# UNITED STATES-Japan Joint Study on Material Attractiveness

Evaluating and Reducing the Risks to Nuclear Materials and Facilities from Potential Malicious Acts

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**Abstract**

This paper presents the status of a joint United States-Japan effort to establish, through science-based study, a mutual understanding of material attractiveness. Material attractiveness is herein defined as the risk of non-state actors conducting malicious acts involving nuclear and radiological materials and facilities. The ultimate goal of this study is to develop a methodology to evaluate, assess, and reduce material and facility attractiveness. Such a methodology could inform nuclear security approaches in other countries hosting civilian nuclear fuel cycles that wish to reduce the risk associated with their nuclear and radiological facilities and materials. This paper presents the development status of this methodology. This study is being performed at the request of the United States Department of Energy/National Nuclear Security Administration and the Japanese Ministry of Education, Culture, Sports, Science, and Technology.

## INTRODUCTION

This paper presents the status of a joint United States-Japan effort to establish, through science-based study, a mutual understanding of material and facility attractiveness, herein defined as the risk from non-state actors conducting malicious acts involving nuclear and radiological materials and facilities. This study is being performed at the request of the United States Department of Energy/National Nuclear Security Administration (DOE/NNSA) and the Japanese Ministry of Education, Culture, Sports, Science, and Technology (MEXT).

### Background

The United States and Japan share a common obligation to ensure that their respective nuclear facilities do not become the source of materials used in a terrorist nuclear or radiological attack. As leaders in the international civilian nuclear energy sector, the two countries share a responsibility to set a global standard for responsible security and storage of nuclear and radiological materials. To achieve these goals, the two countries are jointly analyzing the technical aspects of nuclear material and facility attractiveness. This work is carried out under Goal 9 of the Nuclear Security Working Group (NSWG), established under the U.S.-Japan Bilateral Commission on Civil Nuclear Cooperation. It builds upon an earlier joint study for reducing material attractiveness performed from 2011 to 2013. [1] That earlier study considered the risks only from nuclear explosive devices (NEDs), whereas the current study considers a broader range of nuclear and radiological malicious acts. In this context, the overall risk of an NED can be weighed against the risks of other nuclear and radiological malicious acts.

A graded approach to physical protection is a fundamental principle in International Atomic Energy Agency (IAEA) Nuclear Security Series (NSS) No. 13 (INFCIRC/225/Revision 5) and its Implementing Guide (Nuclear Security Series No. 27-G). [2, 3] These documents provide guidelines for nuclear security categories based on nuclear material type, isotopic quantity, and irradiation history. These factors form the basis of the IAEA's categorization table - Table 1 in NSS 13. Both documents state that other factors can be considered in a graded approach to security, but provide no specific guidance. Other factors such as physical/chemical form and degree of dilution are also considered in this Goal-9 study. The IAEA's categorization table was drafted in 1972. [4] Since that time, the table and INFCIRC/225 have become the cornerstones of international nuclear security guidelines championed by the IAEA. While the table itself has largely remained unchanged since its creation, the international security landscape has evolved drastically.

Through the late 1980s, the prevailing belief was that only a nation state had the ability and resources to develop an NED. Subsequent acts of mass casualty terrorism perpetrated globally have utilized sophisticated technologies and demonstrated the willingness of some terrorists to sacrifice their own lives to advance their goals. Several terrorist organizations have expressed a desire to obtain weapons of mass destruction, including NEDs. Additionally, a number of known instances of theft and trafficking of nuclear materials, predominantly in the 1990s and 2000s, provided evidence that security was insufficient at some nuclear facilities. These instances also showed that an adversary lacking the means for either isotopic enrichment or irradiation/reprocessing might nevertheless be able to acquire nuclear material. In this context, it is important to understand the relative risks associated with nuclear and radiological malicious acts and to provide that information to regulators and other stakeholders.

### Previous Study

The United States and Japan conducted a joint scientific study on material attractiveness in 2011-2013 with the goal of establishing a mutual understanding of the attractiveness of six nuclear materials for possible use in a terrorist NED. The findings of the study were presented at the Global 2013 International Fuel Cycle Conference in fulfilment of the U.S.-Japan pledge to socialize material attractiveness concepts at international venues. [1] The 2011-2013 joint study concluded that:

* The attractiveness of separated plutonium is typically high. Denatured plutonium is similar in attractiveness to deep-burn plutonium, and both have an attractiveness of medium.
* The attractiveness (due to the ingrowth of plutonium) of irradiated commercial light-water reactor fuel assemblies with nominal values of burn-up and cooling time is low to very low.
* Unless diluted with natural uranium, the attractiveness of pure plutonium products is high.
* Plutonium oxide or metal with a 50% concentration of natural uranium reduces material attractiveness from high to medium.
* Fresh mixed oxide (MOX) in any form (i.e., powder, pellets, or fuel pins) is medium attractiveness because of its plutonium content.
* Fresh low-enriched uranium commercial fuel (i.e., less than 10% U-235 enrichment) is very low attractiveness.
* Pure plutonium solutions and solutions diluted with 50% or greater natural or depleted uranium are medium in attractiveness.
* Fresh metallic and oxide fuels for sodium fast reactors are both medium in attractiveness. Within this attractiveness level, metallic fuel is slightly more attractive than MOX fuel, because the former is a d generally contains a slightly higher plutonium concentration.
* Spent fuel stored in a dry cask or in a pond for 10 to 30 years is between low and very low attractiveness depending on cooling period.

## Scope of current study

In 2016, the United States and Japan agreed to continue the Goal-9 technical collaboration and initiated a two-part project in October 2017 to develop a methodology to evaluate material attractiveness (Part A) and to develop concepts and technologies for proactively reducing material attractiveness (Part B).

### Develop Methodology to Evaluate Material Attractiveness (Part A)

Compared to the original 2011-2013 study, the scope of the current study was expanded significantly to develop a comprehensive methodology to evaluate the risks of nuclear materials within the nuclear fuel cycle for non-state actor use in a nuclear or radiological malicious act and the risks associated with acts of sabotage against nuclear and radiological facilities. This study is the first to use a science-based methodology to examine both unauthorized removal (theft) from and sabotage of nuclear and radiological facilities. Typical civilian nuclear fuel cycle facilities considered in this current study are summarized in Fig. 1. Nuclear and radioactive materials considered include those associated with all feed, product, in-process, and waste materials in the facilities and the transportation of these materials between facilities.



*FIG. 1. NUCLEAR FUEL CYCLE FACILITIES TO BE CONSIDERED IN THIS STUDY*

### Development of Concepts and Technologies for Proactively Reducing Material Attractiveness (Part B)

The goal of Part B of this Goal-9 study is to develop and evaluate concepts for proactively reducing nuclear material attractiveness. To this end, we are going to examine concepts for the proactive reduction of nuclear material attractiveness including, but not limited to, the following approaches:

* Dilution to increase the volume and mass of material that must be stolen, and to force the adversary to process,
* Addition of elements and compounds that specifically make processing more time-consuming and/or more difficult, and
* Physical conditioning that makes the form more difficult to process.

We surveyed existing concepts and standards for termination of safeguards based on reducing material attractiveness, recognizing that there are ongoing international efforts related to termination of safeguards for geological disposal of dilute waste forms. Our examination included the U.S. Department of Energy order and standard on nuclear material control and accountability (DOE Order 474.2 [5] and DOE-STD-1194-2011, [6] respectively), IAEA safeguards termination criteria, the IAEA nuclear security recommendation on physical protection of nuclear material and nuclear facilities (INFCIRC/225/Rev.5), U.S. approaches to plutonium disposition under the U.S.-Russia Plutonium Management and Disposition Agreement [7], and UK approaches to plutonium management [8]. Once the methodology developed in Part A has been sufficiently vetted, we will apply that methodology to evaluate the various factors described above for reducing material attractiveness.

## Progress of methodology development in Part A

### Spectrum of Malicious Acts

Malicious Act

Theft

Sabotage

Nuclear

Radiological

Radiological

Nuclear

Nuclear Explosive Device
(NED)

Criticality Device
(CD)

Radiation Exposure Outside Facility
(RE-OF)

Radiological Dispersal Device with Explosive
(RDD-Ex)

Radiological Dispersal Device without Explosive
(RDD-nEx)

Contamination Food and Water
(CFW)

Uncontrolled Criticality
(RE-UC)

Uncontrolled Exposure to Radioactive Materials
(RE-UE)

Dispersal by Equipment Failure
(RD-EF)

Dispersal by External Means
(RD-DbE)

*FIG. 2. MALICIOUS ACT TREE*

In this Goal-9 study, we reviewed potential nuclear security threats and then proposed a comprehensive malicious act spectrum, shown in Fig. 2. Nuclear security events are first divided into theft of material and sabotage of facilities that contain nuclear material. The acts of theft are further divided into nuclear and radiological manifestations. There are two main types of nuclear-theft malicious acts: NED and criticality device (CD). In both acts, human casualties result from radiation exposure but in the NED malicious act significant additional human casualties and property damage result from blast overpressure. In the radiological malicious acts, radiation exposure outside facility (RE-OF) considers human casualties due to radiation exposure via theft of a highly radioactive material and its subsequent placement in a location that causes human exposure. While RE-OF acts focus on external exposure, radiological dispersal device (RDD) acts focus on both internal and external exposures. Furthermore, we consider separately RDDs with chemical explosives (RDD-Ex) and without (RDD-nEx). RDD-nEx acts consider human casualties due to radiation exposure resulting from dispersal of radioactive materials by spraying or scattering via non-explosive means. On the other hand, RDD-Ex acts consider in addition the further dispersion of radioactive materials, the deadly effect of chemical explosives themselves, and the high-temperature chemical behavior of materials, i.e. radiological aerosol generation. Contamination of food and water (CFW) acts consider human casualties due to internal exposure resulting from the intentional introduction of radioactive/nuclear materials into food and/or drink.

Four sabotage-based malicious acts were identified. Radiological event- uncontrolled criticality (RE-UC) is a sabotage act that creates supercritical events. Radioactive dispersal by equipment failure (RD-EF) is a sabotage act that disperses radioactive materials through malfunction of equipment in facilities. Radioactive dispersal by external means (RD-DbE) is a sabotage act that disperses radioactive materials by means brought to the facility (such as explosives transported to the facility). Lastly, uncontrolled exposure to radioactive materials (RE-UE) is a sabotage act resulting in human casualties.

Simple examples of all of these malicious acts are provided in Table 1.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Example | Tertiary | Secondary | Primary | Radiological/ Nuclear Consequence |  |
| A Fat-Man or Little-Boy-like NED | Internal Radiation | External Radiation | Physical Damage | Nuclear Explosive Device(NED) | Nuclear | Theft |
| A plutonium solution in a spherical container | Denial of Land and Structures Use | Internal Radiation | External Radiation | Criticality Device(CD) |
| An encapsulated piece of radioactive material |  |  | External Radiation | Radiation Exposure Outside Facility(RE-OF) | Radiological |
| A truck containing radioactive materials and explosives | Denial of Land and Structures Use | Internal and External Radiation | Physical Damage | RDD with ExplosiveTABLE 1. EXAMPLES OF MALICIOUS ACTS(RDD-Ex) |
| A crop duster spreading radioactive material | Denial of Land and Structures Use | External Radiation | Internal Radiation | RDD without Explosive(RDD-nEx) |
| Addition of 137Cs or 60Co to a water supply |  | Loss of Food or Water Supply | Internal Radiation | Contamination Food and Water(CFW) |
| Intentional criticality accident in a reactor | Denial of Land and Structures Use | Internal Radiation | External Radiation | Uncontrolled Criticality(RE-UC) | Nuclear | Sabotage |
| Lift spent fuel out of cooling pond |  |  | External Radiation | Uncontrolled Exposure to Radioactive Materials(RE-UE) | Radiological |
| Disrupt coolant flow leading to reactor core meltdown | Denial of Land and Structures Use | External Radiation | Internal Radiation | Dispersal by Equipment Failure(RD-EF) |
| RPG directed at processing plant or storage facility | Denial of Land and Structures Use | Internal and External Radiation | Physical Damage | Dispersal by External Means(RD-DbE) |

### Assumed Adversary

In general, perceived threats, vulnerability assessments, and intelligence should lead to the development of a detailed description of a design basis threat (DBT). Such a DBT becomes the basis of design for physical protection systems that are intended to prevent malicious acts. The DBT should be a comprehensive description of the motivation, intentions, capabilities, and resources of potential adversaries against which protection systems are designed.

The DBT need not be the same worldwide; rather, it should vary from country to country because security, economic, and political situations differ in each country. In addition, such threats may include non-nuclear related events. Three types of adversaries are being considered to cover a wide range of possible adversaries. The attributes and characteristics for the three types (Case 1: single individual, Case 2: sub-state group and Case 3: near state-level group) of assumed adversaries were determined by reference to IAEA Nuclear Security Series No. 10, "Development, Use and Maintenance of the Design Basis Threat." [9] Some of them are as follows.

* Willingness to put one's own life at risk;
* Intentions: radiological sabotage of material or of a facility, theft, causing public panic and social disruption, instigating political instability, causing mass injuries and casualties;
* Group size: attack force, coordination personnel, support personnel;
* Weapons: types, numbers, availability;
* Explosives: type, quantity, availability, triggering sophistication, acquired or improvised;
* Modes of transportation: public, private, land, sea, air, type, number, availability;
* Technical skills: engineering, use of explosives, chemicals, paramilitary experience, communications skills;
* Insider threat issues: collusion, passive or active involvement, violent or non-violent engagement, number of insiders;
* Tactics: use of stealth, deception, or brute force.

In consideration of information security, only generic facilities are being assessed in this Goal-9 study.

### Material Attractiveness

Material attractiveness is herein defined as the risk of non-state actors conducting malicious acts involving nuclear and radiological materials and facilities. Material attractiveness should also take into account the logistical and technical challenges. Three distinct phases are considered for each malicious act: acquisition, processing, and utilization. For each potential malicious act, metrics - physical properties by which to gauge material attractiveness - are identified. Metrics are only considered if they can potentially provide an effective barrier to one or more of the three assumed adversaries. Nuclear material is graded against each metric. This provides the overall attractiveness of the nuclear material to an adversary, which is a measure of the probability that the adversary could successfully execute the malicious act in question. The study also considers the overall consequences of such malicious acts, because overall attractiveness for each nuclear or radiological material is not the complete picture. The traditional definition of risk is the probability of executing a malicious act multiplied by the consequence of that malicious act.

#### Basic methodology

The study considers all nuclear fuel cycle facilities and nuclear/radiological material handling in these facilities, with the exception of uranium mining, milling, and conversion facilities. The nuclear materials and nuclear facilities shown in Table 2 are evaluated in the initial phases of this work. These materials and facilities are common to the civilian nuclear industries of the United States and Japan. Factors that reduce the intrinsic attractiveness of a material include the gross weight (heavier items are more difficult to move offsite), radiation dose rate, processing complexity accounting for chemical dilution, heat content, and other material properties that either provide self-protection or increase the required mass of material that must be stolen. For example, in the case of nuclear material theft for an NED, the intrinsic factors selected are gross weight, radiation dose rate, processing complexity, bare critical mass (BCM), and heat content. Each nuclear material is graded against these five factors. The overall material attractiveness of the nuclear material is evaluated using these graded scores.

Assigning an attractiveness to a given material or facility for acts of sabotage has proven difficult and the appropriate approach is still under consideration. For example, an event or fault tree for safety analysis could be used for evaluation of attractiveness by counting the number of steps that potentially impede an act of sabotage. Each sabotage threat assessment depends on facility design and nuclear/radiological material handling in the facility. The methodology to evaluate attractiveness for sabotage will continue to be studied based on the development of baseline scenarios and model facilities.

Additionally, the study considers the overall consequences of such malicious acts, including the number of deaths, number of injuries, and economic impacts of each act. In order to evaluate the consequence of each malicious act comprehensively and quantitatively, the International Nuclear Event Scale (INES) [IO], the value of statistical life (VSL), and use of a cost estimation code in combination with a Level-3 PSA code to evaluate economic impacts have been considered.

Combined, the obtained risks of individual malicious acts at a facility provides a quantitative measure of the overall nuclear and radiological relative risk of a given material or facility.

TABLE 2. FACILITIES AND MATERIALS TO BE EVALUATED IN INITIAL PHASE

|  |  |
| --- | --- |
| **Facility** | **Materials (Starting Form)** |
| Enrichment | UF6 (Enriched, Natural, Depleted) |
| Re-/De-conversion | UF6 (Enriched, Natural, Depleted), UO2 (Enriched, Natural, Depleted) |
| Uranium fuel fabrication | UO2 (Enriched, Natural, Depleted), UOX fresh fuel |
| Light water reactor | UOX fresh assembly, UOX irradiated assembly |
| Dry storage | UOX and MOX irradiated assembly |
| Reprocessing | Primary dissolver solution, Organic solution, Pu nitrate solution, 50/50 Pu/U nitrate solution, rep-UO3, HALW, HASW |
| MOX re-/de-conversion | 50/50 Pu/U nitrate solution, MOX powder, PuO2 powder |
| MOX fuel fabrication | MOX powder, pellets, fresh assembly, Pu scrap, Pu waste, PuO2 powder |
| MOX reactor | MOX fresh assembly, MOX irradiated assembly |

#### Phases, metrics and breakpoints

Only the methodology to assess the technical difficulty for theft threats is presented in this paper, because sabotage threats are still being studied. The technical difficulties associated with a successful adversary attack and theft were evaluated based on material properties identified as relevant metrics in three different phases:

1. Acquisition phase to remove nuclear material from a facility and transport it to the adversary's facility to process the material.
2. Processing phase to transform the nuclear material from its initial form into the final form for its intended use. This phase includes chemical processing such as purification, concentration or converting to the final form (e.g., metal for an NED and solution for a CD).
3. Utilization phase to build a threat device with the processed nuclear material, to transport it to the location of its intended use, and to use it.

Metrics applicable to these three phases are listed in Table 3. Each metric independently increases the technical difficulty for the adversary independently based upon its relevant material intrinsic properties. These metrics can be categorized into three types of difficulties: handling, delivery, and processing/fabrication. For instance, gross weight and radiation dose are identified as the applicable metrics in the acquisition phase. The difficulty of success during the acquisition of a nuclear material is determined by the intrinsic properties of the material, e.g., weight and radiation dose rate. Processing complexity was identified as the metric for measuring the technical difficulty in the processing phase. It is evaluated based on processing diagrams identified for the different malicious acts. An example processing diagram for an NED and a CD is shown in Fig. 3. The processing diagrams outline the generic steps required to complete the material transformation into the adversary's intended use form. After the initial form and the intended use form of a nuclear material for a specific threat are determined, the shortest pathway can be identified with the diagrams. The technical difficulty can be evaluated for each processing step.

TABLE 3. TENTATIVE METRICS IN EACH PHASE

|  |  |  |  |
| --- | --- | --- | --- |
| Phase | Metric | Unit of measure | Comment |
| Acquisition | Gross weight | kg |  |
| Radiation dose | Gy/h |  |
| Processing | Complexity | Descriptive |  |
| Utilization | BCM-metal (NED) | kg | NED only |
| BCM-solution (CD) | kg | CD only |
| Heat content | W | NED only |
| Radiation dose | Gy/h |  |

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*FIG. 3. PROCESSING DIAGRAM FOR NED AND CD*

The breakpoints to determine the “bins” of material-attractiveness scoring for each metric were defined quantitatively whenever possible. For example, the radiation dose breakpoints shown in Table 4 were defined based on the radiation dose level causing incapacitation during theft of a material. Otherwise, they were defined descriptively based on the assessed capabilities of the three different adversaries:

* Very High (VH): Any adversary could succeed;
* High (H): Only a Case 1, Case 2, or Case 3 adversary could succeed;
* Medium (M): Only a Case 2 or Case 3 adversary could succeed;
* Low (L): Only a Case 3 adversary could succeed;
* Very Low (VL): Only a state level adversary could (all of Case 1 to 3 could not) succeed.

TABLE 4. RADIATION DOSE BINS IN ACQUISITION PHASE

|  |  |
| --- | --- |
| Attractiveness | Comments |
| Very low | Incapacitating at contact |
| Low | Incapacitating at 30cm or less |
| Medium | Incapacitating between 30cm and 1m |
| High | Incapacitating between 1m and 3m |
| Very high | Incapacitating at greater than 3m |

## conclusion

This paper presents the status of a joint U.S.-Japan effort to establish, through science-based study, a mutual understanding of material attractiveness. The scope of the current study is to develop a methodology to evaluate material attractiveness (Part A) and to use that methodology to evaluate concepts and technologies for proactively reducing material attractiveness (Part B). To begin, we first reviewed the 2011-2013 joint study on material attractiveness. Compared to the original study, the scope of this current study was expanded significantly to develop a comprehensive methodology to evaluate the risks of nuclear materials within the nuclear fuel cycle of terrorist use in a nuclear or radiological malicious act and the risks associated with acts of sabotage against nuclear and radiological facilities. We developed a spectrum of malicious acts and assumed adversaries. We identified nuclear and radiological facilities and the materials typically found in those facilities for evaluation. We refined the definition of attractiveness, identifying three major phases to be considered: acquisition, processing, and fabrication/utilization. At each phase, metrics were proposed along with four breakpoints to create five bins describing difficulty.

This joint study will continue for two to three more years to develop methodologies for evaluating attractiveness as it applies to acts of sabotage, to evaluate the consequences of malicious acts, and to evaluate the overall risk. The overall methodology will be validated using generic facility models. The validated methodology will be used to evaluate concepts for proactively reducing material attractiveness. The final results will be presented at relevant academic meetings. Plans for holding a stakeholder workshop to share the study’s results are also being considered.

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