Algorithm for Establishing Safeguards Termination Concentration Limits

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ABSTRACT

This paper presents an algorithm for estimating the maximum concentration limits for terminating safeguards on nuclear materials. These limits are important because such material is no longer subject to accounting, reporting or inspections after the International Atomic Energy Agency (IAEA) has approved the termination of safeguards on nuclear material declared by a State to be waste. Maximum concentration limits for different waste forms generated within nuclear fuel cycle facilities must be sufficiently conservative such that termination of safeguards does not become a weak link in the safeguards system. The concentration limits must also remain practical in order to ensure IAEA resources are used effectively and efficiently to implement safeguards in the State. These termination limits should be technically-based while remaining objective and reasonable to implement by the State. In support of the original IAEA guidance on concentration limits for termination of safeguards prepared in the early 1990s, the U.S. developed an algorithm to estimate concentrations that would make recovery of nuclear material from waste on which safeguards had been terminated at least as unattractive as undeclared production from uranium ore or diversion of similar nuclear material. In 2016, the IAEA sought technical advice from a meeting of experts from selected member States to support updating its internal guidance on termination of safeguards. Their recommendations included extending the guidance to consider additional waste forms. The experts in the 2016 meeting recommended that the IAEA limits should more clearly reflect the technical difficulty and level of effort required to recover nuclear material from the various waste forms. This paper identifies and assesses the most likely techniques a State might use to recover nuclear material from the waste forms identified by the experts and determines how the safeguards termination algorithm could be revised to more accurately reflect the difficulty of recovering one significant quantity of nuclear material from these waste forms.

BACKGROUND

The International Atomic Energy Agency (IAEA) document, “The Structure and Content of Agreements Between the Agency and States Required in Connection with the Treaty on the Non-Proliferation of Nuclear Weapons” (INFCIRC/153 (corrected)), which serves as the basis for comprehensive safeguards agreements (CSAs), identifies that there is an ending point to IAEA safeguards on some nuclear material. Specifically, INFCIRC/153 (corrected) states “the Agreement should provide that safeguards shall terminate on nuclear material subject to safeguards… upon determination by the Agency that it has been consumed, or has been diluted in such a way that it is no longer usable for any nuclear activity relevant from the point of view of safeguards, or has become practicably irrecoverable.[1]” Defining “practicably irrecoverable” in a manner that is technically justifiable, objective, and verifiable is a significant challenge. It is imperative that the IAEA define it in a manner that does not weaken safeguards assurances. In the mid-1990s, the IAEA established an internal policy for implementing this legal obligation. The internal policy addressed conditioned waste and unconditioned waste that was of interest to the IAEA at that time. Maximum concentration guidelines for unconditioned waste were based on recommendations of experts who participated in a series of consultants' meetings on the topic that preceded establishment of the IAEA's internal policy[i]. The maximum concentration limits for termination of safeguards on conditioned waste that the consultants recommended were based on an algorithm that used cost as a surrogate for the level of effort of recovering nuclear material from nuclear waste.

After the IAEA determines that IAEA safeguards may be terminated on a material that the State considers to be waste, the State reports an inventory change that removes the nuclear material from the facility's inventory. In a State with only a CSA, no further reporting and no further verification of the nuclear material would be performed. In a State with an additional protocol in force, the State is obligated to provide the IAEA with "information regarding the location or further processing of intermediate or high-level waste containing plutonium, high enriched uranium, or uranium-233 on which safeguards have been terminated.[2]"

In 2016, the IAEA convened a consultants' meeting for revising the technical criteria for termination of safeguards[ii]. The objective of the meeting was to review the existing safeguards termination criteria and extend the termination criteria to additional forms of nuclear-material-bearing waste materials. With respect to the maximum concentrations for termination of safeguards, the consultants made the following recommendations:

- Recovery from waste should be less desirable than alternative acquisition pathways.
    - For enriched uranium and plutonium, a ten-fold factor should be used to increase the level of effort for recovery from waste over production of similar nuclear material from ore.
    - The level of effort for recovery of natural or depleted uranium or thorium from waste could be equivalent to that for production from ore.
- Levels of recoverability effort should be established for different waste types to establish valid points from which the termination concentration criteria can be established.
- The level of effort should be proportionally greater for unconditioned waste that has been treated by strong acid leaching versus waste that was not similarly treated.
- The level of effort should be proportional with respect to whether the processing location must be in a hot cell, glove box, or lower level of containment and shielding.
- The amount of nuclear material required to be recovered should be proportional to the 'significant quantity' of that nuclear material.

During the 2016 consultants' meeting, the representatives of the European Commission stated that the Euratom safeguards termination concentrations (alluded to in Commission Regulation 302/2005)

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[i] One of the authors participated in the mid-1990's IAEA consultants' meetings to establish the maximum concentration limits for termination of safeguards on unconditioned waste.

[ii] Two of the authors participated in the 2016 IAEA consultant's meeting related to termination of safeguards.

were based on the concept that nuclear material in waste should remain under safeguards as long as its concentration is not less than that of uranium in uranium-bearing ores entering the nuclear fuel cycle and coming under Euratom safeguards[3]. This is in contrast to proposed IAEA safeguards termination criteria, which have been based on processing costs or on a defined maximum plutonium concentration in unconditioned waste. The concentration for uranium bearing ores is defined in Commission Regulation No. 9 (of 22 Feb 1960) as 1000 g/metric ton (t) or more uranium. Euratom termination concentration values for low enriched (LEU), high enriched uranium (HEU), and plutonium (Pu) in waste were derived based on a 'safeguards equivalence' to the respective significant quantities (SQs). The Euratom safeguards termination criteria do not consider the forms of waste for which safeguards termination has been requested.

This paper reports on the authors' work to develop an algorithm for calculating the maximum concentration for termination of safeguards that addresses the recommendations of the consultants.

ALGORITHM METHODOLOGY

Taking into account the consultants' recommendations, the authors addressed the level of effort for each waste form. To compare relative levels of effort, the authors chose to follow the Euratom example and define the starting point for the safeguards termination algorithm as the level of effort required to recover nuclear material from uranium ore with a concentration of 1000 g/t. The authors broke the recovery process down into five processing steps (see Table 1) in order to assess the relative effort that would be required for processing nuclear material contained in a particular waste form to a purified nuclear material oxide that could be used in a nuclear fuel cycle.

Table 1. Process steps for recovery of nuclear material from uranium ore and nuclear material waste

Process Step	**1**	**2**	**3**	**4**	**5**
Definition of Process Step	Pretreatment to prepare for recovery operations	Action to improve leaching	Leaching/ dissolution	Extraction/ purification	Conversion from extraction output to nuclear material oxide
Examples	removal of waste from container, slagging of molten metal, incineration of combustible waste	cutting, crushing, grinding, milling, and/or roasting	dissolving in hot concentrated acid (e.g., nitric acid) or carbonate	solvent extraction, ion exchange, selective precipitation with filtering, preceded or followed by evaporation (if applicable)	denitration, precipitation and firing, calcination

The discussions of the experts participating in the 2016 consultants' meeting identified forms of unconditioned and conditioned waste that are currently used or are expected to be produced by nuclear fuel cycle facilities. In developing the algorithm, the authors considered the following waste types:

- Combustible waste
- Noncombustible waste
- Ash, evaporation solids, or sludge
- Dissolution residuals/fines
- Supercompacted non-metallic waste
- Overpacked waste containers of unconditioned waste
- Bitumen
- Cement
- Geopolymer
- Glass
- Ceramic
- Supercompacted or melted metal

Next, the safeguards significance of the nuclear material is considered by multiplying the relative effort by the SQ value for the type of nuclear material[iii]. This accounts for the differences in the weapons-usability of a given nuclear material and quantities of nuclear material that must be processed to fabricate a nuclear weapon. For example, recovered plutonium is directly usable in weapons, while depleted uranium would need to be irradiated (possibly in a clandestine reactor or through misuse of a declared reactor) and processed chemically to recover the produced plutonium (again either in a clandestine hot cell or shielded processing facility or through misuse of a declared facility). Each step increases the level of effort required to obtain weapons-usable material from the waste, and introduces additional opportunities for detection by the IAEA.

Finally, a constant is used to convert the relative level of effort to a concentration. This constant is determined by applying the algorithm to uranium ore and setting the maximum concentration limit equal to 1000 g/t[iv].

ALGORITHM FACTORS

The primary factor in the algorithm is the relative level of effort to recover nuclear material from a given waste form. The level of effort for each process step (as defined in Table 1) for a given waste type was estimated relative to the effort required for the same process step for recovering natural uranium (NU) from ore. To ensure that the efforts were comparable, the uranium ore and each waste type was assumed to have a 1000 g/t concentration of natural uranium. The processing effort was also required to recover more than 90% of the nuclear material content in the waste. In cases in which there were multiple processing methods to recover the nuclear material, the processing path that was deemed the lowest level of effort was selected. In all cases, processing methods that utilized commercially-available equipment were selected. Experts at the four institutions represented by the authors (i.e., Argonne National Laboratory, Oak Ridge National Laboratory, Texas A&M University, and Y-12 National Security Complex) were asked to identify how they would recover nuclear material from the waste forms and how that level of effort would compare to the level of effort required to recover nuclear material from uranium ore. The level of effort for each processing step for uranium

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[iii] To establish consistency across the SQ values, the SQ values for LEU and HEU are converted to kilograms of total uranium by dividing a given SQ value by the weight percentage of uranium that is U-235 (i.e., the enrichment). The authors also considered using effective kilograms as a basis for the concentration limits, but at this time chose to use SQ values, as were used in prior studies.

[iv] Note that by using the reference of uranium ore with a 1000 g/t limit and defining the level of effort relative to natural uranium recovery from ore, this addresses the consultants' recommendation that the level of effort to recover natural or depleted uranium could be approximately that of ore. At this time, the algorithm does not address the recommendation to increase the level of effort to recover enriched uranium or plutonium by a factor of ten.

ore was assigned an arbitrary value of '100.' Table 2 briefly describes the actions required for each processing step and provides initial estimates of relative effort values for some waste forms.

The values for E_1, E_2, E_3, E_4, and E_5 are based on expert judgement (and therefore, somewhat subjective) and attempt to take into consideration objective characteristics of the waste forms such as actions needed to handle waste forms and chemical elements that could interfere with processing. The level of effort required to accumulate and install the processing equipment needed and differences in average processing time were not considered in the relative effort. Much of the equipment is common to milling and concentration of mineral ores and is likely to be available within a country. Processing time was determined to have little impact on effort once the waste was in the processing equipment. Not all of the factors that contribute to the effort were identified or quantifiably assessed. The authors and experts consulted used their experience to estimate the relative effort values initially used in developing the algorithm. These values will be reviewed further by subject matter experts familiar with each waste form to develop better consensus values. It should be noted that the experts for this assessment did not regard the effort to crush, grind, and mill (process step 2) any of the non-metal solid waste forms to be significantly different using commercially available equipment used in the mining industry.

Table 2. Example relative efforts for the five process steps

Process Step	**1**	**2**	**3**	**4**	**5**
	E_1	E_2	E_3	E_4	E_5
Reference: Uranium ore with 1000 g/t nuclear material	opening of and transfer from container	crushing, grinding and milling to a powder	leaching of ore with hot strong acid or carbonate followed by thickening and filtration from dissolver liquid	evaporation followed by ion exchange or solvent extraction	conversion of solution to oxide
	100	100	100	100	100
Waste encapsulated in cement with 1000 g/t nuclear material	cutting container and peeling off from waste	crushing, grinding and milling to a powder	leaching with strong acid or carbonate followed by thickening and filtration from dissolver liquid	evaporation followed by ion exchange or solvent extraction	conversion of solution to oxide
	200	100	100	100	100
Waste converted to ceramic matrix with 1000 g/t nuclear material	cutting container and peeling off from waste	crushing, grinding and milling to a powder	leaching with hot strong acid, hot strong acid with ferric ions, or carbonate followed by thickening and filtration from dissolver liquid	evaporation followed by ion exchange or solvent extraction	conversion of solution to oxide
	200	250	100	100	100

Process Step	1	2	3	4	5
	***E*₁**	***E*₂**	***E*₃**	***E*₄**	***E*₅**
Combustible waste with 1000 g/t nuclear material	opening of and transfer from container				
	100				
	AND incineration or pyrolysis of combustible waste	milling of ash to a powder	leaching of ash with hot strong acid or carbonate followed by thickening and filtration from dissolver liquid	evaporation followed by ion exchange or solvent extraction	conversion of solution to oxide
	100	20	100	100	100

The algorithm recognizes that the baseline relative level of effort for each process step (as defined in Table 1) are not equivalent. For example, a baseline level of effort of 100 for emptying a container of uranium ore is not equivalent to a baseline level of effort of 100 for crushing, grinding, and milling uranium ore to a powder. Each process step has associated with it a factor, k_p, that normalizes the relative effort for that process step against the other process steps. Nominal values for the relative efforts between the different process steps are listed in Table 3.

The relative level of effort, E_p, is also affected by differences in containment and shielding required to process waste with different radiological health hazards. A health hazard index, H_p, is included in the algorithm to account for both external (e.g., gamma radiation) and internal (e.g., alpha radiation) radiological hazards. H_p represents three processing environments: (a) low health hazard index: allowing an open room environment (e.g., uranium ore mill), (b) moderate health hazard index: warranting a glove-box environment (i.e., containment against an inhalation hazard, such as plutonium processing), and (c) high health hazard index: requiring a hot-cell environment (i.e., heavily shielded environment for highly irradiated material). Initial values of H_p were developed based on operating costs of uranium purification and conversion versus reprocessing (to determine a 'high' health hazard index), and uranium fuel fabrication versus plutonium-uranium mixed oxide fuel fabrication (to determine a 'moderate' health hazard index). In order to define when each health hazard index should be used, the initial recommendation is to utilize a dose rate, measured at a distance of one meter from the waste. This has the benefit of accounting for external radiological hazards and being practical to verify; however, it does not account for internal radiological hazards. Another factor may be applied in the future to account for the internal health risks of handling plutonium. The values that define 'low', 'moderate', and 'high' health hazard indices are not based on U.S. or well-developed safety regulations, but rather are an attempt to quantify dose rates where workers exposed to the radiological field would have approximately a 70% probability of emesis if exposed throughout a four-hour shift (>1 Gy/hr at 1 m: moderate health hazard index) or a 70%

probability of total incapacitation if exposed throughout the same four-hour shift (>10 Gy/hr at 1 m: high health hazard index)[4].

An additional correction to the relative level of effort accounts for the changes in processing volumes versus the reference volumes from processing of uranium ore, and the associated impact that has on the level of effort. This modification accounts for changes in volumes during the processing steps. For example, 1 t of ore transferred from a container in the pre-treatment step would also be received as 1 t of input to the crushing/grinding/milling step; however, 1 t of combustible waste incinerated in the pre-treatment step would likely result in less than 0.1 t of ash received as input to the crushing/grinding/milling step (as well as an increase in nuclear material concentration). For combustible waste, this reduction in volume would reduce the level of effort required to process the waste through the crushing/grinding/milling processing step, as well as the dissolution and extraction steps. The resulting ash would have a V_p = 0.1 (or less) for processing steps 2 (crushing/grinding), 3 (dissolution), and 4 (extraction). Alternatively, a dissolution that would take twice as much acid to dissolve the nuclear material from the waste would result in twice the volume that must be processed by the extraction step. This material would have a V_p = 2 for processing step 4 (extraction). V_p adjusts the relative level of effort for the quantity processed with respect to the value of E_p, which was determined based on the assumption that equal volumes were processed.

Based on the above considerations, the following safeguards termination algorithm (Equation 1) is proposed for the calculation of maximum concentrations for the termination of safeguards:

$$T = c\,W\,\sum_{p=1}^{5} k_p\,E_p\,H_p\,V_p \qquad \textbf{(Equation 1)}$$

Table 3 describes each term in the algorithm.

Table 3. Description of algorithm terms, definitions, and values

Term			Definition	Values (Subject to Change)
Symbol	**Name**	**Units**		
T	Maximum concentration for termination of safeguards	g/t	The maximum allowable concentration of a nuclear material in a specific waste form	Calculated using algorithm
c	Constant	t^{-1}	Converts level of effort to concentration	Calculated by setting T = 1000 g/t for natural uranium in ore
W	Weapons-relevance of nuclear material	kg	Accounts for the quantity of a nuclear material that must be processed to produce a nuclear explosive	where E = Enrichment $W = \begin{cases} 8\ kg, for\ Plutonium; \\ \frac{25}{E}\,kg, for\ uranium\ with\ E \geq 20\%; \\ \frac{75}{E}\,kg, for\ uranium\ with\ E < 20\%; \\ 10{,}000\ kg\ for\ natural\ uranium; \\ 20{,}000\ kg\ for\ depleted\ uranium\ and\ thorium. \end{cases}$

Term			Definition	Values (Subject to Change)
Symbol	Name	Units		
p	Index of summation	unit-less	Subscripts defining process steps applicable to each variable	p=1 for pretreatment (e.g., removal from container, incineration, or segregation) p=2 for action to improve leaching (e.g., cutting, crushing, grinding, milling, and/or roasting) p=3 for leaching or dissolution p=4 for extraction (i.e., chemical separation) p=5 for conversion (i.e., resulting in an oxide product)
k_p	Relative level of effort for processing step 'p'	unit-less	Accounts for relative differences in effort between the processing steps (independent of starting material form)	k_1 = 0.05; k_2 = 0.35; k_3 = 0.25; k_4 =0.15; k_5 = 0.20
E_p	Effort required for processing step 'p'	unit-less	The relative effort for performing a process step for a given specific waste (relative to a reference material form)	Defined in a "Level of Effort" table (See Table 2)
H_p	Health hazard index for processing step 'p'	unit-less	Modifies the effort by accounting for different radiation (external and internal) hazards	$H_p = \begin{cases} x; if\ DR \geq 10\frac{Gy}{h} @\ 1m \\ y; if\ 10\frac{Gy}{h} @\ 1m > DR \geq 1\frac{Gy}{h} @1m \\ z; if\ DR < 1\frac{Gy}{h} @1m \end{cases}$ Assumed values: x = 20, y = 5, and z = 1
V_p	Volume of waste containing nuclear material at processing step 'p', relative to the reference waste volumes for processing of uranium ore	unit-less	Modifies the effort by accounting for volume changes during processing steps for different waste forms; determined by the ratio of the waste volume handled in processing step 'p' relative to the reference waste volume for that process step	$V_p = \begin{cases} x; where\ x\ is\ the\ fraction\ of\ the\ residual\ waste \\ matrix\ input\ to\ processing\ step\ 'p' \\ that\ contains\ nuclear\ material, relative\ to\ the \\ reference\ waste\ volume\ for\ process\ step\ 'p' \end{cases}$ x < 1 indicates waste volume bearing nuclear material has been reduced in the previous processing step, relative to the reference waste volume; x = 1 indicates waste volume bearing nuclear material is the same, relative to the reference waste volume; x>1 indicates waste volume bearing nuclear material has been increased in the previous processing step, relative to the reference waste volume.

EXAMPLES

The authors' main objective for developing this algorithm was to establish a technically-based, objective methodology that could be used by the IAEA for determining when a State's request for termination of safeguards on waste can be approved. The algorithm creates a structure based on relative levels of effort. The variables currently used to estimate the termination criteria require refinement. If the IAEA utilized the algorithm to determine maximum concentration limits for which safeguards may be terminated on waste, values for any of the factors could be revised based on IAEA's broader experience with and confidence in the data on waste. Table 4 presents some of the calculated termination limits, using assumed values (Table 3) applied to the developed safeguards termination algorithm.

Table 4. Safeguards termination limits calculated using the termination algorithm

Waste Form	Nuclear Material	T = Termination Concentration (g/t)	Quantity of Waste (at a concentration equal to T) that would contain 1 SQ of Nuclear Material
Reference (uranium ore)	NU	1000	10,000 t ore
Waste encapsulated in cement	NU	1050	9,500 t
	LEU (5 wt%)	160	9,500 t
	HEU (90 wt%)	3	9,500 t
High-level waste encapsulated in ceramic	LEU (5 wt%)	4160	360 t
	HEU (90 wt%)	80	360 t
	Pu	22	360 t
Unconditioned combustible waste	NU	350	29,000 t
	LEU (5 wt%)	50	29,000 t
	HEU (90 wt%)	1	29,000 t

For any given waste form, the mass of waste (at a concentration equal to the termination concentration) that would contain 1 SQ of a nuclear material is the same. This is because the algorithm includes the SQ of the nuclear material as a factor in determining the maximum concentration for which safeguards may be terminated. The termination concentration and SQ values are different, depending on the type of nuclear material contained in the waste, but the ratio of the two is equal across any given waste form. For example, for the termination concentrations given above, 360 t of ceramic waste with a concentration of 4160 g/t LEU (5 wt%) contains 1 SQ of LEU and 360 t of ceramic waste with a concentration of 22 g/t Pu contains 1 SQ of Pu. The termination concentration limit is significantly lower for Pu than for LEU because it is direct-use fissile material. To demonstrate how the algorithm accounts for the varying levels of effort to recover material from different waste forms the termination limit for LEU (at 5 wt%) in unconditioned combustible waste is 50 g/t, while the termination limit for LEU (at 5 wt%) in high-level waste encapsulated in ceramic is 4160 g/t. This accounts for the significantly lower level of effort required to recover LEU from combustibles, as compared to ceramic, as well as the additional effort required to recover LEU from high-level waste.

CONCLUSIONS

The authors developed the structure for a technically-justifiable algorithm that defines the maximum concentration limits for nuclear material in multiple waste forms. This algorithm (Equation 1) is based on the relative level of effort of recovering nuclear material from each waste form, as well as the safeguards-significance of the nuclear material that would be recovered from the waste. The algorithm can be consistently applied across all waste forms identified in the 2016 IAEA Consultants' Meeting. The values for the factors themselves can be adjusted based on data from the IAEA, should the IAEA choose to utilize this structure in the future to further develop internal policies.

Developing an objective algorithm that can be consistently applied across multiple waste forms is an essential step in ensuring that termination of safeguards in waste is not a weak link in the safeguards system. This is particularly important, given that in States with only a CSA in force, no further reporting is required and no further verification is performed on material for which safeguards has been terminated, once the facility has removed the nuclear material from its inventory. Additionally, as the IAEA continues to promote safeguards by design and integrating safeguards early in the process of designing nuclear facilities, allowing waste treatment facilities to know IAEA termination limits would increase the efficiency of the design process. IAEA transparency regarding the technically-justifiable and objective methodology used to determine these limits would also increase State's confidence in the IAEA policy for termination of safeguards.

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