NENE 2017 September 11-14 BLED-SLOVENIA
26th International Conference Nuclear Energy for New Europe

State Level Concept: Quantification of State Specific Factors

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ABSTRACT

This paper demonstrates a novel mathematical instrument for quantification of the Acquisition path analysis. The numerical estimation of the State-specific factor of nuclear fuel cycle of a state is proposed. Application of quantitative approach provides objective and impartial assessment of potential nuclear capabilities of the state.

1 INTRODUCTION

Nuclear fuel cycle (NFC) technologies are constantly improving, which provides new abilities for potential nuclear weapon production. Thus, it is important to increase reliability of the International Atomic Energy Agency (IAEA) safeguards by modification of the existing instruments and models.

One of the core developments of IAEA regulation system is State-level concept (SLC), which contains the comprehensive consideration of the State nuclear program aspects. This concept is realized by three main steps: 1) determination of State-specific factors (SSFs); 2) Acquisition path analysis (APA); 3) establishing of the effective safeguards measures. Further, in accordance with the results, State-level safeguards approaches (SLAs) are developed [1].

The IAEA expert group performs all abovementioned steps by means of qualitative evaluation of a state nuclear activity. It is evident that such approach is quite subjective and therefore receives criticism. In this respect IAEA suggests high-priority tasks to improve state characterization factors as well as acquisition path analysis and its implementation techniques as a part for Development and Implementation Support Programme for Nuclear Verification 2016-2017 [2]

2 STATE SPECIFIC FACTORS

SSFs represent the collection of information regarding to a State in accordance to its safeguards regulation approach. The factors are based on the actual information of the particular State and they are evaluated by experts within the safeguards implementation. In general, there are six factors [1,3]. However, APA requires only one SSF that corresponds to the nuclear fuel cycle and related technical capabilities of the State.

2.1 The numerical evaluation of the nuclear fuel cycle of the state

Due to the evident criticism of the SLC [4], this research suggests development of the specific characterization parameters of the nuclear fuel cycle of the state including establishment of the particular value for each of them (Table 1). The analysis of Russian and worldwide literature was carried out in order to prove the reliability of the created system [5-7].

Table 1: characterization parameters of the NFC

№	Parameter	NFC of the State	Numerical value
1	N_{NFC}	NFC stages number in edges chain	Pcs.
2	T_{NFC}	The NFC facility type, weighting coefficient	Ore mining – 0 Milling of ore – 0 Conversion – 1,5 Enrichment – 3 Fuel fabrication – 1,5 Operation: - LWR – 1 - GCR – 1 - PHWR – 1,5 - FBR –2 - Research reactor – 2 Reactor SNF storage – 1 Interim storage of SNF – 1,5 Reprocessing – 2,5 Final disposal – 0
3	N_{TRAN}	The number of ambient transactions	Pcs.
4	T_{MAT}	Nuclear material type at a site	Unit of account
5	Q	Nuclear material quantity at a site	Unit of account
6	TP_{OUT}	Principal possibility of theft capabilities at different stages of NFC, weighting coefficient	Presence – 1,25 Absence – 0,75
7	IE	Presence/absence of import/export of nuclear material and technologies at different stages of NFC, weighting coefficient	Import – 0,75 Export – 1,25 Absence – 1

Each of the parameters is discussed in more detail below.

Parameters #1 and #3 correspond to the quantity of NFC facilities and nuclear material transactions between these facilities. The increase of these numbers will make safeguards administration more difficult. The growth of the facilities number included in NFC leads to the increase of the possibilities of the diversion. The transaction is considered as one of the most critical stages of the NFC, due to the lack of monitoring and security measures. Thus, the risk of undetected theft increases.

Parameter #2 is proposed taking into account technical difficulties and proliferation time of nuclear material for each particular spent nuclear fuel (SNF) stage that are required for the diversion to nuclear weapon production.

The first considered stage is U or Th ore mining. The materials in such form are not included into the Common System of Accounting and Control of Nuclear Materials, due to the fact that it is not valid for nuclear weapon production.

The ore milling stage comprises the extraction of U from the ore and its further conversion into the uranium oxide powder. In general, uranium ore consists of large amount of naturally occurring additional elements that are further removed by special physicochemical procedures. The final product in this process is U_3O_8 – powder that contains 90% of naturally enriched uranium. At this stage material is suitable neither for nuclear weapon production nor for enrichment; both abovementioned processes require special conversion technologies [7].

Uranium conversion is the process in which natural uranium in the form of U_3O_8 powder is converted to UF_6, such form of uranium is appropriate for further isotope enrichment [6]. Despite the natural enrichment level of the nuclear material, the conversion stage is critical in terms of nuclear material proliferation due to the form of the final product.

Enrichment stage is the most sensitive and critical regarding to the production of nuclear weapon quality material, due to the fact that quality of nuclear material is determined by the percentage of the fissile isotope (U_{235} or Pu_{239}). Each of the existing isotope separation technologies allows to increase the fissile isotope content to more than 90%, which is sufficient for the production of nuclear weapons [7].

At the stage of the fuel fabrication the conversion of the enriched material to the form suitable for further exploitation in nuclear reactor is performed. The sensitivity of the stage mainly depends on the enrichment percentage, which is taken into account by corresponding weighting coefficients. The risk of the considered stage in terms of nuclear weapon production is related to the existence of the technology for conversion of the gaseous nuclear material into a solid that is sufficient for nuclear weapons [5].

The next stage of the NFC is the main process in nuclear power engineering. It is the operation of a nuclear reactor. The research is conducted within the framework of maintaining the international nuclear non-proliferation regime, thus the international classification of reactor types can be applied. The following types of reactors are discussed:

1) Light-water reactor (LWR) type includes the pressurized water reactor (PWR), the boiling water reactor (BWR) and the supercritical water reactor (SCWR). When we consider nuclear nonproliferation issues, it has to be mentioned that LWR has two main features: low-enriched uranium (3-5%) fuel (LEU) and poor breeding capabilities. However, the reactor core has significant amount of fuel due to its low enrichment level. This fact makes LWR potentially capable for clandestine nuclear program [8].

2) Gas-cooled reactor (GCR) type has the same characteristics as LWR in respect to proliferation application. [8].

3) Pressurized heavy water reactor (PHWR) has controversial properties: on the one hand, heavy water has low neutron absorption cross section, that allows to use natural uranium as a fuel and exclude the fuel enrichment stage from the NFC – all these facts significantly decrease proliferation risks. However, on the other hand, natural uranium has much better breeding potential due to conversion U_{238} isotope to Pu as result of neutron capture [8, 9].

4) The main feature of Fast breeder reactor (FBR) is a breeding blanket of fertile material (usually, natural or depleted uranium) that surrounds the core. The blanket allows to breed significant amount of weapon or sub-weapon grade Pu. Beside this fact, one more proliferation challenge related to FRB is the possibility to use MOX-fuel as fissile material. MOX-fuel consists of U and Pu isotopes that potentially could lead to diversion of fuel itself for military purposes. [9].

5) Majority of Research reactors (RR) use high-enriched uranium (HEU) as fuel. IAEA has initiated RR conversion from HEU to (LEU) [10]. Despite this fact, many of RR worldwide are still not engaged into this initiative.

The described classification of reactor types intentionally excludes industrial breeder reactors that were designed and tailored for weapon-grade plutonium breeding, because that type is operated in nuclear weapon states only.

Next stage of NFC is SNF reactor storage in a specialized pool at a reactor's site. This process has started immediately after a fuel load of a reactor is removed from the core and placed to a pool. Despite of SNF inherent security properties (due to high radiation hazard), it may have high percentage of Pu that can be used for military purposes. [5]. Taking into account the fact that decision to diverse a material to a weapon program is to be made by government, the possibility of application of specialized equipment for handling high-radioactive SNF has to be considered. The radioactivity of SNF is significantly decreasing after 3-5 years and, usually, spent fuel is transferred to dry or wet interim fuel storage facility. However, it has to be mentioned that inherent security level is decreasing as well. At the same time the Pu amount still remains the same [6]. So, proliferation risks on stage of interim storage are higher than during reactor storage.

The SNF reprocessing process could be used by a State for separation most valuable isotopes and further MOX-fuel production. Reprocessing stage is the most sensitive in respect to development of Pu-based nuclear weapon. Nevertheless, there are some limiting factors: high-radiation level, inseparable impurities etc. [11].

Any NFC has a back-end – disposal of radioactive wastes that has no valuable material and not supposed to have any use in further activities. So, wastes are useless in nuclear weapon production. Modern waste's immobilization technologies even more limit the possibilities of malicious use of wastes and prevent its' recovery [11].

Parameter #6 considers an increase of proliferation risks that is related to the theft capabilities of nuclear materials at different stages of NFC. Theft capabilities are understood as covered transfer of nuclear material from NFC for malicious purposes that cannot be identified during IAEA inspection.

Parameter #7 is dedicated to indicate presence/absence of import/export of nuclear material and technologies. Nuclear technologies import requires application of additional procedures of export control, thus decreasing the diversion attractiveness. Otherwise, an export of nuclear-related items highlights deep knowledge and know-how of a State and that significantly increases diversion possibilities.

"Nuclear material type at a site" (T_{MATi}) and "Nuclear material quantity at a site" (Q_i) are the units of account and descripted below by equation (1) and (2).

T_{MATi} consists of 5 factors, descripting the applicability of nuclear material for production of nuclear weapon. The parameter is based on multiplicative model (1) defined by the fact that the factors under consideration are interdependent and have strong mutual influence.

$$T_{MATi} = WG_i \cdot M_i \cdot R_i \cdot Ch_i \cdot Ph_i \,, \quad (1)$$

where WG_i – weapon grade nuclear material («no» = 1, «yes» = 100);

M_i – presence of inseparable impurities («no» = 1, «yes» = 0,3);

R_i – inherent security due to high radioactivity («no» = 1, «yes» = 0,3);

Ch_i – chemical form («metal» = 1, «ceramics» = 0,9 , «other composition» = 0,8);

Ph_i – physical state of a matter («gaseous» = 1, «solid» = 0,7 , «liquid» = 0,3).

WG_i is uranium with enrichment higher than 90% and plutonium that has in composition less than 20% of 238, 240, 241, 242 isotopes. Nuclear materials of such quality are called "direct use material" that allow to create a nuclear weapon without additional technological process.

The factor "M_i" defines presence of impurities that are inseparable at state-of-art methods. The impurities taken into account should influence the possibility of military application of nuclear material via significant increase of its' critical mass.

The inherent security – "Ri" is defined by quantity of short-lived isotopes.

"Ph_i" demonstrates the possibility of application of the current state of nuclear material to a weapon program. It is important to mention, that the highest value belongs to a "gaseous" state. Despite its unsuitability for direct use in nuclear weapon production, it allows to perform material enrichment.

To define a relative number of nuclear explosive devices that is possible to create, the nuclear material quantity has to be taken into account:

$$Q_i = \frac{m_{FISi}}{SQ_{ISi}}, \quad (2)$$

where m_{FISi} – fissile isotope mass;

SQ_{ISi} – IAEA Significant Quantity of the isotope.

Significant quantity is the approximate amount of nuclear material for which the possibility of manufacturing a nuclear explosive device cannot be excluded [12].

3 ACQUISITION PATH ANALYSIS

SLC' key stage is APA, that covers all technically possible acquisition paths of nuclear materials which are suitable for nuclear weapon production.

APA is performed in three stages: 1) paths' net modelling, based on IAEA experts review approach and physical model; 2) analysis of all possible paths of the developed net; 3) state strategic evaluation.

Mathematically modelled net is calculated in accordance with the graph theory [3]. Analogy between APA elements and graph theory is provided in Table 2.

Table 2: Element analogy

Graph theory	Acquisition path analysis
Node	Material form
Edge	Stage of nuclear fuel cycle
Path	Acquisition path
Edge weight	Attraction of an acquisition path

Qualitative approach to APA is based on the three factors of attractiveness [3] that have the roots in GIF methodology [13]. The attractiveness factors are evaluated by IAEA Expert Group by relative qualitative scale (from 0 to 3).

The modelled graph is analyzed in order to estimate paths attractiveness and costs on discovering all technically possible acquisition paths. This information is the basis to edge weight calculation. Further, the path attractiveness is calculated by totalizing each edge's weight [3].

3.1 Mathematical instrument of qualitative approach to Acquisition Path Analysis

The fundamentals of qualitative approach to APA is the set of parameters with appropriate numerical characteristics.

The multiplicative model is proposed for an edge weight calculation (ω_e). The model will depend from NFC stage and type and quantity of nuclear material at a facility:

$$\omega_{ei} = T_{NFCi} \cdot T_{MATi} \cdot Q_i \, . \quad (3)$$

Calculated value of ω_e is the most fundamental to identifying the possibility of nuclear material diversion of the particular stage of NFC.

Within the qualitative approach the equation of the general attractiveness is the following:

$$l_j = \frac{(\sum \omega_{ei} \cdot \sum IE_i \cdot \sum TP_{OUTi}) \cdot (N_{NFCj} + N_{TRANj})}{n_e}, \quad (4)$$

where n_e – path’ edge quantity

Quantitative evaluation of the general attractiveness of potential acquisition path will be more objective in comparison with qualitative approach, because quantitative approach is based on the set of weight factors and numerical characteristics.

4 APPROACH VALIDATION

The test was conducted on the Hypothetical State, in order to validate the set of parameters and mathematical instrument as the whole. The State has three potential paths for obtaining a nuclear weapon: #1 is based on HEU RR (enrichment rate is 90%); #2 – LEU RR (15%); and #3 – LEU LWR (5%).

The graph was modeled and the paths were prioritized as the result of APA.

After paths’ attractiveness comparison (Table 3), it was discovered that the most attractive path of nuclear material acquisition is path #1. Despite the path containing small quantity of nuclear material, it has “direct use” status. It is important to highlight that the mass of material at the path is exceeding the Significant Quantity and is allowing creation of the nuclear weapon within a rather short term. Moreover, the weapon-grade of U is the reason of high level of vulnerability of three edges at Path #1, at the same time Path #2 and Path #3 have only one high-risk edge.

Table 3: General attractiveness of potential acquisition path of nuclear materials

	Path #1	Path #2	Path #3
General attractiveness of path	26 383,41	390,34	11 063,37

The obtained results have proved the correctness of qualitative approach to APA, because the results of proliferation threat identification as at single NFC stages as at each path in general have discovered that qualitative and quantitative results coincide. The particular results related to research reactors had underlined the importance of IAEA “HEU-LEU” initiative.

5 CONCLUSION

The criticism of SLC focuses on the subjective evaluation of SSFs. The quantitative approach proposed in this study provides numerical evaluation of the potential paths of acquiring the nuclear material that enables the impartiality of the choice of IAEA safeguards for further implementation. The approach was successfully validated and the obtained results totally correlate with the prior risk qualitative assessment of NFC stages. In further work it is suggested to improve the quantitative approach by evaluation of each of the NFC stages separately in order to perform comparative analysis of the obtained results. Moreover, the approach can be modified by addition of the possibility to determine safeguard measures for each particular stage. The final version of the quantitative approach is to be implemented by a software.

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