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Title: THE GLOBAL NUCLEAR MATERIAL CONTROL MODEL

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Global Nuclear Material Control Model

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Abstract

The nuclear danger can be reduced by a system for global management, protection, control, and accounting as part of a disposition program for special nuclear materials. The development of an international fissile material management and control regime requires conceptual research supported by an analytical and modeling tool that treats the nuclear fuel cycle as a complete system. Such a tool must represent the fundamental data, information, and capabilities of the fuel cycle including an assessment of the global distribution of military and civilian fissile material inventories, a representation of the proliferation pertinent physical processes, and a framework supportive of national or international perspective. We have developed a prototype global nuclear material management and control systems analysis capability, the Global Nuclear Material Control (GNMC) model. The GNMC model establishes the framework for evaluating the global production, disposition, and safeguards and security requirements for fissile nuclear material.

1.0 Introduction

With the end of the cold war and the dissolution of the Soviet Union, the threat of a global nuclear exchange is essentially non-existent. However, the global proliferation of fissile material has become one of the foremost threats to U.S. national and international security. This nuclear danger can be reduced by a system for global management, protection, control, and accounting as part of a disposition program for special nuclear materials, plutonium, and highly enriched uranium (HEU) to prevent their use for weapons purposes. Recent initiatives within the U.S. government and a study by the National Academy of Sciences (NAS) are supportive of such measures. One of the primary recommendations of the NAS[1] study was "that the United States pursue new international arrangements to improve safeguards and physical security over all forms of plutonium and HEU worldwide."

Globally, proliferation concerns are currently focused on the accessibility and disposition of the excess and dismantled weapons-grade nuclear material resulting from past military production. The existence and potential availability of this material presents an acquisition opportunity for politically unstable and less technically capable states, sub-national organizations, or terrorists. Additionally, states with nuclear fuel cycle facilities outside of international safeguards, advances in commercially available technology, large and increasing quantities of civilian fissile material, an increasing spectrum of potential weapons materials, and accessibility of deliver technologies present a number of proliferation opportunities. These opportunities, together with the dissemination of nuclear weapons design information and the potential to secure scientific and technical design expertise and capabilities, create a distressing situation. With relatively little effort, it is possible that a terrorist group, sub-national organization, or rogue state could attempt to procure fissile weapons material and fabricate a nuclear weapon.

The total quantity of this excess and dismantled separated weapons plutonium is minor relative to the quantity of non-separated plutonium that is contained in stored spent fuel and that

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[1] National Academy of Sciences, Committee on International Security and Arms Control, *Management and Disposition of Excess Weapons Plutonium*, Washington, D.C., National Academy Press, 1994, p. 2

inventories, a representation of the proliferation pertinent nuclear fuel cycle physical processes, and a framework supportive of national or international consideration.

2.0 Global Nuclear Material Control Model

During the last year we have developed a prototype global nuclear material management and control systems analysis capability, the Global Nuclear Material Control (GNMC) model, 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.[7] There are three fundamental components to the GNMC model: physical process representation, model infrastructure design, and data and contextual information.

The physical process representation component has the primary functional computational capabilities of the GNMC model. 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.[8] 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-[9] 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, the physical production processes and material flow is simulated. This allows for the study of alternative fuel cycles. The final feature of the model infrastructure is the geographic illustration

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[7] NAS (note 1), pp. 1 - 27

[8] International Atomic Energy Agency - Safeguards Criteria, 1990-11-21

[9] A graph $G=(V, E)$ is defined by a set V of vertices and a set E of edges. A graph may be either directed (each edge is an ordered pair of distinct vertices) or undirected (each edge is an unordered pair of distinct vertices).

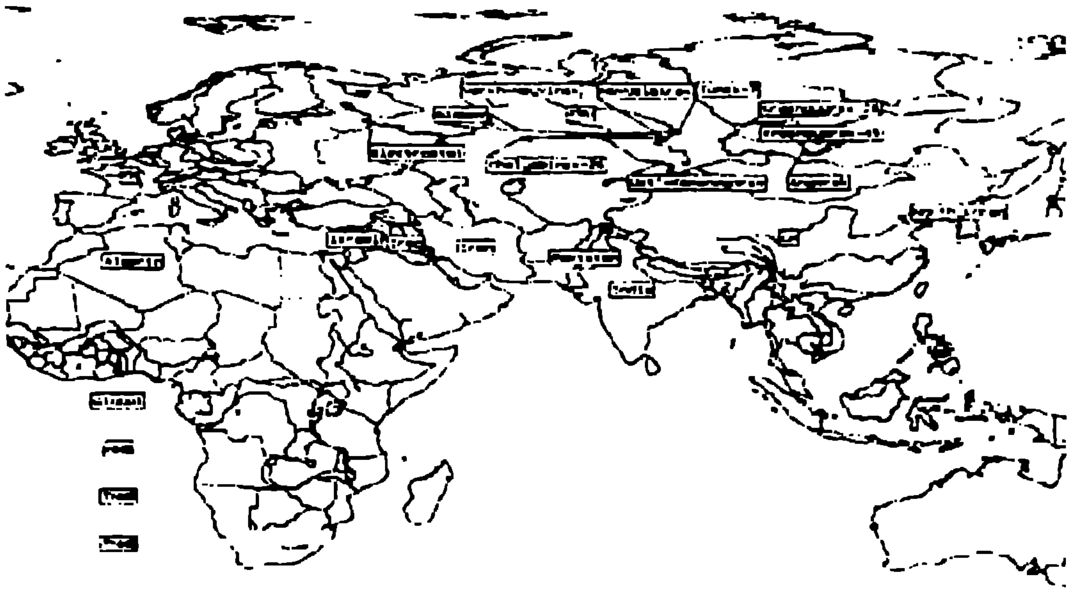

Figure 2. Global Nuclear Material Control Model Geographic Contextual Information

2.1 Reactor Production

The GNMC model has three approaches for the calculation of the production of fissile material in military, power, and research reactors. This first approach follows Albright's[11] method for estimating plutonium content of spent fuel. This method calculates the quantity of spent fuel discharged for a specific period of time, $F_t = E_t / [24B\,[n/100]] - C$, where E_t is the gross thermal output of the reactor during the specific time period t. B is the fuel design equilibrium burnup, n is the gross thermal efficiency of the reactor, and C is a half-core of fuel. The mean plutonium content in the spent fuel is calculated, Pu_{sf}. This is achieved by using one of five different functions that calculate the plutonium content based on typical initial fuel enrichment and reactor type. By multiplying the amount of fuel discharged by the mean plutonium content, the total amount of plutonium in the discharged spent fuel, Pu_{tot}, is estimated: $Pu_{tot} = F_t \times Pu_{sf}$. The advantage of this approach is the computational speed and ease of implementation, and it is not necessary to know the initial fuel enrichment. The disadvantage with this method is that no indication of the isotopic composition of the plutonium, uranium, and other isotopes is provided, and it is a broad estimate with potentially significant error.

For the purposes of the GNMC model, it is usually necessary to determine the isotopic composition of the plutonium, uranium, and other actinide products with better precision. The second approach is based on a C++ version of Little's BURN[12] code to calculate the production of fissile materials in military and power reactors. The BURN code requires the specification of

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[11] Albright, D., Berkhout, F., & Walker, W., World Inventory of Plutonium and Highly Enriched Uranium 1992, Appendix B, Oxford University Press, 1993

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4) analytical methodologies to approximate the resource requirements for international nuclear material inspection and protection;
5) the capability to visually represent contextual information related to nuclear materials (e.g., quantity, location, and form), nuclear material movement, and geographic characteristics surrounding facilities; and
6) it provides the foundation for the development of graph theoretic network flow analysis and constrained path analysis (i.e., minimal distance) associated with material shipment and facility siting determination studies.

We are currently engaged in testing and validation studies and are designing a study for international inspection and protection resource requirement estimation. We believe that the approach taken with the prototype GNMC model has resulted in an unique tool that supports exhaustive systems analysis study and investigation, which enables the study of questions such as the degree of certainty associated with the estimation of material quantities based on available inventory information and potential production capability, the verification of resources needed for safeguarding excess weapons materials, or the changes in fissile materials inventories as technologies for fissile materials disposition are introduced. An area that we intend to research with this model is the determination of the effectiveness of safeguards. This requires further research into the trade-off between inspection and protection resources and safeguards technologies and the effectiveness of these technologies within the context of facility features and fissile material inventories.

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1.0 Introduction

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will continue to be separated if the closed fuel cycle (spent fuel is reprocessed and recycled) is more widely adopted. Whether or not the closed fuel cycle is pursued by more states, the plutonium contained in the spent fuel will constitute the greatest proliferation problem in the future, with projected growth rates of 60 to 70 MT per year.[2]

The combination of the military weapon and civilian energy fuel cycles has resulted in a significant quantity of plutonium being produced. This was estimated to be 1095 MT by the end of 1993.[3] The breakdown of this military and civilian plutonium inventory is summarized in Table 1. The military related plutonium inventory represented about 23% of the total. The military inventory was rougnly a third of the civilian inventory, but only about 17% of the civilian plutonium was separated. Several features distinguish the military plutonium inventory. All of the military inventory is separated and 91% of it is weapons-grade, some in weapon component form. Imminently resolving the proliferation concerns of this military inventory is critically important. The menacing implications of the military plutonium outweighs the numerical imbalance with respect to the total quantity of plutonium produced in both the military and civilian fuel cycles.

Table 1:

Global Inventory	Total Pu (MT)	Total Pu Separated (MT)	Separated Pu Grade & Quantity (MT)
Civilian	845.0	144.0	Fuel/Reactor 144.0
Military	250.0	250.0	Weapon 228.0 Fuel/Reactor 22.0

Source: Derived from Albright, D., Arkin, W., Berkhout, F., Norris, R., & Walker, W., *SIPRI Yearbook 1995 Armaments, Disarmament, and International Security*, (SIPRI, 1995), Oxford University Press, pp. 317 - 324

One of the few remaining technical barriers to proliferation is the management and control of fissile materials. Management and control should be extended to include not only the plutonium and HEU arising from military production but to all civilian spent fuel, separated plutonium, and HEU.[4] Any regime for managing U.S. and Russian excess weapons fissile materials should anticipate and assume that it serves as a model for an international material management and control regime and standard.[5] Therefore, the development of an international fissile material management and control regime requires conceptual research considering the nuclear fuel cycle as a complete system.[6] The objective of this research must be to minimize proliferation while enabling study from both a national and an international perspective.

To undertake this conceptual research requires an analytical and modeling tool to support its investigation and study. The fundamental data, information, and capabilities for such a tool include an assessment of the global distribution of military and civilian fissile material

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[2] NAS (note 1), p. 4

[3] Albright, D., Arkin, W., Berkhout, F., Norris, R., & Walker, W., *SIPRI Yearbook 1995 Armaments, Disarmament, and International Security*, (SIPRI, 1995), Oxford University Press, p. 319

[4] NAS (note 1), pp. 9, 27

[5] NAS (note 1), pp. 2, 9, 18, 26, 27

[6] NAS (note 1), p. 26

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(see Fig. 2); 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.

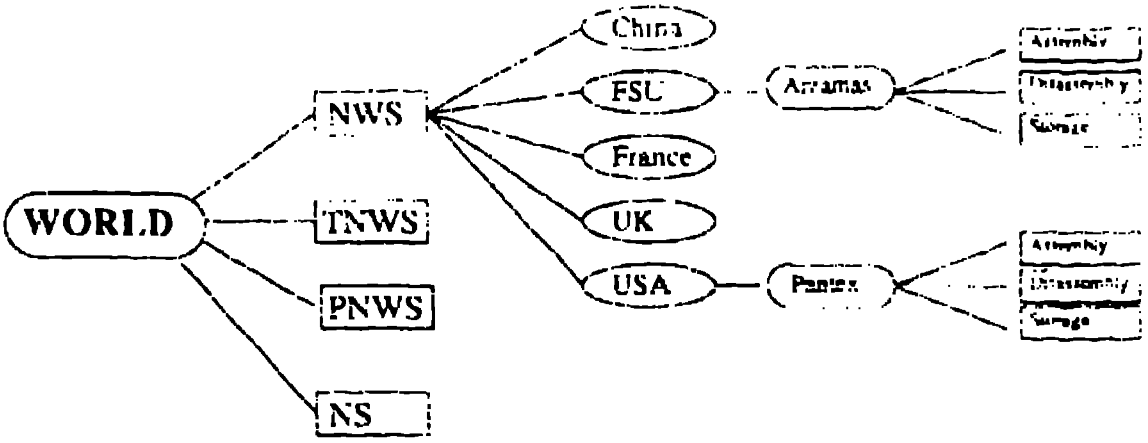

Figure 1. Global Nuclear Material Control Model Structural Hierarchy

The last component of the GNMC model 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 2 depicts some of the nuclear sites included in the model. Examples of some of the data are 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 used a number of publications including the recently released Department of Energy report on plutonium[10] and are investigating the availability and accuracy of existing databases. The GNMC model uses 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 GNMC model provides the capability to estimate future material production and adjust the inventory data accordingly.

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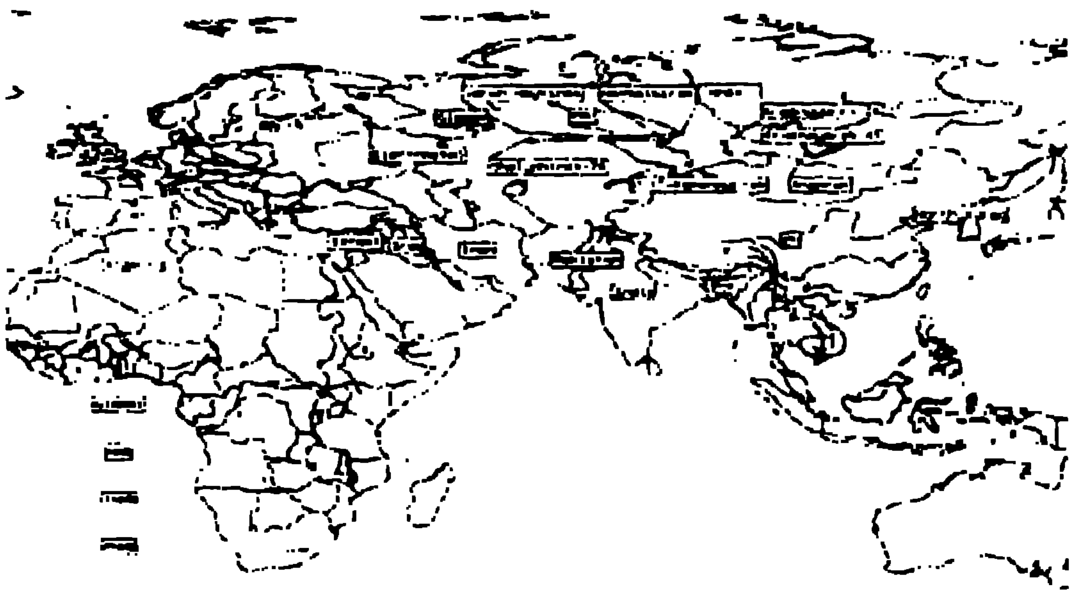
[10] U.S. Department of Energy. *Plutonium: The First 50 Years. United States plutonium production, acquisition, and utilization from 1944 to 1994*, February 1996



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the initial fuel enrichment, reactor type, core weight, burnup, power, and decay time. BURN computes the resulting weight (kg), radiation (cur), and weight fraction for the uranium, plutonium, and other isotopes. The advantages of the BURN code are that the output provides an accurate computation of the isotopic content of the spent fuel, is relatively computationally responsive, and is applicable for a large number of different reactor types. The apparent disadvantage is the need to provide the initial fuel enrichment, which is not generally known for military reactors and may be proprietary information for power reactors. However, if the actual fuel enrichment is not known, based on the type of reactor and whether it is being operated for the maximum production of fissile material or power, the optimal initial fuel enrichment is assumed. Assuming that the optimal fuel enrichment is used eliminates the potential disadvantage due to the lack of information and enables the most accurate results.

The third method is used to estimate the possible fissile material production in thermal research reactors. Information regarding the operation and fuel enrichment of research reactors is particularly sparse, necessitating an approach that places a bound on the quantity of fissile material that can be produced, $Pu_{maxprod}$. This approach is based on a study published on the unreported plutonium production at six research reactors that confirmed the "Binford line." The "Binford line" is based on the "estimate that a minimum reactor power of 40 MW(th) is required to make 8 kg of fissile plutonium per year by unreported irradiations with a load factor (LF) of .85."[13] An upper bound on the maximum possible amount of plutonium that can be produced based on the reported power level of a research reactor results by assuming a .90 load factor for the Binford estimate. The GNMC model employs the following modified parameterized expression, permitting the load factor to be specified to allow for a variety of computations depending on the availability of utilization data:

$$Pu_{maxprod}[\mathrm{kg/yr}] = .249\frac{\mathrm{kg}}{\mathrm{MW(th)\,yr}} \times LF \times OperPwrLevel\,[\mathrm{MW(th)}]\,.$$

4.0 Summary

The prototype GNMC model establishes the framework and an analytical model for evaluating and assessing the global production, distribution, disposition, movement, and safeguards and security resource requirements for fissile nuclear material. Additionally a visualization tool for representing specific geographic and other relevant information concerning specific nuclear facilities/sites has been developed. The model supports conceptual research and addresses a number of issues and capabilities that are of interest to the US and an international fissile material disposition program:

1) a characterization of the global inventory of fissile nuclear material globally by state designation, country, and where information exists, down to the site and facility level,
2) analytical methodologies that represent the physical processes in the nuclear fuel cycle and the dismantlement of nuclear weapons, enabling an estimation of future nuclear materiel production capability or the quantity of material resulting from various dismantlement schedules;
3) analytical methodologies that represent the physical processes associated with a number of disposition options;

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13. Moriarty, T. F. and Bragin, V. N., "Unreported Plutonium Production At Large Research Reactors," 35th annual Proceedings of the INMM, July 17 - 20 1994, Naples, Florida. p. 1173 - 1178

4) analytical methodologies to approximate the resource requirements for international nuclear material inspection and protection;

5) the capability to visually represent contextual information related to nuclear materials (e.g., quantity, location, and form), nuclear material movement, and geographic characteristics surrounding facilities, and

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