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Nuclear Futures Analysis and Scenario Building

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Abstract

This LDRD project created and used advanced analysis capabilities to postulate scenarios and identify issues, externalities, and technologies associated with future "things nuclear". "Things nuclear" include areas pertaining to nuclear weapons, nuclear materials, and nuclear energy, examined in the context of future domestic and international environments. Analysis tools development included adaptation and expansion of energy, environmental, and economics (E3) models to incorporate a robust description of the nuclear fuel cycle (both current and future technology pathways), creation of a beginning proliferation risk model (coupled to the (E3) model), and extension of traditional first strike stability models to conditions expected to exist in the future (smaller force sizes, multipolar engagement environments, inclusion of actual and latent nuclear weapons (capability)). Accomplishments include scenario development for regional and global nuclear energy, the creation of a beginning nuclear architecture designed to improve the proliferation resistance and environmental performance of the nuclear fuel cycle, and numerous results for future nuclear weapons scenarios.

Background and Research Objectives

At the beginning of the project no real capabilities existed at Los Alamos or any other major research institution that would:

- 1) provide a full description of present day and advanced nuclear fuel cycles in the context of larger demand-driven, supply-side Energy, Environment, and Economics (E3) models that project total energy environments on both regional and global scales over decade timeframes;
- 2) track form, inventories, and isotopics of nuclear materials created or used within the commercial nuclear fuel cycle on both regional and global scales;

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- 3) couple nuclear energy demand and nuclear materials models to create a systematic, beginning framework for determination and assessment of relative proliferation risks as a function of locale and time;
- 4) allow analysis of future nuclear weapons scenarios and stockpile issues under conditions postulated for the future – reduced stockpile sizes, extension of “deterrence” from two major players (the United States and the former Soviet Union) to other nuclear weapons states, and to create an model framework to assess complex relationships between “weapons in being” and those derivable from national, latent capabilities.

This LDRD effort had as its research objectives the creation and use of tools to postulate and examine scenarios associated with "nuclear futures" through

- a) analysis of potential regional and global energy needs;
- b) forecasting of the role that nuclear power might play in such scenarios;
- c) determining the dynamics of nuclear materials occurring during the next fifty or more years;
- d) assessing the impact that present and new technologies might have on such inventories;
- e) determining "metrics" to quantify proliferation risks from nuclear materials in the civilian fuel cycle; and
- f) extending stability relationships for nuclear weapons from bipolar to multipolar security environments including connectivity to energy and latency analysis areas

Importance to Los Alamos Science and Technology Base and National R&D Needs

This LDRD project produced analysis tools, methodologies, and expertise that aided in creating

- a better understanding of the context and rationale for pursuit of a broad spectrum of nuclear science and technology at the Laboratory;
- beginning frameworks for more quantitative understanding of factors impacting, or leading to, proliferation risk enhancement in commercial nuclear energy systems; and

- an identification and understanding of complex linkages existing among elements of the nuclear enterprise.

The development and use of the capabilities created from the project allow assessment of the roles, and provide justifications for, the development of new and innovative technologies, such as fuels technology development for plutonium management, advanced nuclear materials processing, accelerator-driven systems, materials protection control and accountability (MPC&A) technologies, *etc.*

The work directly supports three major competency areas -- Analysis and Assessment, Nuclear and Advanced Materials, and Nuclear Weapons Science and Technology as well as major program activities in each of the Laboratory directorates.

This project also provides analytical capabilities relevant to several major areas within the Department of Energy. These include the Office of Nuclear Energy, Science, and Technology, the Nuclear Cities Initiative, and parts of the Office of Nonproliferation and National Security. An example of impact on program directions of these DOE offices occurs in the area of proliferation-resistant nuclear systems. The objective to create such systems is a major theme in the Office of Nuclear Energy's Nuclear Energy Research Initiative (NERI). However no consistent basis exists to better define, or more importantly, to evaluate performance of such systems. The analysis model developed under this project provides a beginning basis to create such a capability and tool. (A follow-on LDRD effort is now focusing on development of a consistent methodology to assess nuclear fuel cycle performance in terms of proliferation resistance, environmental attributes, and economics).

Results from analysis using the capabilities developed under this LDRD were presented to the President's Committee of Advisors on Science and Technology (PCAST) and used as background information in the preparation of their 1997 report, "Federal Energy Research and Development Challenges for the Challenges of the Twenty-First Century". Other areas -- 1996 DoD Experts Summer Study on Nuclear Weapons Deterrence and the International Atomic Energy Agency's consultancy project on International Nuclear Energy Futures. -- were impacted by information produced via analysis supported by this Project.

Scientific Approach and Accomplishments

The scientific approach of the project was the creation of advanced modeling capabilities to address the four deficiency areas identified under "Background and Research Objectives". The approach also utilized unique Laboratory expertise in areas of nuclear systems and technology to both develop them and to apply them realistically. The three major areas are discussed below. Afterwards selected accomplishments are highlighted. Documents appearing in the Publications section provide a complete description of approaches, models, and results.

1) Energy Systems and Nuclear Fuel Cycle Modeling

The model framework chosen is the Edmonds, Reilley, and Barnes E³ model described in Los Alamos report LA-UR-96-1931, "Global Energy Modeling in Support of Understanding Long-Term Nuclear Futures", R. A. Krakowski. This model treats the following features in 13 global regions – energy disaggregation into six primary fuel types, four secondary fuel types, three energy services all considered at times out to the year 2100. The model also includes elasticities related to price adjustments and energy demand growth patterns, description of technology improvement and introduction times, and regionally resolved energy prices and tariffs. The nuclear fuel cycle model describes a sequence of processes associated with regional and/or nuclear power implementation (for example mining, milling, conversion of uranium; enrichment and fuel fabrication; reactors, spent fuel cooling and storage; advanced nuclear systems for material management and/or material breeding, and repository disposal.). Forms and inventories of nuclear materials are tracked at all portions of the fuel cycle model which serve as one part of the proliferation risk model described in the next section.

2) Proliferation Risk Modeling

A complete description of the approach used and the model framework that was developed is found in the Los Alamos Report, LA-UR-96-96-3620 (Rev. March 25, 1999), "A Multi-Attribute Utility Approach to Generating Proliferation-Risk Metrics," by R. A. Krakowski. It centered around creation of systems framework to focus on evaluation of the proliferation/breakout decision from both technology

and incentives/disincentives perspectives. In the model this decision is determined by a composite of the following inputs:

- a) Incentives to build, possess, integrate, maintain, and threaten to use nuclear weapons;
- b) Disincentives to proliferation (sanctions, overt actions, etc.)
- c) Technical Means needed to build nuclear weapons; and
- d) Material Availability and access to nuclear material needed to build nuclear weapons.

Since commercial nuclear fuel-cycle related proliferation risks depend sensitively on the form and function of nuclear materials flows, which in turn are strong functions of the specific characteristics of the fuel cycle [*e.g.*, once-through, uranium- recycle, uranium/plutonium-recycle, tightly coupled plutonium (Liquid Metal Reactor), *etc.*] a rather complete description of possible material diversion points was incorporated in the model as illustrated in Figure 1. (Note that materials diversion *per se* represents but one component in the complex framework required for assessing the likelihood of nuclear proliferation/breakout. The framework of the model also allows other factors to be described and impacts assessed.) This model is based on multi-attribute utility (MAU) theory as applied to decision making under conditions of uncertainty. Specifically diversion of material from a point in the nuclear fuel cycle can be translated into a "value" or a risk to the proliferator. This worth is measured in terms of a value function, $v(x_1, x_2, \dots, x_j)$, if the choice among the i options can be made with certainty, where x_j represents a series of criteria or attributes against which the merit of choosing point i is measured. When the value of a given choice, as measured by a given (expected) outcome, is characterized by uncertainty, the "worth" of diverting material from point i in the fuel cycle must be measured probabilistically in terms of a utility function, $u_i(x_1, x_2, \dots, x_j)$. The direction taken by the proliferator's decision process is modeled in terms of MAU functions, which measure the multiple consequences or attributes of specific decisions made under conditions of uncertainty

Figure 1. Simplified fuel cycle illustrating potential points of clandestine nuclear-materials diversion addressed in the proliferation model developed under this LDRD

3) Deterrence Theory Development and Application

This work used advanced deterrence and game theory techniques to examine stability issues and scenarios associated with nuclear weapons environments of the future. The research approach investigated the use of game theory techniques to (1) model situations in which there is asymmetric information; (2) determine what it means for a threat or promise to be credible; and (3) explore important, but difficult to measure, psychological factors in deterrence, such as the threshold of "unacceptable damage" and the perceived state of crisis. The approach, based significantly on new information gleaned from Russian perspectives on deterrence theory and stability, examined deterrence from the index of costs to the first striker rather than overall stability. Additionally, in contrast to past efforts, this work also investigated two simultaneous, but very different optimizations. The first is associated with the allocation of weapons to targets at any given time; the second is associated with the creation of future weapons (known as nuclear latency or the ability of a nation to call up inactive or reserve weapons or to build them).

4. Accomplishments

The models developed were used to develop scenarios for nuclear energy and nuclear materials futures. An example of nuclear energy demand results appears in Figure 2.

Figure 2: Nuclear energy scenarios and trends as determined using the model described above. The right portion of the figure indicates ranges of total global nuclear energy demand under differing assumptions concerning population growth, energy efficiency, productivity etc. The left portion of the figure breaks out the reference demand case into components associated with demand in developed countries (OECD), the former Soviet Union countries (FSU) and industrializing countries (IND).

Similar information was produced for nuclear material inventory growth under these nuclear energy demand scenarios. The model framework also allowed development of novel fuel cycle systems and assessment of their performance on inventory growth of nuclear materials such as plutonium in spent nuclear fuel. Results from such analyses were used as a partial basis for the nuclear fuel cycle architecture proposed in the 1999 Issues in Science and Technology paper, "Plutonium, Nuclear Power, and Nuclear Power" by R. L. Wagner, E. D. Arthur, and P. T. Cunningham. An example of impacts on global plutonium inventories is shown in Figure 3.

Figure 3: Comparison of the impacts of the global nuclear fuel cycle architecture created using results and capabilities from this LDRD project on global plutonium inventories. (Curve 1 indicates plutonium (and spent fuel) inventory growth associated with current practices where most is in temporary, dispersed storage requiring long-term disposal. Curve 2 indicates plutonium amounts in reactors under an extrapolation of current approaches. Curves 3,4 and 5 respectively indicate total plutonium, plutonium in high-radiation environments, and plutonium in secure storage under the proposed architecture.)

The third major accomplishment area tested conditions that stabilize (and others that destabilize) deterrence metrics associated with nuclear weapons stockpile sizes, particularly as such stockpiles are driven towards lower numbers. Analysis results showed that reintroduction of multiple warhead launchers had a significant near-term destabilizing impact. Time dependence was introduced into the stability model and initial testing began of stability indices impacts and sensitivity. This work set the stage for explicit incorporation of latency effects, especially in the area of capabilities for nuclear weapons materials creation.

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