuel storage. How to manage long-term storage of an open fuel cycle's radioactive waste products has never been satisfactorily resolved. In the United States, although the Department of Energy has designated Yucca Mountain as a repository for high-level radioactive waste, congressional and public opposition, as well as the very large cost associated with such storage, make the site's eventual acceptance of waste questionable (Riddel and Shaw, 2003). Currently, holding tanks at nuclear electric generating sites store waste products. Other countries with the open fuel cycle face similar dilemmas. Reprocessing used fuel attempts to address this concern because a closed fuel cycle generates fewer tons of radioactive waste. That reduction of tonnage, however, comes with additional costs (Bunn, 2006; Von Hippel, 2001).[14]

5.2. Proliferation—Terrorism Threats

Another element moderating nuclear growth is the radical transformation of the nature of international terrorism. In the past 25 years, an increasing number of

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[14] Safety and security concerns have prompted technological development to reduce some of those concerns, but in the process also reduces demand for uranium fuel. For example, the U.S. Global Nuclear Energy Partnership (GNEP) supports multinational efforts to develop new reactor recycling technologies taking reactors to a closed fuel cycle (but one that is proliferation resistant); India supports thorium-based nuclear power; and South Africa, with investment also from Russia, is developing flexibly fueled pebble bed reactors. Furthermore, the international investment in fusion research through Iter could one day change the nuclear landscape entirely.

international extremist and religious-based terrorist groups such as al-Qaeda and Aum Shinrikyo have rapidly developed and emerged—groups whose interest in acquiring nuclear materials is well documented. Many of these groups have also publicly declared their desire to inflict massive casualties and cause major economic disruption to Western countries they consider legitimate targets. For instance, the world's fifteen worst terrorist attacks, as indicated by the number of casualties and fatalities, have all occurred since 1982, with two-thirds occurring between 1993 and 2006 (Enders and Sandler, 2006; Hoffman, 2006). Al-Qaeda's September 11, 2001, attacks, as well as other attacks before and after, clearly demonstrate that we have entered a new era of large-scale threats (Kunreuther and Michel-Kerjan, 2004).

The scenario of the terrorist use of weapons of mass destruction is thus becoming more and more plausible. As a reference, a 10-kiloton nuclear bomb planted in a shipping container that explodes in the port of Long Beach, California, could inflict total direct costs estimated to exceed $1 trillion (not to mention ripple effects on trade and global supply chains that could even result in a global recession) (Meade and Molander, 2006). But even the explosion of a small nuclear device in a large metropolitan area would have tremendous economic impact. And the fear and economic implications of a dirty bomb (a device that disperses radiological material but does not sustain a nuclear reaction) are also major.

The predominant danger is that terrorists need only to succeed once. In April 2006, Bill Emmott stepped down from editorship of the *Economist*. Following the longstanding tradition, he wrote his only signed article when he departed. Emmott's valedictory provided a clairvoyant view on economic, technological, social, and political developments in the world during his thirteen-year tenure. He referred to the fast development of globalization as a critical element of those past years. While he forecasted an even faster and deeper globalization of economic activities in the future, he also challenged this path and asked what could stop or even reverse it. Among the potential candidates: "[E]ven more decisive tipping would come from the use by terrorists of some form of weapons of mass destruction. (…) Are these thoughts more apocalyptic than realistic? History suggests not" (Emmott, 2006). Emmott is not alone in this analysis. A 2005 survey of experts put the likelihood of a nuclear attack somewhere in the world within ten years at 20 percent; further survey response put the likelihood of a radiological attack at double that.[15]

Thus, fears surround the spread of nuclear energy and the possible diversion of nuclear materials from the fuel cycle process—either slightly enriched uranium for a dirty bomb, or the much harder-to-handle (but more deadly) reprocessed plutonium for a nuclear bomb (Levi, 2007). Fears also surround increased enrichment capabilities and the spread of weapons-grade material–making ability—because what inhibits terrorists from producing a nuclear device is not the physics of construction but access to fissile material (Zimmerman and Lewis, 2006).

One final danger is the possibility of nuclear sabotage: a terrorist acting from within a nuclear plant and causing another Chernobyl-scale disaster or a group of terrorists directly targeting a nuclear power plant for either takeover or direct destruction. Some have suggested the industry take the lead and establish a World Institute of Nuclear Security to work with the IAEA - at a higher level than the World Association of Nuclear Operators already does (Bunn, Weir, 2006). However, the point remains that the more nuclear facilities that exist, so do more dangerous possibilities for terrorist interference.

5.3. Proliferation—The Specter of the Multi-State Nuclear Weapon Capability

Absent any accident in one of the nuclear plants worldwide or of terrorist use of nuclear/radiological weapons, the main challenge for the development of the uranium market relates less to economics than to international security: that is, the nonproliferation challenge. It is rarely in a country's economic interest to enrich its own uranium to make fuel for its nuclear reactors. Given industry returns to scale and significant technological investments, buying enriched uranium from established producers is currently cheaper (especially for small quantities).

Nevertheless, some countries might decide not to buy but to develop their own uranium enrichment capacity for at least three reasons. First, full fuel cycle ability provides more stability to their fuel supply, which in turn lowers the expected discounted

[15] This was the median. The average in this survey of 85 experts from Therese Delpech to R. James Woolsey put the likelihood of a nuclear attack over 10 years at 29.2 percent and the average likelihood at 40 percent, same as that median (Lugar, 2005, p. 6).

cost of the total electric power per kilowatt-hour delivered. Second, even if the local demand for nuclear energy is not high, an enrichment facility can cover part of its cost by providing enrichment services to other countries and other reactors (including research reactors). Finally, an enrichment capability provides more political stability, generates increased prestige and power, and allows for a possible “breakout” to nuclear weapon capabilities.

The international community is highly concerned about the result of this possible race for enrichment capacity. As with the terrorism threat, this is where the future of nuclear energy markets crosses international security. Debate on the internationalization of the dangerous aspects of the nuclear fuel cycle actually predates the IAEA’s inception in the 1950s, but the issue, never fully resolved,[16] has become even more vexing today.

On one hand, the end of the Cold War ushered in a major international effort to reduce nuclear weapon stockpiles worldwide. On the other hand, the world is not bipolar anymore, which means that more countries could develop their own enrichment capacity, build nuclear bombs and use them against other countries—or, intentionally or not, let them fall into the hands of terrorists. Iran and North Korea are two obvious examples, but others might very well follow suit. As Graham Allison, former U.S. Assistant Secretary of Defense and one of the leading experts on nuclear security, recently stated, “If Iran crosses its nuclear finish line, a Middle Eastern cascade of new nuclear weapons states could trigger the first multi-party nuclear arms race, far more volatile than the Cold War competition between the United States and the Soviet Union” (Allison, 2006). Today, it seems the finish line is about to be crossed by Iran.

Moreover, globalization might not only evolve the nuclear threat by providing easier access to fissile material, but also could cause any nuclear attack to have an immediate and enduring effect. The interconnectivity of worldwide social and economic activities rationalized by short-term economies of scale and the development of transportation and telecommunications pushed by our “just-in-time” civilization have globalized threats more and more.

[16] Study and discussions –e.g., the Acheson-Lilienthal 1946 report on international control of atomic energy– predate even President Dwight D. Eisenhower’s 1953 proposal for an international fuel bank.

As the World Economic Forum recently reinforced at its annual meeting in Davos, these threats are also becoming more interdependent: an event happening 5,000 miles away will certainly be felt locally. Such a globalization of the risks implies that any organization, or even country, is finding it more difficult to manage these risks alone (World Economic Forum, 2007). This is the question we turn to now.

6. How To Better Address The Proliferation Challenge To Assure Robust Nuclear Energy Markets

6.1. Relying on Governments

As a result of nuclear threats posed by unconstrained proliferation, the international community is currently considering ways to better manage nuclear energy markets (Decker and Michel-Kerjan, 2006 and 2007). Recently, IAEA Director General Mohamed ElBaradei challenged the world to tackle again the ways in which internationalization of the nuclear fuel supply could reduce fuel cycle dangers and increase assurance of fuel supplies so that countries do not feel compelled to establish their own enrichment facilities. Several fuel supply assurance proposals are currently receiving international attention (Meier, 2006; Wolfsthal, 2004; Müller, 2005). Here we briefly summarize some of the proposals.

Multilateral Fuel Bank(s)

Multilateral fuel banks are one way of economically reducing the risk associated with fuel access. In order to have a bank or fuel service company, a country must offer to host and possibly to lead it. Russia supports an international enrichment center as a joint stock or venture company, and has offered one to be based in Russia and operating under Russian laws. Multilateral fuel banks and fuel service companies that could guarantee fuel to their member/owners may appear attractive to some richer states that can afford the investment in a joint venture.

In reality, most countries can barely if at all afford to finance their reactor investments, let alone a large upfront investment in a separate fuel company. If the developer of a multilateral fuel bank wants these countries to “buy in,” then he needs to offer a fuel contract entitling a country to eventual and certain purchase rights or to a cooperative interest in the company. Options instruments could develop both for the fuel and services and for ownership in the company.

A country or utility would only invest in a fuel service bank if it deemed the company was both reliable enough to provide fuel and services and efficient enough to make stock options profitable—if the company were to be a commercial enterprise and not a cooperative established only to assure fuel. The investing country would still face some political risk, however, if the company operated on the sovereign territory of one country and was not subject to special contractual laws.

The political risk incentive to invest is based on the belief that the host country is an unwavering ally fully capable of arranging all services and transport and that the partial ownership by the utility/country entitles it to special rights. Designating the land of this or any international facility as “international territory” with special treaty rights should help mitigate some political risk but certainly not all. While Russia can attempt this on its own and see who joins –for instance Kazakhstan, the world’s third largest miner of uranium, has indicated an interest in partnering–many are still wary of Russia’s nuclear industry after Chernobyl and worry about Russian efficiency and laws—despite some good reports on Russian service. The main challenge beyond that aspect is that such a project would require large long-term investments in/by new countries.

IAEA Fuel Bank

The methods for providing fuel assurances discussed with the most salience thus far include the provision of IAEA and other joint guarantees on enrichment backed perhaps by the establishment of regional fuel centers. What has been discussed most prominently is the development of an IAEA fuel bank stocking low-enriched uranium that could be fabricated to meet the supply needs of a country facing supply chain disruption for political reasons not related to proliferation concerns, as determined by IAEA under prearranged guidelines. The German government has further proposed that such fuel banks be considered extraterritorial.

The nonprofit Nuclear Threat Initiative (NTI)—backed by investor/philanthropist Warren Buffet—made recently a generous pledge of $50 million to IAEA to help create such a low-enriched uranium stockpile.[17] The pledge required IAEA to obtain match-funding of $100 million. The resulting $150 million in enriched uranium would be enough to fuel a typical power reactor. In June 2007, the U.S. House of Representatives passed a new bill (now pending in Senate committee), the International Nuclear Fuel for Peace and Nonproliferation Act (HR 885), that would support under specific restrictions the creation of such an IAEA fuel bank on the territory of a non–nuclear weapons state. Under this bill, the U.S. government would appropriate another $50 million, leaving it to the rest of the international community to bring in the remaining $50 million.

This fuel bank would represent less than 1 percent of the nuclear fuel used globally each year though. While this was deemed a sufficient amount for last resort assurances, according to former senator Sam Nunn, cofounder of NTI (Adler, 2006), it also raises the question: What would happen if there were a major disruption (e.g., a major natural disaster devastating an entire region combined with some political risk between the major producers and the countries demanding fuel)?

6.2. Relying on Private Markets

The above proposals focus on different types of intervention in uranium and nuclear fuel markets at only one very discrete point of concern to IAEA—that is, uranium enrichment. They might be insufficient if the IAEA wants to support the development of nuclear power and dissuade enrichment. A problem arises, however, if - for example - no fuel fabricator can or will make and arrange transport for the fuel. Political interference could disrupt any part of the fuel supply, not just the enrichment process, leading states to discount the value of any enriched fuel bank.

The assurance given to states, therefore, must be credible and potentially available throughout the whole fuel acquisition cycle—not just the portion the IAEA and the enriching states want to inhibit. The best way to provide assurance is by securing existing dependencies and by offering alternative suppliers within the system. Moreover, the need

[17] The funds are conditioned on IAEA approving establishment of the stockpile and raising an additional $100 million in funds or the equivalent value in low-enriched uranium (200 percent matching) in the next two years. Whether the stockpile is real or virtual, how it is controlled, and the requirements for its use are all left up to the IAEA and its members.

for overlapping assurances is clear—no single solution is sufficient for assuring supply and discouraging enrichment.

Insurance and Reinsurance Markets

One possibility that, to our knowledge, has not been discussed would provide assurances by using the financial capacity of private sector partners who could provide the financial basis as well as expertise in the field of managing large-scale risks. The insurance and reinsurance industry seems to be a very natural candidate for this task. First, this sector has become the largest industry in the world—with $3.4 trillion in yearly premium revenue, plus another trillion dollars in investment income in 2004 (Mills and Lecomte, 2006). Second, insurers' and reinsurers' core business is, precisely, dealing with risk management and risk financing optimization. Third, and importantly here, the international community might perceive insurers as a more neutral third party than countries with enrichment capacity. Despite that, none of the current proposals view the insurance industry as a possible partner.[18]

IAEA, nuclear utilities, and interested countries could pay additional attention to the possibility of private insurance/mutual risk management mechanisms adding to the stability of existing or new fuel supply arrangements. Such a discussion would support the recommendations from the 2005 IAEA Expert Group report and from the World Nuclear Association, which both emphasized the reinforcement of existing market mechanisms.

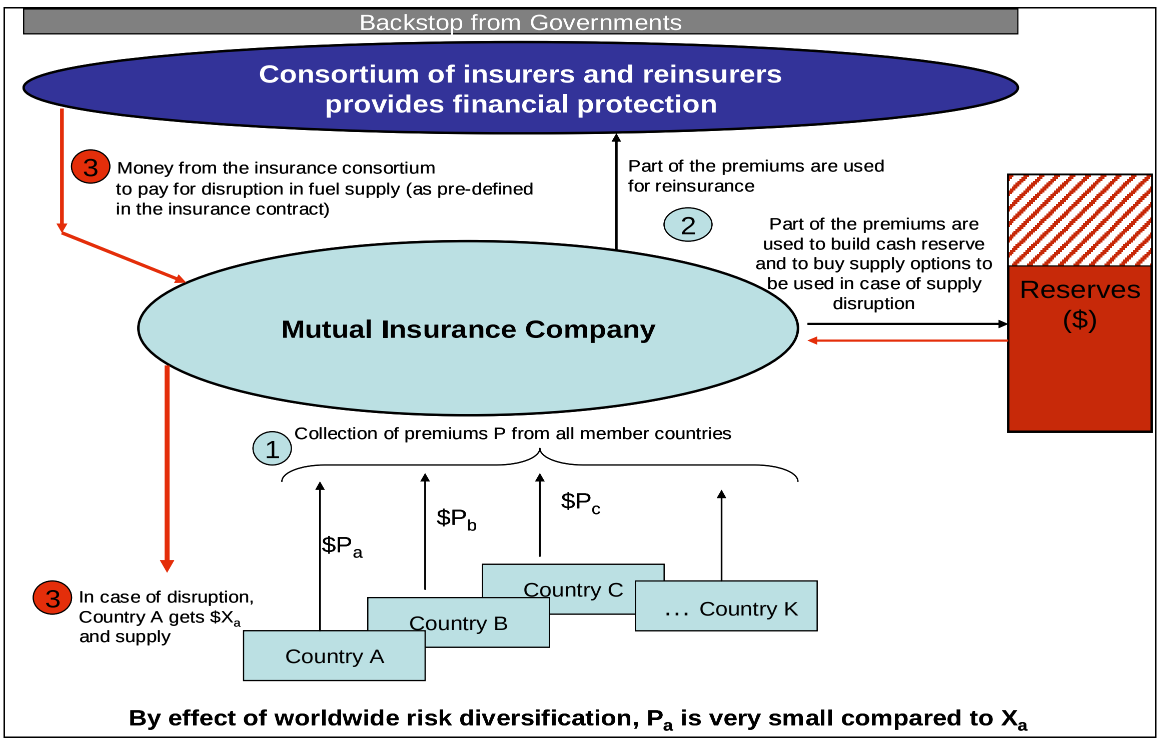
One way to do this would be for members of the international community to form a mutual insurance entity aiming to insure in order to assure fuel supplies. Indeed, the entity could combine assurance of the full fuel cycle (i.e., conversion, enrichment, fabrication, and transportation) against political interruptions with other risks (e.g., a major natural disaster), and insurance of some of the economic losses associated with temporary fuel supply disruption. The mutual would comprise either the countries that need enriched uranium for their nuclear plants or the owners of these plants. They would pay premiums that the mutual would use both to purchase financial coverage via

[18] The lack of interaction between the worlds of national security and insurance/finance exist in many countries; see Auerswald, Branscomb, LaPorte and Michel-Kerjan (2006) for a systematic analysis of how to enhance effective collaboration between the public and private sectors to protect critical infrastructures.

insurance and reinsurance and to establish a cash reserve. Additional conditions on participation in the mutual would have to be discussed (see Decker and Michel-Kerjan (2007) for a more detailed discussion of this proposal).

Insurers/reinsurers who would participate in the consortium covering this entity would analyze the risks associated with a shortage in the supply of each specific type of fuel and end user. Based on these risk assessments, the entity would charge premiums to the mutual's member countries that use nuclear fuel.[19] To limit insurers' and reinsurers' exposure to a level at which they would be comfortable participating, they would also benefit from an additional layer of protection through federal backstop from IAEA member countries (see Figure 5).[20]

Figure 5. **Insuring to Assure Nuclear Fuel Supply**



[19] IAEA could subsidize rates so that utilities pay based on their supply needs and not on their political risk. By in essence subsidizing rates to those members with higher political risks, the IAEA would induce them to join the mutual and thus stabilize their revenues and operations over time, disregarding untoward events that might affect their capacity to access fuel.

[20] As an element of benchmark, since the terrorist attacks on September 11, 2001, (which inflicted more than $35 billion of insured losses) several governments in OECD countries have partnered with private insurers and reinsurers to cover economic consequences of future terrorist attacks. Insurers and reinsurers typically cover a first layer up to a certain level of industry losses, with the government providing some backstop above that threshold (Kunreuther and Michel-Kerjan (2004); Michel-Kerjan and Pedell (2006)).

If a state did not receive its nuclear fuel, the following would happen: it would inform the mutual insurance entity, which would rule based on preestablished guidelines (such as the state not being under UN Security Council sanctions).[21] This arrangement would make the insuring entity's supply ombudsman role financially viable. Suppliers would receive compensation for developing and setting aside some capacity, for bumping other customers out of line (who might be compensated), or for working overtime to fulfill the supply need. The entity would define compensation schemes in advance so every participating country knows exactly what it gets for any delay in access to supply and the role the insurance consortium plays in facilitating the supply.

If the IAEA supported the insurance entity, it could require all members to have some political risk insurance on its nuclear fuel—perhaps based on the amount of enriched uranium used—and then no adverse selection would occur. That is, no state would gain an asymmetric knowledge advantage in which they would buy more insurance at the same price as others because they knew their suppliers were about to cut them off. Instead, the IAEA would, in essence, request all members of the mutual to pay in advance for the privilege of buying enriched uranium, thus helping fund the utility's purchase of reinsurance, and possibly of supply options (see below).

That insurance facility proposal is beneficial because of its universal applicability: states, including the major enrichment states, recognize their dependence on international markets for different aspects of their fuel, from ore to fabrication, and elect to participate. This proposal covers the full supply chain, not just enrichment, and provides financial support to the assurance-of-supply framework proposed by the World Nuclear Association (WNA) and others.

Under this insurance entity, a state could be less likely to use its nuclear fuel supplies for leverage against others— as this would not only cause it to lose its own guarantees but also to find its actions with much less effective. Including private insurers and reinsurers as part of the mutual equation also removes some of the politics: the mutual facility would automatically supply a utility when called upon unless *force majeure* (e.g., the UN Security Council) prohibited it from doing so. In addition, this facility could

[21] Consideration should be given to the structure of other commodity market programs in designing the approach (e.g., the arbitration program and other aspects of the London Metals Exchange).

foster private markets by using public trading platforms to make uranium purchases—thereby helping to further commoditize that market. Furthermore, the facility could even be expanded to cover all forms of fuel in its assurances.

The Use of Supply Options

Both the lack of commoditization of the nuclear fuel market and insurance companies' extra care in dealing with political risks have been cited as problems for using financial risk management tools. In addition, and most critical, is a utility's real need for fuel as opposed to simply financial compensation for the lack of it (or a significant delay in purchasing it).

For this new entity to provide more than just financial coverage, it would use its cash reserve to purchase supply options (assurance of fuel supply). Ideally, member countries would also approve exports in advance without consent rights on the fuel supply options or on the new insurance facility's direct market purchases of electric supply off available grids. Insurance mechanisms, including contract options, could not only prove a useful part of the proposed assurances, but also, if desired, provide the framework for managing the development of new supplies. Nuclear fuel plants are not like batteries in how they provide energy; they do not just go out. There is some limited discretion regarding the timing of fuel assembly changeouts and the enrichment levels of the fuel going into assembly. We believe these are economic decisions that can be compensated if the nuclear system does not operate at optimum capacity. It could also be possible to ask a fuel customer to forego his place in the fuel fabrication line in exchange for compensation; money and time are two variables that can be managed and insured.

Developing Performance Bonds

Another way to provide some coverage is through political risk insurance on group performance bonds. A performance bond is a financial tool used to guarantee that, in the event of a contractor's default, funds are available to guarantee the proper delivery of a good or service. For example, large real estate construction or technology complexes often use performance bonds. Applied to fuel supply, a group of suppliers would provide a proof of bond that would offer insurance coverage if one of its members could/would not fulfill a supply contract. In this case, the bond is exercised and the insurers make payments directly to the other suppliers who would need to divert some of their supplies to fulfill the contract. This would compensate the other suppliers for diverting their supplies and potentially for paying their regular customers for delays as the suppliers performed some of the work one of its members could not perform. This could also make the bonded suppliers more attractive as sources for those purchasing the fuel but would not necessarily eliminate the political risks.

Uranium as a Commodity

The long-term market-based approach would be to develop enriched uranium into a commodity product. For a good to be a commodity, however, it must be available as a standard product and bought in sufficient amounts to form a stable market. This might be possible at some point with enriched uranium products, given that this would certainly require additional security measures in place to prevent nuclear proliferation.

While the dominance in the market of government-affiliated players would have to be managed, with agreements covering dumping, introduction of HEU supplies, and other issues, enriched uranium existing as a commodity would have several benefits. First, supply becomes more fungible, so purchasers need not be locked into one supplier. The diversity of suppliers and their actual presence in the market add to a utility's security and allow for better risk management while futures markets and options trading also develop. As the commodity market is growing more robust, the mutual insuring entity we described above would not need to depend solely on supply options but could look to direct market purchases to fulfill its insurance obligations. Second, a well-organized market facilitates trade without respect to identity (although physical deliveries could go only to safeguarded, IAEA-approved sites). Standardized contracts could also facilitate title trading, all of which would help obviate political risk. Third, investors/speculators would draw more funds to the market, and this increased demand would drive up prices—and increasing supply. As a result, commodity product prices should decrease over time. Fourth, only the most efficient producers would dominate, discouraging new low efficient market entrants, which could reduce proliferation.

If fuel is a commodity, some might worry about fluctuations in prices but not as much about the availability of supplies. Furthermore, futures markets could cover price fluctuations. The IAEA or an IAEA-affiliated entity could set up an affiliated arm to educate buyers, actively form the market, and control contract deliveries. It could maintain a fuel bank with contracts purchased online from multiple suppliers but that it need not deliver to a warehouse—it could continually trade out to the future.

In fact, the NY Mercantile Exchange has just initiated a futures exchange for uranium—although without physical delivery (NY Mercantile Exchange, 2007). And New York Nuclear Corporation has instituted recently a trading platform in an attempt to standardize market trading of the physical commodity.[22] The question is could IAEA set up a nonprofit Exchange-traded fund with effective delivery?

7. CONCLUSION

Nuclear energy markets have long perplexed economists. They are not only opaque but also semi-government-controlled. Today the intrigue is even greater as we find nuclear energy markets at the crossroads of heightened economic, political, and military interests. These interests interact with each other in a complex dynamic that takes place on the national as well as international scenes.

This article has attempted to dispel some of this perplexity and clarify the important underlying influences that have driven the market in the past and are expected to drive it – positively and negatively – in the future.

The use of nuclear energy appears likely to continue to increase in the foreseeable future, both in absolute terms and in relative contribution to world electricity generation. As this so-called "nuclear renaissance" unfolds, uranium prices are reaching historic records in a marketplace not only defined by prices. The nuclear future will evolve quickly over the next several years — in terms of demand (defining how much nuclear power the public will accept if economic rates are promised) and supply (determining what new states, if any, will begin enriching). Thus, discovering sustainable ways to address the market's challenges we discussed in this paper, especially its nuclear security challenge, becomes more vital as well. Indeed, as Tadatoshi Akiba, Mayor of the City of

[22] Investor expectation of good returns in the uranium market is evident in the Uranium Participation Corporation successfully raising C$100 million in 2006 for uranium investments; its stock is traded on the Toronto Exchange.

Hiroshima, warned, “We cannot and must not allow ourselves to have the message of Hiroshima and Nagasaki fade completely from our minds. For if we do, we have but one course left for us. And that flash of light will not only rob us of our vision, but it will rob us of our lives, our progeny, and our very existence” (Akiba, 1999).

Here one must ask how the bad “genie” can be kept in the nuclear bottle—while fuel is supplied. The combination of nuclear fuel markets that have worked and the continuous monitoring and preventive actions by the international community have been critical in the past. As a result, the non-use of nuclear weapons since 1945 certainly remains the single most important phenomenon of the nuclear age (Tannenwald, in press). More countries have actually become non-nuclear who were than have become nuclear over the last several decades (e.g., Libya, Taiwan, South Africa, and South Korea have renounced their nascent nuclear weapons programs). About 50 countries have weapons-usable uranium to produce nuclear weapons but do not (Cirincione, 2007).

However, the world is changing rapidly. As nuclear fuel demand increases, additional assurances may well be needed to keep the markets working and to assess any reason to initiate new nuclear capabilities. We believe the insurance and financial industry should be viewed by governments and the international community as a serious partner who could help develop an extra layer of assurance. By so doing, this sector could notably contribute not only to enhanced security but also to the economic development of tomorrow’s energy markets.

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