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

Oak Ridge National Laboratory

U.S. Nuclear Regulatory Commission
Office of Nuclear Material Safety and Safeguards
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A Risk-Informed Basis for Establishing Non-Fixed Surface Contamination Limits for Spent Fuel Transportation Casks

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ABSTRACT

The current internationally accepted basis for establishing non-fixed surface contamination limits for spent fuel casks is the same as that for other transportation package types. This study examined the suitability of the currently used exposure model, taking into account exposure pathways and parameters representative of typical light-water-reactor spent fuel cask handling, loading, and transportation activities. Because the currently used model was found to be inappropriate for spent fuel casks, a new exposure model was developed using pathways and parameters specific to spent fuel casks. Results show that individual and collective doses to members of the public are very low and that worker doses dominate the total collective dose from non-fixed surface contamination. Worker doses that vary as a function of allowable surface contamination limits were calculated and were found to be dominated by doses due to decontamination and surface contamination monitoring activities performed after the cask is drained. An approach was developed for evaluating the overall dose implications of higher allowable non-fixed surface contamination limits. This approach was used to examine the reduction in doses to workers performing cask decontamination and monitoring activities necessary to offset increased doses due to other worker and public exposure pathways.

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FOREWORD

Contamination incidents in the late 1990s involving shipments of spent nuclear fuel in Europe highlighted the need to reexamine the regulatory basis for limiting non-fixed radioactive contamination on the external surfaces of spent fuel transportation casks. The international transport safety community responded to this need, and the International Atomic Energy Agency (IAEA) initiated a Coordinated Research Project (CRP) on Radiological Aspects of Package and Conveyance Non-Fixed Contamination. Several IAEA member states and one international organization participated in the CRP by performing research related to non-fixed radioactive contamination on all package types (not just spent fuel casks).

The U.S. Nuclear Regulatory Commission represented the United States in the CRP and undertook an examination of the radiological basis for non-fixed contamination on spent fuel casks. This examination included identifying the dose pathways for cask contamination and developing calculational approaches for quantifying resulting doses. This report presents the results of this examination and provides results for all significant dose pathways, both to workers and members of the public. The results provide information and approaches that can be used to determine if radiation doses from spent fuel cask contamination are optimized. Understanding the extent to which these doses are optimized is an important element in determining if contamination limits are risk informed.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the contributions by all the participants in the IAEA CRP. Their work, particularly the work of the Modeling Group, was instrumental in identifying and evaluating possible dose pathways from non-fixed surface contamination. Several of the approaches used in the CRP are also used in this report and in other cases were modified for use in this report. By building on the CRP approaches, this study was able to focus on and expand consideration of the dose pathways specific to spent fuel cask transportation.

The contributions of B. L. Broadhead and R. L. Coleman, Oak Ridge National Laboratory, in performing calculations and reviewing the draft report are also gratefully acknowledged.

1 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.

In general, non-fixed contamination on the surface of a package can result in doses through the following pathways:

- Radiation emitted from the contaminated package surface and incident onto the body (direct exposure)
- Dispersal of the surface contamination into the air in a handling facility, leading to subsequent
  - Inhalation intakes
  - Deposition onto the body and subsequent irradiation
- Transfer of contamination to the hands during handling of the packages, leading to
  - Irradiation of the hands
  - Transfer of contamination from the hands to the face with irradiation of the face
  - Ingestion of contamination from the hands
- Direct ingestion (which is considered sufficiently unlikely that it is not considered further)
- Dispersal into the environment
  - Inhalation (including material resuspended following deposition)
  - Deposition onto the body (including material resuspended following deposition)
  - Ground shine (exposure to radiations emitted by contamination on the ground
  - Ingestion via the food chain

There can also be doses that while not resulting directly from the contamination, are strongly influenced by and attributable to 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.

1.1 FAIRBAIRN MODEL ASSUMPTIONS

The Fairbairn model limits its consideration to inhalation of airborne contamination and transfer of contamination to the hands under a specified set of exposure scenarios. The permissible levels of contamination are constrained to not result in (1) an airborne concentration greater than the maximum permissible concentration in air (MPCa) specified in the 1959 recommendations of the International Commission on Radiological Protection (ICRP)[2] and (2) contamination of the hands beyond what was considered to be good practice in the 1960s. These constraints were applied to ^{239}Pu (an alpha emitter) and ^{90}Sr (a beta emitter), which were considered the most hazardous alpha- and beta-emitting radionuclides at that time. Good practice regarding hand contamination was based on limiting the irradiation of the basal layer of the skin, because the potential ingestion of contamination from the hands was found to be less restrictive. The model resulted in surface activity limits of 0.4 and 4 Bq cm^{-2} for alpha and beta emitters, respectively.

1.2 SHORTCOMINGS OF THE FAIRBAIRN MODEL FOR LWR SNF PACKAGE SHIPMENTS

- The exposure scenarios of the model are characterized by conservative parametric values. This includes the resuspension factor (4×10^{-5} m^{-1}) and the exposure time (2000 h per year). Because only a fraction of the workers' time involves package preparation and shipment activities, this exposure time assumption is extremely conservative for SNF cask operations.

- The radiological parameters used in the model were taken from ICRP Publication 2, issued in 1959, and have been superseded by subsequent ICRP guidance.[3] Thus, the model is not consistent with current practice. For example, current prospective planning constrains a worker's annual exposure to an effective dose[3] of 20 mSv, not the 50-mSv value used in 1959. Although the effective dose constraint has been lowered, the applicable dose coefficients yield permissible workplace airborne concentrations for ^{239}Pu and ^{90}Sr that are 3 and 30 times higher, respectively, than the MPCa values used in the model. Thus, the currently accepted ICRP dose coefficients would result in contamination limits 3 to 30 times higher, assuming the same resuspension factors are used.

- Given the wide variation in magnitude of the dose coefficients among the radionuclides, a comprehensive model must be capable of addressing more than two radionuclides. The Fairbairn model relied on a high degree of conservatism in its selection of model parameters and in its consideration of only the most restrictive alpha- and beta-emitting radionuclides (^{239}Pu and ^{90}Sr). These radionuclides, while limiting, are inappropriate for LWR SNF packaging applications. The use of ^{134}Cs, ^{137}Cs, ^{58}Co, and ^{60}Co is more appropriate for SNF applications, because these are the radionuclides most frequently encountered in significant quantities on cask surfaces following immersion in spent fuel pools.

- The inhalation intakes are based on a scenario occurring "in a confined space with conditions arranged to simulate very dusty conditions."[1] This approach is very conservative, considering the conditions under which SNF packages are stored, prepared, and transported today.

- The Fairbairn model is based on a transport worker who handles packages and works in the vicinity of packages continuously for 2000 h per year. The model does not take into account exposures to the following groups:
  - the public, during the course of transport, and
  - workers preparing packages for transport.

1.3 APPLICABILITY OF THE FAIRBAIRN MODEL TO SPENT FUEL CASKS

In summary, 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.

2 SUMMARY OF OTHER STUDIES

The studies described in **Appendix A—Summary of Selected Previous Contamination Studies** concern previous work aimed at determining derived limit values for non-fixed surface contamination levels.

The NUREG study[4] includes both public dose and worker dose contributions to the total dose estimates. However, only limited dose pathways are considered and the data used in the study are outdated. The study indicates that for low direct-exposure dose-rate situations (1 mrem h^{-1} in the cask vicinity), it is possible to calculate an optimum additional decontamination time. This optimal time is dependent on the efficacy of the decontamination procedure but appears to be about 20 additional minutes for an assumed decontamination factor of 10 for each 30 min of decontamination effort. On the other hand, the study also shows that for the envisioned scenarios with direct exposure rates of about 10 mrem h^{-1} (100 μSv h^{-1}), the optimal additional decontamination time is zero. This finding indicates that the total dose resulting from additional decontamination effort increases as additional work near the cask is performed. (A very small decrease in public exposure due to the reduced contamination levels is greatly outweighed by the increase in worker exposure.)

The NRPB study[5] includes a limited number of pathways but focuses on deriving contamination limits and does not include public dose contributions. The study does indicate that derived limits of about 500–700 Bq cm^{-2} are appropriate for typical radionuclides found in spent fuel applications.

The IAEA has undertaken a Coordinated Research Project (CRP) on "Radiological Aspects of Package and Conveyance Non-Fixed Contamination." Technical contributions to the CRP include development of a model to calculate doses to the public and workers resulting from surface contamination for four different package types. The CRP developed a set of dose pathways, exposure parameters, and calculational techniques for estimating the doses to workers and the public. Where possible, this report has attempted to use approaches that are consistent with the IAEA CRP. However, since the CRP model covers four package types (small manually handled, small remotely handled, large remotely handled, and spent fuel casks), the CRP model is more general in approach than this report (which deals solely with spent fuel casks). The CRP model does not take into account the doses received due to the contents of the spent fuel cask, nor does it calculate collective doses to workers and the public (a factor that is necessary for examining optimization). As described in Sect. 4.3.1.2, doses to workers from the cask contents vary as a function of the allowable contamination level, because the time required to perform decontamination and contamination monitoring will vary. Consequently, some variations from the CRP approach have been made in order to include all significant dose pathways for spent fuel casks.

3 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[6] 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.

3.1 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 total effective dose due to removable surface contamination on the spent fuel casks can be expressed as

$$E_{tot} = E_{wkr} + E_{pub} \tag{1}$$

where

E_{tot} = total effective dose,

E_{wkr} = effective dose to workers, and

E_{pub} = effective dose to the public.

3.2 WORKER DOSE

The effective dose to workers is dependent on all the sources of exposure that vary as a function of the surface contamination limits. Since exposures due to decontamination and monitoring functions include both internal and external pathways, these must be considered in calculating worker exposure.

The effective dose to workers (E_{wkr}) can be expressed as

$$E_{wkr} = E_{win} + E_{wex} \tag{2}$$

where

E_{win} = effective dose to workers from internal exposure, and

E_{wex} = effective dose to workers from external exposure.

Some internal and all external worker doses will vary as a function of time spent near the cask. Because the time required to complete tasks necessary to comply with the surface contamination limits will vary with the contamination limits, these tasks must be considered separately when determining doses to workers. During these tasks, workers will be exposed to internal and external sources from both the cask itself and the work area.

The dose designated E_{win} consists of all those contributors to ***internal*** exposure to workers when they are performing contamination-related work on the cask and can be expressed as

$$E_{win} = E_{wincask} + E_{winamb} \tag{3}$$

where

$E_{wincask}$ = effective dose to workers due to internally deposited radionuclides originating from the cask surface, and

E_{winamb} = effective dose to workers due to internally deposited radionuclides from the ambient atmosphere in the work area.

The dose designated $E_{wincask}$ consists of two primary pathways by which contamination from the cask surface can be internally deposited in workers: inhalation of resuspended surface contamination and ingestion of contamination transferred from the cask surface to workers' hands and subsequently to the lips and mouth. This can be expressed as

$$E_{wincask} = E_{wincaskinh} + E_{wincaskinges} \tag{4}$$

where

$E_{wincaskinh}$ = effective dose to workers due to inhaled radionuclides, and

$E_{wincaskinges}$ = effective dose to workers due to ingested radionuclides.

The dose designated E_{wex} consists of all those contributors to ***external*** exposure to workers and can be expressed as

$$E_{wex} = E_{wexcask} + E_{wexamb} \tag{5}$$

where

$E_{wexcask}$ = effective dose to workers due to exposure to cask-related sources of external radiation, and

E_{wexamb} = effective dose to workers due to external exposure to ambient radiation in the work area.

The dose designated $E_{wexcask}$ consists of two cask-related pathways that can lead to worker exposure: direct external radiation from the contamination on the package surface and external radiation emanating from the cask itself (due to its radioactive contents). This can be expressed as

$$E_{wexcask} = E_{wexcasksurf} + E_{wexcaskcon} \tag{6}$$

where

$E_{wexcasksurf}$ = effective dose to workers due to direct external radiation from the contamination on the cask surface, and

$E_{wexcaskcon}$ = effective dose to workers due to external radiation from the cask contents.

The equations for worker exposure, both internal and external, can be combined and simplified as

$$E_{wkr} = E_{wincaskinh} + E_{wincaskinges} + E_{winamb} + E_{wexcasksurf} + E_{wexcaskcon} + E_{wexamb}.$$

3.3 PUBLIC DOSE

The effective dose to the public can be expressed as

$$E_{pub} = E_{pin} + E_{pex} \tag{7}$$

where

E_{pin} = effective dose to the public due to internally deposited radionuclides originating from the cask surface, and

E_{pex} = effective dose to the public due to external exposure to removable contamination on the cask surface.

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 public dose pathways and dose calculations are presented in Sect. 5.

3.4 CALCULATION OF DOSES

Table 1 shows the variables that are included in this study of doses due to removable surface contamination on spent fuel casks.

Table 1 Doses that vary due to removable surface contamination on spent fuel casks

<table>
<tr><td colspan="8">Total dose (E_{tot})</td></tr>
<tr><td colspan="6">Dose to workers (E_{wkr})</td><td colspan="2">Dose to the public (E_{pub})</td></tr>
<tr><td colspan="3">Worker internal dose (E_{win})</td><td colspan="3">Worker external dose (E_{wex})</td><td>Public internal dose (E_{pin})</td><td>Public external dose (E_{pex})</td></tr>
<tr><td colspan="2">From cask contamination ($E_{wincask}$)</td><td rowspan="2">Ambient (E_{winamb})</td><td colspan="2">From contamination and cask contents ($E_{wexcask}$)</td><td rowspan="2">Ambient (E_{wexamb})</td><td colspan="2" rowspan="2">▨</td></tr>
<tr><td>Inhalation ($E_{wincaskinh}$)</td><td>Ingestion ($E_{wincaskinges}$)</td><td>Contamination on surface ($E_{wexcasksurf}$)</td><td>Cask contents ($E_{wexcaskcon}$)</td></tr>
</table>

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 has been developed for this analysis using the values identified in the literature[7] and confirmed qualitatively with another nuclear plant operator.[8] Four primary contaminants were identified in LWR spent fuel pool water (^{134}Cs, ^{137}Cs, ^{58}Co, and ^{60}Co). For the purposes of this study, the quantitative results reported in Ref. 7 have been used to derive a reference mix of contaminants on the cask surface that are proportional to their presence in the pool water, as shown in Table 2.

Table 2 Reference spent fuel pool water radionuclide composition

Radionuclide	Average activity in pool water (μCi cm^{-3})	Fraction of activity present
^{58}Co	6×10^{-4}	0.217
^{60}Co	2×10^{-3}	0.722
^{134}Cs	7×10^{-5}	0.025
^{137}Cs	1×10^{-4}	0.036

Using this mix of contaminants, it is possible to derive reference committed effective dose per unit intake factors for the mixture, using the fractions and dose per unit intake factors shown in Table 3. The committed effective doses per unit intake via inhalation for workers [those for $e(g)_{5\mu m}$ for lung absorption type M] have been taken from Ref. 6.

Table 3 Radionuclide characteristics for reference mixture of contaminants for workers

Radionuclide	Committed effective dose per unit intake via inhalation[6] ($Sv\ Bq^{-1}$)		Committed effective dose per unit intake via ingestion[6] ($Sv\ Bq^{-1}$)	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	**5.9×10^{-9}**	**8.2×10^{-9}**	**3.6×10^{-9}**	

These weighted committed dose per unit intake factors are used in Sects. 4 and 5 to calculate individual and collective doses for the exposure scenarios.

4 CALCULATION OF WORKER DOSE (E_{WKR})

Doses to workers resulting from removable contamination on the cask surface can result in both internal and external exposures. These can result from the following pathways:

- Internal (E_{win})
  - Resuspension of the surface contamination into the air, leading to subsequent inhalation intakes
  - Transfer of contamination to the hands during handling of the packages, leading to
    - Ingestion of contamination transferred from the hands to the lips and mouth
  - Direct ingestion (which is considered sufficiently unlikely that it is not considered further)
- External (E_{wex})
  - Radiation emitted from the contamination (external exposure)
  - Cloud shine (irradiation by a "cloud" of resuspended contamination)
  - Resuspension of the surface contamination into the air, leading to subsequent deposition onto the body or clothing
  - Deposition of resuspended activity onto the floor of the handling facility and subsequent irradiation from "ground shine"
  - Transfer of contamination to the hands during handling of the packages, leading to
    - Irradiation of the hands
    - Transfer of contamination from the hands to the face, resulting in irradiation of the skin of the face

The IAEA CRP has examined these pathways and has determined (with sample calculations) that the following pathways are "minor" and do not contribute significantly to worker dose:

- cloud shine (irradiation by a "cloud" of resuspended contamination),
- deposition of resuspended activity onto the floor of the handling facility,
- deposition of resuspended activity onto the skin, and
- deposition of resuspended activity onto clothing.

Consequently, these pathways are not considered further in this study.

Therefore, the remaining worker exposure pathways from removable surface contamination that are considered in this study are as follows:

- Internal (E_{win})
  - Resuspension of the surface contamination into the air, leading to subsequent inhalation intakes (see Sect. 4.2.1.1)
  - Transfer of contamination to the hands during handling of the packages, leading to ingestion of contamination transferred from the hands (see Sect. 4.2.1.2)
- External (E_{wex}) (see Sect. 4.3.1.1)
  - Radiation emitted from the contamination on the cask surface
  - Transfer of contamination to the hands during handling of the packages, leading to
    - Irradiation of the hands
    - Transfer of contamination from the hands to the face, resulting in irradiation of the skin of the face

Additionally, the following external doses received during decontamination and monitoring activities that will vary as a function of allowable contamination limits are considered:

- radiation from the cask contents (see Sect. 4.3.1.2), and
- ambient (background) radiation in the work area (see Sect. 4.3.2).

4.1 WORKER EXPOSURE PARAMETERS

In order to calculate the total doses to workers due to the removable surface contamination limits, it is necessary to determine the following:

1. time and distances spent in the vicinity of the cask and
2. time spent in plant areas that result in doses due to ambient conditions.

In the late 1980s and early 1990s, the U.S. Department of Energy (DOE) sponsored several studies of doses resulting from spent fuel transportation, including those due to cask-handling operations. These studies provide detailed breakdowns of cask-handling operations, ambient dose rates in the areas where work is performed, and resulting doses to workers. One study, DOE-CH/TPO-001, by Pacific Northwest Laboratory,[9] examined a postulated commercial spent fuel transportation system and is particularly useful in evaluating doses due to spent fuel cask-handling operations.

DOE-CH/TPO-001 provides a breakdown of worker tasks by craft function, number of workers present, time spent in the work area, and time spent near the cask. Using a reference cask and dose rate projections at various distances from the cask, the report develops dose estimates for each of the tasks, which can be summed to provide dose projections for an entire cask-handling operation. **Appendix B—Worker Parameters from DOE-TPO/CH-001** contains an extract from DOE-CH/TPO-001 that provides the details of the cask-handling operations for a pressurized-water reactor (PWR) and a boiling-water reactor (BWR) truck cask. A spreadsheet was developed from the worker time and motion information in DOE-CH/TPO-001 so that the information could be aggregated as needed.

4.2 EFFECTIVE DOSES TO WORKERS DUE TO INTERNALLY DEPOSITED RADIONUCLIDES (E_{WIN})

In this section worker doses due to inhalation and ingestion of removable surface contamination are calculated and worker doses due to ambient conditions are addressed.

4.2.1 Effective Dose to Workers Due to Internally Deposited Radionuclides from the Cask Surface ($E_{wincask}$)

4.2.1.1 Inhalation ($E_{wincaskinh}$)

Resuspension of the surface contamination into the air, leading to subsequent inhalation intakes, is a time-dependent parameter. Using the approach adopted by the CRP, the airborne activity concentration (in becquerels per cubic meter) in a facility is given by

$$C_d = \frac{RR \times A \times A_c}{V \times f_{ex}} \tag{8}$$

where

RR = resuspension rate, 10^{-4} h^{-1};

A = surface area of the cask from which resuspension occurs, 130 m^2 or 1.3×10^6 cm^2;

A_c = activity concentration on the package surface, Bq cm^{-2};

V = assumed room volume, 2000 m^3 (200-m^2 floor area × 10 m high); and

f_{ex} = assumed air exchange rate, 2 h^{-1}.

For a unit activity concentration on the cask surface (1 Bq cm^{-2}), C_d is equal to 3.25×10^{-2} Bq m^{-3}.

Assuming that all resuspended activity is respirable (a conservative assumption) and that the airborne contamination is uniformly suspended in the defined volume near the cask, the committed effective dose from inhalation of resuspended activity from a cask is given by

$$E = C_d \times T \times INH \times R_{10} \tag{9}$$

where

C_d = airborne activity concentration, 3.25×10^{-2} Bq m^{-3};

T = exposure time, h;

INH = breathing rate, taken as 1.2 m^3 h^{-1}; and

R_{10} = inhalation dose coefficient for the reference contamination, 5.9×10^{-9} Sv Bq^{-1} (see Sect. 3.4).

Equation (9) can be used to derive a committed effective dose per unit time:

$$\frac{E}{T} = C_d \times INH \times R_{10}\,. \tag{10}$$

For the reference mixture of contaminants, this gives an inhalation annual committed effective dose per unit time of 2.3×10^{-10} Sv h^{-1} from a unit activity concentration of 1 Bq cm^{-2} on the cask surface.

From Appendix B, the individual worker who spends the most time on cask activities can be identified. Where more than one worker in a craft type is identified as being involved in a task (e.g., the entry under "number doing cask work" is greater than 1), the workers in that craft type are divided into worker number 1, number 2, etc.). Where only a single worker in a craft is identified for a given task, all the time is assigned to worker number 1 in that craft type.

If the 200-m^2 floor area used in Eq. (8) is assumed to be square and a cask diameter of 2.5 m is taken into account, all work performed within approximately 6 m (20 ft) of the cask is within the inhalation volume. Using the spreadsheet representation of Appendix B, it was determined that the worker who spends the most "activity time in minutes" in the area at a "work distance from cask in feet" of 20 ft or less, is OP1 (a reactor site operator), who has a total time of 14 h in this area. Conservatively assuming that all of the time of OP1 is within the 2000-m^3 area of the suspended activity, the **maximum individual dose per cask turnaround due to inhalation is 3.2×10^{-9} Sv** per unit of surface activity concentration. The total time that workers are within 20 ft of the cask is approximately 41 person-h per cask turnaround (from receipt at the plant through dispatch from the plant). This results in **total worker exposure per turnaround due to inhalation of 9.4×10^{-9} person-Sv.**

4.2.1.2 Ingestion ($E_{wincaskinges}$)

Transfer of contamination to the hands during handling of the packages that leads to ingestion of contamination transferred from the hands is an event-dependent exposure. Even though work processes in nuclear plants are likely to preclude hand contamination that leads to ingestion of radionuclides, it is assumed that a worker's hands become contaminated once per cask-handling day. The IAEA CRP approach for calculating worker committed effective dose due to ingestion is based on assuming that the transfer of contamination from the hands to the mouth is due to touching the lips and mouth, from which the contamination is subsequently ingested. It is assumed that the area of the hands is 400 cm^2 and that 1% of the activity on the hands is ingested. This is equivalent to ingesting the contamination on 4 cm^2 of the hands. The equation for calculating ingestion dose is given by

$$E = A_c \times area \times f \times f_{ing} \times R_9 \tag{11}$$

where

A_c = activity concentration on the package surface, Bq cm^{-2};

area = area of hands from which contamination is ingested, assumed to be 4 cm^2;

f = fraction of activity on the package transferred to the hands, 20%;

f_{ing} = fraction ingested of contaminated hand area, 100%; and

R_9 = ingestion dose coefficient, 3.6×10^{-9} Sv Bq^{-1} (see Sect. 3.4).

The maximum individual dose per cask turnaround due to ingestion is 2.9×10^{-9} Sv from a unit activity concentration on the cask surface (1 Bq cm^{-2}). Based on the operational analysis in Appendix B, as many as eight workers could perform cask operations that lead to contact with the cask surface [4 OPs, 1 Radiation Monitor (RM), and 3 Maintenance Crafts (M-Cs)]. Consequently, the **total worker exposure per turnaround due to ingestion is 2.3×10^{-8} person-Sv.**

4.2.2 Effective Dose to Workers Due to Internally Deposited Radionuclides from the Ambient Atmosphere in the Work Area (E_{winamb})

Information from U.S. utilities indicates that no significant ambient airborne radioactivity occurs that could lead to measurable inhalation doses inside buildings. Therefore, this parameter is assumed to be negligible.

4.3 DOSES TO WORKERS DUE TO EXTERNAL EXPOSURE (E_{WEX})

4.3.1 Effective Dose to Workers Due to External Exposure to Removable Contamination on the Cask Surface and from the Cask Itself ($E_{wexcask}$)

Workers can receive external exposures from the following:

1. Radiation originating from the contamination on the cask surface
   - Direct radiation from the contamination on the cask surface
   - Contamination transferred from the cask surface to the hands, with subsequent irradiation of the skin of the hands
   - Contamination transferred from the hands to the face, with subsequent irradiation of the skin of the face
2. Radiation originating from the cask contents after the cask is loaded with spent fuel

4.3.1.1 External exposure from contamination on the cask surface ($E_{wexcasksurf}$)

4.3.1.1.1 Direct external exposure from contamination on the cask surface

Workers will be exposed to direct external radiation from the presence of contamination on the cask surface. Based on the results of the IAEA CRP, calculations performed with Microshield show that the dose rate from a unit activity surface contamination is highest for ^{60}Co. Therefore, the dose rates are based on this value. Based on an assumed flat vertical surface area of 14.2 m^2, the CRP-calculated dose rate at 1 m normal to the surface is 1.23×10^{-8} Sv h^{-1} for 1 Bq cm^{-2} of ^{60}Co. In order to calculate the external exposures to workers from the surface contamination, it is assumed that the dose rate decreases as a $1/r$ function of distance from the cask surface and that dose rates are calculated for all tasks that take place at a distance of 50 ft (15 m) or less.

To determine the doses due to contamination, total worker time spent at each distance from the cask was determined by analysis of the information in Appendix B. Since all workers will be exposed to the external radiation from the surface contamination and these doses will vary with the contamination limits, they are included. Some modification of the information in Appendix B was required in order to include only those steps where workers will receive external radiation exposure that varies with allowable contamination limits. For example, when the cask is in the spent fuel pool, workers are well shielded from any radioactive contamination on the cask surface. When the cask comes out of the pool, however, the contamination on the outer surfaces is dependent on the pool water cleanliness, not on the transportation contamination limits. Consequently, steps 10 through 13 of Appendix B are not considered in this pathway.

In some cases the information in Appendix B had to be further analyzed to account for all workers present for each task. For example, the number of workers in the area is reported but the distance between the cask and these workers is not reported. Four different cases of reported worker exposures were considered as follows:

1. **Case 1:** time spent doing cask work at a specified distance—The "staff number doing cask work" is multiplied by the "activity time near cask" for each "work distance from cask."
2. **Case 2:** time spent in the area by staff not doing cask work—The ("staff total number in area" minus "staff number doing cask work") is multiplied by the "activity time in area." This value is then added to the "staff number doing cask work" multiplied by ("activity time in area" minus "activity time near cask"). Since no distance is specified for the distance from the cask, a range of possible distances were examined.
3. **Case 3:** time spent at a specified "work distance from cask" when there are no "staff number doing cask work"—These activity times were calculated for each "work distance from cask."
4. **Case 4:** time reported in a inconsistent manner—In three instances (steps 1.3, 3.2, and 14.2), the reported information is not logically complete (e.g., where "time in area" is smaller than "time near cask"). In these cases, the information was revised to be consistent and exposures calculated for the revised parameters.

For case 1, corresponding dose rates at the distances reported in Appendix B are shown in Table 4, along with the calculated total worker time and dose at each distance. These doses are based on "staff number doing cask work" multiplied by the "activity time near cask."

Table 4 Parameters and doses to workers "doing cask work" due to external radiation from 1 Bq cm^{-2} surface contamination of ^{60}Co (one cask turnaround cycle)

Distance (ft)	Distance (m)	Total worker time (person-h)	Dose rate (Sv h^{-1})	Total worker dose (person-Sv)
1	0.3	0.05	4.1×10^{-8}	2.1×10^{-9}
3	0.9	11.8	1.4×10^{-8}	1.7×10^{-7}
5	1.5	6.17	8.2×10^{-9}	5.1×10^{-8}
6	1.8	0.83	6.8×10^{-9}	5.7×10^{-9}
8	2.4	0.5	5.1×10^{-9}	2.6×10^{-9}
10	3	2.15	4.1×10^{-9}	8.8×10^{-9}
20	6	2.42	2.1×10^{-9}	5.1×10^{-9}
30	9	2.33	1.4×10^{-9}	3.3×10^{-9}
38	11.5	0	1.1×10^{-9}	0
50	15.2	0	8.1×10^{-10}	0
Total				2.5×10^{-7}

For case 2, the effect of an assumed distance from the cask was examined. The time spent in the area at unspecified distances from the cask that was not reported as "doing cask work" was 1184 person-min (19.7 h). These activities would result in exposures that range from 1.3×10^{-7} to 1.6×10^{-8} person-Sv, corresponding to assumed worker distances from the cask of 1.8 and 15.2 m, respectively.

For case 3, time spent at a specified "work distance from cask" when there are no "staff number doing cask work" was calculated for each "work distance from cask." These exposures resulted in a total worker dose of 1.7×10^{-8} person-Sv.

For case 4, the time and distance values were revised for three steps as follows: step 1.3 – one Site Yard Driver (YD) for 10 min at 3 m, step 3.2 – one Security Guard (SG) for 15 min at 1.8 m, and step 14.2 – two OPs for 45 min at 0.9 m. The resulting total worker dose for these cases is 2.3×10^{-8} person-Sv.

Combining all four cases shows that total worker dose due to external contamination on the cask surface varies from 4.2×10^{-7} to 3.1×10^{-7} person-Sv, depending on the assumed distance from the worker to the cask for case 2. For an assumed distance of 2.5 m during the "time in area" while not doing "cask work," total exposure is approximately 4×10^{-7} person-Sv. This value was chosen to be reasonably representative of cask operations as reported in Appendix B.

Consequently, the **total worker dose per cask turnaround due to external radiation from surface contamination is 4.0×10^{-7} Sv** from a unit activity concentration on the cask surface (1 Bq cm^{-2}). The information in Appendix B identifies worker OP1 as receiving the **maximum individual worker exposure due to external radiation from surface contamination with a dose of 1.8×10^{-7} Sv per cask turnaround.**

4.3.1.1.2 External exposures to workers due to transfer of contamination

Transfer of contamination to the hands may lead to irradiation of the skin of the hands and possible subsequent transfer to the face with irradiation of the skin of the face. This dose pathway is unlikely due to the contamination control measures and work practices typically employed in nuclear power plants. However, it is included for completeness in estimating the potential doses to workers. The calculational approaches used here are derived from the CRP-developed approaches.

Hand contamination. During cask handling, workers typically wear gloves that will provide some shielding of beta emissions. Because the reference radionuclide mix for spent fuel cask contamination consists mainly of photon emitters, no shielding due to the presence of gloves is assumed.

Assuming that outstretched hands have an area of 200 cm^2 on each side and that contamination occurs only on the palm side following touching the cask, 400 cm^2 of 400-μm-thick skin (palm side) will be contaminated.[10] In the calculation of effective dose, it is assumed that the hands are contaminated for 8 h per day. This assumes that a worker's hands are contaminated at the start of the working day, are decontaminated (by washing or removal of gloves) during a midday break, and then recontaminated during the afternoon. The contamination would be ultimately removed prior to exiting the radiologically controlled area.

DOE-CH/TPO-001 indicates that it typically requires approximately 1000 min (16.7 h) elapsed time to turn around a legal-weight truck cask. Based on an 8-h working shift, it is assumed that each worker receives hand irradiation for 2 days (16 h) per cask turnaround.

The skin equivalent dose resulting from hand contamination is given by

$$H_{SKIN_{HANDS}} = A_c \times f \times T \times (\beta_{skin} + \gamma_{skin}) \tag{12}$$

where

A_c = level of contamination, 1 Bq cm^{-2};

f = fraction transferred, assumed to be 20%;

T = time exposed, assumed to be 16 h per cask turnaround;

β_{skin} = skin equivalent dose rate to the basal layer of skin epidermis for beta irradiation for 400-μm-thick skin, Sv h^{-1} per Bq cm^{-2}; and

γ_{skin} = skin equivalent dose rate to the basal layer of skin epidermis for gamma irradiation, Sv h^{-1} per Bq cm^{-2}.

Using the radionuclide mix described in Sect. 3.4, the beta skin equivalent dose rates from Kocher and Eckerman,[11] and the gamma skin equivalent dose rates from the CRP report, a weighted total (both beta and gamma) skin equivalent dose rate of 1.1×10^{-7} Sv h^{-1} per Bq cm^{-2} was calculated for 400-μm-thick skin. From Eq. (12), this results in a skin equivalent dose of 3.5×10^{-7} Sv.

The IAEA CRP approach for calculating worker effective dose due to irradiation of the skin applies a factor given as the quotient of the area of skin contaminated (for hands, assumed to be 400 cm^2) and the total area of ultraviolet radiation–exposed skin (taken as 3000 cm^2). This approach is not consistent with recent recommendations by the National Council on Radiation Protection and Measurements (NCRP) and the U.S. Nuclear Regulatory Commission (NRC). NCRP Statement No. 9, issued March 30, 2001, recommends that the dose at a depth of 70 μm be averaged over an area of 10 cm^2 (or the exposed area, if larger) in deriving the skin dose from any external radiation exposure—regardless of the source or geometry of the irradiation. The NRC endorsed the NCRP recommendations in Commission Statement SECY-02-0021 titled "Final Rule on Revision of the Skin Dose Limit, 10 CFR Part 20." In this document the IAEA CRP approach for computing the effective dose to the skin is not used. Instead, an approach that is consistent with the NCRP and NRC recommendations is applied.

The effective dose from skin contamination due to touching the cask during handling is given by

$$E_{SKIN} = H_{SKIN_{HANDS}} \times w_{SKIN} \tag{13}$$

where[12]

$H_{SKIN_{HANDS}}$ = 3.5×10^{-7} Sv, and

w_{SKIN} = tissue-weighting factor for skin, 0.01.

This results in an **effective dose equivalent to an individual worker from contamination transferred to the hands of 3.5×10^{-9} Sv** from a unit surface activity per cask turnaround. Based on the operational analysis in Appendix B, as many as eight workers could perform cask operations that lead to contact with the cask surface (4 OPs, 1 RM, and 3 M-Cs). This results in a **collective effective dose to workers from contamination transferred to the hands of 2.8×10^{-8} Sv.**

Transfer of activity to the face. Other areas of skin, for example, the face, could become contaminated indirectly from the contamination on the hands. In these calculations it is assumed (consistent with the CRP approach) that 4% (20% of 20%) of the activity level on the surface of the package is transferred to the face and that the affected area of face is 100 cm^2, approximately the area of one cheek. An average exposure time of 8 h per day has been assumed, since the face may not be washed during the course of the day and the contamination would be removed prior to exiting the radiologically controlled area. Based on an 8-h working shift, it is assumed that each worker receives face irradiation for 2 days (16 h) per cask turnaround.

The skin equivalent dose resulting from face contamination is given by

$$H_{SKIN_{FACE}} = \chi \times f_{face} \times T \times (\beta_{skin} + \gamma_{skin}) \qquad (14)$$

where

$\chi =$ activity of contamination available for transfer to the face;

$\chi = A_c \times f$;

and

$A_c =$ level of contamination, assumed to be 1 Bq cm^{-2};

$f =$ fraction transferred to the hands, assumed to be 20%;

$f_{face} =$ fraction transferred from the hands to the face, assumed to be 20%;

$T =$ time exposed, assumed to be 16 h per cask turnaround;

$\beta_{skin} =$ skin equivalent dose rate to the basal layer of skin epidermis for beta irradiation for 40-μm-thick skin, Sv h^{-1} per Bq cm^{-2}; and

$\gamma_{skin} =$ skin equivalent dose rate to the basal layer of skin epidermis for gamma irradiation, Sv h^{-1} per Bq cm^{-2}.

Using the radionuclide mix described in Sect. 3.4, the beta skin equivalent dose rates from Kocher and Eckerman,[11] and the gamma skin equivalent dose rates from the CRP report, a weighted total (both beta and gamma) skin equivalent dose rate of 1.6×10^{-7} Sv h^{-1} per Bq cm^{-2} was calculated for 40-μm-thick skin. From Eq. (14), this results in a skin equivalent dose of 1.0×10^{-7} Sv.

The effective dose from contamination of the face due to the transfer of contamination from the hands to the face is given by

$$E_{SKIN} = H_{SKIN_{FACE}} \times w_{SKIN} \qquad (15)$$

where

$w_{SKIN_{FACE}}$ = tissue-weighting factor for skin, 0.01 (Ref. 12).

This results in an **effective dose to an individual worker from contamination transferred to the face of 1×10^{-9} Sv** from a unit surface activity per cask turnaround. Based on the operational analysis in Appendix B, as many as eight workers could perform cask operations that could lead to contact with the cask surface (4 OPs, 1 RM, and 3 M-Cs) and subsequent transfer of contamination to the face. This results in a **collective effective dose to workers from contamination transferred from the hands to the face of 8×10^{-9} Sv.**

4.3.1.2 External exposure from the cask contents ($E_{wexcaskcon}$)

Workers will also be exposed to external radiation from the loaded cask, particularly when they are performing work near the cask. Appendix B provides details from DOE-CH/TPO-001 on the calculated doses to workers from the cask. These estimated doses are presented in this section to illustrate the relative magnitude of worker doses received from cask operations. Section 6.2 presents information from additional sources that are used to derive a more generic estimate of worker doses due to cask contents during decontamination and monitoring activities.

The worker doses reported in DOE-CH/TPO-001 include several steps that are tied directly to the efforts required to comply with the current transport surface contamination limits, as shown in Table 5. Since the doses received from these steps will vary with the allowable contamination limits (less time is needed to comply with higher contamination limits), they are considered separately from the overall work flow of cask handling.

Table 5 Doses due to radiation from the cask contents as a result of cask decontamination and monitoring tasks to current contamination limits

Step no.	Activity	Number and type of staff*	Time near cask (h)	Dose due to cask work (person-Sv)
14.1	Survey cask surface[†]	1 RM	0.25	1.8×10^{-6}
14.2	Decontaminate cask	2 OP	0.75	3.0×10^{-5}
15.2	Decontaminate area between lids	2 OP	0.08	3.3×10^{-5}
19.1	Radiation survey of cask and vehicle[†]	1 RM	0.5	5.3×10^{-5}
19.1	Radiation survey of cask and vehicle[†]	1 OP	0.4	2.3×10^{-5}
19.2	Spot decontamination	1 OP	0.17	5.0×10^{-5}
21.1	Radiation survey and recording[†]	1 RM	0.17	5.8×10^{-6}
21.1	Radiation survey and recording[†]	1 QC	0.17	5.8×10^{-6}
Total				2.0×10^{-4}

* OP = Reactor Site Operator; RM = Radiation Monitor; QC = Inspector.

[†] These doses have been reduced 30% from the doses reported in Appendix B. This reduction is to account for approximately 30% of the reported dose in these tasks being attributable to radiation level measurement rather than contamination measurement.

Consequently, the collective decontamination and monitoring worker dose per cask turnaround due to external radiation from the cask contents is 2.0 × 10^{-4} Sv and the maximum individual dose due to the cask contents is OP1 (assumed to be involved in all the OP tasks), with a dose of 1.0 × 10^{-4} Sv per cask turnaround.

4.3.2 Effective Dose to Workers Due to External Exposure to Ambient Radiation in the Work Area (E_{wexamb})

When workers are performing cask-handling operations, they are also exposed to external ambient radiation from the work area. These worker doses include several steps that are tied directly to the efforts required to comply with the transport surface contamination limits, including those shown in Table 6. Since the doses due to ambient radiation levels in the work areas will vary with the allowable contamination limits (less time is needed to comply with higher contamination limits), they are considered separately from the overall work flow of cask handling.

Table 6 Doses due to radiation from the work area as a result of cask decontamination and monitoring tasks to current contamination limits

Step no.	Activity	Number and type of staff*	Time in area (h)	Dose due to ambient external radiation (person-Sv)
14.1	Survey cask surface[†]	1 RM	0.33	4.7 × 10^{-6}
14.2	Decontaminate cask	2 OP	0.83[‡]	1.7 × 10^{-5}
15.2	Decontaminate area between lids	2 OP	0.08	3.3 × 10^{-6}
19.1	Radiation survey of cask and vehicle[†]	1 RM	0.67	2.3 × 10^{-6}
19.1	Radiation survey of cask and vehicle[†]	1 OP	0.4	1.5 × 10^{-6}
19.2	Spot decontamination	1 OP	0.17	8.3 × 10^{-7}
21.1	Radiation survey and recording[†]	1 RM	0.5	1.8 × 10^{-6}
21.1	Radiation survey and recording[†]	1 QC	0.17	5.8 × 10^{-7}
Total				3.2 × 10^{-5}

* OP = Reactor Site Operator; RM = Radiation Monitor; QC = Inspector.

[†] These doses have been reduced 30% from the doses reported in Appendix B. This reduction is to account for approximately 30% of the reported dose in these tasks being attributable to radiation level measurement rather than contamination measurement.

[‡] The value for "time in area" reported in DOE-CH/TPO-001 appears to be in error since it is less than the time reported for near-cask activities. This value has been revised to be the near-cask time (0.75 h) plus 0.08 h to account for entry and exit from the area. This time correctly corresponds to the reported dose due to ambient external radiation.

The collective decontamination and monitoring worker dose due to ambient external radiation is 3.2×10^{-5} Sv, and the maximum individual dose due to ambient external radiation to workers performing decontamination and monitoring tasks occurs for OP1, who has a dose of 1.3×10^{-5} Sv per cask turnaround.

4.4 SUMMARY OF WORKER DOSES

Using the results of Sects. 4.2 and 4.3, the doses to workers resulting from the current contamination limits of 4 Bq cm^{-2} for beta and gamma emitters can be calculated. 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 (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. (Where appropriate, the values for dose per unit of surface activity in Sects. 4.2 and 4.3 are multiplied by 4.) These results are presented in Tables 7 and 8.

Table 7 Individual dose to workers by all pathways

Individual dose to workers (E_{wkr}) in Sv – Normalized to 4 Bq cm^{-2}			
Worker internal dose (E_{win})		Worker external dose (E_{wex})	
From cask (contamination) ($E_{wincask}$)	Ambient (E_{winamb})	From cask (contamination and cask contents) ($E_{wexcask}$)	Ambient (E_{wexamb})
Inhalation: 1.3×10^{-8} Ingestion: 1.2×10^{-8} Total: 2.5×10^{-8}	N/A	From contamination: Direct – 7.2×10^{-7} Hand – 1.4×10^{-8} Face – 4.0×10^{-9} Total: 7.4×10^{-7}	1.3×10^{-5} (decontamination and monitoring only)
		From cask itself (decontamination and monitoring only) – 1.0×10^{-4}	

The results in Table 7 show that the doses to the maximally exposed individual worker can be categorized by the following:

1. Doses that will increase if contamination limits are raised (inhalation and ingestion, as well as direct, hand, and face exposures). These doses total 7.7×10^{-7} Sv per cask turnaround, for a contamination level of 4 Bq cm^{-1}.

2. 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). These doses total 1.1×10^{-4} Sv per cask turnaround, for a contamination level of 4 Bq cm^{-1}.

Table 8 Collective dose to workers by all pathways

Collective dose to workers (E_{wkr}) in person-Sv – Normalized to 4 Bq cm^{-2}			
Worker internal dose (E_{win})		Worker external dose (E_{wex})	
From cask (contamination) ($E_{wincask}$)	Ambient (E_{winamb})	From cask (contamination and cask contents) ($E_{wexcask}$)	Ambient (E_{wexamb})
Inhalation: 3.8×10^{-8} Ingestion: 9.2×10^{-8} Total: 1.3×10^{-7}	N/A	From contamination: Direct – 1.6×10^{-6} Hand – 1.1×10^{-7} Face – 3.2×10^{-8} Total: 1.7×10^{-6}	3.2×10^{-5} (decontamination and monitoring only)
		From cask contents (decontamination and monitoring only) – 2×10^{-4}	

The results in Table 8 show that the collective worker dose can be categorized by the following:

1. Collective dose that will increase if contamination limits are raised (inhalation and ingestion, as well as direct, hand, and face exposures). These doses total 1.8×10^{-6} person-Sv per cask turnaround for a contamination level of 4 Bq cm^{-1}.

2. 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). These doses total 2.3×10^{-4} person-Sv per cask turnaround for a contamination level of 4 Bq cm^{-1}.

4.5 WORKER DOSES AS A FUNCTION OF CONTAMINATION LIMITS

Based on the results in Sect. 4.4, 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 9. The dose savings that would result from reduced decontamination and monitoring times and optimizing overall worker exposures are discussed in Sect. 6.

Table 9 Worker doses that increase due to higher removable contamination levels

Type of worker dose	Contamination limit	Dose
Individual	4	7.7×10^{-7} Sv
	40	7.7×10^{-6} Sv
	400	7.7×10^{-5} Sv
Collective	4	1.8×10^{-6} person-Sv
	40	1.8×10^{-5} person-Sv
	400	1.8×10^{-4} person-Sv

5 CALCULATION OF PUBLIC DOSE

As described in Sect. 3.3, 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.

5.1 EFFECTIVE DOSES TO THE PUBLIC DUE TO INTERNALLY DEPOSITED RADIONUCLIDES

Removable surface contamination can be dispersed into the environment, leading to

- inhalation,
- deposition onto the body,
- ground shine (exposure to radiation emitted by contamination on the ground), and
- ingestion via the food chain.

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.

5.1.1 Exposure Scenarios

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.[13] In RADTRAN 5, the incident-free exposure scenarios include the following public groups:

1. off-link population (persons residing in the vicinity of the transport route),
2. on-link population (persons traveling in the vicinity of the shipment during transport), and
3. population in the vicinity of the shipment during stops.

These groups would also be the ones exposed to airborne contamination resuspended from the surface of a cask.

The characteristics of the reference spent fuel cask are consistent with the IAEA CRP and are assumed to be the following:

1. surface area of cask [130 m^2 (1.3×10^6 cm^2)], and
2. resuspension rate from cask surface [10^{-4} h^{-1} (3×10^{-8} s^{-1})].

Using these characteristics for a cask and a reference contamination level of 1 Bq cm^{-2} results in an activity release rate of 4×10^{-2} Bq s^{-1}. As shown in Sect. 3.4, contamination on spent fuel casks consists of a mixture of radionuclides with a weighted committed effective dose per unit intake via inhalation for the public of 8.2×10^{-9} Sv Bq^{-1}.

5.1.2 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 Appendix C. 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) per unit of surface contamination (1 Bq cm^{-2}).

5.1.3 Off-Link (Persons Residing in the Vicinity of the Transport Route)

5.1.3.1 Dose to an individual

Ordinarily, the population along a route used to transport spent fuel lives some minimum distance away from the roadway or rail line. In the United States, this minimum distance is typically 30 m for rural freeways, rural nonfreeways, and suburban freeways and 27 m for suburban nonfreeways.

The exposed population residing along a route will consist of some combination of persons indoors and outdoors (pedestrians, working, playing, etc.). For simplicity and to be conservative, all persons along the route are assumed to be outdoors when the shipment passes.

Using Eq. (C-3) of the model in Appendix C, the expected dose from surface contamination to the **most exposed individual at the edge of a road** when a cask passes by at 100 km h^{-1} (30 m from the passing conveyance) is

$$\begin{aligned} E &= Q\frac{\Psi}{Q}\dot{V}\, e \\ &= \left(4\times10^{-2}\, Bq\, s^{-1}\right)\left(2.49\times10^{-4}\, s^2\, m^{-3}\right)\left(2.55\times10^{-4}\, m^3 s^{-1}\right)\left(8.2\times10^{-9}\, Sv\, Bq^{-1}\right) \\ &= 2.1\times10^{-17}\, Sv. \end{aligned}$$

5.1.3.2 Population dose

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, noncontrolled access).[14] 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.

Using a two-person crew, it takes the conveyance 47.5 h to make the journey (1.7 × 10^5 s). The time and distances spent on the two different road types are as follows:

Type of road	Distance (km)	Transit time (s)
Multilane divided	4365	1.6 × 10^5
Other	198	7.1 × 10^3

Using Eq. (C-6) of the model in Appendix C, the collective doses for inhalation of resuspended contamination by the public residing along the route are calculated as shown in Sects. 5.1.3.2.1 and 5.1.3.2.2.

5.1.3.2.1 Multilane divided highway

For multilane divided highways, the dose is as follows:

$$\begin{aligned} S &= \rho Q \frac{\bar{x}}{Q} \dot{V} (y_2 - y_1) v e t \\ &= (1.2\times10^{-4} m^{-2})(4\times10^{-2}\ Bq\, s^{-1})(5.61\times10^{-7} s\, m^{-3})(2.55\times10^{-4}\ m^3\, s^{-1})(770\, m)(27.8\, m\, s^{-1}) \\ &\quad (8.2\times10^{-9} Sv\, Bq^{-1})(1.6\times10^5 s) \\ &= 1.9\times10^{-14}\ person-Sv. \end{aligned}$$

5.1.3.2.2 Other highway

For other highways, the dose is as follows:

$$\begin{aligned} S &= \rho Q \frac{\bar{x}}{Q} \dot{V} (y_2 - y_1) v e t \\ &= (1.2\times10^{-4} m^{-2})(4\times10^{-2}\ Bq\, s^{-1})(6.89\times10^{-7} s\, m^{-3})(2.55\times10^{-4}\ m^3\, s^{-1})(770\, m)(27.8\, m\, s^{-1}) \\ &\quad (8.2\times10^{-9} Sv\, Bq^{-1})(7.1\times10^3 s) \\ &= 1.0\times10^{-15}\ person-Sv. \end{aligned}$$

Thus, the total inhalation dose to the public along the route is 2 × 10^{-14} person-Sv per cask shipment.

5.1.4 On-Link (Persons Traveling in the Vicinity of the Shipment During Transport)

The exposed groups consist of

- persons in vehicles following the shipment,
- persons in vehicles traveling in the same direction as the shipment and passing it, and
- persons in vehicles traveling in the opposite direction to the shipment.

Parameters were chosen to be representative of highway geometries and, using the model in Appendix C, the doses in Sects. 5.1.4.1 through 5.1.4.4 were calculated.

5.1.4.1 Individuals in vehicles following the shipment

5.1.4.1.1 Multilane divided highway

It is unlikely that a member of the public would follow a truck traveling at the speed limit on a divided highway for more than 4 h (1.4×10^4 s) as this is the time at which the drivers would leave the highway to take a fuel or rest break. Applying Eq. (C-4) of the model in Appendix C (Figure C.1, car #1), the dose to a member of the public following the cask for 4 h would be

$$\begin{aligned} E &= Q\frac{\chi}{Q}\dot{V}\,e\,t \\ &= \left(4\times10^{-2}\ Bq\,s^{-1}\right)\left(1.18\times10^{-4} s\,m^{-3}\right)\left(2.55\times10^{-4} m^3 s^{-1}\right)\left(8.2\times10^{-9} Sv\,Bq^{-1}\right)\left(1.4\times10^{4}\ s\right) \\ &= 1.4\times10^{-13}\ Sv\,. \end{aligned}$$

5.1.4.1.2 Other highway

Assuming that a person in a car following the shipment on an undivided highway remains behind the shipment for the entire duration of the "other highway" portion of the journey (7.1×10^3 s), the dose would be as follows:

$$\begin{aligned} E &= Q\frac{\chi}{Q}\dot{V}\,e\,t \\ &= \left(4\times10^{-2}\ Bq\,s^{-1}\right)\left(1.18\times10^{-4} s\,m^{-3}\right)\left(2.55\times10^{-4} m^3 s^{-1}\right)\left(8.2\times10^{-9} Sv\,Bq^{-1}\right)\left(7.1\times10^{3}\ s\right) \\ &= 7.0\times10^{-14}\ Sv\,. \end{aligned}$$

5.1.4.2 Individuals in vehicles passing the shipment in the same direction as the shipment

5.1.4.2.1 Multilane divided highway

Assuming that the passing vehicle is traveling at 5 km h^{-1} faster than the vehicle transporting the cask and applying Eq. (C-3) of the model in Appendix C (Figure C.1, car #2), the following individual dose is derived:

$$
\begin{aligned}
E &= Q\frac{\Psi}{Q}\dot{V}\,e \\
&= \left(4\times10^{-2}\ Bq\,s^{-1}\right)\left(9.79\times10^{-4}\ s^{2}\,m^{-3}\right)\left(2.55\times10^{-4}\ m^{3}s^{-1}\right)\left(8.2\times10^{-9}\ Sv\,Bq^{-1}\right) \\
&= 8.2\times10^{-17}\,Sv\,.
\end{aligned}
$$

5.1.4.2.2 Other highway

If it is assumed that a vehicle passing the shipment is traveling 5 km h^{-1} faster than the shipment when it is traveling on a nondivided highway and that the lane dimensions are equal, the dose to an individual on an "other" highway will be the same as that for a multilane divided highway.

5.1.4.3 Individuals in vehicles traveling in the opposite direction to the shipment

Assuming the lane geometry and velocities given in Appendix C, the following individual doses can be calculated for an individual in these vehicles.

5.1.4.3.1 Multilane divided highway

Two vehicles are modeled: one in the nearest lane to the shipment (Figure C.1, car #3) and one in the next lane removed (car #4). The dose to an individual in car #3, from Eq. (C-3), would be

$$
\begin{aligned}
E &= Q\frac{\Psi}{Q}\dot{V}\,e \\
&= \left(4\times10^{-2}\ Bq\,s^{-1}\right)\left(1.75\times10^{-4}\ s^{2}\,m^{-3}\right)\left(2.55\times10^{-4}\ m^{3}s^{-1}\right)\left(8.2\times10^{-9}\ Sv\,Bq^{-1}\right) \\
&= 1.5\times10^{-17}\,Sv\,.
\end{aligned}
$$

Similarly, the dose to an individual in car #4 would be proportional to the integrated concentration per unit release rate for car #3:

$$
\begin{aligned}
E &= \left(\frac{1.54\times10^{-4}}{1.75\times10^{-4}}\right)\left(1.5\times10^{-17}\right) \\
&= 1.3\times10^{-17}\ Sv\,.
\end{aligned}
$$

5.1.4.3.2 Other highway

Also according to Eq. (C-3) of Appendix C, the **dose to an individual in a vehicle traveling in the opposite direction to the shipment in the adjacent lane** would be

$$E = \left(4\times10^{-2}\ Bq\ s^{-1}\right)\left(3.9\times10^{-4}\ s^{2}\ m^{-3}\right)\left(2.55\times10^{-4}\ m^{3}s^{-1}\right)\left(8.2\times10^{-8}\ Sv\ Bq^{-1}\right)$$
$$= 3.3\times10^{-17}\,Sv\,.$$

5.1.4.4 On-link collective doses due to inhalation

With the exception of cars following the transport vehicle, the collective dose to on-link persons is influenced by the number of cars approaching or passing the transport vehicle, the assumed occupancy of the cars, and the individual doses as calculated in previous sections. The modeling algorithms developed in Appendix C were applied to calculate on-link collective doses and are described in more detail in Appendix D.

It was assumed that vehicles sharing the highway were following each other with a minimum separation distance of 55 m and that the traffic stream was continuous in both directions. This very conservative traffic density over the entire route was offset with an assumption of one person per vehicle. A spreadsheet analysis was performed as described in Appendix D, and the results are shown in Table 10.

Table 10 On-link collective inhalation doses

Exposed group	Lane number	Persons affected	E (person-Sv)
Following shipment—multilane and other highway	1	100	4.9×10^{-13}
Passing in same direction—multilane and other highway	2	3,968	4.0×10^{-13}
Traveling in opposite direction—multilane near lane	3	162,695	2.9×10^{-12}
Traveling in opposite direction—multilane far lane and other highway	4	165,927	2.8×10^{-12}
Total			$\mathbf{6.6 \times 10^{-12}}$

5.1.5 Doses Due to Inhalation at Stops

The IAEA CRP examined doses to members of the public during stops at distances ranging from 5 to 50 m. The geometric approach used in the CRP was appropriate for relatively short distances but is not suitable for longer distances unless modifications in the methodology are made to account for additional atmospheric effects. Based on analysis of the CRP approach, modifications were made that allow extrapolation out to 800 m. This permitted the development of results that are as consistent as possible with the CRP results while providing the dose estimates at longer distances required for calculating the collective internal public dose.

Details of how the CRP approach was extrapolated to longer distances are provided in **Appendix E—Inhalation Population Dose from Contamination at Stops**. The approaches described in the appendix were incorporated into a spreadsheet to calculate the doses.

Assuming a population density as described in Sect. 5.1.3.2 and that there are eleven 0.5-h stops during the journey (approximately one stop every 4 h) in the band of population from 5 to 800 m, the **collective population dose from inhalation during stops is 3.5×10^{-13} person-Sv.** Assuming that an individual would be present at only one stop during the shipment (resulting in 0.5-h exposure time per shipment) and the distance at which the exposure occurs is relatively close (5 m), the resulting **maximum individual dose from inhalation of 3.3×10^{-14} Sv.**

5.1.6 Summary of Public Doses Due to Inhalation

From the previous results, it can be seen that the doses to members of the public from the inhalation of resuspended contamination from a cask surface are very low. The results are provided in Tables 11 and 12.

Table 11 Inhalation doses to the maximum exposed member of the public

	Exposure scenario	Individual dose (Sv per cask shipment)
5.1.3.1	Individual at 30 m from route	2.1×10^{-17}
5.1.4.1	Following the shipment—multilane	1.4×10^{-13}
5.1.4.1	Following the shipment—other highway	7.0×10^{-14}
5.1.4.2	Passing shipment in same direction—multilane or other highway	8.2×10^{-17}
5.1.4.3	Traveling in opposite direction—multilane near lane	1.5×10^{-17}
5.1.4.3	Traveling in opposite direction—multilane far lane	1.3×10^{-17}
5.1.4.3	Traveling in opposite direction—other highway	3.3×10^{-17}
5.1.5	At stops	3.3×10^{-14}
Highest individual public inhalation dose (1 Bq cm^{-2})		**1.4×10^{-13}**

Table 12 **Inhalation collective dose to the public**

	Exposure scenario	Collective dose (person-Sv per cask shipment)
5.1.3.2	Population along the route—multilane and other highway	2.0×10^{-14}
5.1.4.4	Following the shipment—multilane and other highway	4.9×10^{-13}
5.1.4.4	Passing shipment in same direction—multilane and other highway	4.0×10^{-13}
5.1.4.4	Traveling in opposite direction—multilane near lane	2.9×10^{-12}
5.1.4.4	Traveling in opposite direction—multilane far lane and other highway	2.8×10^{-12}
5.1.5	At stops	3.5×10^{-13}
Total collective public inhalation dose (1 Bq cm^{-2})		**7.0×10^{-12}**

5.2 DOSES TO THE PUBLIC DUE TO EXTERNAL EXPOSURES

5.2.1 Exposure Scenarios

Because there will be direct external exposures to members of the public from the contamination on the cask surface with exposure scenarios as described previously for inhalation, these doses have been calculated.

5.2.2 Public External Dose Model

The methodologies used in the model are provided in more detail in **Appendix F—External Exposures to Members of the Public.** Using the approach described in the appendix, 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 sieverts) per unit of surface contamination (1 Bq cm^{-2}).

5.2.3 Off-Link Population (Persons Residing in the Vicinity of the Transport Route)

5.2.3.1 Dose to an individual

Ordinarily, the population along a route used to transport spent fuel lives some minimum distance away from the roadway or rail line. In the United States this minimum distance is typically 30 m for rural freeways, rural nonfreeways, and suburban freeways and 27 m for suburban nonfreeways.

The exposed population residing along a route will consist of some combination of persons indoors and outdoors (pedestrians, working, playing, etc.). For simplicity and to be conservative, all persons along the route are assumed to be outdoors when the shipment passes.

The maximum expected dose to a person along the transport route resulting from 1 Bq cm^{-2} surface contamination occurs when a cask passes by at 27 m from a person. **The maximum off-link individual dose is 1.4×10^{-14} Sv.**

5.2.3.2 Population dose

Analysis of a representative spent fuel transport route in the United States (Surry Nuclear Power Station, Virginia to Yucca Mountain, Nevada) using the ORNL TRAGIS routing and population model shows that the route consists of 96% multilane divided highway and 4% other highway (two or more lanes, noncontrolled access).[14] 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.

Using a two-person crew, it takes the conveyance 47.5 h to make the journey (1.7×10^5 s). The times and distances spent on the two different road types are as follows:

Type of road	Distance (km)	Transit time (s)
Multilane divided	4365	1.6×10^5
Other	198	7.1×10^3

5.2.3.2.1 Multilane divided highway

The calculation of collective dose to persons along the route due to direct external exposure to the surface contamination must take into account the greater distance that the population is away from the cask on the far side of a multilane divided highway. The resulting collective dose is as follows:

Population nearest the shipment: 1.0×10^{-9} person-Sv

Population opposite the shipment: 7.5×10^{-10} person-Sv

Total multilane collective dose: 1.8×10^{-9} person-Sv

5.2.3.2.2 Other highway

Exposure distances are slightly shorter for other highways (27 vs 30 m), but the much shorter distances and lower population counts result in much lower collective doses along these segments:

Population nearest the shipment: 4.8×10^{-11} person-Sv

Population opposite the shipment: 4.5×10^{-11} person-Sv

Total multilane collective dose: 9.3×10^{-11} person-Sv

Thus, the **collective off-link dose to the public from 1 Bq cm^{-2} of surface contamination is 1.9 × 10^{-9} person-Sv per cask shipment.**

5.2.4 On-Link (Persons Traveling in the Vicinity of the Shipment During Transport)

The exposed groups consist of

- persons in vehicles following the shipment,
- persons in vehicles traveling in the same direction as the shipment and passing it, and
- persons in vehicles traveling in the opposite direction to the shipment.

Parameters were chosen to be representative of highway geometries. Using the model in Appendix F, the doses in Sects. 5.2.4 and 5.2.5 were calculated.

5.2.4.1 Individuals in vehicles following the shipment

5.2.4.1.1 Multilane divided highway

It is unlikely that a member of the public would follow a truck traveling at the speed limit on a divided highway for more than 4 h (1.4×10^4 s), because this is the time at which the drivers would leave the highway to take a fuel or rest break. **The maximum external dose to an individual following the shipment on a multilane highway is 1.6×10^{-11} Sv.**

5.2.4.1.2 Other highway

Assuming that a person in a car following the shipment on an undivided highway remains behind the shipment for the entire duration of the "other highway" portion of the journey (7.1×10^3 s), the **maximum dose to an individual following the shipment on an "other" highway is 1.2×10^{-11} Sv.**

5.2.4.2 Individuals in vehicles passing the shipment in the same direction as the shipment

5.2.4.2.1 Multilane divided highway

Assuming that the passing vehicle is traveling at 5 km h^{-1} faster than the vehicle transporting, the **maximum individual dose when passing the shipment is 1.9×10^{-12} Sv.**

5.2.4.2.2 Other highway

If it is assumed that a vehicle passing the shipment is traveling 5 km h^{-1} faster than the shipment when it is traveling on a nondivided highway and that the lane dimensions are equal, the dose to an individual is the same (1.9×10^{-12} Sv).

5.2.4.3 Individuals in vehicles traveling in the opposite direction to the shipment

Assuming the lane geometry and velocities given in Appendix C and using the approaches described in Appendix F, individual doses were calculated.

5.2.4.3.1 Multilane divided highway

Two vehicles are modeled: one in the nearest lane to the shipment and one in the next lane removed. **The dose to an individual in car #4 traveling in the opposite direction to the shipment is 7.2×10^{-15} Sv, and the dose to an individual in car #3 is 8.2×10^{-15} Sv.**

5.2.4.3.2 Other highway

The maximum dose to an individual in a vehicle traveling in the opposite direction to the shipment in the adjacent lane is 4.8×10^{-14} Sv.

5.2.4.4 On-link collective doses due to external exposures

Using the same assumptions described in Sect. 5.1.4.4, collective doses due to external radiation were calculated as described in Appendix F and are shown in Table 13.

Table 13 Collective on-link doses due to external radiation

Exposed group	Lane number	Persons affected	*E* (person-Sv)
Following shipment—multilane and other highway	1	100	1.9×10^{-10}
Passing in same direction—multilane and other highway	2	4,148	8.1×10^{-9}
Traveling in opposite direction—multilane near lane	3	162,695	1.3×10^{-9}
Traveling in opposite direction—multilane far lane and other highway	4	165,927	1.5×10^{-9}
Total			$\mathbf{1.1 \times 10^{-8}}$

5.2.5 Doses Due to External Exposures at Stops

In a manner similar to that in described in Sect. 5.1.5, the IAEA CRP approach was extended to allow calculation of individual and collective doses to the public from external radiation during stops. Details of how the CRP approach was extrapolated to longer distances and how they were used to calculate collective doses are provided in Appendix F. The approaches described in the appendix were incorporated into a spreadsheet that calculated the doses.

Assuming a population density as described in Sect. 5.1.3.2 and eleven 0.5-h stops during the journey (approximately one stop every 4 h) in the band of population from 5 to 800 m, **the collective population dose from external exposure during stops is 4.2×10^{-9} person-Sv.** Assuming that an individual would be present at only one stop during the shipment (resulting in 0.5-h exposure time per shipment) and the distance at which the exposure occurs is assumed to be relatively close (5 m), the resulting **maximum individual dose from external exposure during stops of 2.5×10^{-10} Sv.**

5.2.6 Summary of Public Doses Due to External Exposure

From the previous results, 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 (as described in Appendix F) are summarized in Tables 14 and 15 for the same reference route used in Sect. 5.1 and a surface activity concentration of 1 Bq cm^{-2}.

Table 14 External exposure dose to the maximum exposed individual member of the public

	Exposure scenario	Individual dose (Sv per cask shipment)
5.2.3.1	Individual at 27 m from route	1.4×10^{-14}
5.2.4.1	Following the shipment—multilane	1.6×10^{-11}
5.2.4.1	Following the shipment—other highway	1.2×10^{-11}
5.2.4.2	Passing shipment in same direction—multilane or other highway	1.9×10^{-12}
5.2.4.3	Traveling in opposite direction—multilane near lane	8.2×10^{-15}
5.2.4.3	Traveling in opposite direction—multilane far lane	7.2×10^{-15}
5.2.4.3	Traveling in opposite direction—other highway	4.8×10^{-14}
5.2.5	At stops	2.5×10^{-10}
Highest individual public external dose (1 Bq cm^{-2})		**2.5×10^{-10}**

Table 15 External exposure collective dose to the public

	Exposure scenario	Collective dose (person-Sv per cask shipment)
5.2.3.2	Population 30–800 m from route	1.9×10^{-9}
5.2.4.4	Following the shipment—multilane and other highway	1.9×10^{-10}
5.2.4.4	Passing shipment in same direction—multilane and other highway	8.1×10^{-9}
5.2.4.4	Traveling in opposite direction—multilane near lane	1.3×10^{-9}
5.2.4.4	Traveling in opposite direction—multilane far lane and other highway	1.1×10^{-9}
5.2.5	At stops	4.2×10^{-9}
Total collective public external dose (1 Bq cm^{-2})		**1.7×10^{-8}**

5.3 PUBLIC DOSES FROM HIGHER CONTAMINATION LIMITS

The results of Sects. 5.1 and 5.2 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 16.

Table 16 Collective and individual doses from higher contamination levels

Exposure type	Contamination value ($Bq\ cm^{-2}$)	Collective dose (person-Sv)	Maximum exposed individual dose (Sv)
Internal	1	7.0×10^{-12}	1.4×10^{-13}
	4	2.8×10^{-11}	5.6×10^{-13}
	40	2.8×10^{-10}	5.6×10^{-12}
	400	2.8×10^{-9}	5.6×10^{-11}
External	1	1.7×10^{-8}	2.5×10^{-10}
	4	6.8×10^{-8}	1.0×10^{-9}
	40	6.8×10^{-7}	1.0×10^{-8}
	400	6.8×10^{-6}	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 17.

Table 17 Increases in public doses due to higher contamination levels

Exposure type	Contamination value ($Bq\ cm^{-2}$)	Increase in collective dose (person-Sv)	Increase in maximum exposed individual dose (Sv)
Internal	4	0	0
	40	2.5×10^{-10}	5.0×10^{-12}
	400	2.8×10^{-9}	5.5×10^{-11}
External	4	0	0
	40	6.1×10^{-7}	9.0×10^{-9}
	400	6.7×10^{-6}	9.9×10^{-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.

6 OPTIMIZING SPENT FUEL CONTAMINATION LIMITS

6.1 EFFECT OF ALLOWABLE CONTAMINATION LIMITS ON WORKER DOSES

As discussed in Sect. 4, 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.

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

This section provides information on doses received by workers during the performance of decontamination and monitoring activities. These doses are influenced by the times and distances from the cask that are required to complete the tasks. The reported doses 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.

6.2.1 DOE-CH/TPO-001

This report[9] includes the actions, duration, and doses due to decontamination and monitoring activities. The combined doses reported to workers due to the cask contents and ambient conditions, as analyzed in Sects. 4.3.1.2 and 4.3.2, are as follows:

Decontamination:	0.13×10^{-3} person-Sv
Monitoring:	0.1×10^{-3} person-Sv
Total:	0.23×10^{-3} person-Sv

6.2.2 CEPN/EDF Report

A report published by Centre d'Etude sur l'Evaluation de la Protection dans le Domaine Nucleáire/Electricité de France (CEPN/EDF)[15] provides detailed information on worker doses that result from activities related to preparation and shipment of spent fuel casks from EDF power plants. The report indicates the following findings:

The total dose for all cask dispatch operations is categorized as follows:

Preparation:	5.2×10^{-3} person-Sv
Monitoring:	1.3×10^{-3} person-Sv
Total:	6.5×10^{-3} person-Sv

The doses related to decontamination and monitoring are broken down into two values.

- The dose related to prevention and elimination of contamination (Sect. 3.1.4 of the report) is as follows:

  1.51×10^{-3} person-Sv (29% of total preparation dose).

- Monitoring for contamination includes 422 smears taken over 300-cm^2 areas by two teams, that is, double monitoring and radiation-level monitoring. It is stated that 90% of the collective dose is due to contamination monitoring (Sect. 3.2.3 of the report):

  1.17×10^{-3} person-Sv.

The CEPN/EDF numbers are applicable to well-trained and experienced crews (200 casks per year total, shipped from several reactor sites on a routine basis).

6.2.3 Information from a U.S. Reactor Operator[8]

This information was collected during ongoing operations that involved experienced crews employed in regularly making shipments.

Doses due to decontamination (two casks per shipment) are reported as:

Shipment #1:	1.13×10^{-3} person-Sv	(0.57×10^{-3} person-Sv per cask)
Shipment #2:	0.85×10^{-3} person-Sv	(0.43×10^{-3} person-Sv per cask)
Shipment #3:	0.99×10^{-3} person-Sv	(0.5×10^{-3} person-Sv per cask)
Average:	0.99×10^{-3} person-Sv	(0.5×10^{-3} person-Sv per cask)

Doses due to health physics (HP) support are also reported. Based on discussions with operations personnel at the U.S. light-water power reactor, it is estimated that 20–30% of the doses reported under HP support are due to decontamination monitoring. This value is lower than the CEPN/EDF data since the reported U.S. operations involve taking most of the contamination smears as the cask is being decontaminated and are reported as "decontamination" doses. The HP support contamination smears are more confirmatory in nature. If it is assumed that 25% of the monitoring/HP support dose is due to contamination monitoring, the doses due to contamination monitoring are as follows:

Shipment #1:	1.8×10^{-4} person-Sv	(0.9×10^{-4} person-Sv per cask)
Shipment #2:	1.6×10^{-4} person-Sv	(0.8×10^{-4} person-Sv per cask)
Shipment #3:	1.0×10^{-4} person-Sv	(0.5×10^{-4} person-Sv per cask)
Average:	1.5×10^{-4} person-Sv	(0.7×10^{-4} person-Sv per cask)

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

Source of information	Decontamination (person-Sv)	Monitoring (person-Sv)
1. DOE-CH/TPO-001	0.13×10^{-3}	0.1×10^{-3}
2. CEPN/EDF report	1.51×10^{-3}	1.17×10^{-3}
3. U.S. reactor information	0.5×10^{-3}	0.07×10^{-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.**

6.3 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:

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

As shown in Sect. 4.5, Table 9, the increases in individual and collective worker doses due to higher contamination limits can be calculated. These increases would be as follows:

Type of worker dose	Contamination limit	Dose	Dose increase
Individual	4	7.7 × 10^{-7} Sv	0
	40	7.7 × 10^{-6} Sv	6.9 × 10^{-6} Sv
	400	7.7 × 10^{-5} Sv	7.6 × 10^{-5} Sv
Collective	4	1.8 × 10^{-6} person-Sv	0
	40	1.8 × 10^{-5} person-Sv	1.6 × 10^{-5} person-Sv
	400	1.8 × 10^{-4} person-Sv	1.8 × 10^{-4} person-Sv

When considered in combination with the worker dose received during decontamination and monitoring activities (1.2 × 10^{-3} person-Sv, see Sect. 6.2), the worker dose from surface contamination on the cask (both internal and external pathways, see Sect. 4.4) 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. Figure 1 compares the collective worker doses due to surface contamination with the doses due to decontamination and monitoring activities.

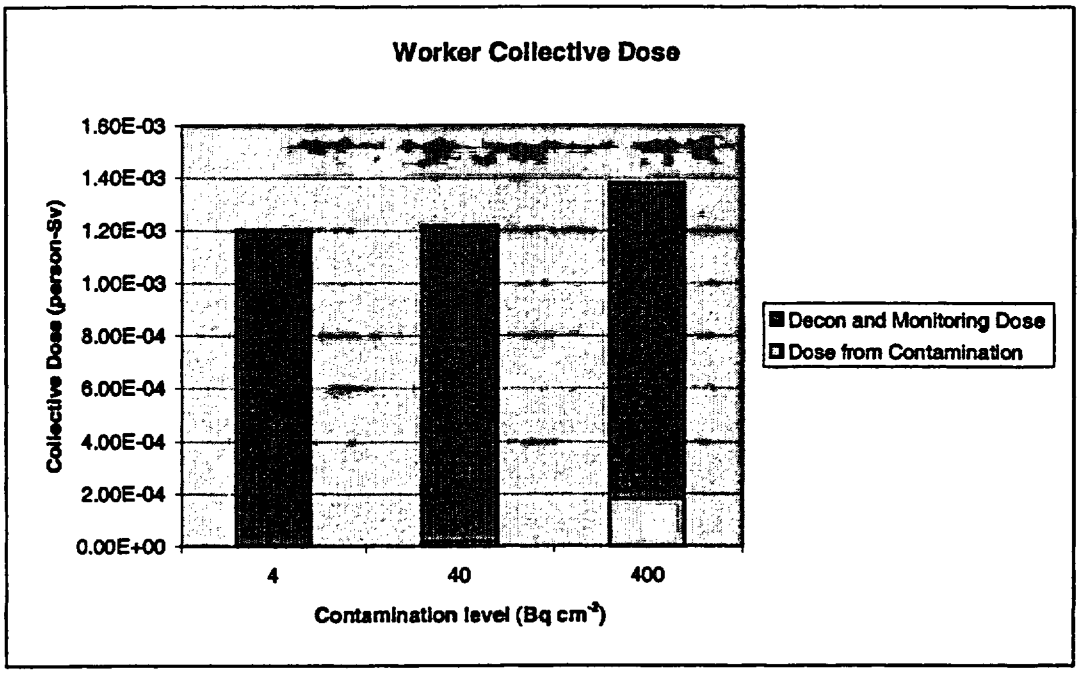


Figure 1 Worker collective dose components

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:

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

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 derived in Sect. 6.2, the required DRFs to offset the increases due to higher contamination limits are as follows:

Contamination limit	Increase in doses due to higher contamination limits	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[15] 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}.

6.4 OVERALL DOSE IMPACTS DUE TO HIGHER CONTAMINATION LIMITS

Using the values calculated in Sects. 5.3 and 6.3, the overall increases in collective and individual doses due to higher allowable contamination limits can be summarized as follows:

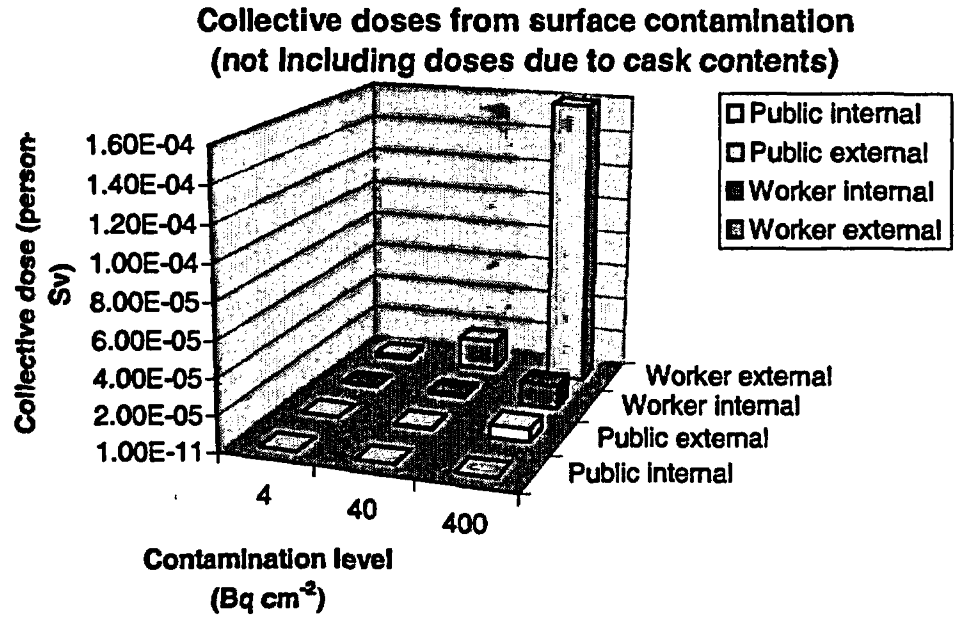
Exposed group	Contamination value ($Bq\ cm^{-2}$)	Increase in collective dose (Sv) (internal + external)	Increase in maximum exposed individual dose (Sv) (internal + external)
Workers	4	0	0
	40	1.6×10^{-5}	6.9×10^{-6}
	400	1.8×10^{-4}	7.6×10^{-5}
Public	4	0	0
	40	6.1×10^{-7}	9.0×10^{-9}
	400	6.7×10^{-6}	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}.

Figure 2 illustrates 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.



	4	40	400
□ Public internal	2.80E-11	2.80E-10	2.80E-09
□ Public external	6.80E-08	6.80E-07	6.80E-06
■ Worker internal	1.30E-07	1.30E-06	1.30E-05
▣ Worker external	1.70E-06	1.70E-05	1.70E-04

Figure 2 Collective dose—all groups

6.5 CONSERVATISMS AND SENSITIVITIES IN THE MODEL

Discussions with reactor operators indicate that the worker exposure scenarios in the models for inhalation, hand and face contamination, and ingestion are very conservative. Radiological control practices such as protective clothing (sometimes including double layers), work habits (influenced by extensive training), and monitoring practices (during work and when exiting radiological areas) reduce incidents of personnel contamination to very few. Consequently, assumptions such as "all workers that touch the cask have skin and face contamination and ingestion" are conservative and result in high estimates of the collective doses to these workers. This results in conservative estimates of the increase in worker collective dose that would occur with higher allowable contamination limits.

Conservative estimates of the increase in worker doses due to higher allowable removable contamination, combined with realistic estimates of the doses received during monitoring and decontamination activities, result in very conservative estimates of the DRFs. The actual DRFs that would be needed to produce an overall dose savings to workers are likely to be much lower than those calculated in this report.

Some parameters were chosen to be representative of spent fuel shipment conditions in the United States, such as a high transport vehicle speed (shipments are required to maximize their use of the interstate highway system), a long-distance route, low overall population density, and long shipment duration. The outcome of the model used in this study is relatively insensitive to these parameters since the public dose (collective and individual) during the shipment is low. The highest individual public dose is during stops, where an individual is assumed to be in relatively close proximity to the cask for a short period of time. Similarly, approximately 25% of the collective public dose is attributable to stops.

7 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.

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APPENDIX A

SUMMARY OF SELECTED PREVIOUS CONTAMINATION STUDIES

APPENDIX A—SUMMARY OF SELECTED PREVIOUS CONTAMINATION STUDIES

A.1 SUMMARY OF NUREG/CR-1858

The U.S. Nuclear Regulatory Commission sponsored a study at Pacific Northwest Laboratory concerning removable surface contamination on radioactive material transportation containers.[A.1] The study, NUREG/CR-1858, published in 1981, addresses various categories of radioactive material, including the consideration of the dose to workers and the public associated with the transport of spent fuels. Estimates of the additional economic costs incurred by lowering the current limits by factors of 10 and 100 were presented.

The modeling effort in NUREG/CR-1858 specifies a generic model that is applied across the various transport containers considered in that study. The potential significant radiation exposure pathways considered are

- ingestion (intakes of non-fixed contamination transferred to hands);
- inhalation (intakes of airborne contamination resuspended from container surfaces and from worker's contaminated hands); and
- direct exposure (to container surface contamination, skin contamination, and during decontamination of container surfaces).

The dosimetric evaluations are based on the pre–ICRP Publication 30 models and thus are more than 20 years out of date. An interesting aspect of the study is the significance attributed to the ingestion pathway. The exposure scenario involves a transfer of non-fixed contamination from the package surfaces to the hands, foodstuffs, and other items that enter the mouth. The direct exposure model did not address exposures to the contents of the containers. The model did consider both workers and members of the public.

In applying the model to spent fuel casks, it was noted that such containers are in exclusive use and hence not recycled for other uses, which could potentially lead to contamination entering other pathways leading to members of the public. Transportation workers were assumed to ingest surface contamination from 5×10^{-5} m^2 for each container. No release of the surface contamination was considered during the actual transport, and thus the model does not consider inhalation intake by members of the public. The assumed lack of release from the container also means that members of the public were not directly exposed to non-fixed contamination (only to direct exposure to the contents of the container). However, despite stating the assumption of no exposure to the public, an ingestion intake via ten individuals was assumed as the only source of public exposure to non-fixed surface contamination.

The impact on the collective radiation dose of decontamination activities was evaluated. The analysis considers the total time spent decontaminating at a fixed rate of decontamination, the exposure rate of the worker to the contents of the cask and to the non-fixed contamination, and the reduction in the public dose resulting from the reduced surface contamination. The relative impact of these factors is shown in Figure A.1 (adapted from the study). A surface contamination level of 10^{-4} µCi cm^{-2} (4 Bq cm^{-2}) was assumed, as well as the achievement of a uniform decontamination factor of 10 for each 30 min of effort. That figure indicates that an optimum decontamination time and total dose occur for a direct exposure rate of 1 mrem h^{-1} (10 µSv h^{-1}), and as such, dose savings from decontamination are possible only when there is a low direct exposure rate. This reflects the finding that it is the worker direct exposure considerations that are driving this model.

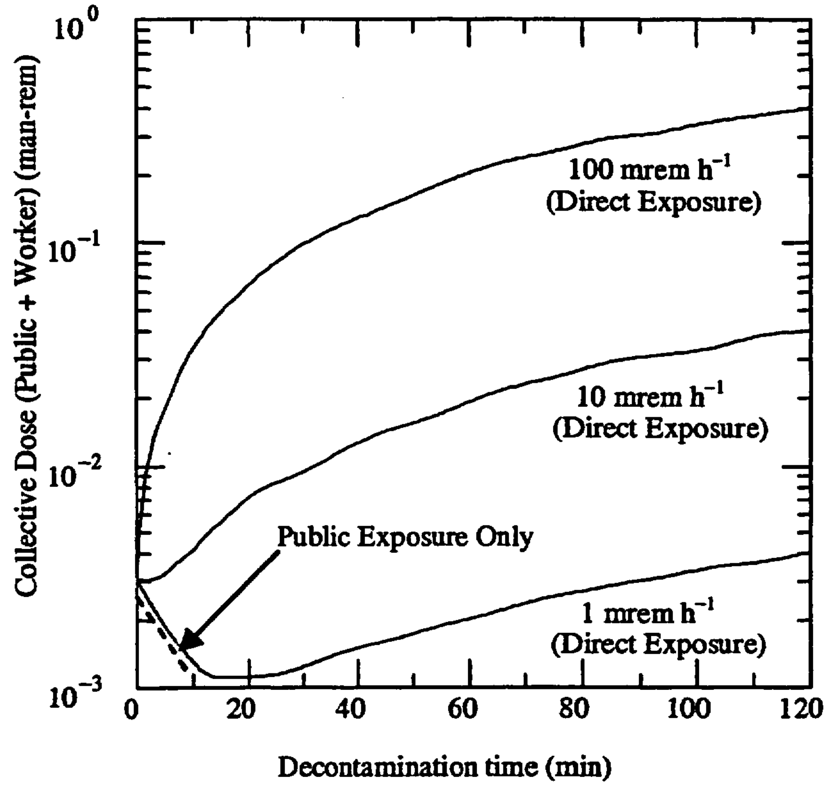

Figure A.1 Collective dose vs decontamination time for spent fuel container. (Adapted from Ref. A.1.)

A.2 SUMMARY OF NRPB REPORT

The United Kingdom National Radiation Protection Board (NRPB) conducted a study[A.2] for the U.K. Department for Transport to establish limits for non-fixed contamination on the surface of transport packages. This effort included formulation of an assessment model to translate the appropriate dose limits to derived limits on surface contamination. The study was reported in 1987.

The exposure pathways for workers considered by the NRPB included

- external irradiation of the skin,
- inhalation of resuspended surface contamination, and
- ingestion of surface contamination transferred to the hands.

The model addresses only the exposure to workers, and, while suggesting that the only significant pathway should be inhalation of dispersed contamination during transport, it is noted that such exposures are "exceedingly low." Thus, the model includes no provisions for assessing the exposure to members of the public. The focus of the NRPB report is on deriving contamination limits and thus does not address health risk or a balancing of worker and public exposure.

Derived limits were reported for 49 radioisotopes under various parameter assumptions. Of these nuclides, only two (^{134}Cs and ^{137}Cs) were included that would be appropriate for spent nuclear fuel (SNF). Derived limit results of 600 and 700 Bq cm^{-2} were reported for ^{137}Cs and ^{134}Cs, respectively, assuming average distance and time parameter values ("choice estimate" terminology used in the report). Values for ^{60}Co were not reported, but the results for cesium indicate that an increase in the derived limits of about a factor of 100 is possible for typical SNF applications.

A.3 SUMMARY

The NUREG and NRPB reports are thus somewhat contradictory in their assessment of the relevant exposure scenarios. The somewhat arbitrary selection of parameter values in the models appears to lead to conservative assignments as appropriate in the stated application. However, a model suitable for balancing health risk in the occupational and public exposures as resulting from the level of decontamination requires use of a more detailed and complete modeling effort. Parameter and model uncertainties should be addressed in formulating any future models for setting surface contamination levels.

A.4 REFERENCES

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APPENDIX B

WORKER PARAMETERS FROM DOE-TPO/CH-001

Table B.1 Worker parameters from DOE-TPO/CH-001

Step No.	Description	Area dose rate ($\mathrm{mrem\ h^{-1}}$)	Staff			Activity Time (min)		Work distance from cask (ft)	Dose rate for cask work ($\mathrm{mrem\ h^{-1}}$)	Dose (person-mrem)		
			Type*	Total number in area	Number doing cask work	In area	Near cask			Cask work	Area	Total
1	Receive transport vehicle and empty cask-monitor inspect. Unhook over-the-road carrier's drive unit and attach utility drive unit.											
1.1	Vehicle arrives and is spotted at fixed monitoring location at outer inspection gate. Check documentation.	0	TD	2	0	5	0	20	0	0.000	0.000	0.000
		0	SG	1	0	5	0	30	0	0.000	0.000	0.000
		0	RM	1	0	5	0	30	0	0.000	0.000	0.000
		0	QC	1	0	5	0	30	0	0.000	0.000	0.000
		0	SG	1	0	5	0	30	0	0.000	0.000	0.000
1.2	Monitor transport vehicle, perform security search, perform visual inspection, and disconnect carrier drive unit from transport vehicle.	0	RM	1	1	20	5	5	0.1	0.008	0.000	0.008
		0	SG	1	1	20	5	5	0.1	0.008	0.000	0.008
		0	TD	2	0	20	10	10	0	0.000	0.000	0.000
1.3	Connect utility drive unit to transport vehicle.	0	YD	1	0	10	10	10	0	0.000	0.000	0.000
										0.017	0.000	0.017

Table B.1 (continued)

Step No.	Description	Area dose rate (mrem h^{-1})	Staff			Activity Time (min)		Work distance from cask (ft)	Dose rate for cask work (mrem h^{-1})	Dose (person-mrem)		
			Type*	Total number in area	Number doing cask work	In area	Near cask			Cask work	Area	Total
2	Move transport vehicle and cask to inspection and washdown area.											
2.1	Move from outer guardhouse to inner guardhouse.	0	YD	2	0	10	0	20	0	0.000	0.000	0.000
		0	SG	1	0	10	0	20	0	0.000	0.000	0.000
2.2	Pass through inner gate and travel to inspection and washdown area.	0	YD	2	0	10	0	20	0	0.000	0.000	0.000
		0	OP	1	0	10	0	20	0	0.000	0.000	0.000
		0	SG	1	0	15	0	20	0	0.000	0.000	0.000
										0.000	**0.000**	**0.000**
3	Wash transport vehicle and cask-monitor inspect.											
3.1	General washdown.	0	OP	2	2	15	10	6	0.1	0.033	0.000	0.033
3.2	Retract personnel, barrier, spot washdown by wand, monitor and visual inspection.	0	OP	2	2	10	10	3	0.2	0.067	0.000	0.067
		0	OP	2	1	10	10	5	0.1	0.017	0.000	0.017
		0	RM	1	1	10	10	3	0.2	0.033	0.000	0.033
		0	SG	1	1	15	0	5	0.1	0.000	0.000	0.000
3.3	Air drying.	0	--			20			0	0.000	0.000	0.000
										0.150	**0.000**	**0.150**

Table B.1 (continued)

Step No.	Description	Area dose rate (mrem h^{-1})	Staff: Type*	Staff: Total number in area	Staff: Number doing cask work	Activity Time (min): In area	Activity Time (min): Near cask	Work distance from cask (ft)	Dose rate for cask work (mrem h^{-1})	Dose (person-mrem): Cask work	Dose (person-mrem): Area	Dose (person-mrem): Total
4	Move transport vehicle and cask to vehicle loading area.											
4.1	Move from washdown area to loading area.	0.5	YD	2	0	10	0	20	0	0.000	0.167	0.167
										0.000	**0.167**	**0.167**
5	Prepare cask for removal from transport vehicle; remove impact limiters and tiedowns.											
5.1	Obtain and replace power and hand tools.	0.5	M-C	2	0	10	0	20	0	0.000	0.167	0.167
5.2	Area radiation survey.	0.5	RM	1	1	15	10	3	0.2	0.033	0.125	0.158
5.3	Crane retrieves hooks and grapples for impact limiters.	0.5	CO	1	0	10	0	20	0	0.000	0.083	0.083
		0.5	M-C	1	0	10	0	20	0	0.000	0.083	0.083
5.4	Impact limiter removal.											
	Remove impact limiter bolts, clamps, etc.	0.5	M-C	2	2	10	10	3	0.2	0.067	0.167	0.233
		0.5	OP	1	1	10	10	5	0.1	0.017	0.083	0.100
	Store impact limiter fasteners.	0.5	M-C	2	0	10	0	10	0	0.000	0.167	0.167

Table B.1 (continued)

Step No.	Description	Area dose rate (mrem h^{-1})	Staff: Type*	Staff: Total number in area	Staff: Number doing cask work	Activity Time (min): In area	Activity Time (min): Near cask	Work distance from cask (ft)	Dose rate for cask work (mrem h^{-1})	Dose (person-mrem): Cask work	Dose (person-mrem): Area	Dose (person-mrem): Total
	Remove impact limiters with crane, and place in setdown area (two trips required—time to complete both trips). Seal bolt holes.	0.5	CO	1	0	15	0	20	0	0.000	0.125	0.125
		0.5	M-C	2	2	20	10	3	0.2	0.067	0.333	0.400
		0.5	M-C	1	1	20	10	5	0.1	0.017	0.167	0.183
		0.5	M-C	1	1	25	10	5	0.1	0.017	0.167	0.183
5.5	Tiedown removal. Remove tiedowns, store tiedowns.	0.5	M-C	2	2	30	20	3	0.2	0.133	0.500	0.633
		0.5	OP	1	1	30	20	5	0.1	0.033	0.250	0.283
		0.5	M-C	2	0	10	0	20	0	0.000	0.167	0.167
5.6	Disconnect cask monitoring equipment.	0.5	M-C	2	2	10	5	3	0.2	0.033	0.167	0.200
		0.5	OP	1	1	10	5	3	0.2	0.017	0.083	0.100
5.7	Apply lubricant to trunnions.	0.5	M-C	1	1	5	5	3	0.2	0.017	0.042	0.058
										0.450	2.875	3.323
6	Remove cask from vehicle and place on cask service pad.											
6.1	Pick up yoke, check operation, and carry to cask.	0.5	CO	1	0	45	0	30	0	0.000	0.375	0.375
		0.5	OP	1	0	45	0	30	0	0.000	0.375	0.375
6.2	Attach yoke.	0.5	CO	1	0	5	0	20	0	0.000	0.042	0.042
		0.5	OP	1	1	5	5	5	0.1	0.008	0.042	0.050

Table B.1 (continued)

Step No.	Description	Area dose rate (mrem h^{-1})	Staff			Activity Time (min)		Work distance from cask (ft)	Dose rate for cask work (mrem h^{-1})	Dose (person-mrem)		
			Type*	Total number in area	Number doing cask work	In area	Near cask			Cask work	Area	Total
6.3	Upend cask and lift off supports.	0.5	CO	1	0	20	0	20	0	0.000	0.167	0.167
		0.5	OP	1	1	20	10	8	0.1	0.017	0.167	0.183
6.4	BWR extra yoke and adjustment.	0.5	CO	1	0	30	0	0	0	0.000	0.250	0.250
		0.5	OP	1	1	30	20	5	0.1	0.033	0.250	0.283
6.5	Carry cask to pad.	0.5	CO	1	0	15	0	20	0	0.000	0.125	0.125
		0.5	OP	1	1	15	10	10	0	0.000	0.125	0.125
6.6	Lower cask to pad and remove yoke.	0.5	CO	1	0	5	0	20	0	0.000	0.042	0.042
		2	OP	1	1	5	5	5	0.1	0.008	0.167	0.175
6.7	Install work platform.	2	CO	1	0	15	0	38	0	0.000	0.500	0.500
		2	OP	2	2	15	10	0	0.1	0.033	1.000	1.033
							PWR			**0.067**	**3.125**	**3.191**
							BWR			**0.100**	**3.625**	**3.724**
7	Remove transport vehicle from loading area.											
7.1	Move vehicle out of loading area to external parking area.	5	YD	1	0	29	0	N/A	0	0.000	0.167	0.167
										0.000	**0.167**	**0.167**

Table B.1 (continued)

Step No.	Description	Area dose rate (mrem h^{-1})	Staff			Activity Time (min)		Work distance from cask (ft)	Dose rate for cask work (mrem h^{-1})	Dose (person-mrem)		
			Type*	Total number in area	Number doing cask work	In area	Near cask			Cask work	Area	Total
8	Prepare cask for placement in loading pit; remove outer lid; loosen inner lid.											
8.1	Remove outer lid bolts and store.	2	M-C	2	2	10	10	3	0.2	0.067	0.667	0.733
		2	OP	1	1	10	10	5	0.1	0.017	0.333	0.350
8.2	Remove outer lid and store.	2	CO	1	0	10	10	10	0	0.000	0.333	0.333
		2	M-C	1	1	10	10	3	0.2	0.033	0.333	0.367
		2	OP	1	1	10	10	6	0.1	0.017	0.333	0.350
8.3	Seal bolt and pin holes.	2	M-C	1	1	10	10	3	0.2	0.033	0.333	0.367
		2	OP	1	1	10	10	3	0.2	0.033	0.333	0.367
8.4	Radiation survey of inner lid.	2	RM	1	1	5	5	3	0.2	0.017	0.167	0.183
8.5	Measure cask cavity pressure.	2	OP	1	1	10	10	3	0.2	0.033	0.333	0.367
8.6	Sample cask cavity gases.	2	OP	1	1	10	10	3	0.2	0.033	0.333	0.367
8.7	Vent cask.	2	OP	1	1	5	5	3	0.2	0.017	0.167	0.183
8.8	Fill cask with water.	2	OP	1	1	30	5	3	0.2	0.017	1.000	1.017

Table B.1 (continued)

Step No.	Description	Area dose rate (mrem h^{-1})	Staff			Activity Time (min)		Work distance from cask (ft)	Dose rate for cask work (mrem h^{-1})	Dose (person-mrem)		
			Type*	Total number in area	Number doing cask work	In area	Near cask			Cask work	Area	Total
8.9	Sample water in cask.	2	OP	1	0	10	0	20	0	0.000	0.333	0.333
	Loosen inner lid bolts.	2	M-C	2	2	20	20	3	0.2	0.133	1.333	1.467
		2	RM	1	1	20	20	3	0.2	0.067	0.667	0.733
		2	OP	1	1	20	20	5	0.1	0.033	0.667	0.700
8.11	Remove and store inner lid bolts.	2	M-C	2	2	10	10	3	0.2	0.067	0.667	0.733
		2	OP	1	1	10	10	5	0.1	0.017	0.333	0.350
8.12	Apply lubricant in trunnions.	2	M-C	1	1	5	5	3	0.2	0.017	0.167	0.183
8.13	Remove work platform.	1	CO	1	0	10	10	20	0	0.000	0.167	0.167
		1	OP	2	2	10	10	8	0.1	0.033	0.333	0.367
										0.683	**9.333**	**10.017**
9	Move cask to loading pit; remove inner lid bolts; place cask in loading pit.											
9.1	Bring yoke to cask and attach.	2	CO	1	0	5	0	20	0	0.000	0.167	0.167
		2	OP	1	1	5	5	3	0.2	0.017	0.167	0.183
9.2	Lift cask, move to loading pit, lower into water, pause for bolt removal, and lower to bottom of pit.	2	CO	1	0	30	0	20	0	0.000	1.000	1.000
		4	M-C	1	1	10	10	3	0.2	0.033	0.667	0.700
		4	RM	1	1	10	10	3	0.2	0.033	0.667	0.700
		3	OP	1	1	30	20	3	0.2	0.067	1.500	1.567
										0.150	**4.167**	**4.317**

Table B.1 (continued)

Step No.	Description	Area dose rate (mrem h^{-1})	Staff: Type*	Staff: Total number in area	Staff: Number doing cask work	Activity Time (min): In area	Activity Time (min): Near cask	Work distance from cask (ft)	Dose rate for cask work (mrem h^{-1})	Dose (person-mrem): Cask work	Dose (person-mrem): Area	Dose (person-mrem): Total
10	Prepare cask for loading; remove inner lid; inspect and clean inner cavity.											
10.1	Remove yoke, cask lid, and fuel spacers; store lid and spacers on service pad.	2	CO	1	0	20	0	20	0	0.000	0.667	0.667
		3	OP	1	1	20	10	3	0.2	0.033	1.000	1.033
		3	RM	1	1	10	10	3	0.2	0.033	0.500	0.533
10.2	Flush cask if needed.	4	OP	1	0	10	0	20	0	0.000	0.667	0.667
10.3	Inspect cask interior.	4	OP	1	0	10	0	20	0	0.000	0.667	0.667
		4	QC	1	0	10	0	20	0	0.000	0.667	0.667
10.4	Check lid seals and replace as necessary.	2	M-C	2	2	20	20	3	0.2	0.133	1.333	1.467
		2	OP	1	1	20	20	3	0.2	0.067	0.667	0.733
		2	QC	1	1	20	10	3	0.2	0.033	0.667	0.700
										0.300	6.833	7.133
11	Move spent fuel assemblies from storage pool to the loading pit. Place spent fuel assemblies in cask.											

Table B.1 (continued)

Step No.	Description	Area dose rate (mrem h^{-1})	Staff Type*	Staff Total number in area	Staff Number doing cask work	Activity Time (min) In area	Activity Time (min) Near cask	Work distance from cask (ft)	Dose rate for cask work (mrem h^{-1})	Dose (person-mrem) Cask work	Dose (person-mrem) Area	Dose (person-mrem) Total
11.1	Identify spent fuel assemblies (SFA) to be loaded; perform accountability.	4	OP	2	0	30	0	Not Applicable	0	0.000	4.000	4.000
		4	OP	2	0	75	0	Not Applicable	0	0.000	10.000	10.000
		4	QC	1	0	30	0	Not Applicable	0	0.000	2.000	2.000
		4	QC	1	0	75	0	Not Applicable	0	0.000	5.000	5.000
11.2	Move SFA to loading area and place in cask.	4	OP	2	0	30	0	20	0	0.000	4.000	4.000
		4	OP	2	0	75	0	20	0	0.000	10.000	10.000
										0.000	**10.000**	**10.000**
12	Install fuel spacers and inner lid on the shipping cask.									**0.000**	**25.000**	**25.000**
12.1	Pick up yoke and lid.	4	CO	1	0	5	0	20	0	0.000	0.333	0.333
		4	OP	1	1	5	5	3	0.2	0.017	0.333	0.350
12.2	Lower lid into position and install yoke.	4	CO	1	0	15	0	20	0	0.000	1.000	1.000
		4	OP	1	0	15	0	20	0	0.000	1.000	1.000
		4	QC	1	0	15	0	20	0	0.000	1.000	1.000
										0.017	**3.667**	**3.683**
13	Lift cask from loading pit; install four inner lid bolts; place cask on service pad.											

Table B.1 (continued)

Step No.	Description	Area dose rate (mrem h^{-1})	Staff			Activity Time (min)		Work distance from cask (ft)	Dose rate for cask work (mrem h^{-1})	Dose (person-mrem)		
			Type*	Total number in area	Number doing cask work	In area	Near cask			Cask work	Area	Total
13.1	Lift cask to water surface.	4	CO	1	0	10	10	20	0	0.000	0.667	0.667
		4	RM	1	1	10	5	5	2	0.167	0.667	0.833
		4	OP	1	1	10	2	10	0	0.000	0.667	0.667
13.2	Install four lid bolts.	4	M-C	1	1	5	5	3	10	0.833	0.333	1.167
		4	OP	1	1	5	5	5	2	0.167	0.333	0.500
13.3	Lift cask out of water and allow to drip dry (wash cask during lift).	4	CO	1	1	15	10	20	0	0.000	1.000	1.000
		4	OP	1	1	15	10	5	0	0.000	1.000	1.000
		4	RM	1	1	15	10	5	0	0.000	1.000	1.000
13.4	Move cask to service pad.	2	CO	1	1	10	10	20	0	0.000	0.333	0.333
		2	OP	1	1	10	10	10	0	0.000	0.333	0.333
13.5	Place cask on service pad.	2	CO	1	1	5	5	20	0	0.000	0.167	0.167
		2	OP	1	1	5	5	10	0	0.000	0.167	0.167
13.6	Disengage yoke and install work platform.	2	CO	1	1	10	10	20	0	0.000	0.333	0.333
		2	OP	2	2	10	10	10	0	0.000	0.667	0.667
										1.167	**7.667**	**8.833**

Table B.1 (continued)

Step No.	Description	Area dose rate (mrem h^{-1})	Staff			Activity Time (min)		Work distance from cask (ft)	Dose rate for cask work (mrem h^{-1})	Dose (person-mrem)		
			Type*	Total number in area	Number doing cask work	In area	Near cask			Cask work	Area	Total
14	Decontaminate cask exterior.											
14.1	Survey cask surface.	2	RM	1	1	20	15	5	1	0.250	0.667	0.917
14.2	Decontaminate cask.	2	OP	2	2	25	45	3	2	3.000	1.667	4.667
										3.250	2.333	5.583
15	Prepare cask for shipment: install lids; flush, drain, and dry cask; seal cask.											
15.1	Install inner lid bolts.	2	M-C	3	3	15	15	3	20	15.000	1.500	16.500
		2	OP	1	1	15	10	3	3	0.500	0.500	1.000
		2	QC	1	1	15	10	3	3	0.500	0.500	1.000
15.2	Decontaminate area between lids.	2	OP	2	2	5	5	3	20	3.333	0.333	3.667
15.3	Install instrumentation.	2	OP	2	1	30	10	3	3	0.500	2.000	2.500
15.4	Flush and drain cask.	2	OP	2	1	30	3	1	200	10.000	2.000	12.000
15.5	Dry cask cavity.	2	OP	2	1	10	3	3	200	10.000	0.667	10.667
				0	0	60	0	NA	0	0.000	0.000	0.000
				0	0							

Table B.1 (continued)

Step No.	Description	Area dose rate (mrem h^{-1})	Staff			Activity Time (min)		Work distance from cask (ft)	Dose rate for cask work (mrem h^{-1})	Dose (person-mrem)		
			Type*	Total number in area	Number doing cask work	In area	Near cask			Cask work	Area	Total
15.6	Leak test cask inner lid seal.	2	OP	2	1	10	3	3	200	10.000	0.667	10.667
		2	QC	1	1	10	10	5	10	1.667	0.333	2.000
15.7	Fill cask with inert gas.	2	OP	1	1	10	5	30	1	0.083	0.333	0.417
15.8	Plug and lockwire cavity openings.	2	M-C	2	2	5	5	3	200	33.333	0.333	33.667
		2	OP	1	1	5	5	5	30	2.500	0.167	2.667
15.9	Inspect outer lid, gaskets, etc.	2	M-C	2	2	30	30	30	1	1.000	2.000	3.000
15.10	Install outer lid.	2	CO	1	1	10	10	20	2	0.333	0.333	0.667
		2	M-C	2	2	20	10	3	30	10.000	1.333	11.333
		2	OP	1	1	20	15	5	10	2.500	0.667	3.167
15.11	Install water-absorbent material around cask lid.	2	OP	2	2	5	5	3	10	1.667	0.333	2.000
										102.917	**14.000**	**116.917**
16	Move cask to vehicle loading area.											
16.1	Move yoke to cask.	2	CO	1	1	10	10	20	2	0.333	0.333	0.667
16.2	Remove work platform.	2	CO	1	1	10	10	20	2	0.333	0.333	0.667
		2	OP	2	2	10	10	5	10	3.333	0.667	4.000

Table B.1 (continued)

Step No.	Description	Area dose rate (mrem h^{-1})	Staff			Activity Time (min)		Work distance from cask (ft)	Dose rate for cask work (mrem h^{-1})	Dose (person-mrem)		
			Type*	Total number in area	Number doing cask work	In area	Near cask			Cask work	Area	Total
16.3	Attach yoke to cask.	2	CO	1	1	10	10	20	2	0.333	0.333	0.667
		2	OP	1	1	10	2	10	8	0.267	0.333	0.600
16.4	Lift cask and travel to loading area.	2	CO	1	1	15	15	30	1	0.250	0.500	0.750
		2	OP	1	1	15	5	10	8	0.667	0.500	1.167
										5.517	3.000	8.517
17	Move transport vehicle to loading area.											
17.1	Move vehicle into loading area.	0.5	YD	1	0	20	0	50	0	0.000	0.167	0.167
										0.000	0.167	0.167
18	Place the cask on the transport vehicle.											
18.1	Lower cask into position on vehicle.	0.5	CO	1	1	15	15	20	2	0.500	0.125	0.625
		0.5	OP	1	1	10	5	3	20	1.667	0.083	1.750
18.2	BWR extra yoke adjustment.	0.5	CO	1	1	30	30	20	2	1.000	0.250	1.250
		0.5	OP	1	1	30	30	10	8	4.000	0.250	4.250
18.3	Remove absorbent material from cask top.	0.5	OP	1	1	5	5	3	10	0.833	0.042	0.875

Table B.1 (continued)

Step No.	Description	Area dose rate (mrem h^{-1})	Staff			Activity Time (min)		Work distance from cask (ft)	Dose rate for cask work (mrem h^{-1})	Dose (person-mrem)		
			Type*	Total number in area	Number doing cask work	In area	Near cask			Cask work	Area	Total
18.4	Disconnect, remove yoke, and store.	0.5	CO	1	1	10	5	20	2	0.167	0.083	0.250
		0.5	OP	1	1	10	2	3	20	0.667	0.083	0.750
							PWR			**3.833**	**0.417**	**4.250**
							BWR			**8.833**	**0.917**	**9.750**
19	Contamination survey; decontaminate cask exterior.											
19.1	Radiation survey of cask and vehicle.	0.5	RM	1	1	40	30	5	15	7.500	0.333	7.833
		0.5	OP	1	1	25	25	10	8	3.333	0.208	3.542
19.2	Spot decontamination.	0.5	OP	1	1	10	10	3	30	5.000	0.083	5.083
										15.833	**0.625**	**16.458**
20	Prepare loaded vehicle for shipment—install cask tiedowns, impact limiters, and personnel barrier.											
20.1	Pick up and store yokes and hooks.	0.5	CO	1	0	30	20	20	2	0.000	0.250	0.250
		0.5	OP	1	1	30	20	20	2	0.667	0.250	0.917
20.2	Install cask tiedowns.	0.5	M-C	2	2	30	20	3	30	20.000	0.500	20.500
		0.5	OP	1	1	30	20	5	5	1.667	0.250	1.917
20.3	Install impact limiters.	0.5	M-C	2	2	30	20	3	20	13.333	0.500	13.833
		0.5	CO	1	1	20	20	20	2	0.667	0.167	0.833
		0.5	OP	1	1	30	30	5	5	2.500	0.250	2.750

Table B.1 (continued)

Step No.	Description	Area dose rate (mrem h^{-1})	Staff Type*	Staff Total number in area	Staff Number doing cask work	Activity Time (min) In area	Activity Time (min) Near cask	Work distance from cask (ft)	Dose rate for cask work (mrem h^{-1})	Dose (person-mrem) Cask work	Dose (person-mrem) Area	Dose (person-mrem) Total
20.4	Install monitoring equipment.	0.5	M-C	2	2	30	5	3	10	1.667	0.500	2.167
		0.5	OP	1	1	30	5	5	5	0.417	0.250	0.667
20.5	Install personnel barrier and security seals.	0.5	M-C	2	2	10	10	3	20	6.667	0.167	6.833
		0.5	OP	1	1	10	10	5	5	0.833	0.083	0.917
										48.417	**3.167**	**51.583**
21	Final inspection and contamination survey—monitor; [illegible] inspect; document.											
21.1	Radiation survey and recording.	0.5	RM	1	1	30	10	10	5	0.833	0.250	1.083
		0.5	QC	1	1	10	10	10	5	0.833	0.083	0.917
21.2	General inspection of cask and vehicle.	0.5	OP	1	1	30	30	5	10	5.000	0.250	5.250
		0.5	M-C	1	1	30	30	5	10	5.000	0.250	5.250
		0.5	QC	1	1	20	20	10	5	1.667	0.167	1.833
										13.333	**1.000**	**14.333**
22	Move transport vehicle out of security area.											
22.1	Move vehicle to parking area near guardhouse.	0.5	YD	1	1	10	10	20	2	0.333	0.083	0.417
										0.333	**0.083**	**0.417**

Table B.1 (continued)

Step No.	Description	Area dose rate (mrem h^{-1})	Staff Type*	Staff Total number in area	Staff Number doing cask work	Activity Time (min) In area	Activity Time (min) Near cask	Work distance from cask (ft)	Dose rate for cask work (mrem h^{-1})	Dose (person-mrem) Cask work	Dose (person-mrem) Area	Dose (person-mrem) Total
23	Release cask and transport vehicle to carrier for Office of Civilian Radioactive Waste Management (OCRWM) acceptance and transportation.											
23.1	Disconnect transport vehicle from utility drive unit.	0	YD	1	1	5	5	10	2	0.167	0.000	0.167
23.2	Connect transport vehicle to carrier's drive unit.	0	TD	2	1	10	5	10	2	0.167	0.000	0.167
23.3	Security observation.	0	SG	1	1	15	15	30	1	0.250	0.000	0.250
23.4	Complete certification and release cask to carrier.	0	QC	1	1	15	15	30	1	0.250	0.000	0.250
		0	YD	1	1	15	15	30	1	0.250	0.000	0.250
		0	OP	1	1	15	15	30	1	0.250	0.000	0.250
23.5	Notify appropriate organizations of the shipment departure.	0	S	1	0	30	0	0	0	0.000	0.000	0.000
										1.333	0.000	1.333

Table B.1 (continued)

Step No.	Description	Area dose rate (mrem h^{-1})	Staff: Type*	Staff: Total number in area	Staff: Number doing cask work	Activity Time (min): In area	Activity Time (min): Near cask	Work distance from cask (ft)	Dose rate for cask work (mrem h^{-1})	Dose (person-mrem): Cask work	Dose (person-mrem): Area	Dose (person-mrem): Total
								PWR cask	Total Dose =	197.767	72.792	270.557
								BWR cask	Total Dose =	202.800	88.792	291.590

Worker Group	Dose (person-rem)
TD	0
SG	0
RM	7.4
QC	30.4
YD	1.184
CO	37.22
S	1.333
OP	274
M-C	21.26
Total	372.8

* CO = Crane Operator; OP = Reactor Site Operator; RM = Radiation Monitor; QC = Inspector; TD = Offsite Truck Driver/Rail Crew; YD = Site Yard Driver; SG = Security Guard; M-C = Maintenance Craft; S = Supervisor

APPENDIX C

MODELING PUBLIC EXPOSURE TO RESUSPENDED SURFACE CONTAMINATION DURING MOVEMENT

APPENDIX C—MODELING PUBLIC EXPOSURE TO RESUSPENDED SURFACE CONTAMINATION DURING MOVEMENT

C.1 SUMMARY OF MODELING APPROACH

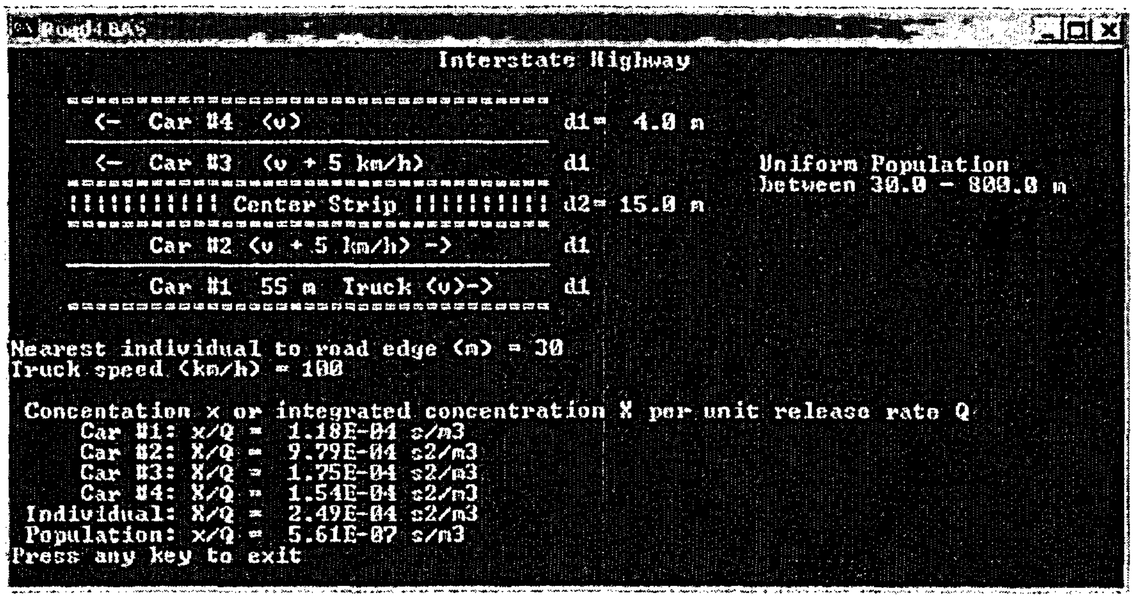
During movement, removable contamination resuspended from the package surface will disperse into the environment. The airborne activity concentration resulting from this resuspension depends primarily on the rate of release, Q, and the speed of the transport vehicle, v. The activity concentration can be estimated using the Gaussian plume model. The activity concentration distribution per unit release rate at location (x, y) from a ground-level point source is given by

$$\chi / Q(x, y) = \frac{1}{\pi v \sigma_y \sigma_z} e^{-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2} \qquad \text{(C-1)}$$

where σ_y and σ_z denote the variance of the Gaussian distribution in the y (crosswind) and z (vertical) direction, respectively.[C.1] The values of σ_y and σ_z are functions of the downwind distance x and depend on the "stability" of the atmosphere. The calculations performed here assume a stability class C and utilize the so-called Pasquill-Gifford curves for the variances as a function of downwind distance.[C.2]

Consider a divided limited-access roadway as shown in Figure C.1.

Activity released from the truck will initially be diluted by the turbulence in the wake of the truck. The point source formulation of Eq. (C-1) can be corrected by considering a virtual source displaced by a distance x_0 that corresponds to the dilution due to mixing in the truck's wake.[C.1] The activity concentration in the wake per unit release is given by the reciprocal of the product of the cross-sectional area of the truck and its speed. The practice of constraining the wake dilution, in this case to one-third the theoretical value, is followed here.[C.3]



```
                                Interstate Highway

     ======================================
       <-  Car #4  (v)                       d1=  4.0 m
     --------------------------------------
       <-  Car #3  (v + 5 km/h)              d1               Uniform Population
     ======================================                   between 30.0 - 800.0 m
     !!!!!!!!!!! Center Strip !!!!!!!!!!!    d2= 15.0 m
     ======================================
           Car #2 (v + 5 km/h) ->            d1
     --------------------------------------
           Car #1  55 m  Truck (v)->         d1
     ======================================

Nearest individual to road edge (m) = 30
Truck speed (km/h) = 100

 Concentation x or integrated concentration X per unit release rate Q
     Car #1: x/Q =  1.18E-04 s/m3
     Car #2: X/Q =  9.79E-04 s2/m3
     Car #3: X/Q =  1.75E-04 s2/m3
     Car #4: X/Q =  1.54E-04 s2/m3
 Individual: X/Q =  2.49E-04 s2/m3
 Population: x/Q =  5.61E-07 s/m3
Press any key to exit
```

Figure C.1 Schematic of a divided limited-access highway with the truck (lower lane) proceeding at speed "v." The screen shows the calculation of the concentration or time-integrated concentration per unit release for various individuals and an assumed uniform population adjacent to the roadway. See the text for further details.

Consider an individual located at a distance *d* from the edge of the road with lanes of width *dl*. The closest individual is at a distance *d + 0.5 dl* from the centerline of the truck. The integrated airborne concentration per unit release rate Ψ / Q at the location of the individual is

$$\Psi / Q = \int \chi / Q(x_0 + vt, d + 0.5\, d1)\, dt \tag{C-2}$$

where

v the speed of the truck.

The effective dose E to that individual resulting from inhalation of the dispersing activity is

$$E = Q \frac{\Psi}{Q} \dot{V} e \tag{C-3}$$

where

Q = the activity release rate (Bq s^{-1}),

Ψ / Q = the integrated airborne concentration per unit release rate (s^2 m^{-3}),

$\dot{V}$ = the individual's air intake rate (m^3 s^{-1}), and

e = the effective dose coefficient (Sv Bq^{-1}).

The airborne activity concentration in the car following the truck is given by Eq. (C-1), with x being the sum of the displacement of the virtual source x_0 and the separation distance of the vehicles (55 m in Figure C.1). The effective dose E to an individual in the car resulting from inhalation is

$$E = Q \frac{\chi}{Q} \dot{V}\, e\, t \tag{C-4}$$

where

χ / Q = the airborne concentration per unit release rate (s m^{-3}), and

t = the time the car follows the truck (s).

All other terms are defined above. Similar equations can be written for individuals in cars approaching or passing the truck.

Consider a population of uniform density located between y_1 and y_2 from the edge of the roadway. The airborne concentration averaged over the population is given by

$$\bar{x}/Q = 0.5\left[\int dt \int_{y_1}^{y_2} dy\, \chi/Q(x_0+vt, 0.5\, d1+y) + \int dt \int_{y_1}^{y_2} dy\, \chi/Q(x_0+vt, 3.5\, d1+d2+y)\right] \tag{C-5}$$

where the first term corresponds to the population adjacent to the lane containing the truck, the second term represents that on the opposite side of the highway, and $d2$ is the width of the center strip (see Figure C.1).

The collective dose S (in person-sieverts) due to inhalation is

$$S = \rho\, Q \frac{\bar{x}}{Q} \dot{V}\, (y_2 - y_1)\, v\, e\, t \tag{C-6}$$

where

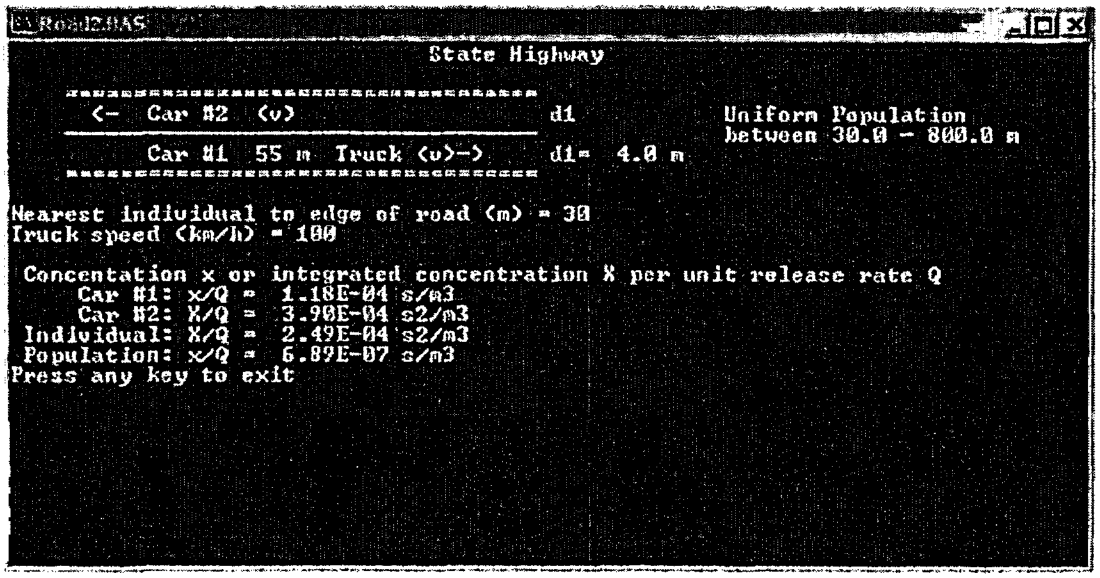
ρ = the population density (# m^{-2}),

y_2 and y_1 = the upper and lower bound distances (m) of the population from the roadway,

v = the speed of the truck (m s^{-1}), and

t = the total travel time (s) in the populated region.

The dispersion data for a two-lane roadway (state highway) are shown in Figure C.2.



```
                                  State Highway

   ==============================================
     <-  Car #2  (v)                             d1                Uniform Population
   ______________________________________________                  between 30.0 - 800.0 m
         Car #1  55 m  Truck (v)->               d1=  4.0 m
   ==============================================

Nearest individual to edge of road (m) = 30
Truck speed (km/h) = 100

 Concentation x or integrated concentration X per unit release rate Q
      Car #1: x/Q =  1.18E-04 s/m3
      Car #2: X/Q =  3.90E-04 s2/m3
 Individual: X/Q =  2.49E-04 s2/m3
 Population: x/Q =  6.89E-07 s/m3
Press any key to exit
```

Figure C.2 Schematic of a two-lane highway with the truck (lower lane) proceeding at a speed "v." The screen shows the calculation of the concentration or time-integrated concentration per unit release for various individuals and an assumed uniform population adjacent to the roadway.

C.2 ILLUSTRATIVE EXAMPLES

A few illustrative sample calculations are presented based on Figure C.1 and the dispersion parameters in the figure. Assume that the release rate of ^{137}Cs from the truck is 1 Bq s^{-1}. The committed effective dose coefficient for inhalation of ^{137}Cs by an adult is 4.6×10^{-9} Sv Bq^{-1} (Ref. C.4), and the air intake rate is 22 m^3 day^{-1} or 2.55×10^{-4} m^3 s^{-1} (Ref. C.5). The dispersion parameters are shown in Figure C.1.

Car #1. Assuming that the car follows the truck for a period of 3 h (1.08×10^4 s), then the effective dose [per Eq. (C-4)] is

$$
\begin{aligned}
E &= Q\frac{\chi}{Q}\dot{V}\,e\,t \\
&= \left(1.0\,Bq\,s^{-1}\right)\left(1.18\times10^{-4}\,s\,m^{-3}\right)\left(2.55\times10^{-4}\,m^{3}s^{-1}\right)\left(4.6\times10^{-9}\,Sv\,Bq^{-1}\right)\left(1.08\times10^{4}\,s\right) \\
&= 1.5\times10^{-12}\,Sv.
\end{aligned}
$$

Car #2. The dose to an individual in car #2 [per Eq. (C-3)] is

$$
\begin{aligned}
E &= Q\frac{\Psi}{Q}\dot{V}\,e \\
&= \left(1.0\,Bq\,s^{-1}\right)\left(9.79\times10^{-4}\,s^{2}\,m^{-3}\right)\left(2.55\times10^{-4}\,m^{3}s^{-1}\right)\left(4.6\times10^{-9}\,Sv\,Bq^{-1}\right) \\
&= 1.2\,10^{-15}\,Sv\,.
\end{aligned}
$$

Collective dose: Assuming that a strip of land (30 to 800 m wide) adjacent to a highway has a population density of 80 km^{-2} (8.0×10^{-5} m^{-2}) and that the extent of this strip is such that it takes the truck 4 days (3.46×10^{5} s) to traverse, then the collective dose [per Eq. (C-6)] is

$$
\begin{aligned}
S &= \rho\,Q\frac{\bar{\chi}}{Q}\dot{V}\,(y_2 - y_1)\,v\,e\,t \\
&= (8.0\,10^{-5}m^{-2})\,(1\,Bq\,s^{-1})\,(5.61\,10^{-7}\,s\,m^{-3})\,(2.55\,10^{-4}\,m^{3}\,s^{-1})\,(770\,m) \\
&\quad (27.8\,m\,s^{-1})\,(4.6\,10^{-9}\,Sv\,Bq^{-1})\,(3.46\,10^{5}\,s) \\
&= 3.9\,10^{-13}\;person - Sv\,.
\end{aligned}
$$

C.3 REFERENCES

C.1. D. B. Turner, *Workbook of Atmospheric Dispersion Estimates*, Publication 999-AP-26, Public Health Service, Cincinnati, Ohio, 1967.

C.2. F. A. Gifford, Jr., "Use of Routine Meteorological Observations for Estimating Atmospheric Dispersion," *Nucl. Saf.* 2(4), 44–57 (1961).

C.3. W. G. Snell and R. W. Juback, *Technical Basis for Regulatory Guide 1.145*, NUREG/CR-2260, U.S. Nuclear Regulatory Commission, Washington, D.C., 1981.

C.4. International Commission on Radiological Protection, *Age-Dependent Doses to Members of the Public from Intakes of Radionuclides, Part 4*, ICRP Publication 71, Pergamon Press, Oxford, U.K., 1995.

C.5. International Commission on Radiological Protection, *Human Respiratory Tract Model for Radiological Protection*, ICRP Publication 66, Pergamon Press, Oxford, U.K., 1994.

APPENDIX D

COLLECTIVE INTERNAL DOSE TO PASSENGERS IN VEHICLES DURING TRANSPORT

APPENDIX D

COLLECTIVE INTERNAL DOSE TO PASSENGERS IN VEHICLES DURING TRANSPORT

The calculation of the collective internal dose to the public in vehicles due to inhalation of resuspended surface radioactivity from fuel casks transported by highway uses the algorithm discussed in Appendix C, which calculates the time-integrated value of χ/Q for vehicles following, passing, and meeting the shipment on a multilane highway (Figure C.1) or other highway (Figure C.2).

The collective internal dose for vehicles following (traffic lane #1) the shipment is estimated by using the summation of χ/Q (s m^{-3}) for the first 100 vehicles behind the transport, corresponding to a distance of 5.5 km for a following distance of 55 m between each vehicle. The value of χ/Q falls rapidly with trailing distance, as shown in Figure D.1, so that the exclusion of vehicles beyond 5.5 km does not affect the estimate appreciably. The resulting summation gives the following value:

$$\sum_{i=1}^{100} \left(\chi/Q\right)_i = 3.31 \times 10^{-4}\,\mathrm{s\,m}^{-3}.$$

Using this value with the other factors given in Sect. 5.1.4.1 gives a collective dose of 4.9×10^{13} person-Sv. The total affected population is 100, assuming there is one passenger per vehicle.

Collective internal doses to passengers in vehicles passing (traffic lane #2) or meeting (traffic lane #3 and lane #4) shipments of spent fuel casks are estimated as the product of the number of affected passengers and the integrated values for χ/Q provided in Appendix C. The number of affected passengers is related to the number of vehicles going past the transport, given as the product of the total time *en route* and the speed of vehicles in the other lanes relative to that of the shipment, divided by the following distance of the vehicles going past the transport. The total time *en route* is the ratio of total distance to transport speed on a multilane roadway for lanes #2 and #3. The total time for lane #4 takes into account both distance on multilane roadways and on other roads (state highways). Estimates of the collective doses using the same factors as in Sect. 5.1.4.2 (lane #2) and Sect. 5.1.4.3 (lane #3 and lane #4, multilane highway, and lane #4, other highway) are shown in Table D.1.

Table D.1 Collective dose for on-link exposures

Lane	Persons affected	E (person-Sv)
2	3,968	3.96×10^{-13}
3	162,695	2.90×10^{-12}
4	165,927	2.78×10^{-12}

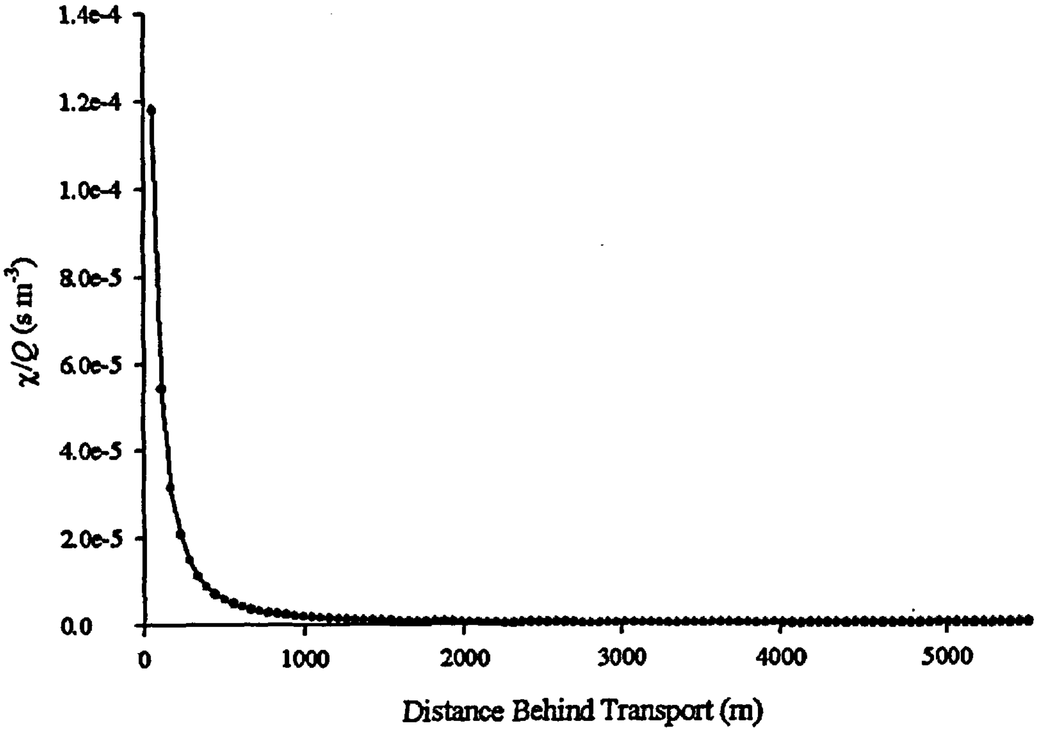


Figure D.1 Values of χ/Q for vehicles following a spent fuel cask transport

APPENDIX E

INHALATION POPULATION DOSE FROM CONTAMINATION AT STOPS

APPENDIX E

INHALATION POPULATION DOSE FROM CONTAMINATION AT STOPS

E.1 INTRODUCTION

The committed effective dose equivalent (CEDE) from inhalation is given[E.1] by

$$E = C_d \, f \, T \, B_{inh} \, R_{10} \;,$$

where

C_d = the airborne activity concentration (Bq m^{-3}),

f = the respirable fraction,

T = the exposure time (h),

B_{inh} = the respiration rate (m^3 h^{-1}), and

R_{10} = the inhalation dose coefficient (Sv Bq^{-1}).

The CEDE due to resuspended activity from a contaminated shipping cask during a stop (such as for food and fuel) is estimated by assuming that the exposed population is uniformly distributed in concentric rings around the transport in the direction of the wind. There are two such rings in our analysis—one adjacent to the shipment and an adjoining one at greater distances. Therefore, the total CEDE is the sum of the proximal dose E_p (from intakes up to 100 m from the cask) and the distal dose E_d (for intakes >100 m from the package):

$$E = E_p + E_d \; . \tag{E-1}$$

(Gaussian plume diffusion models may be used, if desired, in estimating airborne concentrations and doses at distances >100 m from the source.) All factors used in calculating CEDE for a population are the same in the two rings, except for the airborne activity concentration, which diminishes as the contamination diffuses into a larger volume downwind from the source. The number of exposed individuals also changes with distance from the source (because of lateral and vertical dispersion of the contamination) when calculating population dose.

E.2 PROXIMAL DOSE

The proximal dose to the population is calculated using an average airborne activity concentration for the exposed population from a minimum distance a to 100 m from the source. (Minimum distances from 5 to 75 m are defined by Ref. E.1 for populations exposed during different stop scenarios.) The average airborne concentration is defined as

$$\overline{C_d} = \frac{\int_{r=a}^{100} C_d \, dr}{\int_{r=a}^{100} dr} . \qquad \text{(E-2)}$$

When the transport is outside, the airborne activity concentration C_d (Bq m^{-3}) is a function of the distance r downwind from the source and is given by

$$C_d = \frac{R A A_c C}{v Q} , \qquad \text{(E-3)}$$

where

$R =$ the resuspension rate (10^{-4} h^{-1}),

$A =$ the surface area of the cask (130 m^2),

$A_c =$ the non-fixed areal contamination density (Bq m^{-2}),

$C =$ the containment factor ($C = 0.01$ for covered casks and $C = 1$ for uncovered), and

$v =$ the average wind speed (2 m s^{-1}).

Parameter values, where given, are from Ref. E.1.

The variable Q represents the effective cross-sectional area of the plume as a function of distance from the cask:

$$Q = 10 f_r A , \qquad \text{(E-4)}$$

where f_r takes on the values below[E.1] for specific values of r:

r (m)	5	10	30	50
f_r	1.5	2	6	10

To determine values of f_r for 5 to 100 m from the cask for the proximal dose, f_r can be modeled using the information above by noting that

$$f_r = (0.1\, r + 1), \text{ for } 5 \text{ m} \le r < 10 \text{ m},$$

and

$$f_r = 0.2\, r, \text{ for } 10 \text{ m} \le r \le 50 \text{ m}.$$

Extrapolating f_r from 50 to 100 m,

$$f_r = 0.2\ r, \quad \text{for } 50\ \text{m} < r \leq 100\ \text{m}.$$

The resulting relation of f_r to r over the whole range $5\ \text{m} \leq r < 100\ \text{m}$ is shown graphically in Figure E.1.

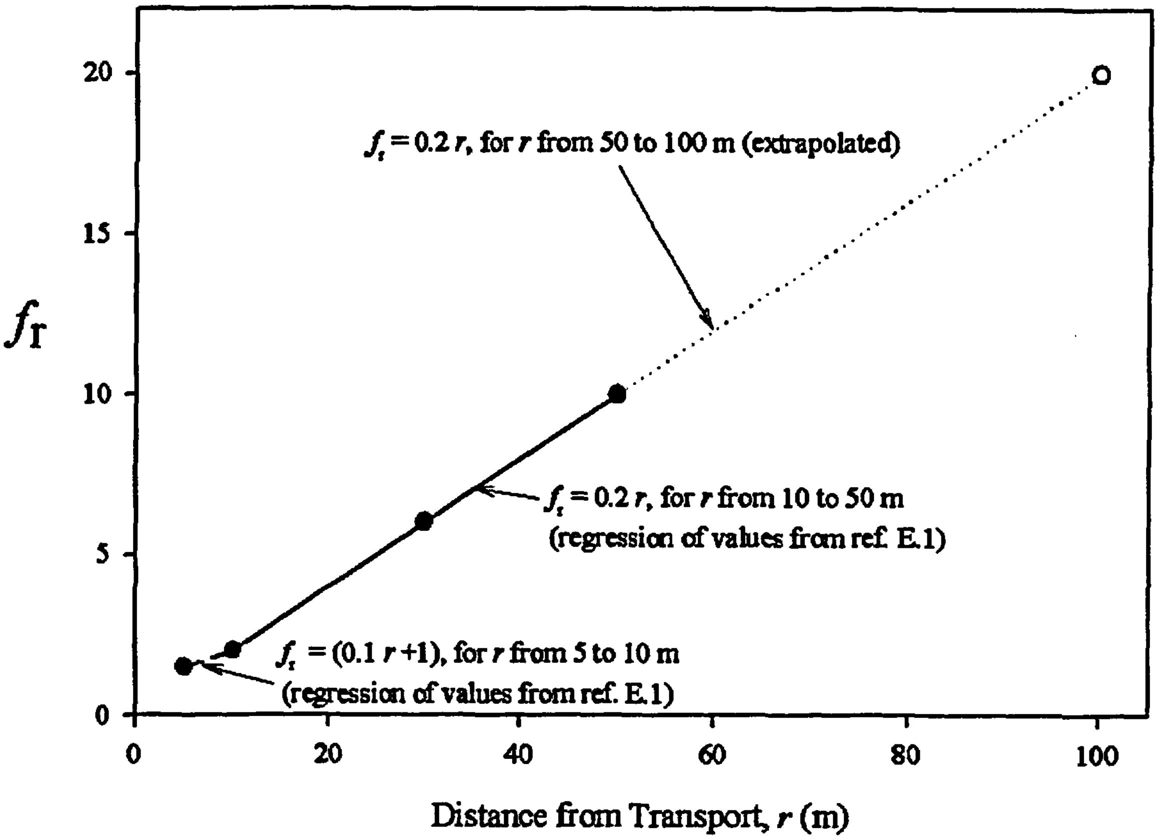


Figure E.1 Values of f_r for distances of 5 to 100 m from the transport

E.2.1 Dose to the Maximum Exposed Individual

The maximum exposed individual is located in the proximal region for all scenarios proposed by the International Atomic Energy Agency (IAEA) Coordinated Research Project (CRP) modeling group for stops during highway or rail transport.[E1] The activity concentration C_d at a specific distance r, and not the average concentration, is used in determining dose to the maximally exposed individual. The dose to the maximum exposed individual is given by

$$E_{\text{max}} = C_d\ f\ T\ B_{\text{inh}}\ R_{10} = \frac{R\ A\ A_c\ C}{v Q} f\ T\ B_{\text{inh}}\ R_{10} = \frac{R\ A_c\ C}{10 v\ f_r} f\ T\ B_{\text{inh}}\ R_{10}. \qquad \text{(E-5)}$$

E.2.2 Population Dose

The estimates of doses from contamination at stops assume that the downwind direction is toward populations on the same side of the road as that on which the stops occur. An average airborne concentration for evaluating doses to a population from a distance a, 5 to 100 m from the transport, is calculated using

$$\overline{C}_d = \frac{\int_{r=a}^{100} C_d\,dr}{\int_{r=a}^{100} dr} = \frac{R\,A\,A_C\,C}{10\,A\,v}\,\frac{\int_{r=a}^{100} \frac{dr}{f_r}}{\int_{r=a}^{100} dr} = \frac{R\,A_C\,C}{10v}\,\frac{\int_{r=a}^{100} \frac{dr}{f_r}}{\int_{r=a}^{100} dr}\ . \qquad \text{(E-6)}$$

To account for the case where the closest exposed individual is less than 10 m from the transport (i.e., for 5 m ≤ a < 10 m (since $a \geq 5$), the expression for average airborne concentration becomes

$$\overline{C}_{d,5\text{-}100} = \frac{R\,A_C\,C}{10v}\,\frac{\left[\int_{r=a}^{10} \frac{dr}{1+0.1r} + \int_{r=10}^{100} \frac{dr}{0.2r}\right]}{\int_{r=a}^{100} dr} = \frac{R\,A_C\,C}{10v}\,\frac{10\ln(1+0.1r)\Big|_{r=a}^{10} + 5\ln r\Big|_{r=10}^{100}}{\int_{r=a}^{100} dr}$$

$$= \frac{R\,A_C\,C}{10v}\,\frac{10\ln\left(\frac{2}{1+0.1a}\right) + 11.5}{100-a}\ . \qquad \text{(E-7)}$$

If, on the other hand, the closest exposed individual is 10 m or more from the transport (i.e., 10 m ≤ a ≤ 100 m, then

$$\overline{C}_{d,10\text{-}100} = \frac{R\,A_C\,C}{10v}\left[\frac{\int_{r=a}^{100} \frac{dr}{0.2r}}{\int_{r=a}^{100} dr}\right] = \frac{R\,A_C\,C}{10v}\left[\frac{5\ln r\Big|_{r=a}^{100}}{r\Big|_{r=a}^{100}}\right] = \frac{R\,A_C\,C}{10v}\left[\frac{5\ln\left(\frac{100}{a}\right)}{100-a}\right]. \qquad \text{(E-8)}$$

The average CEDE in the proximal exposure region, then, is given by one of two expressions, either

$$\overline{E}_p = \frac{R\,A_C\,C}{10v}\,f\,T\,B_{\text{inh}}\,R_{10}\left[\frac{10\ln\left(\frac{2}{1+0.1a}\right) + 11.5}{100-a}\right], \quad \text{for } a < 10\,, \qquad \text{(E-9)}$$

or

$$\overline{E}_{\mathrm{p}} = \frac{R A_{\mathrm{C}} C}{10 v} f \, T B_{\mathrm{inh}} R_{10} \frac{5 \ln\left(\dfrac{100}{a}\right)}{100 - a} \, , \quad \text{for } 10 \leq a \leq 100 . \tag{E-10}$$

E.3 DISTAL DOSE

To estimate an average airborne concentration at distances exceeding 100 m, for determining the distal dose, it is assumed that $f_r = 0.2\, r$. However, f_r is constrained to take on a constant value ($f_r = 0.2\, r_b$) beyond the downwind distance r_b, where the height of the cross-sectional area that f_r defines becomes equal to the height h_b of the mixing layer (planetary boundary layer). This constraint addresses the situation in a thermal inversion, when warm air aloft prevents vertical diffusion and curtails dilution of airborne contaminants.

The cross-sectional area defined by the quantity Q is assumed to be a square with its bottom edge at ground level, so that r_b is determined from

$$Q = 10 A f_r = 10 A (0.2\, r_{\mathrm{b}}) = h_{\mathrm{b}}^2 \, , \tag{E-11}$$

giving

$$r_{\mathrm{b}} = \frac{h_{\mathrm{b}}^2}{2A} \, . \tag{E-12}$$

Note that $r_b > 800$ m (and f_r is, therefore, unconstrained by the mixing layer in our analysis) unless the height of the mixing layer is less than about 456 m. The average airborne concentration in the region from 100 to 800 m from the transport is then given, when $r_b < 800$ m ($h_b \leq 456$ m), by

$$\begin{aligned} \overline{C}_{\mathrm{d,100\text{-}800}} &= \frac{R A_{\mathrm{C}} C}{10 v} \left[\frac{\displaystyle\int_{r=100}^{800} \frac{\mathrm{d}r}{f_r}}{\displaystyle\int_{r=100}^{800} \mathrm{d}r} \right] = \frac{R A_{\mathrm{C}} C}{10 v \, r \Big|_{r=100}^{800}} \left[\int_{r=100}^{r_{\mathrm{b}}} \frac{\mathrm{d}r}{0.2\, r} + \int_{r=r_{\mathrm{b}}}^{800} \frac{\mathrm{d}r}{0.2\, r_{\mathrm{b}}} \right] \\ &= \frac{R A_{\mathrm{C}} C}{10 v \, (800 - 100)} \left[5 \ln r \Big|_{r=100}^{r_{\mathrm{b}}} + \frac{5 r}{r_{\mathrm{b}}} \Big|_{r=r_{\mathrm{b}}}^{800} \right] = \frac{R A_{\mathrm{C}} C}{7000 v} \left[5 \ln\left(\frac{r_{\mathrm{b}}}{100}\right) + \frac{5 (800 - r_{\mathrm{b}})}{r_{\mathrm{b}}} \right] \\ &= \frac{R A_{\mathrm{C}} C}{7000 v} \left[5 \ln\left(\frac{h_{\mathrm{b}}^2}{200 A}\right) + \frac{10 A}{h_{\mathrm{b}}^2} \left(800 - \frac{h_{\mathrm{b}}^2}{2 A} \right) \right] \, , \end{aligned} \tag{E-13}$$

and, when $r_b \geq 800$ m ($h_b \geq 456$ m), by

$$\overline{C}_{\mathrm{d},100\text{-}800} = \frac{R A_{\mathrm{C}} C}{10v}\left[\frac{\int\limits_{r=100}^{800}\frac{\mathrm{d}r}{f_{\mathrm{r}}}}{\int\limits_{r=100}^{800}\mathrm{d}r}\right] = \frac{R A_{\mathrm{C}} C}{10 v\, r\Big|_{r=100}^{800}}\left[\int\limits_{r=100}^{h}\frac{\mathrm{d}r}{0.2 r}\right] \tag{E-14}$$

$$= \frac{R A_{\mathrm{C}} C}{7000v}\left[5\ln\left(\frac{h_{\mathrm{b}}^{2}}{200A}\right)\right] .$$

A graphical representation of the activity concentration with distance from the cask for a non-fixed surface contamination level of 1 Bq cm^{-2}, mixing layer at 300 m, and representative values of the other parameters from Ref. E.1 is shown in Figure E.2.

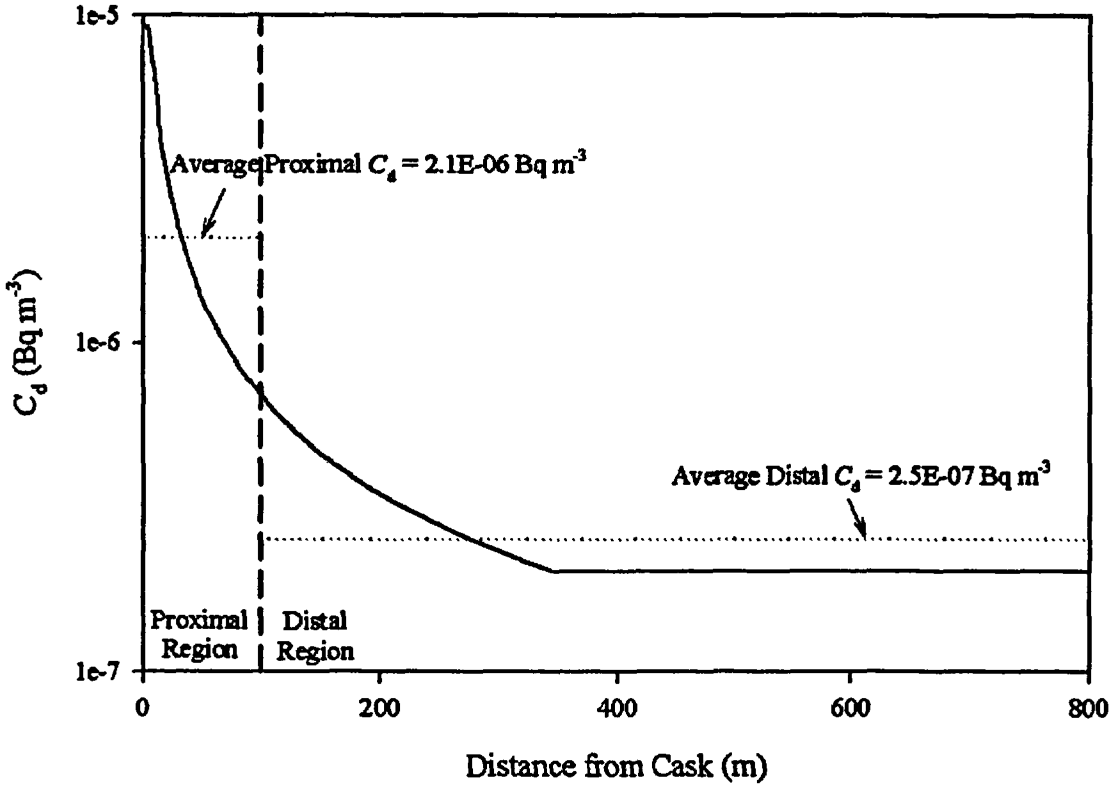


Figure E.2 Atmospheric activity concentration with distance from the source for a 300-m mixing layer (A_c = 1 Bq cm^{-2})

One of two equations is then used to determine the average CEDE in the distal exposure region, either

$$\overline{E}_d = \frac{R A_C C}{7000 v} f T B_{inh} R_{10} \left[5 \ln\left(\frac{h_b^2}{200 A}\right) + \frac{10 A}{h_b^2}\left(800 - \frac{h_b^2}{2 A}\right)\right] \text{, for } h_b \le 456 \text{ m,} \tag{E-15}$$

or

$$\overline{E}_d = \frac{R A_C C}{7000 v} f T B_{inh} R_{10} \left[5 \ln\left(\frac{h_b^2}{200 A}\right)\right] \text{, for } h_b > 456 \text{ m.} \tag{E-16}$$

E.4 TOTAL POPULATION DOSE

Population dose is the product of the number of exposed individuals and the average dose, summed over each region of exposure,

$$E_{Pop} = \sum_i n_i \overline{E}_i \ . \tag{E-17}$$

The number of exposed individuals in the *i*th region is the product of population density (m^{-2}) and area (m^2) subtended by the plume of airborne contamination. The contamination is assumed to disperse into a cross-sectional area defined as the product (10 $A f_r$), and with the simplifying assumption that this area is a square with one edge, having length $\sqrt{(10 A f_r)}$, at ground level. The dispersion footprint of the plume of contamination is shown in Figures E.3 and E.4. Figure E.3 shows the dispersion footprint at distances between 10 and 800 m downwind from the source of contamination, corresponding to the region where $f_r = 0.2\ r$. Figure E.4 shows the dispersion footprint between 5 and 10 m downwind, where $f_r = (1 + 0.1\ r)$.

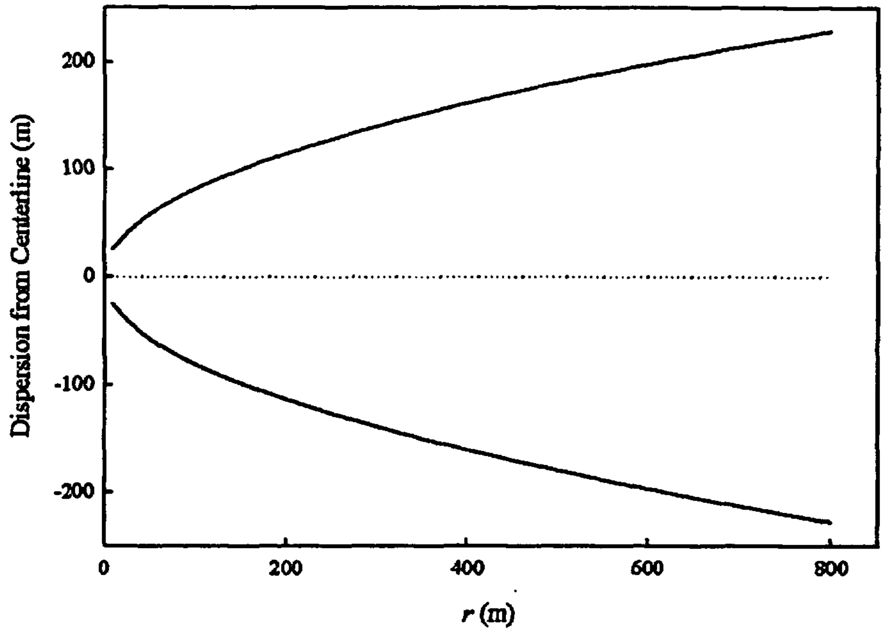


Figure E.3 Ground footprint of airborne contamination (10 to 800 m from cask, no inversion)

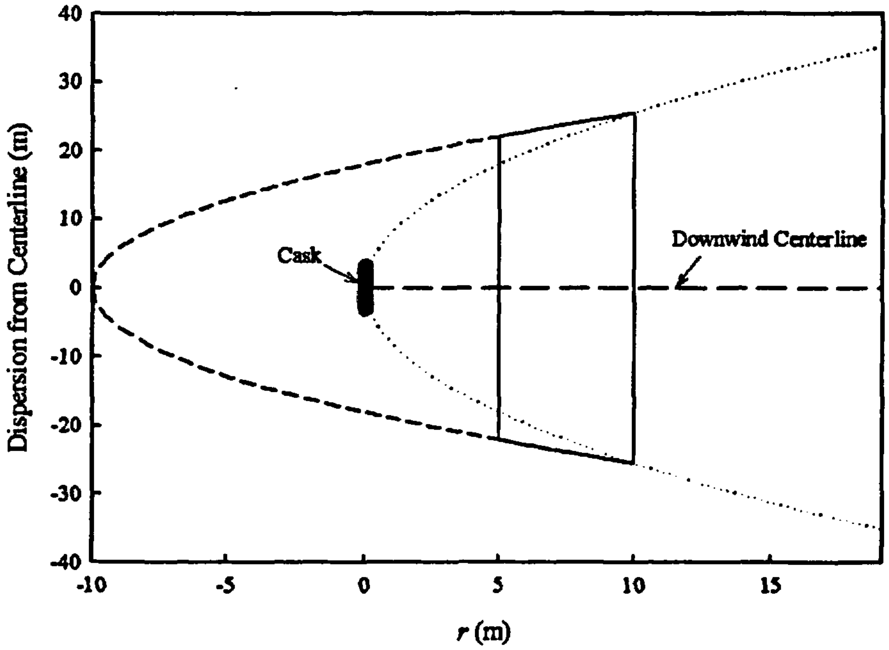


Figure E.4 Ground footprint of airborne contamination 5 to 10 m from cask (dashed line). Area subtended by the plume of contamination is bounded by the solid lines. The footprint for distances exceeding 10 m from the cask is shown (dotted line) for comparison.

The area subtended by the plume of contamination at distance r from the cask is the integral of the length of cross-sectional area at ground level,

$$\alpha_r = \int_{r=a}^{r_{\max}} \sqrt{10 A f_r}\, dr \ . \tag{E-18}$$

This integral solves to give

$$\alpha_r = \frac{2\sqrt{2A}}{3}\left(r_{\max}^{3/2} - a^{3/2}\right) \ , \ \text{for } a \geq 10\,\text{m} , \tag{E-19}$$

and

$$\alpha_r = \frac{2\sqrt{A}}{3}\left(r_{\max}^{3/2} - a^{3/2}\right) + \sqrt{10A}\left(r_{\max} - a\right) \ , \ \text{for } a < 10\,\text{m} . \tag{E-20}$$

Dispersion in the proximal area, then (since $r_{\max} = 100$ m) leaves a footprint of

$$\alpha_{r,p} = \frac{2\sqrt{2A}}{3}\left(100^{3/2} - 10^{3/2}\right) + \frac{2\sqrt{A}}{3}\left(10^{3/2} - a^{3/2}\right) + (10 - a)\sqrt{10A} \tag{E-21}$$

for $a < 10$ m, and

$$\alpha_{r,p} = \frac{2\sqrt{2A}}{3}\left(100^{3/2} - a^{3/2}\right) \tag{E-22}$$

for $a \geq 10$ m.

Both lateral and vertical dispersion are assumed to cease when a thermal inversion exists at the point where the dispersion height equals the height of the mixing layer [i.e., when $r_b < 800$ m ($h_b \leq 456$ m)]. The area subtended by the plume of airborne contamination constrained in this way in the distal region is rectangular, with width h_b and length $(r_{\max} - r_b)$. The total area subtended by the plume of contamination in the distal region is given, therefore, by

$$\begin{aligned} \alpha_{r,d} &= \frac{2\sqrt{2A}}{3}\left(r_b^{3/2} - a^{3/2}\right) + h_b\left(r_{\max} - r_b\right) \\ &= \frac{2\sqrt{2A}}{3}\left[\left(\frac{h_b^2}{2A}\right)^{3/2} - 100^{3/2}\right] + h_b\left(800 - \frac{h_b^2}{2A}\right) \ , \end{aligned} \tag{E-23}$$

when an inversion exists [*i.e.* $r_b < 800$ m ($h_b < 456$ m)], and by

$$\alpha_{r,\mathrm{d}} = \frac{2\sqrt{2A}}{3}\left(r_{\max}^{3/2} - a^{3/2}\right) = \frac{2\sqrt{2A}}{3}\left(800^{3/2} - 100^{3/2}\right) \qquad \text{(E-24)}$$

when $r_b \geq 800$ m ($h_b \geq 456$ m).

E.5 REFERENCE

E.1. Personal communication, Xavier Bernard-Bruls, International Atomic Energy Agency (IAEA), Vienna, Austria, to R. R. Rawl, ORNL, August 13, 2003, transmitting *The Radiological Aspects of Package and Conveyance Non-Fixed Contamination* (Version August 2003, Final draft report of an IAEA Coordinated Research Project).

APPENDIX F

EXTERNAL EXPOSURES TO MEMBERS OF THE PUBLIC

APPENDIX F

EXTERNAL EXPOSURES TO MEMBERS OF THE PUBLIC

F.1 MAXIMUM EXPOSED PERSON

The maximum exposed person from the on-link population must be determined from persons in another vehicle passing or meeting the shipment in an adjacent lane or immediately following the shipment in the same lane. The maximum exposed person from the off-link population is a stationary individual located beside the roadway immediately adjacent to the lane of a passing shipment.

F.1.1 Dose from Following a Transport at a Fixed Distance

The external dose E to a person following a transport at fixed distance d is simply the product of dose rate $\dot{D}$ at that distance and the following time t. At the distances applicable to exposure to members of the public, the dose rate is related to the reference dose rate $\dot{D}_0$ by the inverse square of distance, so that

$$E = \dot{D}t = \dot{\mathrm{D}}_0 t\left(\frac{d_0}{d}\right)^2 \tag{F-1}$$

where d_0 is the distance at which $\dot{D}_0$ is determined.

F.1.2 Dose from a Passing Transport

In this scenario, the exposed person is standing unshielded at a fixed distance from the roadway. A cask with a surface contamination reference dose rate at 1 m ($\dot{D}_0$) passes the person at a fixed rate. The time-dependent distance from cask to person is given by

$$d^2 = \mathrm{a}^2 + (\mathrm{r}t)^2 \tag{F-2}$$

where d is the distance from cask to person, a is the distance of the person from the roadway, r is the rate of travel of the cask, and t is time. The instantaneous dose rate to the person, assuming $1/d^2$ dependence (appropriate for the distances in these scenarios), is

$$\dot{D}_t = \frac{\dot{\mathrm{D}}_0}{d^2} = \frac{\dot{\mathrm{D}}_0}{\mathrm{a}^2 + (\mathrm{r}t)^2} \quad , \tag{F-3}$$

and the total dose delivered by the passing cask is

$$E = \int_{t=-\infty}^{\infty} \dot{D}(t)\,\mathrm{d}t = 2\int_{t=0}^{\infty} \dot{D}(t)\,\mathrm{d}t = 2\int_{t=0}^{\infty} \frac{\dot{\mathrm{D}}_0}{\mathrm{a}^2 + (\mathrm{r}t)^2}\,\mathrm{d}t = \frac{2\,\dot{\mathrm{D}}_0}{\mathrm{r}^2}\int_{t=0}^{\infty} \frac{\mathrm{d}t}{\left(\frac{\mathrm{a}}{\mathrm{r}}\right)^2 + t^2} \,, \tag{F-4}$$

where $t = 0$ is the time when the cask-to-person distance is the minimum distance, a. The integral is of the form

$$\int \frac{\mathrm{d}x}{\mathrm{b}^2 + x^2} = \frac{1}{\mathrm{b}}\tan^{-1}\frac{x}{\mathrm{b}} \,, \tag{F-5}$$

which yields a solution for the total dose,

$$E = \frac{2\,\dot{\mathrm{D}}_0}{\mathrm{ra}}\tan^{-1}\left(\frac{\mathrm{r}t}{\mathrm{a}}\right)\Bigg|_{t=0}^{\infty} = \frac{\pi\dot{\mathrm{D}}_0}{\mathrm{ra}} \,. \tag{F-6}$$

The minimum distance a for a person standing by the roadside depends on the type of highway. For interstate highways, a = 30 m; for other highways, a = 27 m.

This same expression can be used to determine the dose to on-link individuals in vehicles passing or meeting the transport. The value of r in this case is the relative velocity between the cask and the passenger vehicle. The minimum distance a is taken as the distance between centerlines of the lane of travel of the cask and that of the passenger vehicle (a = 4 m for passing vehicles and for vehicles meeting the transport on other highways; a = 23 m for vehicles meeting the transport on multilane divided highways).

F.2 EXTERNAL EXPOSURES—COLLECTIVE DOSE

Collective doses from external exposures to on-link populations (passengers in vehicles) in lanes #2, #3, and #4 are estimated using the same expression as for dose from a passing shipment and the number of persons affected. Doses to passengers in lane #1 are estimated using the distance-corrected dose rate to the first 100 vehicles behind the shipment. An "effective distance" (corresponding to the average dose rate) can be used for all 100 vehicles, as described below, to simplify this calculation. The time of exposure is the duration of the shipment.

Collective doses from external exposures to off-link populations can be estimated using the same expression as for dose from a passing shipment if the entire population in contiguous exposed areas is assumed to be concentrated at a distance from the roadway receiving a dose rate equal to the average dose rate for the dispersed population. The population thus concentrated is in an annulus around the cask during stops and is in a line along the roadway when the cask is in motion.

F.2.1 Average Distance of the Exposed Population from the Transport

The population living near a highway where spent fuel casks are transported is assumed in this analysis to be uniformly distributed within a strip with its nearest boundary a distance a from the roadway and its furthest boundary a distance b from the roadway. A cask on the roadway delivers a dose rate to an individual in this strip given by

$$\dot{D}(r) = \dot{D}_0\left(\frac{d^2}{r^2}\right) , \tag{F-7}$$

where $\dot{D}_0$ is the reference dose rate from the surface contamination at distance d, and r is the individual's distance from the cask ($a \le r \le b$). The average population dose rate is given by

$$\overline{D}_S = \frac{\int_{r=a}^{b} \dot{D}(r)\,dr}{\int_{r=a}^{b} dr} = \frac{\int_{r=a}^{b} \dot{D}_0\left(\frac{d^2}{r^2}\right) dr}{\int_{r=a}^{b} dr} = \frac{\dot{D}_0 d^2 \int_{r=a}^{b}\left(\frac{dr}{r^2}\right)}{\int_{r=a}^{b} dr}$$

$$= \frac{\dot{D}_0 d^2\left(-\frac{1}{r}\right)\Big|_{r=a}^{b}}{r\Big|_{r=a}^{b}} = \frac{\dot{D}_0 d^2\left(\frac{1}{a}-\frac{1}{b}\right)}{b-a} . \tag{F-8}$$

The average population dose rate corresponds to the dose rate delivered by a cask with the reference dose rate but delivered at a distance given by

$$r_{eff} = \sqrt{\left(\frac{\frac{1}{a}-\frac{1}{b}}{b-a}\right)^{-1}} . \tag{F-9}$$

This effective distance is used in estimating population doses from a shipment on the highway. If the reference distance is 1 m, then the expression for total unit collective dose delivered by the cask in motion along the entire length of its route is found by substituting r_{eff} for r in the equation. The unit collective dose for a stopped transport is the product of dose rate at r_{eff} and the time interval that the transport is stopped. Values for a and b depend on the location of the population segment with respect to the transport and on the type of roadway, as shown in Table F.1.

Table F.1 Values of a and b for estimating collective doses from external exposures

Highway	Population segment	a (m)	b (m)
State	Nearest to transport	29	798
State	Opposite from transport	33	802
Interstate	Nearest to transport	32	786.5
Interstate	Opposite from transport	59	813.5

A spreadsheet was developed to apply the above approaches to calculate the individual and collective doses reported in Sect. 5 of this report.

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11. **ABSTRACT** *(200 words or less)*

The current internationally accepted basis for establishing non-fixed surface contamination limits for spent fuel casks is the same as that for other transportation package types. This study examined the suitability of the currently used exposure model, taking into account exposure pathways and parameters representative of typical light-water-reactor spent fuel cask handling, loading, and transportation. Because the currently used model was determined to be inappropriate for spent fuel casks, a new exposure model was developed using pathways and parameters specific to spent fuel casks. Results show that individual and collective doses to members of the public are very low and that worker doses dominate the total collective dose from non-fixed surface contamination. Worker doses that vary as a function of allowable surface contamination limits were calculated and are dominated by doses due to decontamination and surface contamination monitoring activities performed after the cask is drained. An approach was developed for evaluating the dose implications of higher allowable non-fixed surface contamination limits.

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