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Mapping and Evaluation of Technologies for Maintaining Chain of Custody during a Nuclear Weapons Monitored Dismantlement

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Abstract

During fiscal year 2015, Savannah River National Laboratory (SRNL) led a team of Arms Control and technology development subject matter experts in a Chain of Custody (CoC) Technology Mapping and Evaluation project. The team was comprised of experts from Lawrence Livermore National Laboratory (LLNL), the National Nuclear Security Administration (NNSA), Oak Ridge National Laboratory (ORNL), Pacific Northwest National Laboratory (PNNL), the Pantex Plant, Sandia National Laboratories (SNL), and Savannah River National Laboratory (SRNL). Experts from the Atomic Weapons Establishment (AWE) of the United Kingdom (UK) also contributed. The primary task of the project was to develop and evaluate chain of custody regimes for monitoring a notional nuclear warhead dismantlement given three technology constraint cases: using only equipment approved for use in the START and New START Treaties; using equipment that is currently fieldable; and using equipment that is expected to be fieldable within the next 5 years. General frameworks for both the dismantlement process and the chain of custody process were developed. Equipment and procedures were integrated into these frameworks to develop a monitoring regime for each constraint case. The project team attempted to optimize the regime for each constraint case given the limited tool kits permitted, and given the need to balance verification requirements with issues of certification, cost, and operational impact. Each regime was assessed against specific criteria. The assessment criteria were developed by the team with input from other experts in different stakeholder communities. Regime strengths, weaknesses and gaps were identified to inform the development of each subsequent regime. The weaknesses and gaps identified are being used to inform decisions by the NNSA's Office of Nuclear Verification (NA-243) on future technology development needs.

Introduction

Chain of custody (CoC) is the process whereby measures are taken to ensure that an accountable item is not substituted or diverted while held under control. CoC methods are used wherever strict control of an item is required to accomplish the mission at hand.

The Chain of Custody (CoC) Technology Mapping and Evaluation Project was undertaken to accomplish two objectives: first, to document current capabilities, weaknesses and gaps for maintaining chain of custody of a nuclear warhead during the dismantlement process as part of a notional warhead monitored dismantlement regime; and second, to develop recommendations for future research and development. Four tasks were defined for the project team to accomplish the project objectives:

1. Review of available CoC technologies.
2. Development of evaluation criteria - develop evaluation criteria to enable a comparative assessment of the technologies surveyed and the monitoring regimes developed by the project.

3. Mapping of technologies - map down-selected technologies into monitoring functions defined by the project team for three different technology constraint cases: (a) a START/New START Treaty constraint case; (b) a currently available technologies constraint case; and (c) a constraint case based on technologies that could be fielded within five years.
4. Final report - complete a final report documenting the overall project observations and lessons learned, and recommendations for the future.

Smaller sub-teams were formed for the review of technologies and criteria development tasks. These tasks were performed to provide tools for the team to use in performance of the technology mapping task. The deliverable for each task was a report documenting the findings of the team. The entire team contributed to technology mapping and the final report. The final report summarized the work performed during each task and identified observations and lessons learned. These are summarized throughout this paper as part of the review of each major project task.

While the project looked specifically at capabilities for maintaining nuclear warhead chain of custody during dismantlement, an assumption was that the technologies and approaches considered, evaluation criteria developed, conclusions drawn, and recommendations made, would have broader applicability for other potential monitoring scenarios. By focusing on a more challenging scenario (monitored dismantlement), it was anticipated that it may be possible to extend solutions and recommendations to monitoring scenarios that may be considered less challenging.

Review of Available Chain of Custody Technologies

The purpose of this task was to develop a list of CoC technologies that were appropriate for use in arms control applications and then to prepare summary assessment sheets for each of these technologies to help inform subsequent project tasks. Each summary provides a general discussion of the technology, a list of strengths and weaknesses, history of use for DOE and Department of Defense (DoD) applications and expected facility considerations for potential deployment at a facility like the Pantex Plant.

The summaries were separated into six basic classes of CoC technologies:

- Tags
- Seals
- Tamper Indicating Enclosures
- NDA equipment
- Surveillance equipment
- Non-destructive evaluation (NDE) equipment

Due to the broad array of technologies available, the team focused primarily on technologies that were specifically designed for use in international safeguards and arms control applications. A list of candidate technologies was prepared drawing from documents detailing development activities undertaken by the Department of Energy (DOE) and IAEA[i,ii]. The technologies identified in these documents were combined into a single list, which was subsequently refined to remove technologies that were narrowly designed for safeguards verification tasks that have

no analog in arms control applications. Some additions were also made based on subject matter expert knowledge and participation in the project.

Observations regarding the process for review of CoC technologies:

- The identification of candidate technologies could have been streamlined and better focused. It may be helpful to first identify the CoC functions, and then to group technologies according to the CoC functions identified as part of the technology mapping task (to be described later in the report).
- Project team member familiarity with different technologies was very useful, but may have biased some of the selections made.
- It would be helpful to document the rationale for not selecting technologies. Documenting the rationale for non-selection would help ensure technologies are not overlooked in the future based on incomplete information or incorrect assumptions, and may help guide further research and development.

Criteria Development

The objective of this task was to develop criteria for evaluating the effectiveness of the chain of custody regimes developed in the Technology Mapping task for confirmation of dismantlement of a nuclear warhead under a hypothetical monitoring scenario. The approach for development of the evaluation criteria was described in detail to facilitate future adaptation of the criteria to evaluation of monitoring capabilities and regimes outside the scope of this specific project. The team began with several potential criteria that were later narrowed to the following six criteria:

- Confidence Provided
- Certifiability
- Authenticatability
- Deployability
- Operational Impact
- Cost

These primary evaluation criteria were further defined by sub-criteria and a series of yes/no evaluator questions linked to the sub-criteria that could be applied by evaluators to draw conclusions regarding individual technology options as well as the strengths and weaknesses of the broader monitoring approaches developed during technology mapping.

In order to determine how to appropriately weigh each of the six evaluation criteria, the Analytic Hierarchy Process (AHP) was used. The AHP is a well-recognized method for structuring the decision making process for complex systems. By using head-to-head (pairwise) comparisons between criteria, the AHP provides a ranking of the relative importance of all of the criteria.

All of the CoC team members ranked the six criteria using the AHP. In addition, the AHP process was applied to input provided by six additional stakeholders.

AHP input from the CoC team members and input from the stakeholders was consolidated and resulted in the weighting (importance) factors shown below.

- Confidence Provided: 30.5%
- Certifiability: 19.8%
- Authenticatability: 15.5%
- Operational Impact: 15.0%
- Deployability: 12.9%
- Cost: 6.3%

These weighting factors were used to assess the overall strength of the CoC regimes developed during Technology Mapping.

Observations regarding the process for criteria development:

- Criteria and sub-criteria should be unique and mutually exclusive. For example, many of the factors that influence the certifiability and authenticatability of specific technologies are the same, although viewed from a different perspective. A consequence of having separate weighting factors for certifiability and authenticatability was that their combined weight (19.8% +15.5% = 35.3%) was greater than the weight of confidence provided (30.5%).
- Except for the confidence provided criterion, the other high-level criteria pertained to an ability to accept, or implement, a monitoring regime. A potential alternative approach could be to re-organize the criteria and their weighting so that confidence accounts for 50 percent or more of any evaluation value, while factors associated with the ability to implement a regime account for the remaining percent.
- Determining the best way to characterize an overall evaluation for each of the monitoring regimes was a challenge.
- For pairwise comparisons, the perspective, experience, and knowledge of evaluators influenced their input.

Technology Mapping

Technology Mapping Objective and Assumptions

The objective of this task was to develop and evaluate chain of custody regimes for monitoring nuclear warhead dismantlement using three technology constraint cases:

- Using only equipment approved for use in the START and New START Treaties
- Using equipment that is currently fieldable
- Using equipment that is expected to be fieldable within the next 5 years.

General frameworks for both the dismantlement process and the chain of custody process were developed. Equipment and procedures were integrated into these frameworks for the three "constraint case" monitoring regimes, beginning first with the START/New START technology constraint case. Each regime was assessed against criteria established under the Criteria Development task, and regime strengths, weaknesses and gaps were identified to inform the development of each subsequent regime.

A number of assumptions were made with respect to the notional regime, including:

1. The basis for the work is a notional Warhead Monitored Dismantlement treaty
2. Treaty monitored dismantlement work will be done during the first shift, 7 days per week

3. All dismantlement work will be conducted at an assembly/disassembly facility like the Pantex Plant
4. A portion of the Plant will be segregated to form a "plant within the plant". This section of the plant will support treaty-related work, including monitored chain of custody and dismantlement confirmation.
5. The item being introduced into the facility is actually a warhead
6. Warheads to be monitored contained plutonium pits
7. The warhead pit and canned subassembly (i.e., secondary) were the only neutron-emitting objects in the warhead
8. All monitoring equipment will be inspector provided, unless otherwise noted
9. The host allowed continuous on-site inspector presence during monitoring activities (though inspectors would not be permitted inside bays or cells while dismantlement operations were being performed)
10. Access to live video would be permitted by the host

The first two assumptions were based on the requirements for the project as established by the sponsor. The remaining assumptions were established based on the deliberations of the team. It should be noted that changing any of these assumptions would affect the decisions made regarding technologies and approaches selected.

Chain of Custody Functions

For the purposes of the warhead monitored dismantlement considered in this project, the chain of custody process was broken down into the following functions:

Initialize Chain of Custody

Throughout the dismantlement process there will be stages when a containerized warhead will be entered (or re-entered) into the chain of custody regime. Initialization is the process by which this occurs. It is expected to occur when a containerized warhead is received at the facility's loading dock, and any time inspectors are presented a new container configuration for the warhead or the warhead is removed and replaced into the same container. Initialization of Chain of Custody may include the following tasks:

- Applying seals
- Establishing a warhead template and confirming agreed upon attributes
- Recording a container identifier and photographing seal orientations

Inspect and Secure Bays and Cells

Prior to entrance of a warhead into a process or staging room, the room will be inspected for potential diversion pathways and security measures must be applied to prevent diversion of the pit. Room preparation may include the following tasks:

- Sweeping for sources
- Sweeping for undeclared diversion pathways
- Securing pathways with seals and surveillance as appropriate

Maintain Chain of Custody

There will be times during monitored dismantlement when the containerized warhead will be in temporary storage in a staging bay. This is most likely to occur between receipt of the warhead

at the loading dock and initiation of dismantlement in a dismantlement bay, but this may occur at other points throughout the dismantlement process as well. In addition, any time a warhead container must enter or exit a room secured with a seal or a warhead container must be opened, chain of custody will be verified. Maintaining chain of custody may include the following tasks:

- Verifying physical security of the sealed rooms
- Verifying the containment of a warhead
- Verifying a warhead template and confirming agreed upon attributes
- Verifying the integrity of an equipment bay or storage container

Monitor for Diversion During Dismantlement Activities

While dismantlement activities are being performed, inspectors will not be allowed to enter the dismantlement bay or cell (generically – the dismantlement room). To prevent diversion, the dismantlement room will be maintained under surveillance. The room will be sealed if dismantlement activities are suspended while a warhead remains in the dismantlement room, in effect turning the dismantlement room into a temporary staging area. Measures for maintaining surveillance may include the following tasks:

- Establishing continuous surveillance of entryways and exits
- Screening items entering or exiting the dismantlement room

Verify Dismantlement

Upon completion of dismantlement operations, the warhead dismantlement will be verified. Specifically, this requires confirming the separation (and segregation into different containers) of the pit and the high explosives. Dismantlement verification tasks may include:

- Verifying the presence of the containerized pit as declared
- Verifying that no high explosives are in the container holding the pit

Confirm No Diversion after Warhead Exits a Room

At any point in the process when a warhead exits a dismantlement room, measures will be taken to confirm a diversion has not occurred. Tasks to be completed will be similar to those described in the Inspect and Secure Bays and Cells function above, and may include:

- Sweeping for sources
- Sweeping for undeclared diversion pathways
- Verifying the integrity of secured pathways

If the room is to be left vacant, all entryways into the room will be sealed to limit the inspection activities required when activities resume.

Selection of Technologies for Maintaining Chain of Custody

The technologies considered for the START/New START constraint case were limited to technologies previously used for or allowed by the START/New START treaties or the currently available analog. For Current Technologies and Future Technologies constraint cases, use of Analytic Hierarchy Process was considered for selection of technologies. However, given the time constraints of the project, the team asked the SME's of the various technology areas to present to the team recommended technology options for the respective constraint cases.

Mapping of Technologies to Chain of Custody Functions

Using the SME recommended technologies, the CoC team applied these technologies to the CoC functions for each of the constraint cases. Table 1 shows the types of technologies selected by the team for the Initialize CoC and Maintain CoC functions. The two functions were combined because there was some overlap between their subfunctions. Tables were also prepared to summarize the mapping of technologies to the other functions. For the actual study, specific technologies were selected for the subfunctions in each regime. However, Table 1 reflects the thought process used by the team for selection of technologies. Note that when proceeding from one regime to the next, a technology was not replaced unless the benefits of using a newer technology were expected to outweigh the potential problems.

Table 1. Comparison of Technologies Utilized to Initialize Chain of Custody/Maintain Chain of Custody

Function	Subfunction	START/New START Regime	Current Technologies Regime	Future Technologies Regime
Initialize/ Maintain Chain of Custody	**Seal and verify warhead container**	Passive loop seal Adhesive Seal Digital Camera Photo printer	Passive loop seal Adhesive Seal Digital Camera Photo printer	Active loop seal Adhesive Seal Improved seal reader technology
			No change. No currently available seals meet the needs better.	Active seal reduces costs & data management burdens while simplifying seal application & verification. Improved adhesive seal reader stores images digitally, reduces costs & complexity while improving accuracy.
	Create and verify NDA template	Gross neutron detector w/ information barrier	Spectroscopic gamma detector w/ built-in information barrier	Spectroscopic gamma detector w/ built-in information barrier
		Information barrier concept is not integral to the detector and has not been proven	Higher fidelity template than START/New START detector	No change. Current Technologies detector meets the needs for this subfunction.
	Maintain CoC of inspection equipment	Passive loop seal Continuous inspector presence/ random inspections during off shifts Adhesive Seal Digital Camera Photo printer	Active loop seal Tamper indicating enclosure (TIE) for equipment, sealed w/ loop seal Secure video camera and image analysis software surveillance of equipment room	Active loop seal Tamper indicating enclosure for equipment, sealed w/ loop seal Improved video camera and image analysis software surveillance of equipment room Improved camera TIE
			Active seal improves efficiency and anomaly resolution. TIE provides mobile equipment storage. Video camera eliminates off-shift continuous inspector presence. Image analysis software improves efficiency of camera image storage & review.	Advances in technology allow for a less expensive and more efficient video surveillance solution

Observations regarding the process for technology mapping:

- The project team made a number of significant assumptions that affected the technologies selected and enabled the development of viable monitoring regimes
- The process of developing monitoring regimes evolved through the course of the project and was iterative, and the project team allowed itself to amend Technology Mapping details as insights were gained
- The AHP process was too time-consuming to use for detailed decision-making given the project's schedule and resources
- Technologies must be considered within the context of use cases and procedures

Evaluation of Regimes against the Assessment Criteria

After applying technologies to the CoC functions in each regime, the team scored the regimes using the evaluation criteria as a guide. As discussed in the criteria development section of this report, the primary evaluation criteria were further defined by sub-criteria and a series of yes/no evaluator questions linked to the sub-criteria. For instance, the following yes/no questions were used for the Confidence Provided criterion:

- Familiarity: Are the functions and capabilities of the monitoring system components generally understood?
- Completeness of coverage: Can all phases of the dismantlement process be covered by some form of monitoring or chain of custody?
- Redundancy: Are there any critical single points of failure?
- Mitigation of equipment vulnerabilities: Have identified equipment vulnerabilities been mitigated?
- Risk of defeat detection: Is the probability of detection high enough to deter diversion or attack attempts?
- Level of inspector access: Is inspector access adequate to ensure host compliance with treaty obligations?

The team used the answers to these questions to grade the confidence provided by each regime on a 1-5 scale, with a score of 5 indicating high confidence and a score of 1 indicating low confidence. This process was repeated for each of the criteria. These scores were then combined with the weighting factors developed during criteria development to generate overall regime scores. This resulted in the following overall scores:

Regime	Overall Score
START/New START	3.3
Current Technologies	3.4
Future Technologies	4.2

The overall scores suggest that the Current Technologies regime presents only a minimal improvement over the START/New START regime. This may warrant a closer look at the assessment criteria and their weighting: Confidence Provided, Operational Impact, and Cost each improved when comparing the Current Technologies constraint case against the START/New START constraint case, and yet the overall score for the Current Technologies regime improved only by a tenth of a point. This was inconsistent with the project team's expectations, but it did underscore the importance of certification and authentication. The Future Technologies regime scored highest overall, which was more consistent with the project team's expectations, as it was an optimized regime that drew from the largest set of technologies.

Conclusion

In addition to the observations and lessons learned that were specific to each step of the CoC technology mapping process, the team gained the following general insights:

- Focused, in-person collaboration is highly beneficial
- Multi-site, multi-disciplinary teams significantly strengthen information availability and conclusions reached
- The involvement of Pantex Plant personnel is essential when considering potential regimes that may include monitoring at a facility like the Pantex Plant.
- The establishment of evaluation criteria at the beginning of the project significantly benefitted subsequent work completed
- Documentation of assumptions was important in establishing initial parameters and throughout project execution

It is the authors' hope that insights gained through this technology mapping exercise will be useful to the international arms control and safeguards community. Specifically, the approach undertaken and the insights gained may be useful for future analyses of monitoring and verification technologies and approaches.

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* George Weeks took an assignment at Hanford halfway through the project, and was no longer available to lead the team at that point.

References

[i] "Safeguards Techniques and Equipment: 2011 Edition", International Nuclear Verification Series No. 1 (Rev 2), International Atomic Energy Agency, Vienna, 2011.

[ii] "Development and Implementation Support Program for Nuclear Verification 2014-2015" STR-377, International Atomic Energy Agency, Vienna, December 2013.