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Use of Mailbox Approach, Video Surveillance, and Short-Notice Random Inspections to Enhance Detection of Undeclared LEU Production at Gas Centrifuge Enrichment Plants

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ABSTRACT

Current safeguards approaches used by the IAEA at gas centrifuge enrichment plants (GCEPs) need enhancement in order to detect undeclared LEU production with adequate detection probability. "Mailbox" declarations have been used in the last two decades to verify receipts, production, and shipments at some bulk-handling facilities (e.g., fuel-fabrication plants). The operator declares the status of his plant to the IAEA on a daily basis using a secure "Mailbox" system such as a secure tamper-resistant computer. The operator agrees to hold receipts and shipments for a specified period of time, along with a specified number of annual inspections, to enable inspector access to a statistically large enough population of UF_6 cylinders and fuel assemblies to achieve the desired detection probability. The inspectors can access the "Mailbox" during randomly timed inspections and then verify the operator's declarations for that day. Previously, this type of inspection regime was considered mainly for verifying the material balance at fuel-fabrication, enrichment, and conversion plants. Brookhaven National Laboratory has expanded the "Mailbox" concept with short-notice random inspections (SNRIs), coupled with enhanced video surveillance, to include declaration and verification of UF6 cylinder operational data to detect activities associated with undeclared LEU production at GCEPs. Since the "Mailbox" declarations would also include data relevant to material-balance verification, these randomized inspections would replace the scheduled monthly interim inspections for material-balance purposes; in addition, the inspectors could simultaneously perform the required number of Limited-Frequency Unannounced Access (LFUA) inspections used for HEU detection. This approach would provide improved detection capabilities for a wider range of diversion activities with not much more inspection effort than at present.

I. Introduction

Uranium enrichment is one of the methods by which a State can obtain nuclear materials usable in nuclear weapons. Since the gas centrifuge enrichment process is one of the most versatile enrichment technologies, the International Atomic Energy Agency (IAEA), often referred to herein as the Agency, must apply effective and efficient safeguards at gas centrifuge enrichment plants (GCEPs) located in Non-Nuclear Weapons States to detect and deter the proliferation of nuclear weapons.

There are three principal safeguards concerns at gas centrifuge uranium enrichment facilities declared for the production of low-enriched uranium (LEU, with <20% U-235). These are:

1. Production and diversion of a significant quantity of uranium with enrichment greater than declared (in particular, highly enriched uranium (HEU) with ≥20% U-235).

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2. Diversion of a significant quantity of declared uranium (particularly in the form of LEU product).
3. Production of LEU in excess of declared amounts (e.g., using undeclared feed).

The goal of IAEA safeguards is the timely detection of diversion of a significant quantity (SQ) of nuclear material. The IAEA defines an SQ of U-235 contained in LEU and in HEU as 75 kg and 25 kg U-235, respectively. The IAEA defines the timeliness goal for detecting a diversion of U-235 contained in LEU as one year and in HEU as one month. For LEU, the IAEA goal is to detect, within one year and with a 50% detection probability, the diversion of 75 kg of U-235 contained in LEU. For HEU, the goal is to detect, within one month and with "high confidence", the undeclared production of 25 kg of U-235 contained in HEU.

In 1980, the centrifuge technology holders and the international inspectorates (i.e., the IAEA and Euratom) undertook the Hexapartite Safeguards Project (HSP) to reach an agreement on an international safeguards approach for GCEPs. The HSP participants included the IAEA, Euratom, the United States, Japan, Australia, and the URENCO partner States (United Kingdom, Germany, and the Netherlands). After 2-1/2 years of intensive study, from November 1980 to March 1983, the HSP agreed on an approach for gas centrifuge enrichment plants subject to INFCIRC/153-type agreements[1]. This approach includes inspection activities outside cascade halls (primarily to detect diversion by verification of declared nuclear-material flows and inventories) and inside cascade halls (primarily to detect production of HEU).

The activities inside cascade halls are based on a Limited-Frequency Unannounced Access (LFUA) approach. During an LFUA inspection activity, the operators agreed to provide inspectorate access to the cascade halls within two hours, either during the course of an announced routine inspection or on a completely unannounced, random basis.

The activities to be performed by the Agency and Euratom outside cascade halls to verify the declared nuclear material balance were based on traditional techniques, including examination of records and reports; gross, partial, and bias-defect verification measurements of relevant nuclear materials; and the application of containment and surveillance techniques to maintain continuity of knowledge. The HSP also agreed that provisions should be made to give the Agency(s) the opportunity to verify the feed, product, and tails before they are fed to, or shipped from, the plant. The HSP declared that the mode of inspection would be intermittent. For facilities up to about 1000 metric tonnes of separative work units per year (MTSWU/yr), the average frequencies of routine inspection visits for activities outside and inside the cascade areas were expected to be in the range of 12-15 times per year, and 4-12 times per year, respectively.

The conclusions of the HSP have been the basis for IAEA safeguards at gas centrifuge enrichment plants since 1983. The HSP did not address the question of undeclared feed. The current IAEA safeguards approach at gas centrifuge enrichment plants does not involve any specific measures for detection of undeclared feed or the undeclared product and tails that might be produced from it. However, as a result of the IAEA "Programme 93+2", environmental sampling inside and outside the cascade halls emerged as an additional tool for the detection of HEU production. It was not until the April 2005 meeting entitled "Techniques for IAEA Verification of Enrichment Activities" that the IAEA addressed in earnest the issue of timely detection of excess production of LEU from undeclared feed and deterrence by risk of early detection. The latest draft safeguards approach by the IAEA addresses possible solutions to this problem. Brookhaven National Laboratory (BNL) has contributed to this effort by proposing use of an enhanced “Mailbox” approach combined with video surveillance and short-notice random inspections (SNRIs). The "Mailbox"/SNRI concept was first introduced by Gordon and Sanborn at BNL in 1984 for potential IAEA safeguards application at the Portsmouth Gas Centrifuge Enrichment Plant [2].

"Mailbox" declarations have been used in the last two decades to verify receipts, production, and shipments at some bulk-handling facilities (e.g., fuel-fabrication plants) [3]. The operator declares the status of his plant to the IAEA on a daily basis using a secure "Mailbox" system such as a secure tamper-resistant computer. The operator agrees to hold receipts and shipments for a specified period of time, along with a specified number of annual inspections, to enable inspector access to a statistically large enough population of UF_6 cylinders and fuel assemblies to achieve the desired detection probability. The inspectors can access the "Mailbox" during randomly timed inspections and then verify the operator's declarations for that day. Previously, this type of inspection regime was considered mainly for verifying the material balance at fuel-fabrication, enrichment, and conversion plants.

We have expanded the "Mailbox"/SNRI concept, coupled with enhanced video surveillance, to include declaration and verification of UF6 cylinder operational data to detect activities associated with undeclared LEU production at GCEPs. Since the "Mailbox" declarations would also include data relevant to material-balance verification, these randomized inspections would replace the scheduled monthly interim inspections for material-balance purposes; in addition, the inspectors could simultaneously perform the required number of Limited Frequency Unannounced Access (LFUA) inspections used for HEU detection. This approach would provide improved detection capabilities for a wider range of diversion activities with not much more inspection effort than at present at those declared centrifuge enrichment facilities under IAEA safeguards.

II. "Mailbox" Declarations for Material Balance Verification

In this portion of the approach, the operator would declare the final accountability values for feed, product, and tails cylinders on a daily basis; these declarations probably should be made by the nuclear-materials accountability staff so the values can be checked for completeness and correctness. The operator would also agree to hold the cylinders for an agreed period of time (called the "residence time"), after which the cylinders could be fed to the process or shipped. The IAEA would verify these declared values during the course of short-notice random inspections using the current traditional verification methods of weighing, gamma-ray non-destructive analysis (NDA), and sampling for destructive analysis (DA). The probability of detecting a falsified cylinder depends on the number of random inspections performed per year, the residence time, and the number of NDA and DA measurements performed.

We have used two methods for calculating detection probabilities based on the above "Mailbox" SNRI approach. The first is based on the calculations of Gordon and Sanborn[2]. The second is based on the work of Nishimura, who recently developed an alternative mathematical formulation at Nuclear Fuel Industries in Japan[4]. Both use the aforementioned concept of a "residence" or holding time for feed cylinders received at the plant and product cylinders to be shipped from the plant. The Sanborn-Gordon methodology notes that the probability (P_D) with which the IAEA will detect a falsified cylinder depends on the probability that any given declared cylinder is on site at the time of an inspection, and on the probability (P_G) that a falsified cylinder will be selected for verification if it is on site. The detection probability P_D is then given for each stratum (i.e., feed, product, and tails) by:

$$P_D = P_G * N\ T_2/MBP* \text{Integer}[(T_1 + (n-1)\ T_2 + T_3)/T_2 + 1] \tag{1}$$

where for each stratum:

P_D = probability that a falsified cylinder will be detected
P_G = probability of selection of falsified cylinder if on site
N = average number of inspections per year
n = number of cylinders that must be falsified to obtain a Significant Quantity
T_1 = cylinder residence or holding time, days
T_2 = cylinder filling or emptying time, days
T_3 = duration of a single inspection, days
MBP = Material Balance Period, days = 365 days.

The cylinder emptying or filling time is given by:

$$T_2 = MBP/(N_{cyl}) \tag{2}$$

where N_{cyl} equals the number of feed, product, or tails cylinders that move through the GCEP in the course of a year. One should note that the above approach assumes a simplified case of only one feed/withdrawal station per feed, product, and tails cylinder operating in the plant at a time. The probability of selecting a cylinder, P_G, is adjusted to give an overall detection probability P_D of at least 50%. For most of our calculations, the required value of P_G ranged between 60-80%, depending on the stratum. The value was selected on the basis of optimizing P_D to be close to 50% and maintaining a reasonable T_1 value all dependent on the average number of inspections per year, N. Then, based on the chosen value of P_G, we have calculated the number of NDA and DA measurements that must be performed to achieve it, using the standard IAEA method for such calculations[5,6].

$$n_s = N_{item}\ (1- \beta^{\ 1/m}) \tag{3}$$

where:

n_s = total sample size
N_{item} = the number of items in a stratum
β = non-detection probability = 1- P_D
m = M/x
M = goal amount, kgU of U235 = 75 kgU of U-235 for LEU
x = average nuclear material weight of an item in the stratum, kgU of U235.

This formula approximates the sample size that would result from application of the hypergeometric probability distribution (sampling without replacement). The IAEA allocates the total sample size among several IAEA accountancy verification methods, specifically methods for detecting gross, partial, and bias defects. In this study, we grouped both gross and partial defect methods together as the NDA measurements. The bias defect method includes the DA measurements. The relative standard deviation, δ, is the measurement uncertainty for the NDA or DA methods in the stratum and is chosen from the International Target Values[7]. The δ values are main factors in determining how many NDA versus DA samples are taken in a sample size of n_s.

The cylinder residence time, T_1, and the average number of inspections/year, N, were varied to obtain reasonable combinations of T_1 and N. Depending on N, the duration of a single inspection was estimated from knowledge of IAEA enrichment inspection activities and the time to fulfill them during a MBP.

Our second set of calculations used Nishimura's methodology[4], which defines the probability of detection, P_D, for each stratum as:

$$P_D = \quad 1 - [1\text{-}p\{1\text{-}(1\text{-}n/m)^{q}\}]^{mk} \tag{4}$$

where:

p = probability that an cylinder present is defective = D/N
N = number of cylinders processed during the material balance period
D = Number of falsified cylinders with gross defects = SQ/(γy)
SQ = Significant Quantity in kg of U-235; for LEU = 75 kgU of U-235
γ = Defect ratio = 1 (i.e., the size of the falsification is the entire content of the cylinder)
y = amount of nuclear material in a cylinder, in kgU-235
n = number of cylinders verified during an inspection (Note: n must be $\leq$ m)
m = number of cylinders present at any given time = NT/(MBP)
MBP = Material Balance Period, days = 365 days
T = residence time, days
k = number of inspections during the MBP
q = 1 (i.e., if a falsified item is measured, it will be detected by the NDA or DA)
δ = stratum relative standard deviation of measurement uncertainty for NDA or DA [7].

After determining the number of cylinders in each stratum to be measured per year (i.e., n*k) in order to achieve a P_D of at least 50%, we then calculated the number of NDA and DA measurements per year, using the methodology shown in the above Equation 3 with the appropriate δ for the stratum as briefly described above.

We calculated four cases with each method for a GCEP with a capacity of 1000 MTSWU/yr, with product assay of 5% and a tails assay of 0.34% using natural uranium (assay = 0.711%) as feed. We calculated reasonable values for T_1 and N from the Sanborn-Gordon method and then input these values into the Nishimura method to compare the probability of detection calculated and the number of measurements needed in each case to obtain the desired P_D of 50%. The use of both methods allowed us to compare differences in methodologies for SNRI. The results are in Figure 1 for 6, 10, 14, and 18 SNRIs per year with 32, 20, 14, and 11 days taken as residence times, respectively. It should be noted that for the Sanborn-Gordon schemes we assumed that the inspection effort for 6, 10, 14, and 18 SNRIs per year was equal to 5, 3, 3, and 2 days per inspection, respectively. The graph also compares the current regime of 11 Interim Inventory Verification (IIV) and 1 Physical Inventory Verification (PIV) with a nominal 30-day holding time to the SNRI Mailbox schemes.

The graph compares not only the number of inspections and cylinder holding times but also the cylinder measurement plans. The inspector must randomly select a certain number of cylinders during the year with the proper ratio of non-destructive assay (NDA) to destructive assay (DA) samples to reach the goal of $P_D = 50\%$. One notices that the number of DA samples for Sanborn-Gordon, Nishimura, and current safeguards (SG) approach are not significantly different. Both the Sanborn-Gordon and Nishimura schemes demand more NDA samples than the current SG scheme requires. However, the making of NDA measurements requires less inspection time than taking DA samples. Furthermore, DA samples are more expensive to analyze both in the length of time to get the results and the laboratory costs. Hence, an increase in NDA samples will not impact inspection resources to a great extent. It was also reassuring that both SNRI Mailbox calculation methods gave similar results starting from similar first principles but deriving their equations with slightly different assumptions.

One can see that one can save on inspection trips by using a small number of SNRIs. However, the holding time increases to levels that the operator would probably not want to tolerate. On the other hand, with more numerous inspections the holding time decreases but the number of inspection trips increases beyond what the Agency would prefer. Therefore an optimum should exist. With the number of inspections lying between 10-14, both the Agency and the operator should be able to function without onerous constraints.

III. "Mailbox" Declarations for Detection of Excess LEU Production

Next we consider the use of "Mailbox" declarations as an aid in detecting the production of undeclared LEU from undeclared feed. In this case, the IAEA must detect the presence of undeclared feed, product, and/or tails cylinders attached at the cascade feed and withdrawal stations. A potential way of achieving this would include "Mailbox" declarations of declared cylinder operations, coupled with short-notice or unannounced random inspections and video surveillance of feed, product, and tails cylinders attached at the feed and withdrawal stations. In this approach, the operator would enter data regarding the declared feed, product, and tails cylinders on a near-real-time basis into the "Mailbox" computer. The data to be entered for each cylinder would include the cylinder identification number, the feed/withdrawal station number, the cylinder gross-full weight, and gross-empty weight (as applicable), the nominal U-235 concentration, and the times and dates of cylinder connection and disconnection. The IAEA would then perform random inspections to confirm these declarations. The video surveillance of cylinders attached at the feed/withdrawal stations would detect attempts by the operator to remove undeclared cylinders during the time interval between the announcement of the inspection and subsequent IAEA access to the feed/withdrawal area. In this case, these cameras need not operate continuously; rather, they could be activated by the IAEA at the onset of the random inspection. Alternatively, the cameras could be operated continuously, in which case the video records could verify on a daily basis the "Mailbox" declarations of the operator with respect to how many cylinders are connected to the process. The video also could detect activity around the feed and withdrawal stations that would be signs of undeclared activity such as unusual maintenance work indicative of attempts to feed and withdraw UF_6 by unorthodox means to circumvent the safeguards system.

The probability of detection of undeclared cylinders depends on the frequency of random inspections and how long the undeclared cylinders are attached to the cascade. The latter depends on how much separative capacity is devoted to undeclared LEU production. It would be unlikely that the operator would devote the entire plant to undeclared production. As an example, assume that the operator has understated his separative capacity by 20%. Thus, in the example 1000 MTSWU/yr GCEP described above, it will take 75 kgU-235/4.08 kgU-235 per day or 18.4 = 19 days to produce a Significant Quantity of undeclared LEU; during this time, undeclared feed, product and tails cylinders will be present. We also assumed that the operator will not perform undeclared operations when he knows for sure that the IAEA will be present, namely, at the annual PIV (assumed to take place over a 14-day period). Thus the time available for undeclared feed and withdrawal operations is 365-14 = 351 days. The detection probability P_D is given by:

$$P_D = 1 - (1 - T/T_0)^r \qquad (5)$$

where:

r = number of random inspections
T_0 = total number of days when the undeclared feed/withdrawal would take place = 351
T = total days when falsified cylinders are present = 19

For P_D to be equal to 50%, the IAEA must perform 13 SNRIs during the year (see Figure 2). Thus, in this example, while the Agency could perform fewer inspections during the year and still verify the declared material balance, the Agency would need to do at least 13 SNRIs during the year to have timely detection of excess production of LEU from undeclared feed. Of course, if the operator used less of his separative capacity for undeclared LEU operations, then the IAEA could achieve its goal with fewer inspections.

IV. Conclusions

The IAEA previously has considered the Mailbox/SNRI inspection regime mainly for verifying the material balance at fuel-fabrication and enrichment plants. BNL has expanded the "Mailbox" SNRI concept, coupled with enhanced video surveillance, to include declaration and verification of UF6 cylinder operational data to detect activities associated with undeclared LEU production at GCEPs. Since the "Mailbox" declarations would also include data relevant to material-balance verification, these randomized inspections would replace the scheduled monthly interim inspections for material-balance purposes; in addition, the inspectors could simultaneously perform the required number of Limited Frequency Unannounced Access (LFUA) inspections used for HEU detection. At present, the IAEA performs 6-10 LFUAs outside of scheduled inspections at present GCEPs. With the annual PIV and 11 IIVs, as well as pre-PIV activities, the IAEA is going to GCEPs up to 17-21 times a year without any capability to detect undeclared LEU production. Furthermore, Figure 3 shows how holding time could be reduced to the advantage of the operator with Mailbox/SNRI inspection regime. Hence, the proposed Mailbox/SNRI approach with a PIV and 14 SNRIs would provide improved detection capabilities for a wider range of diversion activities with equivalent or not much more inspection effort.

In the case of 14 SNRIs with a 14-day residence time, we have increased the inspection effort by a few inspections but reduced the holding time of the cylinders. The IAEA has responded to operator requests in the past to visit the facility and perform IIVs outside of the normal schedule or performed flow verification of product cylinders right after a LFUA so that an operator could ship out LEU on schedule to a fuel fabrication plant. The 14-day holding time may eliminate the need for such extra inspections. Furthermore, advances in safeguards technology may allow some of the verification activities to be done by unattended and remote monitoring systems to further save inspection resources and intrusion into the operator's routine. However, one should not lose sight of the value of having inspector presence at a facility to insure that verification activities are authentic and valid.

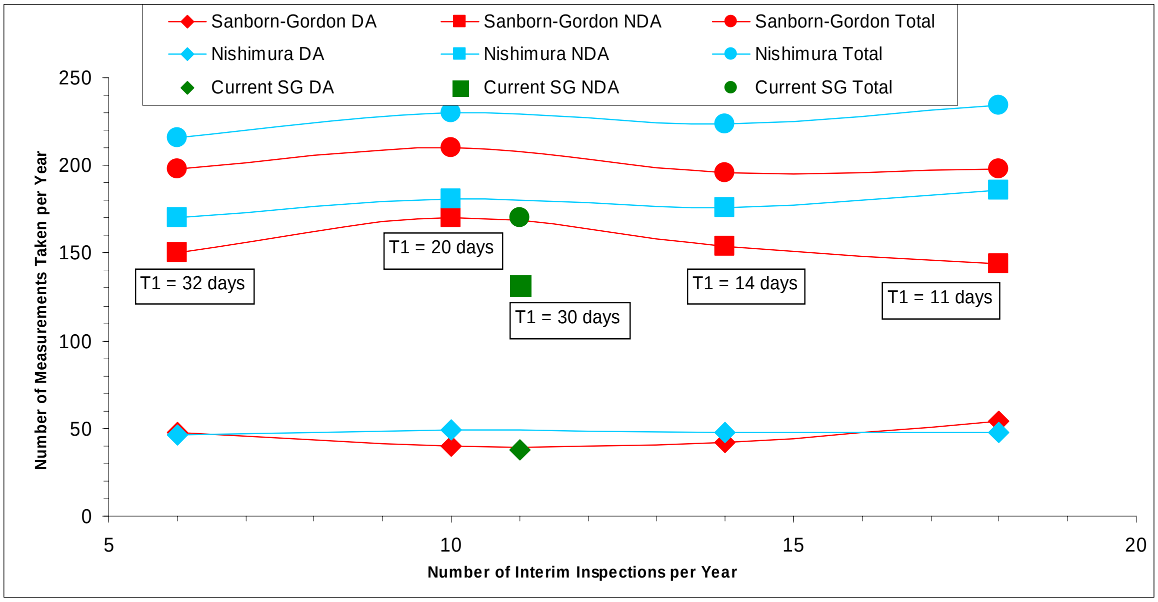

Figure 1: Frequency of SNRIs and Sampling Plans at an SNRI

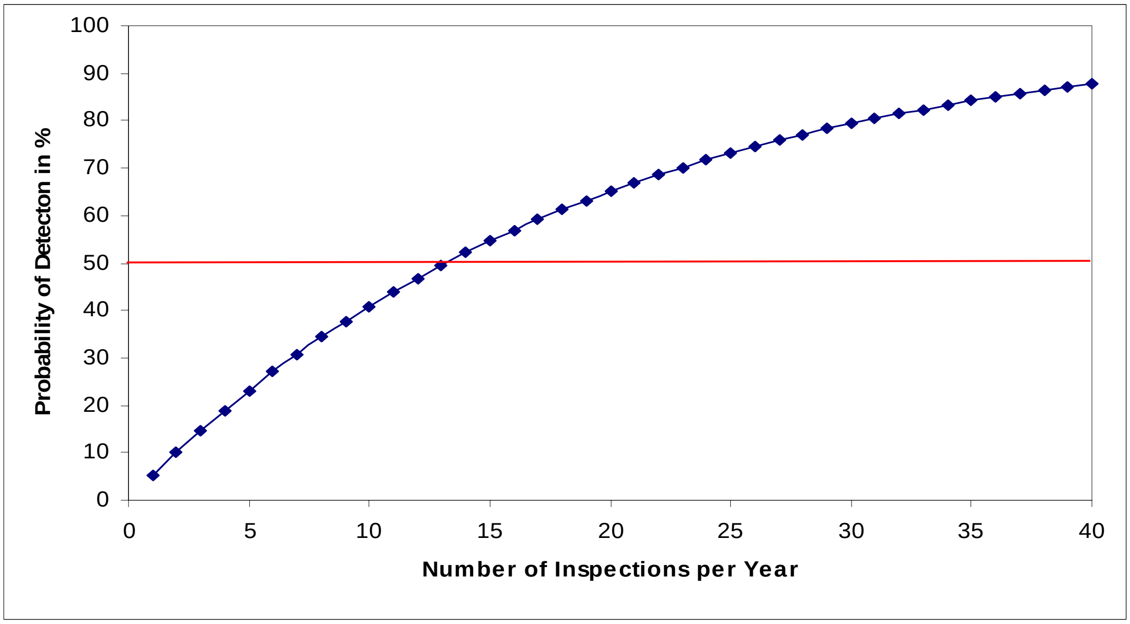

Figure 2: Frequency of SNRIs for Detecting Undeclared Activities

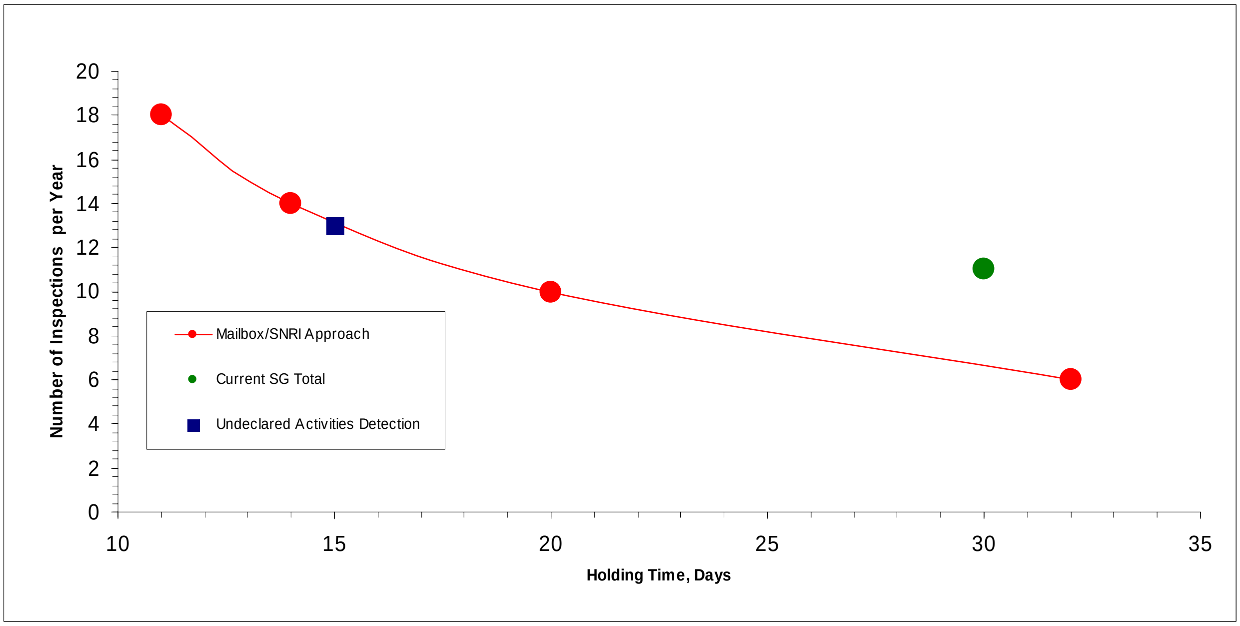

Figure 3: Comparing Frequency of SNRIs and Holding Time for Optimal Inspection Effort

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