MAXIMUM MASS RULES FOR CALCULATING TRANSPORT INDEX FOR SAFE SHIPMENT OF FISSILE MATERIAL PACKAGES

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ABSTRACT

According to the U.S. Code of Federal Regulations (10 CFR 71), any fissile material package must be controlled by either the shipper or the carrier to ensure that an array of such packages remains subcritical during both normal conditions of transport (NCT) and hypothetical accident conditions (HAC). To enable this control, the criticality safety analyst of a fissile material package shall derive a dimensionless number, called the transport index (TI), which must be placed on the label of a package to designate the degree of criticality control required. A rigorous procedure has been developed to calculate the TI for safe shipment of fissile material packages containing low-enrichment uranium (LEU) ingots in steel-banded wooden shipping containers [1,2]. A practical yet conservatively safe procedure based on previously established maximum subcritical masses for certain types of ingots may be used to derive expeditiously the TI for other similar types of ingots. These empirical maximum mass rules are based on extensive explicit modeling results obtained by the rigorous procedure. This paper confirms the validity of these rules and demonstrates how these rules may be used to derive the TI for safe shipment of packages containing LEU ingots in steel-banded wooden shipping containers.

INTRODUCTION

In fulfilling its diverse civilian and defense missions, the U.S. Department of Energy (DOE) and its predecessors have transported various types of nuclear materials in certified packages within the country for more than half a century. Before a package can be certified for transportation, it must meet three basic packaging safety design requirements, i.e., subcriticality, radiation shielding, and containment of radioactive materials, and must be in compliance with government safety regulations promulgated in the Code of Federal Regulations, 10 CFR Part 71[3]. The certification process of a package by DOE requires rigorous and independent technical review of the Safety Analysis Report for Packaging (SARP), conducted according to the DOE Packaging Review Guide [4]. The outcome of the SARP review is documented in a Safety Evaluation Report (SER), which provides the technical basis for issuing a Certificate of Compliance (CoC) for the package. The SER is part of the approval record of the package and is accessible to the public.

Design and review of criticality safety of a fissile-material package generally require complicated computational analyses, and the results must be clearly communicated in terms that can be understood by all involved parties, including shippers, couriers, and receivers. One such term is the transport index (TI), which is defined as

$$TI = 50 / N \qquad (1)$$

where N is a number derived from the maximum allowable number of packages in a shipment that is criticality-safe under various NCT and HAC conditions specified in 10 CFR 71. Any package that contains nuclear fissile materials must have a TI value specified in the CoC. A rigorous procedure has been developed to calculate N, and thereby TI, through a finite-array criticality analysis of packages that use steel-banded wooden shipping containers (SBWSCs) for the shipment of unirradiated LEU ingots [1,2].

LEU ingots have various uranium enrichments (0.956 to 1.256 wt.% U-235), diameters (9 to 13 in. OD), and lengths (1 to 30 in. L). Each ingot can weigh from 50 to 1,500 kg, depending on its size. Because the criticality safety of an array of fissile material packages must be evaluated for each ingot type under the most reactive configurations defined in 10 CFR 71.59, explicit modeling of potentially hundreds of different combinations of sizes and enrichments of these ingots is required in order to determine the optimal TI for criticality safety and shipping economy. The explicit modeling approach is rigorous but very time-consuming. For some ingot types, such as the FERMCO scraps with lengths ranging from 1 to 30 in., rigorous and explicit modeling of an array of these ingots is almost impossible. However, such modeling is usually not necessary for all practical purposes. By properly grouping or bracketing them together according to their lengths, we can make an approximation to determine the appropriate TI for these scrap ingots. A practical yet conservative procedure has been developed to safely derive the TI for certain ingots without going through the time-consuming effort of explicit modeling. Based on previously established maximum subcritical masses for given types of ingots, certain rules may be used to derive expeditiously the TI for other types of ingots with similar characteristics. These empirical maximum mass rules are derived from extensive explicit modeling results. This paper uses rigorous explicit modeling results to confirm the validity of these rules and demonstrates how these rules may be used to derive the TI for safe shipment of packages containing LEU ingots in SBWSCs.

EXPLICIT MODELING

According to 10 CFR 71, subcriticality for arrays of fissile packages must be demonstrated under NCT for 5 x N undamaged packages and under HAC for 2 x N damaged packages. The hypothetical accidents consist of a sequence of events (e.g., 9-m vertical drops, fire at 800^0C for 30 min, and immersion in water) that would damage the package. These events usually represent the most limiting conditions for criticality safety of fissile packages. Therefore, it is reasonable and conservative to assume after HAC that the uranium ingots are scattered and arranged in the most reactive configuration, with interspersed hydrogenous moderation and total water (30 cm) reflection, as required by 10 CFR 71.59. The task is therefore to determine the maximum number of ingots in this most reactive configuration that would remain subcritical with an adequate safety margin. Once the maximum number of ingots that remains subcritical under both NCT and HAC is obtained, the number N can be determined according to the ingots loaded per package, and the minimum TI for criticality control in a shipment can then be calculated easily according to Eq. 1.

As illustrated in Ref. 1, the determination of the maximum number of ingots under the most reactive configuration requires two steps: (a) a search for the optimal lattice parameters, i.e., pitch, axial gap, and moderator density, that would maximize the neutron multiplication factor k for an infinite array of ingots in a close-packed hexagonal lattice; and (b) determine iteratively the radius of a finite array of ingots arranged in a spherical enclosure that would have an adjusted neutron multiplication factor (k_{adj}), meeting the subcriticality requirement according to the formula [2]

$$k_{adj} = k_{eff} + 0.00258 + 2\,(0.006^2 + \sigma^2)^{0.5} < 0.95 \qquad (2)$$

where k_{eff} and σ are the effective neutron multiplication factor and uncertainty calculated by the MCNP-4.2 code package, respectively [6]. The subcriticality criterion of $k_{adj} < 0.95$ is the generally accepted upper limit for the adjusted neutron multiplication factor in transport package certification [4,5]. The adjusted neutron multiplication factor has included the MCNP code bias (0.00258) and uncertainty (0.006) obtained by the applicant from analyses of relevant critical benchmark experiments [2].

In the search for the optimal lattice parameters that maximize k for each ingot type, we typically considered six axial moderator gap sizes, five moderator (water) densities, and eight lattice pitches. Thus, a total of 240 (6 x 5 x 8) MCNP calculations were systematically performed to search for optimal values over the parametric spaces. After the optimal lattice parameters for a given ingot type were determined, a series of MCNP calculations was performed for various sizes of spherical enclosures for finite arrays of such ingots until the maximum radius was found that satisfies the subcriticality requirement ($k_{adj} < 0.95$) in Eq. 2. Based on the maximum radius for this subcritical finite array, the maximum subcritical mass and its corresponding number of ingots are obtained, and the number N can be determined according to the ingots loaded per package. Finally, according to Eq. 1, the minimum TI for criticality control in a shipment can be calculated. This rigorous procedure is required to determine the minimum TI for both criticality safety and optimal payload for shipping economy.

MAXIMUM MASS RULES

The above explicit modeling procedure to determine the maximum subcritical mass for each ingot type is the most rigorous (but also very time-consuming) approach. A practical yet conservatively safe procedure based on previously established maximum subcritical masses for certain types of ingots can be used to expeditiously derive the TI for other types of ingots with certain similarity. This procedure relies on empirical rules derived from extensive maximum subcritical mass results obtained by explicit modeling of many different ingot types by the rigorous procedure. Three such empirical rules have been established and are discussed below. Results based on rigorous explicit modeling of LEU ingots in SBWSCs are used to confirm the validity of these three rules.

Rule 1 - For ingots with fixed diameter and enrichment, the maximum subcritical mass based on a shorter ingot may be used to derive TI for longer ingots.

The maximum subcritical mass for ingots with fixed diameter and enrichment increases with ingot length. This is demonstrated in Figure 1, where the maximum subcritical masses for the 13 in. outer diameter (13" OD) FERMCO scrap ingots were plotted against ingot lengths, ranging from 1 to 12 in. The maximum subcritical masses are 1,071, 2,323, 4,312, 6,075, 12,144, and 25,120 kg, corresponding to 1, 2, 3, 4, 6, and 12 in. ingot lengths, respectively. All results were optimized from explicit modeling procedures for each ingot length. Because maximum subcritical mass increases monotonically with ingot length, it is obvious that the maximum subcritical mass based on a shorter ingot may be used to safely derive the TI for longer ingots. The conservatism and subcriticality of Rule 1 can be seen in Figure 2 for the 13" OD FERMCO scrap ingots. The variation of k_{adj} was plotted against ingot lengths, assuming that the maximum subcritical mass of 2,323 kg based on 2 in. length is applied to longer ingots (3 to 30 in.). The subcriticality safety margin increases steadily as the ingot length increases. For example, when the subcritical mass of 2,323 kg based on the 2 in.

long ingots is used for the 15 in. long ingots, the k_{adj} is only ≈ 0.8, well below the 0.95 subcriticality limit.

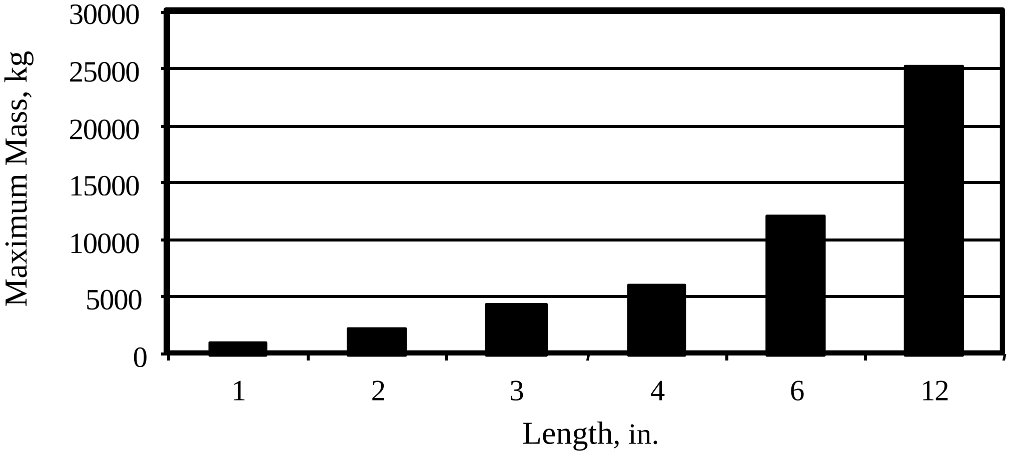

Figure 1. Maximum subcritical mass versus ingot length for 13" OD FERMCO scrap ingots

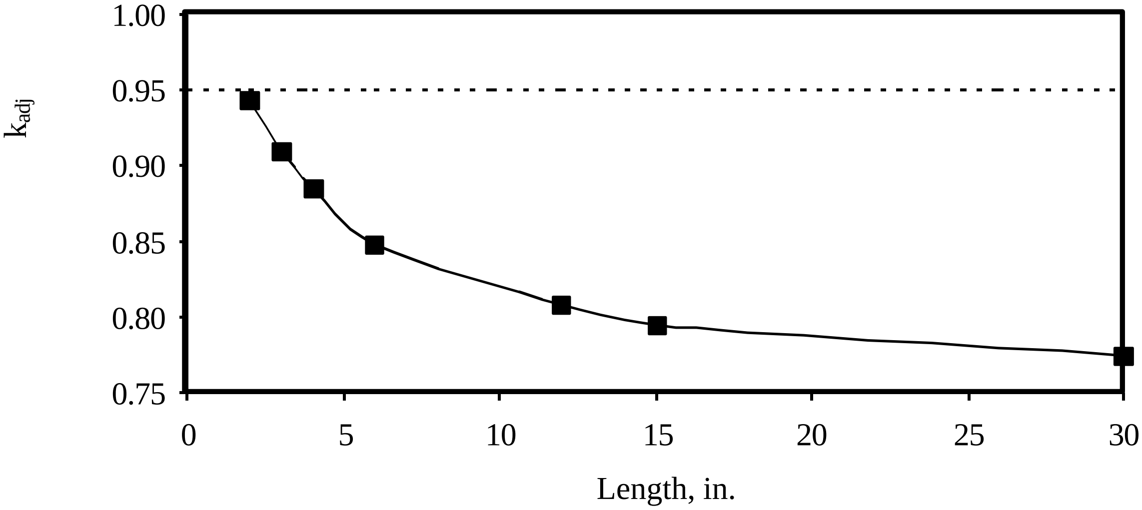

Figure 2. Variation of k_{adj} when maximum subcritical mass of 2,323 kg based on 13"OD x 2"L FERMCO scrap ingot is applied to ingots of same diameter but longer lengths

Rule 2 - For ingots with fixed length and enrichment, the maximum subcritical mass based on a smaller diameter ingot may be used to derive TI for larger diameter ingots.

The maximum subcritical mass for ingots with fixed length and enrichment increases with ingot diameter. Because the maximum subcritical mass increases monotonically with ingot diameter, it is obvious that the maximum subcritical mass based on a smaller diameter ingot may be used to safely derive the TI for larger diameter ingots. The conservatism and subcriticality of Rule 2 can be seen in Figure 2 for the 15 in. long (15" L) FERMCO primary ingots. The variation of k_{adj} was plotted against ingot diameters, assuming that the maximum subcritical mass of 13,067 kg based on 9" OD ingot was applied to ingots with larger diameters (10" to 13" OD). The subcriticality safety margin increases steadily as ingot diameter increases. For example, when the subcritical mass of 13,067 kg based on the 9" OD ingot is used for the 13" OD ingot, the k_{adj} is only ≈ 0.9, well below the 0.95 subcriticality limit.

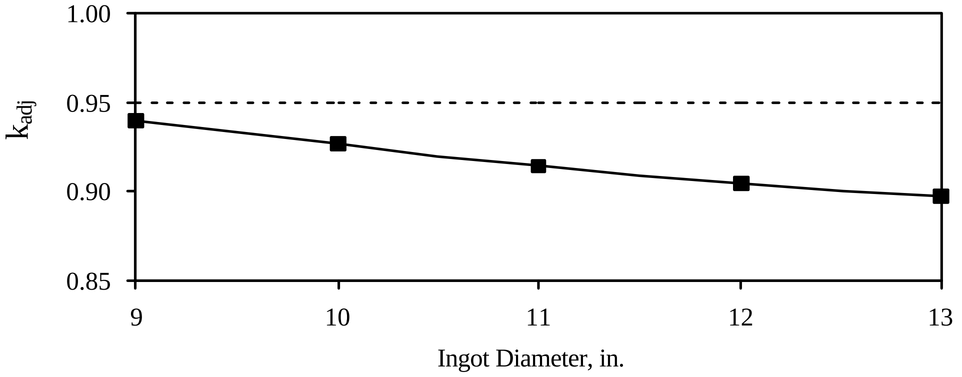

Figure 3. Variation of k_{adj} when maximum subcritical mass of 13,067 kg based on 9" OD ingot is applied to larger diameter but fixed-length (15" L) FERMCO primary ingots

Rule 3 - For ingots with same enrichment but different lengths and diameters, the maximum subcritical mass based on a shorter and smaller diameter ingot may be used to derive TI for longer and larger diameter ingots.

Rule 3 is a combination of Rule 1 and Rule 2. For a given enrichment, the maximum subcritical mass will increase with ingot length and diameter. Because maximum subcritical mass increases monotonically with ingot length and diameter, it is obvious that the maximum subcritical mass based on a shorter and smaller diameter ingot may be used to safely derive the TI for longer and larger diameter ingots. The conservatism and subcriticality of Rule 3 can be seen in Figure 4, where the maximum subcritical masses versus length for various diameter FERMCO ingots were plotted. The conservatism of applying the maximum subcritical mass based on the shorter and smaller diameter ingots to the longer and larger diameter ingots can be illustrated as follows: For example, when the maximum subcritical mass of 3,400 kg based on the 9-in.-outer-diameter x 3-in.-long (9"OD x 3"L) ingots is used for the 11"OD x 4"L ingots (which have a maximum subcritical mass of 3,584 kg), there is a subcriticality safety margin of 3,584 - 3,400 = 184 kg in payload mass. When this application is extended to the 13"OD x 6"L ingots (which have a maximum subcritical mass of 12,144 kg), an excessive subcriticality safety margin of 12,144 - 3,584 = 8,560 kg in payload mass will be achieved. Because of its ultra-conservative nature, Rule 3 has not been used in determining TI for safe shipment of packages containing LEU ingots in SBWSCs.

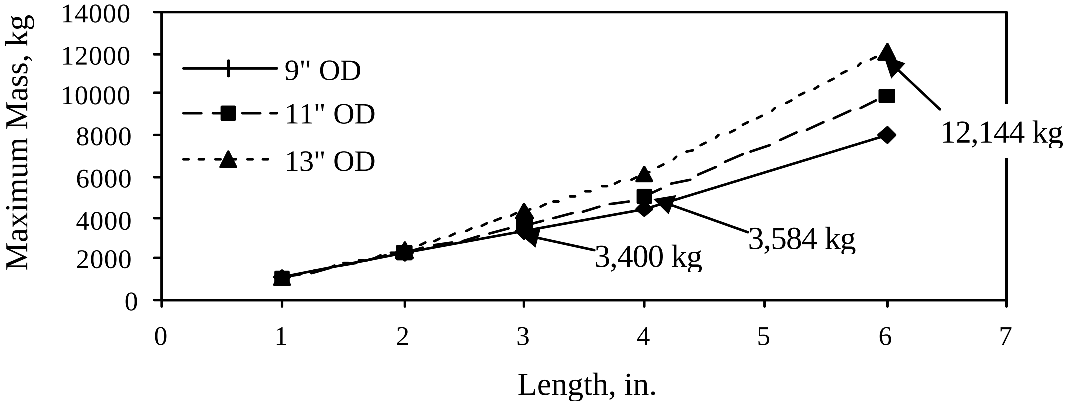

Figure 4. Maximum subcritical mass versus ingot length for 9", 11", and 13" OD FERMCO ingots

DEMONSTRATION OF APPLICATION

How these rules can be used to derive the TI for safe shipment of packages containing LEU metal ingots in steel-banded wooden shipping containers are demonstrated by using Rule 1. The applications of the other two rules are analogous to Rule 1 and will not be repeated. Demonstration of Rule 1 can be shown in Table 1. The maximum subcritical mass of 12,144 kg based on the 13"OD x 6"L ingots was applied to 13"OD x 12"L and 13"OD x 30"L FERMCO scrap ingots. For example, the 13"OD x 12"L ingot weighs 496 kg, and the number of ingots in 12,144 kg is 12,144 / 496 = 24.48. Because only one ingot is loaded per package, the 2 x N damaged packages is 24.48 / 1 = 24.48, and N = 24.48 / 2 = 12.24. The transport index TI = 50 / N = 50 / 12.24 = 4.1 after rounding up to the first decimal point [4]. Once the TI for the package is determined, the maximum number of packages per shipment can be calculated. For exclusive-use shipment [3], the sum of TI for all packages must be less than 100; therefore, the maximum number of packages per shipment is 100 / 4.1 = 24 packages. Because of its simplicity and conservatism, Rule 1 has been used extensively in determining TI for safe shipment of packages containing LEU ingots in SBWSCs. This has been particularly useful when dealing with the FERMCO scrap ingots because of their wide range of lengths.

Table 1. Application of Rule 1 to determine TI for FERMCO scrap ingots

FERMCO Payload Description	Ingot Sizes OD x L, in.	Each Ingot Wt, kg	Maximum Subcritical Mass, kg	Ingot Per Package	2xN	N	TI	Packages Per Shipment
Scrap	13 x 6	248	12,144	2	24.48	12.24	4.1	24
Scrap	13 x 12	496	12,144	1	24.48	12.24	4.1	24
Scrap	13 x 30	1,237	12,144	1	9.81	4.91	10.2	9

SUMMARY

This study used rigorous and explicit modeling results to confirm the validity of three maximum subcritical mass rules and demonstrated how these rules can be used to derive the transport index (TI) for safe shipment of packages containing low-enrichment uranium ingots in steel-banded wooden shipping containers. Without these maximum mass rules, it is necessary to explicitly model potentially hundreds of different combinations of sizes and enrichments of these ingots in order to determine the optimal TI for criticality safety and shipping economy. A practical yet conservatively safe procedure based on these maximum mass rules has been used extensively to calculate TI expeditiously for various LEU ingots in steel-banded wooden shipping containers. Because the TI determined from these maximum mass rules is not optimized for the particular ingot size, a smaller payload will be shipped. This penalty in shipping economy can be minimized if the maximum subcritical mass of proper ingot size is carefully chosen as the reference. Furthermore, these maximum mass rules are empirical and are valid only for low-enrichment uranium ingots; their applicability for other fissile packages has yet to be demonstrated.

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