Potential Indoor Worker Exposure from Handling Area Leakage:

Dose Calculation Methodology and Example Consequence Analysis

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Introduction

The U.S. Department of Energy (DOE) is currently considering design options for preclosure facilities in a license application for a geologic repository for spent nuclear fuel and high-level radioactive waste at Yucca Mountain, Nevada. CNWRA developed the PCSA Tool Version 3.0.0 software (CNWRA, 2005) for the U.S. Nuclear Regulatory Commission (NRC) to aid in the regulatory review of a potential DOE license application. The objective of this paper is to demonstrate PCSA Tool modeling capabilities (i.e., a generic two-compartment, mass-balance model) for estimating radionuclide concentrations in air and radiological dose consequences to indoor workers in a control room from potential leakage of radioactively contaminated air from an adjacent handling area. The presented model computes internal and external worker doses from inhalation and submersion in a finite cloud of contaminated air in the control room and augments previous capabilities for assessing indoor worker dose (CNWRA, 2002, Section 7.2). As a complement to the example event sequence frequency analysis in the companion paper, example consequence calculations are presented in this paper for the postulated event sequence.

Work Description

Methodology

Fig. 1 introduces symbols for input variables and schematically shows the arrangement of the rooms and air flows. Equations for radionuclide concentration, C_0 and C_1 (Ci/m^3) in Rooms 0 and 1, were derived based on conservation of the mass for the radionuclides in the system. The rate of change of radioactivity in either room equals the rate of any radioactivity flowing into the room (from the adjoining room) minus the rate of radioactivity flowing into the exhaust system minus the rate of radioactivity removed by radioactive decay (decay constant , in s^{-1}):

(1)

and

(2)

An initial condition for the model is an instantaneous distribution of radionuclide activity, $A_0 = C_0(0) / V_0$, within the air volume of the handling area. Air in both rooms is assumed to be well mixed.

The dose to a worker from inhalation of an individual radionuclide is

(3)

where BR is the breathing rate (m^3/s); OF is the occupancy factor, indicating the fraction of the time that the exposed worker is present in Room 1, $0 \leq OF \leq 1$ (unitless); and DF_I is the inhalation dose factor (rem/Ci) (EPA, 1998). The dose to a worker from submersion in air contaminated by the radionuclide is

(4)

where DF_S is the submersion dose factor, rem-m^3/Ci-s (EPA, 1993) and GF is the geometric factor to account for the finite extent of the contaminated air in the control room (unitless) (Humphreys et al., 1998).

In equations (3) and (4), $I(t)$ is the time-integrated radionuclide concentration over the exposure time t:

(5)

for and

(6)

for . Pathway dose is obtained by summing the individual radionuclide doses. The total worker dose, referred to as a total effective dose equivalent (TEDE), equals the summation of the inhalation and submersion pathway doses.

The original leakage model assumed complete loss of ventilation exhaust air flow from the handling area ($Q_{02} = 0$), but leakage scenarios without complete loss of handling-area ventilation ($Q_{02} \neq 0$) can also be modeled. To account for simultaneous leakage and exhaust ventilation air flows from the handling area, a leakage rate of ($Q_{01} + Q_{02}$) should be entered, and the output dose should be scaled by a factor equal to $Q_{01} / (Q_{01} + Q_{02})$.

Example Consequence Analysis—Hypothetical Case

Because the event sequence has the potential to be a Category 1 event sequence (expected number of occurrences ≥ 1 before permanent closure), as indicated by the companion paper, radiological consequences to an indoor worker are assessed. Example leakage calculations were performed for both degraded HVAC system performance with a reduced ventilation flow rate and no exhaust ventilation for the handling area (see Fig. 1). A single open container containing 21 pressurized water reactor (PWR) assemblies in the spent nuclear fuel pool was used to estimate a normal operation source term. Based on a previous conservative estimate of 1 percent for the percentage of fuel rods with breached cladding (DOE, 2005), a gaseous source term from 0.21 PWR assemblies is used as the quantity of nuclear material with cladding leaks available for normal operation releases (as specified by *OF* in Fig. 1 to account for the source term being a noninteger number of assemblies in this example). Effective release fractions of 0.3 (zero for particulates) were used for gases to simulate gaseous releases from the pool (DOE, 2001). No credit was taken for wet decontamination of noninert gases released into the pool in this example, which will overestimate their dose contributions (e.g., tritium released from the spent nuclear fuel is also assumed to be released from the pool into air where it is modeled to contribute inhalation dose as tritiated water vapor). Average spent nuclear fuel characteristics were used to determine the inventories of 69 radionuclides in PWR spent nuclear fuel (CNWRA, 2002).

Results

Fig. 2 shows a composite plot of example results from the indoor worker dose model. Individual deterministic PCSA Tool runs were performed for each data point. The leakage rate was varied with assigned values equal to either a factor of 100; 1000 (nominal); or 10,000 times less than the nominal control room ventilation rate of 4.2 m^3/s [150 ft^3/s] for two different handling-area ventilation rates ($Q_{02} = 0$ and $Q_{02} = Q_{12}$). The magnitude of the dose scaled with the handling-area leakage rate (i.e., an increase in the handling-area leakage rate by a factor of 10 resulted in a dose increase by a factor of 10).

Overall, the investigated variations in the handling-area leakage rate affected the calculated dose by a factor of 100. The effect of the handling-area exhaust ventilation rate was much smaller and can be quantified by the ratio of the dose for no exhaust ventilation relative to the dose for a ventilation rate of 4.2 m^3/s, which ranged from 1.01 to 1.24 (a 1-percent to 24-percent effect) for increasing exposure times between 1 and 15 minutes.

As shown by Fig. 3, increases in exposure time by a factor of 15 increased dose by a factor of 24 and 20 for cases with no handling-area exhaust ventilation and a ventilation rate equal to the control room exhaust rate, respectively. Worker dose decreased for slightly higher handling-area ventilation rates, due to a larger proportion of airborne radioactive material evacuating out of the handling area ventilation exhaust rather than leaking into the worker room. For this example calculation that includes some conservative assumptions and only presents whole body doses (i.e., organ doses are not presented here), doses from inhalation accounted for more than 99 percent of the total dose.

Conclusions

This paper presents a model for estimating radiological doses to indoor workers for the leakage of airborne radioactive material from handling areas. Sensitivity of model results to changes in various input parameters was investigated via illustrative example calculations. Indoor worker dose estimates were strongly dependent on the duration of worker exposure and the handling-area leakage flow rate. In contrast, doses were not very sensitive to handling-area exhaust ventilation flow rates. For the presented example, inhalation was the dominant radiological dose pathway. The two companion papers demonstrate independent analysis capabilities of the regulator for performing confirmatory calculations of frequency and consequence, which assist the assessment of worker safety during a risk-informed regulatory review of a potential DOE license application.

Acknowledgments

This paper was prepared to document work performed by CNWRA for NRC under Contract No. NRC–02–02–012. The activities reported here were performed on behalf of the NRC Office of Nuclear Material Safety and Safeguards, Division of High-Level Waste Repository Safety. This paper is an independent product of CNWRA and does not necessarily reflect the views or regulatory position of NRC.

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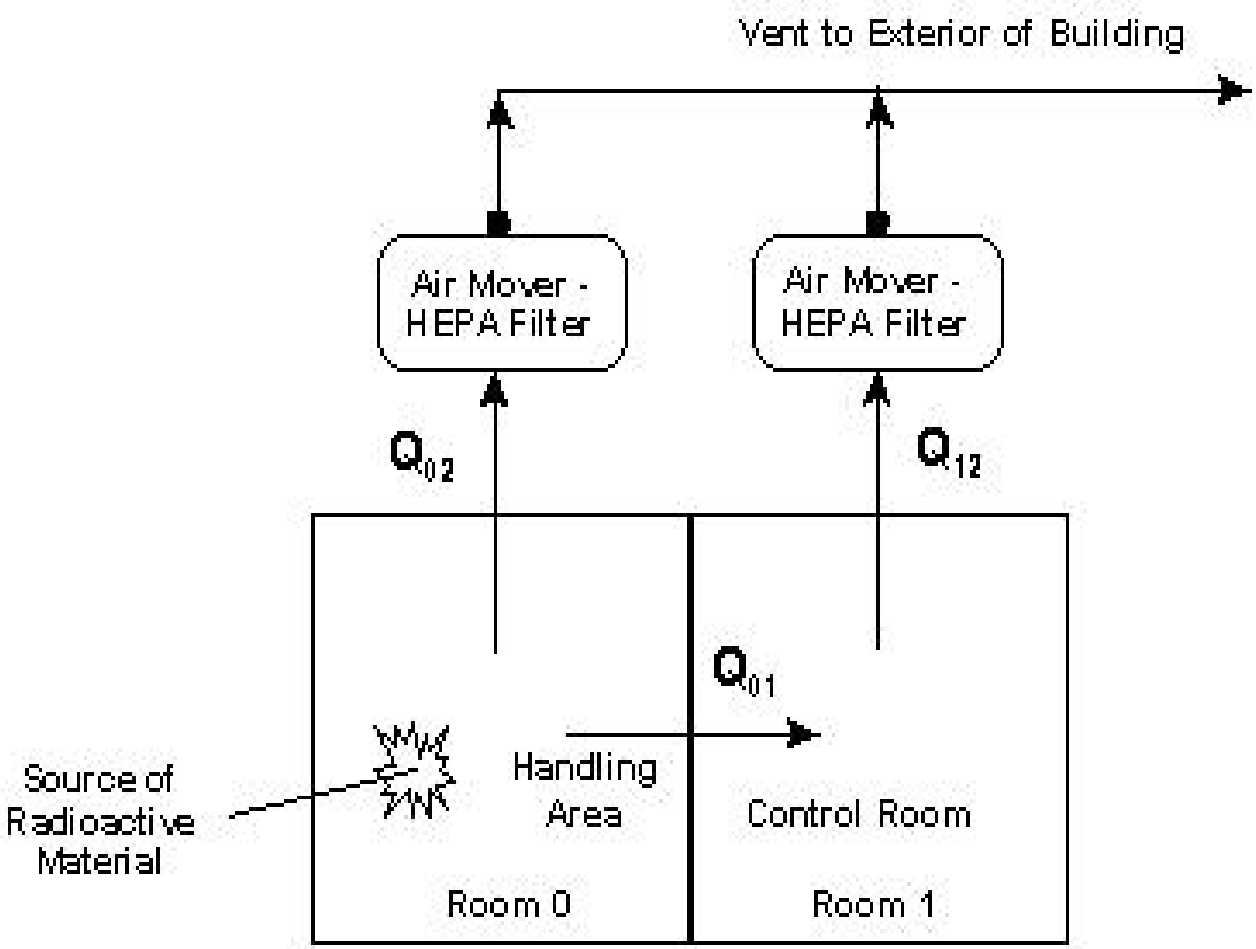

Variable	Symbol	Value[(a)]
Handling area air volume (arbitrary value for illustration)	V_0	6000 m^3
Worker room volume (arbitrary value for illustration)	V_1	1000 m^3
Breathing rate (Humphreys, 1998)	BR	3.50×10^{-4} m^3/s
Time duration (assumed)	t	Varies (1 to 15 min)
Occupation factor (calculated)	OF	0.21
Ventilation rate from handling area (assumed)	Q_{02}	Varies (0 or 2.1 m^3/s)
Ventilation exhaust rate from worker room (assumed)	Q_{12}	4.2 m^3/s (15 air changes per hour)
Leakage rate from handling area into worker room (assumed)	Q_{01}	Varies (0.00042 to 0.042 m^3/s)

[(a)] 1 m^3/s = 35.3 ft^3/s
1 m^3 = 35.3 ft^3
1% air change per min leakage = 1.0 m^3/s
1% air change per hour ventilation rate in worker room = 0.278 m^3/s

Fig. 1. Schematic of the two-compartment model for handling area leakage and example input parameter values.

Fig. 2. Worker total dose (1 mSv = 100 mrem) for different leakage and handling-area ventilation rates.

Fig. 3. Worker total dose (1 mSv = 100 mrem) for different handling-area ventilation rates with a fixed leakage rate of 0.042 m^3/s. The ventilation and leakage rates are displayed in Fig. 1.