INL/CON-09-15191
PREPRINT

Nuclear Symbiosis – A Means to Achieve Sustainable Nuclear Growth While Limiting the Spread of Sensitive Nuclear Technology

Global 2009

David E. Shropshire

September 2009

Nuclear Symbiosis - A Means to Achieve Sustainable Nuclear Growth while Limiting the Spread of Sensitive Nuclear Technology

David E. Shropshire, P. E.
Idaho National Laboratory
PO Box 1625, Idaho Falls, ID 83415-3870
Tel (208) 526-6800, Fax (208) 526-2930, Email: David.Shropshire@inl.gov

Abstract – *Global growth of nuclear energy in the 21st century is creating new challenges to limit the spread of nuclear technology without hindering adoption in countries now considering nuclear power. Independent nuclear states desire autonomy over energy choices and seek energy independence. However, this independence comes with high costs for development of new indigenous fuel cycle capabilities. Nuclear supplier states and expert groups have proposed fuel supply assurance mechanisms such as fuel take-back services, international enrichment services and fuel banks in exchange for recipient state concessions on the development of sensitive technologies. Nuclear states are slow to accept any concessions to their rights under the Non-Proliferation Treaty. To date, decisions not to develop indigenous fuel cycle capabilities have been driven primarily by economics. However, additional incentives may be required to offset a nuclear state's perceived loss of energy independence. This paper proposes alternative economic development incentives that could help countries decide to forgo development of sensitive nuclear technologies. The incentives are created through a nuclear-centered industrial complex with "symbiotic" links to indigenous economic opportunities. This paper also describes a practical tool called the "Nuclear Materials Exchange" for identifying these opportunities.*

I. INTRODUCTION

Global growth of nuclear energy in the 21st century is creating new challenges to limit the spread of nuclear technology without hindering adoption in countries now considering nuclear power. Independent nuclear states desire autonomy over energy choices and seek energy independence. However, this independence comes with high costs for development of new indigenous fuel cycle capabilities. Nuclear supplier states and expert groups have proposed fuel supply assurance mechanisms such as fuel take-back services, international enrichment services and fuel banks in exchange for recipient state concessions on the development of sensitive technologies. Recipient states are slow to accept any concessions to their rights under the Non-Proliferation Treaty (NPT). To date, decisions not to develop indigenous fuel cycle capabilities have been driven by economics. Additional incentives, perhaps even outside of the nuclear realm, may be required in the future to offset the nuclear user state's perceived loss of energy independence, according to a recent congressional study (CRS 2008). This paper proposes new economic development mechanisms that could help move nuclear user states and nuclear suppliers toward common ground. Key to this conciliation process is "nuclear symbiosis" that matches the inputs and outputs from a nuclear power plant to nuclear user state capabilities and desired economic, energy, and infrastructure development end states. The desired result from this "symbiosis" is a nuclear-centered industrial complex that creates new economic opportunities through infrastructure improvements, human resource skills development, and development of new sustainable industries.

This paper also describes the Nuclear Materials Exchange (NME) as a practical tool for performing nuclear symbiosis. The NME could be used to define existing and new international nuclear resources and their linkages and relationships with current and future users within the international nuclear system. During 2007/2008, the NME was developed as a prototype relational database and populated with data sets of the capacities and operational data for existing reactors and fuel cycle facilities located throughout the world. Additional information sets can be included, such as nuclear power plant construction and start-up infrastructure requirements; projected nuclear user state infrastructure capabilities such as human resources, materials and services, and raw resources; primary to secondary industries such as agricultural, petro chemical, water supply systems, and biofuels; industries that use nuclear products in medicine, manufacturing, and engineering; historical, current, and projected quantity details for feedstocks, primary products, by-products, waste flows, and utilities; commodity prices and disposal costs; and generic profiles of nuclear construction and manufacturing processes.

A search of the open literature indicates that no nuclear materials exchange model of comparable features and capability as the NME exists. Design for the NME database structure was leveraged off the design of an existing system developed by Bechtel called the Industrial Materials Exchange Planner (IMEP). The IMEP was developed to look at how industrial symbiosis could be used to transition waste products from one industrial process into an input for another industrial process, thereby reducing the volume of waste and pollution, the costs of transportation and waste treatment, and the consumption of natural resources. This application of beneficially using nuclear by-products as inputs to other industrial processes was the initial focus for developing the NME. This paper describes the current capabilities, including the data sets, data structure, and available queries, as well as ideas for future capability enhancements.

II. OBJECTIVE

The objective is to define mechanisms that support fuel cycle policy decisions by nuclear user states that limit expansion of sensitive technologies. These mechanisms must balance the perceived loss of energy independence by gains in economic development. The loss results from volunteering to give up development of sensitive technology such as enrichment and reprocessing. The economic development gain results from a nuclear-centered industrial complex that utilizes the nuclear user state resources to create new indigenous economic opportunities. The opportunities will be derived through infrastructure improvements, human resource skills development, and development of new sustainable industries. This paper suggests that by using nuclear symbiosis, nuclear user states and nuclear supplier states can reach equitable positions that can support global sustainable nuclear energy growth.

III. NUCLEAR USER STATE DECISION OPTIONS

In order to appreciate the types of decisions facing nuclear user states, an overview of emerging fuel service procurement strategies is provided in Figure 1. Currently, international nuclear suppliers (Canada, China, Former Soviet Union, Japan, United States, France, United Kingdom, and Russia) provide the bulk of the fuel cycle services used globally. Some states have limited fuel cycle capabilities (uranium), and others have vertically integrated capabilities supporting all areas of the nuclear fuel supply (France). The use of sensitive technologies (enrichment and reprocessing) have been primarily limited to nuclear weapons states, which share the opinion that development of these technologies should be strictly limited. However, the NPT provides that all signatories have the right to these technologies within the conditions of the treaty.

The current open market provides for services for reactor fuel, including low-enriched uranium (LEU) and mixed-oxide fuel (MOx). The open market could be supplemented with an internationally controlled fuel bank (presumably by the International Atomic Energy Agency [IAEA]), which would stockpile modest quantities of fuel in case of supply disruption. Several versions of the fuel supply strategies have been compiled by the IAEA. Market competition aspects of proposed multilateral fuel supply arrangements have been studied by the Nuclear Energy Agency (OECD 2008) and by the Weapons of Mass Destruction Commission. (Muller 2006).

The fuel cycle decision options for independent nuclear user states are separated into two tracks. Each track is discussed separately; however, combinations of the two tracks are possible. In Track 1, nuclear user states could sell resources in the open market, purchase services, own a stake in a fuel cycle facility, and/or lease fuel cycle services. If a nuclear user state sells/buys resources in the open market, they would be subject to independent verification, and would have limited price and supply protection. Through partial ownership of the multi-lateral controlled facility, the nuclear user state would not gain access to sensitive technology, but would be guaranteed a production share from the facility. In fuel supply leasing agreements, the nuclear user state would be guaranteed fuel supplies (potentially to include used fuel take-back), but could require conditions prohibiting development of sensitive technologies. The outcome from Track 1 is that a nuclear user state would decrease their energy independence (increasing reliance on the market and global suppliers) and be expected to give up their right to sensitive technologies. This track may not be readily adopted by nuclear user states without further offsets.

In Track 2, countries would continue to use and potentially sell existing indigenous capabilities (e.g., uranium yellow cake) and could pursue development of new fuel cycle capabilities such as conversion, enrichment, fabrication, reprocessing, and used fuel storage. The nuclear user state may also desire to sell these new services in order to leverage the cost of the new fuel cycle facilities. A country may prefer this track since it affords them with the greatest energy independence, and provides the geopolitical gain through recognition as a nuclear state. However, this track would also be very expensive and may not be acceptable to the global community due to the increased nuclear security risks. Few countries would be in a position to make the financial commitments required for enrichment and reprocessing unless they have interests that extend beyond commercial nuclear power applications.

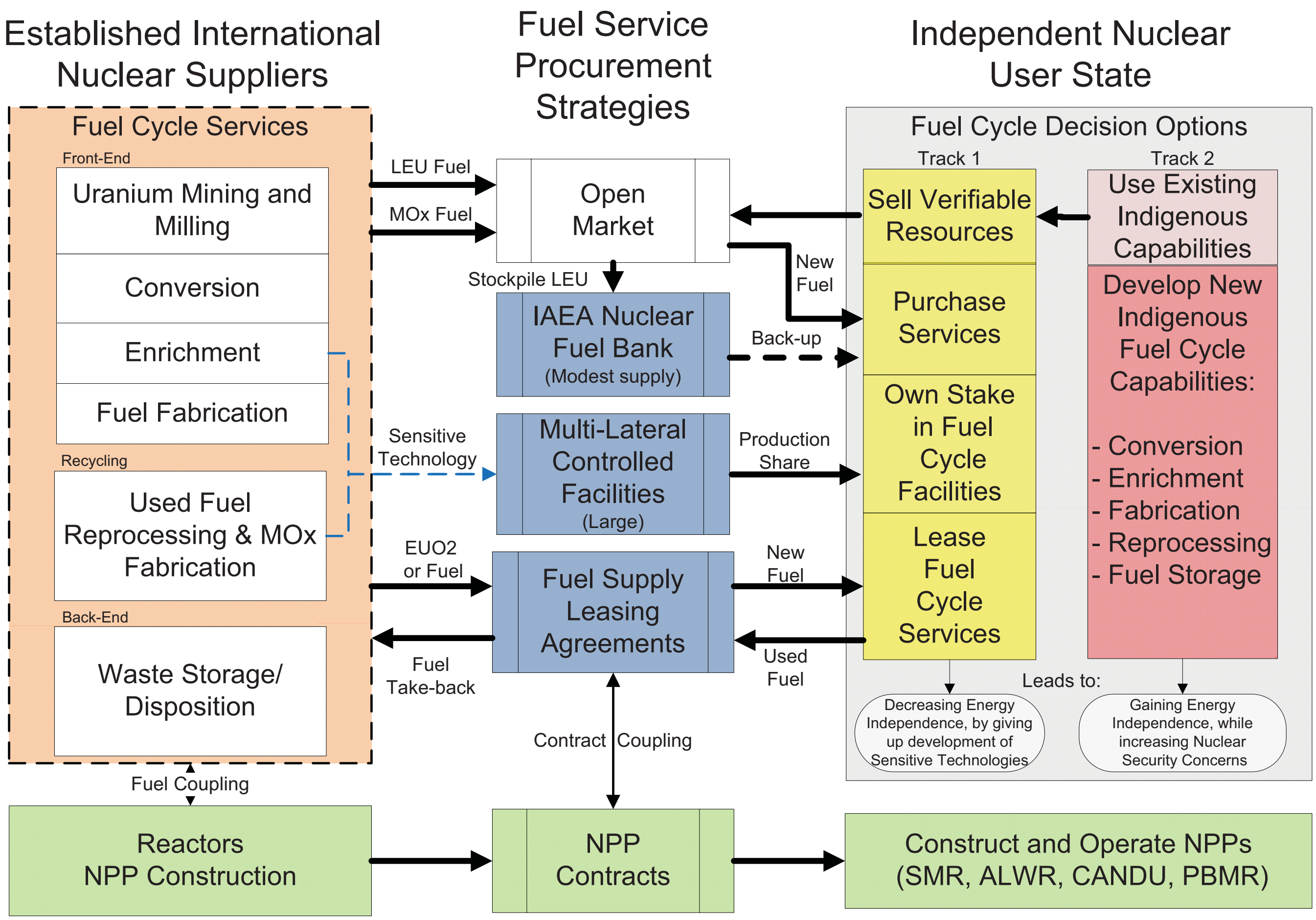

Fig. 1. Fuel cycle procurement strategies and nuclear user state decision options.

IV. OPPORTUNITIES FOR NUCLEAR SYMBIOSIS

In combination with the nuclear user state choices for fuel services is the choice of nuclear power plant (NPP) supplier. The NPP supplier could couple the purchase of the reactor with a fuel supply leasing agreement. The terms of these fuel contracts could be limited to a few years or last for the entire operational life of the reactor. The supply contract would likely include periodic renegotiation clauses to allow for adjustments of the prices or terms to protect the supplier against cost increases or supply constraints. The nuclear user state could be potentially locked into such agreements, with limited alternative supply options.

From this discussion on fuel cycle decision options and procurement strategies, it appears there is no clear winner from both a nuclear supplier and a nuclear user state perspective. Both Track 1 and Track 2 have their advantages and disadvantages from the user/supplier perspectives. The globally preferred outcome results from the nuclear user state obtaining secure, economic, and reliable nuclear fuel in exchange for voluntary limits on the expansion of sensitive technologies. The key to achieving this outcome is that the nuclear user state must concede that the loss of nuclear capability (independence) is supplanted by indigenous economic growth and international harmony. The process to achieve the economic gain involves matching or linking the resource requirements and output energy products from nuclear power to the nuclear user state (input) resource capabilities and (output) industries as described below and depicted in Figure 2. Identifying the potential match is the first step toward stimulating economic growth and development. The role of the nuclear supplier states and international governmental entities would be to assisting nuclear user states in:

1. Identifying requirements for human resources, materials and services, and raw resources to construct, start-up, operate and maintain, and decommission the NPP. Once the NPP is built these skills and resources

can be put to use in other nuclear user state industries. For example, a concrete plant that is built to support construction of the NPP could later be used to support infrastructure development projects such as highways, bridges, airports, etc.

2. Linking the energy products (e.g., electricity, heat, and recycled products) from a NPP to current industries (e.g., food, agriculture) and to future use opportunities (IAEA 2008). Electricity could be supplied to upgraded electricity grids to support local load centers that enable improvements to critical infrastructure projects (water, sewer, agriculture production, etc.). Heat produced by NPPs, particularly from high temperature gas reactors, have many potential uses including municipal heating, desalination, production, or extraction of other energy products (hydrogen, oil recovery from oil sands and shale). Industries could be coupled into renewable energy systems. For example, potable water produced by desalination could be used in fish farming; the sludge from fish farming could be used as fertilizer in agriculture to in turn produce biomass for the production of ethanol and biodiesel. Nuclear isotopes could be recycled back from the nuclear suppliers, or produced through secondary industries, to be used in public health care (medical lasers, pharmaceuticals, therapeutic administration of radiation), manufacturing and construction (welding, lighting), and food industries (food preservation).

3. Identifying nuclear supply resources and regional trade-partners to maximize a nuclear user states energy security, supply diversification, while maintaining the goals of nuclear non-proliferation.

This approach involves developing customized nuclear user state capabilities that are centered on the nuclear enterprise. The mapping of nuclear user state specific input/output resources to the NPP would be provided through the NME. The NME could also be a planning tool for national, regional, and global planning scenarios that ask questions such as: “For a new reactor, where could the necessary services, materials, and fuel services be obtained?” or, “What is the potential for developing supporting industries to supply an expanding nuclear capacity?” This nuclear-centered application can directly leverage work by the United Nations and the IAEA to use nuclear techniques in food and agriculture, and to improve human health (IAEA 2008).

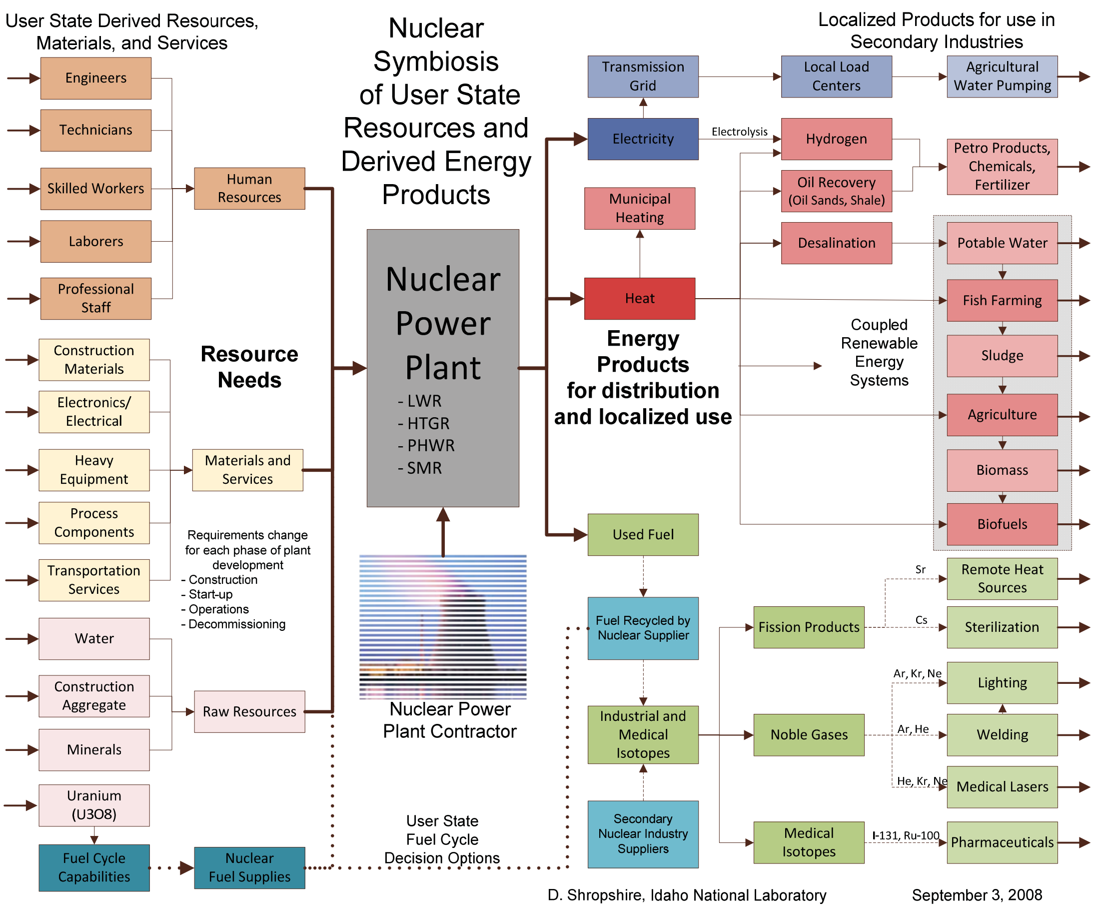

Fig. 2. Application of industrial ecology and nuclear power: Potential Energy, Material & Resource Flows with Nuclear Energy.

V. NUCLEAR MATERIALS EXCHANGE DATABASE

V.A. Data Sets

The first step in developing the NME has been to provide a comprehensive database of nuclear reactors and fuel cycle production facilities. The intent is to add primary supporting industries, including engineering and design, infrastructure, and components. The data has been aggregated by country, region, and alliance so that available national and regional capabilities can be identified. The NME could be used by U.S. and international users to:

- Locate fuel cycle suppliers (e.g., uranium supplies, conversion, enrichment, and fuel fabrication)
- Locate raw resources (e.g., concrete, switches, rebar, and castings) needed to improve the electrical grid, construct and/or operate a particular nuclear fuel cycle facility or reactor
- Locate human resources (e.g., Architect-Engineering consultants and safety analysts) needed during the following phases of nuclear power development: planning and licensing, construction, and operation and maintenance
- Identify linkages between a reactor and its supporting fuel cycle facilities
- Isolate opportunities wherein construction and operation of a NPP can lead to domestic industry enhancement and economic benefit in new nuclear states.

Additional queries and data sets that may be added to the NME would allow it to:

- Show historical facility capacity information, current state, and future projections based on the expected operating life
- Show how regional blocks of countries could trade unique capabilities to build new nuclear generation capacity
- Show how recycled or un-recycled output streams could be used by secondary industries (e.g., medical isotopes)
- Show secondary industry expansion of country core infrastructures (e.g., manufacturing and construction) to support nuclear power
- Show operational inputs and outputs to a global nuclear fuel bank
- Show economic tradeoffs and opportunities from sharing hard and soft capital resources, make/buy/trades, consuming new resources versus recycled resources, using or adapting technologies developed by other countries, and regional deployment of similar technologies.

The initial data set includes existing reactor and fuel cycle facilities located throughout the world. Data has been mined from the following sources to date:

- Country Nuclear Fuel Cycle Profiles (IAEA 2005)
- Integrated Nuclear Fuel Cycle Information System (IAEA 2009a)
- World Nuclear Association Reactor Database (2009)
- Nuke Database System (2009).

Critical to operationalizing the NME model is database development. In order to identify the opportunities for industrial symbiosis, data concerning the relevant resources and economic sectors of emerging nuclear states needs to be located and built into the NME architecture. A systematic and a phased approach will be needed.

V.B. Data Structure

The prototype version of the NME was structured with an initial set of use cases or queries in mind, and the design of the IMEP as a reference. The design objective of the NME is to promote modularity in data and interfaces, so incremental enhancements are easily made, and fit within the overall design philosophy of the system. As new requirements are specified, the design will be adapted accordingly by adding new data structures.

The design philosophy of the NME has been to modularize data according to a hierarchical relationship among entities represented in the system. The data relationship diagram in Figure 3 shows the relationships between each of the tables and respective fields, also known as the “back-end” of the database. The links between each of the tables are shown with lines between the data fields that are specifically linked, and include an infinity (∞) or one (1) symbol. The infinity symbol identifies a “many” relationship and the one (1) identifies a unique relationship. For example, each facility has a unique listing with a unique identification number in the “Facility” table, but may be listed multiple times in the “OperatingOrg-Facilities” table where the relationship between the facility and its Operating Organization (OpOrg) is defined. The same is true for an OpOrg; it has only one unique listing in the “OperatingOrg” table, but may be listed many times in the “OperatingOrg-Facilities” table.

The highest-level entity in the NME is the OpOrg. An operating organization is a specific company or organization. OpOrgs are associated with a country, and made up of facilities. Countries can be grouped into alliances.

The next level in the hierarchy below the OpOrg is the facility. Multiple facilities can be associated with an OpOrg.

The final level is the “TransformFunction”. Multiple TransformFunctions can be associated with one facility.

TranformFunctions have inputs and outputs of materials and services. TransformFunctions are typically key process steps that produce one or more finished products or services. The TransformFunction keeps track of its material and service flows via a "Quantity" table. This table tracks the quantities, and, if available, the source or destination of its inputs or outputs. The source/destination is intended to be identified at the facility level.

This basic design is relatively simple and elegant, especially considering the large amount of data that will ultimately be collected. This design may need to evolve over time as additional functionality is needed in order to satisfy additional applications that may pose questions that could not be produced via a database query to the existing data structure. The "modularlized" design philosophy should be maintained when the data structure grows and/or is modified.

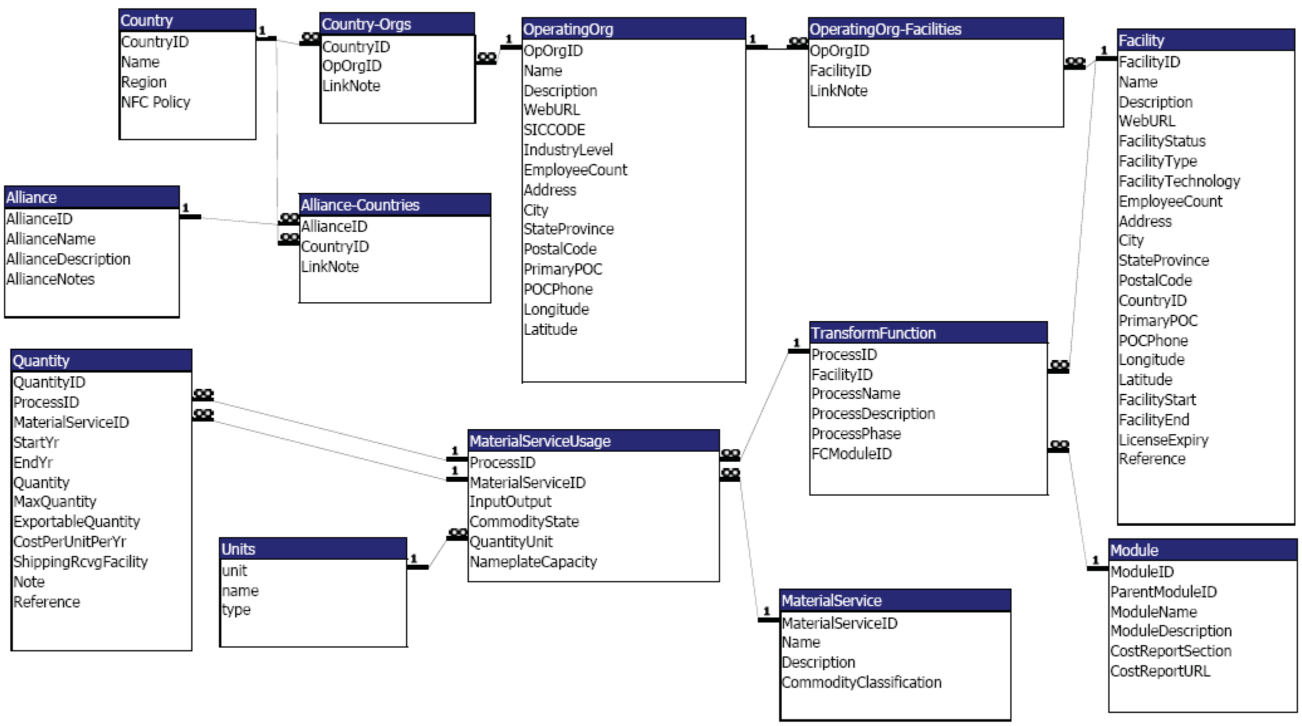

Fig. 3. Relationship diagram for the Nuclear Materials Exchange database.

VI. FUTURE STEPS

Next steps for the NME include data additions, data verification, and additional query development in addition to continued collaboration with groups such as IAEA and the Organization for Economic Cooperation and Development (OECD).

VI.A. Data Additions

Data collection will be focused on specific NME applications to further demonstrate and evaluate the usefulness of nuclear symbiosis. Potentially, the data requirement is extensive because of the scope of the NME is expanding to essentially all facets of the world-wide nuclear industry, secondary industries associated with nuclear programs, nuclear user state infrastructure data, human resources, etc. Assistance from international organizations is desired to complete and verify datasets. Furthermore, data additions or modifications will be a constant effort as new facilities are added, facility statuses change (some facilities have seen recent increases in capacity), and existing facilities come off-line. Future data updates could be made through use of a data-mining tool that sends alerts when facility changes occur.

Other possible data additions that may be incorporated into the NME fall into the following areas:

1. Current country/operating organization alliances, treaties, partnerships, regional consortium, and participation in international organizations (IAEA, etc.).
2. Nuclear user state information, including human resources, materials and services, and raw resources that may be used or adapted from other uses to application to support for an NPP. This may include information on the countries economic development status, current power generation, country infrastructure, industry capability, and effect on and

development of secondary industries. Company material balance profiles for region-specific industrial symbiosis scenarios; historical, current, and projected quantity details for feedstocks, primary products, by-products, waste flows, and utilities; commodity prices and disposal costs.

3. Linkage data that defines which operating organization/facility supplies another facility and vice versa. This may include historical data as well as links for new nuclear reactors that are in the planning, licensing, and/or construction phase. Operating organization information may also be collected.
4. Generic NPP input requirements for human resources, materials and services, and raw resources. Generic NPP potential outputs such as electricity, heat, and recycled fuel product applications.
5. Geographic information may also be collected to support future Geographical Information System (GIS) capabilities.

Data verification will need to play a large role in the development of the NME and will need to include checks of data quality, validation, and consistency. Some of the sources that have been identified to use during the data validation are:

- Power Reactor Information System (IAEA 2009a)
- International Nuclear Safety Center (INSC 2009)
- The United Nations Department of Economic and Social Affairs, Statistics Division, Country Profiles of Statistical Systems (2009)
- World Trade Organization, International Trade and Tariff Database (2009)
- The CIA World Factbook (2009).

VI.B. Additional Queries

There are a number of additional database queries that could be developed based on the compiled dataset. A selection of additional queries that could be developed includes:

- Showing how regional blocks of collocated countries could trade unique capabilities to build new nuclear generation capabilities. For example, during reactor construction, one country supplies electronic equipment, another construction labor and management, and another country has unique large metal fabrication capabilities.
- Showing how recycled or un-recycled output streams could be used by secondary industries (production of medical isotopes, radiation therapy, thermal waste heat use, etc.). This use case involves identifying output streams that could be used by secondary industries. A more in-depth data search will be needed to obtain quantitative information on the availability of isotopes, including both the major isotopes used in medical treatment and the major isotope vendors in the world.
- Secondary industry expansion of country core infrastructures (e.g., manufacturing, construction) to support nuclear power.
- Operational inputs/outputs of a nuclear fuel bank based on the projected scenario where supplier countries would input various fuels to the fuel bank, and user nations would make fuel withdrawals and then return the used fuel for supplier countries to separate and disposition accordingly.
- Symbiotic relationships across various reactor types and their associated fuel cycles (e.g., light water reactors (LWR), heavy water reactors (HWR), and fast reactors) to identify potential synergisms across fuel cycles.
  - LWR RU (outputs) links to fuel (inputs) for HWR (CANDU), as in the Direct Use of Spent PWR Fuel in CANDU (DUPIC) fuel cycle. (KO 2001).
  - Fast breeder reactor (FBR) recycled 233U/U, combined with thorium, linking to fuel (inputs) for small high-temperature gas reactors (HTGR) for use in developing countries (Liem 2007).
  - Show how countries (e.g., France) using mixed uranium-plutonium oxide (MOX) recycled fuel can be linked to countries with UREX+ technology, to recycle the used MOX fuel in advanced burner reactors to destroy the transuranics.
  - Economic tradeoffs and opportunities from the sharing of hard and soft capital resources, make/buy/trades, using new resources versus recycled resources, and economies of scale from using or adapting technologies developed by other countries (Shropshire 2008).
  - Deployment ramifications on economics.

VI.C. Optimization

So far in the NME and in the queries or use cases, the only question asked is, “Where are materials or services available?” and not, “How can the material and service demands of a particular facility be met in the most economic manner?” or “Can the demands of a facility be feasibly met by the available supply?” Production and transportation costs are two factors that determine economics. Available supply and demands given from other facilities can be used to determine the feasibility of meeting the demand from a new facility. In both cases, linear optimization programs can address each of these questions.

The NME could be developed to produce a linear programming (LP) formulation that is output to an LP solver, which would return a solution to NME for reporting and analysis. Visual Basic (VB) code in NME would write a text file in a format specific to the optimization solver used. In designing the NME optimization capability, first, an appropriate optimization problem should be formulated (e.g., minimize development of sensitive nuclear technologies). Second, a LP solver should be chosen, and a VB code would be used to produce an output a text file as input to the solver, in a format specific to the solver.

Formulations, such as a nuclear fuel cycle production problem, can be used to find optimal linkages, find infeasibilities, and determine requirements for additional capacity throughout the entire supply chain, from mining and milling to power generation, to fuel reprocessing and storage. In fact, it is only through an optimization approach that basic questions of available supply and demand can be addressed. Otherwise, the NME would only be able to determine the availability of capabilities, and not the availability of particularly quantities of materials or services. In some cases, it will be sufficient to know only if a country or operating organization has a certain capability, such as the availability of engineering expertise in a particular domain, or the capability to utilize nuclear-generated process heat in a secondary industry. However, in other cases, knowing the required or available supply quantities will be important.

VI.D. GIS Integration and Optimization

Graphical display and interactive graphics of NME scenarios can be a powerful and useful tool for analysis, presentations, and communication of results.

Another potentially useful application is that of GIS capabilities. GIS functionality can range from the generation of maps showing the locations of facilities and the flow of materials, to providing detailed information about the locations of facilities, including available infrastructure (highways, railways, water, etc.) and environmental information. GIS systems can also calculate distances between facilities and provide factors for calculating actual transportation distances via different modes of transportation, including highway, rail, inland water, ocean, air, and multi-modal transportation.

Simple mapping systems, such as MapMaker (www.mapmakker.com) or Google Maps (www.maps.google.com) could be used to locate facilities and generate maps. GIS software such as AGIS for Windows (www.agismap.com) has additional GIS capabilities and could be incorporated.

If transportation costs and planning is an important consideration in NME planning, GIS systems can provide actual transportation distances and costs for material shipment. With latitude and longitude data for a given facility (which is part of the NME data structure), GIS systems can determine the costs and available transportation modes. However, for nuclear materials, additional data input may still be required to identify secure transportation and handling requirements for the materials.

Future NME design might include additional parameters for materials to indicate whether there are special transportation, handling, and security requirements.

VII. CONCLUSIONS

The aim of this paper has been to identify an incentive pathway for the growth of nuclear energy without spreading dangerous nuclear technologies. Nuclear symbiosis provides an avenue for nuclear user states to create economic value from the development and utilization of nuclear energy. With the support of nuclear suppliers and international organizations, nuclear user states can optimize their use of domestic resources and engage industries to create economic growth in non-nuclear sectors. With these incentives, nuclear user states could choose to forgo development of sensitive nuclear technologies.

ACKNOWLEDGMENTS

The author acknowledges David Cobb (retired Bechtel), Paul Worhach, and Sunil Ghose (NEXANT) for their inspiration in creating the IMEP and support in defining a new structure for nuclear applications.

NOMENCLATURE

CRS	Congressional Research Service
FBR	Fast Breeder Reactor
GIS	Geographical Information System
HTGR	High-Temperature Gas Reactor
IAEA	International Atomic Energy Agency
IMEP	Industrial Materials Exchange Planner
INSC	International Nuclear Safety Center
LEU	Low-Enriched Uranium
LP	Linear Programming
Mox	Mixed-Oxide Fuel
MOX	Mixed Uranium-Plutonium Oxide
NME	Nuclear Materials Exchange
NPP	Nuclear Power Plant
NPT	Non-Proliferation Treaty
OECD	Organization for Economic Cooperation and Development
OpOrg	Operating Organization
PRIS	Power Reactor Information System
SMR	Small-Medium Reactor
VB	Visual Basic
WMDC	Weapons of Mass Destruction Commission
WNA	World Nuclear Association
WTO	World Trade Organization

REFERENCES

1. Central Intelligence Agency, 2009, The World Factbook, https://www.cia.gov/library/publications/the-world-factbook/, Web page accessed May 2009.
2. Congressional Research Service Report for Congress, 2008, Managing the Nuclear Fuel Cycle: Policy Implications of Expanding Global Access to Nuclear Power, Congressional Research Service (March 2008).
3. IAEA, 2005, Country Nuclear Fuel Cycle Profiles, Technical Report Series No. 425 (TRS 425), 2nd Edition (2005).
4. IAEA, 2008, Department of Nuclear Sciences and Applications, http://www-naweb.iaea.org/na/our-work-na.html, Web page accessed May 2009.
5. IAEA, 2009a, Integrated Nuclear Fuel Cycle Information System (iNFCIS), http://www-nfcis.iaea.org/iNFCISMain.asp, Web page accessed May 2009.
6. IAEA, 2009b, Power Reactor Information System (PRIS), http://www.iaea.or.at/programmes/a2/, Web page accessed May 2009.
7. KO, W., KIM, H., 2001, Analysis of Nuclear Proliferation Resistance of DUPIC Fuel Cycle, *Journal of Nuclear Science and Technology*, Vol. 38, **No. 9**, p., 757–765 (September 2001).
8. International Nuclear Safety Center, World List of Nuclear Power Reactors, http://www.insc.anl.gov/pwrmaps/ Web page accessed on May 2009.
9. Liem, Peng Hong, et al, 2007, Small high temperature gas-cooled reactors with innovative nuclear burning, *Progress in Nuclear Energy*, Vol. 50, **Issues 2-6**, p., 251-256 (December 2007).
10. Muller, H., 2006, Weapons of Mass Destruction Commission, *Multilateral Nuclear Fuel-Cycle Arrangements*, **No. 35** (2006).
11. Nuke Database System, http://www.icjt.org/plants/index.html, Web page accessed May 2009.
12. OECD, 2008, Market Competition in the Nuclear Industry, Nuclear Development, NEA No. 6246.
13. Shropshire, D. E., et al., 2008 Advanced Fuel Cycle Cost Basis, INL/EXT-07-12107 (March 2008).
14. United Nations statistical databases, 2009, http://unstats.un.org/unsd/snaama/selectioncountry.asp , Web page accessed May 2009.
15. WNA Reactor Database, 2009, http://db.world-nuclear.org/reference/reactorsdb_index.php, Web page accessed May 2009.
16. WTO International trade and tariff data, 2009, http://www.wto.org/english/res_e/statis_e/Statis_e.htm , Web page accessed May 2009.