Progress in Nuclear Energy 110 (2019) 75–79

Contents lists available at ScienceDirect

Progress in Nuclear Energy

journal homepage: www.elsevier.com/locate/pnucene

# Assessment of the impact of diversification of uranium switching on the risk of its non-energy use

Vasily Glebov

*National Research Nuclear University MEPhI, 115409, Moscow, Kashirskoe Shosse, 31, Russia*

ARTICLE INFO

*Keywords:*
Diversification of switching
Significant quantity
Low-enriched uranium
NM safe management
Insider

ABSTRACT

The main objective of the IAEA verification activities is the timely detection of the switching of a significant quantity of nuclear material (NM). However, from the point of nuclear security the multiple switching of "small" quantities of nuclear material with the aim of their subsequent collection also constitutes one of the main threat to ensuring the exceptionally peaceful use of nuclear materials. In this article this threat assessments were performed under the scenario of diversification of uranium switching. It is shown that diversification of 4%-uranium switching can lead to a substantial increase (up to 30 times) of the risk of uranium disuse even with carrying out proper uranium control and protection. However this effect is observed only when there are large opportunities to search for insiders (the search area is comparable to the existing set of nuclear facilities). The obtained results also prove that a reduction in the level of NM safe management at facilities could allow the collector to complete a chain of unauthorized actions with a significant probability ($P_{SQ} > 0.1$).

## 1. Introduction

In the problems related with NM safe management the threat to perform a chain of the unauthorized actions (UA) may be quantitatively assessed in the following risk terms:

$$R = P \cdot D, \quad P = P_{div} \cdot P_{man}, \tag{1}$$

where $P$ is a total probability to perform all UA with uranium-bearing materials; $P_{div}$ – probability of uranium switching from nuclear site; $P_{man}$ – probability to successfully complete a chain of out-site operations with uranium; D – potential damage caused by destructive application of a nuclear explosive device (NED), which can be evaluated in the term of the energy yield (Y). In the case of uranium, the energy yield depends mainly on uranium amount and uranium enrichment.

From the standpoint of NM safe management, any unauthorized switching of significant quantity (IAEA Safeguards Glossary, 2002) (SQ) of nuclear materials must be completely excluded. Within the frames of the risk assessment [Masterov et al., 2016] this means that:

$$R_{NED} \le R_{CED}, \tag{2}$$

where indices NED and CED are used to designate nuclear and chemical explosive devices respectively.

If the energy yield (Y) of NED is measured in equivalent mass of chemical explosives (TNT, for instance), then condition (2) can be rewritten in the terms of relative risk:

$$R(M) = P(M) \cdot Y(M) \le M, \quad M \in [M_0(x), M_1(x)], \tag{3}$$

where $M_0$ and $M_1$ are the lowest and the largest values of NM mass needed for NED manufacturing (Masterov et al., 2016). *P(M)* is a relative probability for NED manufacturing in the respect to probability of CED manufacturing.

So, the main mission of the system of NM safe management (and, first of all, NM control and protection system) is to reduce the relative risk *R(M)* in such a way that its value will never exceed the acceptable level.

The acceptance criteria conditions (2) were studied in (Masterov et al., 2016). If only the uranium diversion stage is considered, then the simplest relationship can be derived from general formula (1) to assess the risk of uranium switching for further NED manufacturing:

$$R(M, x) = P_{div} \cdot Y(M_f, x_f) = \exp(-\alpha \cdot M(x)) \cdot Y(M_f, x_f), \tag{4}$$

where $M$ - mass of the switched uranium; $\alpha$ - the effectiveness, which characterizes the action of control measures, per unit of the switched uranium mass.

As seen, for the fixed value of final uranium enrichment $x_f$, the diversion risk is a function of uranium mass and initial uranium enrichment $x$.

The energy yield $Y(M_f, x_f)$ produced by final uranium product was calculated with the application of the model described in (Mark, 1993). According to the model, the energy yield from the chain fission reaction (CFR) is proportional to the cubic degree of the exponent $\beta$ in time-

*E-mail address:* vbglebov@mephi.ru.

https://doi.org/10.1016/j.pnucene.2018.09.014
Received 27 April 2018; Received in revised form 22 August 2018; Accepted 12 September 2018
0149-1970/ 

dependency of neutron population growth:

$$Y \sim \beta^3 \quad, \beta = (k_{EFF} - 1)/l, \tag{5}$$

where $k_{EFF}$ - maximal value of effective neutron multiplication factor during CFR; $l$ - average prompt neutron lifetime. These parameters were determined by direct modelling of the neutron multiplication process with the application of Monte Carlo code MCNP-4B (Breismeister, 2000).

In the paper (Masterov et al., 2016) switching of the NM significant quantity from nuclear site was considered. This scenario meets the major technical purpose of the IAEA inspection activity in order to solve the non-proliferation problem.

Nevertheless, from the standpoint of nuclear security the diversions of insignificant NM quantities by a malicious person or group for their further accumulation can also represent a serious threat to ensuring the exceptionally peaceful use of nuclear materials. That is why this problem requires studying and taking precautionary measures. The purpose of this paper is to estimate the risk of uranium non-energy use under the scenarios of diversification of its switching.

The paper is organized as follows. The scenario of diversification and the model for accumulation of significant uranium quantity were considered in section 2. Section 3 introduces the metric for effectiveness of the control and protection systems. The results and discussion of modelling of multiple LEU diversions from nuclear sites are given further. Finally, the summary and conclusions are presented.

## 2. The model of diversification of uranium switching from nuclear site

### 2.1. Scenario for accumulation of significant uranium quantity by means of multiple diversions

Let N be a characteristic for total scale of nuclear activity in a country or region, i.e. N is the total number of nuclear sites and nuclear facilities where uranium is used under their own systems of uranium control and protection. A collector of illegal uranium investigates nuclear sites and tries to establish new contacts or use the already available contacts with the nuclear sites staff for further uranium diversion. Maybe, some staff members of nuclear sites, insiders, are able to commit UA with NM for the certain remuneration. The collector is not informed about the insiders, and their possible contacts with the collector should be considered as random events. The following question arises whether the probability for the illegal uranium collector to contact with insiders, have a deal with them on uranium diversion and, finally, accumulate significant uranium quantity is really great. Let us assume that the illegal uranium collector is the owner of sufficiently large material resources, and, therefore, (s)he is able for the agreement of financial remuneration for uranium diversion with the insider.

It is generally known that the major barrier created by nuclear security is an inaccessibility of nuclear materials in the respect to any UA. That is why administration of a nuclear site must pay much attention to the proper maintenance of high-efficiency NM control and protection system. This is a powerful barrier and deterrent for insiders in the respect of any UA with nuclear materials. So, it may be certainly assumed that

$$d \ll N, \tag{6}$$

where d – the total number of insiders at all nuclear sites.

Let k be a multiplicity for diversification of significant NM quantity. To analyze the impact of diversification on risk of unauthorized uranium application, we assume k = 2, 3, …, 10. A successful switching of significant NM quantity requires $k \leq d$. In accordance with limitation (6), the following inequality can be obtained: $N \gg k$. For the range of accepted multiplicity values k, the latter inequality may be re-written as $N > 10^2$.

### 2.2. Human factor effects on the risk of the unauthorized NM applications

The presence of insiders at nuclear sites depends on many factors including financial well-being of the staff members, labor discipline, political, personal and so on. Also, the number of insiders depends on general level of the nuclear security culture (Mladineo and Frazar, 2013) and real mass m of nuclear materials to be diverted. It is obvious that the larger m is the lower number of potential inner adversaries d, and vice versa.

The level of NM safe management may be estimated as high, if total NM amount $M_{div}$, which potentially could be diverted by all the insiders, would be lower the significant quantity (SQ). The following relationship

$$M_{div} = SQ \tag{7}$$

defines the exact upper value for the number of insiders (d = k) at high level of the NM safe management.

If the following inequality is correct,

$$M_{div} > SQ, \tag{8}$$

then, the level of NM safe management at nuclear sites should be estimated as low.

#### 2.2.1. In the case of insignificant quantity of insiders in nuclear sites

The probability to collect significant NM quantity can be obviously increased if the number of insiders d increases too. Therefore the upper value for the number of insiders (d = k) should be used to determine the upper value of the diversion risk from nuclear sites with high level of the NM safe management.

In general, the illegal uranium collector could investigate not all N nuclear sites but only n of them because of the limited capability for searching for insiders. In this case, the first question of accumulation of significant quantity calls for the following second question: how large is a probability for the illegal uranium collector to contact and agree with k insiders, if the search is carried out on a part of nuclear sites (n of N, $n \geq k$)? The question was answered in (Balakrishnan and Navzorov, 2003). The probability for the illegal uranium collector to contact with k insiders $P_{col}(k)$ is defined by hyper-geometrical distribution and, at high level of the NM safe management, is equal to:

$$P_{col}(k) = C_{N-k}^{n-k}/C_N^n, \tag{9}$$

where $C_a^b$ - binomial coefficients.

If uranium switching is diversified, then formula (4) for the diversion risk of uranium for future NED manufacturing should be re-written in the following form:

$$R(k, \alpha, n) = P_{SQ}(k, \alpha, n)\cdot Y(M_f, x_f) = P_{div}(k, \alpha)\cdot P_{col}(k, n)\cdot Y(M_f, x_f), \tag{10}$$

where $P_{div}(k, \alpha)$ – the probability of uranium diversion, when effectiveness of uranium control and protection system is equal to α; k – multiplicity for splitting of significant uranium quantity on several insignificant quantities; $P_{col}(k, n)$ – the probability to collect significant uranium quantity from n nuclear sites; $Y(M_f, x_f)$ – energy yield from final uranium state.

#### 2.2.2. In the case of significant quantity of insiders in nuclear sites

If the level of NM safe management is low, then the following inequality takes place: d > k. The probability for the illegal uranium collector to contact with $l$ insiders (from their total number d) is defined by general-type hyper-geometrical distribution:

$$P_{col}(l, d, n) = C_d^l\cdot C_{N-d}^{n-l}/C_N^n, \tag{11}$$

where $C_a^b$ - binomial coefficients.

Then, the probability of uranium diversion and accumulation of significant uranium quantity can be calculated by using the following