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Nuclear proliferation-resistance and safeguards for future nuclear fuel cycle

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A B S T R A C T

Corresponding to the world nuclear security concerns, future nuclear fuel cycle (NFC) should have high proliferation-resistance (PR) and physical protection (PP), while promotion of the peaceful use of the nuclear energy must not be inhibited. In order to accomplish nuclear non-proliferation from NFC, a few models of the well-PR systems should be developed so that international community can recognize them as worldwide norms. To find a good balance of 'safeguard-ability (so-called extrinsic measure or institutional barrier)' and 'impede-ability (intrinsic feature or technical barrier)' will come to be essential for NFC designers to optimize civilian nuclear technology with nuclear non-proliferation, although the advanced safeguards with high detectability can still play a dominant role for PR in the states complying with full institutional controls. Accomplishment of such goal in a good economic efficiency is a future key challenge.

1. Introduction

The demand for peaceful use of nuclear power is remarkably increasing, in particular, in order to ensure global energy security, preventing global warming. The number of fast neutron reactors should increase for the demand, and accordingly large scale fuel cycle for such reactors is to be required for efficient use of nuclear material resources, where much larger amount of plutonium than that in the present time must be recycled. In this context, very robust measures for nuclear security, namely nuclear proliferation-resistance (PR) and safeguards have to be taken to prevent nuclear proliferation. The proliferation resistant nuclear fuel cycle (NFC) impedes diversion by host states seeking to acquire nuclear weapons or other nuclear explosive devices. It is said that PR should be supported by intrinsic features of nuclear energy system and extrinsic, i.e. institutional measures. International Safeguards including comprehensive safeguards agreement (CSA) and additional protocol (AP) is the most effective institutional measures, although the other measures such as bilateral agreements, export control and multilateral supply/control system of nuclear materials can complement the non-proliferation regime. Since 2000, PR on nuclear systems against the increase in nuclear diversion risk has been discussed in international nuclear societies such as INPRO [1] and GIF [2], whereas the demand of the studies to pursue more effective and efficient safeguards system increases and is being discussed in safeguards communities. Optimisation of PR for NFC that should be accepted by international communities is to be studied and proposed. This paper discusses the proliferation-resistance concept for future NFC, including criteria of PR measures to be attained and an example study of the technologies to improve safeguard ability/detectability for reprocessing.

2. Weight of PR measures

In The Gen-IV PR&PP, the methodology is organized to allow evaluations to be performed at the earliest stages of system design [2]. The results are intended for three types of users: system designers, program policy makers, and external stakeholders. Program policy makers will be more likely to be interested in the high-level measures that discriminate among choices, while system designers will be more interested in measures that directly relate to design options that will improve PR&PP performance of the nuclear energy system. The measures employed in the methodology include the following 4 intrinsic (the first 4), and 2 extrinsic measures; proliferation technical difficulty (TD), proliferation cost (PC), proliferation time (PT), fissile material type (MT), detection probability (DP), detection resource efficiency (DE).

Whereas, the INPRO manual mentioned, 'it focuses on the subject of how to assess an Innovative Nuclear Energy System (INS) embedded in an existing (or planned) non-proliferation regime. It primarily guides the INPRO assessor to confirm that adequate PR has been achieved in the INS, but gives also some guidance to the developer of nuclear technology on how to improve PR [1]'.

It is commonly indicated in Gen-IV and INPRO that both intrinsic features and extrinsic measures are essential. However, the

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weight of each intrinsic and extrinsic measure may differ, depending on the political background and degree of institutional system employed of the states. For instance, non-nuclear weapon states, well-developed, under Integrated Safeguards (CSA + AP), i.e. providing itself very high detection probability in a very efficient/effective manner, they may have not only much less chance but also very little intension to divert nuclear materials because of much more benefit in staying in normal trading nations than turning into nuclear weapon states. In this case, the weight of intrinsic measures can be much lower than that of the extrinsic ones. In contrary, in the case of a state which intends to clandestinely possess nuclear weapon, it probably does not enter AP into force, referring to all the recent events (in DPRK and the middle-east countries) of suspected undeclared nuclear program happening without ratification of AP.

A study is made for both the cases; Fig. 1 shows PR on a conventional nuclear fuel cycle under only CSA, whereas, Fig. 2 gives PR on an advanced nuclear fuel cycle under CSA and AP (& integrated safeguards). Detection of either clandestine activities or diversion in a timely manner is difficult with checking the declaration of nuclear materials in the former case, while it is most probable that any trial of diversion/activities to acquire nuclear weapon is detected in a timely manner for the latter case because of so many check-points.

It is found from the above-study that in order to protect nuclear proliferation from nuclear energy system, in particular NFC, strengthening institutional barrier such as ratification of AP and introducing advanced technology that includes robust PR technical difficulty based on the complexity of process or material may be minimum requirement. The technical barrier should function not only to slow down the acquisition of nuclear weapon, but also to discourage any clandestine trial of the acquisition because of timely detection (high detectability) of such an activity, or even for the policy turnaround or abrogation of the international agreement(s). A kind of standard packages of barriers consisting of the main measures for material quality (MQ***l***), material quantity (MQ***t***), material form (MF), institutional structual arrangement (IA), and Detectability (DT) for INPRO (or TD, MT, PT and DP in

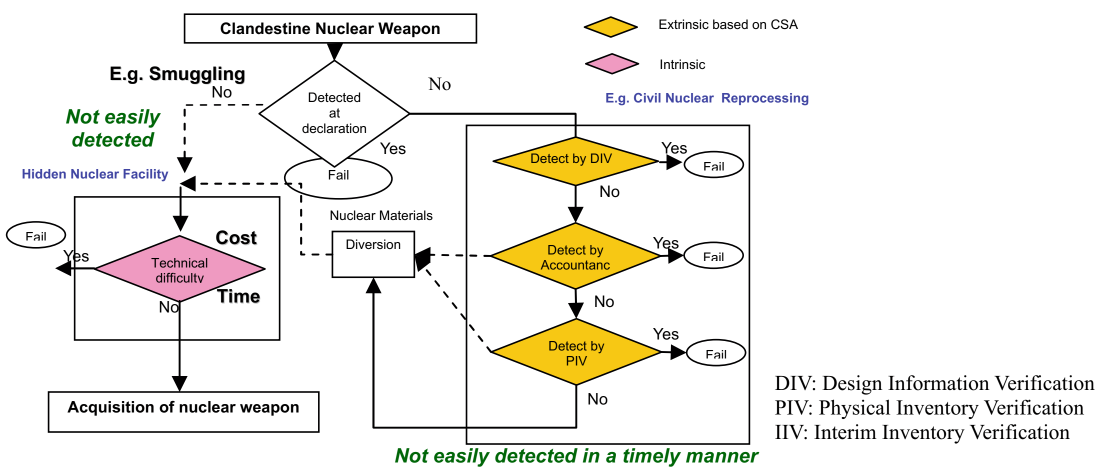

Fig. 1. Proliferation-resistance on conventional nuclear fuel cycle under comprehensive safeguards agreement (CSA).

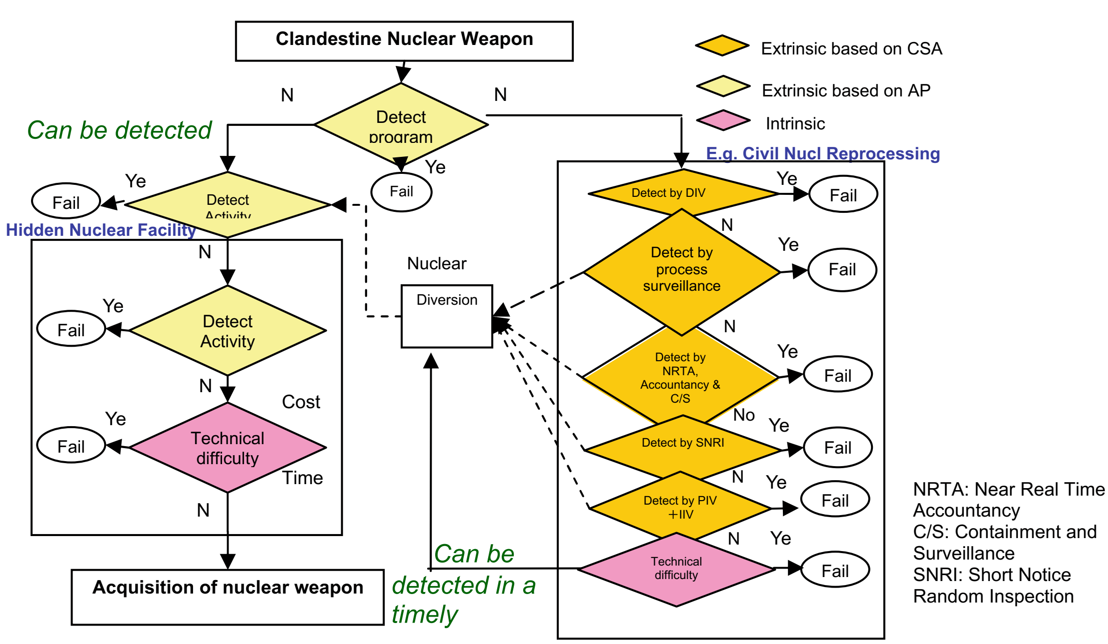

Fig. 2. Proliferation-resistance on advanced nuclear fuel cycle under CSA and additional protocol (& integrated SG).

Gen-IV) should be developed so as to establish internationally-accepted PR norms.

3. Realization of high detectability

As given in the manual [1], safeguards, rationally and well applied, has been the most efficient way to detect and deter further proliferation and to provide state parties with an opportunity to assure others that they are in conformity with their safeguards commitments. For States with safeguards agreements and additional protocols in force, the IAEA aims to provide assurance not only regarding the non-diversion of nuclear material for weapons purposes, but also of the absence of undeclared nuclear material and activities.

Japanese Plutonium Fuel Production Facility has been rehearsing operation of the effective and efficient integrated safeguards systems [3], whereas Rokkasho reprocessing employed many devices for the improvement of detectability [4]. Future NFC (e.g. large Pu throughput reprocessing) should have high detection capability for (i) acquisition of nuclear materials, (ii) modification of facility, (iii) undeclared nuclear fuel production, (iv) undeclared nuclear activity, and (v) misuse of facility in timely, efficient and effective manners. Those all should be covered by the following safeguard-ability ideas;

- more accurate and timely accountancy
- higher detectability of diversion, process modification etc.,

Future safeguards system may be able to realize ‘more accurate and timely accountancy’ in effective/efficient manners with;

(A) Small process inventory.
(B) Accurate interim inventory taking/verification (IIT/IIV) in practically possible frequency, (since the presently employed IIT/IIV may not function as accurate accountancy/verification of nuclear material inventory like physical inventory taking/verification (PIT/PIV)).
(C) Rapid DA measurement for verification like the idea of on-site safeguards laboratory.
Higher detectability in effective/efficient manners can be realized by;
(D) More intrusive design information questionnaire/verification (DIQ/DIV).
(E) Near real time accountancy (NRTA) to RTA with more sophisticated monitors/sensors.
(F) Real time process monitoring with remote monitoring (unattended mode) – connected to containment and surveillance (C/S), Non-destructive analysis (NDA) etc for RTA – for detection of process condition change, process modification etc.
(G) Random (unannounced) inspection.

Those challenges on the improvement of safeguard-ability are to be accomplished by the following proposals;

- All the concepts mentioned above (A–G) are incorporated into the design of facilities, i.e. ‘safeguards by design’ with some extension of existing technologies.
- The item B can be realized by employment of more vessels keeping accountancy-specification that is capable of measuring nuclear materials in an accurate and cost effective manner such as isotopic dilution method that can cancel bulk (volume) measurement errors [5]. Complementally accountancy-friendly operational mode (e.g. computerized solution control) can ease to locate major nuclear material-contained solution to the above mentioned vessels at IIT/IIV.
- To realize the item C in a cost effective manner, quality audit system to the State System for Nuclear Material Accountancy and Control (SSAC) on-site-laboratory can be employed as an alternative to the IAEA-inspector’s Destructive Analysis (DA), although the DA for the nuclear material accountancy by the operator should remain unchanged.
- For the item E (RTA), a direct and real time concentration/isotopics monitor of Pu/U/H^+ (a combination of voltanmetry and density measurement [6]) together with exiting NDAs and advanced solution monitoring can provide plant operation details in real time mode.

One calculation was made to demonstrate the effectiveness of the above-proposal, by taking an example of 12 tons Pu annual throughput reprocessing, with 60 kg size input tank (200 batches/year), 15 kg size output tank (800 batches/year)

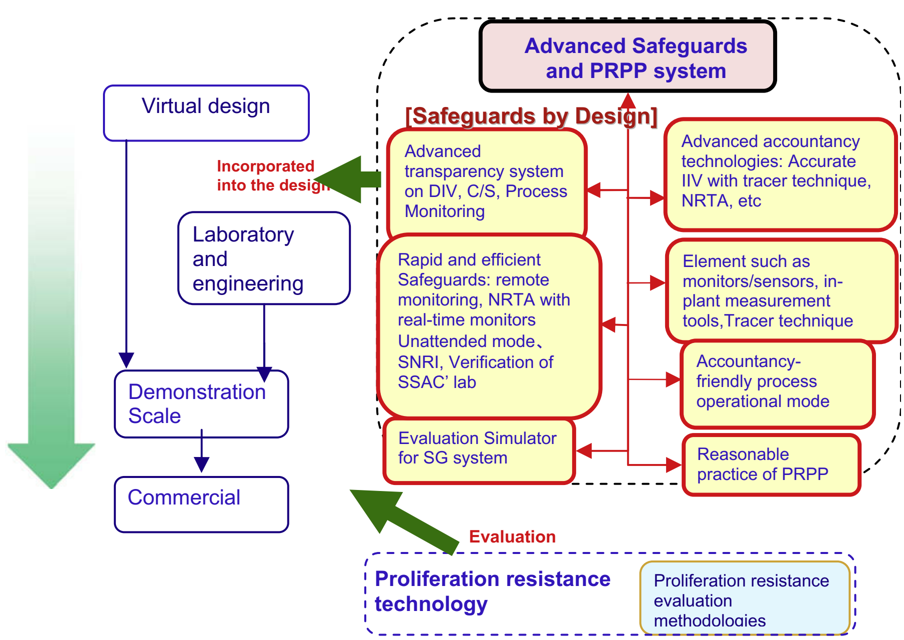

Fig. 3. Summary of high detectable safeguards system for designing NFC.

Table 1
Minimum requirement (shaded region) of PR measures in reprocessing (Pu).

<table>
<tr><td colspan="7">Extrinsic measures</td></tr>
<tr><td rowspan="2">Indicators</td><td rowspan="2">Evaluation Parameter</td><td colspan="5">Evaluation scale</td></tr>
<tr><td colspan="3">W</td><td colspan="2">S</td></tr>
<tr><td rowspan="2">Institutional structural arrangements (IA)</td><td>Safeguards Agreement</td><td colspan="3">No or CSA</td><td colspan="2">CSA+AP</td></tr>
<tr><td>Other institutional arrangement on NM</td><td colspan="3">No</td><td colspan="2">Yes</td></tr>
<tr><td>Detectability (DT)</td><td>NM diversion, Misuse
Process modification</td><td colspan="3">Low</td><td colspan="2">High (timely detection)</td></tr>
<tr><td colspan="7">Intrinsic measures</td></tr>
<tr><td rowspan="3">Indicators</td><td rowspan="3">Evaluation Parameter</td><td colspan="5">Evaluation scale</td></tr>
<tr><td>VW</td><td>W</td><td>M</td><td>S</td><td>VS</td></tr>
<tr><td>W</td><td colspan="2">M</td><td colspan="2">S</td></tr>
<tr><td rowspan="4">Material quality
(MQl)</td><td>Pu fissile composition</td><td>Weapon Grade</td><td colspan="2">WG>fissile >50%</td><td colspan="2"><50%</td></tr>
<tr><td>Radiation field(Dose)</td><td colspan="5">INPRO Manual[1]</td></tr>
<tr><td>Heat generation</td><td colspan="5">Ibid</td></tr>
<tr><td>Spontaneous neutron generation rate</td><td colspan="5">Ibid</td></tr>
<tr><td>Material quantity (MQt)</td><td colspan="6">Ibid</td></tr>
<tr><td>Material form (MF)</td><td>Chemical/physical form</td><td>Pu metal</td><td>POX/Pu Solution</td><td>No Pu - separated</td><td>Spent fuel</td><td>Waste</td></tr>
</table>

whose inventory is assumed 170 kg Pu. ITV-2000 values [7] were used for the measurement uncertainties of all the vessels (i.e., ideas of (A) and (B)), where uncertainty of volume measurement was assumed zero because of employment of the above-proposed isotopic dilution method. From the proposed conditions, the sigma MUF (the error due to measurement system) can be calculated as a time-function, i.e., by the measurement uncertainties on flow + inventory of nuclear materials, since MUF is expressed as (beginning inventory) + (adding material at input tank (flow)) − (subtracting the removals at output tank (flow)) − (ending inventory). It was found that the MUF (Material Unaccounted For) due to the measurement uncertainties can be controlled within 1 significant quantity at 95% confidential level for approximately 30 days if the first IIT/IIV takes place at the 30th day of the plant operation (i.e., between beginning/ending inventory taking). This implies that taking IIT/IIV in every 30 days enables to control nuclear materials within IAEA accountancy goal, which can be regarded realistically possible mode of operation for accountancy.

Improvement of the detectability was also confirmed with the same reprocessing example. 2–4 times higher detection probabilities were found by Markov model-based calculation [8] when the rapid measurement methods as proposed above and up-to-date C/S ideas were employed. Fig. 3 summarizes the high detectable safeguards system to strengthen PR barrier to be reflected to NFC design.

4. Guideline/norm of PR measures for NFC

As discussed in Chapter 2, the nuclear society should develop a kind of internationally-agreed norm or guideline to protect nuclear proliferation from NFC, which needs to be applied for all the states that have intention to introduce NFC. INPRO PR manual [1] proposed acceptance limit (AL) for each user requirement item, showing its criterion. However, it does not represent a whole package of guideline to be attained. We propose the following requirements as future NFC-PR basic, for the preparation of the case that a state wants to newly introduce NFC; (1) ratification of AP, (2) high detection capability as proposed in Chapter 3, (3) no presence of separated-Pu in NFC process, (4) no presence of weapon-grade Pu isotopics. Whole set of evaluation parameters proposed is given in Table 1. The ALs for the other evaluation parameters than those of the above mentioned requirements should be referred to INPRO. NFC, particularly reprocessing, is one of the weakest point among nuclear systems. Therefore, the requirement-1 should be obligatory, whereas, 2–4 may not be easily able to be forced to states where the states may advocate the NPT 4th article. Therefore, it appears that this idea can only be accomplished by establishing the worldwide technology norm of proliferation resistant NFC that should originally involve the above-proposed requirements in its design as a world standard. In this context, the PR-NFC also requires good economic efficiency (as equivalent to the conventional NFC) in order that this robust PR-NFC can be accepted by the states in both the categories.

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