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RANDOMIZATION OF INSPECTIONS

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Abstract

As the numbers and complexity of nuclear facilities increase, limitations on resources for international safeguards may restrict attainment of safeguards goals. One option for improving the efficiency of limited resources is to expand the current inspection regime to include random allocation of the amount and frequency of inspection effort to material strata or to facilities. This paper identifies the changes in safeguards policy, administrative procedures, and operational procedures that would be necessary to accommodate randomized inspections and identifies those situations where randomization can improve inspection efficiency and those situations where the current nonrandom inspections should be maintained.

1. Introduction

Assignment of inspection resources among facilities inspected by the International Atomic Energy Agency (IAEA) is a complex and important function affecting the quality of these inspections and the safeguards conclusions derived from them. Although the IAEA currently meets essentially all of its safeguards goals, planned future increases in the number of nuclear facilities, especially large bulk-handling facilities, combined with restrictions on the growth of inspection resources may leave a shortfall in the inspection effort for continued attainment of Agency goals. This situation could lead to the need for difficult tradeoffs in the inspection effort applied to materials, facilities, and States. A proposed strategy for limiting the reduction in goal attainment would apply randomization of inspections to increase the effectiveness of fixed resources or equivalently to increase their efficiency. Randomization has been considered from a general systems analysis point of view in Refs. 1-3, whereas more detailed mathematical treatments are given in Refs. 4-6.

Among the general strategies for incorporating randomization into IAEA inspection prac for international safeguards may restrict attainment of safeguards goals. One option for improving the efficiency of limited resources is to expand the current inspection regime to include random allocation of the amount and frequency of inspection effort to material strata or to facilities. This paper identifies the changes in safeguards policy, administrative procedures, and operational procedures that would be necessary to accommodate randomized inspections and identifies those situations where randomization can improve inspection efficiency and those situations where the current nonrandom inspections should be maintained.

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Among the general strategies for incorporating randomization into IAEA inspection practice are

- random allocation of the amount and frequency of inspection effort among the strata at a facility, and
- random allocation of the amount and frequency of inspection effort among a group of facilities.

The purpose of this paper is a qualitative survey of these strategies to establish their advantages and disadvantages with respect to IAEA safeguards.

2. Summary

Randomized inspections offer the potential for increasing inspection efficiency when resources for verifying compliance with international agreements governing the use of nuclear materials are limited, whereas the numbers of nuclear facilities to be inspected are increasing. Adoption of randomization at either the stratum or facility level will, however, require fundamental changes in safeguards policy as represented by the Safeguards Implementation Report (SIR) Criteria, in administrative procedures including a possible need for confidentiality of inspection planning, and in operational procedures such as the application of current technology for surveillance.

Independently of the level of randomization (strata or facilities) and the type of randomized inspection (physical inventory or interim), there are several general conclusions possible about the utility of randomization as a means of improving inspection efficiency.

- The probability of anomaly detection cannot be increased for attributes verification at item facilities by randomization strategies where all strata (facilities) are inspected but the applied effort is randomly varied among them.

- The probability of anomaly detection can be increased for variables verification at bulk facilities by randomization strategies where all strata (facilities) are inspected but the applied effort is randomly varied. This conclusion holds when total inspection effort is limited (<50% of the materials are verified) but does not hold at higher levels of inspection effort.

- The most promising randomization strategies are those where some subset of the strata (facilities) are randomly selected for inspection. These strategies improve the efficiency of inspection resources because indirect resources such as time for travel to facilities, opening meetings, and [illegible]

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- The most promising randomization strategies are those where some subset of the strata (facilities) are randomly selected for inspection. These strategies improve the efficiency of inspection resources because indirect resources such as time for travel to facilities, opening meetings, and calibrating instruments at strata (facilities) not visited are converted to resources for direct verification of material at the strata (facilities) randomly chosen for inspection.

I. Evaluation Framework

An assessment of the value to the IAEA of randomized inspections must distinguish between the statistical effectiveness of the strategy as measured by the probability of detecting an anomaly and the safeguards effectiveness as measured by conformity to the SIR Criteria. Extending the current nonrandom inspection regime to include randomized strategies increases the possible inspection strategies and, therefore, generally provides opportunities for increasing the anomaly detection probability. However, these same randomized tactics are generally incompatible with the SIR Criteria and Safeguards Approaches, which prescribe detailed procedures to be carried out at each facility and inspection type.

The principle of random sampling of a population and extrapolation of a characteristic of the sample to the total population is well founded in statistical theory. Indeed, in current IAEA inspection practice, this principle is applied to sampling of items in a stratum to verify the integrity of the entire population even though all items are not verified. In this instance, one can calculate the probability that an anomaly in a single item would have been detected based on the sample size and verification method. Absence of an anomaly in the sample is taken as evidence for the integrity of the entire stratum, recognizing that there is a probability that this conclusion is wrong.

In principle, similar considerations are applicable to any collection of inspected entities including material strata, facilities, or States, and the conclusions are as statistically valid as the previous case of items in a stratum.

Evaluation of the statistical effectiveness of a randomized inspection strategy is most naturally analyzed in a game theoretic framework in which the inspector and State are viewed as opponents. Of course, this assumption of an adversarial relationship is an essential part of safeguards planning to assure the international community of the integrity of safeguards conclusions, whereas the actual implementation of safeguards is a collaborative relationship between the State and the IAEA.

In the context of game theory, the inspector and State each have a set of possible strategies; the inspector's strategies consist of all possible ways of assigning inspection effort among facilities, and the State's strategies consist of all scenarios for gaining unauthorized use of a significant quantity of material. The inspector and State each select a strategy that, when implemented, leads to a specific outcome. The utility of each outcome is measured by the probability of detection with the inspector attempting to maximize the probability and the operator minimizing it. In this formulato be carried out at each facility and inspection type.

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A basic result of game theory identifies the use of randomization over a player's strategy set as a useful and sometimes optimal choice. This tactic is implemented by a priori assigning a probability of selection p_i to each strategy x_i so that $\sum_{i}^{n} p_i = 1$ and randomly selecting each strategy with its assigned probability.

4. Randomized Inspections

Randomization of inspections can be introduced either at the individual facility level by randomly selecting the amount and frequency of inspection effort applied to the strata within a facility or at the level of a group of facilities by randomly selecting the amount and frequency of inspection effort applied to individual facilities. In either case, the randomization could include the possibility that some strata (facilities) receive no verification effort. A further categorization of randomization strategies depends on whether they are applied to physical inventory verification inspections, interim inspections, or both.

Where randomization is applied to strata within a facility, the inspector would follow current practice and prepare a sampling plan for each stratum. For those strata to be verified, a comprehensive set of inspection activities would be completed that are sufficient to allow valid safeguards conclusions; however, the intensity of verifying records and sampling materials for verification would be randomly determined by the sampling plan. Where a stratum was not selected for verification, safeguards conclusions could be based on a calculated detection probability derived from the planned activities if the stratum had been selected.

Randomization could be implemented for a group of facilities within the framework of the 6-month schedule of inspections for a collection of facilities such as those inspected by an operations section. Random selection could be applied to scheduled inspections to determine the facilities to be visited and the inspection effort to be allocated. In principle, this could result in the extremes of either no visit to a facility or completion of all required inspection activities at a facility. Clearly, the a priori random inspection list would have to be modified over time to accommodate changes in facility operating schedules and availability of inspectors. These practical constraints would probably preclude full attainment of a completely randomized inspection schedule.

Although random selection of the effort and frequency of inspections may be applied to an arbitrary group of facilities, for example, a mix of item and bulk facilities, the principles of random sampling suggest that the validity of statistical conclusions about the total population is enhanced when the population sample is homogeneous. For example, extrapolating the results from a sample of reactors to a State's total reactor population is preferable to sampling the population of facilities in a State's tion strategies depends on whether they are applied to physical inventory verification inspections, interim inspections, or both.

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Although random selection of the effort and frequency of inspections may be applied to an arbitrary group of facilities, for example, a mix of item and bulk facilities, the principles of random sampling suggest that the validity of statistical conclusions about the total population is enhanced when the population sample is homogeneous. For example, extrapolating the results from a sample of reactors to a State's total reactor population is preferable to sampling the population of facilities in a State's fuel cycle and extrapolating the results to all facilities, especially if the State's only reprocessing plant is not in the sample.

Because the only facilities of similar type that are likely to exist in a sampling population of reasonable size are reactors, this randomization strategy is probably most applicable to that facility type. However, where multiple facilities of other types such as fabrication plants or reprocessing plants are in the same population, the efficiency of inspections at these facilities may still be enhanced by randomization. Even though the number of these bulk facilities is small, their inspections are much more resource intensive than reactor inspections so that resource savings at these facilities are important.

Whether one is randomizing inspections over a group of strata at a facility or over a group of facilities, there are two general strategies for the randomization procedure:

- inspect all strata (facilities) but randomly vary the inspection effort applied and
- randomly choose a subset of the strata (facilities) for inspection.

The strategy of inspecting all strata (facilities) has the advantage of being consistent with the current SIR criteria for timeliness; however, it will be demonstrated that in most instances this strategy is not better than the current practice of applying the same effort at each inspection. Indeed, it is the second strategy in which some strata (facilities) are not inspected that has the most promise for improving inspection efficiency. This improvement is based on the conversion of indirect resources such as those for travel to facilities, health/safety preparations, and instrument calibration at facilities not visited to resource expenditure for direct verification of material at the inspected facilities. This conversion of indirect to direct resources is the key to realizing the benefits of randomization.

All Strata (Facilities) Inspected

The following example demonstrates that for item facilities that are inspected with attributes measurements, random inspections in which all facilities are visited but inspection effort is varied cannot be more effective than nonrandom strategies in which inspection effort is the same at each inspection.

Example

Assume that two identical facilities each contain a single material stratum that is to be verified by the same attributes method. If the State is equally likely to divert from either stratum and the inspector applies identical effort $e/2$ to each facility, then the probability of detection is $P(e/2)$, where e is the total available effort.

Alternatively, under a randomization strategy that varies the effort applied to each facility, assume the efforts $2e/3$ and $e/3$ are randomly assigned to the two facilities. This domly vary the inspection effort applied and

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Alternatively, under a randomization strategy that varies the effort applied to each facility, assume the efforts 2e/3 and e/3 are randomly assigned to the two facilities. This leads to a detection probability of $\frac{1}{2}P(2e/3) + \frac{1}{2}P(e/3)$. However, because the curve P representing the detection probability for attributes measurements is concave, it is always true that

$$P(e/2) > \frac{1}{2}P(2/3e) + \frac{1}{2}P(e/3) \quad .$$

This relationship is illustrated in Fig. 1.

Fig. 1. Detection probability for random and nonrandom strategies.

This example demonstrates the principle that randomly assigning the inspection effort among facilities with a concave probability function while visiting all facilities cannot increase overall detection probability compared with a nonrandom strategy of assigning the same effort to each facility at each inspection. The general validity of this conclusion for an arbitrary number of facilities is demonstrated in the Appendix. Further, because the detection probability function for bulk facilities inspected by variables sampling is convex for low levels of inspection effort and concave for higher levels of inspection effort (sufficient for verification of at least 50% of the materials), we can conclude that nonrandom inspection strategies are also at least as good as random strategies at bulk facilities when inspection effort is sufficiently high.

k-out-of-N Inspected

Assuming that there are N facilities (strata) to be inspected but insufficient resources to fully attain the safeguards objectives at these facilities (strata), an alternative to inspecting all facilities at a low level is to concentrate the inspections on a randomly selected subset of k facilities, where k < N. Improvements in inspection efficiency result from the increased inspection resources that are available from the facilities not visited. Indeed, resources that would have been used for travel, opening meetings, health/safety activities, and instrument calibration at the facilities not inspected are now available [illegible]

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Example

As an example, consider a facility with two material strata that are to be verified with an attribute measurement for detecting a gross defect in an item. Assume that the strata are identical, each containing 10 items, and that each item contains a significant quantity of material.

The inspector has a total of 60 units of time to complete the inspections, and each item requires 5 units of time for its measurement. In addition, there is a set-up cost of 10 units associated with the inspection of a stratum, which includes health/safety preparation, instrument calibration, and retrieval of items to be measured. The inspector has the options of verifying all of stratum A, all of stratum B, or 40% of both A and B.

The interaction between the three possible inspection strategies and two possible diversion scenarios for obtaining a significant quantity is shown in Table I. Clearly, the inspector can guarantee a detection probability of at least 0.4 by choosing strategy 2 and repeating this procedure at each inspection.

TABLE I

EFFECTIVENESS OF INSPECTION STRATEGIES FOR EXAMPLE PROBLEM

Inspection Strategy	State's Strategies: Divert One Item from Stratum A	Divert One Item from Stratum B
1 Inspect Stratum A	1.0	0
2 Inspect Strata A & B	0.4	0.4
3 Inspect Stratum B	0	1.0

However, randomization of inspection activities offers an improvement over the practice of repeating the same activities at each inspection. In the example, if the inspector chooses strategy 1 with probability 0.5 or strategy 3 with probability 0.5, the overall probability of detecting a material defect becomes 0.5, an improvement over the 0.4 associated with the nonrandom strategy.

5. Administrative and Operational Considerations Related to Randomization

Implementation of randomized inspections would cause some changes to the administrative and operational procedures currently employed by the IAEA. These changes are related primarily to the planning and implementation of inspections as carried out by the Operations Divisions.

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Confidentiality

The principal change under a regime of randomized inspections is an increased need for confidentiality in the inspection planning process. Because prior knowledge by a facility operator that a planned inspection would not be carried out invalidates its deterrent effect, confidentiality of the planned inspections is essential to ensure the validity of safeguards conclusions based on randomization. The operational implementation of confidentiality in inspection planning conflicts with the need for an inspector to arrange visas, travel, shipment of equipment, and so forth before an inspection. Presence or absence of these activities would disclose the intent with respect to the inspection. Alternatives for maintaining the deterrent element for inspections not carried out are to complete all aspects of planning as if the inspection were to be done or to keep the absence of planning confidential.

Operator Declaration

At some time before the date of a planned inspection that is not to be implemented, it would be necessary to inform the facility operator of that fact. To ensure that disclosure of the inspection plan does not invalidate the safeguards conclusions based on random sampling, it is essential that the facility operator commit to a physical inventory listing describing the status of materials before the notification of intent by the inspectorate. In practice, this could be accomplished by telexing such a list a few days before the planned inspection date.

Inspection Scheduling

Inspection randomization could be carried out by a priori random selection from the six month schedule of some fraction α of the planned inspections that are to be actually implemented. Where that fraction is not confidential, completion of the fraction α of planned inspections before the end of the six-month period discloses the absence of inspections for the remainder of that period. This deficiency is remedied by keeping the fraction α confidential or by independently deciding with probability α whether to carry out a planned inspection on a case by case basis. Although the latter tactic would cause the total fraction of inspections carried out to fluctuate around α, it avoids premature disclosure of inspection plans.

Unannounced Inspections

The possibility of unannounced inspections outside the framework of those scheduled has been suggested but would seem to be inconsistent with the advance notice needed for operators to prepare a facility for inspection.[8] Indeed in some instances such as verification of core fuel in a reactor, no inspection is possible unless the reactor's operating schedule and operator

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However, in those instances where inspection activities can be identified that are consistent with no advance notice to the operator and are relevant to detection of certain diversion scenarios, unannounced inspections could have some value. Indeed this concept has found routine application in the safeguards approach for U-235 enrichment plants based on ultracentrifuge technology, where limited frequency unannounced inspector access to the centrifuge cascade area provides assurance that highly enriched uranium is not being produced.[9]

because the biggest resource expenditure, inspector travel to the cluster, would not be saved. For example, if there are several facilities in a cluster and a randomized inspection plan selected only one facility for inspection, traveling to the cluster for one inspection would reduce the efficiency gained by the clustering principle.

A related facet of operational planning is the possibility of correlations between inspections at different facilities. For example, the schedule for servicing film cameras at clusters of reactors is frequently on the same cycle so that all film cameras can be serviced on a single inspection tour of the cluster. Randomization would disrupt the coordination of these inspection activities.

Surveillance

Application of surveillance as an inspection activity for verifying a material stratum poses special problems not encountered for other verification methods. Surveillance in the form of film cameras or closed-circuit television is routinely applied as a verification measure, primarily in the spent fuel storage at reactors or reprocessing plants. Current surveillance technology requires that these devices be serviced at about 3-month intervals to retrieve the surveillance record and to renew the surveillance mechanism.

Under the constraints of current technology, randomization of this verification method could be implemented by the following procedures. The surveillance record is retrieved on schedule, but the decision to review the record is randomized. This achieves savings in inspector resources at headquarters, while maintaining a deterrent effect because of the possibility that the film is reviewed. Of course, this procedure is inconsistent with the SIR Criteria requirement that successful surveillance must include a review of the record.

The timing interval between surveillance recordings could be randomly adjusted at each interim visit, which in effect randomizes duration of time before the surveillance record must be replenished. Although this allows randomized interim inspections with no loss in surveillance, the changes in timing interval may reduce the number of scenarios that are covered.

Finally, the inspector could randomize the retrieval of the surveillance record at the usual 3 month interval. Although this achieves some resource saving, the absence of retrieval and review of surveillance for the previous 3

Incorporation of unannounced inspections into IAEA procedures requires a method for giving credit to the "surprise" effect and for deciding how many announced inspections could be replaced by an unannounced visit.[8]

Correlations Among Facilities

Frequently, facilities to be inspected are divided into geographically close clusters with facilities in the same cluster inspected during the same inspection tour. This procedure might restrict the benefits of randomization of inspections at facilities within the same cluster because the biggest resource expenditure, inspector travel to the cluster, would not be saved. For example, if there are several facilities in a cluster and a randomized inspection plan selected only one facility for inspection, traveling to the cluster for one inspection would reduce the efficiency gained by the clustering principle.

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Application of surveillance could be made more consistent with randomized inspections if the technology were available for extending the current maximum interval between servicing surveillance units. For example, if a surveillance unit could function unattended for a period of time much greater than 3 months, the inspector could randomly choose to retrieve the surveillance record at a spent fuel pond during each interim inspection. Ultimately this stratum would be verified when the unit was serviced, but randomization of the time of retrieval would save resources while maintaining a probability of anomaly detection. Extended surveillance could be achieved with current technology by chaining cameras so that when one camera reaches the end of its film, another camera activates.

Appendix

Theorem

Assume a zero-sum, two-person game in which the inspector attempts to detect item defects in K identical facilities and has the pure strategies

$$(n_1, n_2, \ldots, n_K): \sum_{i=1}^{K} n_i = n$$

where n_i is the sample size in the i^{th} facility, the operator selects item defects and has the pure strategies

$$(r_1, r_2, \ldots, r_K): \sum_{i=1}^{K} r_i = r \quad ,$$

where r_i is the number of item defects in the i^{th} facility, and the payoff function is the probability of detecting an item defect. Under the assumption that the n_i can be considered as continuous variables, the inspector has a pure strategy (all facilities inspected with the same sample size at each inspection) that is at least as good as any random strategy.

Proof

Let N be the number of items in each of the K facilities, n the total number of sampled items to be selected from the K facilities, and save resources while maintaining a probability of anomaly detection. Extended surveillance could be achieved with current technology by chaining cameras so that when one camera reaches the end of its film, another camera activates.

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Proof

Let N be the number of items in each of the K facilities, n the total number of sampled items to be selected from the K facilities, and r the total number of defected items to be determined by the operator.

For attribute sampling, the probability of detecting at least one defective item among the K facilities is

$$P[(n_1, \ldots, n_K); (r_1, \ldots, r_K)]$$

$$= 1 - \prod_{i=1}^{K} \prod_{j=0}^{r_i - 1} \left[1 - \frac{n_i}{N - j}\right] \quad .$$

Because $\partial p/\partial n_i \partial n_m < 0$ for $1 < i, m < K$, P is a concave function of the sample size variables.

If p_j is the probability that the inspector chooses the sample distribution $n_j = (n_{1j}, n_{2j}, \ldots, n_{Kj})$, where $\Sigma p_j = 1$, and q_k is the probability that the State chooses the defect distribution $\bar{r}_k = (r_{1k}, r_{2k}, \ldots, r_{Kk})$, where $\Sigma q_k = 1$, then the detection probability is

$$\sum_k q_k \sum_j p_j \; P(n_j; \bar{r}_k) \quad .$$

By the concave property of P

$$\sum_k q_k \sum_j p_j \; P(\bar{n}_j; \bar{r}_k) \leq \sum_k q_k \; P(\sum_j p_j \; \bar{n}_j; \bar{r}_k) \quad .$$

The sum

$$\sum_j p_j \; n_j = (\Sigma \; p_j \; n_{1j}, \ldots, \Sigma \; p_j \; n_{Kj})$$

represents a nonrandom strategy in which the sample size $\Sigma \; p_j \; n_{ij}$ is applied at each inspection of the ith facility.

This demonstrates that, for any random strategy for the inspector, there is a corresponding nonrandom inspector strategy that is at least as good.

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