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Framework for Proliferation Resistance and Physical Protection for Nonproliferation Impact Assessments

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March 2008

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ABSTRACT

This report describes a framework for proliferation resistance and physical protection evaluation for the fuel cycle systems envisioned in the expansion of nuclear power for electricity generation. The methodology is based on an approach developed as part of the Generation IV technical evaluation framework and on a qualitative evaluation approach to policy factors similar to those that were introduced in previous Nonproliferation Impact Assessments performed by DOE.

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1. INTRODUCTION

The National Nuclear Security Administration (NNSA) of the Department of Energy (DOE) is performing a Nonproliferation Impact Assessment (NPIA) to support the DOE Secretarial decision on how to proceed with the GNEP program. This report includes an overview of the PR&PP framework that is useful for comparing the nonproliferation aspects of alternatives. The NPIA and the Programmatic Environmental Impact Statement (PEIS) for GNEP are supporting studies for the Secretarial decision.

The assessment framework for the NPIA is based in part on the PR&PP evaluation methodology [1] that was developed as part of the Generation IV technical evaluation framework and on a qualitative evaluation approach to policy factors similar to those that were introduced in previous NPIA studies [2]. Taken together, the overall assessment consists of a short list of technical and policy factors. We note that the GNEP PEIS is a review of programmatic alternatives and the GNEP is an R&D program that has yet to select all of the technologies and sites. To the extent possible, each factor is graded (or rated) for each alternative to or within GNEP. Where appropriate, the factors that are expected to be important in the subsequent assessments of GNEP technology or sites are listed. The grading is expressed in qualitative terms with each grade supported by specific technical and policy evaluations as described in the following subsections.

2. DEFINITION OF PROLIFERATION RESISTANCE

A clear definition of proliferation resistance is needed to establish a firm foundation for the analysis and assessment to be performed in this NPIA. The definition given below has been agreed to by the Generation IV International Forum (GIF) and agrees with the definition established at the international workshop sponsored by the IAEA in Como, Italy, in 2002 [3]. For comparison and distinction, the PR&PP definition of physical protection is also given.

Proliferation resistance is that characteristic of a nuclear energy system (NES) that impedes the diversion or undeclared production of nuclear material or misuse of technology by the Host State seeking to acquire nuclear weapons or other nuclear explosive devices.

The nuclear energy system for GNEP is regarded here to be the facilities that comprise it, their safeguards, their physical security, the fuel supply and take-back services among its participants, and the corresponding transportation of nuclear materials or sensitive technology. Thus the GIF definition of proliferation resistance applies to GNEP.

It is important to note that while the PR&PP definitions provide a foundation for evaluating the relative PR&PP risks of GNEP, there can be other factors which influence the nonproliferation impact of GNEP. For example, the nuclear fuel cycle decisions of various countries need to be consider with regard to the benefits and challenges for GNEP. This is discussed in Section 4.

As noted above, the definition of physical protection is also important to recognize. According to PR&PP, it is as follows.

Physical protection ***(robustness)*** is that characteristic of an NES that impedes the theft of materials suitable for nuclear explosives or radiation dispersal devices (RDDs) and the sabotage of facilities and transportation by sub-national entities and other non-Host State adversaries.

These definitions are given further specificity in terms of the measures for evaluating PR&PP. These are discussed in Section 4. While PP is discussed here for completeness and to distinguish it from PR, it is not evaluated for GNEP in this NPIA. The relevant PP factors will be discussed here, and a complete evaluation will be part of technology and site selections.

3. ANALYTICAL APPROACH

Figure 1 illustrates the basic paradigm for the PR&PP methodological approach. For a given system, analysts define a set of ***challenges***, analyze ***system response*** to these challenges, and assess ***outcomes***. The challenges to the GNEP system are the threats posed by potential proliferant States and by sub-national adversaries. The technical and institutional characteristics of the NES are used to evaluate the response of the system and determine its ***resistance*** to proliferation threats and ***robustness*** against sabotage and terrorism threats. The outcomes of the system response are expressed in terms of PR&PP ***measures*** and assessed.

The evaluation methodology accounts for both the intrinsic and extrinsic protective features of the GNEP system. Intrinsic features include the physical and engineering aspects of the GNEP system; extrinsic features include institutional aspects such as safeguards and external barriers.

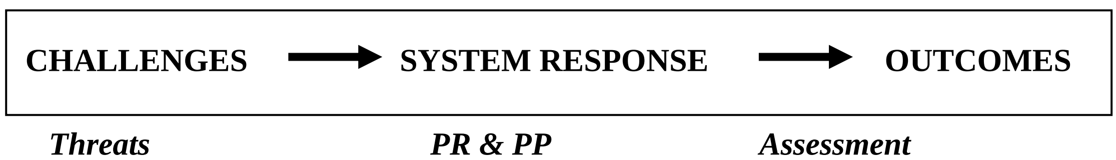

Figure 1 Basic Framework for the PR&PP Evaluation Methodology for GNEP

Figure 2 provides an expanded outline of the methodological approach. The first step is *threat definition*. For both PR and PP, the threat definition describes the challenges that the system may face and includes characteristics of both the actor and the actor’s strategy. For PR, the actor is the Host State within the GNEP system, and the threat definition includes both the proliferation objectives and the capabilities and strategy of the Host State. For PP threats, the actor is a sub-national group or other non-Host State adversary. The PP actors’ characteristics are defined by their objective, which may be either theft or sabotage, and their capabilities and strategies.

The challenges to GNEP are defined in terms of a standard Reference Threat Set (RTS), covering the anticipated range of actors, capabilities, and strategies.

For PR, the threats include

- Concealed diversion of declared materials
- Concealed misuse of declared facilities
- Overt misuse of facilities or diversion of declared materials
- Clandestine dedicated facilities.

For PP, the threats include

- Radiological sabotage
- Material theft
- Information theft.

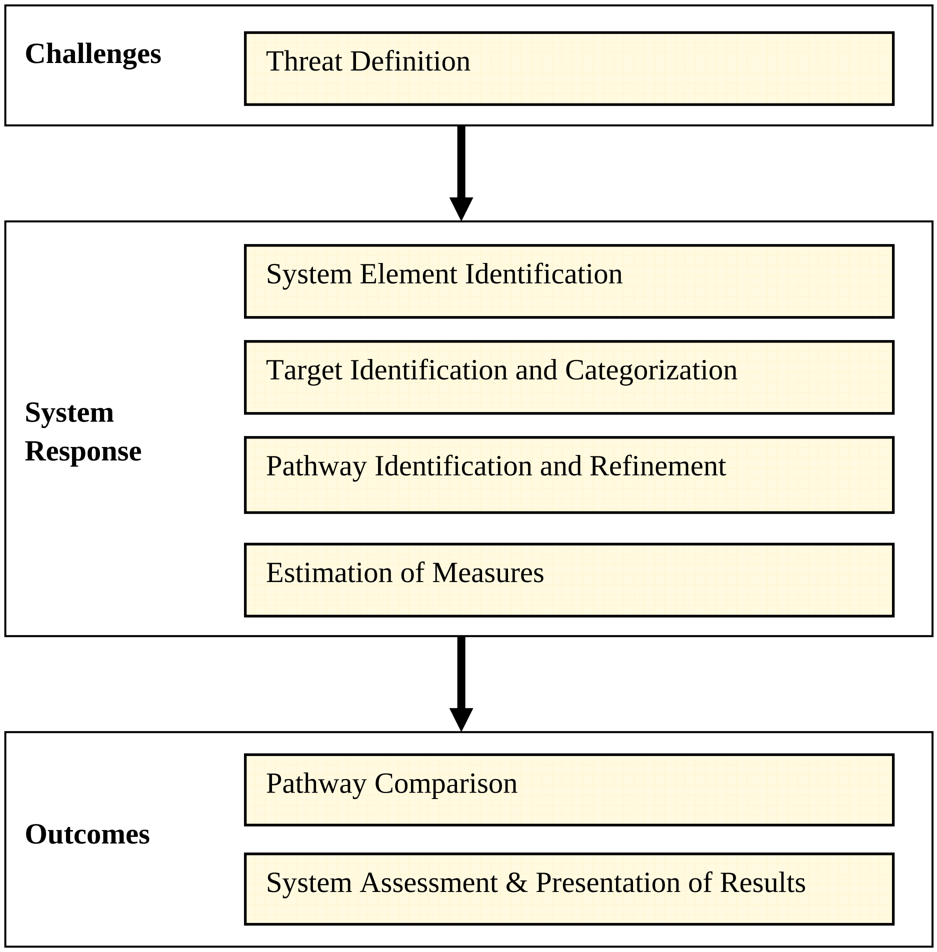

Figure 2 Detailed Framework for the PR&PP Evaluation Methodology

The selection of potential threats to include is performed at the beginning of a PR&PP evaluation. The uncertainty in the system response to a given threat is then evaluated independently of the probability that the system would ever actually be challenged by the threat. In other words, PR&PP evaluations are contingent on the challenge occurring.

After the threats have been sufficiently detailed for the GNEP evaluation, the system response is performed and has four components:

1. **System Element Identification**. The GNEP system is decomposed into smaller elements or subsystems at a level amenable to further analysis. The elements can comprise a facility (in the systems engineering sense), part of a facility, a collection of facilities, or a transportation system within the identified GNEP subsystem where acquisition (diversion) or processing (PR) or theft/sabotage (PP) could take place.

2. **Target Identification and Categorization.** Target identification is conducted by systematically examining the GNEP system for the role that materials, equipment, and processes in each element could play in each of the strategies identified in the threat definition. PR targets are nuclear material, equipment, and processes to be protected from threats of diversion and misuse. PP

targets are nuclear material, equipment, or information to be protected from threats of theft and sabotage. Targets are categorized to create representative or bounding sets for further analysis.

3. **Pathway Identification and Refinement.** Pathways are potential sequences of events and actions followed by the actor to achieve objectives. For each target, individual pathways are divided into segments through a systematic process, and analyzed at a high level. Segments are then connected into full pathways and analyzed in detail. Selection of appropriate pathways will depend on the scenarios themselves, the state of design information, the quality and applicability of available information, and expert input.

4. **Estimation of Measures.** The results of the system response are expressed in terms of PR&PP measures. Measures are the high-level characteristics of a pathway that affect the likely decisions and actions of an actor and therefore are used to evaluate the actor's likely behavior and the outcomes. For each measure, the results for each pathway segment are aggregated as appropriate to compare pathways and assess the system so that significant pathways can be identified and highlighted for further assessment and decision making.

For PR, the measures are

- *Proliferation Technical Difficulty* (TD) – The inherent difficulty, arising from the need for technical sophistication and materials handling capabilities, required to overcome the multiple barriers to proliferation.
- *Proliferation Cost* (PC) – The economic and staffing investment required to overcome the multiple technical barriers to proliferation including the use of existing or new facilities.
- *Proliferation Time* (PT) – The minimum time required to overcome the multiple barriers to proliferation (i.e., the total time planned by the Host State for the project)
- *Fissile Material Type* (MT) – A categorization of material based on the degree to which its characteristics affect its utility for use in nuclear explosives.
- *Detection Probability* (DP) – The cumulative probability of detecting a proliferation segment or pathway.
- *Detection Resource Efficiency* (DE) – The efficiency in the use of staffing, equipment, and funding to apply international safeguards to the NES.

For PP, the measures are

- *Probability of Adversary Success* – The probability that an adversary will successfully complete the actions described by a pathway and generates a consequence.
- *Consequences* – The effects resulting from the successful completion of the adversary's action described by a pathway.
- *Physical Protection Resources* – the staffing, capabilities, and costs required to provide PP, such as background screening, detection, interruption, and neutralization, and the sensitivity of these resources to changes in the threat sophistication and capability.

The final steps in PR&PP evaluations are to integrate the findings of the analysis and to interpret the results. Evaluation results include best estimates for numerical and linguistic descriptors that characterize the results, distributions reflecting the uncertainty associated with those estimates, and appropriate displays to communicate uncertainties.

4. TECHNICAL FACTORS AND METRICS

As noted above, there are two categories of factors and metrics that are essential to the NPIA: technical factors and policy factors. The former are derived from the PR&PP methodology while the latter capture the broader suite of policy, legal, and institutional approaches used to secure nonproliferation objectives. This section elaborates on the technical aspects and Section 5 discusses policy aspects.

The link between technical factors, PR&PP measures, and their underlying metrics can be summarized by the following.

1. The measures are the fundamental constituents of proliferation resistance
2. The metrics are the scales or units in which they are expressed
3. The technical factors are higher level expression of proliferation resistance that are more readily usable by the decision maker. They are supported by the measures.

Three high level technical factors are evaluated in this NPIA. They are:

- T1: Avoiding Proliferator Success
- T2: Facilitating Cost Effective International Monitoring
- T3: Resulting in Less Attractive Material Types and Forms

These technical factors are informed by the PR&PP measures by the following association.

Technical Factors	Associated PR&PP Measures
Avoiding Proliferator Success (T1)	• Technical Difficulty (PR) • Proliferation Cost (PR) • Proliferation Time (PR) • Detection Probability (PR) • Probability of Adversary Success (PP) • Consequences (PP)
Facilitating Cost Effective International Monitoring (T2)	• Detection Resource Efficiency (PR) • Detection Probability (PR) • Physical Protection Resources (PP)
Resulting in Less Attractive Material Types and Forms (T3)	• Material Type (PR) • Consequences (PP)

Grading Structure for Technical Factors

A grading structure is proposed for the three technical factors

- Immediate and substantial impact
- Delayed but substantial impact
- Significantly delayed and/or minimal impact

There are other grading approaches as well, but undefined notions of high, medium, and low are not very useful since they are not particularly descriptive. The example grades give a qualitative notion of time and scale of possible consequence.

Proliferation Resistance Measures

For evaluation of proliferation resistance to host state threats, after measures have been estimated for pathways, pathways are compared and ranked to identify the significant pathways. To facilitate pathway comparison, quantitative metrics are applied to the TD, PC, PT, MT, and DP measures to relate them to linguistic values, from very low to very high, that would suggest the likely decision-making by a proliferant State. Likewise, for the DE measure, a quantitative metric is applied to reflect the magnitude of required resources, relative to the resources that the IAEA commonly applies to safeguard facilities. The analyst may select other quantitative metrics appropriate for comparing pathways for the specific threat being considered. As a starting point, the analyst may choose to apply the approximate, representative metrics given in Table 1, below. These are presented as one example approach to evaluation. The evaluation of measures is not prescriptive and is generally tailored to the specific questions being addressed.

In Table 1, the PP measures have also been included, for completeness. However, explicit example metrics are not shown in this report. These would be tailored to the purposes and needs of a national assessment and would be associated with the specific threats to be addressed. A brief discussion of the PP measure is given at the end of this section.

Each of the PR measures and corresponding metrics are discussed in greater detail below.

Proliferation Technical Difficulty (TD) Measure

The TD measure is estimated using a metric scale as shown in the example given in Table IV.3. Technical difficulty arises from inherent characteristics of the pathway that create difficulty and thus a potential for failure from technical problems. When scaled to reflect the State's capability, the TD measure assists in distinguishing pathways a proliferant State would judge to have higher risk of technical problems and to have the potential to greatly increase the time and resources to complete a pathway or to result in the failure to complete a pathway.

Estimation of TD uses expert judgment to identify the sources of intrinsic difficulty in completing a pathway segment, such as difficulty from criticality hazards, radiation, lack of design information, lack of access, or inability to fabricate or produce equipment or materials covered by export controls. Estimation of TD for a complete pathway uses the combined sources of difficulty for all segments.

The metric scale for the TD measure reflects the probability that a pathway will end in failure and thus depends on the resources and capabilities available to a proliferant State. Thus, for example, the TD of an external segment to construct and operate a concealed centrifuge enrichment plant may become lower if a State has an operating commercial enrichment capability or can access expert guidance. However, the TD for manufacturing specific components for centrifuges, such as frequency invertors, may remain high if a State does not have a domestic commercial capability to manufacture these components. Most of the nuclear components that have high TD to manufacture are monitored by international export controls and by national intelligence services. The evaluation of the DP measure may include the potential for export controls to detect the acquisition of such equipment.

The use of probabilistic methods can facilitate aggregation of the TD measure associated with each segment in a pathway. Examples based on Markov models are contained in Yue, Cheng, Papazoglou, Azarm, and Bari [4]. Table 2 summarizes key characteristics of the TD measure.

Table 1 Example Quantitative Metrics and Scales for PR Measures

(qualitative PR ranking [Very Low → Very High],
numerical range for bins, and median numerical values)

Measures and Metrics	Metric Scales Bins (Median)	Proliferation Resistance
Proliferation Resistance Measures Determined by Intrinsic Features		
Proliferation Technical Difficulty (TD) Example metric: Probability of pathway failure from inherent technical difficulty considering threat capabilities	0-5% (2%)	Very Low
	5-25% (10%)	Low
	25-75% (50%)	Medium
	75-95% (90%)	High
	95-100% (98%)	Very High
Proliferation Cost (PC) Example metric: Fraction of national resources for military capabilities	0-5% (2%)	Very Low
	5-25% (10%)	Low
	25-75% (50%)	Medium
	75-100% (90%)	High
	>100% (>100%)	Very High
Proliferation Time (PT) Example metric: Total time to complete pathway	0-3 mon (2 mon)	Very Low
	3 mon-1 yr (8 mon)	Low
	1-10 yr (5 yr)	Medium
	10 yr-30 yr (20 yr)	High
	>30 yr (>30 yr)	Very High
Fissile Material Type (MT) Example metric: Dimensionless ranked categories (HEU, WG-Pu, RG-Pu, DB-Pu, LEU); interpolation based on material attributes	HEU	Very Low
	WG-Pu	Low
	RG-Pu	Medium
	DB-Pu	High
	LEU	Very High

Table 1 Example Quantitative Metrics and Scales for PR Measures (continued)

Measures and Metrics	Metric Scales Bins (Median)	Proliferation Resistance
Proliferation Resistance Measures Determined by Extrinsic Measures and Intrinsic Features		
Detection Probability (DP) Example metric: Cumulative detection probability	a	Very Low
	b	Low
	c	Medium
	d	High
	e	Very High
Detection Resource Efficiency (DE) Example metric: GW(e) years of capacity supported (or other normalization variable) per Person Days of Inspection (PDI) (or inspection $)	<0.01 (0.005 GWyr/PDI)	Very Low
	0.01-0.04 (0.02 GWyr/PDI)	Low
	0.04-0.1 (0.07 GWyr/PDI)	Medium
	0.1-0.3 (0.2 GWyr/PDI)	High
	>0.3 (1.0 GWyr/PDI)	Very High
Probability of Adversary Success (for PP)		Very Low
		Low
		Medium
		High
		Very High
Consequences (for PP)		Very Low
		Low
		Medium
		High
		Very High
Physical Protection Resources (for PP)		Very Low
		Low
		Medium
		High
		Very High

NOTES: HEU = high-enriched uranium, nominally 95% ^{235}U; WG-Pu = weapons-grade plutonium, nominally 94% fissile Pu isotopes; RG-Pu = reactor-grade plutonium, nominally 70% fissile Pu isotopes; DB-Pu = deep burn plutonium, nominally 43% fissile Pu isotopes; LEU = low-enriched plutonium, nominally 5% ^{235}U.

a Significantly lower cumulative detection probability than the IAEA detection probability and timeliness goal for depleted, natural, and LEU uranium.
b 50% in 1 year (This equates to IAEA detection probability and timeliness goal for 1 significant quantity of depleted, natural, and LEU uranium).
c 20% in 3 months, 50% in 1 year (This equates to IAEA detection probability and timeliness goal for 1 significant quantity of spent fuel/irradiated material).
d 50% in 1 month, 90% in 1 year (This equates to IAEA detection probability and timeliness goal for 1 significant quantity HEU/separated Pu).
e Significantly greater cumulative detection probability than the IAEA detection probability and timeliness goal for HEU/separated Pu.

Table 2 Summary of Characteristics for the Proliferation Technical Difficulty (TD) Measure

Characteristic	Description
Definition	Inherent difficulty of the segment
Typical attributes to be considered for estimation	Criticality hazards Radioactivity levels Availability of open information Access to specialized export-controlled components or materials
Example metric	Probability of pathway failure from inherent technical difficulty considering threat capabilities
Segments-to-pathway aggregation method	Calculate the probability of pathway failure on the basis of the segments involved.

Proliferation Cost (PC) Measure

The PC measure is estimated in dollars and can be scaled with the total resources available to a proliferant State for military expenditures, which may be on the order of $2 billion per year for a reactor state or $20 billion per year for a fuel cycle state. Table 3 provides an index for scaling the value of PC from low (< 10%) to very high (> 100%). This measure expresses the economic and staffing investment required to overcome the multiple barriers that impede completion of the action associated with the segment.

The PC measure is aggregated over a pathway by summing the value of the measure for each segment in the pathway. In many cases, this measure will be dominated by one segment. Note that this measure does not include the cost of the declared Generation IV NES but does include the cost of modifications made to that system to complete the segment. These modifications may include process modifications as well as modifications intended to defeat safeguard verification activities. Table 3 summarizes key characteristics of the PC measure.

Table 3 Summary of Characteristics for the Proliferation Cost (PC) Measure

Characteristic	Description
Definition	Total cost of segment
Typical attributes to be considered for estimation	Minimum cost for setting up the minimum needed infrastructure to complete the segment Cost from misuse of civilian infrastructure/personnel
Example metric	Fraction of national resources for military capabilities
Segments-to-pathway aggregation method	Sum of segment estimates. Can be normalized to national resources for military capabilities.

Proliferation Time (PT) Measure

The PT measure is estimated in units of time, as shown in Table 4, and ranges from very low (< 3 months) to very high (> 30 years). The proliferation time is the minimum time required to overcome the multiple barriers that impede completion of the action associated with the acquisition and processing segments. Typically, PT is measured from the time that the proliferant State initiates its first detectable activity (e.g., its first action to divert material or misuse a declared facility). However, the analyst may select other initiation times, such as the time when the proliferant State's planning starts if the analyst judges this to be important in affecting the State's preferences between pathways. The analyst should state explicitly, the basis used for selecting an initiation time and use it consistently. Typically PT is estimated at the end of the processing segment and does not include the weapon fabrication time (which is subsumed in the MT measure). In practice, though, weapon fabrication time can be expected to be short (a few weeks) compared to the PT, so this distinction is not important.

For example, abrupt diversion of spent fuel from a storage facility might require less than 1 month. Extraction of plutonium from irradiated targets might require 3 to 12 months, assuming that the extraction facility (whether clandestine or obtained through misuse of a declared facility) is already available. In making these estimates, the analyst must clearly state assumptions. These assumptions include what preparations the proliferant State has completed before initiating the action associated with the segment (e.g., an assumption that the proliferant State constructed and commissioned a clandestine plutonium extraction facility before initiating this segment and assumed throughput).

For a pathway, the PT measure is aggregated by summing serial activities and taking into account parallel activities. Parallel and serial activities depend on the details of each pathway. Table 4 summarizes key characteristics of the PT measure.

Table 4 Summary of Characteristics for the Proliferation Time (PT) Measure

Characteristic	Description
Definition	Total time required to complete segment
Typical attributes to be considered for estimation	Maximum diversion or production rate Storage duration Extent of required equipment modifications
Example metric	Total time to complete pathway (e.g., months, years)
Segments-to-pathway aggregation method	Appropriate aggregation of parallel and serial activities

Fissile Material Type (MT) Measure

The MT measure ranks types of fissile material produced by the processing segment—typically metal—based on their utility for use in fabrication of a nuclear explosive and the relative preference of a proliferant State. As such, the MT measure is only estimated for pathways; it is not estimated for segments. It is, however, of interest to report MT at the end of major stages. For, example, as an intermediate result, a designer may want to know the various possible MTs emerging from the acquisition stage.

The specific design tradeoffs that arise from fissile material properties will affect several areas that would be important to the objectives of a proliferant State: technical performance (e.g., reliability of yield, both in achieving a successful first test and in achieving reliable performance after a sequence of tests), the ability to stockpile the material, and deliverability.

Because detailed information on the relationship between MT and weapons design is sensitive, the PR methodology applies an approximate ranking (Table 5) of nuclear material types. This ranking reflects relative PR based on the preferences of a proliferant State in attempting to acquire its first few weapons. The ranking ranges from material like high-enriched uranium (HEU), for which design and fabrication of nuclear explosives has very low difficulty (very low PR ranking), to low-enriched uranium (LEU), for which fabrication of a workable nuclear explosive is essentially impossible (very high PR ranking). The basic range is as follows:

- very low PR – HEU
- low PR – weapons-grade plutonium (WG-Pu)
- medium PR – reactor-grade plutonium (RG-Pu)
- high PR – “deep-burn” plutonium (DB-Pu)
- very high PR – LEU.

The very low PR ranking for HEU results primarily from the extremely low spontaneous neutron emission rate compared to all plutonium compositions. This difference substantially simplifies weapons design and gives a proliferant State high confidence in obtaining reliable performance on the first test or use of nuclear weapons.

For plutonium, a very wide range of isotopic compositions can be generated depending on the conditions of reactor operation and recycle of spent fuel. The basis for categorizing the attractiveness of different plutonium compositions is complex and, when presented in detail, is sensitive and classified. Here the MT PR ranking for plutonium compositions is based on the study of the U.S. National Research Council on the spent-fuel standard [5]:

> “If it is assumed that proliferators in all categories will ultimately be capable of obtaining reasonably pure plutonium metal…then the main intrinsic barriers in this category are those associated with deviation of the plutonium's isotopic composition from 'weapons grade.' …”
>
> “In the case of…a proliferant State we rate the barrier [from reactor-grade plutonium] as 'moderate' in importance: such a state would probably prefer to avoid if possible the burdens posed by isotopic deviations for design, fabrication, and maintenance of nuclear weapons, but it would also probably have the capabilities to cope with the burdens in ways that achieved a level of weapon performance adequate for the proliferant State's initial purposes.”

When plutonium is recycled, it is possible to further degrade the isotopic composition. For the MT measure, such degraded plutonium is listed as DB-Pu, which would have high concentrations of Pu-238 and thus high heat generation rates. A proliferant State would be expected to expend great effort to identify proliferation pathways that would result in acquiring material with a lower MT PR ranking, and thus the MT PR ranking of DB-Pu is listed as high. A more detailed discussion regarding the level of preference that a proliferant State would display between materials of higher and lower MT ranking is contained in Appendix D of the PR&PP methodology report [1].

In many cases, the simple MT ranking, along with the qualitative discussion of MT provided above and in Appendix D.4 of the PR&PP methodology report [1], will be sufficient to allow pathways to be compared and ranked. Table 5 summarizes key characteristics of the MT measure.

Table 5 Summary of Characteristics for the Fissile Material Type (MT) Measure

Characteristic	Description
Definition	Characteristics of metal for weapons fabrication
Typical attributes to be considered for estimation	Spontaneous neutron emission rate Heat generation rate Gamma radiation activity Bare-sphere critical mass
Example metric	Dimensionless ranked categories (HEU, WG-Pu, RG-Pu, DB-Pu, LEU); interpolation based on material attributes
Segments-to-pathway aggregation method	Not applicable

Detection Probability (DP) Measure

The DP measure expresses the probability that action described by a pathway segment is detected. DP results from measurements that (1) detect anomalies generated during the execution of pathway segments and (2) are performed to assess that anomalies originate from actions in actual pathway segments rather than legitimate, inadvertent sources. DP is generally expressed as a cumulative probability function. If a defined safeguards approach is not available, however, DP can only be expressed by a very wide uncertainty band.

In addition, a variety of concealment strategies may affect DP. The effects of a concealment strategy are determined by analyzing pathways that include the strategy, not by assigning an arbitrary DP uncertainty for assumed effects of concealment methods.

Safeguards involve continuously evolving technology. A number of system attributes can affect both the optimal approach for the application of safeguards and the effectiveness of that approach in providing high DP. The following assumes a robust IAEA safeguards regime with the attendant technologies that would promote safeguardability of facilities and operations.

To detect *internal material diversion segments*, measurements may be combined to detect the material transfer and the resulting change in material inventory uncertainty in detection arises from three sources: (1) instrument measurement uncertainty; (2) the possibility that a measured anomaly has a legitimate origin, such as inadvertent hold up of material, inadvertent operator destruction of a seal, or inadvertent delay of an inspection due to legitimate safety or access restrictions; and (3) uncertainty that the actual facility configuration is the same as that assumed in the design of the safeguards system, where, for example, an undeclared penetration may exist in or be added to a facility.

To detect *internal facility misuse segments*, measurements to detect misuse must be tailored to detect anomalies that the action of a segment would generate. Uncertainties in detection of misuse have similar origins to those listed above for internal material diversion segments.

To detect *external segments*, methods include the use of tools such as commercial satellite photography and environmental sampling, as well as the use of various types of information that may be supplied by third party sources, such as information from national export control programs, which monitor and detect purchases or transfers of sensitive or dual purpose equipment and technologies, and information gathered by national technical means. External segments that use equipment diverted from declared facilities, such as frequency invertors in enrichment plants, could also be detected by monitoring the inventory of this equipment in declared facilities. Although the IAEA does not currently have goals for detection of clandestine activities and facilities, the IAEA utilizes information obtained from a variety of sources, including non-safeguards databases, open sources and third parties.

A potentially significant tool for enhancing the detection of external segments is the Additional Protocol (AP). This tool would make programs to develop nuclear capabilities, including enrichment and reprocessing, in NPT countries, more transparent (and also subject to verification). It would create a broader IAEA toolkit, including location-specific environmental sampling, to verify the declarations. AP, for example, would be a principal means of verifying that a user state that had agreed to forego development of ENR in exchange for fuel assurances was in fact in compliance with such an understaking, and that there was no evidence of activities that might be inconsistent with this. AP is thus relevant to both internal segments—misuse of a declared facility—and external segments (e.g., a declared 10-year national fuel cycle plan that provides a baseline against which to evaluate such things as procurements that are inconsistent with that plan.

Under modern integrated safeguards, safeguards detection resources such as the frequency of inspections are increased progressively as anomalies are detected. This provides a higher cumulative confidence of detection with lower detection resources. Likewise, safeguards approaches that provide multiple and diverse measurements capable of detecting the actions described by a pathway segment increase the DP.

For internal pathway segments, the reference metric scale for the DP measure, shown in Table 6, is based on a comparison with the applicable IAEA safeguards detection goals contained in the IAEA safeguards criteria. A "medium" DP meets the IAEA safeguards detection goals for spent fuel and irradiated materials. A "high" DP meets IAEA goals for HEU and separated plutonium, and a "low" DP meets IAEA goals for depleted uranium, natural uranium, and LEU.

For external pathway segments, DP may have large uncertainty unless the segment generates obvious visual, thermal, or other signatures. If detection uncertainty is large, it may be useful to provide decision makers with a qualitative, general description of the methods available to detect the external segment, particularly if the actual DP cannot be readily evaluated and presented on a metric scale like that of Table 6. Table 6 summarizes key characteristics of the DP measure.

Detection Resource Efficiency (DE) Measure

The DE measure is estimated for each pathway segment by summing estimates of the manpower (e.g., Person Days of Inspection, PDI) or the cost (in $) required to implement the detection methods for the segment. Safeguards resources are then aggregated for all segments of a pathway, using logical assumptions (e.g., a single instrument may provide detection capabilities for multiple segments). Estimates of time or cost will necessarily be based on currently accepted safeguards approaches but anticipated changes to safeguards approaches and safeguards technology (e.g., increased use of remote monitoring) should be considered that could occur over the multi-decade life cycle for most nuclear facilities The DE measure is normalized by a variable such as the energy production supported by the system element, and is presented as the ratio of that normalization variable divided by the inspection time or cost (for example, in units of gigawatt years per PDI). Table 7 summarizes key characteristics of the DE measure.

Table 6   Summary of Characteristics for the Detection Probability (DP) Measure

Characteristic	Description
Definition	Cumulative probability and confidence level for detection of a pathway segment
Typical attributes to be considered for estimation	Attributes important to design information verification Transparency of layout Possibility to use 3-d scenario reconstruction models Possibility to have visual access to equipment while operational Comprehensiveness of facility documentation and data Attributes important to nuclear material accounting Uniqueness of material signature Hardness of radiation signature Possibility of applying passive measurement methods Item/bulk Throughput rate Batch/continuous process Nuclear material heat generation rate Attributes important to containment and surveillance Operational practice Extent of automation Standardization of items in transfer Possibility to apply visual monitoring Number of possible transfer routes for items in transit
Example metric	Cumulative detection probability.
Segments-to-pathway aggregation method	Calculate the probability of pathway detection on the basis of the segments involved. (e.g. the probability of pathway detection will be $P(d) = 1 – P(nd)$, where the probability of pathway non-detection, $P(nd) = \Pi(1-P_i(d))$, with $P_i(d)$ being the probability of detection of the i^{th} segment, under the hypothesis of the independence of detection events).

Table 7 Summary of Characteristics for the Detection Resource Efficiency (DE) Measure

Characteristic	Description
Definition	Total inspector time or cost of safeguarding the segment
Typical attributes to be considered for estimation	See Table 2.10 of Reference [1]
Example metric	GW(e) years of capacity supported (or other normalization variable) per Person Days of Inspection (PDI) (or inspection $)
Segments-to-pathway aggregation method	Aggregation to total inspection time or safeguards cost, normalized to an appropriate scale, such as nuclear energy production supported [GW(e) year]

Physical Protection Measures

The three PP factors are considered differently.

- Probability of Adversary Success (PAS) **-** The probability that an adversary will successfully complete the actions described by a pathway and generates a consequence. This measure assesses the probability that an adversary will successfully complete the actions described by a pathway and generate a consequence. If the actions required to complete the pathway are within the resources and capability of the adversary, then the probability of adversary success depends on the capability of the PPS to detect the actions, delay the adversary, and neutralize the adversary before the actions can be completed. The PAS measure is commonly used in the design and analysis of PPSs, and various tools are available to quantitatively evaluate the measure. For some pathways, the PAS may be controlled by a small number of segments, such as the physical difficulty in obtaining access to safety equipment in attempting to sabotage passively safe nuclear reactors and the difficulty of removing and processing spent-fuel assemblies in attempting to steal plutonium.

- Consequences (C) **-** The effects resulting from the successful completion of the adversary's action described by a pathway. Consequences are defined as the effects resulting from the successful completion of the adversary's intended action described by a pathway. This measure reflects both the attractiveness to the adversary and the relative importance of a pathway in generating adverse effects. Theft consequences can be expressed in terms of the quantity and quality of the material removed. Appendix D.4 discusses fissile material quality of materials for nuclear explosives, in relationship to sub-national threats. Sabotage consequences can be measured by the number of physical quantities, acute fatalities, latent fatalities, quantities of material per unit area, etc. Perhaps the most meaningful measurement of sabotage consequences at the coarse pathway level is whether a release is contained, kept to the plant site, or released offsite.

- Physical Protection Resources (PPR) **-** the staffing, capabilities, and costs required to provide PP, such as background screening, detection, interruption, and neutralization, and the sensitivity of these resources to changes in the threat sophistication and capability. This measure reflects the resources devoted to provide extrinsic features-a PPS-to detect, delay, and neutralize an adversary. At the lowest end, in system elements that provide very long intrinsic delay times, this measure may involve the cost of alarm systems and offsite police response. At the high end, this measure may involve extensive investments in maintaining large, armed security forces and in detection, delay, and response systems. The PPR measure quantifies the staff, capabilities, and costs (both infrastructure and operation) required to provide a level of PP for a given NES. As with the DE measure for PR, the PPR measure for a given pathway is evaluated for each pathway segment and then aggregated appropriately, noting that some PPS elements can provide responses to multiple segments. PPR for targets can be evaluated by aggregating resources for all pathways associated with the target. Likewise PPR for a system element can be evaluated by aggregating the resources required for all targets in the system element. The PPR measure can also be expressed as a cost per unit of energy (TWh) produced.

The three measures for PP are consistent with those commonly used by national programs to make efficient investments to protect critical infrastructure and key assets. PP is a national responsibility and thus involves national policies. The goal is to optimally allocate resources to limit risk to a uniform level across both nuclear and non-nuclear critical infrastructure and key assets. Quantitative analysis for PAS, C, and PPR will also be required to support licensing and deployment decisions for new nuclear infrastructure.

5. POLICY FACTORS AND GRADING

In addition to "Technical Factors" that are supported by the PR&PP metrics and measures, the final GNEP NPIA should evaluate alternative actions against notable nonproliferation "Policy Factors." The purpose of this additional aspect of the approach is to capture any high level U.S. nonproliferation policy value. It is difficult to fully evaluate the nonproliferation merit of the GNEP "architecture" as a technology transfer restraining mechanism when measuring purely against technical factors which do not consider the broader suite of policy, legal, and institutional approaches used to secure nonproliferation objectives.

The following draft Policy Factors are proposed for use in the NPIA analysis.

1. Restrains the spread of enrichment and reprocessing technology

This factor would allow policy effect analysis of whether GNEP approaches, products, and facilities contribute to restraint in the spread of sensitive fuel cycle technology beyond existing technology holding states (10 enrichers, 6 reprocessors). This is a presidential (POTUS) level policy factor put forward in the National Defense Univeristy speech by President George Bush in February 2004.

2. Minimizes and avoids accumulation of stocks of separated weapons useable material

This factor would allow policy effect analysis of whether GNEP approaches, products, and facilities contribute to minimization and avoidance of accumulation of separated stocks. This is a POTUS level policy factor put forward in National Security Presidential Directive 17 (NSPD-17) (President George Bush, December 2002) and other documents.

3. Enhances U.S. tangible nonproliferation policy and legal influence on the structure of the international fuel cycle

This factor would allow policy effect analysis on whether GNEP approaches, products, and facilities contribute to tangible enhancement of U.S. influence, for example, through the system of legal obligations set forth in bilateral peaceful nuclear cooperation agreements. The word "tangible" is used to indicate that the effect should be as direct as practicable through policy, regulatory, or legal mechanisms. Indirect effects are also meaningful (setting an "example"), but of much lesser value generally. For example, the "no domestic reprocessing policy" of the U.S. was an indirect policy approach. Some argue that this formed the basis for a policy of global restraint that largely retarded development of reprocessing technology worldwide while others argue that fuel cycle economics have been largely responsible for the current situation rather than the policy. By way of comparison, the general decline of U.S. nuclear manufacturing capability is having a direct and long-term impact on the U.S. ability to influence the future international fuel cycle through an accelerating loss of nuclear trade obligations on technology and material – a direct effect.

4. Strengthens nuclear nonproliferation and nuclear security by encouraging the adoption and implementation of sound nonproliferation infrastructures.

This factor would allow policy effect analysis on whether GNEP approaches lead to the adoption by others, for example, of Additional Protocols; the IAEA Convention on Physical Protection of Nuclear Materials (CPPNM) and its amendment; export controls, and implementation of the United Nations Security Council Resolution 1540 (UNSCR/1540). It could look at capacity building efforts to help others put in place the appropriate legal and regulatory frameworks and develop and deploy the human resources needed. This factor speaks both to the issue of reducing the risk of terrorism world-wide as well as promoting nonproliferation norms.

Proposed Grading Structure

The policy analysis should cast logical arguments as to how GNEP approaches, products, and facilities participate and enable U.S. nonproliferation policy objectives. The analysis should be as brief, straightforward, and understandable as possible to educated lay-persons. Suggest the following set of "Grades" to be applied to the above Policy Factors:

Meets U.S. nonproliferation policy objectives

This grade is given if the vast majority of reasoned argument supports the conclusion. The main points for should be laid out in a bulletized list.

May create U.S. nonproliferation policy uncertainty

This grade is given if significant reasoned arguments can be made for and against. The main points for and against should be laid out in bulletized pro and con lists.

Raises U.S. nonproliferation policy concerns

This grade is given if the vast majority of reasoned argument supports the conclusion. The main points against should be laid out in a bulletized list.

6. REFERENCES

[1] *"Evaluation Methodology for Proliferation Resistance and Physical Protection of Generation IV Nuclear Energy Systems,"* Revision 5, Generation IV International Forum, GIF/PRPPWG/2006/005; http://www.gen-4.org/Technology/horizontal/PRPPEM.pdf, November 30, 2006.

[2] "Nuclear Infrastructure Nonproliferation Impact Assessment," U.S. Department of Energy, DOE/NE-0019, September 2000.

[3] "*Proliferation Resistance Fundamentals for Future Nuclear Energy Systems," IAEA* Department of Safeguards, IAEA (International Atomic Energy Agency), Vienna, Austria, 2002.

[4] "Calculations of Proliferation Resistance for Generation III Nuclear Energy Systems," M. Yue, L. Cheng, I.A. Papazoglou, M.A. Azarm, and R. Bari, Global 2005, Japan, October 9-13 2005.

[5] "*The Spent-Fuel Standard for Disposition of Excess Weapon Plutonium: Application to Current DOE Options,*" National Research Council, Office of International Affairs, National Academy Press, Washington, D.C. 2000. Available online at http://www.nap.edu/books/0309073200/html/