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430.

RELATED CORRESPONDENCE

(2)

UNITED STATES OF AMERICA

NUCLEAR REGULATORY COMMISSION

10 June 1985

BEFORE THE ATOMIC SAFETY AND LICENSING BOARD

Glenn O. Bright
Dr. James H. Carpenter
James L. Kelley, Chairman

DOCKETED
USNRC

'85 JUN 14 A11:17

OFFICE OF SECRETARY
DOCKETING & SERVICE
BRANCH

In the Matter of

CAROLINA POWER AND LIGHT CO. *et al.*
(Shearon Harris Nuclear Power Plant,
Unit 1)

Docket 50-400 OL

ASLBP No. 82-468-01
OL

Letter to the Board and Parties
Forwarding Exhibits (Proposed)
on Eddleman Contention 57-C-10

Attached or enclosed are copies of the proposed Exhibits. All are from documents obtained by discovery.

Wells Eddleman
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DS03

UNITED STATES OF AMERICA
NUCLEAR REGULATORY COMMISSION

In the matter of CAROLINA POWER & LIGHT CO. Et al.)
Shearon Harris Nuclear Power Plant, Unit 1)

Docket 50-400
O.L.

CERTIFICATEOF SERVICE

I hereby certify that copies of Letter forwarding Exhibits (Proposed) on Eddleman 57-C-10, and copies of the proposed Exhibits

HAVE been served this 10 day of June 1985, by deposit in the US Mail, first-class postage prepaid, upon all parties whose names are listed below, except those whose names are marked with an asterisk, for whom service was accomplished by ______

Judges James Kelley, Glenn Bright and James Carpenter (1 copy each)
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Certified by Wells Eddleman

EXH_57-C-10 "A"

HS-2 / January 1984
(Supersedes HS-2 / Parts 1 & 2 / January 1983)

SHELTER SURVEY TECHNICIAN COURSE

Student Manual

FEDERAL EMERGENCY
MANAGEMENT AGENCY

000842

K-45-1 / January 1984
(Supersedes K-45-1 series January 1983)

SHELTER SURVEY TECHNICIAN COURSE

Student Handout Material 1

K-45-2 / January 1984

SHELTER SURVEY TECHNICIAN COURSE

Student Handout Material 2

Forms Required for SST Course

FEDERAL EMERGENCY
MANAGEMENT AGENCY

000841

(2)

57-C-10
'B'

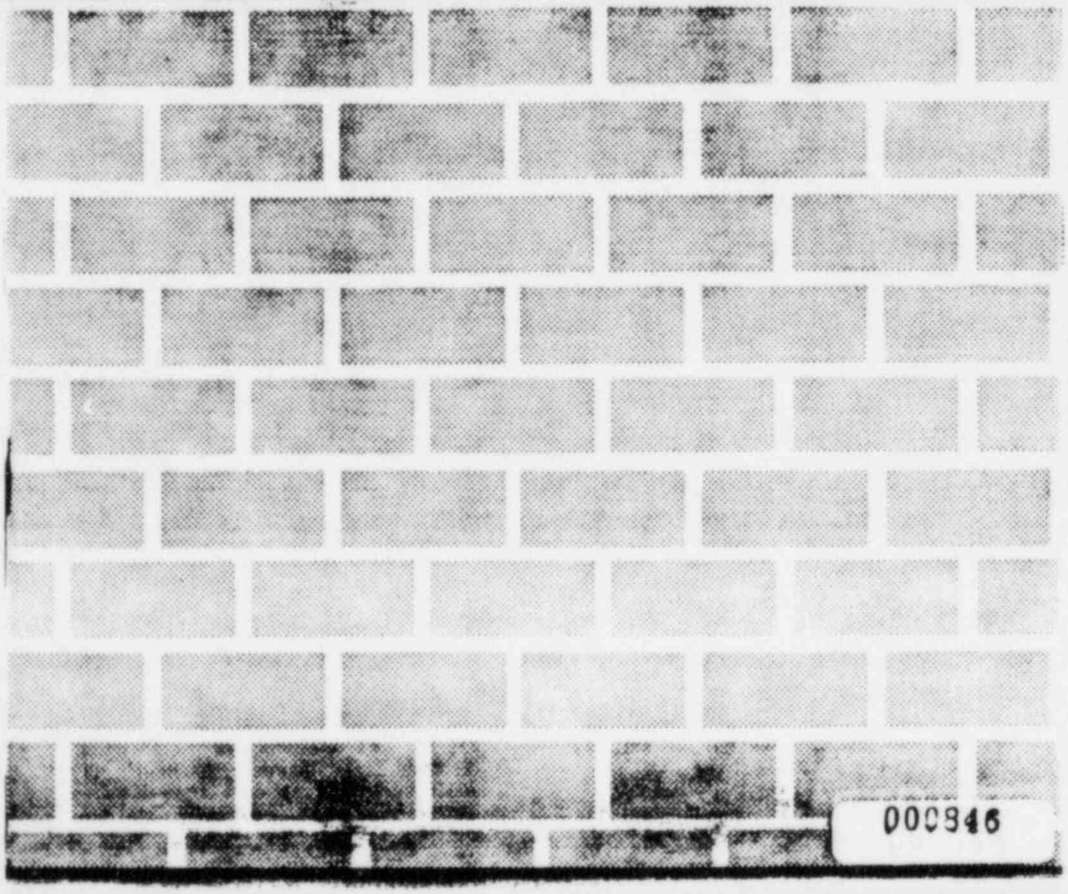
federal emergency
management agency

[illegible]
(Supersedes TR-68 dated
May 1979, which may be used.)

mass thickness manual for walls, floors, and roofs

"TR-68/
January
1984"
supersedes
TR-68
dated
September
1980 which
may be
used"

mass thickness manual for walls, floors, and roofs



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Shelter Analysis for Nuclear Defense (SAND)

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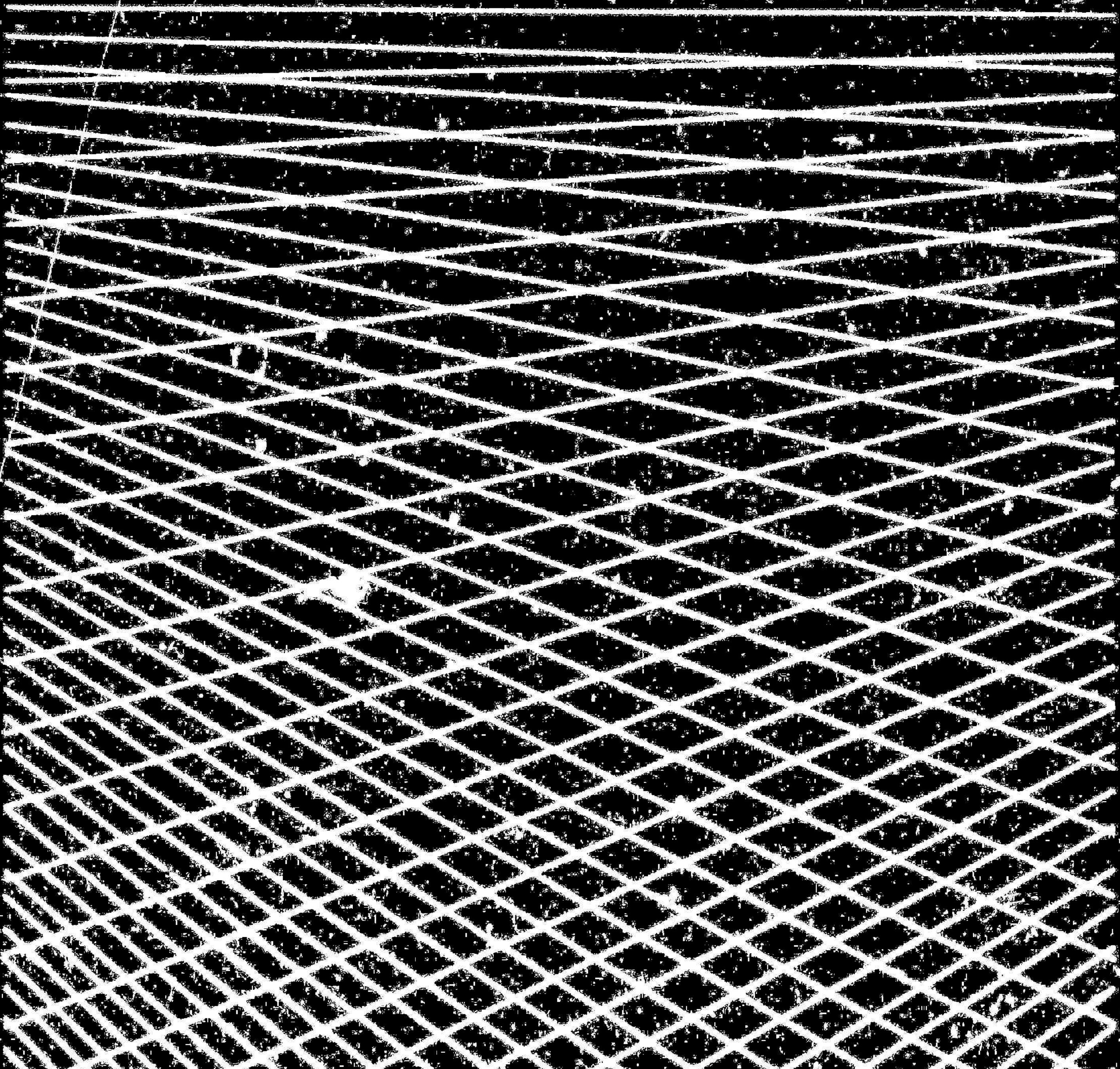


FEDERAL EMERGENCY
MANAGEMENT AGENCY

PREFACE

This document is intended for use by qualified fallout shelter analysts or other individuals who are familiar with the hazards of fallout radiation and the principles of computing the radiation shielding potential of buildings or other structures. Implied with this intended use is an assumption that the reader of this document is familiar with the FEMA publication entitled "Shelter Design and Analysis Fallout Radiation Shielding," TR-20 (Vol. 1) and as a result is aware of the meaning of such terms as protection factor, reduction factor, contributions to the reduction factor, and contaminated planes and is also familiar with the general terms used to describe engineered structures.

FEDERAL EMERGENCY MANAGEMENT AGENCY

FALLOUT SHELTER ANALYSIS BY COMPUTER

A. IDENTIFICATION

	1. FSAC NUMBER	2. PART	3. REV.	4. SUB TYPE	5. PAGE	6. ENTER B - BASIC FSAC SUBMITTAL M - CHANGE BASIC FSAC SUBMITTAL	7. DATE DAY	MONTH	YEAR	*FEMA USE ONLY*
PF	1				0 1					

8. USER CODE ① 9. ANALYST NAME AND MAILING ADDRESS *(Including ZIP Code)*

10. FACILITY NAME AND ADDRESS ②

	11. TOTAL STORIES	12. SUB-BASEMENT	13. STORY 01 DESIGN.
③			0 1

B. DIMENSIONS

HEIGHT (Feet)							LENGTH (Feet)	
1. TOTAL BLDG.	2. SUB-BASE-MENTS	3. BASE-MENT	4. FIRST STORY	5. UPPER STORIES	6. UPPER STORIES (IF CH)	7. STORY OF CH.	8. SIDE A	9. SIDE B

C. FACILITY SKETCH/NOTES

D. CONTAMINATED PLANES

			SIDE A	SIDE B	SIDE C	SIDE D
④	1. SECTOR 1	a. SECTOR 1 ANGLE				
⑤		c. PLANE 1 (+, −, H, P, R) HEIGHT				
		d. PLANE 1 WIDTH				
⑥		e. PLANE 2 (+, −, H) HEIGHT				
		f. PLANE 2 WIDTH				
		g. PLANE 3 (+, −, H) HEIGHT				
		h. PLANE 3 WIDTH				
⑦	2. SECTOR 2	a. SECTOR 2 ANGLE				
		c. PLANE 1 (+, −, H, P, R) HEIGHT				
		d. PLANE 1 WIDTH				
⑧		e. PLANE 2 (+, −, H) HEIGHT				
		f. PLANE 2 WIDTH				
		g. PLANE 3 (+, −, H) HEIGHT				
		h. PLANE 3 WIDTH				
⑨	3. SECTOR 3	a. SECTOR 3 ANGLE				
		c. PLANE 1 (+, −, H, P, R) HEIGHT				
		d. PLANE 1 WIDTH				
⑩		e. PLANE 2 (+, −, H) HEIGHT				
		f. PLANE 2 WIDTH				
		g. PLANE 3 (+, −, H) HEIGHT				
		h. PLANE 3 WIDTH				

E. APERTURES

		SIDE A			SIDE B			SIDE C			SIDE D		
	E. APERTURES	TOTAL WIDTH	Sill Hgt	HEAD HEIGHT	TOTAL WIDTH	Sill Hgt	HEAD HEIGHT	TOTAL WIDTH	Sill Hgt	HEAD HEIGHT	TOTAL WIDTH	Sill Hgt	HEIGH
⑪	1 AREAWAY												
	2 BASEMENT												
⑫	3 FIRST STORY												
	4 UPPER STORY												
⑬	5 UP STORY (CHANGE)												
	6 STORY OF CHANGE												

FEMA Form 85-30, MAR 81

SUPERSEDES DCPA FORM 679B, JUNE 75 WHICH IS OBSOLETE.

FEMA Form 85-30, MAR 81

SUPERSEDES DCPA FORM 679B, JUNE 75 WHICH IS OBSOLETE.

	F. EXTERIOR WALL MASS THICKNESS	SIDE A	SIDE B	SIDE C	SIDE D
⑭	1. AREAWAY				
	2. BASEMENT OR CRAWL SPACE				
	3. FIRST STORY				
	4. UPPER STORY				
⑮	5. UP STORY (CHANGE)				
	6. STORY OF CHANGE				

	G. OFFSETS	Story	S φ	From Side A	S φ	From Side B	S φ	From Side C	S φ	From Side D
⑯	1. OFFSET 1									
	2. OFFSET 2									
	3. OFFSET 3									

	H. BASEMENT EXTENSIONS	From Side A	From Side B	From Side C	From Side D
⑰	1. DISTANCE				
	2. OVERHEAD MASS THICKNESS				

	J. PARTIAL BASEMENTS		From Side A	From Side B
⑱	PARTIAL BASEMENT 1	1. DISTANCE TO NEAR SIDE		
		2. DISTANCE TO FAR SIDE		
	PARTIAL BASEMENT 2	3. DISTANCE TO NEAR SIDE		
		4. DISTANCE TO FAR SIDE		

	K. SPECIAL DETECTORS	Story	From Side A	From Side B
	1. BASEMENT			
	2. FIRST STORY			
	3. UPPER STORY			
⑲	4. FIRST ADDITIONAL			
	5. SECOND ADDITIONAL			
	6. THIRD ADDITIONAL			

	L. ROOF AND OFFSET MASS THICKNESS		Roof	Offset 1	Offset 2	Offset 3
⑳						
	M. FLOOR MASS THICKNESS	Story of Change	Upper Story Change	Upper Story	First Story	Basement

FLOOR MASS THICKNESS CHANGE	STORY	MASS (psf)	DISTANCE TO CHANGE IN FLOOR MASS THICKNESS				
			FROM SIDE A	FROM SIDE B	FROM SIDE C	FROM SIDE D	A
NO. 1							
NO. 2							

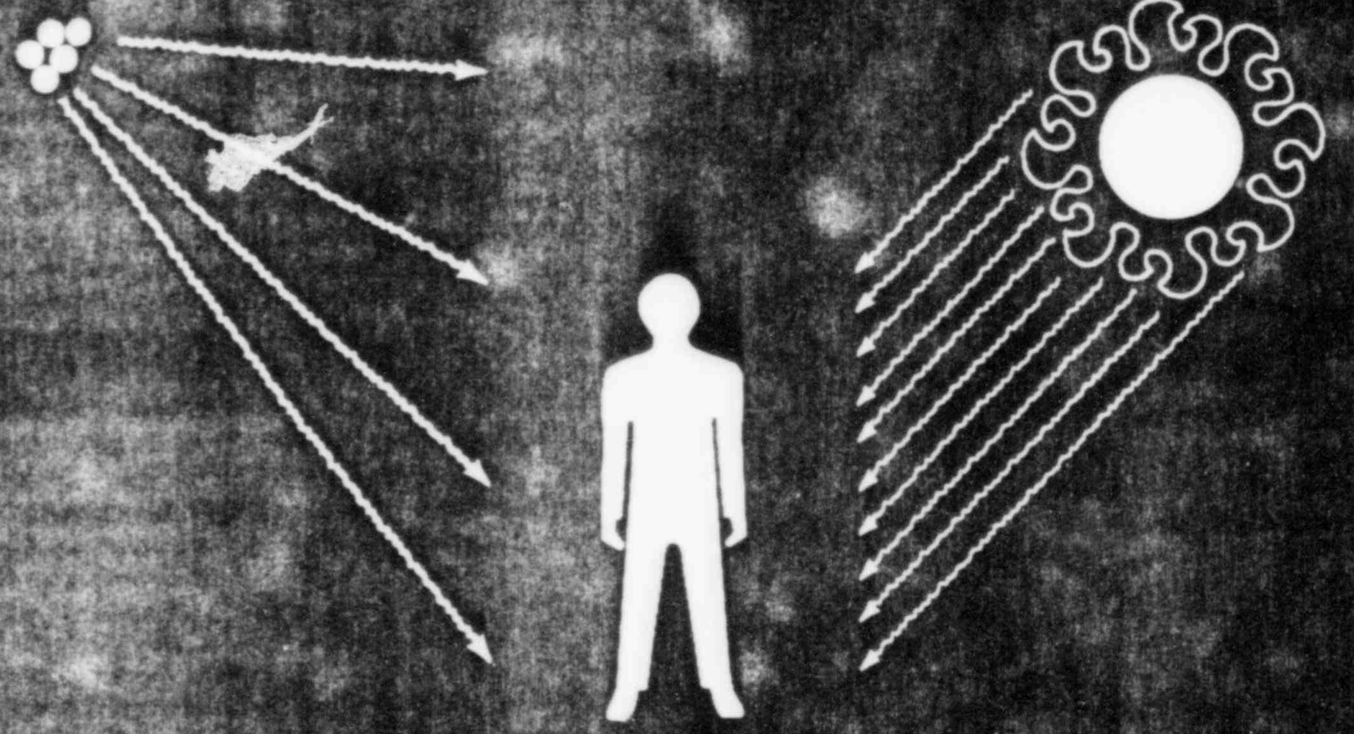
FALLOUT SHELTER ANALYST SIGNATURE	FSA CERTIFICATE NUMBER	DATE

	N. AREAWAYS	Areaway 1	Areaway 2	Areaway 3	Areaway 4
㉑	1. SIDE AND STORY				
	2. HEIGHT FLR. ABOVE STORY FLR.				
	3. WIDTH				
	4. LENGTH				
	5. DISTANCE FR. BLDG. PT. CORNER				

	P. INTERIOR PARTITIONS		PARTITION 1		PARTITION 2		PARTITION 3		PARTITION 4	
			Distance	Mass Thkness	Distance	Mass Thkness	Distance	Mass Thkness	Distance	Mass Thkness
	BASEMENT									
㉒	1. FROM SIDE A									
	2. FROM SIDE B									
	FIRST STORY									
㉓	3. FROM SIDE A									
	4. FROM SIDE B									
	UPPER STORY									
	5. FROM SIDE A									
	6. FROM SIDE B									
	Upper Story (Change 1)	STORY								
㉔	7. FROM SIDE A									
	8. FROM SIDE B									
	Upper Story (Change 2)	STORY								
	9. FROM SIDE A									
㉕	10. FROM SIDE B									
	Upper Story (Change 3)	STORY								
	11. FROM SIDE A									
	12. FROM SIDE B									

NOTES:

THE SAND FORM (cont.)

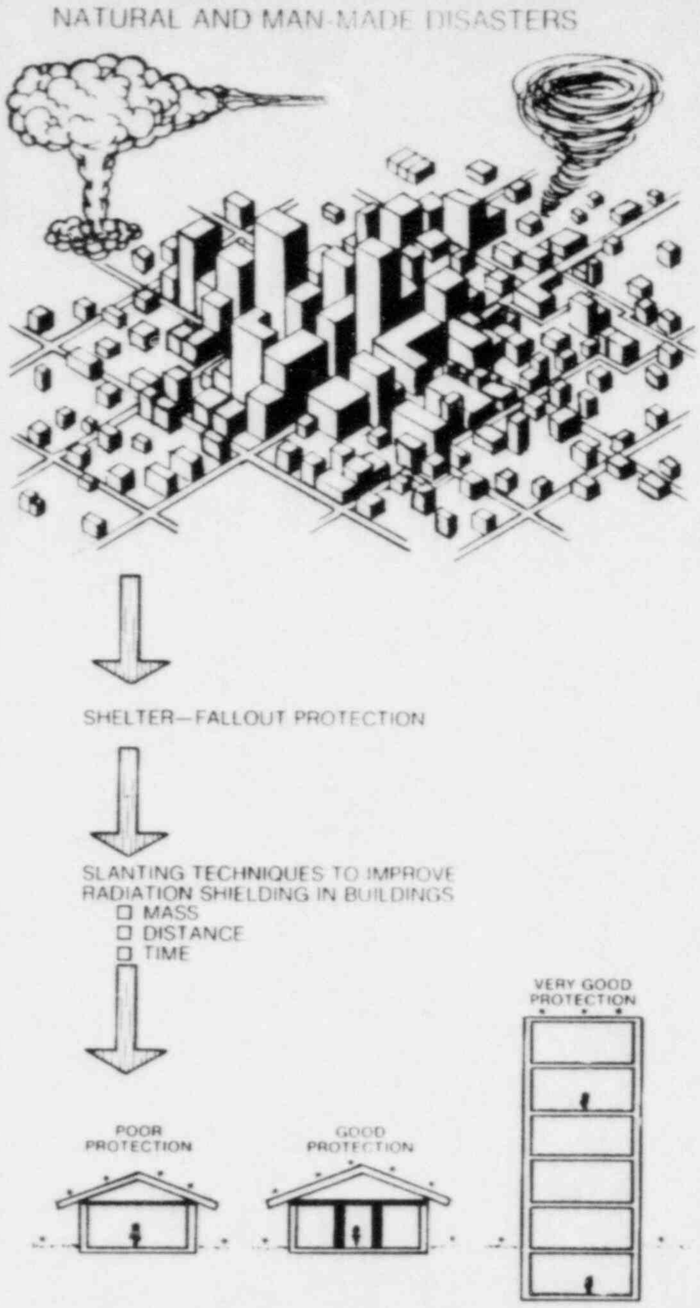


building design for radiation shielding and thermal efficiency

tr-85 defense civil preparedness agency december 1977

000853

emergency preparedness and radiation shielding



Principle More mass between occupant and radiation source means better radiation shielding

Emergency preparedness in the United States takes many forms. Basically, it encompasses planning and other preparations by Federal, State, and local governments for the protection of people and property from the effects of nuclear attack. This is the primary mission of the Defense Civil Preparedness Agency (DCPA). A secondary role of the Agency is to provide guidance and assistance to mitigate the effects of natural and other man-made disasters.

Radiation shielding to protect people from radioactive fallout that would result from surface nuclear bursts is a specific emergency preparedness function. Buildings and other protected spaces, such as mines, tunnels, and caves, throughout the United States have been surveyed to determine their radiation protection factors. Protected spaces in these facilities, which could shelter many thousands of Americans from fallout radiation, have been designated as public fallout shelters.

A number of building design techniques have been developed over the past two decades for incorporating good radiation shielding into buildings. The most feasible techniques utilize material mass—the density and thickness of building materials and earth—to achieve the shielding.

Often the mass of the material used in the basic construction of a building—such as reinforced concrete—has been adequate to provide the desired shielding. In other cases, belowground construction provides the desired shielding. Sometimes materials of the basic design had to be changed, amounts of material increased, modifications made in space layout, or openings in walls altered to achieve the desired radiation shielding.

In all the various techniques, the basic design approach for radiation shielding is to separate the occupants of the shelter from outside radioactive fallout by a suitable amount of material mass.

57-C-10
(E) ②

National Shelter Survey Instructions

FEDERAL EMERGENCY
MANAGEMENT AGENCY

TR-84
May 1982
Supersedes May 1981

000851

TABLE I (CONT'D)

Zonal Ventilation Requirements by County

AREA	CFM
REGION IV (Cont'd)	
Georgia (Cont'd)	
Wheeler	20
Wilcox	20
Wilkinson	20
Worth	20
All Others	15
Kentucky	
Boyd	10
Carter	10
Elliott	10
Fulton	20
Graves	20
Greenup	10
Hickman	20
Johnson	10
Lawrence	10
Lewis	10
Martin	10
Pike	10
All Others	15
Mississippi	
Adams	25
Amite	25
Franklin	25
George	25
Hancock	25
Harrison	25
Jackson	25
Jefferson	25
Pearl River	25
Pike	25
Stone	25
Walthall	25
Wilkinson	25
All Others	20
North Carolina	
Bladen	20
Brunswick	20
REGION IV (Cont'd)	
North Carolina (Cont'd)	
Columbus	20
Cumberland	20
Hoke	20
New Hanover	20
Onslow	20
Pender	20
Robeson	20
Sampson	20
Scotland	20
All Others	15
South Carolina	
Abbeville	15
Anderson	15
Cherokee	15
Chester	15
Greenville	15
Greenwood	15
Lancaster	15
Laurens	15
McCormick	15
Newberry	15
Oconee	15
Pickens	15
Spartanburg	15
Union	15
York	15
All Others	20
Tennessee	
Benton	20
Carroll	20
Chester	20
Crockett	20
Decatur	20
Dickson	20
Dyer	20
Fayette	20
Gibson	20
Giles	20
REGION IV (Cont'd)	
Tennessee (Cont'd)	
Hardeman	20
Hardin	20
Haywood	20
Henderson	20
Henry	20
Hickman	20
Houston	20
Humphreys	20
Lake	20
Lauderdale	20
Lawrence	20
Lewis	20
McNairy	20
Madison	20
Maury	20
Obion	20
Perry	20
Shelby	20
Stewart	20
Tipton	20
Wayne	20
Weakley	20
All Others	15
*Canal Zone	35
REGION V	
Illinois	
Boone	10
Bureau	10
Carroll	10
Cook	10
De Kalb	10
Du Page	10
Ford	10
Grundy	10
Henry	10
Iroquois	10

*All counties have identical CFM.

Wilkie

ORNL/TM-6526 ②

57-C-10 (F)

Effects of Man's Residence Inside Building Structures on Radiation Doses from Routine Releases of Radionuclides to the Atmosphere

D. C. Kocher

HEALTH AND SAFETY RESEARCH DIVISION

000839

OAK RIDGE NATIONAL LABORATORY

OPERATED BY UNION CARBIDE CORPORATION FOR THE DEPARTMENT OF ENERGY

ORNL/TM-6526
Dist. Category UC-41

Contract No. W-7405-eng-26

Health and Safety Research Division

EFFECTS OF MAN'S RESIDENCE INSIDE BUILDING STRUCTURES ON RADIATION DOSES FROM ROUTINE RELEASES OF RADIONUCLIDES TO THE ATMOSPHERE

D. C. Kocher

Date Published: December 1978

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
operated by
UNION CARBIDE CORPORATION
for the
DEPARTMENT OF ENERGY

CONTENTS

EFFECTS OF MAN'S RESIDENCE INSIDE BUILDING STRUCTURES ON RADIATION DOSES FROM ROUTINE RELEASES OF RADIONUCLIDES TO THE ATMOSPHERE

D. C. Kocher

ABSTRACT

The effects of man's residence time inside building structures on radiation doses from routine releases of radionuclides to the atmosphere are studied using models which are suitable for radiological assessments involving arbitrary source terms. Dose reduction factors from building shielding are calculated for internal exposure from inhaled radionuclides and external photon exposure from airborne and surface-deposited radionuclides. The model for internal dose accounts for air ventilation and the deposition of radionuclides on inside surfaces of the building. External photon dose rates are calculated using the point-kernel integration method. The computer code BUSH is used to implement the models. The results of model-parameter sensitivity studies and an application of the models to a radiological assessment are discussed.

1. INTRODUCTION

In estimating radiation doses to the population from releases of radionuclides to the atmosphere, it is often assumed that man spends all of his time outdoors standing on a smooth infinite plane. It is known, however, that man spends most of his time indoors,[1] so that substantial reductions in radiation doses may result compared with the usual estimates.

We have implemented models to study the effects of man's residence time inside building structures on radiation doses from routine releases of radionuclides to the atmosphere. We consider both internal dose from inhaled radionuclides and external photon dose from airborne and surface-deposited radionuclides.* We do not consider other exposure pathways, such as ingestion and immersion in contaminated water, for which the dose to man is presumably not affected by residence time inside buildings. The effect of indoor residence on internal dose takes into account air ventilation and the deposition of radionuclides on inside surfaces of the structure.[2] Building shielding effects for external photon exposure are estimated using the point-kernel integration method.[3,4] A brief discussion of the effects of building shielding on external exposure to beta radiation is also given.

For each exposure pathway, the effect of a building structure on the radiation dose is described quantitatively by a dose reduction factor, which is defined as the ratio of the dose to a reference individual inside the building to the corresponding dose with no building present. With this definition, the smaller the value of the dose reduction factor, the greater is the shielding against radiation exposure.

A detailed computational methodology, called the engineering manual method, has previously been developed to predict building shielding effects for radionuclides deposited on the ground.[5,6] This method is normally applied to the study of shielding effects for a wide variety of

---

*We use the terms "internal" and "external" to denote the dose from sources inside and outside the body, respectively, not to denote sources inside and outside the building.

structures for particular radioactive sources only, such as ^{60}Co, ^{137}Cs, and fallout from a nuclear weapon detonation or nuclear reactor accident.[5-7] A disadvantage of the engineering manual method is that it is not readily applicable to arbitrary mixtures and concentrations of radionuclides deposited on the ground.

Little work has previously been done to study building shielding effects for external exposure from airborne radionuclides and for inhalation exposure.[2,7]

In the present work, our objective was to develop models to describe internal and external dose reduction factors for a simple type of building structure which can easily be applied to arbitrary radionuclide source terms. With these models, estimates of building shielding effects on population doses from routine releases of radionuclides to the atmosphere can readily be incorporated into standard radiological assessment procedures.

2. INTERNAL DOSE REDUCTION FACTOR

The internal dose from inhaled radionuclides is proportional to the radionuclide concentration in the air. We assume a steady-state condition in which the radionuclide concentration outside a building, S_v, is constant with time. We assume that the radionuclide concentration inside the building, S_v', is increased by air ventilation into the building but is decreased by air ventilation out of the building, deposition of radionuclides on inside surfaces, and radioactive decay. The radionuclide concentration inside the building is thus described by the first-order differential equation

$$\frac{dS_v'}{dt} = \lambda_v S_v - \lambda_v S_v' - \left[\frac{V_{df}\sigma_f + V_{dw}\sigma_w + V_{dc}\sigma_c}{\Omega} \right] S_v' - \lambda S_v' \ , \qquad (1)$$

where

t = time,

λ_v = air ventilation rate (in units of time^{-1}),*

V_{df}, V_{dw}, V_{dc} = deposition velocities (in units of length/time) on floor, walls, and ceiling,

$\sigma_f, \sigma_w, \sigma_c$ = surface areas of floor, walls, and ceiling,

Ω = volume of building, and

λ = radioactive decay constant ($\ln 2/T_{1/2}$).

Assuming zero radionuclide concentration inside the building at time zero, it is easy to show by integrating Eq. (1) that the reduction factor is given by

$$RF_{in}(t) = S_v'(t)/S_v = \frac{\lambda_v}{\lambda_a}\left(1 - e^{-\lambda_a t}\right), \tag{2}$$

where

$$\lambda_a = \lambda_v + (V_{df}\sigma_f + V_{dw}\sigma_w + V_{dc}\sigma_c)/\Omega + \lambda .$$

By setting $(1 - e^{-\lambda_a t}) = 1$, which is accurate for times greater than a few hours in most assessments of chronic releases to the atmosphere, the time-independent reduction factor becomes

$$RF_{in} = \lambda_v/\lambda_a . \tag{3}$$

---

*In the present formulation, we have implicitely assumed that the ventilation rates into and out of the building are the same and that the ventilation rate of the radionuclides in either gaseous or particulate form is the same as the air ventilation rate. The quantity λ_v in the first two terms of the equation may easily be modified if these conditions are not met.

Note that the steady-state internal dose reduction factor is just given by the ratio of two time constants--λ_v describing the increase in indoor air concentration and λ_a describing the decrease in concentration.

Recommended air ventilation rates for single-family housing units are $\lambda_v = 0.5 - 1.5\ hr^{-1}$ (ref. 8). Therefore, for radionuclide half-lives greater than about one day, the reduction factor is independent of the specific radionuclide and depends only upon the air ventilation rate, deposition velocities on inside building surfaces, and building geometry.

To perform calculations with Eq. (3), we make the simplifying assumptions that the building is a hemispherical shell parameterized by the radius, a, and the deposition velocities are described by the single parameter, V_d. Calculations were performed for the following values of input parameters:

$a = 2, 5, 10$ m,

$\lambda_v = 0.2, 1.0, 5.0\ hr^{-1}$,

$V_d = 0.0001, 0.01, 1.0$ cm/sec.

The range of values for V_d is based on theoretical and experimental results for dry deposition processes[9,10] and experiments on iodine vapors.[11] The calculated internal dose reduction factors for V_d = 0.01 and 1.0 cm/sec are shown in Fig. 1. For V_d = 0.0001 cm/sec, the reduction factor is greater than 0.96 for all values of the other parameters.

The internal dose reduction factor decreases (i.e., the protection provided by residence inside the building against inhaled radionuclides increases) with decreasing building radius and air ventilation rate and with increasing deposition velocity. The reduction factor varies by about three orders of magnitude for the range of parameter values studied here.

The model predicts significant reductions in inhalation dose for both short-lived radionuclides (half-lives less than $1/\lambda_v$) and radionuclides occurring in particulate form with deposition velocities greater than about 0.01 cm/sec. For some important radionuclides, however, a

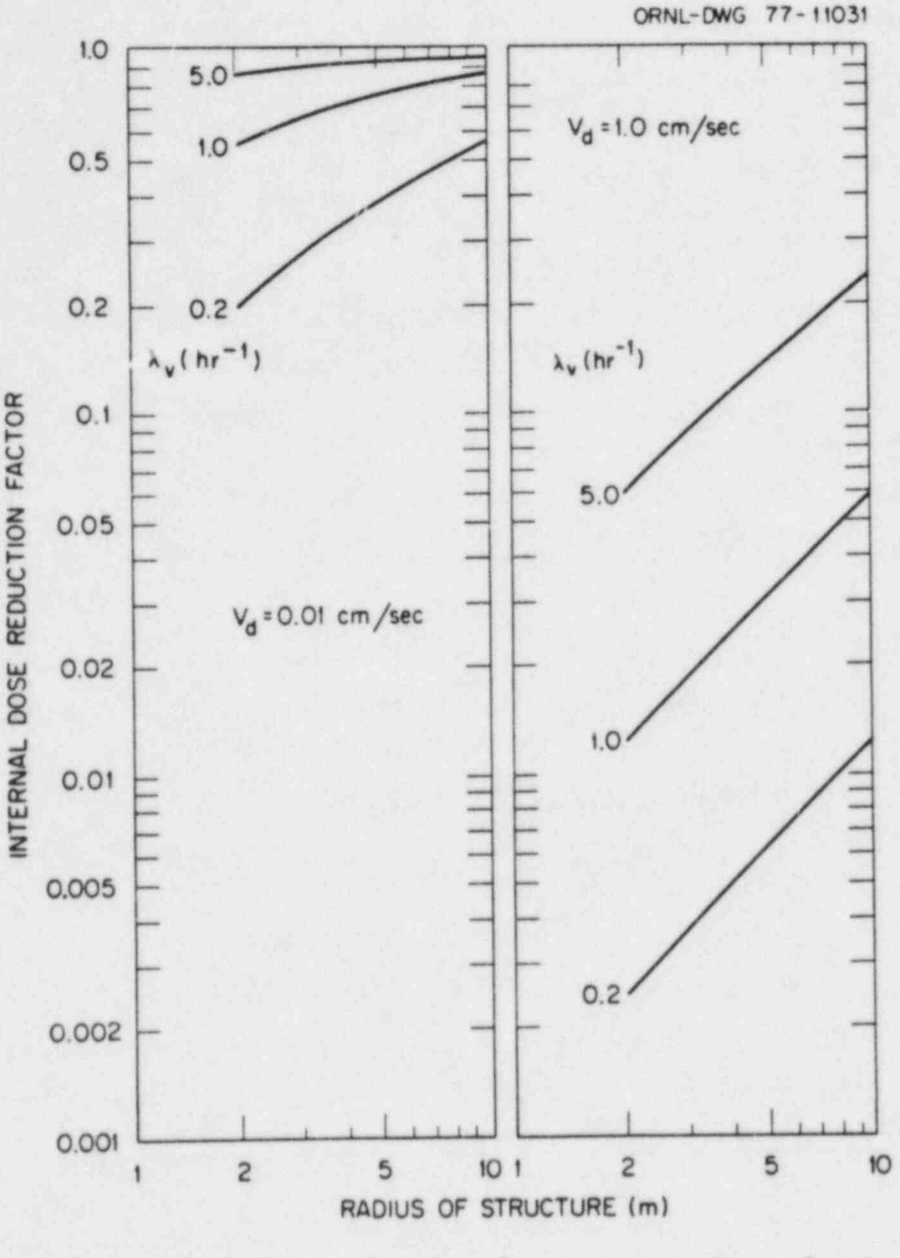


Fig. 1. Internal dose reduction factor vs. radius of a hemispherical building for selected values of the air ventilation rate, λ_v, and deposition velocity, V_d.

building is expected to provide no reduction in inhalation dose. For long-lived noble gases (e.g., ^{85}Kr), the reduction factor is unity since there is no deposition on surfaces. The radionuclides ^{3}H and ^{14}C are expected to occur in the form of tritiated water vapor and carbon dioxide, respectively. Under long term, steady-state conditions, it is reasonable to assume that an equilibrium exists between the rate of deposition and rate of resuspension on inside building surfaces, so that there is no net deposition. Consequently, buildings should provide no reduction in inhalation dose for ^{3}H and ^{14}C under the assumed conditions. This conclusion is not valid if ^{3}H and ^{14}C can be removed from inside air by other means, such as air conditioning, but such processes are not included in the model.

3. EXTERNAL DOSE REDUCTION FACTOR FOR PHOTON EXPOSURE

Building structures provide two kinds of protection against external dose from airborne and surface-deposited radionuclides. One is a geometrical protection resulting from the possible exclusion of radionuclides from inside the building. The other is a reduction in dose from the attenuation by the building walls of radiation originating outside the structure.

In this section, we consider external dose reduction factors from exposure to photon radiation. Absorbed dose rates in air* with and without a building present are calculated using the point-kernel integration method, assuming uniform distributions of radionuclides in the air and on the ground and building surfaces.

3.1. External Dose Rates from Airborne Radionuclides

The absorbed dose rate for photons in air at a given point from a specified volume, v, of airborne radionuclides is given by[12]

---

*Although the absorbed dose rate in air is not the same as the dose-equivalent rate in an exposed individual, the dose reduction factors are essentially the same in the two cases.

$$D_v = kS_v \sum_i \left[\frac{\mu_{en,i}}{\rho}\right] f_i E_i \int_v \frac{1}{4\pi r^2} B_{en}(\mu_i r)\, e^{-\mu_i r}\, dv \ , \qquad (4)$$

where

D_v = absorbed dose rate in air in rad/sec,

$k = 1.6 \times 10^{-8}$ g-rad/MeV,

S_v = airborne radionuclide concentration in dis/cm^3-sec,

$\mu_{en,i}$ = linear energy-absorption coefficient for *ith* photon in air in cm^{-1},

ρ = density of air in g/cm^3,

f_i = intensity of *ith* photon in number per disintegration,

E_i = energy of *ith* photon in MeV,

r = distance from source point to receptor position in cm,

B_{en} = energy-absorption buildup factor in air, and

μ_i = linear attenuation coefficient for *ith* photon in air in cm^{-1}.

The summation is over all photons emitted by the particular radionuclide.

With no building present, we assume that the radionuclides are distributed over a hemispherical volume of infinite radius. The dose rate is then

$$D_{v,o} = \frac{1}{2} kS_v \sum_i \left[\frac{\mu_{en,i}}{\rho}\right] f_i E_i \int_o^\infty B_{en}(\mu_i r)\, e^{-\mu_i r}\, dr \ . \qquad (5)$$

We use the Berger form of the buildup factor[13] given by

$$B_{en}(\mu_i r) = 1 + C_i \mu_i r\, e^{D_i \mu_i r} \ . \qquad (6)$$

The values of the coefficients C_i and D_i are functions of the photon energy.

To calculate the dose rate inside a building, we assume that the structure is a hemispherical shell with radius, a, and wall thickness, x. The dose rate from airborne radionuclides inside the building is obtained from Eqs. (4) and (6) by replacing the outside airborne concentration, S_v, by the inside airborne concentration, $S_v(\lambda_v/\lambda_a)$, from Eq. (3) and integrating over the building interior. Calculation of the dose rate from airborne radionuclides outside the building requires an approximation to the buildup factor for a two-layer medium (air followed by wall material). We use the Bowman-Trubey form[14] given by

$$B_{en}(\mu_i r, \mu_{i,w}x) = B_{en}(\mu_i r)\, B_{en,w}(\mu_{i,w}x)\, e^{-\mu_{i,w}x} + B_{en,w}(\mu_i r + \mu_{i,w}x)\left(1 - e^{-\mu_{i,w}x}\right), \tag{8}$$

where the subscript w denotes buildup factors and attenuation coefficients in the wall material. By using Eq. (6) for both air and wall material, Eq. (4) can then be integrated over the volume outside the building. With the assumed approximations for building shape and buildup factors, the integrals occurring in the expressions for the dose rates from inside and outside the building can be evaluated in closed form. The resulting equations are given in Appendix A.

3.2. External Dose Rates from Surface-Deposited Radionuclides

In calculating external photon dose rates from surface-deposited radionuclides, we assume a constant rate of deposition on the ground and on inside and outside surfaces of the building. Assuming zero radionuclide concentration on surfaces at time zero, the absorbed dose rate in air at a given point from a specified surface, s, of deposited radionuclides is given by

$$D_s(t) = \frac{kS_v V_d}{\lambda} (1 - e^{-\lambda t}) \sum_i \left[\frac{\mu_{en,i}}{\rho}\right] f_i E_i$$

$$\times \int_S \frac{1}{4\pi r^2} B_{en}(\mu_i r) \, e^{-\mu_i r} \, ds \ , \qquad (9)$$

where

t = time in sec,

V_d = deposition velocity in cm/sec,

λ = radioactive decay constant in sec^{-1}.

The remaining quantities are defined in Eq. (4). We note that the dose rate from surface-deposited radionuclides is explicitly time-dependent. The dose rate is monotonically increasing with time and approaches its asymptotic limit when $\lambda t >> 1$. We also note that Eq. (9) assumes that the only mechanism for loss of surface-deposited activity with time is radioactive decay. The inclusion of an empirical model to describe the loss of activity deposited on the ground with time via penetration into the soil and other weathering processes is described in Sect. 6.1.

With no building present, we assume that the radionuclides are deposited on a smooth infinite plane. At a height, z, above the plane, the dose rate is obtained from Eqs. (6) and (9) as

$$D_{s,o}(t) = \frac{1}{2} \frac{kS_v V_d}{\lambda} (1 - e^{-\lambda t}) \sum_i \left[\frac{\mu_{en,i}}{\rho}\right] f_i E_i$$

$$\times \left[\tilde{E}_1(\mu_i z) - \frac{C_i}{(D_i - 1)} e^{(D_i - 1)\mu_i z}\right] . \qquad (10)$$

The quantity $\tilde{E}_1(\mu_i z)$ is the well known first-order exponential integral

$$\tilde{E}_1(\mu_i z) = \int_z^\infty \frac{1}{r} e^{-\mu_i r} dr . \tag{11}$$

With a building present, we calculate the dose rate from radionuclides deposited on (1) the inside walls and ceiling, (2) the floor inside the building, (3) the ground outside the building, and (4) the outside walls and ceiling. As with the calculations for airborne radionuclides, we assume that the building is a hemispherical shell. For term (3), we ignore variations in wall thickness with distance of the source point from the receptor position. The dose rates are calculated from Eqs. (6), (8), and (9). For term (1), the quantity V_d is replaced by $V_d'(\lambda_v/\lambda_a)$ from Eq. (3), where $V_d' = (1/2)(V_{dw} + V_{dc})$. Similarly in term (2), V_d is replaced by $V_{df}(\lambda_v/\lambda_a)$. In term (4), we assume a uniform deposition velocity of $V_d/2$ over the outside walls and ceiling, since the projected area of a hemisphere onto the ground is one-half of the surface area of the hemisphere. Also in term (4), the buildup factor for a two-layer medium given by Eq. (8) is expressed in the form appropriate for wall material followed by air. All integrals can be evaluated in closed form except for first-order exponential integrals. The resulting equations for dose rates inside a building from surface-deposited radionuclides are given in Appendix A.

From the dose rates with and without a building present for airborne and surface-deposited radionuclides given by Eqs. (7) and (10) and the equations in Appendix A, the external dose reduction factor for photon exposure can be calculated in a straightforward manner.

4. PARAMETER SENSITIVITY STUDIES FOR EXTERNAL DOSE REDUCTION FACTOR FOR PHOTON EXPOSURE

In studying the sensitivity of the external dose reduction factor for photon exposure to the various model parameters, we use a fixed accumulation time of t = 20 yr for radionuclides deposited on the ground and the outside walls of the building.* For deposition on inside surfaces, the explicit time-dependence of the dose rates is retained as a free parameter to describe the frequency with which radionuclides are removed by cleaning or other processes.

For an assumed airborne concentration, S_v, the external dose reduction factor depends on the following model parameters:

building radius, a;

air ventilation rate, λ_v;

deposition velocity on floor, V_{df}, and inside walls and ceiling, V_{dw};

deposition velocity on ground and outside walls, V_d;

height of receptor position above ground, z;

wall thickness, x, and building material; and

accumulation time for radionuclides deposited on floor, τ_f, and inside walls, τ_w.

The reduction factor for airborne radionuclides depends only on the parameters a, λ_v, V_{df}, V_{dw}, x, and the building material. The reduction factor for surface-deposited radionuclides depends on all parameters.

The remainder of this section discusses the results of parameter sensitivity calculations for different types of radionuclides.

4.1. Long-Lived Noble Gases

For long-lived noble gases, only airborne radionuclides contribute to external exposure, and since $\lambda \ll \lambda_v$, the dose reduction factor depends only on the building radius, the wall thickness, and the building

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*This accumulation time corresponds to one-half of the expected lifetime of a hypothetical fuel reprocessing plant (see Sect. 7). Since the accumulation time on the ground does not depend on the presence or absence of a building, it is not varied as part of the parameter sensitivity analysis.

material. Calculations for ^{85}Kr, which emits a single photon with E = 514 keV (ref. 15), are shown in Fig. 2. The assumed wall material is concrete with density 2.35 g/cm^3. The building provides very little reduction in external dose for $x \lesssim 5$ cm, a thickness which corresponds to one mean-free-path for a 514-keV photon (1 m.f.p. $\equiv 1/\mu$). The reduction factor is independent of radius for $x \lesssim 10$ cm. For $x > 10$ cm, the reduction factor shows a rapid decrease with increasing wall thickness. For wall thicknesses approaching 30 cm, the reduction factor varies by about a factor of two for a factor of five change in building radius.

4.2. General Results for Other Radionuclides

The external dose reduction factor for airborne and surface-deposited radionuclides is a complicated function of the model parameters and the photon energies, photon intensities, and radionuclide half-life. Therefore, it is difficult to draw conclusions with regard to the sensitivity of the reduction factor to the various parameters that are valid for a wide range of parameter values and photon spectra. To state that the reduction factor is sensitive to a given parameter, we mean that a fractional change in the parameter value results in a comparable fractional change in the reduction factor.

In spite of the large number of parameters involved, the parameter sensitivity analysis has demonstrated that useful qualitative results for the sensitivity of the reduction factor to the input parameters can be obtained for two important cases; namely, a thin-walled structure, defined as having a thickness less than about two photon mean-free-paths, and a thick-walled structure, defined as having a thickness greater than about five photon mean-free-paths.

A thin-walled structure, by definition, allows appreciable transmission of photons through the walls from activity outside the building. Consequently, the reduction factor is relatively large, typically 0.5 or greater in our analysis. In this case, the most important parameter in determining the reduction factor is the wall thickness. Large variations in the other parameters produce only small changes in the reduction factor. For all radionuclides, the variation in dose reduction factor

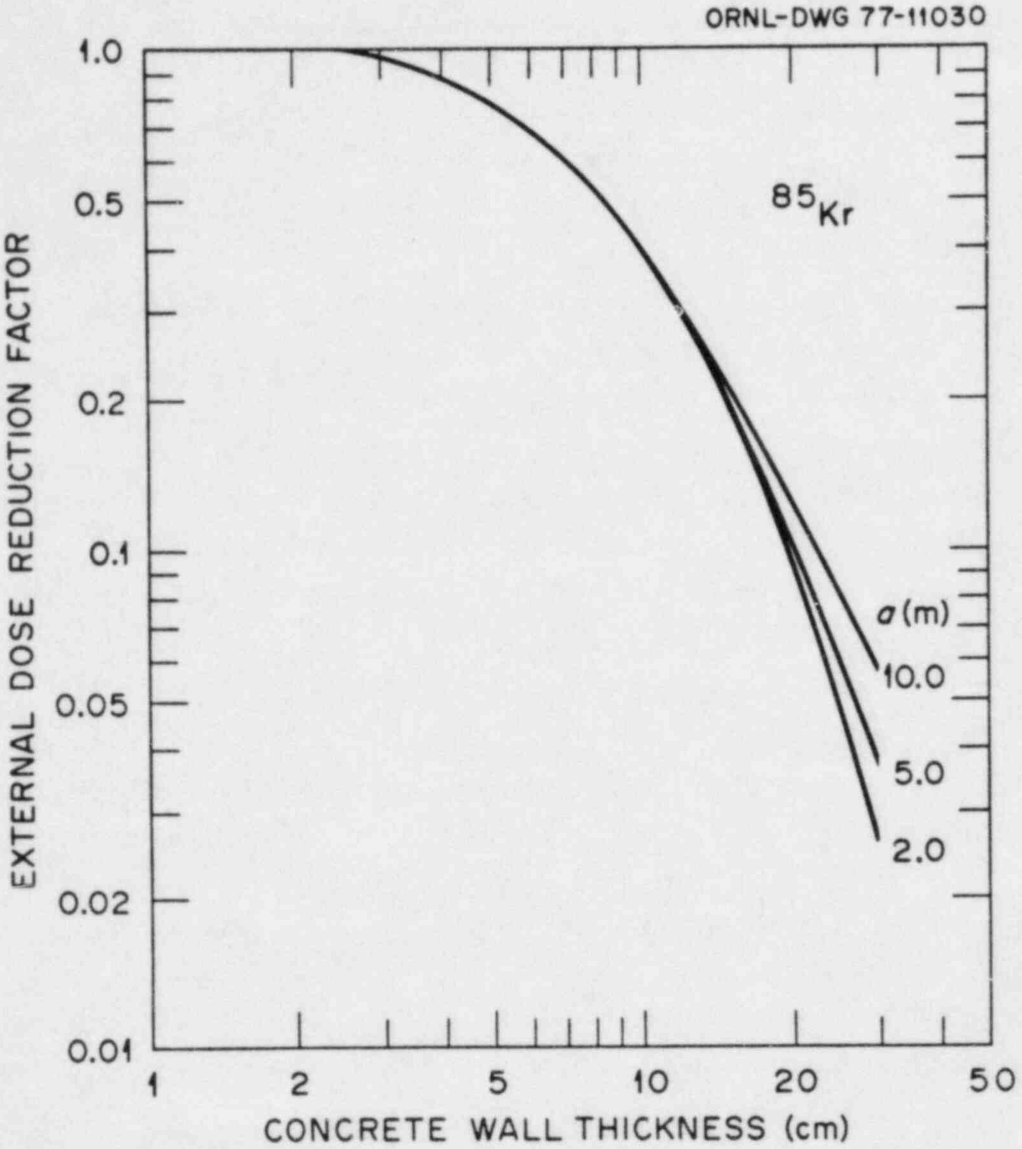

Fig. 2. External dose reduction factor for ^{85}Kr vs. wall thickness of concrete for selected values of the building radius, a.

with wall thickness for thicknesses less than two photon mean-free-paths is very similar to the results for ^{85}Kr for $x < 10$ cm shown in Fig. 2.

A thick-walled structure, on the other hand, allows negligible transmission of photons through the walls from activity outside the building, so that the dose rate is determined almost entirely by the contributions from radionuclides inside the building. The reduction factor is usually reduced significantly compared with values for thin-walled structures, and is independent of the wall thickness as long as the thick-walled condition is maintained. The reduction factor for airborne radionuclides decreases with increasing deposition velocity and decreasing building radius and air ventilation rate. This term is most sensitive to the radius, with less sensitivity to the other parameters. The reduction factor for surface-deposited radionuclides decreases with decreasing building radius, air ventilation rate, and accumulation time for radionuclides deposited on inside surfaces. The dependence on deposition velocities depends on the assumed relationship between the outdoor deposition velocity, V_d, and the indoor deposition velocities, V_{df} and V_{dw}. The most sensitive parameters are the accumulation time and the building radius.

Some numerical results from the parameter sensitivity analysis which are applicable to the cases of thin-walled and thick-walled structures are discussed in the following section.

4.3. Calculations for Specific Radionuclides

External dose reduction factors were calculated for specific radionuclides for the following ranges of parameter values:

$$a = 2 - 10 \text{ m},$$

$$\lambda_v = 0.2 - 5.0 \text{ hr}^{-1},$$

$$V_{df} = V_{dw} \equiv V_d' = 0.0001 - 1.0 \text{ cm/sec},$$

$$V_d = 10V_d',$$

$$z = 1 \text{ m},$$

$$x = 1 - 30 \text{ cm},$$

Wall material = concrete (density = 2.35 g/cm^3), and

$\tau_f = \tau_w \equiv \tau = 7$ d - 20 yr.

The assumed relation between V_d and V_d' recognizes that the two parameters are strongly correlated and that dry deposition velocities in still air indoors are less than deposition velocities outdoors.[9-11] The single value of z used is characteristic of a one-story structure. As a consequence of the assumed relationship between V_d and V_d' and the assumed 20-year accumulation time for radionuclides deposited on outside surfaces, the dose rate from surface-deposited radionuclides is almost always larger than the dose rate from airborne radionuclides.[*]

Many radionuclides of importance in routine releases to the atmosphere emit only low-energy photons ($E < 100$ keV) and/or X rays. Examples are ^{129}I and most alpha-emitting radionuclides. For low-energy photon emitters, the results of the parameter sensitivity analysis described previously for a thick-walled structure are applicable for $x \gtrsim 10$ cm. The dose reduction factor is found to vary widely over the range of parameter values studied. For example, the reduction factor for ^{242}Cm, which emits mostly 14-keV X rays,[15] varies from 0.2 down to as low as 1×10^{-5}.

Many important radionuclides emit mostly high-energy photons ($E > 500$ keV). For these radionuclides, the photon transmission through building walls is non-negligible for thicknesses as large as the maximum value of 30 cm of conrete studied in this analysis. Consequently, the most important parameter for determining the reduction factor is the wall thickness. The reduction factor for ^{134}Cs, for example, varies from 0.03 to 1.1 for the range of parameter values studied. The total variation in reduction factor is thus much less for high-energy than for low-energy

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[*] Calculations were also performed which assumed a 40-year accumulation time for radionuclides deposited on surfaces outside the building, in order to test the sensitivity of the dose reduction factor to this parameter. For long-lived radionuclides emitting only low-energy photons, this change decreased the dose reduction factor by as much as a factor of 2-3 for a few combinations of input parameter values. For most combinations of parameter values, and for all radionuclides emitting high-energy photons, however, the change in dose reduction factor was negligible.

photon emitters. It is noteworthy that for certain parameter values, the model predicts that the presence of a building can actually increase the external photon dose rate compared with no building present. Such an increase occurs only for the smallest values of the wall thickness, and results from an increase in the dose rate from surface-deposited radionuclides. In this case, it appears that the hemispherical structure has the effect of locating surface-deposited radionuclides closer to the receptor point that does a smooth infinite plane.

5. EXTERNAL DOSE REDUCTION FACTOR FOR BETA EXPOSURE

The effects of building shielding on external beta radiation were not considered in Sect. 3. Beta radiation differs from photon radiation in that the former has a finite range in penetrating through matter. This property can be used to obtain estimates of external dose reduction factors for beta radiation which are applicable to most radiological assessments.

From the known ranges of beta particles in matter,[16] the walls of a building can be considered impenetrable to beta radiation emitted by radionuclides. Therefore, in estimating external dose reduction factors for beta exposure, we need only consider radionuclide concentrations inside the building compared with the concentrations with no building present. The estimates given here are based on the observation that most beta particles emitted by radionuclides have average energies less than 1 MeV,[15] so that the range in air is less than about 4 m.[16]

First we consider the beta dose reduction factor for airborne radionuclides. For a building radius greater than 4 m (i.e., a radius greater than the maximum range of beta particles in air), a receptor inside the building would receive the same beta dose from airborne radionuclides as he would from a semi-infinite cloud of the same concentration. Therefore, the reduction factor is just the ratio of the indoor to outdoor concentration, which, from Eq. (3), is

$$RF^{\beta}_{ex}\ (\text{airborne}) = \lambda_v/\lambda_a\ . \qquad (12)$$

For building radii less than the range of beta particles in air, the reduction factor would be less than the value given by Eq. (12). Therefore, this result provides a conservative upper limit for the beta dose reduction factor for airborne radionuclides.

For surface-deposited radionuclides, a receptor inside a building of radius greater than the range of beta particles in air would receive a beta dose only from radionuclides deposited on the floor. Assuming that radioactive decay is the only mechanism for loss of surface-deposited activity and recalling that a surface concentration is the product of an airborne concentration and a deposition velocity, the reduction factor is given by

$$RF_{ex}^{\beta}\ (\text{surface}) = (V_{df}/V_d)\ (\lambda_v/\lambda_a)\ . \tag{13}$$

For building radii less than the range of beta particles in air, the dose to a receptor from surface-deposited radionuclides inside the building would be increased, so that Eq. (13) does not provide a conservative upper limit for the reduction factor. In this case, more detailed calculations based on Loevinger's empirical formula can be used.[17]

6. THE COMPUTER CODE

The computer code BUSH (BUilding SHielding) was written to calculate internal and external dose reduction factors. The code is written in FORTRAN IV for the IBM 360-75/91 computers. The code calculates internal dose reduction factors from Eq. (3). External dose reduction factors for photon radiation are calculated from Eqs. (7) and (10) for the dose rates with no building present and Eqs. (14)-(19) in Appendix A for the dose rates inside a building. The code does not calculate external dose reduction factors for beta radiation.

The code is designed to perform two types of calculations. For a given radionuclide, the user may specify more than one value for each of the model input parameters, in which case the code calculates dose reduction factors for all possible combinations of the different parameters. The same calculations can then be repeated for different radionuclides. This type of calculation is used, for example, to perform a parameter sensitivity analysis. On the other hand, calculations for the purpose of radiological assessments are concerned with source terms containing a mixture of radionuclides with different airborne concentrations. In this case, the code calculates the overall external dose reduction factor for the entire source term as well as the reduction factor for each radionuclide separately. For this type of calculation, only one set of values of the model input parameters may be specified, but the parameter values may differ for each nuclide. The available options for calculations and input data are described in Sect. 6.3.

6.1. Description of Subroutines and Calculational Procedures

A listing of the code BUSH is given in Appendix C. The code consists of a main program, seven subroutines and function subprograms, and a locally available systems function.

The MAIN PROGRAM handles the input of all radionuclide data and model parameter values, calculates photon attenuation coefficients, energy-absorption coefficients, and buildup factor parameters from data libraries described in Sect. 6.2, and handles all output of data and dose reduction factors.

CONVER converts input values of times to units of seconds using the locally available systems function ICOMPA.

YINTER, a single precision version of the double precision function YLAG,[18] performs Lagrangian interpolation of a function of one variable.

PFINT calculates internal dose reduction factors.

SUBROUTINE PFEXT calculates dose rates and reduction factors for external exposure to photon radiation.

E1 calculates first-order exponential integrals using polynomial and rational approximations.[19]

EXPF1 calculates expressions of the form

$$f(x) = \frac{1}{x}\,(1 - e^{-x}),\ x > 0\ ,$$

for which a loss of significance can occur when $0 < x << 1$. For $0 < x \leq 0.03$, the expression is evaluated using the first seven terms of its power series expansion.

RETEN calculates the time dependence of the dose rate from radionuclides deposited on the ground. If we assume that the only loss mechanism for radionuclides deposited on the ground is radioactive decay, the retention function for a unit concentration of activity is

$$R(t) = e^{-\lambda t},$$

where λ is the radioactive decay constant. As given in Eq. (10) and in Eq. (18) in Appendix A, the time-dependence of the dose rate is then

$$D(t) \sim \frac{1}{\lambda} (1 - e^{-\lambda t}) .$$

In order to account for the reduction in dose rate with time resulting from penetration into the ground and other weathering effects, the user may choose instead a retention function

$$R(t) = f_w(t)\ e^{-\lambda t} ,$$

where $f_w(t)$ is given by Eqs. (VI 8-1) and (VI 8-2) of ref. 20 as

$$f_w(t) = 0.63\ e^{-1.13t} + 0.37\ e^{-0.0075t} .$$

In these expressions, t is in years and λ in yr^{-1}. For either retention function R(t), the time-dependence of the dose rate from activity deposited on the ground during the release period is

$$D(t) \sim \int_0^t R(t')\, dt' .$$

6.2. Data Libraries

In order to calculate external dose reduction factors, values of the attenuation and energy-absorption coefficients in air, the attenuation coefficients in the building material, and the Berger buildup factor coefficients for energy-absorption buildup factors in air and the building material are required for each photon. The code calculates these quantities by quadratic interpolation from reference values of these parameters contained in data statements in the main program. The data statements contain the values of each parameter at twenty-five energies between 10 keV and 10 MeV.

For photons in air, the reference values of mass attenuation and mass energy-absorption coefficients were obtained from ref. 21. The buildup factor parameters were obtained from a linear least-squares fit to energy-absorption buildup factors given in refs. 22 and 23.

To calculate photon transmission through the building walls, the user chooses a wall material from four options--concrete, water, aluminum, or wood. Mass attenuation coefficients for each material were obtained from ref. 21. The values for wood were obtained by assuming that the material is cellulose ($C_6H_{10}O_5$) and adding the values for carbon, hydrogen, and oxygen in proportion to the atomic weight of each constituent. The buildup factor parameters for concrete, water, aluminum, and wood were obtained from energy-absorption buildup factors given in refs. 24, 22, 25, and 23, respectively. Buildup factors for aluminum and wood have not been published for energies less than 0.5 MeV. At these energies, the buildup factor parameters for aluminum and wood are assumed to be the same as the values for concrete and water, respectively, since the corresponding pairs of materials have similar average atomic numbers.

6.3. Description of Input

The card input for the computer code is divided into 17 card sets. The description for each card set given below contains the variables in the order in which they are entered, the FORTRAN format, the definition of the variables and their identification with parameters defined in Sect. 4, and directions or limitations for use of the card set.

Card Set 1: NMIX - I1

NMIX = 0 - Calculate overall external dose reduction factor for mixture of nuclides and airborne concentrations to be read in (limit of 75 nuclides)

1 - Omit calculations of overall external dose reduction factor for mixture of input nuclides

For NMIX = 0, only a single value of each input parameter can be used for each nuclide (i.e., enter 1 for all parameters on Card Set 6 and 13). For NMIX = 0, all nuclides in the source term must emit at least one photon, and NEXD must be 0 on Card Set 2.

Card Set 2: NINT, NEXD, NPEN - 3I1

NINT = 0 - Output internal dose reduction factors
1 - Omit output of internal dose reduction factors
NEXD = 0 - Calculate external dose reduction factors and output all contributions to dose rates and dose reduction factors; NEXD must be 0 if NMIX = 0 on Card Set 1
1 - Calculate external dose reduction factors and output only total dose reduction factor for airborne plus surface-deposited radionuclides
2 - Omit external dose reduction factor calculations
NPEN = 0 - Calculate dose rates from radionuclides deposited on the ground using the retention function which allows for penetration into the ground as well as radioactive decay
1 - Calculate dose rates from radionuclides deposited on the ground using the retention function which allows only for radioactive decay

Card Set 3: INUCL, THALF, UNIT - 2A4, 2X, E10.4, 1X, A1

INUCL - Radionuclide name
THALF - Radionuclide half-life in units of seconds, hours, days, or years
UNIT - Units for half-life (S, H, D, or Y)

Card Set 4: E(I), FINT(I) - 2F10.5

E(I) - Energy of i*th* photon in MeV
FINT(I) - Intensity of i*th* photon in number per decay
Read one card for each photon emitted by the radionuclide (limit of 300 photons); following the last photon card, enter E = 0.0 to

end this card set. If the radionuclide emits no photons, enter E(1) = 0.0 as the entire card set.

If NEXD = 2 from Card Set 1 or the radionuclide emits no photons, go to Card Set 13.

The following applies if a complete set of input data has previously been read. If NGO = 4 from Card Set 17 and NMIX = 0 from Card Set 1, go to Card Set 7. If NGO = 4 and NMIX = 1, go to Card Set 17.

Card Set 5: IMAT, NMAT, RHOM - 2A4, I2, F10.3

IMAT - Building material name (CONCRETE, WATER, ALUMINUM, or WOOD)

NMAT - Index to identify building material; 1 = CONCRETE, 2 = WATER, 3 = ALUMINUM, 4 = WOOD

RHOM - Density of building material in g/cm^3

Card Set 6: NVD, NZ, NT, NTFW - 4I2

NVD - Number of values of the deposition velocity on the ground and outside walls of the building, V_d, to be read in on Card Set 8; NVD must equal NVDFW on Card Set 13

NZ - Number of values of the height of the receptor position above ground, z, to be read in on Card Set 9

NT - Number of values of the wall thickness, x, to be read in on Card Set 10

NTFW - Number of values of the accumulation time for activity deposited on the floor, τ_f, and inside walls, τ_w, of the building to be read in on Card Set 11

The limit for each parameter on this card set is 10. Enter NVD = NZ = NTFW = 1 if the outdoor deposition velocity, V_d, is zero. Enter NVD = NZ = NT = NTFW = 1 if NMIX = 0 from Card Set 1.

Card Set 7: SV - E10.4

SV - Airborne radionuclide concentration, S_v, in nCi/cm^3

If a complete set of input data has previously [illegible] read and if NGO = 4 from Card Set 17 and NMIX = 0 from Card Set 1, go to Card Set 17.

Card Set 8: VD(1), VD(2), ..., VD(NVD) - 8E10.4

VD - Deposition velocity on the ground and outside walls of the building, V_d, in cm/sec; enter NVD values (see Card Set 6)

Card Set 9: Z(1), Z(2), ..., Z(NZ) - 8E10.4

Z - Height of receptor position above ground, z, in cm; enter NZ values (see Card Set 6)

Card Set 10: T(1), T(2), ..., T(NT) - 8E10.4

T - Wall thickness, x, in cm; enter NT values (see Card Set 6)

Card Set 11: TF(1), UNF(1), TW(1), UNW(1), TF(2), UNF(2), TW(2), UNW(2), ..., TF(NTFW), UNF(NTFW), TW(NTFW), UNW(NTFW) - 8(E8.2, 1X, A1)

TF - Accumulation time for activity deposited on the floor of the building, τ_f, in units of seconds, hours, days, or years; enter NTFW values (see Card Set 6)

UNF - Units for TF (S, H, D, or Y)

TW - Accumulation time for activity deposited on inside walls of the building, τ_w, in units of seconds, hours, days, or years; enter NTFW values (see Card Set 6)

UNW - Units for TW (S, H, D, or Y)

Card Set 12: TG - E10.4

TG - Accumulation time for activity deposited on the ground and outside walls of the building in years

Card Set 13: NA, NCLV, NVDFW - 3I2

NA - Number of values of the building radius, a, to read in on Card Set 14

NCLV - Number of values of building air ventilation rate, λ_v, to be read in on Card Set 15

NVDFW - Number of values of deposition velocity on floor, V_{df}, and inside walls, V_{dw}, of building to be read in on Card Set 16; NVDFW must equal NVD on Card Set 6

The limit for each parameter on this card set is 10, and the product of the three values cannot exceed 125. Enter NVDFW = 1 if the indoor deposition velocities, V_{df} and V_{dw}, are zero. Enter NA = NCLV = NVDFW = 1 if NMIX = 0 from Card Set 1.

Card Set 14: A(1), A(2), ..., A(NA) - 8E10.4

A - Building radius, a, in cm; enter NA values (see Card Set 13)

Card Set 15: CLV(1), CLV(2), ..., CLV(NCLV) - 8E10.4

CLV - Building air ventilation rate, λ_v, in hr^{-1}; enter NCLV values (see Card Set 13)

Card Set 16: VDF(1), VDW(1), VDF(2), VDW(2), ..., VDF(NVDFW), VDW(NVDFW) - 8E10.4

VDF - Deposition velocity on floor of building, V_{df}, in cm/sec; enter NVDFW values (see Card Set 13)

VDW - Deposition velocity on inside walls of building, V_{dw}, in cm/sec; enter NVDFW values (see Card Set 13)

Card Set 17: NGO - I1

NGO = 0 - Exit from program
1 - Input new building material and subsequent input for the same radionuclide; go to Card Set 5
2 - Input new radionuclide and subsequent input; go to Card Set 3
3 - Input new parameter values for the same radionuclide and building material; go to Card Set 6
4 - Input new radionuclide data only; go to Card Set 3

The card sets described above can be divided into six groups. Card Sets 1 and 2, which are input only once each time the program is run, provide controls over the type of calculations to be performed and the output of dose reduction factors. Card Sets 3 and 4 give the radionuclide data. Card Set 5 gives the data on the building material. Card Sets 6-12 give the model parameters required to calculate external dose reduction factors which are not used to calculate internal dose reduction factors. Card Sets 13-16 give the model parameters required to calculate both internal and external dose reduction factors. Card Set 17 provides a control for choosing additional calculations during the same run.

A large number of calculations may be performed during a single run with a minimum of card input for each calculation. Suppose, for example, that the user wishes to perform a parameter sensitivity analysis for more than one radionuclide in which the building material and model parameter values are the same for each nuclide.* For the first nuclide, all card sets are entered. If NGO = 4 on Card Set 17, only Card Sets 3, 4, and 17 are entered for all subsequent nuclides. For each nuclide, the code calculates dose reduction factors for all possible combinations of the following six groups of parameters: a; λ_v; V_d, V_{df}, and V_{dw}; z; x; and τ_f and τ_w. The parameters within each group (e.g., V_d, V_{df}, and V_{dw}) are not varied independently. Therefore, the number of internal dose reduction factors calculated is the product of NA, NCLV, and NVDFW (see Card Set 13); the number of external dose reduction factors calculated is the product of NA, NCLV, NVD, NZ, NT, and NTFW (see Card Sets 6 and 13).

As a second example, suppose the user wishes to calculate the overall external dose reduction factor for a given source term, with the same building material and model parameter values for each nuclide in the source term. Again, all card sets are entered for the first nuclide, with only one value of each model parameter allowed. If NGO = 4 on Card

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*In a parameter sensitivity analysis, calculations of the overall dose reduction factor for a mixture of the input nuclides are not performed (i.e., NMIX = 1 on Card Set 1). It is then convenient to set the airborne concentration, S_v, on Card Set 7 equal to unity for all nuclides.

Set 17, only Card Sets 3, 4, 7, and 17 are entered for the remaining nuclides.

For either of the two examples described above, parameter values may be changed as desired after the calculations for any radionuclide by use of the parameter NGO on Card Set 17. Examples of input data decks for different types of calculations are given in Appendix B.

7. APPLICATION OF MODELS TO RADIOLOGICAL ASSESSMENTS

The building shielding effects models were developed for the purpose of providing estimates of internal and external dose reduction factors for routine radiological assessments of chronic releases of radionuclides to the atmosphere. In this section, we apply the models to a population dose assessment on a regional U.S. scale.

Dose reduction factors were calculated for a source term for routine emissions from a hypothetical fuel reprocessing plant. The source term radionuclides and their emission rates are given in Table 1. Since the half-lives for most of the nuclides are long compared with expected residence times in the atmosphere, the airborne concentration at any location relative to the release point was assumed to be proportional to the release rate in Table 1. Calculations were performed for buildings of both concrete and wood construction using the assumed average parameter values given in Table 2. The accumulation time for radionuclides deposited on the ground was taken to be 20 years, and the retention function incorporating penetration of activity into the ground with time (Sect. 6.1) was used. Internal dose reduction factors were also calculated using an indoor deposition velocity of 0.01 cm/sec for particulates and 0.04 cm/sec for iodine. The resulting dose reduction factors are given in Table 3. These results assume that man spends 100% of his time indoors; they may easily be corrected to account for the average indoor residence time of about 90%.[1]

For radiological assessment purposes, the larger values of the internal dose reduction factors corresponding to the smaller deposition velocities should be appropriate, since the resulting population doses are

Table 1. Source term for a fuel reprocessing plant[a]

Nuclide	Release Rate (Ci/yr)	Nuclide	Release Rate (Ci/yr)
^{3}H	2.42E+4[b]	^{233}U	5.99E-12
^{14}C	1.33E-1	^{234}U	7.16E-9
^{85}Kr	3.94E+4	^{235}U	6.21E-9
^{89}Sr	2.00E-3	^{236}U	9.64E-8
^{90}Sr	2.83E-2	^{238}U	1.14E-7
^{95}Zr	1.02E-2	^{237}Np	1.96E-7
^{95m}Nb	2.16E-4	^{239}Np	6.36E-6
^{95}Nb	2.17E-2	^{236}Pu	1.59E-7
^{103}Ru	2.26E-3	^{238}Pu	1.07E-3
^{106}Ru	2.99E-1	^{239}Pu	1.21E-4
^{129}I	1.39E-3	^{240}Pu	1.80E-4
^{131}I	7.23E-12	^{241}Pu	3.98E-2
^{134}Cs	6.39E-2	^{242}Pu	4.97E-7
^{137}Cs	3.84E-2	^{241}Am	1.11E-4
^{137m}Ba	3.59E-2	^{242m}Am	1.46E-6
^{141}Ce	2.10E-4	^{242}Am	1.46E-6
^{144}Ce	1.67E-1	^{243}Am	6.36E-6
^{144}Pr	1.67E-1	^{242}Cm	2.19E-3
^{147}Pm	3.1E-2	^{243}Cm	1.45E-6
^{232}U	3.06E-9	^{244}Cm	8.88E-4

[a] Obtained from ref. 26.

[b] Read as $2.42 \times 10^{+4}$.

likely to be conservative. In order to obtain an average value for the external dose reduction factor for any region of the U.S., a weighted average of the values for concrete and wood can be used, depending on the relative abundance of each type of building material.[28]

It should be emphasized that the calculated external dose reduction factors are probably conservative; that is, they underestimate the actual building shielding effects on population doses. We have assumed that all buildings are simple one-story structures and, thus, have not

Table 2. Parameter values for dose reduction factor calculations for source term from fuel reprocessing plant

Parameter	Value
Building radius, a	5 m
Air ventilation rate, λ_v	1 hr^{-1}
Indoor deposition velocities, V_{df} and V_{dw}	0.1 cm/sec - particulates; 0.4 cm/sec - iodine
Outdoor deposition velocity, V_d	10 V_{df}
Height of receptor position above ground, z	1 m
Wall thickness, x	9 cm - concrete[a] 17 cm - wood[a]
Accumulation times on floor and walls, τ_f and τ_w	1 year

[a] Obtained from ref. 27.

properly accounted for residence time in schools, office buildings, apartment houses, etc., which provide considerably more shielding.[7] In addition, our models do not account for the effects of ground roughness and terrain irregularities[7,29,30] and for mutual shielding of buildings in urban environments.

The calculations of external dose reduction factors may be refined by allowing the relative concentrations of the different radionuclides in the source term to vary with distance from the release point in order to account for differing rates of decay and plume depletion. Such a modification may be important when the radionuclides have half-lives comparable with the residence time in the atmosphere or widely different deposition velocities. For example, calculations allowing for radioactive decay and plume depletion for the source term from a nuclear reactor

Table 3. Dose reduction factors for source term from fuel reprocessing plant

Internal exposure

Nuclides	Indoor deposition velocity (cm/sec)	Dose reduction factor
Particulates	0.01	0.76
	0.1	0.24
Iodine	0.04	0.44
	0.4	0.072
^3H, ^{14}C, ^{85}Kr	0.0	1.0

External exposure

Building material	Thickness (cm)	Dose reduction factor
Concrete	9	0.52
Wood	17	0.82

accident[20] showed a change in external dose reduction factor of 10% over a distance of 50 miles from the release point.

8. CONCLUSION

This report has presented models to describe the effects of man's residence inside buildings on internal dose from inhaled radionuclides and external photon dose from airborne and surface-deposited radionuclides. The models are formulated so that they are readily applicable to any radionuclides and, thus, are useful in routine radiological assessments of population doses from chronic releases to the atmosphere from any type of nuclear facility or other source.

The external dose rates calculated using the point-kernel integration method are based on several approximations and simplifying assumptions. Among the most important are: (1) assuming infinite, uniform distributions of radionuclides in the air and on the ground; (2) assuming a single simple building geometry and homogeneous walls of uniform thickness; (3) applying buildup factors for infinite, homogeneous media to calculations for finite structures; and (4) using the Berger and Bowman-Trubey approximations for buildup factors. It is clear, therefore, that the ability to calculate accurate absolute dose rates for the variety of indoor environments encountered during man's daily activities is inherently limited. In calculating ratios of dose rates inside and outside a building, however, some inaccuracies in the separate dose rates will tend to cancel. Furthermore, the models probably underestimate actual building shielding effects. Therefore, we believe that the calculated dose reduction factors provide useful estimates for the purpose of population dose assessments. For some applications, uncertainties in the proper values of some of the model parameters, such as the deposition velocities and accumulation times for activity deposited on surfaces, may limit the accuracy of the calculations more than limitations inherent in the models.

Our application of the building shielding effects models has demonstrated the potential importance of radionuclide deposition on inside building surfaces on the dose reduction factors for both internal and external exposure. This process appears not to have been considered in previous work. The calculated internal dose reduction factors can vary by about two orders of magnitude for reasonable variations in the indoor deposition velocity. For external photon exposure, the calculated dose reduction factor is essentially proportional to the accumulation time for activity deposited on inside building surfaces for radionuclides having long half-lives and emitting only low-energy photons.

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