Attaining and Maintaining a Continuity of Knowledge to Draw Safeguards Conclusions with Confidence

Robert S. Bean
Purdue University[1]
400 Central Drive, West Lafayette, IN 47907
bean@purdue.edu

Dianna S. Blair
Sandia National Laboratories[2]
PO Box 5800 MS 1371, Albuquerque, NM 87185-1371
dsblair@sandia.gov

Chris A. Pickett
Oak Ridge National Laboratory[3]
PO Box 2008 MS6166, Oak Ridge, TN 37831-6166
pickettca@ornl.gov

Abstract:
As the 21st century progresses, new nuclear facilities and the expansion of nuclear activities into new countries will require the International Atomic Energy Agency (IAEA) to place a higher reliance on attaining and maintaining a Continuity of Knowledge (CoK) of its safeguards information than is currently practiced. Additionally, a conceptual view of where and how CoK can be applied will need to evolve to support improved efficiency and efficacy of drawing a safeguards conclusion for each Member State. The ability to draw a safeguards conclusion for a Member State will be predicated on the confidence that CoK has been attained and subsequently maintained with respect to the data and information streams used by the IAEA. This confidence can be described as a function of factors such as elapsed time since the measurement, surveillance of attributes, authentication of information, historic knowledge of potential system failures, and the number and type of data collections. A set of general scenarios are described for determining what is required to attain CoK and whether CoK has been maintained. A high-level analysis of example scenarios is presented to identify failures or gaps that could cause a loss of CoK. Potential areas for technological research and development are discussed for the next generation of CoK tools.

Keywords: Safeguards; Continuity of Knowledge

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1. Introduction

Beginning with the entry into force of the "Treaty on the Non-proliferation of Nuclear Weapons" in 1970, signatory Member States agreed to declare to the International Atomic Energy Agency (IAEA) the location, quantity, and use of fissile materials under their control. [1] The IAEA in turn is charged with verifying the declaration with the goal of drawing a safeguards conclusion regarding whether the fissile material in the Member State has remained in peaceful use. [2] The IAEA develops a safeguards approach with each country, typically under the auspices of INFCIRC/153, to gather, both via declaration by the State and measurement and inspection activities by the IAEA, the information needed to draw a safeguards conclusion. [3] Under the Additional Protocol, the IAEA has additional authority to access and inspect all aspects of a State's nuclear activities in order to verify that there are no undeclared fissile materials or activities related to diversion of nuclear material from peaceful purposes. Therefore, the IAEA is tasked with verifying the *correctness* (i.e. declared materials and activities) and the *completeness* (i.e. lack of undeclared materials and activities) of each Member State's declarations.

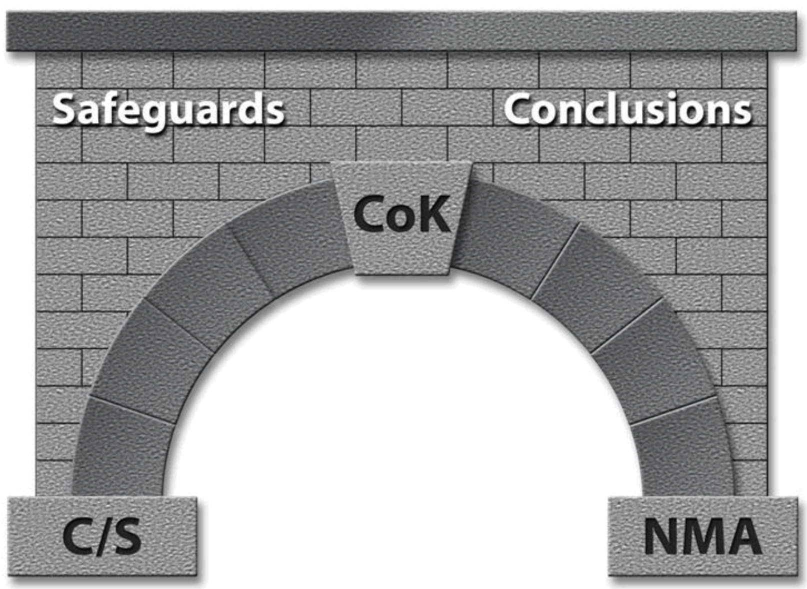

Figure 1. Built on a foundation of nuclear material accountancy (NMA) and containment and surveillance measures (C/S), Continuity of Knowledge (CoK) provides the confidence to support a safeguards conclusion. [4]

Historically, nuclear material accountancy (NMA), or rather direct measurement of the nuclear material (via either destructive or nondestructive assay), has formed the basis for safeguards conclusions. For example, a Member State's declarations of material production can be verified by an inspector measuring the product material with IAEA equipment. In addition to NMA, containment and surveillance (C/S), often in the form of container seals and video camera systems, provides a complementary means to verify Member State declarations. For example, declarations involving fuel movements can be checked against video footage to determine if the IAEA system recorded the same number of fuel elements being loaded, or intact seals can verify that other fuel has not been transferred without being declared. Together, NMA and C/S are used to attain knowledge about the nuclear material activities, and then further used to maintain that knowledge, preferably in a continuous fashion. Continuity of Knowledge (CoK) for safeguards is the outcome of "a system of data or information regarding an item or activity that is uninterrupted and authentic and provides the IAEA with adequate insight to draw definitive conclusions that nuclear material is not being diverted from peaceful purposes." [4, 5] In other words, attaining and maintaining CoK is the goal of safeguards measures. If this outcome is achieved, a safeguards conclusion can be supported with confidence.

Note that while the examples of NMA and C/S were used to describe attaining and maintaining CoK, the principle is fully extensible to other types of data that are used to inform the safeguards conclusion. Complimentary access visits under the Additional Protocol, surveys of literature and publications, and shipping and receiving records, are other examples of means to provide information and therefore contribute to attaining and maintaining CoK. As the IAEA further refines the state level concept and moves to safeguard not only newly constructed but new *types* of nuclear facilities (such as long-term geologic repositories), the safeguards approach will require a reliance on information that goes beyond traditional NMA.

The ability of the IAEA to draw a safeguards conclusion about a Member State's activities will be predicated on IAEA confidence that it has been able to attain and subsequently maintain CoK.

2. Sampling Theory

Maintaining CoK requires that periodic "checks" be performed to renew confidence that the knowledge is still current and correct. While continuous and/or real-time monitoring are often espoused as the ideal, the reality is that continuous or near-continuous checks generate a tremendous quantity of data that may not necessarily improve the confidence that CoK has been maintained. There is an optimum rate that produces the maximum information, or rather confidence that the collected information is correct, without overwhelming both the data collection system and the safeguards inspector who must evaluate the results.

The case of simple production of digital sound files provides an example of sampling theory. [6] A natural signal, from a voice or from a musical instrument is inherently analog. To process these signals in computers, we must convert them to a digital form. While an analog signal is continuous in both time and amplitude, a digital signal is discrete for both. A process called "digitizing," or "sampling" is used to convert a signal from continuous time to discrete time. The value of the original signal is measured, or sampled, at certain time intervals. The necessary rate of taking samples to ensure appropriate preservation of the original analog information is defined by the Sampling Theorem. The Sampling Theorem simply states that if the original signal contains high frequency components, it must be sampled at a rate higher than the highest frequency

Long-term fuel storage: A case where CoK will be primary over NMA

When spent nuclear fuel is packaged for long term disposition in a geological repository, the nuclear material quantities should be established via NMA. Whether measured by existing techniques, or future advanced techniques [9], NMA establishes the inspector's knowledge of the nuclear material quantity. During short term storage and transportation to the geologic repository, additional measures such as C/S to maintain CoK can eliminate the need for to re-measurement of the fuel. During the operational and post-closure periods C/S measures could provide CoK for the site and the material under safeguards.

As the geologic repository is filled, it becomes increasingly difficult to perform NMA. Measures such as C/S are used to maintain CoK of the nuclear material. Eventually, the repository will be backfilled, and further NMA will be impossible. Even C/S measures such as container seals will have reduced effectiveness due to the inability to physically verify those that have been buried. Maintaining CoK through measures such as C/S on the repository entrance and seismic monitoring for undeclared digging will become the primary means to maintain Cok and thus support a safeguards conclusion about the nuclear material.

component in the original signal to avoid losing information. [7] To preserve the full information of the signal, it is necessary to sample at a rate of twice the maximum frequency of the signal, known as the Nyquist rate. The Nyquist rate gives a reliable benchmark for accurately preserving analog information.

If we sample a signal at a frequency lower than the Nyquist rate it will exhibit a phenomenon called “aliasing” when the signal is converted back into a continuous time signal. Aliasing results from unwanted or missing frequency components in the reconstructed signal and can distort the resulting information. Examples of aliasing can be seen on automobiles where the wheels of a moving vehicle appear to be turning backwards as the vehicle propels forward. This is due to your eye sampling the image at a slower rate (around 10 or 12 times per second) than the vehicle’s distinctive rim or hubcap features are moving. The eye, therefore, is losing information because it is sampling too slowly. Conversely, movies appear to display continuous motion because they are filmed at a rate of 30 frames per second—at least twice the rate your eye refreshes—although your eye still will perceive the film of a wheel rotating backward due to the limitations of the eye.

In safeguards, we must ask ourselves, “How much information is needed to maintain CoK?” The sampling rate for checking and re-checking an information stream must be equivalent to or greater than the Nyquist rate for the information signal being sampled. This will be determined by factors such as the type of technology collecting the information, the attractiveness of the nuclear material, the potential diversion or misuse of that material, and the time scale of the diversion or misuse actions. For example, in a situation where low enriched uranium fresh reactor fuel is in storage before being loaded into a reactor, the combination of C/S, possible diversion scenarios (such as diversion to a clandestine enrichment facility and subsequent enrichment to highly enriched uranium), and the safeguards inspection schedule would allow a diversion analysis to be performed on the time required for operator diversion of one significant quantity of U-235 (75 kg of U-235 in the form of enriched uranium enriched to <20%). If we assume that in this case the result of the analysis is that the diversion would take twelve months, then maintaining CoK by “sampling” the facility every six months or less provides assurance that the diversion would be detected without creating an overwhelming demand for either physical inspections or information collection.

Additionally, the concept of nested sampling, familiar to computer programmers, must be considered. For each potential concern, each component will need to be sampled at a minimum rate equal to the Nyquist rate. For example, while it may be necessary for an inspector to visually verify an electronic seal only on a monthly basis, the seal electronics may need to self-test for tamper indications every millisecond and verify communications connections with the data collection system every few seconds. Each part of the system must be sampled, or monitored, such that there is confidence that no information has been lost.

3. Maintaining Continuity of Knowledge

Once knowledge has been attained, maintaining CoK is required to have confidence that the knowledge is still correct and, therefore, useable. Continuity of Knowledge must be maintained in such a way that the information is sampled at the appropriate rate to identify issues in a timely fashion. Continuity of Knowledge must be attained and subsequently maintained with sufficient confidence that the knowledge can be used to support a safeguards conclusion. This confidence can be described as a function of factors such as the level of initial knowledge, elapsed time since the measurement, surveillance of attributes, authentication of information, historic knowledge of potential system failures, and the number and type of data collections. Additional information, such as indications of attempted tampering, adversary sophistication, and advances in technology will also impact this confidence. This concept is described by the following function:

$$C_{CoK\ method} = f(initial\ knowledge, time, sampling\ rate, failure\ rate, adversary\ actions, \dots) \quad \text{(Eq. 1)}$$

where $C_{CoK/method}$ is the confidence that CoK has been maintained by the particular system or method in question. The value of $C_{CoK/method}$ would be expressed as a percentage between 0 and 100%, where 0% indicates no confidence at all and 100% represents complete confidence that the method in question has maintained CoK. For simplicity, if you assume that the various factors are independent of each other, the confidence that CoK has been maintained by that method can be expressed in the form:

$$C_{CoK\ method} = f(initial\ knowledge) \times f(time) \times f(sampling\ rate) \times f(failure\ rate) \times f(\dots) \quad \text{(Eq. 2)}$$

where this equation represents $C_{CoK\ method}$ as a function of the indicated factor. These functions can also be described in terms of the confidence that they provide to the overall $C_{CoK\ method}$.

$$C_{CoK\ method} = C_{time} \times C_{CoK\ sampling\ rate} \times C_{CoK\ failure\ rate} \times \dots \quad \text{(Eq. 3)}$$

Similarly, the confidence that each component provides would range from 0 to100%. Mathematically, equation 2 is multiplicative, because the failure of any component ($C_{CoK/component} = 0$) would drive $C_{CoK/method}$ for the entire method to zero. In practice, the principle of defense in depth leads to the use of multiple, potentially redundant, methods to maintain CoK. In this case the overall confidence that CoK was maintained will be additive as in:

$$C_{CoK\ overall} = \frac{\sum_{i=1}^{n} \omega_i C_{CoK\ method\ i}}{\sum_{i=1}^{n} \omega_i} \quad \text{(Eq. 4)}$$

where ω_i is the weighting factor, or "quality or effectiveness" of each method, indicating how much that method contributes to the overall confidence that CoK has been maintained. Note that equation 4 is a significant simplification as there may be interdependencies (such as common modes of failure) and no matter how many methods are used total confidence cannot exceed 100%.

In practice, confidence that CoK has been maintained will be highest at the time of a verification action. For an item of nuclear material, this would ideally be quantitative assay. As time passes, confidence that the knowledge in the records correctly reflects the safeguarded item declines. Questions about actions since the last verification - Has the item been moved? Has the seal been broken? Has the unattended monitor failed? Has the operator done something that impacts the item? – can reduce, per equations 2 and 3, the confidence that CoK has been maintained. When the next monitoring action is taken, the confidence is restored to a high level. Failure of a component ($C_{CoK/component} = 0$) will cause a step change to lower confidence that CoK has been maintained. At some reduced level of confidence, it can no longer be sufficiently assured that CoK has been maintained to depend on that knowledge to draw a conclusion. In this case, a full re-verification is necessary to re-establish CoK.[4]

[4] It should be noted that this is a departure from the current IAEA practice regarding the use of multiple containment and surveillance (C/S) methods to maintain CoK. According to the IAEA Safeguards Glossary [10], where a "dual C/S" system is used (i.e. more than one method to give an overall confidence that CoK has been maintained) "…an acceptable C/S result is obtained when both C/S devices function as specified, their data confirm the validity of the operator's declarations and there is no evidence of tampering." The inverse of this is that when either system fails, the confidence that CoK has been maintained is lost (e.g. $C_{CoK\ overall} = 0$). The more robust concept described in this paper would have a reduced overall confidence in the event of component or method failure, but would avoid an "all or nothing" approach, resulting in a different impact on the requirement for reverification activities.

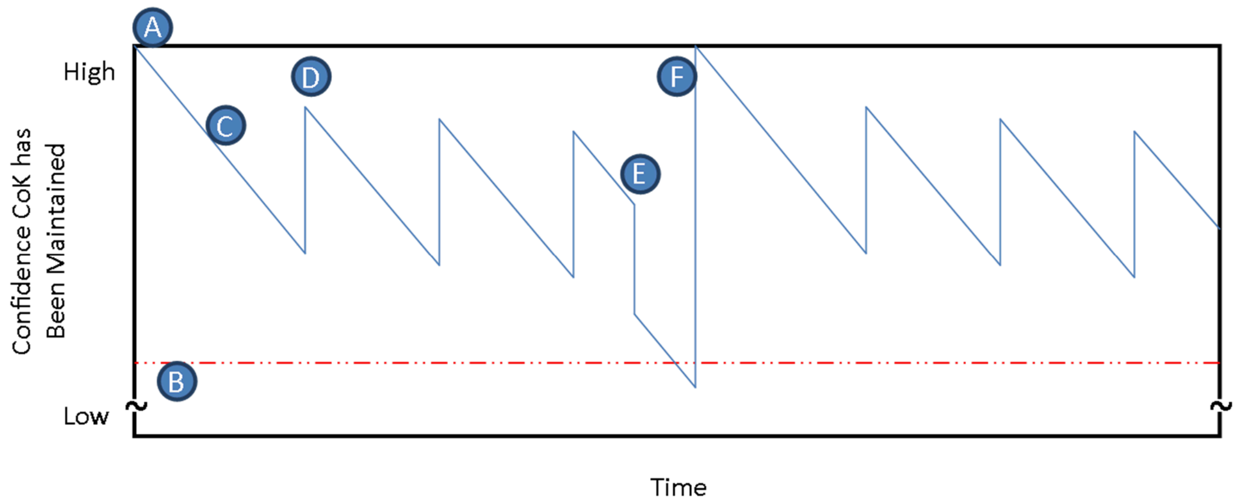

Figure 2. Confidence that CoK has been maintained changes over time. A) When knowledge is first attained (through NMA for a safeguarded item), confidence is highest. B) There is some level of confidence below which it can no longer be assured that CoK has been maintained. C) Confidence that CoK has been maintained falls as time passes. D) Sampling the system (such as through a physical inventory, review of unattended monitoring data, etc.) increases the confidence. E) Events such as equipment failure can cause a step change reduction in confidence. F) If the confidence that CoK has been maintained is lost, a re-verification is required.

Previous work has demonstrated this principle, see Figure 3. [8] For both a passive and an active tamper indicating device (TID), the probability of sensing a tamper event was calculated with respect to time. The rising and falling of the probability of detecting a tamper event for the passive TID correspond to when the device is monitored (i.e. visually inspected) and subsequently left in place. The much smaller fluctuations of the active device are due to the faster sampling rate, allowing the confidence in the TID to be maintained at a high level. In both cases, the probability of sensing a tamper event (in other words, the confidence that the device has maintained CoK of the sealed item) is a function of time, selected technology, and potential adversary actions as described in equation 3.

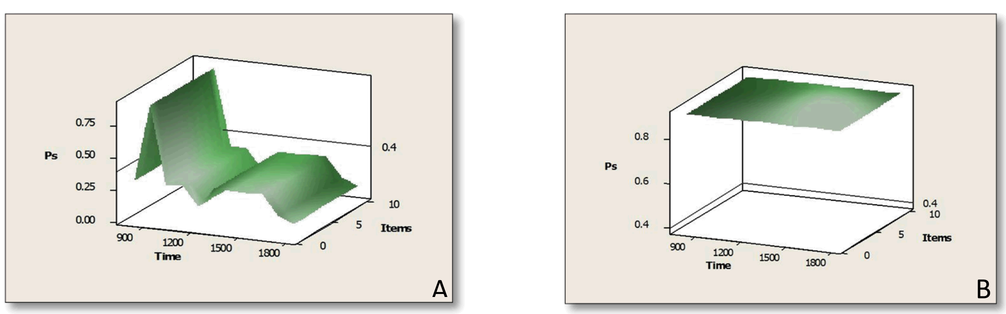

Figure 3. A) Surface Plot of Probability of Sensing Tamper by Passive TID. B) Surface Plot of Probability of Sensing Tamper by Active TID. [8]

The systems chosen to attain and maintain CoK must, therefore, take into account the principles of:

- accuracy and precision of initial knowledge;
- appropriate sampling rate for each component, or sub component;
- appropriate reporting rate for active items (not necessarily the same as the sampling rate);

- effects over time of confidence in CoK for each component, such as:
    - technology failure rates,
    - effectiveness of technology selections, and
    - adversary capability advances; and
- a systems approach for avoiding common failure modes and loss of sufficient confidence in maintaining CoK that re-verification is required.

When a monitoring system is selected properly, there will be sufficient confidence that knowledge regarding the status of the nuclear material was attained, and that CoK was maintained for drawing an overall safeguards conclusion—with confidence.

4. Safeguards CoK Scenarios

Safeguards activities can be grouped, at a high level, into three categories: stable, dynamic, and transportation. Stable facilities are those where nuclear material is typically stored and safeguarded in place after arrival, or moved on a slow, predictable schedule (i.e. scheduled shipments). Dynamic facilities are those where safeguarded nuclear material movement is a constant or near-constant activity, most notably bulk processing facilities. Not only is the material moving, but it may be changing its physical or chemical characteristics as well. Transportation is the category where the nuclear material is not at a safeguarded facility, but is in transit between facilities, and possibly between Member States as well. It would also be appropriate to discuss “sub-facilities” or material balance areas as stable or dynamic; for example, the vault at a processing plant may have nuclear material in storage with a long dwell (storage) time, especially as compared to the processing areas of the same plant.

Descriptions are given for a fuel storage facility as a typical example of a stable facility, a bulk processing facility as a dynamic facility, and a general transportation scenario.

4.1. CoK of Stored Nuclear Material

A stable scenario is fairly straightforward with respect to what is required to attain and then maintain CoK of the nuclear material. When nuclear material is shipped or transferred to the facility, initial knowledge must be established. Ideally, this is done by NMA on site. An inspector then must be able to verify that the material is then stored in the declared location. Various tools, such as unique identification numbers or other unique identifiers (UID), on the nuclear material containers or items, seals to ensure that those containers remain closed, cameras to verify equipment and container movement, gamma or neutron detectors (depending on the nature of the nuclear material) to maintain confidence that the movement was of the declared material, and others, will provide confidence that CoK was maintained through the placement of the item into storage. Once in storage, CoK must be maintained for that nuclear material, possibly for a period of decades or more. Periodic verification of UIDs, tamper indication status of seals, radiation signals, and camera footage can be used to verify that the nuclear material is still in place.

4.2. CoK During Bulk Processing

The crucial distinction, in terms of maintaining CoK, between a stable facility and a dynamic one is that in a dynamic facility there is a potential for a loss of CoK *simply due to the bulk processing* itself. To explain this, consider measurement uncertainty and a simple case of moving nuclear material from one container and splitting it among three others via process equipment. The high confidence that all of the reported material is in the first container is replaced by the confidence that all of the material is now in the three secondary containers. Except that it is not all there – some of it is still in the first container as a heel, some of it is in the process equipment as holdup, or some may be in filters. Even if it were possible to easily measure each of these amounts, the total measurement uncertainty will have increased. It is even more important, therefore, to assure that once CoK has been attained, it is maintained throughout the dynamic processes, and it must be maintained at the level of the entire facility, not just for individual items of nuclear material.

As with the stable facility, the nuclear material is, ideally, measured on-site to establish knowledge of the nuclear material quantity. The material will arrive as items or in containers, and thus UIDs and seals can be used to maintain CoK as the material is brought into the facility and prepared for processing (there may be storage areas to be considered, similar to larger stable facilities). Again, cameras, radiation detectors, etc. can be used to verify the movements until the material enters the process. Once in the process, the physical and chemical nature of the material will be changed. It may be chopped, dissolved, chemically converted, mixed, ground, or any other number of steps until the final product is complete. Sufficient monitoring of the processes is vital to provide confidence that the process is operating as declared; in other words, CoK of the process itself must be attained and maintained. This will require process specific monitoring technologies. For example, a CoK of chemical processing plant for spent fuel would use tank level indicators, liquid flow rate monitors, and pH meters, whereas CoK for an enrichment plant would use load cells and enrichment meters. In either case, with maintained CoK, the desired outcome is sufficient confidence that knowledge of the plant operation can be used to draw a safeguards conclusion.

4.3. CoK During Transportation

Maintaining CoK during transportation currently relies upon an active seal attached to a container prior to shipment and verified upon receipt. [9] The goal of the seal is to record any opening of the transport container (e.g., trailer, shipping container, etc.) that occurs during transportation. This approach requires an inspector to be present at either the point of shipment *and* receipt or, minimally, at the point of receipt when the seal is removed. The inspector must verify that the seal was properly applied (e.g., through the hasp) and that the collected information accurately indicates that the item was properly received. This verification also may include a confirmation of physical attribute(s) (i.e. weight and/or NDA).

Many shippers prefer (for a variety of reasons) not to provide real-time active monitoring or surveillance during transport; this type of surveillance has been considered too sensitive or intrusive for shippers to consider. However, emerging needs to improve detection of potential diversion during transport (e.g., of spent fuel) warrant greater monitoring during transport. Technologies and approaches that can provide high assurance that fuel cycle materials leaving one location arrive (intact) to the designated location will need to be developed as the number of global fuel cycle activities that require transportation continue to expand.

4.4 Confidence that CoK Has Been Maintained

When all of the components used for CoK function correctly, an inspector will have sufficient confidence that CoK has been attained and subsequently maintained to use for drawing a safeguards conclusion. When CoK is properly implemented with a systems approach, even the loss of a limited number of components will not reduce the overall confidence enough to lose assurance that the nuclear material is as declared. There will be many commonalities over the three scenarios in the selection of technology and activities to maintain high confidence that CoK has been maintained.

The potential loss of CoK leads to a “Schrödinger’s cat” thought experiment for safeguards. As in the famous example used to explain quantum probabilities, a safeguards inspector has good knowledge of the state of the nuclear material at the time it is verified (i.e. measured and observed). After that, however, the choice of TID, cameras, inspection frequency, unattended monitoring, process monitoring for bulk facilities, etc. gives (or does not give) confidence that the inspector’s knowledge represents the true state of that nuclear material. The purpose for maintaining CoK is to produce an outcome where the confidence is high enough to base safeguards conclusions on that knowledge.

What is needed is a rigorous analysis of the impact of each type of technology and inspection activity on the confidence that CoK has been maintained. Simple cases, such as depicted in Figure 3, need to be extended to incorporate disparate technologies and activities. The analyses must include an understanding of the causes and impacts of events including (but in no way limited to):

- Potential loss of CoK. For example, due to power failure, communications loss, adversary nuisance tampering, or adversary malicious attack.
- Changes in vulnerabilities due to technology selections. For example, designs that create penetrations in a tamper indicating enclosure.
- Operational considerations. For example, the trade-off between hardwire and wireless communications.
- Combining independent data. For example, if a seal appears to be broken, but the camera in the same area shows no undeclared activities, what is the impact on overall confidence in CoK?

5. Conclusions

As the number of safeguarded fuel cycle operations expand, and new types of facilities are built and operated, the importance of attaining and subsequently maintaining CoK will continue to increase. Depending on the facility type and use, dependence on CoK could potentially become the primary method by which safeguards inspectors draw a conclusion. To maintain CoK, the safeguards equipment and practices used will need to monitor, or sample, the status of the nuclear material and the CoK components at a rate sufficient to ensure that potential tamper and diversion pathways will be detected. The sampling rate will also need to be appropriately nested to account for varying monitoring needs such as electronic self-monitoring vs. visual inspection. Selection of technology and actions to maintain CoK at safeguarded facilities needs to take into account the declared activities, the nature of the facility, and potential diversion pathways. Selected components to maintain CoK must be considered together as there may be interdependencies of failure modes and each technology has its own potential vulnerabilities. A rigorous analysis of the confidence that CoK has been maintained is needed to assist safeguards inspectors in understanding when they have sufficient confidence that CoK has been maintained to draw safeguards conclusions.

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