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Global Nuclear Material Flow/Control Model

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Abstract

This is the final report of a two-year, Laboratory Directed Research and Development (LDRD) project at the Los Alamos National Laboratory (LANL). The nuclear danger can be reduced by a system for global management, protection, control, and accounting as part of an international regime for nuclear materials. The development of an international fissile material management and control regime requires conceptual research supported by an analytical and modeling tool which treats the nuclear fuel cycle as a complete system. The prototype model developed visually represents the fundamental data, information, and capabilities related to the nuclear fuel cycle in a framework supportive of national or an international perspective. This includes an assessment of the global distribution of military and civilian fissile material inventories, a representation of the proliferation pertinent physical processes, facility specific geographic identification, and the capability to estimate resource requirements for the management and control of nuclear material. The model establishes the foundation for evaluating the global production, disposition, and safeguards and security requirements for fissile nuclear material and supports the development of other pertinent algorithmic capabilities necessary to undertake further global nuclear material related studies.

Background and Research Objectives

With the end of the cold war and the dissolution of the Soviet Union, the threat of a global nuclear exchange is essentially nonexistent. However, the global proliferation of weapons-grade nuclear material has become one of the foremost threats to US and global security. This nuclear danger can be reduced by a system for global management, control, and disposition of special nuclear materials to prevent their use for weapons purposes. Recent initiatives within the US government and a study by the National Academy of Sciences are supportive of such measures. Development of this global system requires analytical and modeling tools to support its development and implementation including an assessment of the global distribution of these materials, analysis tools to detect deviations from a state's declared nuclear activities, and a modeling tool for evaluating the effect of

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nonproliferation policies on the evolution of global materials distributions and the required verification resources.

Our project proposed characterizing and modeling, from a global perspective, the management, control, and flow of weapons-grade nuclear material (plutonium and highly enriched uranium). The development of this model would for example, provide a computer-based tool that could answer questions such as the degree of certainty associated with the estimation of material quantities based on available inventory information, the verification of resources needed for safeguarding excess weapons materials or verification of a cutoff of fissile materials production for weapons purposes, or the changes in fissile materials inventories as technologies for fissile materials disposition are introduced.

This project addressed five issues that are of interest to the US nonproliferation program:

- 1) characterizing the global inventory of nuclear weapons material,
- 2) characterizing the safeguards accounting and management and control methodologies and enumerating the associated resource requirements,
- 3) developing a macro-system simulation capable of estimating future quantities of nuclear material and estimating future resource requirements for nuclear material management and control,
- 4) developing the capability to visually represent information related to nuclear materials (e.g., management and control, quantity, location, and transit) and the inter-country and intra-country nuclear material flow, and
- 5) supporting the development of other pertinent algorithmic capabilities necessary to undertake further global nuclear material related studies.

There are no other nuclear fuel cycle or nuclear material related analytical modeling tools or systems available that employ this technology and these methodologies. Our Global Nuclear Material Control Model (GNMCM) provides an analytical modeling and systems analysis capability, it is not merely a database of nuclear material related data. When this effort was proposed there were already two nuclear material-related database systems under development within the DOE complex, the EISS database and the INA database. Neither the EISS nor the INA projects have any computer-based analytical modeling and systems analysis functionality, they are strictly database systems.

Addressing the five issues results in the information, tools, and methodologies necessary for reliable analysis concerning global nuclear material management. By developing an automated tool with visual representation, we can study various systems concerning accounting surety and resource estimation and analyze material transits based on the initial location and potential destination of this nuclear material. Modeling this data and

information with the existing or proposed management and control regime provides the capability to undertake high-level studies. Further, including accounting and resource requirements opens the possibility to conduct resource optimization analysis.

Importance to LANL's Science and Technology Base and National R&D Needs

The Laboratory has made the strategic decision to play a lead role in the global management, control, and disposition of nuclear material and in maintaining a preeminent role in reducing, deterring, detecting, and responding to the proliferation of weapons of mass destruction and nuclear materials and their associated dangers. In this sense, this project strongly supports the following tactical goals of the Laboratory: Plutonium Future/Legacy; Reducing the Threat of Nuclear, Biologic, and Chemical Proliferation and Terrorism; and Modeling, Simulation, and High-Performance Computing. This project complements, supports, and enhances the Laboratory's mission of reducing the global nuclear danger. It supports the Nonproliferation and International Security (NIS) Division's mission to maintain a preeminent role in reducing, deterring, detecting, and responding to the proliferation of weapons of mass destruction and nuclear materials. This is accomplished by addressing the methodologies and technology that must be developed and the information and data that must be collected and analyzed to advance the non- and counter-proliferation and nuclear materials management strategic problem areas. Indeed, this project fully supports the DOE's mission of reducing the nuclear danger. The project assists in reducing the global nuclear danger by researching and developing technologies and methodologies that enable efficient and expeditious access to global nuclear material data and information and by supporting systems studies and analysis.

This project strongly supports the Laboratory's Analysis and Assessment; Theory, Modeling, and High-Performance Computing; and Nuclear and Advanced Materials core technical and science competencies. The project implements a recommendation from the National Academy of Sciences (NAS) [1] study, "that the United States pursue new international arrangements to improve safeguards and physical security over all forms of plutonium and highly enriched uranium (HEU) worldwide." The NAS study indicated that the approach to follow was to undertake conceptual research considering the nuclear fuel cycle as a complete system in order to minimize proliferation while enabling study from both a national and an international perspective and to develop an international fissile material management and control regime [2]. This project has developed an analytical and modeling tool to undertake this conceptual research. Another initiative from the highest

levels of the US government, the National Security Science and Technology Strategy (NSSTS) [3] is also supportive of such measures. The NSSTS points out that “the primary technical barrier limiting the spread of nuclear weapons is limits on access to the nuclear materials needed to make them.”

Scientific Approach and Accomplishments

We have developed a prototype global nuclear material management and control systems analysis capability, the GNMCM, on a Sun workstation. This effort was undertaken as a result of our expertise and interest in nonproliferation, national and international security, safeguards, and the NAS recommendations [4]. There are three fundamental components to the GNMCM: physical process representation, model infrastructure design, and data and contextual information.

The physical process representation component has the primary functional computational capabilities of the GNMCM. There are three distinct nuclear-material-related functional capability categories: proliferation, safeguards and security, and disposition options; there is also a graph-theoretic capability category. The proliferation category provides analytical modeling and computational support for the following nuclear fuel cycle production processes and facilities: enrichment, fuel fabrication, reactor, reprocessing, metal fabrication, weapons assembly, weapons disassembly, and storage. The proliferation category permits the investigation and study of fuel cycle production, dismantlement, storage, and inventory depletion issues. The safeguards and security category provides analytical modeling and computational support to study and analyze international inspection and protection resources, requirements, and criteria [5]. The disposition options category provides analytical modeling and computational support for vitrification, geologic repository, and reactor-related research. The graph-theoretic capability category provides the analytical modeling and computational functionality to conduct various graph-theoretic and network-optimization studies, including network (material) flow and shortest or constrained path analysis. This category leverages the underlying graph-theory-based infrastructure design feature.

The model infrastructure has been designed to support investigation across a broad range of detail, specificity, and perspective. There are four aspects to the model infrastructure: the graph-based data framework, the structural hierarchy, the nuclear fuel cycle visual representation, and the geographic illustration. The most fundamental design feature of this model is the graph data framework. This feature enables the application of

graph algorithms and material flow studies. All facilities, sites, countries, and categories are represented as vertices and every connection is represented as either a directed or an undirected edge. The structural hierarchy design decomposes the world into four designations: nuclear weapon states (NWS), threshold nuclear weapon states (TNWS), potential nuclear weapon states (PNWS), and nuclear states (NS). These designations are further decomposed into their constituent countries. The countries are delineated by all their respective nuclear sites. A site is determined by the facilities that exist at the site, as exhibited in Fig 1. In Fig. 1 the vertices are connected by unordered edges. The nuclear related computational capabilities can be executed from this hierarchical representation or from the nuclear fuel cycle visualization. User-specified nuclear fuel cycles can be represented as in Fig. 2, allowing for the study of alternative fuel cycles. The final feature of the model infrastructure is the geographic illustration (see Fig. 3). This provides an interactive map of the world that includes all the modeled facilities and sites and some geographic characteristics, such as rivers and lakes.

The last component of the GNMCM is the data and contextual information. The data and information is specific to each level of the hierarchy of the model. This ranges from facility-specific physical process data to more general world information and data. Figure 3 depicts some of the nuclear sites included in the model. An example of some of the data is: geographic location of facilities; type of facility; physical process data; the Nonproliferation Treaty signatory status of a country; and facility, site, country, category, and world fissile material inventory data. A number of different estimates for the facility, site, country, and global inventory data exist. To estimate the initial global distribution of fissile materials, we have utilized a number of publications including the recently released DOE report on plutonium [6] and investigated the availability and accuracy of existing databases. The GNMCM utilizes inventory data as a foundation and limiting parameter for systems studies concerning fissile material production, disposition options, and international safeguards and security. The physical process component of the GNMCM provides the capability to estimate future material production and adjust the inventory data accordingly.

The high-level scientific and technical objectives/goals of this project were to:

- characterize the global inventory of nuclear weapons material (Pu & HEU),
- characterize the safeguards accounting and management and control methodologies and enumerate the associated resource requirements,
- develop macro-system analytical capabilities to estimate future quantities of nuclear material, estimate the impact on material inventory of disposition options, and estimate future resource requirements for nuclear material management and control,

- develop a visual representation of the information related to nuclear facilities and sites and the inter-country and intra-country nuclear material flow, and
- support the development of other pertinent algorithmic capabilities necessary to undertake further global nuclear material related studies.

The result of this project is a prototype, analytical modeling, systems analysis tool and information system that specifically supports and is capable of conducting a variety of parametric studies concerning the management and control of global nuclear material (Pu and HEU). The model includes the capability to engage in analysis concerning future quantities and disposition of nuclear material, future resource requirements for nuclear material management and control, material transfer issues, nuclear fuel-cycle facility - specific related issues, and geographic feature-specific characterization that supports computational based searches for undeclared facilities. The global disposition of plutonium and highly enriched uranium is visually represented, as well as geographic and facility-specific data and information. The GNMCM includes the technology to undertake macro-level analysis concerning future quantities and disposition of nuclear material, future resource requirements for nuclear material management and control, and material transit issues. Additionally, the technology and methodologies developed for the tool are applicable to other projects and programs. In particular, the data and information methodologies and visualization techniques have been developed as generically as possible and are applicable to various computation-based projects. We have already introduced chemical warfare-related data and information to demonstrate this capability.

To date we have completed three nuclear proliferation related studies (see Publications 1-3). The first study determined that there were two problems with the IAEA Safeguards Criteria. These problems could lead to a proliferation activity, yet the safeguards criteria are not triggered. The second study estimated the quantity of plutonium that could be produced in the thermal research reactors in the potential nuclear weapon states. The third study focused on the North Korean IRT-DPRK research reactor. The study determined that between 5.35 - 21.40 kg of plutonium could have been produced in the North Korean research reactor during the entire period it operated and that an absolute upper bound of 71.232 kg was theoretically possible but unlikely.

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Figure 1. Global Nuclear Material Control Model (GNMCM) structural hierarchy.

Figure 2. An example of the Global Nuclear Material Control Model (GNMCM) nuclear fuel cycle visualization. In the Former Soviet Union, reactor fuel is fabricated at Novosibirsk and sent to a reactor at Krasnoyarsk-26. The spent fuel is sent to Tomsk-7 for reprocessing and weapon component fabrication. The weapon components are sent to Sverdlovsk-45 for assembly and are disassembled at Zlatoust-36.

Figure 3. Global Nuclear Material Control Model (GNMCM) geographic contextual information.