Advanced Safeguards Technology Roadmap for the Global Nuclear Energy Partnership

M.C. Miller[1], L.E. Smith[2], S. Tobin[1], M. Ehinger[3], A. Dougan[4], B. Cipiti[5], A. Bakel[6], R. Bean[7]

[1]Los Alamos National Laboratory, P.O. Box 1663, MS E540, Los Alamos, NM 87545, mmiller@lanl.gov
[2]Pacific Northwest National Laboratory, [3]Oak Ridge National Laboratory, [4]Lawrence Livermore National Laboratory, [5]Sandia National Laboratory, [6]Argonne National Laboratory, [7]Idaho National Laboratory

***Abstract** – Strengthening the nonproliferation regime, including advanced safeguards, is a cornerstone of the Global Nuclear Energy Partnership (GNEP). To meet these challenges, the Safeguards Campaign was formed, whose mission is to provide research and technology development for the foundation of next generation safeguards systems for implementation in U.S. GNEP facilities. The Safeguards Campaign works closely with NNSA's Nuclear Nonproliferation and International Security department (NA-24) to ensure that technology developed for domestic safeguards applications are optimum with respect to international safeguards use. A major milestone of the program this year has been the development of the advanced safeguards technology roadmap. This paper will broadly describe the roadmap, which provides a path to next generation safeguards systems including advanced instrumentation; process monitoring; data integration, protection, and analysis; and system level evaluation and knowledge extraction for real time applications.*

INTRODUCTION

The Global Nuclear Energy Partnership (GNEP) was announced by the President of the United States In February 2006 as part of the Advanced Energy Initiative. GNEP proposes an advanced fuel cycle concept that addresses increasing energy demand, minimizes volume, heat load and radiotoxicity resulting from spent nuclear fuel, and employs both intrinsic and extrinsic measures to address proliferation issues [1]. GNEP is a voluntary international partnership where member states (numbering 21 nations as of February 2008 [2]) agree to the objectives of a) sustainable nuclear power expansion in a way that promotes safe operations and management of wastes; b) development, with the International Atomic Energy Agency (IAEA), of enhanced nuclear safeguards; c) establishment of international supply frameworks to enhance reliable, cost-effective fuel services - thereby creating a viable alternative to acquisition of sensitive fuel cycle technologies (such as enrichment and reprocessing); d) development, demonstration, and deployment of advanced fast reactors that consume transuranic elements from recycled spent fuel; e) promote advanced, grid appropriate reactors; f) development and demonstration of advanced technologies for recycling spent nuclear fuel; and g) taking advantage of the best available fuel cycle approaches [3].

The nonproliferation vision of the GNEP program provides for a strengthened nonproliferation regime as an integral part of the global expansion of nuclear energy by a) discouraging of the spread of enrichment and reprocessing technologies via reliable fuel services, b) reducing the stocks of separated civil plutonium, c) incorporation of safeguards and nonproliferation goals into the design of fuel cycle facilities, and d) development of advanced technologies to support enhanced safeguards and nonproliferation. There is no individual technological solution that will ensure the peaceful use of nuclear power, rather the system and governance framework of nonproliferation and international security must be implemented in an integrated fashion. The challenges faced by the GNEP program also represent an opportunity to enhance the safeguardability of the future nuclear fuel cycle and thereby increase confidence and assurance that such facilities are used only for peaceful purposes [4-6].

A significant research and technology development effort will be required to provide the foundation for achieving the GNEP vision, and as a result the GNEP safeguards campaign has been established to focus on both near term demonstration of advanced technologies as well as foundational research for the longer term to enable significant advancement. The GNEP safeguards campaign benefits from strong cooperation between the Department of Energy's (DOE) Office of Nuclear Energy (NE) and the National Nuclear Security Administration's

(NNSA) Office of Nonproliferation and International Security (NA-24). Technologies developed by the campaign will specifically address domestic safeguards requirements for U.S. GNEP facilities as well as provide the technological basis for enhanced international safeguards.

DOMESTIC SAFEGUARDS CAMPAIGN

The research and development (R&D) component of the GNEP program resides in the Advanced Fuel Cycle Initiative (AFCI) R&D program, which is organized in thrust areas called campaigns. Campaigns are integral experimental and simulation efforts focused on developing key capabilities required for implementation of GNEP. In addition to campaigns, the R&D program includes cross cutting efforts in modeling & simulation as well as safety & regulatory. A technical integration office (TIO) coordinates and integrates the R&D efforts of the campaigns and cross cuts. Informal working groups exist for physics (nuclear data) and materials to help the program identify and prioritize data needs. Figure 1 shows the GNEP campaign structure and cross cutting areas, and their relation to the TIO. Major technology thrust areas of the program are transmutation fuels, advanced separations technologies, systems analysis, domestic safeguards, durable waste forms, and both fast reactors and grid appropriate reactors [7].

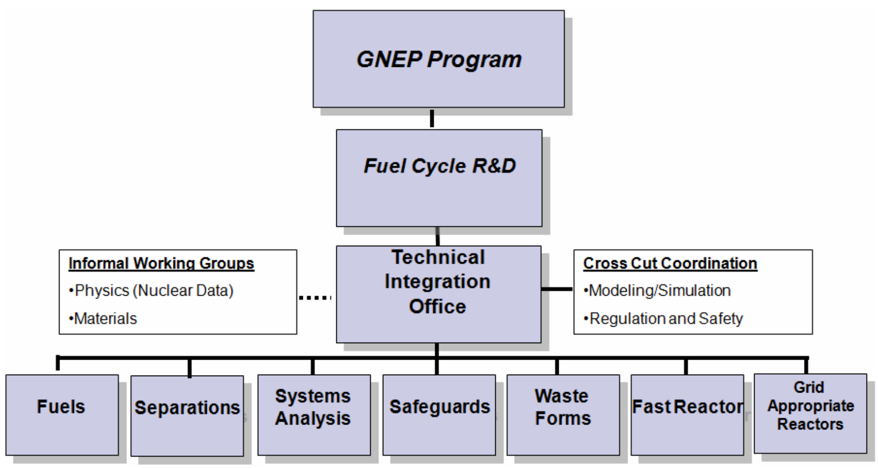

Fig. 1 GNEP R&D management structure showing technical integration office, campaign, and cross cutting areas.

The GNEP safeguards campaign has three core responsibilities: 1) support the GNEP enabling technology facilities with domestic safeguards expertise (Consolidated Fuel Treatment Facility-CFTC, Advanced Recycle Reactor-ARR, Advanced Fuel Cycle Facility-AFCF), 2) provide research and technology development in support of meeting safeguards requirements and to support advanced safeguards, and 3) interface with other campaigns and cross cutting areas. In addition, the campaign provides expertise in the area of domestic regulatory requirements and implementation, and can provide input into the technical review of regulations by both DOE and the NRC. International safeguards are the responsibility of NNSA's Office of Nonproliferation and International Security, with whom the campaign coordinates closely. Figure 2 presents the safeguards campaign structure and relation to the GNEP projects, regulators, and the international safeguards community.

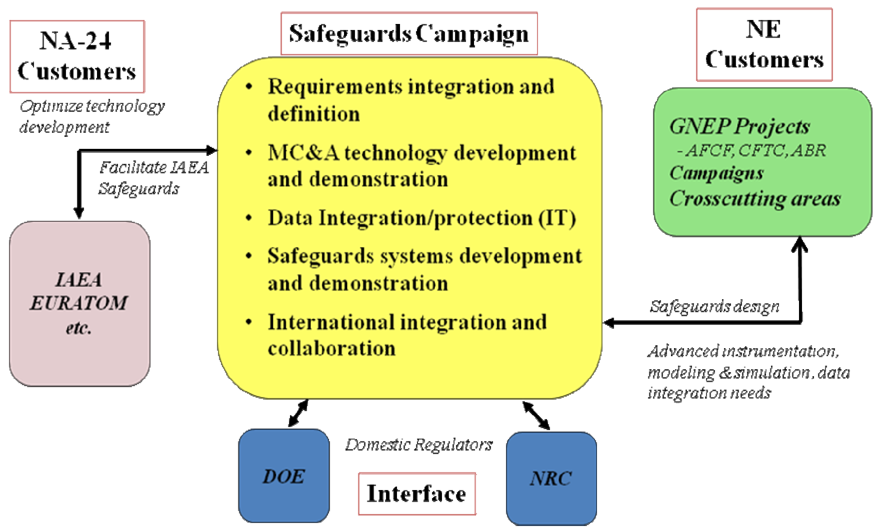

Fig. 2 GNEP safeguards campaign structure.

GNEP SAFEGUARDS TECHNOLOGY ROADMAP

One of the initial tasks of the safeguards campaign was to perform a safeguards enhancement study, to aid in the development of a roadmap approach and identify candidate technologies for both near term advancement of the current state-of-the-art and provide the foundational R&D required for revolutionary advancements [8]. The approach adopted is summarized schematically in Fig. 3, along with an example of how that process is traversed. A recognized need and corresponding requirements provide the starting point. In the example, the need is the direct measurement of Pu in spent fuel (as opposed to today's confirmatory methods that rely on operator-declared information and computations) while the preliminary requirement is quantification of Pu with an uncertainty lower than is achievable with today's indirect methods—approximately 5% on Pu mass. It should be noted that in many cases, the roadmapping need is qualitatively clear, but assigning it quantitative requirements is difficult because, for example, GNEP facility designs are still in development and systems analysis tools that illuminate how instruments and methods interact in a safeguards approach are being developed in parallel [9,10].

Once needs and preliminary requirements were identified, the team solicited input from technologists at seven DOE national laboratories and several universities to create a list of candidate technologies that may offer a solution to that need—some near-term and some much more exploratory. In this spent fuel assay example, two of the candidate technologies were neutron multiplicity combined with neutron albedo, and the lead slowing-down-spectroscopy technique. As a team, the defining potential for each technology, as compared to competing technologies and/or a baseline technology from today, was identified. In order to give an objective picture for each method, key research questions that need to be addressed (in order to assess viability and compare to today's baseline) were also included.

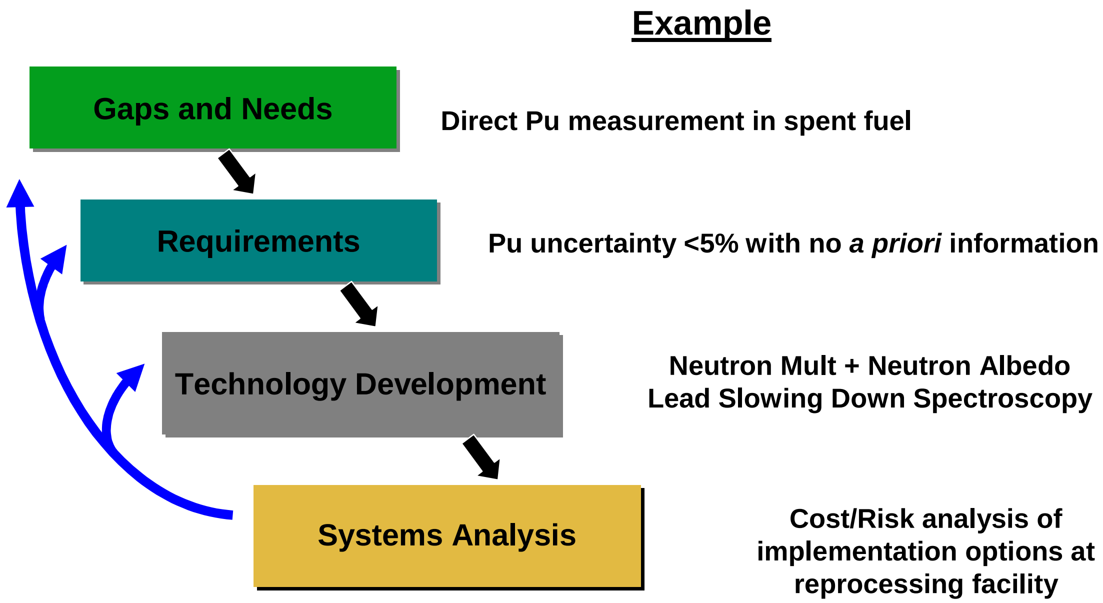

Fig. 3. Overview of technology roadmapping approach, and an example of the path through that process.

The roadmap developed for GNEP safeguards is a living document that will require updating as new information becomes available. For example, the requirements called out in this document are preliminary and should be considered nominal starting values to be refined as technologies mature, and tools for assessing how those technologies interact (e.g. Safeguards by Design) come to fruition. The feedback loops that make the roadmap a living document (i.e. between Technology Development, Systems Analysis, Needs and Requirements) are also shown in Fig. 3. Results from recent bench scale experiments and simulations recently completed by the campaign will be incorporated into the roadmap [11].

Gaps and Needs

The roadmap is founded on recognized gaps and needs in the domestic and international safeguards community. As such, these relatively new GNEP strategy activities will draw heavily on previous studies and experience. For example, the gaps and needs for GNEP safeguards will often be the same, or at least consistent with, those from recent NA-24 strategy documents [12].

The safeguards campaign has organized itself around three major themes: 1) Advanced Instrumentation, 2) Advanced Control and Integration, and 3) Safeguards by Design. The list of needs in Tables 1-3 adopts this vernacular.

TABLE 1. Needs and Preliminary Requirements for Advanced Instrumentation.

Advanced Instrumentation	
Need	**Requirement**
Direct measurement of Pu in spent fuel	Online measurement, Pu uncertainty <5%, no *a priori* information about fuel
Direct measurement of Pu in actinide-bearing materials	Online measurement, Pu uncertainty <2%, no *a priori* information about materials Example materials: MOX fuel fab feed/outputs
Direct measurement of Pu in reprocessing streams	*Continuous, online* monitoring of Pu meeting IAEA diversion and timeliness goals Protracted: <1 SQ per month or <1% Abrupt: near-real-time analysis and <5%
Quantify Np and Am throughout fuel cycle	*Continuous, online* monitoring of Np, Am meeting IAEA diversion and timeliness goals

Basic data measurements (nuclear, chemical, etc.)	With technology developers, identification of high-priority nuclear data needs and perform measurements
Process monitoring of reprocessing streams	*Continuous online* measurement of parameters (e.g. rad signatures, pH, flow) coupled to statistical process control methods that together, significantly reduce laboratory sample analyses
Rapid laboratory sample analysis	Improve sample analysis precision, reduce sample preparation requirements, and reduce sample analysis reporting time

TABLE 2. Needs and Preliminary Requirements for Advanced Control and Integration.

Advanced Control and Integration	
Need	**Requirement**
Data collection, integration, semi-automated evaluation	Provide inspectors with toolbox that allows near-real-time visualization, analysis and reporting
Integration of data validation and authentication methods	Develop implementation guidelines that support new generation of remote, online facility monitoring technologies

TABLE 3. Needs and Preliminary Requirements for Safeguards by Design.

Safeguards by Design	
Need	**Requirement**
High-fidelity integrated safeguards modeling	Safeguards by Design methodology that: • Integrates PR&PP functionality and metrics • Provides discrete-event and dynamic facility simulation • Utilizes independently peer-reviewed risk/cost metrics • Includes benchmarking, blind testing using existing data
Advanced containment and surveillance techniques	Tag/seal technologies for near-real-time tracking of feed/product containers in fuel cycle <1 minute to uniquely identify fuel assembly in pool or air
Advanced design information verification methods	Technology suite that makes DIV integral from construction through decommissioning
Physics-based continuity of knowledge for spent fuel	Use characteristic emissions (e.g. neutron) to track each assembly from reactor to reprocessing or repository

Candidate Technologies

The tabular summary of candidate technologies spans the continuum of technical maturity from highly exploratory concepts to incremental improvements or adaptations of the tried-and-true. Both are important to a long-range R&D plan for nuclear fuel cycle safeguards; the former represents the building blocks that enable the creation of new and improved methods on longer time scales, while the latter can support near-term enhancements at fuel cycle facilities. The defining potential for each technology is important to articulate because there is no single technological solution—each has particular strengths and may bring a different facet to meeting each need/requirements. Realization of a new generation of safeguards will required an integrated approach. An objective discussion about these promising technologies, however, must also include unanswered R&D questions that must be resolved in order to assess technology viability. The tables below provide this information for each candidate technology, and the corresponding need is identified as a heading. Note that some technologies may be suitable for multiple needs and as such the tables are abbreviated.

TABLE 4. Candidate Technologies for Advanced Instrumentation.

Advanced Instrumentation		
Technology	**Potential**	**Research Questions**
Need: Direct Pu measurement in spent fuel, actinide-bearing material		
Passive Neutron Albedo Reactivity	Total fissile mass	• Coupling to other methods for direct total Pu? • Depth of interrogation, partial defect sensitivity? • Calibration techniques and systematic uncertainties?
Lead Slowing Down Spectroscopy	^{235}U, ^{239}Pu, ^{241}Pu through depth of assembly	• Degradation by Cm bkg and n-absorbing isotopes? • Effect of H build-up in clad? • Sensitivity to partial defects?
Ultra-High-Res x-ray	U, Pu mass in outer layer of assembly	• Sufficient Pu signal? • Coupling to other methods for inner parts of assembly? • HPGe sufficient, or is microcalorimetry needed?
Advanced Neutron Multiplicity	Total fissile mass	• Coupling to other methods for direct total Pu? • Value of liquid scintillators (e.g. gamma disc)? • Calibration techniques and systematic uncertainties?
Nuclear Resonance Fluorescence	Fissile isotopics through depth of assembly	• Existence and intensity of actinide signatures? • Interrogating photon sources? • Signal-to-noise over fuel emissions?
Photofission	Fissile and fissionable isotopic mass through depth of assembly	• Minimum detectable mass of fissile isotopes? • Efficacy of dual-energy to discriminate isotopes?
Delayed Neutron Detection	Total fissile mass with emphasis on ^{235}U	• Intense interrogating neutron source (~$1x10^{13}$ n/s)? • Coupling to other methods for direct total Pu?
Differential Die-Away	Total fissile mass with emphasis on ^{239}Pu	• Intense interrogating neutron source (~$1x10^{13}$ n/s)? • Coupling to other methods for direct total Pu? • Severity of self-shielding effects?
Need: Direct Pu measurement in reprocessing streams		
Ultra-High-Res x-ray	U, Pu mass	• Sufficient Pu signal? • Penetration depth into stream? • HPGe sufficient, or is microcalorimetry needed?
Nuclear Resonance Fluorescence	Fissile isotopics	• Existence and intensity of actinide signatures? • Interrogating photon sources? • Signal-to-noise over stream emissions?
Electrochemically-Modulated Separations	Elemental Pu, U, actinides, non-rad based	• Pu detection limits in high U concentrations? • Scale up to reprocessing slip-stream?
Photofission	Fissile and fissionable isotopic mass through depth of assembly	• Minimum detectable mass of fissile isotopes? • Efficacy of dual-energy to discriminate isotopes?
Hybrid K-Edge	Elemental Pu, U, actinides	• Detection limits using state of art sensors? • Scale up to reprocessing slip-stream?
Need: Process monitoring of reprocessing streams		
Statistical Process Control	Online process control to dramatically reduce need for lab analysis	• Optimal utilization of rad, physical parameter and alternative signatures to detect off-normal operations? • Dynamic facility modeling to evaluate SPC?
Multi-Isotope Process Monitor	Improvement on Pu/Cm ratio over wide range of plant conditions	• Accurate separations chemistry models? • Gamma spec sensor design and engineering? • Value for off-normal detection in SPC framework?
Physical Properties Monitoring	Improvement on Pu/Cm ratio over wide range of plant conditions	• Most viable and useful signatures? • Coupling to rad, alternative signatures? • Value for off-normal detection in SPC framework?

Automated Hot Chemistry	Reduce laboratory analysis time by automating DA	• Best sample dissolution and preparation methods? • Efficacy of computer-controlled separations?
UV-Visible Spectroscopy	Oxidation states of U, Np and Pu	• Precision in advanced streams? • Sensitivity to off-normal operation?
Alternative Signatures	Fill gaps, complement rad, physical properties	• Viability of nuclear magnetic signatures for online? • Provide value-added to rad, physical parameters?
Need: Rapid laboratory sample analysis		
Rapid Mass Spectrometry	Reduce analysis time from hours to minutes, and reduce sample prep requirements	• Selectivity, realistic processing times, precision? • Instrument engineering for production mode?
Ultra-High Res Alpha Spec	Remove interferences and improve isotopic selectivity	• Sample prep to limit energy straggling? • Instrument engineering for production operations?
Need: Basic data measurements		
Basic Nuclear Data Measurements	Improve precision of NDA measurements that suffer from large data uncertainties	• High-priority data needs? • Modeling capability to extend to discovery?
Basic Chemical Data Measurements	Enable non-radiation based instrumentation (LIBS, UV/VIS, Fluorescence, etc.)	• High-priority data needs? • Modeling capability?

TABLE 5. Candidate Technologies for Advanced Integration and Control.

Advanced Control and Integration		
Technology	**Potential**	**Research Questions**
Need: Data collection, integration, and semi-automated evaluation		
Bayesian network with 2^{nd} order uncertainty (or equivalent)	Full integration of all available data, knowledge extraction	• How to determine (discover) correlations within disparate data sets? • Near-real time decision making approaches? • How to optimize anomaly detection? • Methods of archiving and 'play back'?
Need: Integrated data validation and authentication		
Data authentication guidelines for classes of instruments and processes	Improve continuity of knowledge, support remote facility monitoring	• Can DOE-DoD Task Force be leveraged? • Recommendations for authentication integration at instrument design stages? • How best to enable remote/off-site facility monitoring?

TABLE 6. Candidate Technologies for Safeguards by Design

Safeguards by Design		
Technology	**Potential**	**Research Questions**
Need: High-fidelity integrated safeguards modeling		
Dynamic facility modeling coupled to rigorous cost/risk analysis	Quantitative evaluation of safeguards options, from both PR and PP perspectives?	• What is correct cost/risk approach and metric? • What coupling is needed to GNEP Systems Analysis? • How to validate tools using existing facility data? • How to find, use blind-testing data sets? • How to define technology performance targets?

Need: Advanced containment and surveillance		
Active and Passive RFID tags	Improved continuity of knowledge reduces need for NDA and DA	• Active tags for complex, highly metallic environs? • Can lifetimes be extended? • How best to integrate data authentication techniques?
Neutron Balance	Continuity of knowledge through back end of cycle	• Optimal measurement locations? • Couple to process monitoring to aid Pu calcs?
Need: Advanced design information verification		
Automated 3-D Feature Recognition	Automate analysis of 3-D laser range-finding data for subtle discrepancies from prescribed design	• Leverage feature recognition tools in other communities? • How to integrate DIV into the construction, commissioning and operating life of facility?
Radiation Imaging	Gamma-ray and neutron imaging are "functional" complement to optical imagery "form".	• Existence and intensity of actinide signatures? • Interrogating photon sources? • Signal-to-noise over fuel emissions?

IMPLEMENTATION

The research and technology development needs of GNEP safeguards fall into three broad categories:

- Advanced Instrumentation – On-line and at-line, near-real time monitoring methods based on radiation and non-radiation signatures operated in active and passive mode and encompassing destructive and nondestructive analysis are needed. Process monitoring should be incorporated in a quantitative manner, and include tracking both hot (Pu and other radioactive species) and cold (non-radioactive) streams. There are nuclear and chemical data needs that support improving advanced instrumentation, evaluation of existing data and developing new data to enable new techniques. Modeling and simulation tools to support sensor design are needed, opportunities exist in new materials by design and in materials evaluation in high radiation environments.

- Advanced Control and Integration – The accuracy and precision required to meet both domestic and IAEA goals using a single measurement technique are somewhere between impossible and impractical with today's technology, and as such modern facility safeguards employ a variety of tailored instruments in optimized configurations along with additional measures such as containment and surveillance, tags and seals, and integrated safeguards. In addition to developing advanced instrumentation, technology also must involve development of an integrated control system that uses all available instruments and other information through an intelligent data analyzer. The development of the advanced control system relies heavily on plant modeling and simulation, basic information management including data security, and it requires an engineering-scale facility for demonstration and optimization.

- Safeguards by Design – Incorporating design features that facilitate safeguards and physical security requirements into the design of new facilities at the earliest possible stage is one of the best opportunities to maximize the efficacy of the safeguards system and minimize the cost and impact to the operator [13]. Models of safeguards performance play a key role to inform decision makers regarding investment of R&D funds as well as to identify advanced approaches. Analysis of the safeguards system needs to occur at adequate levels; including facility, site, region, and global. Implementation of safeguards by design relies on both experimental and theoretical development along with lab-scale and large-scale experimental demonstration.

Modeling and simulation cross cuts all three of the basic thrust areas and plays an important role in sensor and advanced instrumentation development, design of the overall safeguards system for a facility, analysis of components within the safeguards system as well as the nonproliferation regime. Implementation of the advanced control system described will require plant modeling and simulation.

Putting it all together is the concept of the 'safeguards envelope' where data from traditional safeguards, process monitoring, containment and surveillance, personnel movements, etc, is folded together to form a confidence measure that a facility is operating normally. By utilizing all available data, one can envision parameterization in such a way that not only are confidence intervals developed for individual components of the system, but also for aggregates thereby accounting for correlations between disparate data [14]. In addition, experience with such a system could lead to indicators that are more predictive as opposed to reactive in nature, much like observation-based preventative maintenance in non-nuclear industries. Integrated systems models, with adequate levels of fidelity will be an important component of such analysis. The AFCF, which has as one of its missions to provide a test bed for advanced safeguards, will be particularly useful in demonstrating safeguards systems technologies and approaches.

SUMMARY

The GNEP domestic safeguards campaign has completed an initial advanced safeguards technology roadmap, representing an integrated approach across Advanced Instrumentation, Advanced Control and Integration, and Safeguards by Design. The roadmap is a living document and will be updated on a regular basis to reflect status of planned GNEP facilities and program direction, as well as incorporation of results from experiments, simulations, and systems analyses. Refinement of the roadmap will include systematic prioritization.

ACKNOWLEDGEMENTS

The authors would like to acknowledge support from the U.S. Department of Energy, Office of Nuclear Energy and the National Nuclear Security Administration, Office of Nonproliferation and International Security.

REFERENCES

1. US Department of Energy - Global Nuclear Energy Partnership, web site www.gnep.energy.gov.
2. Global Nuclear Energy Partnership international web site http://gneppartnership.org.
3. US Department of Energy, "Global Nuclear Energy Partnership Statement of Principles," web site www.gnep.energy.gov/pdfs/GNEP_SOP.pdf (September 2007).
4. M.M. Pickrell and K. Budlong-Sylvester, "Safeguards Alternatives for a UREX+ Facility," *Los Alamos National Laboratory* report LA-UR-06-1075 (November 2005) and references therein.
5. M.C. Miller, et al. "Safeguards by Design: Research and Technology Development for Domestic GNEP Facilities," *Inst. Nucl. Mater. Manage.* **XXXVI** (2007) and references therein.
6. M.C. Miller, F.J. Goldner, M.W. Goodman, and J.K. Sprinkle, "The Global Nuclear Energy Partnership-Challenges and Opportunities for Nonproliferation and International Security," in *Proc. JAEA-IAEA Workshop on Advanced Safeguards Technology for the Future Nuclear Fuel Cycle*, Tokai-mura, Japan, November 13-16, 2007, LA-UR-08-1671 (to be published 2008).
7. Global Nuclear Energy Partnership Technical Integration Office, "Global Nuclear Energy Partnership Technology Development Plan," *Idaho National Laboratory* report GNEP-TECH-TR-PP-2007-00020 Rev 0 (July 2007).
8. L.E. Smith, et al., "GNEP Safeguards Enhancement Study: FY08 Interim Report," *Pacific Northwest National Laboratory* report PNNL-17431 (March 2008).
9. B.B. Cipiti, et al., "Safeguards Performance Modeling of a UREX+1a Reprocessing Plant," *Sandia National Laboratory* report SAND2007-6586 (October 2007).
10. S. DeMuth, et al., "Advanced Safeguards for the Global Nuclear Energy Partnership (GNEP)," in *Proc. European Nuclear Conference (ENC 2007)*, Brussels, Belgium, September 16-20, 2007, LA-UR-07-5703.
11. P.A. Santi, et al., "Bench Scale Experiments for Advanced Safeguards," *Los Alamos National Laboratory* report (to be published 2008).
12. P.C. Durst, et al., "Advanced Safeguards Approaches for New Reprocessing Facilities," *Pacific Northwest National Laboratory* report PNNL-16674 (June 2007); P.C. Durst, et al. "Advanced Safeguards Approaches for New TRU Fuel Fabrication Facilities," *Pacific Northwest National Laboratory* report PNNL-17151 (November 2007); P.C. Durst, et al., "Advanced Safeguards Approaches for New Fast Reactors," *Pacific Northwest National Laboratory* report PNNL-17168 (December 2007).
13. T.A. Bjornard and R.S. Bean, "Fully Integrating the Design Process," in *Proc. INMM-ANS 8th International Conference on Facility Operations – Safeguards Interface*, Portland, OR, March 30 – April 4, 2008 (to be published 2008).
14. D. Izraelevitz, et al., "On Representing Second-Order Uncertainty in Multi-State Systems via Moments of Mixtures of Dirichlet Distributions," *J. Stat. Comp. Sim.* LA-UR-07-1330 (to be published 2008).