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A REVIEW OF EXISTING MODEL OF NO-NOTICE RANDOMIZED INSPECTION AND THEIR POTENTIAL APPLICATION TO MODEL Pu HANDLING FACILITIES*

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Summary

Literature regarding two "alternative" safeguards concepts - randomization and zones - is reviewed. The concepts were introduced in the early 1980's to address the need to make safeguards more efficient in the light of the increasing number of facilities under safeguards and a fixed IAEA inspection budget. The paper discusses literature broadly relating these approaches to IAEA needs and objectives, reports from IAEA consultants meetings, reports of field trials, and other technical papers. The review suggests that the approaches have been extensively considered on a theoretical and practical level, and that the safeguards community endorses them on a conceptual level as potentially valid ways of achieving safeguards objectives. Actual utilization of the ideas in safeguards practice has to proceed on a case-by-case basis, but progress is being made.

1. Introduction

The purpose of this paper is to review the literature on randomization approaches and zone approaches to safeguards. These two topics are technically distinct, but address a similar issue and are often considered in combination or as alternatives; the 1991 consultants meeting described below, for example, treated the two topics together. The next section briefly discusses what these approaches are, and why they have been considered; section 3 describes four broad discussion papers that motivate the more technical discussions; section 4 discusses IAEA consultants meetings on the topic; section 5 discusses trials in five locations; section 6 considers a number of technical papers; and section 7 provides conclusions.

2. Background

Briefly stated, the issue addressed by alternative safeguards approaches is that constraints on IAEA inspection resources conflict with the increase in facilities and materials under safeguards, if safeguards are required to be (1) based fundamentally on facilities or MBAs and (2) required to be non-discriminatory in implementation at this level. While paragraph 81 of INFCIRC/153 allows for safeguards implementation to depend on the nature of the fuel cycle and the SSAC, such a dependence is not really consistent with technical safeguards requirements as reflected, for example in the 91 - 95 criteria.

One way, in theory, to address the technical problem of maintaining some level of effectiveness in terms of a capability of detecting diversion, while reducing inspection effort, is to use a strategy of doing inspection activities on a randomly selected basis rather than all the time on a fixed schedule. This broadly defined strategy is called "randomization." Because in most cases the essential element necessary for an effectively random approach is a short-

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notice or unannounced inspection, the term "short notice random inspection" (SNRI) is often used.

Another approach to the resource problem is to enlarge MBAs to cover multiple facilities, obviating the need for certain flow verification measurements between MBAs or facilities; this is sometimes called a "zone approach." Combinations of these strategies are also possible.

The following brief chronology summarizes the history of the development of these safeguards concepts.

- 1983 The Hexapartite Safeguards Project (HSP). The HSP endorsed a the "limited frequency unannounced access" strategy, a randomized inspection approach to detect undeclared HEU production.
- 1983 - 87 Canadian zone approach trial. This was reported in 1987; implementation of the zone approach continued.
- 1984 Initial IAEA consultants meeting on application of safeguards to multiple facility fuel cycles.
- 1987 American Nuclear Society meeting; Fuel Cycle Safeguards are considered in one session.
- 1988 General Electric SNRI Trial (USA)
- 1989 Korean Zone Trial
- 1990 NPT Review Conference. The Conference urged continued improvement in the efficiency and effectiveness of safeguards and that "this process be maintained *inter alia* by utilizing new cost effective technologies and methodologies. It invites the IAEA to consider studying new safeguards approaches, including, for example, randomized inspections."[1]
- 1991 The "91 - 95" criteria endorse (1) the concept of zone approaches with simultaneous PIVs and (2) randomized inspections to confirm the absence of borrowing and for the purpose of flow verification at fabrication facilities.
- 1991 Second Consultants Meeting on application of safeguards to multiple facility fuel cycles.
- 1993 Westinghouse SNRI trial
- 1993 - 97 The IAEA considers short notice inspections as an element of the "93+2" programme. The IAEA concluded[2] that unannounced (no-notice) inspections at strategic points at declared facilities (in states with comprehensive safeguards agreements) was within its existing legal authority. The 93+2 Protocol[3] allows for inspections at any place on a site in conduction with design information visits or ad hoc or routine inspections based on a two-hour notice.
- 1996 Swedish SNRI trial

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3. General papers on alternative safeguards approaches

The following four papers address, in general terms, the basic problem of IAEA resource constraints and the relevance of alternative approaches to safeguards.

Gruemm (1984)

Gruemm's article[4] considers potential ideas for improving the efficiency of the safeguards function, in light of IAEA resource constraints. He points out that the IAEA's approach to "non discriminatory" safeguards is to provide equal treatment for each facility of a certain type, and to verify the complete material balance of each type of MBA in an equivalent manner. He suggests that significant savings could result from abandoning the assumption that states harbor clandestine facilities, but concludes that it is improbable that such a drastic change in safeguards philosophy would find support. An alternative possibility is that of a randomized approach to similar facilities in a state; random selection of reactors for inspection, for example. Gruemm concludes that savings may be possible, but that study is need to determine any potential cost in terms of effectiveness

Higgenbotham, Gupta, DeMontmollin (1985)

The authors[5] suggest that, although INFCIRC/153 safeguards is technically based on individual facilities and material balance areas, the goals of detecting diversion should be considered at the state level. They suggest a zone approach to safeguards in which facilities in a state are grouped into three large MBAs corresponding essentially to LEU, spent fuel, and direct-use material. Savings could result from not verifying flows within these MBAs. Furthermore, effort for the new MBAs could be allocated according to the sensitivity of the material in each of them. Thus, safeguards for the LEU zone could consist of an annual PIV alone. They also suggest that the zone approach would benefit from and improved and more timely information and reporting system, and that the resulting information for flow patterns between facilities could provide useful information not available on an individual facility basis.

Petit (1987)

Petit[6,31] states that growth of Agency inspection resources is unlikely to keep pace with the growth in nuclear facilities and materials, suggesting that IAEA efficiency will have to double in terms of the amount of material safeguarded per inspection man-day. He concludes that there is no hope to solve this problem with the approach of uniform application of routine inspection to all similar facilities. He rejects the zone approach mentioned in the previous paragraph because of the impracticality of simultaneous inspections at multiple facilities. He suggests that activities performed at individual facilities be subject essentially to random selection.

Ek (1992).

Ek[7] reports on SAGSI discussions in the late 80s and early 90s on the topic of whether alternative safeguards; in particular the DDG asked SAGSI "... to re-examine how Agency safeguards are implemented in order to advise on ways to reduce costs while meeting new requirements and maintaining effectiveness." SAGSI reported that one way to do this might be fuller use of the state's SSACs, but that the IAEA could not delegate its responsibilities or its ability to arrive at independent conclusions. Other alternative safeguards principles identified by SAGSI were "transparency" and "openness." These principles translated operationally into increased information in the form of declarations, and increased access by inspectors. Ek states that further analysis and field tests are necessary to determine how such principles can

be used in practice to increase effectiveness and efficiency. He notes that such a field test is planned in Sweden (see below; this test is essentially a test of broadened declarations and short-notice inspection).

Moussalli (1996).

Moussalli[32] states that a significant reduction of the safeguards costs could result whenever short notice random inspections are implemented even if the current safeguards implementation regime is maintained.

4. Consultant's Meetings

1984 Consultants Meeting

The IAEA held an initial consultants meeting on "The Application of Safeguards to Multiple Facility Fuel Cycles" in 1984.[8] The purpose of the meeting was to "advise the Agency on investigations to be conducted on means whereby the characteristics of the fuel cycle of a state and entirety of the information available to the Agency concerning the fuel cycle might be more fully taken into account in the planning, implementation and evaluation of safeguard in order to improve the effectiveness and efficiency of safeguards." The meeting supported further testing of the concepts of random selection of facilities and inspection activities, and further investigation of the zone approach. It did not recommend further investigation of conditioning safeguards criteria or diversion assumptions on the nature of the fuel cycle.

1991 Consultants Meeting.

The main purpose of the 1991 meeting[9,10] was to review progress made on the two concepts endorsed by the previous meeting, i.e., the zone and randomization concepts. The working group on the zone approach provided fairly definite and positive conclusions, endorsing the soundness of the basic technical concept of the zone approach, and recommended that the reduced intrusiveness of inspections connected with the zone approach should be recognized. It stated that the zone approach seemed most promising for the natural and LEU fuel cycles, and less promising for plutonium handling facilities. The conclusions of the working group on randomization were somewhat more equivocal, in part because the questions posed to them were framed largely in terms of random selection of facilities for inspection, as opposed to more sophisticated applications of randomization. The technical basis for randomized activities was endorsed, but a number practical problems (confidentiality in inspection planning, impact on inspector's morale, etc.) and presentational issues (e.g., how to report on goal attainment for a facility that was not selected as part of a randomized scheme) were also noted.

5. Field Trials

Canadian Zone Approach Trial.

The IAEA reported in 1987[11] on a four-year trial which implemented a zone approach for unirradiated uranium fuel, starting at the conversion plant, and ending at the reactor. The trial involved four bulk facilities and a large number of reactors. It was noted that flow verification between these facilities would require between 250 and 1000 inspection man-days per year. Furthermore, borrowing was considered a very credible diversion scenario, and a zone approach with simultaneous inventories could address this problem as well. The logistics of arranging for simultaneous or near-simultaneous PIVs posed a number of practical problems,

but these were largely overcome. Certain temporary "bridging measures" were developed for cases where inventories could not be scheduled precisely together. One element of these measures was the use of unannounced inspections. Thus, effectively simultaneous inventories were conducted for four years. The report attributes 8 extra inspection days per year to the requirements of the simultaneous PIVs, a small number in comparison to the alternative of flow verification.

General Electric SNRI Trial.

The General Electric LEU fuel fabrication facility in the U.S. was the site of a trial of the short-notice-random-inspection (SNRI) concept in 1989 - 1990.[12] The automated material accounting system, and large flows of material into and out of the facility made the GE plant an appropriate test bed. The objective of the trial was to verify the flows of material into and out of the facility, based on a randomized schedule of facility visits. The inspectors, however, were not able to measure full fuel assemblies, but did measure rods, and "...trace[d] the rods (to the extent possible) as the assemblies were constructed..." The inspectors also measured UF_6 flows into the facility and powder and pellets shipped from the facility. The randomized schedule was based on the concept that the materials in the flow strata would be held for a fixed "residence time" during which they would have declared values and were potentially available for inspection. The randomized inspection schedule was constructed so that, in theory, every element of a flow stratum had a non-zero chance of being inspected. Inspections were conducted on two hours notice; this involved the resolution of a number of practical problems. However, the report concluded that the "Agency has not implemented all the conditions for complete use of SNRIs" so that was "thus unable to reach its goal to verify 100% of the flows." One of the problems evidently referred to here is the lack of implementation of a "mailbox" declaration, corrected in the Westinghouse trial.

The Westinghouse SNRI Trial

A trial very similar to that at GE was held at the Westinghouse LEU fuel fabrication plant in the US in 1993.[13] As in the GE trial, the objective was flow verification by random selection of inspection times. The procedures included a carefully-implemented "mailbox declaration" whereby the facility declared values for items both by fax to the IAEA, and to a tamper-indicating computer on site. Thus values for items subject to verification were declared before the operator knew if an inspection was to occur. The strata included in the trial were UF_6 cylinders and assemblies; these items were tested for gross and partial defects by NDA. Eight inspections were carried out on a random basis over a period of about six months. Largely successful, the trial had encountered one problem with respect to the residence times of the items in the strata to be verified: a small percentage of the items were not subject to verification because the time between their creation or arrival at a declared value and their shipment or consumption by the process was too short.

The ABB Atom SNRI Trial.

A third trial of the SNRI concept for LEU fuel fabrication was held in Sweden in 1995- 96 at the ABB Atom AB facility.[14] There were significant differences between the Swedish trial and the two previous trials: (1) almost all material in the facility (not just flow strata) was available for verification (however, scrap and waste were not considered); (2) the facility was able to make *advanced* declarations on a weekly basis for the coming week; (3) the verification measurements were predominantly based on sampling and destructive analysis; (4) the method of stratification for verification purposes was based on the concept of a "project" or a fixed

batch of material for a given customer. This approach meant that the problems relating to "residence time" experienced in the two previous trials did not exist. On the other hand, it appears that the approach of verifying by "project" led to some difficulties (although it is not clear that these difficulties were inescapable): first, there was the possibility of substitution of material from one project to another, and second, the report states that resource constraints did not allow adequate detection probability for defects. The inspectorate was able to gain access to the process within 30 minutes. The report concluded very optimistically that the approach is cost-effective, strengthens safeguards, and is favored by the facility operator.

Korean LEU Zone Trial.

During 1989, a zone approach was implemented for one LEU fabrication plant and the eight reactors supplied by that plant.[15] The implementation of the simultaneous inventory was considerably eased by the fact that only two of the reactors had inventories of fresh fuel. The authors conclude that the inspection effort for the fuel fabrication facility was effectively halved by the use of the zone approach

6. Technical studies

This section presents a review of a number of largely technical papers on the zone and randomization approaches.

Extensive studies of zone and zone-like approaches was reported by Fishbone and Higgenbotham (1987).[16,17,18] There are a number of variants of the zone approach that can be conceived, and these are analyzed by these authors in a paper which considered facility-oriented safeguards, a partial-zone approach, a full zone approach, and two types of randomization.[19] In the basic form of the zone approach, verification of interfacility, intra-zone nuclear material flows are eliminated, and PIVs are performed simultaneously for all facilities within the zone. Material in transit at the time of the PIV must also be adequately verified. In an analysis of a fuel cycle consisting of one conversion plant, three fabrication plants, and 21 LWRs, the authors found a reduction of about 30% in inspection effort.

The first formal adoption of a randomized inspection scheme occurred in the context of the Hexapartite Safeguards Project (HSP). A paper by Menzel (1983)[20] summarizes the conclusions of the HSP, which negotiated a safeguards approach to centrifuge enrichment facilities. An important element of that approach is the use of randomized unannounced visits to the cascade hall for the purpose of detecting undeclared HEU production. The average frequency of such visits would depend upon the nature of each facility and how much time would be required to modify the cascade to produce significant quantities of HEU. The average frequency for inspector access to the cascade is given as 4 to 12 times per year.

Flow verification for centrifuge enrichment plants was the subject of a paper by Gordon and Sanborn (1984)[21]. This paper suggests a randomized scheme for verification of the flow of feed and product cylinders. The scheme introduced the mailbox/residence time concept, whereby cylinders would be held for possible inspection for an agreed period after a nuclear material value was irrevocably declared to a "mailbox." A fixed schedule of potential inspection dates is determined which allows each cylinder to be subject to possible inspection, and the inspectorate randomly chooses actual inspections from among those dates. A later paper by Murphey, Emeigh and Lessler (1991)[22] carefully reviews the conditions for statistical validity of an SNRI inspection plan. In particular, they review the conditions for validity of the detection probability in the Sanborn paper, pointing out that in practical circumstances these conditions -

such as short residence times - may not be achieved (this has in fact turned out to be the case in the field trials). The paper also points out the need to consider diversion strategies such as substitution. Fishbone, et. al. (1991)[23] describes the mailbox concept for nuclear material transfers, conditions for the validity of mailbox declarations, and practical conditions necessary for implementation of the concept. The problem of achieving a valid detection probability for flow verification in spite of practical problems such as short residence times was studied by Lu, Teichmann and Lu (1993).[24] This study is based on very realistic residence-time data, and shows the trade-offs between the residence-time distribution, expected number of inspections, and detection probability, for a number of possible inspection strategies.

Randomized strategies can also be applied to inventory verification. The question here is what level of object (e.g., facilities, MBAs, strata, items) should be the object of randomization, and how such randomization could be performed. Canty, Stein, and Avenhaus (1987)[25] consider randomized strategies in which facilities (or facility PIVs) are randomly selected for verification, using a game-theory model. The models parameters are (1) the effort to verify a facility (2) the probability of detecting a diversion, if the facility diverts and the inspector inspects that facility (3) the total inspection effort available. This model attempts to capture the whole fuel cycle at once and is hence not detailed (the effort spent on a facility cannot be altered to change the detection probability, for example, and there is no time dimension to the model). The mathematical results of the game theory analysis are complicated, and not easily summarized. The example the authors provide suggests a radical departure from Agency practice. Markin (1988)[26] considered a number of methods of randomly selecting inspection activities, and assessed their capabilities in terms of "statistical effectiveness" (improved detection probability with fixed inspection resources) and "safeguards effectiveness" (conformity to the SIR criteria). It is pointed out that in many cases the criteria are structured so that improvement in one may violate the other. The paper concludes that randomly selecting strata (or facilities) to be verified, instead of verifying all strata (or facilities) has the potential of increasing statistical effectiveness, while randomly assigning inspection effort when verifying all strata (or facilities) does not. This is true when there is a fixed overhead inspection effort cost associated with gaining access to a stratum (e.g., instrument calibration) or facility (e.g., travel time).

Mathematical models of randomized inspection timing, and how such inspections could fulfill timeliness goals, have been studied. Canty and Avenhaus (1991)[27] consider a game-theoretic model of randomized inspection timing at a facility such as a reactor spent fuel pool. For example, an inspector randomly chooses on which 4 of the 12 inspection opportunities (the beginning of each month) he will inspect. It is assumed that if material has been diverted, detection will occur with high probability. The authors choose "average time to detection" as the objective of the game (as opposed to probability of timely detection). They show that a randomized inspection strategy can achieve shorter average detection times than a fixed periodic inspection. The randomization is achieved by assigning probabilities to each set of potential inspection schedules (e.g., inspections on month 2, 5, 7 and 9 might be given a probability of 0.1). However, Sanborn (1992)[28] looked at the same scenario and arrived at a substantially different conclusion by making a slightly different assumption. It is shown that for a wide class of possible inspector strategies, the inspector cannot achieve a better average detection time than that of simple periodic inspection. The assumption in the Canty paper (and abandoned in the Sanborn paper) is that the adversary has to choose his time to divert before the year starts. When "probability of timely detection" is the criterion, then the optimal inspection strategy is to divide the year into intervals corresponding to the timeliness criterion

(e.g., three months for spent fuel) and to assign a fixed probability to inspections at the end of each period.

Finally, two papers by Lu and Teichmann (1991)[29] and Lu (1993)[30] provide a mathematical model of the interaction between the randomized inspection plan (either selecting inspection opportunities or selecting strata to be verified) and the probabilities of detection of diversion for the individual inspection opportunities or strata. It is pointed out that a given overall goal for probability of timely detection can be fulfilled in a number of ways, either by a fixed schedule of inspections at relatively low probability of detection per inspection, or using a randomized schedule of inspections at a higher probability. The former is suggested by IAEA criteria, while the latter will tend to involve less effort given the overhead necessary for performing an inspection.

7. Conclusion

While non-random, facility-oriented safeguards are posed in INFCIRC/153 as the basis for full-scope safeguards, the theory and practice of safeguards seems to be evolving in the direction of the ideas considered in this paper. The zone approach for natural uranium has been successfully implemented in Canada, and the principle of randomized inspections were endorsed by the 1990 NPT Review Conference and incorporated into the 93+2 Programme and Protocol. The IAEA has considered zone approaches and randomization schemes in two consultants meetings. A substantial body of technical literature exists on these topics. The issue no longer seems to be whether these methods are legitimate, but whether they can be applied in specific circumstances in such a way as maintain or improve safeguards effectiveness and efficiency.

Implementation of these methods to realistic situations for plutonium facilities seems to be one of the questions that has not been covered by the literature.

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