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The Application of Materials Attractiveness in a Graded Approach to Nuclear Materials Security

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Abstract. The threat from sub-state adversaries (*i.e.*, terrorist groups) has recently received greater attention. The capabilities, intent, and risk tolerance of this threat are substantially different than those of traditional state-level adversaries (*i.e.*, proliferant states). Under a graded approach to nuclear material security, optimal security regulations for material quantity and attractiveness would need to be incorporated to counter the threat and to ensure that the protection of nuclear materials is commensurate with their potential utility to adversaries. In this paper, material quantity and material attractiveness are addressed through the lens of a minimum security strategy needed to prevent the construction of a nuclear explosive device (NED) by an adversary. The paper does not address the security issues that are associated with facilities that manufacture nuclear weapons or their component. In addition, the paper does not address threats associated with radiological dispersal devices (RDDs), radiological exposure devices (REDs), or criticality events.

I. BACKGROUND

If an adversary wished to build a nuclear explosive device (NED), it would first need to acquire a sufficient quantity of nuclear material (as defined by the IAEA), which would then need to be processed and utilized in the device.[1] The adversary would face several potential impediments at various stages in this process. The first of these would involve the radiation dose rate and overall net weight of the nuclear material, which would affect the difficulty of acquiring the material from a nuclear facility or nuclear transport vehicle. The second impediment would be the time and complexity involved in converting the nuclear material into a metal or alloy, which would affect the difficulty of processing the material. The third impediment would be the nuclear material mass required to build a NED, as well as the nuclear material heat production rate, which would affect the usability of the material in a NED. For the purpose of nuclear materials security, all of these impediments are collectively assimilated into a single metric: the "attractiveness" of the nuclear material. Those materials that present the fewest obstacles to weaponization are considered to be the *most* attractive to adversaries.[2]

Optimal security regulations for nuclear materials would incorporate both material quantity *and* material attractiveness to ensure that the protection they receive is commensurate with their potential utility to adversaries. Under a *graded approach* to nuclear materials security, these two metrics should govern the various security strategies for protecting materials, with the most stringent levels of protection given to the most attractive materials in quantities in excess of the amount needed to build a NED. Likewise, the security of less attractive materials or quantities that are insufficient to build a NED would require fewer protections given their lower utility to adversaries.

In this paper, material quantity and material attractiveness are addressed through the lens of a minimum security strategy needed to prevent the construction of a NED. The approach does not address additional security issues that are associated with facilities that manufacture nuclear weapons or their components. Additionally, the proposed approach does not address threats associated with radiological dispersal devices (RDDs), radiological exposure devices (REDs), or criticality events, which may require additional security measures even if the threat of a NED is negligible.

I.A Purpose and Scope

The logic of the graded approach to materials security is recognized in the International Atomic Energy Agency (IAEA) document "Nuclear Security Recommendations on Physical Protection of Nuclear Material and Nuclear Facilities (INFCIRC 225/Revision 5)[3]," Section 4.5 of which states the following:

> This categorization [by element, isotope, quantity and irradiation] is the basis for a graded approach for protection against

unauthorized removal of nuclear material that could be used in a nuclear explosive device, which itself depends on the type of nuclear material (*e.g.*, plutonium and uranium), isotopic composition (*i.e.*, content of fissile isotopes), physical and chemical form, degree of dilution, radiation level, and quantity.

This paper is intended as a thought piece to stimulate further dialogue on this subject in international venues.[4] This effort is being conducted as part of the Joint Statement on Nuclear Terrorism, which the governments of the United States, United Kingdom, and France released following the 2012 Nuclear Security Summit.[5] In this statement, the P-3 pledged to "actively engage in international workshops to address graded approaches for the characterization of nuclear material attractiveness to further enhance the effectiveness and sustainability of physical protection measures."

I.B Understanding Adversary Nature

A necessary starting point for developing a graded approach to security is a firm understanding of the adversary against whom these nuclear materials are being defended. The threat from sub-state adversaries (*i.e.*, terrorist groups) has recently received greater attention, and the capabilities, intent, and risk tolerance of this group are substantially different than those of traditional state-level adversaries (*i.e.,* proliferant states).

In particular, the utility of certain nuclear materials to the respective adversaries differs sharply. Nuclear materials that are highly attractive to a state-level adversary for weapons use are not necessarily attractive to a sub-state adversary and vice versa. The latter are presumed to be willing to accept any nuclear yield in excess of the conventional explosive yield. Additionally, there is a greater willingness on the part of many sub-state adversaries to suffer death or bodily harm in acquiring and processing nuclear materials, a difference with profound implications on security policies.

II. A GRADED APPROACH TO SECURITY AND ITS ELEMENTS

Nuclear materials are placed into specific security categories, which define a number of security requirements to protect the material, as outlined by the IAEA in INFCIRC 225/Revision 5.[3] Category I, Category II, and Category III material quantities can be equated to the number of thefts/diversions necessary to acquire a sufficient quantity of nuclear material to build a NED. The number of thefts/diversions required for each Security Category is given in **Table 1**.

Table 1. Equating the Number of Thefts/Diversions Required to the Security Categories.

Security Category	Thefts/Diversions
Category I	In some cases, a single theft/diversion of nuclear material could be a sufficient quantity for the adversary to build a NED
Category II	At least two thefts/diversions of nuclear material are hypothetically required to build a NED
Category III	Many thefts/diversions of nuclear material are required to build a NED
Less than Category III	Theft/diversion of the nuclear material is not substantially useful to build a NED

The constituent elements of this graded approach are described in greater detail below.

II.A Nuclear Materials Quantity

The IAEA security table that equates the security categories with the threshold quantities of Pu, ^{235}U, and ^{233}U is provided in **Table 2**. The irradiated fuel category has been removed as the effect of Radiation Dose Rate is addressed in the latter discussion on nuclear material attractiveness.

Table 2. Categorization of Nuclear Material According to INFCIRC 225, Rev 5.

Material	Enrich-ment	CatI	Cat II	Cat III[a]
1.Plutonium	Any	≥2 kg	≥500 g & < 2 kg	≥15 g & < 500 g
2.Uranium-235 (^{235}U)	≥20% ^{235}U	≥5 kg	≥1 kg & < 5 kg	≥15 g & < 1 kg
	≥10% & <20% ^{235}U		≥10 kg	≥1 kg & < 10 kg
	≥0.71% & <10% ^{235}U			≥10 kg
3.Uranium-233 (^{233}U)	Any	≥2 kg	≥500 g & < 2 kg	≥15 g & < 500 g

[a] Quantities not falling in Category III and natural uranium, depleted uranium, and thorium should be protected at least in accordance with Prudent Management Practices.

II.B Nuclear Materials Attractiveness

Materials attractiveness can be divided into four attractiveness levels, High, Medium, Low, and Very Low. In **Table 3**, the four attractiveness levels are equated with the utility of the material to the adversary and to a minimum security strategy that is necessary to adequately protect the nuclear material. The security strategies are defined latter in the paper.

Determining the material attractiveness is more involved than determining the security category based on material quantity. It requires determining which sub-factors affect nuclear materials attractiveness, quantifying these factors, and then combining the sub-factors into a single factor for the overall material attractiveness.

Table 3. Weapons Utility, Material Attractiveness, and Security Strategies

Weapons Utility*	Material Attractiveness	Security Strategy
Preferred Material	High	Containment-High
Potentially usable, but not preferred material	Medium	Containment-Medium
Impractical, but not impossible material	Low	Detection-Immediate
Impossible material	Very Low	Detection-Non-Immediate

*Note that a material that is impractical or impossible to process and then fashion into a NED for the assumed sub-state adversary may still be potentially usable by a state-level adversary.

II.B.1 Determining Sub-Factors

There are at least five relevant materials attractiveness sub-factors: Overall Net Weight; Radiation Dose Rate; Processing Time and Complexity; Nuclear Mass Requirement; and Nuclear Material Heat Production. These are shown in **Table 4**. In some scenarios, other factors can be relevant, such as the nuclear material neutron emission rate.

Materials attractiveness needs to be considered in three distinct phases in the process to construct a NED: the acquisition phase, processing phase, and utilization phase.

1. In the *acquisition phase*, only properties of the nuclear material that would prevent or deter an adversary from stealing/diverting the material are considered.
2. In the *processing phase*, only properties of the nuclear material that would prevent or deter the adversary from processing the acquired material into a metal or alloy are considered.
3. In the *utilization phase*, only properties of the nuclear material that would prevent or deter an adversary from converting the processed metal or alloy into the desired size and shape and using it in a NED are considered.

II.B.2 Quantifying Sub-Factors

In order to determine the overall material attractiveness of a nuclear material, one must consider each sub-factor of materials attractiveness. The principles of each attractiveness level for each attractiveness sub-factor are provided in **Table 5.**

Table 4. Materials Attractiveness Sub-Factors

Sub-Factor	Phase	Description
Overall Net Weight	Acquisition	Overall weight of the nuclear material item
Radiation Dose Rate		Radiation dose rate of the nuclear material item
Processing Time and Complexity	Processing	A property of the form and concentration of the nuclear material in the nuclear material item or bulk material.
Nuclear Material Mass Requirement	Utilization	Minimum mass of uranium or plutonium that is required to make a nuclear weapon, which is related to the bare critical mass
Nuclear Material Heat Production		Minimum heat produced from the uranium or plutonium in a NED, which is related to the heat content times the bare critical mass

For the Overall Net Weight, High attractiveness is equated to man portable items. Medium attractiveness is equated to items that are portable by a typical vehicle, but are not man portable. Low attractiveness is equated to items that are portable by a heavy duty truck (*i.e.*, somewhat difficult for the adversary to obtain, but not impossible), but are not portable by a typical vehicle. Very Low attractiveness would be equated to items that are not portable by any means available to the adversary. Since nuclear material items are, in most cases, portable by some means, this last category is left as Not Applicable.

For the Radiation Dose Rate, High attractiveness is equated to any item that has a radiation dose rate that is not-lethal. Medium attractiveness is not defined for this sub-factor because not-lethal radiation dose rates do not substantially deter an adversary that is willing to sacrifice their life. Low attractiveness is equated to any item that is not easily shielded (*i.e.*, man portable) and has a lethal dose rate. Very Low attractiveness is equated to any item that is not easily shielded and has an incapacitating radiation dose rate. A lethal radiation dose rate would kill the adversary, but sometime after the theft/diversion occurs. An incapacitating radiation dose rate would incapacitate the adversary before he/she could complete the task of stealing/diverting the nuclear material item. In material acquisition, the attractiveness of a nuclear material is implicitly governed by both the overall net weight and the radiation dose rate sub-factors. For example: acquisition of material from a reprocessing canyon or a spent-fuel pool can be substantially more difficult than acquiring direct-contact-handled bulk material from glove boxes because of the differences in material net weight and radiation field involved.

For Processing Time and Complexity, the materials attractiveness criteria are based on the chemical quality of the nuclear material. High attractiveness is equated to any Pure materials that require no chemical purification before they are converted to a metal or alloy and fashioned into a NED. Medium attractiveness is equated to High Grade materials that may require a simple purification process before they are converted to a metal or alloy and fashioned into a NED. Low attractiveness is equated to Moderately Diluted materials that require a complex purification process before they are converted to a metal or alloy and fashioned into a NED. Very Low attractiveness is equated to materials that are Highly Diluted (*i.e.*, they are practically irrecoverable or too dilute to be of any use to an adversary). For both Moderately and Highly Diluted materials, the degree of dilution needed will be dependent upon the difficulty of recovering nuclear material from the item or bulk material in question.

Attractiveness Phase	**Acquisition Phase**		**Processing Phase**	**Utilization Phase**	
Sub-Factor	Overall Net Weight	Radiation Dose Rate	Processing Time and Complexity	Nuclear Material Mass Requirement	Nuclear Material Heat Production
Attractiveness Level	Item Portability	Acute Health Effects	Nuclear Material Concentration	Uranium Isotopics	Plutonium Isotopics
High	Man Portable	Not-Lethal	Pure	Highly (Very Highly) Enriched	Low Heat Output
Medium	Vehicle Portable	N/A	High Grade	Highly (Moderately) Enriched	Moderate Heat Output
Low	Heavy Truck Portable	Lethal[a]	Moderately Diluted[c]	Low Enriched[e]	High Heat Output[g]
Very Low	N/A	Incapacitating[b]	Highly Diluted[d]	Low (Very Low) Enriched[f]	N/A

Table 5. Proposed Quantification Principles for the Materials Attractiveness Sub-factors

[a] INFCIRC 225/Rev. 5 standard of greater than 1 Gy/h @ 1 m.
[b] To be determined. Probably greater than 10 Gy/h @ 1 m.
[c] To be determined. Probably less than 10% nuclear material, but could be as high as about 25% nuclear material.
[d] To be determined. Probably less than 0.1% nuclear material, but could be as high as about1% nuclear material.
[e] INFCIRC 225/Rev. 5 standard of 10 to 20% ^{235}U.
[f] INFCIRC 225/Rev. 5 standard of less than 10% ^{235}U.
[g] INFCIRC 225/Rev. 5 standard of greater than 80% ^{238}Pu.

For Nuclear Material Mass Requirement, the criteria should be based on the bare critical mass of the uranium or plutonium element or alloy in question, but for ease of application the limits are equated to isotopic enrichment of uranium. In the case of plutonium, its isotopic composition does not have much effect on the mass requirement. Consequently, it is ignored. High attractiveness is equated to Highly Enriched uranium that is Very Highly Enriched in ^{235}U. Medium attractiveness is equated to Highly Enriched uranium that is Moderately Enriched in ^{235}U. Low attractiveness is equated to Low Enriched uranium that has a ^{235}U enrichment between 10 and 20%. Very Low attractiveness is equated to Low Enriched uranium that has a ^{235}U enrichment less than 10%.

For Nuclear Material Heat Production, the criteria should be based on the bare critical mass of the uranium or plutonium element or alloy in question times the heat content of the uranium or plutonium element or alloy in question. For plutonium, the heat content is dominated by the ^{238}Pu isotopic content. In the case of uranium, the heat contents of ^{235}U and ^{233}U are too low to be of any consequence. High attractiveness is equated to Low Heat Output materials (*i.e.*, ^{235}U, ^{233}U, and Pu with low concentrations of ^{238}Pu). Medium attractiveness is equated to Moderate Heat Output materials (*i.e.*, plutonium with moderate isotopic contents of ^{238}Pu. Low attractiveness is equated to High Heat Output material (*i.e.*, plutonium with greater than 80% ^{238}Pu). Very Low attractiveness would be equated to Very High Heat Output materials. Since materials in this category are of substantial concern for potential use in RDDs, however, this category is left as Not Applicable.

II.B.3 Determining the Overall Material Attractiveness
Although there is a more precise method to determine the overall attractiveness, the simplest approach is to use the attractiveness of the sub-factor that seems most relevant to the nuclear material in question. In other words, the overall materials attractiveness is given by the dominant sub-factor or the sub-factor that yields the overall lowest attractiveness level.

II.C Security Strategies
The final step in the proposed graded approach to nuclear material security is to equate appropriate security strategies with nuclear material attractiveness. Nuclear security strategies fall into three broad categories: Denial, Containment, and Detection.

Denial
The Denial security strategy focuses on preventing the construction of a NED onsite or nearby at the facility where nuclear material is stored. This strategy is divided into two variants, Denial of Access and Denial of Task. Denial of Access is aimed at completely denying the adversary access to weapons materials. Denial of Task is aimed at preventing the adversary from successfully assembling a NED where the nuclear material is located.

The Denial strategy only applies to facilities where nuclear weapons or their components are stored or built or to nuclear material transport vehicles when transporting these items.

Containment
In a Containment strategy, the theft/diversion of nuclear material is prevented even if an adversary is able to gain access to the material. That is, the adversary may temporarily take possession of the material but will not be able to remove the material from the site nor have sufficient time to build a NED onsite.

The Containment security strategy is divided into two levels, one for High attractiveness materials and one for Medium attractiveness materials. Since both High and Medium attractiveness materials are potentially usable by the adversary and therefore represent a near-term IND concern, any difference in security associated with High and Medium attractiveness materials should be relatively minor.

Detection
In a Detection strategy, any theft/diversion or attempted theft/diversion is detected in a timely fashion so that appropriate follow-up actions can be taken in a timely manner. An adversary may successfully remove from a site or transport vehicle nuclear material protected under a Detection strategy, but the theft will be promptly detected so that appropriate, timely follow-on actions can be taken.

The Detection security strategy is divided into two levels, Immediate for Low attractiveness materials and Non-Immediate for Very Low attractiveness materials. Post-theft/diversion response for Immediate detection would include either a Pursuit and Recover strategy (*i.e.*, find and recover the nuclear material) or a Prevention of Subsequent Theft Strategy (*i.e.*, prevent "roll-up" or collection of additional attractive items or bulk material). Any post-theft response for Non-Immediate detection would be determined at the time of discovery of the theft/diversion.

III. APPLICATION OF NUCLEAR MATERIALS ATTRACTIVENESS
The proposed quantification scheme of the materials attractiveness sub-factors in **Table 5** can be used to illustrate how material attractiveness can be applied to

materials of interest in the nuclear energy industry. The following cases are considered

1. Uranium Metal, Oxide, and Fluoride
2. Plutonium Oxide in Natural or Depleted Uranium Oxide
3. LWR Commercial Fuel (Used)
4. Transuranic Wastes
5. HEU Research Reactor Fuel (Fresh or Used)
6. LEU Research Reactor Fuel (Fresh or Used)

In the first four cases, the nuclear material attractiveness reduces to a single sub-factor. These cases are summarized in **Table 6**. In the last two cases, the nuclear material attractiveness is a function of two sub-factors. These cases are summarized in **Table 7**.

In the case of uranium metal, oxide, and fluoride, the material attractiveness is given by the degree of ^{235}U enrichment, which is a proxy for the Nuclear Material Mass Requirement. In most cases, the other four attractiveness sub-factors are not relevant.

In the case of plutonium oxide in natural or depleted uranium oxide, the material attractiveness is given by the degree of dilution of the nuclear material, which is a proxy for the Processing Time and Complexity. In most cases, the other four attractiveness sub-factors are not relevant.

In the case of used LWR commercial fuel, the attractiveness cannot be greater than Low because the material is Moderately Diluted. Whether the attractiveness is Very Low or Low depends upon whether the Radiation Dose Rate from the item is incapacitating or not-incapacitating, respectively.

In the case of transuranic wastes, the attractiveness cannot be greater than Low attractiveness because the material is not Pure or High Grade. Whether the attractiveness is Very Low or Low depends upon whether the material is Highly Diluted or Not-Highly Diluted, respectively.

Table 7 below summarizes the last two cases, in which the nuclear material attractiveness is a function of two sub-factors.

Table 6. Nuclear Material Attractiveness as a Function of One Sub-Factor

Material	**Uranium Metal, Oxide, Fluoride**	**Plutonium Oxide in Uranium Oxide**	**LWR Commercial Fuel**	**Transuranic Wastes**	**Security Strategy**
Dominant Attractiveness Sub-factors	Nuclear Material Mass Requirement	Processing Time and Complexity	Radiation Dose Rate	Processing Time and Complexity	
	Uranium Isotopics	Nuclear Material Concentration	Acute Health Effects	Nuclear Material Concentration	
Attractiveness Level					
High	Highly Enriched	Pure	N/A	N/A	Containment-High
Medium	Moderately Enriched	High Grade	N/A	N/A	Containment-Medium
Low	Low Enriched	Moderately Diluted	Not-Incapacitating	Not-Highly Diluted	Detection-Immediate
Very Low	Very Low Enriched	Highly Diluted	Incapacitating	Highly Diluted	Detection-Non-Immediate

Table 7. Nuclear Material Attractiveness as a Function of Two Parameters.

Material	**HEU Research Reactor Fuel**		**LEU Research Reactor Fuel**		**Security Strategy**
Dominant Attractiveness Sub-factors	Processing Time and Complexity	Radiation Dose Rate	Processing Time and Complexity	Radiation Dose Rate	
	Nuclear	Acute Health	Nuclear	Acute Health	

	Material Concentration	Effects	Material Concentration	Effects	
Attractiveness Level					
High	N/A	N/A	N/A	N/A	Containment-High
Medium	Not-Moderately Diluted	Not-Lethal	N/A	N/A	Containment-Medium
Low	Moderately Diluted	Lethal	Not-Highly Diluted	Not-Incapacitating	Detection-Immediate
Very Low	Highly Diluted	Incapacitating	Highly Diluted	Incapacitating	Detection-Non-Immediate

In the case of HEU research reactor fuel, the attractiveness, in most cases, cannot be greater than Medium because the fuel is not a Pure material. If the HEU research reactor fuel is unirradiated, then the attractiveness is given solely by the degree of dilution. If the HEU research reactor fuel is irradiated and not easily shielded, then the attractiveness is Very Low if the material is Highly Diluted or the item has an Incapacitating dose rate. Otherwise, the attractiveness is Low if the material is Moderately Diluted or the item has a Lethal dose rate. Otherwise, the attractiveness is Medium.

In the case of LEU research reactor fuel, the attractiveness cannot be greater than Low because the uranium enrichment is Low (*i.e.*, less than 20% ^{235}U). If the LEU research reactor fuel is unirradiated, then the attractiveness is Very Low if the nuclear material is Highly Diluted. Otherwise, the attractiveness is Low. If the LEU research reactor fuel is irradiated and not easily shielded, then the attractiveness is Very Low if the material is Highly Diluted or the item has an Incapacitating dose rate. Otherwise, the attractiveness is Low.

IV. POTENTIAL APPLICATION TO POLICY

In all of the above examples, High and Medium attractiveness are both equated to a Containment Security Strategy. Medium attractiveness materials are, in general, still potentially usable by the adversary to construct a NED. Consequently, there should be little, if any, difference in the security strategy between High and Medium attractiveness materials. Thus, in terms of potential policy, the four attractiveness levels can be reduced to three attractiveness levels: High/Medium, Low, and Very Low.

In addition, the materials attractiveness sub-factor of Nuclear Material Heat Production is, in general, not relevant and the materials attractiveness sub-factor of Overall Net Weight is, in most cases, adequately captured by the nuclear material concentration criteria under Processing Time and Complexity. Thus, the five materials attractiveness sub-factors can, in most cases, be reduced to only three sub-factors.

The simplified materials attractiveness metrics for policy consideration are given in **Table 8**.

Table 8. Simplified Quantification Principles for Nuclear Materials Attractiveness

Attractiveness Level	**Attractiveness Sub-Factor**			**Security Strategy**
	Radiation Dose Rate	Processing Time and Complexity	Nuclear Material Mass Requirement	
	Acute Health Effects	Nuclear Material Concentration	Uranium Isotopics	
High/Medium	Not-Lethal	Pure & High Grade	Highly Enriched	Containment
Low	Lethal	Moderately Diluted	Low Enriched	Detection-Immediate
Very Low	Incapacitating	Highly Diluted	Low (Very Low) Enriched	Detection-Non-Immediate

V. CONCLUSIONS

Using the attractiveness levels defined in this paper, one can determine appropriate security strategies for any nuclear material of interest. A graded approach to material attractiveness would encourage the nuclear industry to reduce the attractiveness of the materials that are used, stored, and transported. In the case of transportation, the only superior option to reducing the attractiveness is to eliminate transportation altogether by co-locating nuclear facilities.

This graded approach to materials attractiveness recognizes substantial differences in attractiveness between pure reactor-grade Pu oxide (High attractiveness) and fresh MOX fuel (Low attractiveness). In either case, an adversary's acquisition of a Category I quantity of plutonium would be a major incident, but the acquisition of Pu oxide by the adversary would be substantially worse than the acquisition of fresh MOX fuel because of the substantial differences in the time and complexity required of the adversary to process the material and fashion it into a NED.

This paper proposes metrics for materials attractiveness. In addition, it presents a framework for determining security strategies of nuclear materials associated with the civilian nuclear fuel cycle based on their materials attractiveness. These attractiveness metrics and security strategies have a degree of international consensus, but they are open for additional international review and improvement. In this regard, an international team of weapons design, materials processing, radiation health physicists, and security analysis experts should review these proposed attractiveness metrics and security strategies with the goal of developing the broadest international consensus possible.

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