UCRL-CONF-231881

LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

LISSAT Analysis of a Generic Centrifuge Enrichment Plant

H. Lambert, H. A. Elayat, W. J. O#Connell, L. Szytel, M. Dreicer

June 18, 2007

Institute of Nuclear Materials Management 48th INMM Meeting
Tuscon, AZ, United States
July 8, 2007 through July 12, 2007

LISSAT Analysis of a Generic Centrifuge Enrichment Plant

H. Lambert, H. Elayat, W. J. O'Connell, L. Szytel[1], and M. Dreicer
Lawrence Livermore National Laboratory
7000 East Ave., Livermore, CA 94550-9234, USA (925) 422-5195

[1] Currently on assignment with the National Nuclear Security Administration in Washington, DC

ABSTRACT

The U.S. Department of Energy (DOE) is interested in developing tools and methods for use in designing and evaluating safeguards systems for current and future plants in the nuclear power fuel cycle. The DOE is engaging several DOE National Laboratories in efforts applied to safeguards for chemical conversion plants and gaseous centrifuge enrichment plants. As part of the development, Lawrence Livermore National Laboratory has developed an integrated safeguards system analysis tool (LISSAT). This tool provides modeling and analysis of facility and safeguards operations, generation of diversion paths, and evaluation of safeguards system effectiveness. The constituent elements of diversion scenarios, including material extraction and concealment measures, are structured using directed graphs (digraphs) and fault trees. Statistical analysis evaluates the effectiveness of measurement verification plans and randomly timed inspections. Time domain simulations analyze significant scenarios, especially those involving alternate time ordering of events or issues of timeliness. Such simulations can provide additional information to the fault tree analysis and can help identify the range of normal operations and, by extension, identify additional plant operational signatures of diversions. LISSAT analyses can be used to compare the diversion-detection probabilities for individual safeguards technologies and to inform overall strategy implementations for present and future plants. Additionally, LISSAT can be the basis for a rigorous cost-effectiveness analysis of safeguards and design options. This paper will describe the results of a LISSAT analysis of a generic centifuge enrichment plant. The paper will describe the diversion scenarios analyzed and the effectiveness of various safeguards systems alternatives.

1. INTRODUCTION

Lawrence Livermore National Laboratory has developed an integrated safeguards system analysis tool (LISSAT), which is a framework for performing systems analysis of safeguards effectiveness for facilities in all stages of the nuclear fuel cycle. The method has been applied to assess safeguards effectiveness for a conversion facility [1], an enrichment facility [2], and for various types of nuclear reactors [3]. LISSAT has the potential for evaluating safeguards approaches for future proliferation resistant facilities and processes and for evaluating current safeguards tools and methods to assess safeguards strategies beyond current methods.

A particular emphasis of our recent work has been the application of LISSAT to gas-centrifuge plants, where strengthening the effectiveness and cost-effectiveness of safeguards has been a priority for the IAEA. In April 2005, the IAEA hosted a technical meeting in Vienna on April 18-22, 2005 with the aim of further strengthening its inspection and verification approaches applied to uranium enrichment activities. The U.S. Department of Energy (DOE) is interested in developing tools and methods for potential U.S. use in designing and evaluating safeguards systems and for support of IAEA goals [4, 5]. LISSAT is being applied to safeguards problems in the framework of DOE-directed multi-Laboratory projects that bring together expertise in plant design, safeguards, and systems analysis [4, 6].

The key components of LISSAT include directed graph/fault tree analysis, statistical analysis, and time-domain simulation as outlined in Figure 1. The directed graph (digraph) fault tree methodology presents a well-structured systematic approach for generation and analysis of the diversion paths and is more comprehensive and systematic than traditional safeguards analysis methods. The digraph analysis is an effective method to organize and structure the possible diversion activities in a diversion scenario together with the safeguards measures and activities relevant to the diversion scenario.

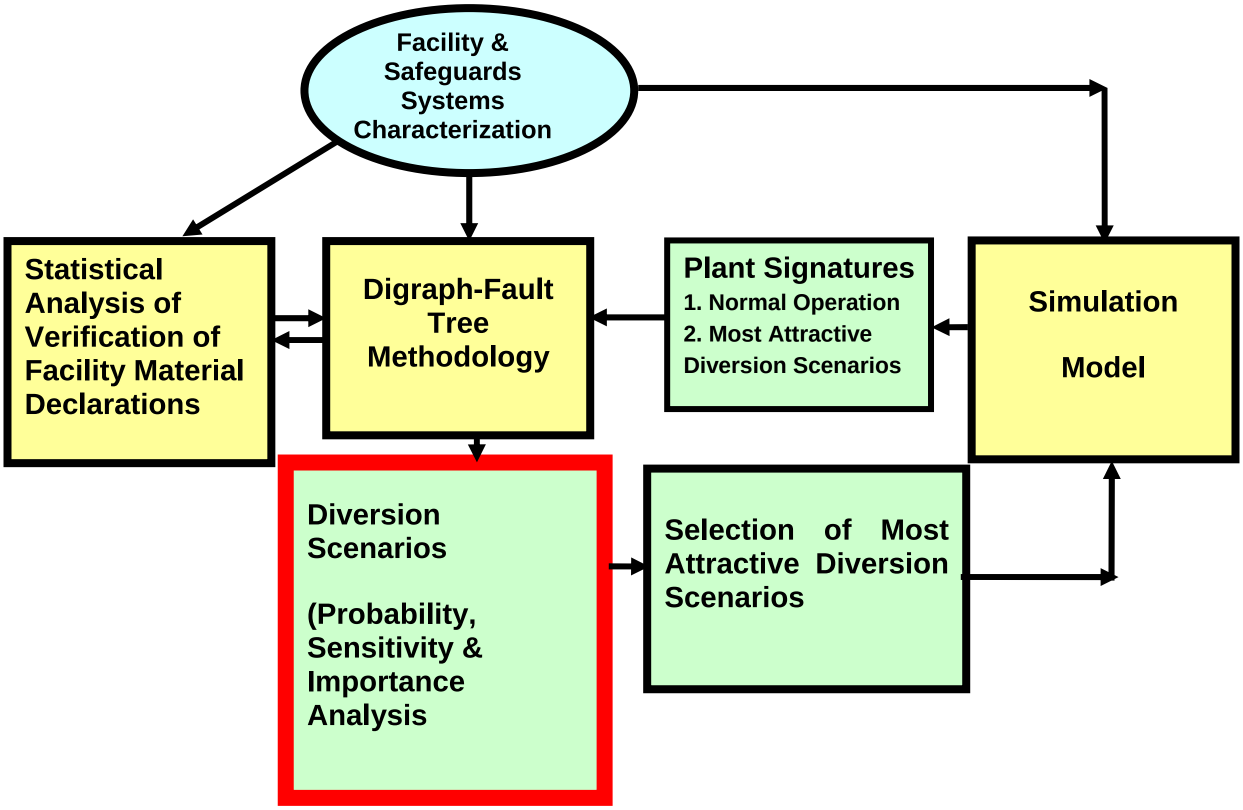

Figure 1. LLNL Integrated Safeguards System Analysis Tool LISSAT for evaluating the the effectiveness of a safeguard system for a nuclear fuel cycle facility

The fault tree analysis incorporates possible failure modes of the safeguards measures and develops a fault tree for the safeguards system taking account of the failure modes. Output of the digraph-fault tree analysis provides an identification of the safeguards elements with the greatest potential for reducing the probability of diversion of nuclear material. Additional outputs include the ranking of the various diversion scenarios in terms of their probability of evading detection.

Statistical analysis, in addition to providing the basic event probabilities for the fault tree, also is used to derive the probability that a given plan of short-notice random inspections will encounter time-clustered physical diversion activities and the probability that a given inspection sampling and measurement plan will detect complex concealment schemes that combine the use of misdeclarations on some material items with deliberate bias in measurements and diversions to the material-unaccounted-for (MUF) balance.

The most attractive diversion scenarios are selected for time-domain simulation. The continuous event simulations track the uranium flow through the enrichment facility. The simulations include normal operation, intermediate storage such as in a feed purification system, normal variations of input flow, and diversion scenarios. Simulation outputs are the time series of material outputs, which illustrate the data signatures of normal operation and diversion schemes. The simulation results for diversions reveal changes both in the accumulated totals of intermediate and final material production and in the time dependence of production. The amplitude of the results shows how much and how soon the monitored signals exceed normal fluctuations.

For diversion paths where the analysis indicates an unacceptably high nondetection probability, the results of the digraph-fault tree analysis and time-domain simulation can suggest further safeguards measures. The fault tree importance analysis can suggest where further redundancy or more reliable instrumentation is required. The results of the simulation help identify the materials that it would be most useful to monitor and identify the optimum placement of monitors. The simulation may also suggest what further indicators the inspector could observe. Digraphs and fault trees are then modified and reanalyzed to determine the reduction in the nondetection probability that could be obtained if these additional measures were implemented. In addition the cost of proposed modifications and their intrusiveness on operations would also be considered.

LISSAT analyses can be used to compare the diversion-detection probabilities for individual safeguards technologies as well as for overall strategy implementations. Additionally, LISSAT could be the basis for a rigorous cost-effectiveness analysis. Finally, the simulations could be used on a facility or process level to aid inspectors in detecting possible material diversions or difficulties with specific instruments in the field.

The following sections illustrate the application of LISSAT to a reference generic plant for centrifuge enrichment, including the evaluation of the benefits of adding specified safeguards enhancements. Plant design specifics and safeguards concerns and options were developed in a multi-Laboratory project [6].

2. GENERIC CENTRIFUGE ENRICHMENT PLANT SAFEGUARDS ANALYSIS

We evaluated current and potential safeguards systems for a generic gaseous centrifuge enrichment plant described by Oak Ridge National Laboratory for use in a training course [7]. This is a medium sized plant with a capacity of 500 MTSWU per year, with 50 cascades of 250 centrrifuges each, producing product at 3.5% enrichment. There are several autoclaves for feeding UF_6 at natural enrichment into the plant, with one in operation at any time. Similarly there are several product and tails withdrawal stations. The simulation models the operations of the storage area, the feed, product, and tails stations, and the weighing and sampling area, as well as transfers between areas. The cascade hall operation is modeled down to the cascade unit.

There are several safeguards concerns regarding GCEPs, including diversion of low-enriched uranium (LEU), excess production of LEU with undeclared feed and product, and reconfiguration of part of the plant to produce HEU [8, 9].

Among the diversion or misuse scenarios analyzed are the following:

1. production and diversion of a significant quantity of highly enriched uranium (HEU) by isolating several cascades and placing them in series [8]
2. diversion by skimming of a significant quantity of declared LEU product [2, 8]
3. production of LEU in excess of declared amounts by using undeclared feed [8, 9]

As an example of the scale for diversion scenario 2, skimming of 2% of the product (equivalent to the product of one cascade) over a year will divert 2300 kg of LEU, containing 80 kg of ^{235}U. This is slightly above the IAEA significant quantity of LEU, which is LEU containing 75 kg of ^{235}U.

Two sets of removal nodes were considered for each scenario --

- Conventional – Feed, Product and Tails Station
- Inside Cascade Hall – Feed and Withdrawal Carts Used

Three safeguards options were considered for each scenario, one representing current practice and two enhancement options that incorporate alternate procedures and equipment, as follows –

1. Current Practice: Conduct 11 fixed Interim Inventory Inspections (IIVs) per year); hold feed, product and tails cylinders for 15 days on average; perform annual Physical Inventory Verification (PIV, 1 to 2 weeks on-site, almost no interruption of throughput flow); and perform 6 Limited-Frequency Unannounced Accesses (LFUAs) inside the cascade hall
2. Option 2: Use "Mailbox" record keeping; conduct 13 Short-Notice Random Inspections (SNRIs) per year (replaces IIVs) [10, 11]; hold product cylinders for 15 days; perform annual PIV; implement video surveillance at feed and withdrawal stations (product and tails) [11]; conduct 6 LFUAs inside the cascade hall; and use Cascade Enrichment Monitor (CEMO) [8]
3. Option 3: Use all Option 2 measures and also use load cells that weigh the input feed and output product and tails [9].

IAEA sampling and measurement plans are used for the input and output verification measurements for MUF under the Fixed Monthly Inspections (FMIs) or SNRI. Observation measures include inspector observations during FMI or SNRIs outside the cascade hall and during LFUA inside the cascade hall. Options examined for continuous monitoring are load cells and video cameras at the feed, product, and withdrawal stations outside the cascade hall, and continuous enrichment monitors (CEMO) on cascade product headers.

The material acccounting verification plan is based on IAEA sampling and measurement plans, and on measurement capabilities taken from Ref. [12]. The observation activities includes inspector activities during inspections and continuous unattended video cameras, load cells, and CEMOs. The video cameras and load cells preclude attaching undeclared cylinders but do not by themselves preclude tampering with declared cylinders after they have been removed from sight of the cameras.

Directed graphs and fault trees structure the plant activities and safeguards measures and their interactions, for each misuse scenario, the feed and withdrawal locations, and the safeguards system options. The evaluated fault trees give the scenario non-detection probabilities. The basic-event probabilities input to the fault trees are only best estimates and are based on classical sampling statistics and generic high-tech industry experience with instrumentation and operations.

The detection probability for each scenario is indicated in Table 1. Each scenario non-detection probability is the product of the material accounting non-detection probability and the inspector verification non-detection probability. Inspector verification refers to all activities other than material accounting the inspector performs that are indicative of diversion such as surveillance. To avoid the appearance of high precision, the probabilities are binned into ranges. The added safeguards measures in Options 2 and 3 improve detection probability for some scenarios, but other scenarios remain only partially covered. Further safeguards measures may be indicated.

The first column in Table 1 lists the scenario, the second column the safeguards option, the third column the feed and withdrawal points, the fourth column the material accounting detection probability, the fifth column computes verification detection probabilities, and the sixth column is the scenario detection probability that combines the material accounting probability and verification activities probability.

<u>Evaluation of current practice (safeguards option 1)</u>

For the skimming scenarios (2A, 2B), IAEA detection goals (detection probability = 50% or higher) are met adequately under safeguards option 1 through the material accounting verification sampling plan. The

HEU production scenario (1A, 1B) is covered by the LFUAs, and for the purposes of this generic-plant assessment, we assume that the scope of the negotiated LFUAs is adequate to meet the IAEA's goal. Option 1 fails, however, to meet the detection goal in the undeclared feed scenarios (3A and 3B), which underscores the need to consider additional measures such as those included in safeguards options 2 and 3. The Hexapartite Safeguards Project (HSP), which recommended measures similar to our safeguards option 1, did not address the undeclared feed scenario [11].

For the HEU production scenario, where safeguards option 1 meets IAEA detection goals, it should be noted that material accountancy alone is not sufficient to meet the IAEA detection goal of $p = 50\%$. Thus, the LFUAs in the cascade hall are important in verifying that HEU production is not occurring.

Evaluation of alternative safeguards options

For safeguards options 2 and 3, the use of video camera and SNRIs significantly increases the detection probability for the undeclared feed scenario provided that withdrawal occurs outside the cascade hall (3C, 3E), because this diversion method requires the use of additional, undeclared feed and product cylinders that can be observed through video surveillance. The use of CEMO in safeguards options 2 and 3 significantly increases the detection probability under all scenarios involving HEU production (scenarios 1C, 1D, 1E, and 1F).

These alternative options are not able, however, to meet IAEA detection goals under undeclared feed scenarios that involve feed and withdrawal locations inside the cascade hall (scenarios 3D and 3F). The only means provided for observing these scenarios is through LFUAs (also used in safeguards option 1) when collection carts are used for feed and withdrawal. Because there are only 6 days of non-compliance, there is insufficient probability that an LFUA will occur while collection carts are in use. (The same limitation to the power of LFUAs applies to skimming scenarios where withdrawal occurs inside the cascade hall, but in these cases, material accountancy is sufficient to offset this limitation.). We do not give any credit for observing piping modifications of these scenarios when LFUAs occur because the modifications are minimal in these cases. **What is needed is an independent measurement or portal surveillance to indicate feed and withdrawal inside the cascade hall.**

Another observed limitation in the evaluated safeguards proposals applies to diversion of product cylinders. Scenarios that particularly apply are 2C and 2E. Under the safeguards options we evaluated, cylinders are visually counted and/or weighed but their identity is not verified. If product cylinders are replaced by bogus cylinders with duplicated serial numbers, the only means to detect this substitution is by the traditional sampling for gross and partial defects or by improved cylinder IDs. For safeguards options 2 and 3, the total number of cylinders processed must equal the number of cylinders declared by the operator, otherwise item anomalies would be generated.

3. PRELIMINARY RECOMMENDATIONS

As the result of our analysis of a generic 500 MTSWU per year facility, preliminary recommendations were made to enhance safeguards at gas-centrifuge enrichment plants. Proposed safeguards options 2 and 3 provide significant improvement in detection probability for certain diversion or misuse scenarios. Further, improved cylinder IDs [8] such as RFID tags [9] should be placed on product cylinders that can not be easily modified or removed from the cylinder. In addition, the operator should apply IAEA seals to product cylinders sent to the product storage area, as is done now in some applications [13]. This measure would detect the operator shipping a bogus cylinder in place of the product cylinder when cylinders are examined at the receiving facility. The generic facility has valves inside the cascade hall that can be used as feed and withdrawal points for any of the three scenarios described above. It would be desirable from a safeguards perspective to design centrifuge enrichment facilities without such valves in

Scenario	Safe-guards Option	Feed and Withdrawal	Detection probability Material Accounting (MA) only	Detection probability Inspector Verification (VER) only	Scenario Detection Probability (MA and VER)
1A – HEU Production	1	normal -- feed and withdrawal	Some	Adequate	Adequate
1B – HEU Production	1	inside cascade hall	Some	Adequate	Adequate
1C – HEU Production	2	normal -- feed and withdrawal	Some	Very high	Very high
1D – HEU Production	2	inside cascade hall	Some	Very high	Very high
1E – HEU Production	3	normal -- feed and withdrawal	Some	Very high	Very high
1F – HEU Production	3	inside cascade hall	Some	Very high	Very high
2A – Skimming	1	normal -- feed and withdrawal	Adequate	None	Adequate
2B – Skimming	1	inside cascade hall	Adequate	Some	Adequate
2C – Skimming	2	normal -- feed and withdrawal	Adequate	Some	Adequate
2D – Skimming	2	inside cascade hall	Adequate	Some	Adequate
2E – Skimming	3	normal -- feed and withdrawal	Adequate	Some	Adequate
2F – Skimming	3	inside cascade hall	Adequate	Some	Adequate
3A – Undeclared Feed	1	normal -- feed and withdrawal	None	None	None
3B – Undeclared Feed	1	inside cascade hall	None	Some	Some
3C – Undeclared Feed	2	normal -- feed and withdrawal	None	Very high	Very high
3D – Undeclared Feed	2	inside cascade hall	None	Some	Some
3E – Undeclared Feed	3	normal -- feed and withdrawal	None	Very high	Very high
3F – Undeclared Feed	3	inside cascade hall	None	Some	Some

Table 1 – Scenario detection probabilities for 18 different cases. The probabilities are only best estimates and are based on classical sampling statistics and generic high-tech industry experience with instrumentation and operations. “Adequate” means the measures meet the IAEA goal, in this case with a detection probability of 50% to 90%. “Some” means less than adequate for the goal. “Very high” means in the range of 99% or higher. The added safeguards measures improve detection probability for some scenarios, but other scenarios remain only partially covered. Further safeguards measures may be indicated.

the cascade hall, placing them instead in an easily monitored common room. This latter approach was used, for example, in the design of the Louisiana Enrichment Services National Enrichment Facility [14]. These recommendations are based on structured logical analysis, statistics, and general high-tech industry experience. **Additional inputs would be needed before taking actual decisions about safeguards approach, including an evaluation of the uncertainty in the probability values, and elicitation of further expert judgment that could be folded into a refined logical analysis.** Future efforts are directed toward determining the safeguards effectivenss of a real time accounting system that would measure feed inputs and product and tails outputs and as a result, reduce the number of inspector days.

4. CONCLUSIONS

LISSAT provides an integrated analysis capability for evaluating proposed and potential future safeguards systems for facilities in the nuclear fuel cycle. The directed graph (digraph)/fault tree analysis provides a systematic approach to structure the moves and countermoves in a diversion/safeguards interaction. This analysis helps quantify the change in probability of detection of a diversion due to the introduction of new safeguards procedures or technology. Significant scenarios can be transferred to time domain simulation, especially those scenarios involving alternate time ordering of events or issues of timeliness. The simulation can provide additional information to the fault tree analysis and can help identify additional plant operational signatures that might assist inspectors as indicators of diversion or misuse. The complete analysis system can provide information on the relative operational and cost effectiveness of proposed safeguards procedures and technology and plant design features. The LISSAT system provided a structured framework for multi-laboratory projects for extending safeguards to uranium chemical purification and conversion plants and to GCEPs. Applications for safeguards at GCEPs and nuclear power reactors are continuing.

REFERENCES

[1] H. A. Elayat, H. E. Lambert, and W. J. O'Connell, "Systems Analysis of Safeguards Effectiveness in a Uranium Conversion Facility," Paper 346, *Proceedings of the 45th Annual Conference of the Institute of Nuclear Materials Management INMM*, July 18-22, 2004, Orlando, FL.

[2] H. A. Elayat, W. J. O'Connell, and B. D. Boyer, "Gas Centrifuge Enrichment Plant Safeguards System Modeling,", *Proceedings of the 47th Annual Conference of the Institute of Nuclear Materials Management INMM*, July 16-20, 2006, Nashville, TN.

[3] A. Bernstein, et. al., Use of Antineutrino Detectors for Nuclear Reactor Safeguards Effectiveness Assessment, Paper 284, *Proceedings of the 47th Annual Conference of the Institute of Nuclear Materials Management INMM*, July 16-20, 2006, Nashville, TN.

[4] B. Boyer, et al, *U.S. DOE Efforts to Enhance Conversion and Enrichment Plant Safeguards*, presented at the 7th International Conference on Facility Operations-Safeguards Interface, February 29-March 4, 2004, Charleston, SC.

[5] B. McGinnis, B. Rollen, M. Whitaker, D. Lockwood, J. Murphy, and B. Moran, "Gas Centrifuge Uranium Enrichment Facilities in The United States – IAEA Safeguards Implementation," Paper 259, *Proceedings of the 46th Annual Conference of the Institute of Nuclear Materials Management INMM*, July 10-14, 2005, Phoenix, AZ.

[6] H. A. Elayat, H. E. Lambert, W. J. O'Connell, Alan Sicherman, M. Whitaker, D. Kovacic, B. D. Boyer, and P. C. Durst, *Systems Analysis of Safeguards Effectiveness in a Generic Gas Centrifuge*

Enrichment Plant, Report UCRL-TR-225931, Lawrence Livermore National Laboratory, December 2006 (document is Official Use Only).

[7] *Training Course, Safeguards for Enrichment Plants*, developed by Oak Ridge National Laboratory for the United States Program for Technical Assistance to IAEA Safeguards, 2003.

[8] E.A. Hakkila and other authors from ten DOE national facilities, *The Safeguards Options Study*, LA-12918-MS, Los Alamos National Laboratory, April 1995.

[9] J. B. Sanborn, B. Moran, and D. Lockwood, "Safeguards at U.S. Centrifuge Enrichment Facilities," Paper 267, *Proceedings of the 47th Annual Conference of the Institute of Nuclear Materials Management INMM*, July 16-20, 2006, Nashville, TN.

[10] D. M. Gordon and J. B. Sanborn, *An Approach to IAEA Material-Balance Verification with Intermittent Inspections at the Portsmouth Gas Centrifuge Enrichment Plant*, Brookhaven National Laboratory, Report BNL-51782, 18 May 1984.

[11] Brian D. Boyer, David M. Gordon, and Jae Jo, "Use of Mailbox Approach, Video Surveillance, and Short Notice Random Inspections to Enhance Detection of Undeclared LEU Production at Gas Centrifuge Enrichment Plants," Paper 423, *Proceedings of the 47th Annual Conference of the Institute of Nuclear Materials Management INMM*, July 16-20, 2006, Nashville, TN.

[12] H. Aigner et al., International Target Values 2000 for Measurement Uncertainties in Safeguarding Nuclear Materials, IAEA Report STR-327, April 2001; also published in JNMM, V. 30 Nr. 2, 2002.

[13] B. D. Boyer, "Enrichment Plant Safeguards: Current Safeguards and Improvements with Remote Monitoring, Mailbox System, and Randomized Inspection Approaches," in 233rd ACS National Meeting, March 2007, and Report LA-UR-07-1806, Los Alamos National Laboratory, March 27, 2007.

[14] *NEF Safety Analysis Report and Integrated Safety Analysis Summary*, Louisiana Enrichment Services, Revision 7, June 2005.

This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract W-7504-Eng-48.