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Methodology for evaluating proliferation resistance of nuclear systems and its case study

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ABSTRACT

A new methodology for evaluating the Proliferation Resistance (PR) of a nuclear energy system is developed. Three top measures of PR are developed by categorizing all the factors that have major influence on PR property. These measures include: the legal & institutional framework of a nation, safeguardability, and material characteristics. The legal & institutional frameworks of a state is the basis for establishing a national regime of proliferation resistance, which include the NPT (Nuclear non-Proliferation Treaty), CSA (Comprehensive Safeguards Agreement), AP (Additional Protocol), and IS (Integrated Safeguards). Several attributes related to these international regimes are created to evaluate the legal & institutional framework. Another measure that determines the PR of a nuclear energy system is the characteristics related to the type of nuclear materials used and how difficult to convert them into weapons-grade material. The initial amount and enrichment level determine the period needed to manufacture weapons-grade nuclear material. Therefore, materials characteristics are essential measure for evaluating PR of a nuclear energy system. An evaluation table for this measure was developed based on the time required to create weapons-grade materials. The last measure used to assess PR is the safeguardability, which is an extrinsic measure evaluated by four attributes. These include, design information questionnaires (DIQ), nuclear material accounting (MC&A), containment & surveillance (C/S), and verification. Each attribute has three or four characteristics that should be considered for evaluation. The DIQ of nuclear facility should be submitted to the IAEA, if a state is a signatory of the NPT and has concluded the CSA with the IAEA. There are four characteristics for evaluating MC&A attributes, such as the uncertainty of material accounting results, annual throughput, amount of material unaccounted for (MUF) and near real time accountancy system. The C/S (Containment & Surveillance) attribute is determined by operational practice, installation of C/S equipment, and number of nuclear material movement paths. Verification is a process used to confirm whether or not there is a discrepancy between the nuclear materials that have been reported. Check lists are developed to evaluate each attribute of safeguardability measure. Case studies show that the developed methodology has well described the PR property of nuclear energy system.

1. Introduction

There have been many studies to develop methodologies for evaluating the Proliferation Resistance (PR) of a nuclear energy system. Most of them are qualitative, although some quantitative attempts have been carried out. However, no consensus has yet been made on the best way to evaluate proliferation resistance of a nuclear energy system and fuel cycle. The most common qualitative approach is the International Project on Innovative Nuclear Reactors and Fuel Cycle (INPRO) project leaded by the IAEA (IAEA document TECDOC-1575 Rev. 1, 2008). The second well-known approach is the proliferation resistance evaluation methodology developed by the GEN-IV PR/PP group (GIF/PRPPWG/2011/003, Rev.6, 2011). Although each study has its own analytical objective, there is an agreement to some extent as to which attributes are important in PR assessments. The concept of PR is considered in terms of intrinsic features and extrinsic measures. There are several attributes that should be considered for PR evaluation. Some examples of them include: the legal & institutional framework of a country, technical difficulty, detection probability, fissile material

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quality, and detection efficiency as well as proliferation time. Whether or not a state follows the international standards set up by the IAEA is an important criterion for evaluating PR. Technical difficulty, fissile material quality and detection efficiency are determined by how easily weapons-grade nuclear materials can be produced after the diversion of nuclear material. Detection probability is closely related to the material features that affect the decision on which detection system to be used for safeguards purposes. Safeguardability is the term that is used to represent the degree of ease with which a nuclear facility can be effectively and efficiently put under international safeguards (IAEA-STR-360, 2009). This attribute is unique because it is an extrinsic measure that can be enhanced through additional efforts. Though safeguards are important to guarantee the PR of a nuclear facility, previous studies on this subject did not pay much attention to its evaluation. It was mainly due to the fact that most safeguards approaches used in current nuclear power systems are determined by the IAEA, leaving little room for decision making of designers. However, for new nuclear fuel cycle systems, such as pyroprocessing, safeguards approaches have not been established yet. Therefore more research is required. In this study, a new methodology called COMPRE (COmprehensive Methodology for PR&PP Evaluation) is developed for evaluating PR of a state or nuclear energy system. This methodology is created by investigating various factors that affect PR and then categorizing them according to their unique features. Evaluation sheets for each measure drawn from this process are also developed. In order to demonstrate the methodology procedure, a case study on hypothetical nuclear facilities is performed. It is true that there have been arguments on evaluating proliferation resistance quantitatively. Proliferation resistance value of nuclear energy systems is not easy to be represented by a numerical score, since some factors that can't be calculated quantitatively are involved in. However, a quantitative evaluation methodology is very useful to compare proliferation resistance values of different nuclear energy systems intuitively. The COMPRE methodology developed in this study can be a useful tool for that purpose. In the COMPRE methodology, the additive aggregation method is used, which means that scores of all measures are added to evaluate the total score of the proliferation resistance for a facility. Since the net contribution from each measure can be identified clearly and intuitively by this way, the additive aggregation method has an advantage over other methods such as the multiplicative aggregation which might require more complicated interpretation (Choo and Wedley, 2008). By adopting the additive aggregation method, it is implicitly assumed that all measures are independent from each other and can be evaluated separately. Although a more delicate approach is required if there are nontrivial interactions among measures, the detailed analysis on this matter is left as a future work.

2. Development of measures

Several methodologies for evaluating PR have been developed since 1970s. Each of these approaches has its own advantages and disadvantages. Despite their differences the methodologies do share several important attributes. Two early studies, the International Nuclear Fuel Cycle Examination (INFCE) and the Nonproliferation Alternative Systems Assessment Program (NASAP), selected time, resources, detection probability and safeguardability as measures for examining PR (Spiewak and Barkenbus, 1980)(DOE/NE-0001/2, 1980). Another methodology, The Technological Opportunities to Increase the Proliferation Resistance of Global Civilian Nuclear Power Systems (TOPS) (US DOE document on TOPS, 2001), formulated a set of qualitative measures. TOPS classified evaluation measures into three categories, such as: material barriers, technical barriers and extrinsic barriers. Each category contains from three to six measures and these measures were used to develop other methodologies. The Simplified Approach for Proliferation Resistance Analysis of Nuclear Systems (SAPRA) was developed in France using similar measures as that of TOPS (D. Greneche, 2007). The PR&PP working group for the Generation IV International Forum developed another detailed methodology which selected six measures for PR evaluation, as shown in Table 1. Those were obtained by regrouping measures used in TOPS. The last example of developed methodologies is the INPRO methodology which defines one BP (Basic Principle) and five URs (User Requirements). In this methodology, PR assessment is carried out by using CRs (Criteria) which are subcomponents of the URs. All approaches mentioned above have focused on intrinsic features including: fissile materials types, technical difficulty, skills, expertise, knowledge and time required to divert or produce nuclear material. Although the PR of a nuclear energy system is greatly affected by intrinsic features, extrinsic measures, such as a state's commitments and implementation of safeguards, are also important factors. In this study, we place more emphasis on the extrinsic measures rather than intrinsic features in the course of developing measures for evaluating PR. There are three measures developed in this study: legal & institutional framework, safeguardability, material characteristics. Including the legal & institutional framework as a measure to evaluate PR is a controversial since it contains a political matter, but it can be used to compare the status of PR in different nations. Safeguards efforts such as MC&A, Verification and C/S are critical factors to evaluate PR because PR can be enhanced by those means. Material characteristics are selected as an evaluation measure since it is a crucial component to determine PR in terms of intrinsic features.

2.1. Legal & institutional framework

A state's legal & institutional framework regarding nuclear nonproliferation is an important factor in evaluating PR of a nuclear energy system. It is an extrinsic measure consisting of three categories: states' commitment, obligations and policies with regard to nuclear non-proliferation, domestic legal framework and competent authority.

The first category includes the international treaties and agreements such as the NPT, CSA (INFCIRC/153 (corrected), 1972), and the AP. The IAEA concludes CSA with all states that ratify the NPT. AP is another important step taken by the IAEA to achieve its safeguards objectives in a state, including the detection of undeclared nuclear materials and activities. After the IAEA assures that a state's nuclear activities are only used for peaceful purposes (broad conclusion), the Integrated Safeguards (IS) approaches can be applied. Therefore, the status on which kinds of approaches are applied to a state can be a useful measure for evaluating PR. The legal framework and competent authority are necessary in order to implement international agreements on nuclear non-proliferation. If a state has an independent legal system and a competent authority regarding nuclear non-proliferation, it can be said that PR is strengthened.

There are other attributes for evaluating legal & institutional framework, such as import/export control and regional cooperation. Table 2 shows attributes comprising legal & institutional framework measure. Quantitative results can be obtained since numerical values are assigned to each attribute.

2.2. Material characteristics

The characteristics of the fissile materials such as isotopic composition, chemical form, radiation level, volume and weight, as