A Risk-Informed Basis for Establishing Non-Fixed Surface Contamination Limits for Spent Fuel Transportation Casks

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1.0 INTRODUCTION

The current limits for non-fixed contamination on packages used to transport radioactive materials were introduced in the 1961 edition of the International Atomic Energy Agency (IAEA) transport regulations and were based on radiation protection guidance and practices in use at that time. The limits were based on exposure scenarios leading to intakes of radionuclides by inhalation and external irradiation of the hands. These considerations are collectively referred to as the Fairbairn model.[1] Although formulated over 40 years ago, the model remains unchanged and is still the basis of current regulatory-derived limits on package non-fixed surface contamination.

There can also be doses that while not resulting directly from the contamination, are strongly influenced by and attributable to transport regulatory requirements for contamination control. For example, actions necessary to comply with the current derived limits for light-water-reactor (LWR) spent nuclear fuel (SNF) casks can result in significant external doses to workers. This is due to the relatively high radiation levels around the loaded casks, where workers must function during the measurement of contamination levels and while decontaminating the cask. In order to optimize the total dose received due to compliance with cask contamination levels, it is necessary to take into account all the doses that vary as a result of the regulatory limit.

The Fairbairn model is based on exposure scenarios that are not appropriate for spent fuel casks. The exposure scenarios (e.g., dusty conditions) considered in the model are not representative of the operational practices and environments associated with handling of spent fuel casks. The model is based on the outdated "critical organ" approach to radiological protection that poorly, if at all, reflects actual health risk. The more recent ICRP recommendations are risk based. Furthermore, the model has no provisions to consider the significant doses to workers resulting from efforts to achieve compliance with surface contamination limits. Finally, the model does not consider doses to other groups such as members of the public.

Limits for non-fixed surface contamination on spent fuel casks should be established by using a model that considers and optimizes the appropriate exposure scenarios both in the workplace and in the public environment. A risk-informed approach is needed to ensure optimal use of personnel and material resources for SNF-based packaging operations.

This paper is a summary of a study sponsored by the US Nuclear Regulatory Commission and performed by Oak Ridge National Laboratory that examined the dose implications for removable surface contamination limits on spent fuel casks. This study was performed as part of the IAEA Coordinated Research Project on the Radiological Aspects of Package and Conveyance Non-Fixed Contamination and the full results of the study are provided in "A Risk-Informed Basis for Establishing Non-Fixed Surface Contamination Limits for Spent Fuel Transportation Casks".[2]

2.0 OPTIMIZATION

Compliance with radiation protection dose limits does not necessarily lead to realizing the benefit from a practice that requires radiation exposure to persons while, at the same time, keeping these exposures to the lowest practicable levels. Radiation protection approaches such as "as low as reasonably achievable" (ALARA), "as low as practicable" (ALAP), and "optimization" have been incorporated into radiation protection principles as ways of achieving this objective.

The IAEA Basic Safety Standards[3] call for the optimization of protection and safety "[i]n relation to exposures from any particular source within a practice . . ." and state that ". . . protection and safety shall be optimized in order that the magnitude of individual doses, the number of people exposed and the likelihood of incurring exposures all be kept as low as reasonable achievable . . . within the restriction that the doses to individuals delivered by the source be subject to dose constraints." In the case of non-fixed surface contamination on spent fuel casks, exposures to both workers and the public must be considered.

2.1 TOTAL DOSE

Optimization of doses resulting from removable surface contamination on spent fuel casks requires a consideration of all doses that could result from the contamination itself and doses that vary as a function of the allowable contamination limit. In this report, when the doses due to surface contamination are evaluated, these doses resulting from the contents of the cask are ignored ***except where these doses vary due to the contamination limits***. That is, where the doses due to the contents are the same regardless of the contamination limits, they are considered a constant and are not factored into the evaluation.

The public dose due to surface contamination on a cask is not a function of the dose rate from the cask contents or the ambient (e.g., background) dose rate, because these doses do not vary as a function of the surface contamination. Since these exposures will not be affected by the surface contamination limits, they are not included in this study.

The radionuclide composition of cask surface contamination is dependent on several factors but is most heavily influenced by the radionuclides present in the pool water in which the cask is immersed. Pool water radionuclide composition varies widely, so a reference pool water composition was developed for this analysis using the values identified in the literature[4] and confirmed qualitatively with another nuclear plant operator.[5] The quantitative results reported in Ref. 4 have been used to derive a reference mix of contaminants on the cask surface that are proportional to their presence in the pool water. Using this mix of contaminants, reference committed effective dose per unit intake factors for the mixture was calculated, using the fractions and dose per unit intake factors shown in Table 1.

Table 1 Radionuclide Characteristics for Reference Mixture of Contaminants for Workers

Radionuclide	Committed Effective Dose Per Unit Intake Via Inhalation[2] ($Sv\ Bq^{-1}$)		Committed Effective Dose Per Unit Intake Via Ingestion[2] ($Sv\ Bq^{-1}$)	Fraction of Activity Present
	Worker	*Public*	*Worker*	
^{58}Co	1.4×10^{-9}	1.6×10^{-9}	7.4×10^{-10}	0.217
^{60}Co	7.1×10^{-9}	1.0×10^{-8}	3.4×10^{-9}	0.722
^{134}Cs	9.6×10^{-9}	9.1×10^{-9}	1.9×10^{-8}	0.025
^{137}Cs	6.7×10^{-9}	9.7×10^{-9}	1.3×10^{-8}	0.036
Weighted Factor	$\mathbf{5.9 \times 10^{-9}}$	$\mathbf{8.2 \times 10^{-9}}$	$\mathbf{3.6 \times 10^{-9}}$	

These weighted committed dose per unit intake factors were used to calculate individual and collective doses for the exposure scenarios.

3.0 SUMMARY OF WORKER DOSES

The full report provides details of the calculation approaches and parameters used to determine worker doses. To calculate doses for internal and external exposures that are consistent with the CRP formulas (calculated for a unit activity concentration of 1 Bq cm^{-2}) and the external exposures derived from DOE-CH/TPO-001[6] (based on experience with cask operations designed to meet the current 4 Bq cm^{-2} limits), the values are normalized to 4 Bq cm^{-2} for a single PWR cask turnaround. The dose to the maximally exposed individual worker and collective worker dose can be categorized by the following:

Table 2 Categories and Total Dose for Maximally Exposed and Collective Worker

Exposure Group	Category	Total Dose Per Cask Turnaround (Contamination Level--4 Bq cm^{-1})
Maximally exposed individual	Doses that will increase if contamination limits are raised (inhalation and ingestion, as well as direct, hand, and face exposures).	7.7 x 10^{-7} Sv
	Doses resulting from decontamination and monitoring tasks that will decrease due to reduced exposure times if contamination limits are raised (from cask contents and ambient).	1.1 x 10^{-4} Sv
Collective worker dose	Collective dose that will increase if contamination limits are raised (inhalation and ingestion, as well as direct, hand, and face exposures).	1.8 x 10^{-6} person-Sv
	Collective dose resulting from decontamination and monitoring tasks that will decrease due to reduced exposure times if contamination limits are raised (from cask contents and ambient).	2.3 x 10^{-4} person-Sv

3.1 WORKER DOSES AS A FUNCTION OF CONTAMINATION LIMITS

It is possible to calculate the individual and collective worker doses that would increase due to higher contamination limits (i.e., dose contributions from all sources of exposure other than external exposure due to the cask contents during decontamination and monitoring tasks). These calculations have been performed for limits that are 10 and 100 times higher than the current limit of 4 Bq cm^{-1} for beta and gamma emitters, as shown in Table 3.

Table 3 Worker Doses That Increase Due to Higher Removable Contamination Levels

Contamination Limit	Maximally Exposed Individual Dose Sv	Collective Dose person-Sv
4	7.7 x 10^{-7}	1.8 x 10^{-6}
40	7.7 x 10^{-6}	1.8 x 10^{-5}
400	7.7 x 10^{-5}	1.8 x 10^{-4}

4.0 CALCULATION OF PUBLIC DOSE

Removable surface contamination on a cask surface can result in both internal and external exposures to members of the public. These doses can be calculated to determine the effect on both the collective public dose and the dose to the most exposed individual.

This study used a typical US spent fuel highway route to model public exposures. Analysis of a representative spent fuel transport route in the United States (Surry Nuclear Power Station, Virginia to Yucca Mountain, Nevada) using the ORNL Transportation Geographical Information System (TRAGIS) routing and population model shows that the route consists of 96% multilane divided highway and 4% other highway (two or more lanes, non-controlled access).[7] The lengths of the route segments are as follows: 4365 km, multilane divided, and 198 km, other highways. The population within 800 m on either side of the centerline of the 4563-km route is 873,000 people. Assuming that the population is uniformly distributed within the band of land from 30 to 800 m on either side of the highway (to account for uninhabited rights-of-way), the land area over which the population is distributed is 7.0×10^9 m^2, giving an average population density of 1.2×10^{-4} persons per square meter.

4.1 EFFECTIVE DOSES TO THE PUBLIC DUE TO INTERNALLY DEPOSITED RADIONUCLIDES

The IAEA CRP performed calculations to determine the magnitude of these exposures and determined that inhalation of contamination resuspended from the cask surface is the only significant internal dose pathway. The CRP focused on the maximum individual doses in relatively close proximities to the cask.

In order to accurately model doses to the public resulting from inhalation of contamination resuspended from the surface of a spent fuel cask during movement, it is necessary to define the scenarios leading to the exposures. The parameters in these scenarios vary from country to country and can be set to provide either country-specific results or to support a more universal contamination dose model. While the doses from these exposures are extremely small, it is useful to calculate them in order to demonstrate that this exposure route is not a significant source of exposure to the public.

The exposure scenarios contained in the risk assessment code RADTRAN 5 provide insight into public exposure groups appropriate for incident-free transportation.[8]

Public Inhalation Dose Model

A dispersion model that takes into account dilution of the airborne activity due to mixing in the "wake" of the moving conveyance was developed to calculate the doses to exposed individuals. The methodologies used in the model are provided in more detail in the full report. Doses can be calculated for individual members of the public as well as collective dose (if parameters for the route and population along the route are specified). The model calculates dose (in Sieverts or Sv) per unit of surface contamination (1 Bq cm^{-2}).

Summary of Public Doses Due to Inhalation

The doses to members of the public from the inhalation of resuspended contamination from a cask surface are very low. The results are provided below:

Table 4 Inhalation Doses to the Maximum Exposed Member of the Public and Collective Public

Highest Individual Public Inhalation Dose (1 Bq cm^{-2})	1.4×10^{-13}
Total Collective Public Inhalation Dose (1 Bq cm^{-2})	7.0×10^{-12}

4.2 DOSES TO THE PUBLIC DUE TO EXTERNAL EXPOSURES

Public External Dose Model

The methodologies used in the model are provided in more detail in the full report. A spreadsheet was developed and used to calculate doses for individual members of the public as well as collective doses (using specified parameters for the route and population). The model calculates dose (in Sv) per unit of surface contamination (1 Bq cm^{-2}).

Summary of Public Doses Due to External Exposure

From the results of the full report, it can be seen that the doses to members of the public from direct exposure to contamination on a cask surface, while higher than those for inhalation, are still very low. These dose calculations are summarized below for a surface activity concentration of 1 Bq cm^{-2}.

Table 5 External Exposure Dose to the Maximum Exposed Member of the Public and Collective Public

Highest Individual Public External Dose (1 Bq cm^{-2})	2.5×10^{-10}
Total Collective Public External Dose (1 Bq cm^{-2})	1.7×10^{-8}

4.3 PUBLIC DOSES FROM HIGHER CONTAMINATION LIMITS

The results can be extrapolated to predict the maximum individual and collective public doses that would result from higher contamination levels. The public doses from higher contamination levels for collective and individual doses are shown in Table 6.

Table 6 Collective and Individual Public Doses from Higher Contamination Levels

Contamination Value (Bq cm^{-2})	**Collective Dose (person-Sv)**		**Maximum Exposed Individual Dose (Sv)**	
	Internal	*External*	*Internal*	*External*
1	7.0×10^{-12}	1.7×10^{-8}	1.4×10^{-13}	2.5×10^{-10}
4	2.8×10^{-11}	6.8×10^{-8}	5.6×10^{-13}	1.0×10^{-9}
40	2.8×10^{-10}	6.8×10^{-7}	5.6×10^{-12}	1.0×10^{-8}
400	2.8×10^{-9}	6.8×10^{-6}	5.6×10^{-11}	1.0×10^{-7}

For a single cask shipment, the increase in public dose (combined off-link and on-link) due to higher allowable contamination limits is shown in Table 7.

Table 7 Increases in Public Doses Due to Higher Contamination Levels

Contamination Value (Bq cm^{-2})	Increase in Collective Dose (person-Sv)		Increase in Maximum Exposed Individual Dose (Sv)	
	Internal	*External*	*Internal*	*External*
4	0	0	0	0
40	2.5 x 10^{-10}	6.1 x 10^{-7}	5.0 x 10^{-12}	9.0 x 10^{-9}
400	2.8 x 10^{-9}	6.7 x 10^{-6}	5.5 x 10^{-11}	9.9 x 10^{-8}

The total collective public dose increases (combined internal and external doses) due to higher contamination levels are dominated by the external collective dose. The increase in collective dose to the public is almost entirely due to exposure to external radiation originating from contamination on the cask surface. The resuspension of removable surface contamination and subsequent inhalation by members of the public is not a significant contributor to the collective public dose.

5.0 OPTIMIZING SPENT FUEL CONTAMINATION LIMITS

5.1 EFFECT OF ALLOWABLE CONTAMINATION LIMITS ON WORKER DOSES

Some worker doses will increase as a result of higher allowable contamination limits and some will decrease due to shorter working times associated with decontamination and monitoring activities. It is possible to determine the conditions under which higher allowable contamination limits will result in offsetting changes to the doses (where increases are equal to savings) and where overall dose savings are possible.

5.2 WORKER DOSES DUE TO SPENT FUEL CASK DECONTAMINATION AND MONITORING ACTIONS

The following sources report doses that were calculated or measured and consist primarily of doses due to external radiation from the cask itself (particularly from the cask contents) and the ambient dose rate in the work area.

DOE-CH/TPO-001[6]-- This report includes the actions, duration, and doses due to decontamination and monitoring activities.

CEPN/EDF Report[9]-- A report published by Centre d'Etude sur l'Evaluation de la Protection dans le Domaine Nucleáire/Electricité de France (CEPN/EDF) provides detailed information on worker doses that result from activities related to preparation and shipment of spent fuel casks from EDF power plants.

U.S. Reactor Operator Information[5]-- This information was collected during ongoing operations that involved experienced crews employed in regularly making shipments.

A comparison of the collective doses is provided below. These collective doses are in person-Sv per cask preparation.

Table 8 Comparison of Decontamination and Monitoring Collective Dose Estimates

Source of Information	Decontamination (person-Sv)	Monitoring (person-Sv)
DOE-CH/TPO-001	0.13 x 10^{-3}	0.1 x 10^{-3}
CEPN/EDF Report	1.51 x 10^{-3}	1.17 x 10^{-3}
US Reactor Information	0.5 x 10^{-3}	0.07 x 10^{-3}

Different reactor facilities and cask designs will give rise to variations in decontamination and monitoring doses. Discussions with other U.S. utilities indicate that typical decontamination exposures range from 0.4×10^{-3} to 1×10^{-3} person-Sv per cask-loading operation.

The decontamination doses given by the CEPN/EDF report and the U.S. reactor operator are 11 and 4 times higher, respectively, than those in DOE-CH/TPO-001, and it appears that the DOE report underestimates the durations and locations used in performing these tasks. In order to take into account the most recent operational data available and to reflect international practices, **an average of all three values is used to reflect current decontamination doses (0.71 × 10^{-3} person-Sv)**. The monitoring doses reported by DOE-CH/TPO-001 and the U.S. reactor are within a factor of 2 of each other and are much lower than the CEPN/EDF values, probably due to the redundant monitoring that is performed in France. In order to be representative of known spent fuel operations, an **average of all three values is used to reflect current monitoring doses (0.45 × 10^{-3} person-Sv)**. This gives a **collective dose for decontamination and monitoring activities of 1.2 × 10^{-3} person-Sv**.

5.3 POTENTIAL WORKER DOSE REDUCTIONS DUE TO HIGHER ALLOWABLE CONTAMINATION LIMITS

Informal communications with reactor operators have shown that no readily available published information exists on the level of contamination on casks when they are first removed from the spent fuel pools and air dried. Reported values ranged from 30 to 400 Bq cm^{-2}. This indicates that most decontamination and monitoring activities could be eliminated if the allowable contamination limits were on the order of 400 Bq cm^{-2}. Some monitoring activities would still be needed to ensure that no “hot spots” were present and to provide assurance of regulatory compliance.

For the purpose of examining the effects that higher contamination limits would have on doses, three cases (i.e., contamination levels) are examined:

1) 4 Bq cm^{-2} beta/gamma (current limits)
2) 40 Bq cm^{-2} beta/gamma (a factor of 10 higher)
3) 400 Bq cm^{-2} beta/gamma (a factor of 100 higher)

The increases in individual and collective worker doses due to higher contamination limits can be calculated. These increases would be as follows:

Table 9 Individual and Collective Worker Doses and Dose Increases for Various Contamination Levels

Contamination Limit	Dose		Dose Increase	
	Individual (Sv)	*Collective (person-Sv)*	*Individual (Sv)*	*Collective (person-Sv)*
4	7.7 x 10^{-7}	1.8 x 10^{-6}	0	0
40	7.7 x 10^{-6}	1.8 x 10^{-5}	6.9 x 10^{-6}	1.6 x 10^{-5}
400	7.7 x 10^{-5}	1.8 x 10^{-4}	7.6 x 10^{-5}	1.8 x 10^{-4}

When considered in combination with the worker dose received during decontamination and monitoring activities (1.2 × 10^{-3} person-Sv, see Sect. 6.2 of the full report), the worker dose from surface contamination on the cask (both internal and external pathways, see Sect. 4.4 of the full report) constitutes 0.15, 1.5, and 13% of the worker collective dose at contamination levels of 4, 40, and 400 Bq cm^{-2}, respectively. The collective worker dose due to decontamination and monitoring activities dominates all dose pathways considered in this study.

If the doses to decontamination and monitoring workers decrease by an amount equal to the increase in doses due to the higher contamination limits, the worker collective dose will remain unchanged. If the doses to decontamination and monitoring workers decrease by a greater amount, there will be a collective worker dose savings from increasing the allowable contamination limits. The required decrease in decontamination and monitoring worker dose (dose reduction factor, or DRF) can be calculated as follows:

$$DRF = \frac{WCDI}{DMWCD}$$ Equation 1

Where:

WCDI = worker collective dose increase due to higher levels of removable surface contamination, and
DMWCD = decontamination and monitoring worker collective dose.

Based on the decontamination and monitoring worker collective dose of 1.2 × 10^{-3} person-Sv, the required DRFs to offset the increases due to higher contamination limits are as follows:

Table 10 Increases in Doses and Required Dose Reduction Factors for Various Contamination Limits

Contamination Limit	Increase in Dose	Required Dose Reduction Factor—DRF
40	1.6×10^{-5}	0.014 (1.4%)
400	1.8×10^{-4}	0.15 (15%)

Consequently, a 1.4% reduction in the dose to decontamination and monitoring workers (due to reduced time required to perform these tasks) would offset the increase in dose to workers due to raising the allowable contamination limits to 40 Bq cm^{-2}. Similarly, a 15% reduction in the dose to decontamination and monitoring workers would offset the increase in dose to workers due to raising the allowable contamination limits to 400 Bq cm^{-2}. Greater reductions in doses to the decontamination and monitoring workers would result in a lower collective worker dose.

The CEPN/EDF report[9] provides some insight into dose reductions that could be possible with higher allowable contamination limits. Section 4 of the report states that ". . . savings could reach more than 11% of the total collective dose if double monitoring was discontinued for every monitoring zone of the cask." The average reported total collective dose for cask preparation and monitoring was 6.5×10^{-3} person-Sv. Eliminating the need for double monitoring could therefore save 7.2×10^{-4} person-Sv per cask shipment. Based on the reported collective dose for decontamination and monitoring activities of 2.68×10^{-3} person-Sv, this would result in a dose reduction of 0.27 or, 27%, easily exceeding the dose reduction factor of 15% required to offset the increased worker collective dose resulting from an allowable contamination limit of 400 Bq cm^{-2}.

5.4 OVERALL DOSE IMPACTS DUE TO HIGHER CONTAMINATION LIMITS

The overall increases in collective and individual doses due to higher allowable contamination limits can be summarized as follows:

Table 11 Increase in Collective and Maximum Exposed Individual Dose for Various Contamination Levels

Contamination Value	Increase in Collective Dose--Internal + External (Sv)		Increase in Maximum Exposed Individual Dose--Internal + External (Sv)	
	Worker	*Public*	*Worker*	*Public*
4	0	0	0	0
40	1.6×10^{-5}	6.1×10^{-7}	6.9×10^{-6}	9.0×10^{-9}
400	1.8×10^{-4}	6.7×10^{-6}	7.6×10^{-5}	9.9×10^{-8}

The increase in collective dose due to higher levels of removable contamination is dominated by the increase in worker doses. The increases in collective worker doses are approximately 20 times higher than the collective dose increases for the public. Consequently, optimizing the worker doses will result in optimizing the collective dose due to removable surface contamination on spent fuel casks at levels up to 400 Bq cm^{-2}.

Table 12 provides the relative magnitude of the collective doses calculated for workers and the public from both internal and external exposures due to non-fixed surface contamination levels of 4, 40, and 400 Bq cm^{-2}. These values **do not** include external doses due to the cask contents (which will decrease as the allowable contamination limits increase) to workers performing decontamination and monitoring activities.

Adding the increased collective public dose to that of the workers does not have a noticeable effect on the DRFs required to realize dose savings. The required DRF for both 40 and 400 Bq cm^{-2} (rounded to two significant figures) do not change. Taking into account both the public and worker collective doses, there will be a reduction in total collective dose if decontamination and monitoring doses can be reduced by more than 1.4 or 15% for surface contamination levels of 40 and 400 Bq cm^{-2}, respectively. The relative insensitivity of the DRF to the public dose is due to the dominance of the worker dose (approximately 20 times higher). Consequently, the optimization of worker dose is the most important aspect of overall dose optimization.

While consideration of collective dose is necessary to evaluate options for optimizing doses, it is also necessary to consider doses to the maximum exposed individual. Worker and public individual doses remain low even at the higher contamination levels.

Table 12 Collective Public and Worker Dose for Various Contamination Levels

Contamination Level (Bq cm^{-2})	Collective Dose to the Public (person-Sv)		Collective Dose to Workers (person-Sv)	
	Internal	*External*	*Internal*	*External*
4	2.8×10^{-11}	6.8×10^{-8}	1.3×10^{-7}	1.7×10^{-6}
40	2.8×10^{-10}	6.8×10^{-7}	1.3×10^{-6}	1.7×10^{-5}
400	2.8×10^{-9}	6.8×10^{-6}	1.3×10^{-5}	1.7×10^{-4}

6.0 CONCLUSIONS

Doses from removable contamination on spent fuel casks are dominated by the doses received by workers preparing the cask for transport. The greatest component of the worker dose is due to decontamination and monitoring work performed in the vicinity of the loaded cask, where the dose rate from the cask contents is relatively high. Based on the three sources of operational information used in this study, the collective dose due to decontamination and monitoring activities (1.2×10^{-3} person-Sv per cask turnaround at a level of 4 Bq cm^{-2}) is much higher than the dose received by workers from the removable contamination by way of inhalation; ingestion; and direct, hand, and face irradiation (1.8×10^{-6} person-Sv per cask turnaround at a level of 4 Bq cm^{-2}). The relative magnitudes of these doses are reflected in the low DRFs that would be required to realize lower collective worker doses due to removable contamination.

Collective and individual doses to members of the public are much lower than those to workers. The increases in public doses that would result from higher allowable removable surface contamination limits (up to a factor of 100 higher) are small and do not contribute significantly to the total collective dose.

7.0 REFERENCES

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