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Assured Fuel Supply: Potential Conversion and Fabrication Bottlenecks

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SUMMARY FINDINGS

This paper is intended to identify bottlenecks that may arise in the conversion and fuel fabrication steps when used in conjunction with the U.S.-sponsored Reliable Fuel Supply (RFS) reserve. Paper is also intended to identify pathways for assessing the magnitude and relevance of potential bottlenecks. Although this paper will raise some issues associated with back-end management, it will focus specifically on front-end issues.

Determining whether or not a RFS should, or could, extend to conversion and/or fabrication services requires a perspective that broadly addresses the worldwide fuel market. Many issues related to an RFS, such as how suppliers and utility customers currently address supply performance risk, have been discussed (although not necessarily resolved) in other venues. Any assessment of the need for assurance of conversion and/or fabrication should take into account the role that these steps play as an element of an extensive dialogue around reliable fuel services.

The overarching question is *whether there is value* for the U.S. to incorporate conversion and/or fabrication as part of a RFS. Many political, economic, and other factors contribute to this equation, including:

- Is there a need and/or desire by states to have the additional assurance of fabricated fuel? Is there a need and/or desire by the market?
- Is it feasible for the U.S. to offer such an assurance? What would be the technical, legal, political, and social challenges? Would such an offer outweigh the implementation challenges and generate nonproliferation and other benefits?
- If such services were to be offered, how would they be implemented? Would they be offered through the United States, through a series of bi- or multilateral agreements with other countries, or through a collaborative effort such as an International Fuel Services Center?

Each of these issues will need to be considered in order to assess the value and relevance of including fuel conversion and/or fabrication considerations into a U.S. RFS. It is recommended that these questions be addressed through a multi-stage analysis:

- Stage 1: Identify the need (and/or desire) for conversion and/or fabrication services, including an assessment of supply and demand.
- Stage 2: Consider technical, legal, political and economic issues. Second-stage analysis should also consider implementation issues. Examination of these issues could be broken into separate studies (e.g. economic factors, political factors) as appropriate.

1.0. INTRODUCTION

On February 11, 2004, President Bush proposed assuring nuclear fuel supply for countries meeting certain nonproliferation criteria. To support the President's policy, in September 2005, Secretary Bodman announced that the Department of Energy (DOE) would set aside 17.4 metric tons (MT) of highly enriched uranium (HEU) to be blended down into low enriched uranium (LEU) for use in a dedicated Reliable Fuel Supply (RFS) reserve.

RFS complements ongoing international efforts to provide fuel assurances. These efforts are mutually supportive; offering a diversity of supply mechanisms will maximize the assurance of supply for states seeking reliable access to nuclear fuel. These efforts include:

- The Putin Initiative to create a multinational enrichment center at Angarsk; Kazakhstan and Ukraine will be partners, with others potentially joining in the future.
- The Nuclear Threat Initiative's (NTI) offer of seed money ($50M) for an IAEA-administered reserve.
- Japan's proposal for an IAEA standby arrangement system, beginning with a nuclear information database and information sharing mechanism.
- UK/Netherlands/Germany's enrichment bond proposal.

1.1. U.S. Reliable Fuel Supply

The United States has identified 17.4 MT HEU to be down-blended into LEU. In mid 2007, the US Department of Energy's National Nuclear Security Administration (NNSA) awarded contracts to Nuclear Fuel Services (NFS) and Wesdyne International to down-blend this material. NFS will down-blend the material in Tennessee to yield some 290 tonnes of LEU (approximately 6-8 reactor reloads) by 2010. Wesdyne, the prime contractor, will then store the LEU at the Westinghouse fuel fabrication plant in South Carolina to be available for the RFS program. The LEU will be provided to qualifying countries only in the event of an emergency, such as a disruption in supply that cannot be corrected through normal commercial means, and would be sold at the current market price. Current draft procedures governing the sale of material from the RFS denote that "the LEU provided would be in the form of uranium hexafluoride (UF_6) at a specific assay and available for delivery at a specific facility".

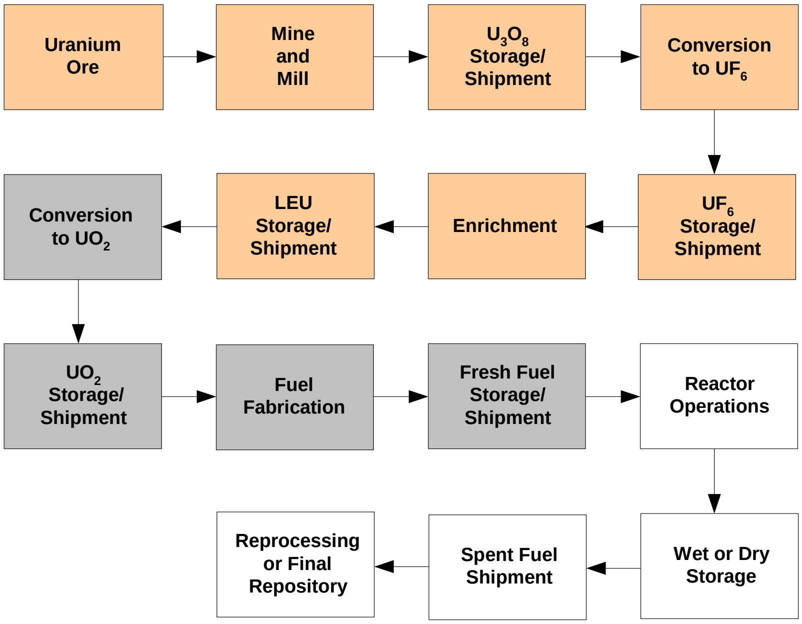
1.2. Japanese Proposal

In its proposal of "IAEA Standby Arrangement Systems for the Assurance of Nuclear Fuel Supply" Japan notes that effective assurance of timely delivery of nuclear fuel in the event of a supply emergency will require assurance of

> *"…not only uranium enrichment but also all important activities of the front-end of nuclear fuel cycle, namely, uranium supply, uranium storage, conversion, enrichment, and fuel fabrication as market failure might occur at various junctures".*

Japan identifies five elements as necessary front-end components of a RFS scheme, so that customers can assess nuclear fuel supply capacity and economic options. However, the current U.S. RFS plan and guidelines explicitly address only the emergency supply of LEU in an intermediary form (UF_6) for the front end of the nuclear fuel cycle. The availability of the LEU in the U.S. RFS plan essentially provides assurance of the first seven stages of the typical Light Water Reactor (LWR) fuel cycle shown in Figure 1. In order to assure reliable fuel supply, it was suggested that the U.S. RFS Initiative may need to consider the future availability of UO_2 conversion[1], fuel fabrication services, and attendant storage and shipment provisions for these two stages.[2]

Figure 1: Typical LWR Fuel Cycle



2.0. CONSIDERATION OF GLOBAL MARKETS

The availability of this U.S. LEU is a significant commitment to the global community and the success scenario is primarily due to the fact that the resources starting from the HEU through its ready-for-delivery LEU UF_6 stage is 100% owned and controlled by the United States Government (USG). The challenges that would be imposed by expanding assurance to the UO_2 conversion and fuel assembly fabrication will go beyond the control and motives of the USG. In today's global nuclear fuel market, the parties involved in the UO_2 conversion and fabrication are truly a mix of semi-private non-USG controlled and private enterprises. To cooperate with international players in the fuel market, the U.S. government would need to consider the financial returns to those organizations, as well as increase governmental agreements.

The global UO_2 conversion and fabrication industry has been faced with consolidations in order to survive the decades of commercial nuclear stagnation. It is expected that all of these facilities will find it difficult to engage in any type of program that is not tied to a real commercial commitment. The DOE down-blending and storage contract mentioned above illustrate this point.

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[1] Conversion, as used in the rest of this document, refers to the required conversion of the LEU to the UO_2 form used in fuel pellets.

[2] There may be additional elements of making fuel that could pose as bottlenecks or create RFS or market failure. These elements (e.g. metals, components, etc.) are not addressed in this paper, but should be considered in the establishment of an RFS.

Accordingly, any expansion of the RFS program into the global commercial arenas of conversion and fabrication will bring additional considerations and challenges, including some confirmations of the current RFS program, in the context of global participants and economic incentives and assurances.

Incentives and assurances are methods employed by the suppliers of UO_2 converters and fabricators to not only minimize, but to practically eliminate all of their risks. The details of these are carefully embedded in the existing contracts with slight variations depending on the actual value and period of performance. Short term, low value, and one-of-a-kind contracts will have a premium attached to it one way or another. On the other hand, the mechanism for a buyer to reduce his risk for the availability of the fuel is to enter into long term contracts. While this may assure product supply, the true economic results cannot be guaranteed in advance. The fluctuations in U_3O_8 prices and the existence of secondary fuel markets continue to gather considerable attention, concerns, and speculations from all of those involved in the front end of the fuel cycle as both supplier and buyer attempt to reduce their respective risks. However, while this level of volatility has not been experienced with enrichment, UO_2 conversion, or fabrication, the actual costs for the conversion and fabrication services are not disseminated. The lack of transparency in this part of the fuel cycle will need to be explored further.

Determining whether or not a RFS should, or could, extend to conversion and/or fabrication services requires a perspective that broadly addresses the worldwide fuel market. Many issues related to an RFS, such as how suppliers and utility customers currently address supply performance risk, have been discussed (although not necessarily resolved) in other venues.[3] Any assessment of the need for assurance of conversion and/or fabrication should take into account the role that these steps play as an element of an extensive dialogue around reliable fuel services.

3.0. CONSIDERATION OF U.S. RFS:

As mentioned above, a team consisting of Wesdyne International, LLC (a subsidiary of Westinghouse Electric Company, LLC) and Nuclear Fuel Services, Inc. (NFS) has received the contract to blend down the 17.4 MT of HEU that will be used in the US RFS, and to store the resulting LEU in the form of UF_6. This contract does not address any conversion to the UO_2 powder form, the storage and/or shipment of the UO_2 powder, that actual fabrication of fuel pellets and the fuel assemblies, nor the storage and/or shipment of the completed fuel assemblies to the waiting reactor. These are the last four stages preceding reactor operations as shown in Figure 1.

Assurance of LEU supply as UF_6 may not be as attractive to countries as assurance of fabricated fuel. This paper is intended to identify bottlenecks that may arise in these last steps of the front-end of the fuel cycle to determine whether there is value in including, or at least formally addressing, any of these stages in the assured fuel supply offered by the U.S. RFS reserve. It will articulate key political, economic, and technical questions related to using UO_2 conversion and fabrication capacity from 1) the United States, and 2) other states, in order to assure supply of LEU fuels for states in good nonproliferation standing. This paper will also identify means of working through those questions and the attendant storage and shipping issues to determine

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[3] For instance, participants in a recent government-industry workshop indicated that there is no need for an assured fuel supply system, as the market is currently functioning effectively. Workshop held by the Pacific Northwest center for Global Security on "Cradle-to-Grave Nuclear Fuel Supply Assurance Workshop: Industry's Potential Role", June, 2007.

whether there is significant benefit to the US in incorporating assurance of conversion and/or fabrication into the operations of a U.S. RFS.

4.0. KEY QUESTIONS

The overarching question is *whether there is value* for the U.S. to incorporate conversion and/or fabrication as part of a RFS. Many factors contribute to this equation, including:

- Is there a need and/or desire by states to have the additional assurance of fabricated fuel?
- Is it feasible for the U.S. to offer such an assurance? What would be the technical, legal, political, and social challenges? Would such an offer outweigh the implementation challenges and generate nonproliferation and other benefits?
- If such services were to be offered, how would they be implemented? Would they be offered through the United States, through a series of bi- or multilateral agreements with other countries, or through a collaborative effort such as an International Fuel Services Center?

The following sections will articulate some of the questions that would need to be addressed in considering whether there is value for the United States in incorporating enrichment and reprocessing as part of an RFS.

3.1. Current Market for Conversion and Fabrication?

Question: How do the conversion and fabrication markets currently operate? Is there a need for additional supply assurance?

Methodology: Develop a baseline. Identify the **current processes** for supplying conversion and fabrication services to the market.

- Identify the current fabrication and delivery systems, and determine the supply capability of these systems.
    - Describe, starting with enriched UF_6, the subsequent steps in fabricating each fuel design and delivering it to the customer.
    - Identify current “typical fuel procurement practices”, including order structure and procurement practices. What steps are involved in the contracting process? Discuss how converters and fabricators use contracts mechanisms to mitigate risk.
    - Establish the minimum time performance required to deliver fuel and avoid the reactor shutting down due to lack of fuel. Assess how much time is associated with completing each step of the fuel delivery process for a normal order.
- Assess the operations of the current systems. Do the current systems work?

3.2. Supply and Demand of Conversion and Fabrication?

Question: What is the capacity of the United States to offer assurances of conversion and/or fabrication services as part of an RFS? What is the capacity of other States?

Methodology: Assess the existing and potential **supply** of conversion and fabrication services.

- Supply of Fabrication: What is the capacity of 1) the United States, and 2) the rest of the world for providing fuel fabrication services?
    - How many fuel designs are in use, and where are they used?
    - Who makes (or can make) each type of fuel?
    - Develop a matrix that identifies types of fuel currently in use, and identify which companies and/or organizations that that can perform fuel conversion and/or fabrication services for each fuel type.
- Supply of Conversion: What is the existing capacity for conversion to UO_2 in the United States? In the world? What capacity could be used as part of an RFS? Is this capacity co-located with the down-blender, the fabricator, or other entity?
- What is the projected growth in supply of conversion and fabrication? Will supply need to increase to meet projected demand?

Question: Is there a **demand** for conversion and/or fabrication services? Is there a current or near-term gap between supply and demand that indicates a need for assurances of conversion and/or fabrication services as part of an RFS?

Methodology: Assess the existing and potential demand for conversion and fabrication services. Fuel fabrication is not a fungible capacity. Answer should address not just the capacity of fuel fabricators, but the capacity of fabricators for each type of fuel.

- Determine demand for each fuel type used. What reactors exist and what is the demand for each type of fabricated LEU fuel?
- Assess whether there are certain fabricators and/or reactors types where there are bottlenecks and might more reasonably desire assurances – i.e. limited or uncertain supply of a particular type of fuel?
- Although there appears to be an overage of fabrication capacity in the market overall, there may be a lack of fabrication capacity for a specific type of fuel. Determine whether it is technically feasible to add this capacity in an economic fashion.
- Determine the needs of individual reactors and the projected increase in reactor types and subsequent demand growth.

Question: What is the need for assurance of fuel conversion and/or fabrication services? **Is there an existing and/or potential supply gap**?

Methodology: Assess the supply and demand for conversion and fabrication services, considering a) overall supply and demand, and b) supply and demand for each type of fabricated fuel.

- Determine whether there is a supply gap, or risk of a supply gap, that would drive states to seek assurances of conversion and/or fabrication.
- Assess potential means to track and communicate existing capacity of all fabricators and converters. How would this information be used to administer the RFS?
- Consider the overall impact on the market of incorporating conversion and/or fabrication into an RFS. Is there an impact on commercial companies manufacturing nuclear fuel (in

the US, Germany, Japan, Kazakhstan) and elsewhere since these use a variety of contract mechanisms to hedge risk?

3.3. Drivers to Seek Conversion and/or Fabrication?

Question: For normal risk, does RFS have to do anything more? The current fuel market seems to operate effectively; however, in light of projected demand growth, i**s there a need and/or desire by states to have the additional assurance of fabricated fuel due to fault in current market operations**, if not for a supply gap?

Methodology: Assess whether market factors or other drivers would move states to seek assurance of conversion and/or fabrication.

- If RFS deals primarily with political risk, are the steps largely political, or is there a shortfall in the ability of the industrial systems to provide the requisite supply/delivery performance for RFS?
- Assess whether incorporating assurance of conversion and/or fabrication would increase the incentive for states to participate in an RFS and sacrifice enrichment and reprocessing capability.
- Assess under what conditions it is appropriate and/or useful to provide assured fuel, as opposed to UF_6, or UO_2. Would it be feasible for participants in an RFS to elect conversion and/or fabrication as part of the assurance? One option might be a phased process, in which customers could choose assurance of UF_6, UO_2, fabricated fuel, or full service, might be one option.
- Consider what US goals are in standing up an RFS, and whether it needs to offer conversion and/or fabrication in order to meet those goals. For instance, is the US content to be one provider of assurances in a network of other providers (who may or may not maintain the same proliferation standards or logistical capabilities)? Or does the US want to be the supplier of fuel assurances of choice?
- Assess whether fuel assurances offered by other states will be effective at dissuading states who have not previously invested in enrichment technology from pursuing domestic capability.
- Identify other factors that would drive states to seek assurance of conversion and/or fabrication.
- Consider whether offering conversion and/or fabrication services would yield benefits that would drive the U.S. to adopt these services as part of a RFS policy.

3.4. Economic and Cost Questions:

Question: Is it **economically feasible** to offer assurance of conversion and/or fabrication in the United States? Through collaboration with other countries?

Methodology: Identify and assess cost factors that would impact implementation of conversion and/or fabrication in a RFS.

- Model what countries would pay for the different fuel options. What would be the premium for assured UF_6? For UO_2? For fabricated fuel?

- Assess whether there would be an additional cost for providing accelerated fabrication of fuel. Is there additional risk premium that is not already priced into the fuel (e.g. there is delivery risk now, and mitigating that risk has a cost dimension, and what this premium would be. Who would be responsible for any additional costs? (Note: This assessment would require the contract features of the RFS scheme.)
- Assess whether there would be a need for contractual and/or financial assurances for the shipment of the LEU to the converter? Would there need to be equivalent assurances for the storage and/or shipment from the UO_2 converter to the fuel fabricator if not co-located? What would the magnitude of cost be for these assurances and mechanism for payments?
- Consider who might pay for any cost differences/penalties associated with any other new or expedited contracts resulting from the need to use the RFS material.
- Determine whether there would be a need to seek and secure new nuclear liability protection for involved US companies from involved foreign organizations/states?

3.5. Logistical Challenges of Conversion and/or Fabrication:

Question: What **transportation** challenges will be faced if conversion and/or fabrication are incorporated into an RFS?

Methodology: Identify current transportation systems. Identify impacts of incorporating fuel conversion and/or fabrication into a RFS.

- Identify how the material is shipped, how it is packaged, and what the maximum and minimum lead times are for arranging shipments.
- Identify any special requirements that shippers must meet (i.e. safety).
- Determine what transportation challenges are associated with moving the material to/from the converter if not in the United States. Are there substantial penalties to moving the converted fuel if conversion capacity is not co-located?
- Determine what technical transportation challenges are associated with the international shipment of UO_2 pellets and finished fuel assemblies. Would there be problems with assuring availability of approved shipping containers?

Question: What **timing** issues must be considered if conversion and/or fabrication are incorporated into an RFS?

Methodology: Identify the current time required to move fuel from UF_6 to fabricated fuel.

- How much notice would a fabricator need in order to supply additional fuel? (i.e. would this involve switching manufacturing runs, etc.)
- Would the RFS need to be involved in the decision of what converter/fabricator is used regardless of any RFS funds available for flow-down?

3.6. Technical Challenges of Conversion and Fabrication:

Question: What **certification** is necessary for a plant to fabricate *and deliver* a given type of fuel? What are the challenges in certifying a plant for a certain type of fuel?

Methodology: Since designs have proprietary elements, fabrication plants must be licensed to make specific fuel types. Identify current license requirements and holders for each fuel type. What are the challenges in licensing a new plant? (i.e. technical challenges, social challenges, intellectual property challenges?)

- What are the licensing agreements currently existing between designers and fabricators?
- Identify commercial agreements needed for a given fabricator to be able to produce a given fuel design that meets fuel specifications.
- Identify the main elements (from a regulatory standpoint) in licensing or certifying a fabricator to make a given fuel design.
- What would be the extent of additional nuclear regulatory licensing efforts necessary and/or possible in the United States, and is there capacity to perform this work. For licensing plants not in the United States?
- Determine, if there is a lack of fabrication capacity for a particular type of fuel, are there intellectual property issues in equipping another fabricator with technical specifications for reactor fuel? Will there be intellectual property issues if the recipient nuclear plant receives fuel from a new fabricator?

Question: What **manufacturing** standards need to be met for fuel to be delivered to countries receiving assurances? How would these standards be met?

Methodology: Assess manufacturing requirements and for recipient countries. What are the technical challenges? Are there political challenges? Intellectual property challenges?

- Assess manufacturing standards, requirements and certifications for recipient countries.
- Determine the process for receiving manufacturing certification. What are the technical challenges? Are there political challenges?

Question: How will the issue of **final disposal** of this RFS-derived spent fuel be addressed? Will including U.S. conversion and/or fabrication change this pathway? Will including non-U.S. conversion and/or fabrication change this pathway?

Methodology:

- Identify current plans for addressing final disposal of RFS-derived spent fuel, including ownership and obligations.
- Discuss whether these obligations change if the RFS were to incorporate U.S. conversion and/or fabrication services. Discuss whether these obligations would change if the RFS were to incorporate non-U.S. conversion and/or fabrication services. For instance, if the U.S. RFS uses blended-down HEU material from the RFS, the fuel is fabricated in Euratom, then used in Japan, the material will have obligations from these suppliers.
- Would there be a take-back guarantee with RFS-supplied fuel – and if so, who would provide this guarantee? In the above (or similar) scenario, how would it be determined if (or which) supplier would have responsibility for the material?
- What would be incentives for the RFS owner (the United States.) or the fabricator (United States or another country) to take back the spent fuel?

3.7. Legal, Political and Social Questions:

Question: What are the **legal and regulatory** challenges involved in offering assurances of conversion and fabrication services as part of an RFS? What are the challenges that differ from assurance of enrichment? Does incorporating conversion and/or fabrication into an RFS, if conversion and fabrication services are provided by a country other than the U.S., change previous assumptions about legal and regulatory requirements? What additional legal, political, and social challenges will be faced?

Methodology:

- Identify the type of agreement for transferring fuel. The U.S. is developing 123 agreements for nuclear cooperation with countries. Do additional agreements need to be put in place if the fuel conversion and/or fabrication takes place in a third country?
- Identify the key elements of that agreement (e.g. end-use, safeguards, retransfer obligations, etc.), and identify whether adding conversion and/or fabrication and activities will require changing these agreements.
- Asses whether existing templates for 123 agreements are sufficient to address nonproliferation concerns.[4]
- Determine whether there are existing 123 or other government-to-government between the all sellers and potential receivers. For instance, if the material were sourced through the U.S. RFS, fabricated in Japan, and sold to South Korea, does there need to be an agreement between Japan and South Korea? Should there be? If countries do not wish to pursue standing agreements, is there the ability to do a one-time short-term agreement? Could another state or organization (such as the IAEA) act as an intermediary?
- Discuss whether it should be the state or the organization that provides the assurance (recognizing that they may be the same in some countries). If it is the state, is there restitution or agreement with the company? If it is the company, is there agreement from the state?

Question: What are the **political and social challenges** involved in offering assurances of conversion and/or fabrication services as part of an RFS? Can incorporating assurance of conversion and/or fabrication be structured to incorporate nonproliferation goals?

Methodology:

- Assess the political transportation challenges are involved in moving nuclear fuel through other countries in order to reach the final recipient. What nuclear plant credentials should recipient states have? What safeguards should their facilities be under? What if a supplier facility is not under safeguards?
- Identify there social or political ramifications for countries agreeing to supply countries with which they may not have existing nuclear agreements?
- Assess under what conditions it is appropriate and/or useful to provide assured fuel, as opposed to UF_6, or UO_2. Would it be feasible for participants in an RFS to elect conversion and/or fabrication as part of the assurance? A phased process, in which customers could choose assurance of UF_6, UO_2, fabricated fuel, or full service, might be one option.
- Define other implementation challenges which may be faced.

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[4] Note: PNNL proposed to do this work, but this work was deferred for political reasons. It is possible that study offers an appropriate opportunity to pursue this assessment.

4.0. RECOMMENDATIONS AND NEXT STEPS

Each of these issues will need to be considered in order to assess the value and relevance of including fuel conversion and/or fabrication considerations into a U.S. RFS. It is recommended that these questions be addressed through a multi-stage analysis:

- Stage 1: Identify the need (and/or desire) for conversion and/or fabrication services, including an assessment of supply and demand.

- Stage 2: Consider technical, legal, political and economic issues. Second-stage analysis should also consider implementation issues. Examination of these issues could be broken into separate studies (e.g. economic factors, political factors) as appropriate.

Appendix A: International Commercial LEU LWR Fuel Fabrication Capacity (MTU)

Country	Owner	Location	Product	MTU/year
Belgium	Areva	Dessel	PWR	500
Brazil	Industrias Nucleares do Brasil	Resende	PWR	240
China	China National Nuclear Corporation	Yibin	PWR	200
France	Areva/Cogema	Romans-Sur-Isère	PWR	1400
Germany	Areva	Lingen	BWR-PWR	650
India	Department of Atomic Energy	Hyderabad	BWR	24
Japan	Global Nuclear Fuel	Kurihama	BWR	750
	Mitsubishi	Tokai-mura	PWR	440
	Sumitomo/Furukawa	Kumatori-machi	PWR	284
		Tokai-mura	BWR	250
Rep. of Korea	Korea Electric Power/KAERI	Daejon	PWR	400
Russia	TVEL	Elektrostal	PWR	620
		Novosibirsk	PWR	1,000
Spain	SEPI/CIEMAT	Juzbado	BWR-PWR	400
Sweden	Toshiba	Västerås	BWR-PWR	600
United Kingdom	Nuclear Decommissioning Authority	Springfields	PWR	330
US	Areva	Lynchburg	PWR	400
		Richland	BWR-PWR	700
	Toshiba	Columbia	PWR	1,150
	General Electric	Wilmington	BWR	1,200
Total				*11,538*

Source: Rothwell, Geoffrey, “Cost Structures and Market Sustainability of the International Light Water Reactor Fuel Fabrication Industry”, July 30, 2007. Pre-publication. Updated September, 2007using IAEA Nuclear Fuel Cycle Information System.

Appendix B: Key Terms

Boiling Water Reactor Fuel: In boiling water reactors (BWR), the fuel is similar to PWR fuel except that the fuel rods are slightly larger in diameter and are arranged in smaller square arrays of either 8x8, 9x9, or 10x10 fuel rods per side. Approximately four BWR fuel assemblies occupy the same space as one PWR fuel assembly. A zirconium alloy is used for the fuel rod tubing.

Conversion to UF_6: After extracting the solid uranium oxide concentrate (yellowcake) from the ore, the uranium (U_30_8) is sent to the UF_6 conversion facility. LWRs use enriched uranium and the current uranium enrichment process needs the feed uranium to be in the form of a gas before it is enriched. The UF_6 is a gas at elevated temperatures, but it is in solid form during normal storage and shipment. It is shipped in strong metal containers. There are conversion plants in at least eight different countries.

Conversion to UO_2: Fuel fabrication for LWRs typically begins with receipt of the LEU in the form of UF_6 from an enrichment plant. The UF_6, still in solid form in containers, is heated to gaseous form, and the UF_6 gas is chemically processed to form uranium dioxide (UO_2) powder. This powder is then pressed into pellets and sintered into ceramic form by baking it at high temperature (over 1400°C). These two processes can be co-located in the same facility. Some fuel fabricators have both of these capabilities integrated into their fuel fabrication facility.

Fuel Fabrication: Fuel fabrication is the last stage of the “front end” of the nuclear fuel cycle., At the fabrication facility the LEU ceramic fuel pellets are encased in metal tubes, usually made of zirconium alloy, to form fuel rods. The rods are then hermetically sealed and assembled in clusters to form fuel assemblies. After successful inspections, the finished fuel assemblies are ready for shipment to nuclear reactors in special shipping containers.

Light Water Reactor Mixed Oxide Fuel (MOX): MOX fuel differs from LEU fuel in that the powder from which the fuel pellets are pressed is a combination of UO_2 and plutonium oxide (PuO_2).

Non-power Reactor Fuel: Non-power reactors are much smaller reactors that do not generate electrical power but are used for research, testing, and training. Non-power reactors can include research reactors and reactors used to produce irradiated target materials. The fuel design varies with the reactor type and manufacturer. Plate-type fuel consists of several thin plates containing a uranium mixture clad with aluminum. Another fuel is in the shape of rods and consists of a uranium and zirconium/hydride mixture. There are also compact, self-contained, low-power (less than 5 watts) tank-type reactors. Although use of highly enriched uranium (HEU) fuel can reduce the size of a nonpower reactor, the US has adopted a policy of discouraging use of HEU fuel.

Other Fuel Types: Some other fuel types include metal alloy fuels, MOX, spherical fuel, Thorium-Uranium mixtures, or Molten Salt.

Pressurized Water Reactor Fuel: In pressurized water reactors (PWR), the fuel is similar to BWR fuel except the fuel rods are slightly smaller in diameter and are arranged in a larger square or hexagonal array. The square arrays have 15 x 15, 16x16, or 17x17 fuel rods per side. The hexagonal arrays found in Russian designed VVER type reactors have either 11 rods or 7 rods per side. Zirconium alloy is used for the tubing that encases the UO_2 pellets. The tubes are about 1 cm in diameter, and the pellet-to-tubing gap is filled with helium gas to improve the conduction of heat to the outside surface of the tubes.

Appendix C: Fuel Cycle Process

The nuclear fuel cycle comprises those activities, which are required to produce suitable fissile material for the operation of the various nuclear power reactors (i.e. front end fuel cycle activities) and those to manage and dispose the used material (i.e. back end fuel cycle activities).

The main front end fuel activities comprise:
- uranium mining and milling;
- uranium refining and conversion;
- uranium enrichment and conversion;
- fuel fabrication.

The main back end fuel cycle activities comprise:
- spent fuel storage;
- spent fuel treatment (for disposal);
- spent fuel reprocessing;
- waste treatment (for disposal).

APPENDIX D: Reactor Types

The reactor (or reactor series) is defined by the materials it uses, the core configuration, the moderator (in case the neutrons need to be slowed down to thermal energy) and the coolant. After many attempts to commercialize a wide range of reactor types, only a few have been selected around the world to generate power, including:

- gas cooled, graphite-moderated reactors (GCR or Magnox with U-metal and advanced gas cooled reactors, AGR, with UO2 fuel);
- reactors cooled and moderated with light water (LWRs), of which there are two types: pressurized water reactors (PWRs, including the Russian version, WWER) and boiling water reactors (BWRs);
- reactors cooled (under pressure) and moderated with heavy water (Canada's CANDU reactor or PHWR or HWR);
- reactors cooled with light water but moderated with a different element: graphite (LWGRs or RBMKs, in Russian) and heavy water (the Japanese advanced thermal reactor, ATR);
- not moderated reactors or fast breeder reactors (FBRs or LMFBRs), which are cooled with liquid metal (sodium).