Building Protection Factors for Environmental Exposure to Radionuclides and Monoenergetic Photon Emissions

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Presentation Overview

- Background
- Functions and Factors
  - Example calculation
  - Comparisons with other work
- Application
- Technical Bases
  - Housing survey
  - Model development
  - PF calculations
- References

Background

- Building Protection Factors (PF) - Characterize the quality of shielding available to a local population.
  - P = Building Protection Factor
  - D_o = Standard Protected location
  - D = Unprotected Location (Shielded)

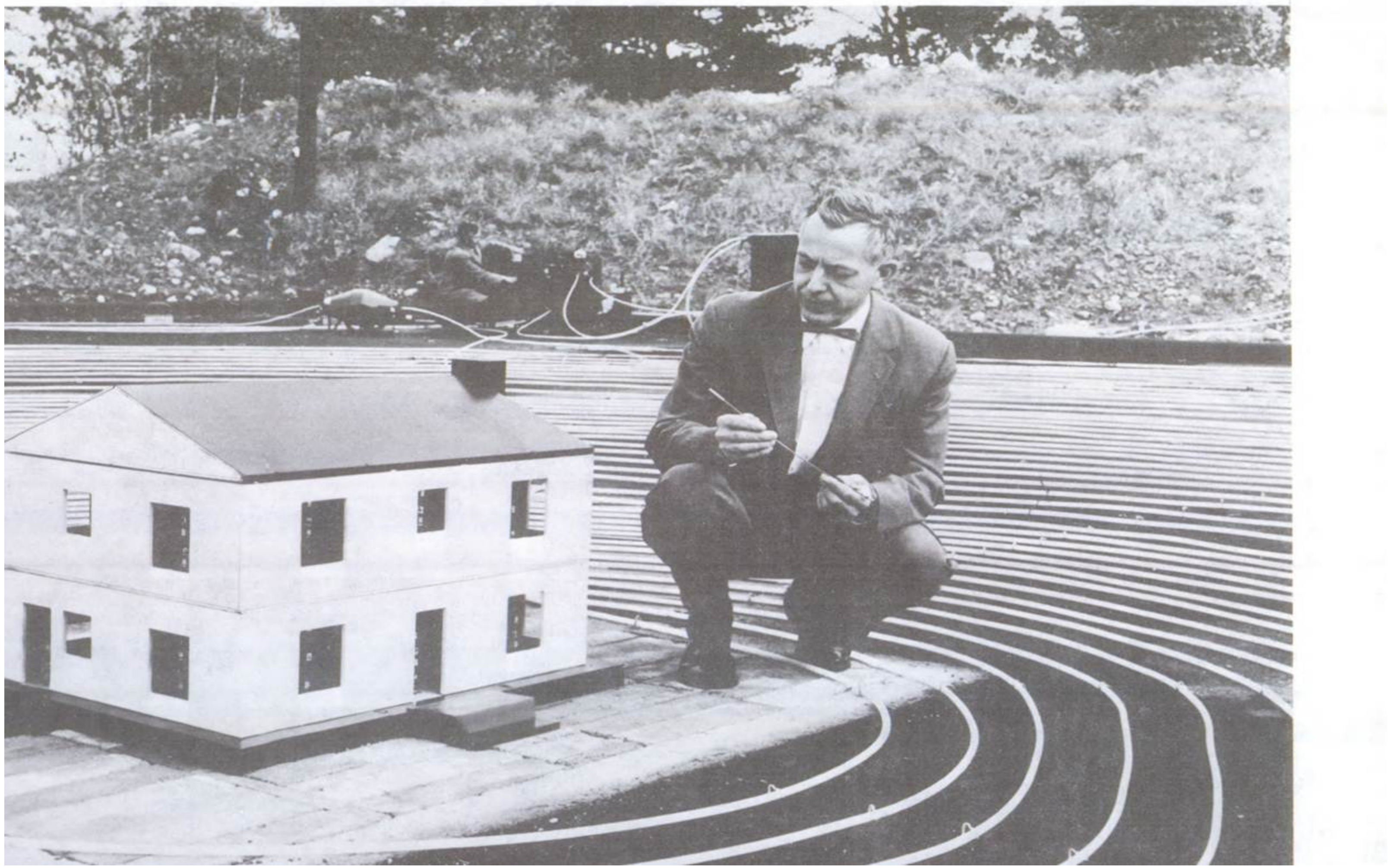
$$P = \frac{D}{D_o}$$

- Generally, two types;
  - Semi-infinite cloud, and
  - Contaminant deposition.

- Concept of sheltering populations from radiation fallout has been studied since the early-1950
  - National Fallout Shelter Survey.
  - Various methods have been used to estimate Factors (Measurement, Point-kernel- and Monte Carlo calculations)
  - Burson and Profio (1975) are commonly references values (several consequence studies).

- Limitations…
  - 1950's and 1960's era construction technology and practices.
  - Few building-types. Circular referencing.
  - Applicable to limited source terms…
  - Impractical to develop factors specific to a spectrum of photons emitted by each radionuclide of interest.

Background



Early full-scale shielding measurement with tube and source experimental setup.

Cut to the chase… Functions, Factors, and Results

- **This work – Developed PFs for generic one- and two-story housing-unit models that are source-term dependent.**
    - **Simple, referenceable tool to compute tailor-made PF for consequence analysis.**

- **Functions** –
    - Based on a series of Monte Carlo photon transport simulations (MCNP5) for 16 monoenergetic energies from 0.10 to 3.0 MeV which characterize the 3D radiation fluence through each housing-unit produced by two idealized, yet realistic, environmental exposure scenarios.
        - (1) Semi-infinite cloud and (2) Deposition on surrounding surfaces.
        - Models based on standard building practices and material properties developed by table-top experiments
    - Simulations results used to develop fitted logarithmic functions correlate an estimated factor to any monoenergetic photon energy up to 3.0 MeV.
    - Compatible with EPA FGR DCFs for external exposures.

- **Factors** –
    - Purpose was to verify Functions ability to predict PFs (instead of performing individual, time-intensive Monte Carlo simulations.)
    - Simulations were performed for a select set of radionuclides to develop radionuclide-specific PF. (ICRP-107 decay data)
        - Xe-135m (~0.3 MeV) – “Low-energy”
        - Cs-137/Ba-137m (~0.6 MeV) – “Medium-energy”
        - Co-60 (>1.0 MeV) - “High-energy”
        - IR-192

- **Result** –
    - Good agreement is achieved between PF Functions and those calculated directly using Monte Carlo methods.
    - Found general agreement with other study results reported on similar structures which applied various computational methods and source-terms.

How the Functions work… example calculation

- House-type: **Two-story, vinyl siding, and asphalt roof**
- Environmental Exposure: **Deposition**
- Source term: **Cs-137/Ba-137m**
- Applicable Protection Factor (PF) Functions:

Second Floor	$PF = 0.0466\ln(x) + 0.5378$	$R^2 = 0.9950$
First Floor	$PF = 0.0491\ln(x) + 0.5540$	$R^2 = 0.9934$
Basement	$PF = -0.0160\ln(x) + 0.0604$	$R^2 = 0.9631$
Weighted Average	$PF = 0.0333\ln(x) + 0.3900$	$R^2 = 0.9924$

Source: Table B5 of E D Dickson and D M Hamby 2016 J. Radiol. Prot. 36 579

  - Where x is photon energy in MeV
- Calculation:
  - **Step 1** – Compute a PF for each photon energy (energy range between 0.05-3.0 MeV)
  - **Step 2** – Normalize each PF per nuclide disintegration by multiplying the photon energy %-contribution per disintegration
  - **Step 3** – Sum the Normalized PFs to compute a total PF per nuclide disintegration

Steps 1&2

Cs-137/Ba-137m Gamma Spectra Data				Protection Factors PF * E-%/dis			
γ-#	MeV	Intensity/dis	E-%/dis	2nd Floor	1st Floor	Basement	Weighted
1	0.004	0.000	0%	3.51E-05	3.54E-05	2.49E-05	2.58E-05
2	0.004	0.000	0%	2.02E-05	2.04E-05	1.40E-05	1.49E-05
:	:	:	:	:	:	:	:
20	0.662	0.898	71%	4.74E-01	4.88E-01	8.34E-02	3.44E-01
			PF Sum =	**0.51**	**0.52**	**0.10**	**0.37**

Step 3

Validation: PF Function Prediction vs MCNP-specta			
Location	Predicted	MCNP	%-Difference
Second Floor	0.51	0.51	**0.00%**
First Floor	0.52	0.52	**0.00%**
Basement	0.09	0.09	**0.00%**
Weighted Average	0.37	0.37	**0.00%**

Note: Excellent Agreement

Radionuclide-specific factors…

- Okay to use these if you don't want to go through the trouble to computing your own.

Table C2. Two-story housing unit—radionuclide-specific cloud immersion factors.

Wall barrier	Housing-unit type and location	Protection factors				Shielding factors			
		Co-60	Cs-137	Ir-192	Xe-135m	Co-60	Cs-137	Ir-192	Xe-135m
Vinyl siding									
	With out basement								
	Second floor	0.89	0.85	0.81	0.83	0.80	0.76	0.72	0.75
	First floor	0.77	0.72	0.67	0.68	0.75	0.70	0.64	0.66
	Weighted average	0.83	0.79	0.74	0.76	0.77	0.73	0.68	0.71
	With basement								
	Second floor	0.88	0.85	0.80	0.83	0.80	0.76	0.72	0.75
	First floor	0.76	0.71	0.66	0.67	0.74	0.69	0.63	0.65
	Basement	0.43	0.37	0.32	0.34	0.42	0.36	0.31	0.33
	Weighted average	0.69	0.64	0.60	0.61	0.65	0.60	0.55	0.58
Brick siding									
	With out basement								
	Second floor	0.64	0.56	0.50	0.52	0.58	0.49	0.44	0.47
	First floor	0.45	0.36	0.31	0.32	0.44	0.35	0.30	0.31
	Weighted average	0.55	0.46	0.41	0.42	0.51	0.42	0.37	0.39
	With basement								
	Second floor	0.64	0.55	0.49	0.52	0.58	0.49	0.44	0.47
	First floor	0.44	0.35	0.31	0.32	0.43	0.34	0.29	0.31
	Basement	0.21	0.16	0.13	0.15	0.21	0.16	0.12	0.15
	Weighted average	0.43	0.36	0.31	0.33	0.41	0.33	0.29	0.31

Source: Table B5 of E D Dickson and D M Hamby 2016 J. Radiol. Prot. 36 579

Comparisons with other published factors (deposition)

- Methods Applied:
  - Stickler – Full-scale Measurements
  - Burson – Point-kernel calculations
  - Meckbach – Monte Carlo calculations

- Take-aways…
  - General agreement between methods and structures.
  - **Functions provide a quick way to compute source-term specific PF**
  - Source terms differ and change with time…

Table 6. Comparison between other study results and the one- and two-story function predicted Protection Factors.

Previous studies

	Stickler and Auxier (1960)[a]		Burson (1975, 1977)[b]		Meckbach *et al* (1988)[c]		
	Co-60 sources		Reactor source term[d]		0.3 MeV	0.662 MeV	3.0 MeV
Location	Wood	Concrete block	Wood, 1 and 2 story	Brick, 1 and 2 story	Pre-fabricated (wood walls, concrete roof)		
Attic	—	—	—	—	0.54	0.62	0.67
Second floor	—	—	—	—	—	—	—
First floor	0.23–0.43	0.23–0.29	—	—	0.47	0.50	0.58
Basement	0.08	0.07	0.03–0.05	0.03–0.05	0.01[e]	0.02[e]	0.05
Averaged	—	—	0.40	0.20	0.34	0.38	0.43

Current study

	Table B2 functions		Table B5 functions		Table B5 functions		
	Co-60 source spectra ICRP 107		Reactor source term		0.3 MeV	0.662 MeV	3.0 MeV
Location	Vinyl	Brick	Vinyl, 1 and 2 story	Brick, 1 and 2 story	Vinyl	Vinyl	Vinyl
Attic	—	—	—	—	—	—	—
Second floor	—	—	—	—	0.48	0.52	0.59
First floor	0.55	0.29	—	—	0.47	0.51	0.59
Basement	0.07	0.06	0.07–0.08	0.04–0.06	0.10	0.09	0.06
Averaged	0.31	0.18	0.31–0.40	0.18–0.21	0.36	0.37	0.40

Source: E D Dickson and D M Hamby 2016 J. Radiol. Prot. 36 579

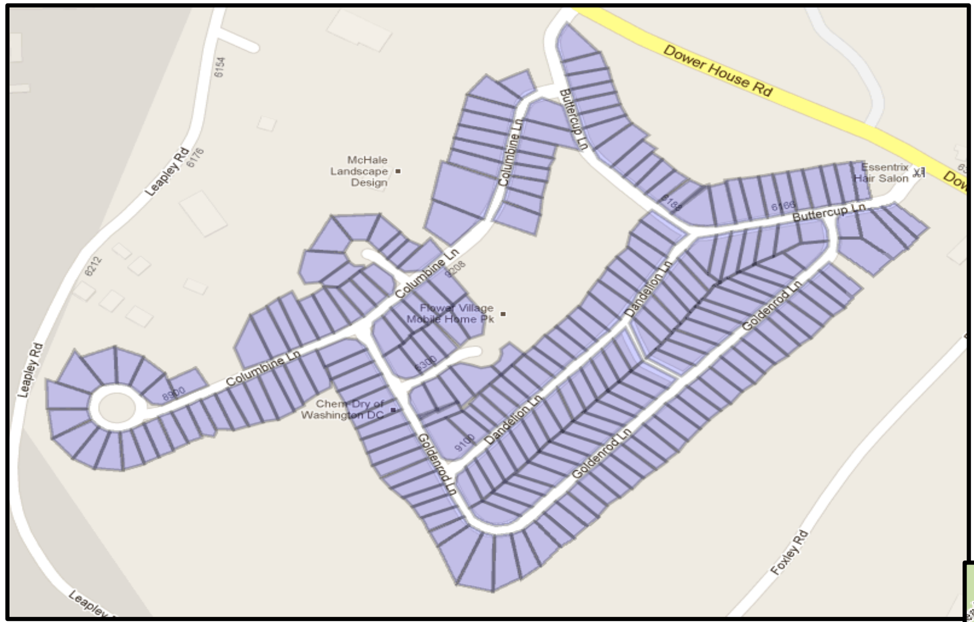
Body of work…

- Dickson E and Hamby D 2016 Building protection- and building shielding-factors for environmental exposure to radionuclides and monoenergetic photon emissions J. Radiol. Prot. 36 579
- Dickson E and Hamby D 2015 Contaminant deposition building shielding factors for US J. Radiol. Prot. 34 317–41
- Dickson E and Hamby D 2014b Cloud immersion building shielding factors for US residential structures J. Radiol. Prot. 34 853–71
- Dickson E and Hamby D 2014a Experimental shielding evaluation of the radiation protection provided by the structurally significant components of residential structures J. Radiol. Prot. 34 201–21
- Dickson E 2013 Experimental shielding evaluation of the radiation protection provided by residential structures Dissertation Corvallis, Oregon State University

Other Items…

- Papers referenced by various organizations (EPA FGR 15, FRMAC, NRC)
- Continued planning/work to develop a ‘utility’ to automate calculations
- Develop PF for other environmental sources (at depth soil contamination)
- Make MCNP housing model input decks publicly available.
- Other continued research…

Application – (Sheltering decisions)



← Manufactured Home Community

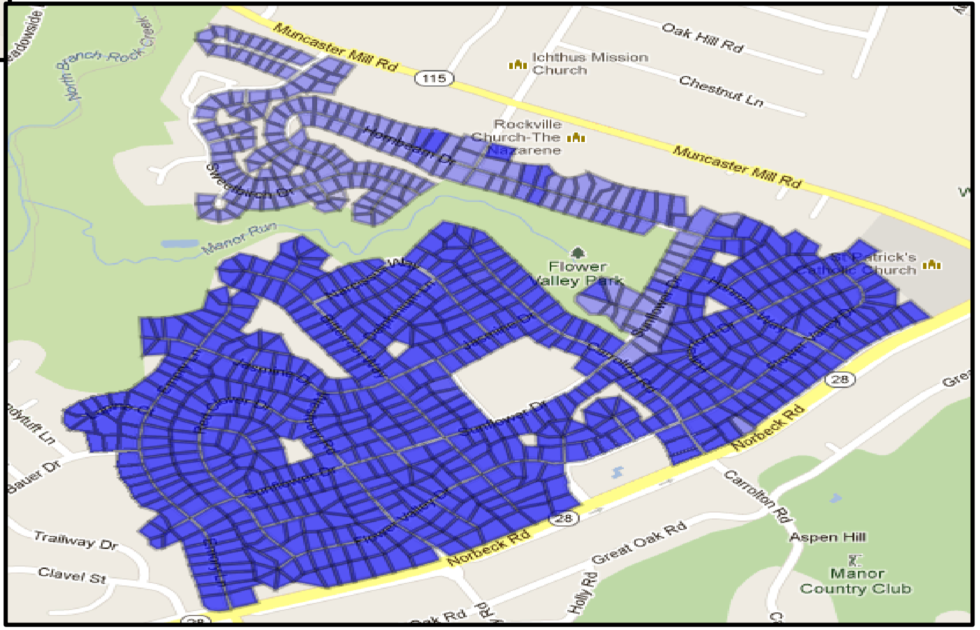
← 170 units, 680 residents, 1360 people/km^2

← Assume unprotected population dose is 680 person-Gy

← Apply 0.82 PF to each resident under shelter-in-place protective actions.

← Protected dose = 558 person-Gy

← Estimated 18% population dose reduction



→ Single family Housing Community

→ 680 units, 1640 residents, 158 people/km^2

→ Assume unprotected population dose is 1640 person-Gy

→ 29%, PF = 0.65

→ 71%, PF = 0.36

→ Protected dose = 730 person-rem

→ Estimated 55% population dose reduction

Technical Bases – Multiple steps.

- Defining Generic Homes - Housing Survey

- Model Development -
  - Narrow- and Broad-beam (table-top experiments)
  - Narrow- and Broad-beam computational models (MCNP)
  - Full-scale computational codels (MCNP)

- Function- and Factor Development

Technical Bases – Housing Survey

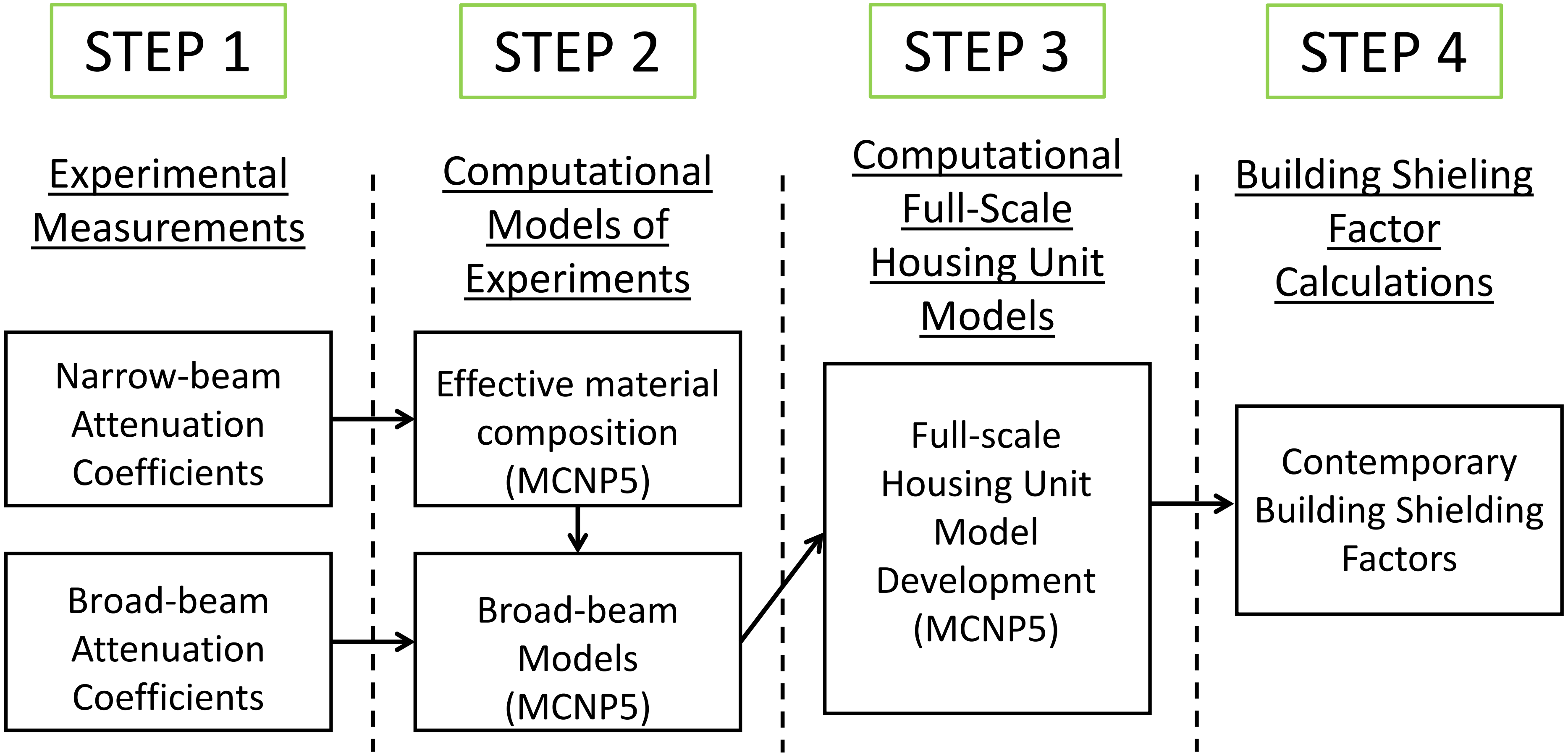
Goal:

Decision tree analysis results

RANK	END STATE	DECISION OUTCOME
1	14.77%	SINGLE_SIDING_COMP
2	8.24%	SINGLE_BRICK_COMP
3	7.55%	SINGLE_WOOD_COMP
4	4.97%	SINGLE_SIDING_ASPHALT
5	4.89%	SINGLE_STUCCO_COMP
6	3.13%	MOBILE HOME_SIDING_METAL
7	2.77%	SINGLE_BRICK_ASPHALT
8	2.54%	SINGLE_WOOD_ASPHALT
9	1.67%	APT 2 TO 4 UNITS_BRICK_COMP
10	1.64%	SINGLE_STUCCO_ASPHALT

Data: 2009 American Housing Survey for the United States (HUD, 2009)

Technical Bases – Model Development

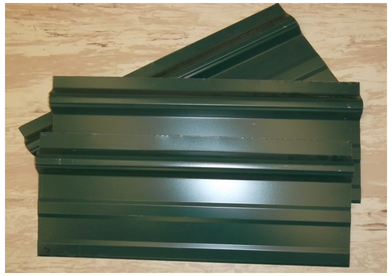


13 experimental photon measurements from 60 Kev to 3 MeV

Source term: Nuclide-specific (ICRP 107) and mono-energetic gamma-rays

Technical Bases – Model Development (**Step 1**)

- **Narrow-beam measurements** - measure the material absorption ability over a spectrum of photon energies.
  - 14 general construction materials
  - Average attenuation coefficients and effective material properties were developed.

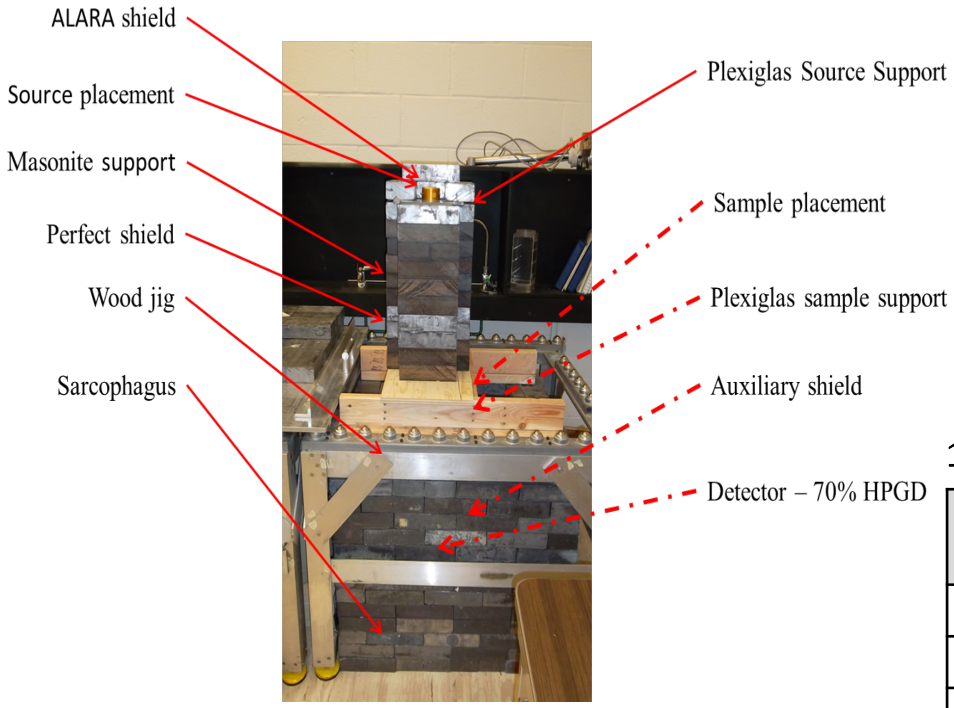




- **Broad-beam measurements** - simulate realistic shielding/free-in-air photon fluence interactions.
  - Ten “shields” were designed and built:
    - 6 walls: vinyl-, brick-, wood-, stucco-, steel-sided, and interior; and
    - 4 Roofs: asphalt-, metal-, shake-, and terracotta-type.



Combination of the 10 shields represent 61% of all homes in the U.S.

Technical Bases – Model Development (**Steps 1 and 2**)

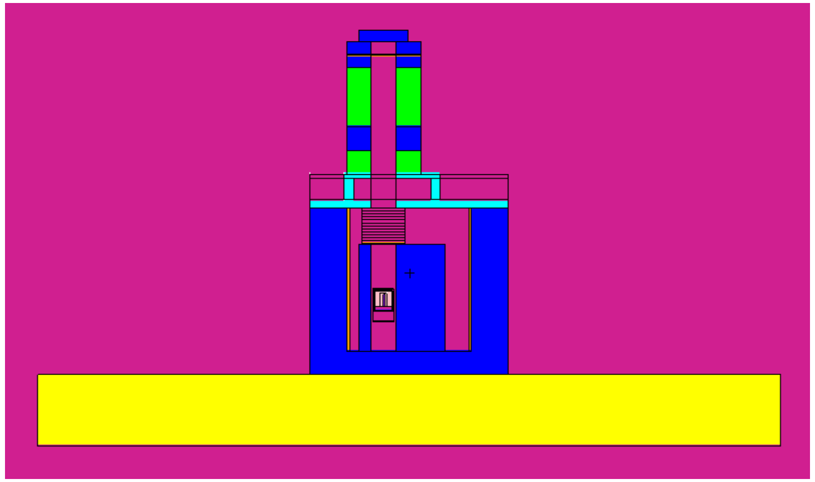


Narrow Bream Experimental Assembly

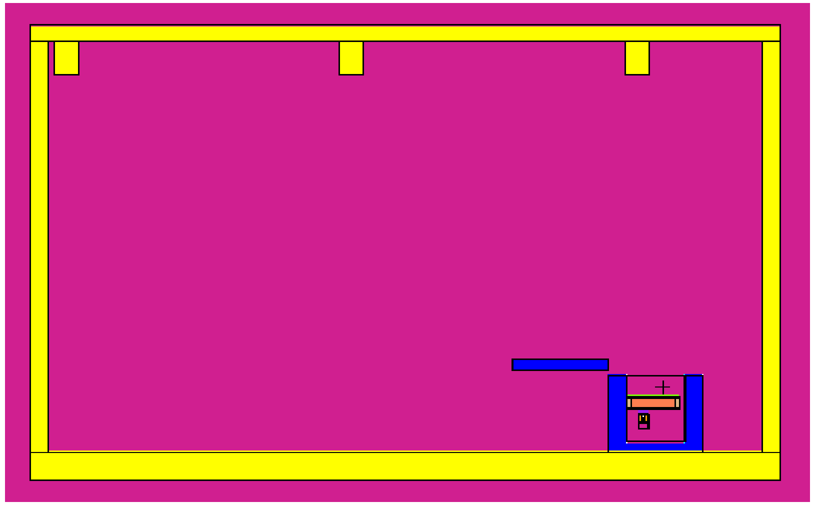
Selection of 4 radionuclides (Am-241, Cs-134, Co-60, and Na-24) which collectively emit thirteen characteristic photons within the desired range

13 experimental photon measurements

Photon #	Nuclide	Photon Energy [MeV]
1	Am-241	0.059
2	Cs134	0.475
3	Cs134	0.563
4	Cs134	0.569
5	Cs134	0.605
6	Cs134	0.795
7	Cs134	0.801
8	Cs134	1.039
9	Cs134	1.167
10	Co-60	1.174
11	Co-60	1.333
12	Na24	1.369
13	Na24	2.755

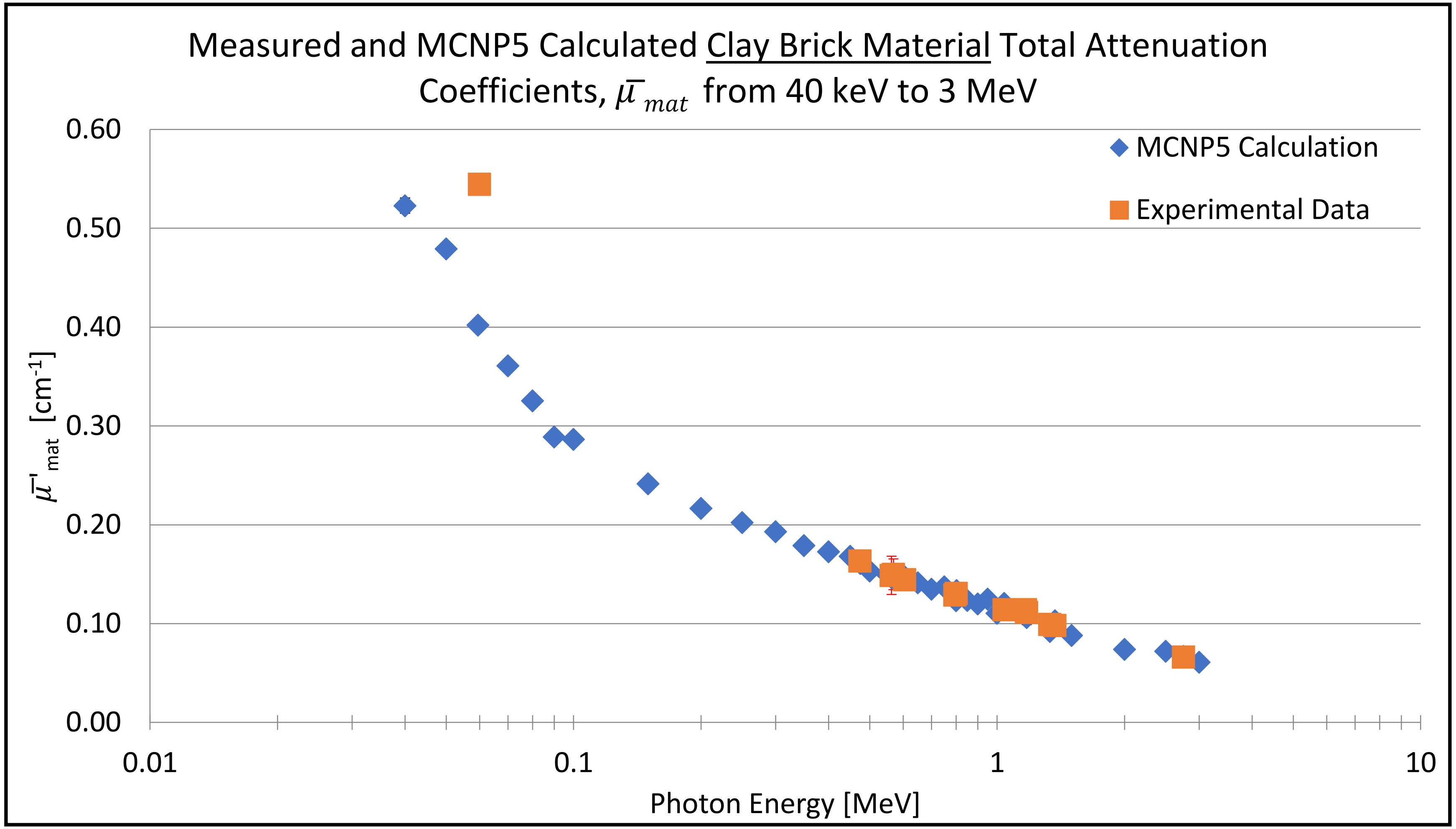


MCNP5 narrow-beam model



MCNP5 broad-beam model

Technical Bases – Model Development (**Steps 1 and 2 Results**)



Clay brick material Experimental vs Computes attenuation coefficients from 40 Kev to 3 MeV

Note: Validated material parameters identified in the narrow- and broad-beam analyses.
Agreement found between all measurements and MCNP calculations over entire energy range.

Technical Bases – Model Development (Step 3 – House Models)

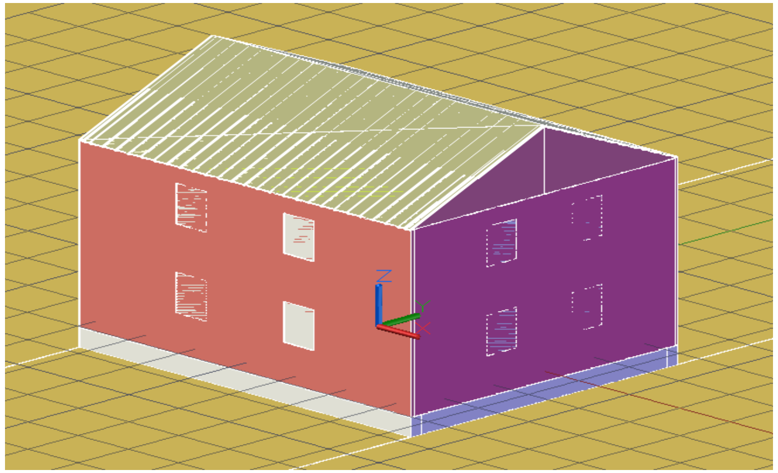
- Use of validated material parameters identified in the narrow- and broad-beam analyses.

- Full-scale housing unit models are based on common housing models typical in U.S. suburbs.
  - **Two-story colonial**, 160 m^2 livable space (240 m^2 w/basement).
  - **One-story ranch**, 160 m^2 livable space (320 m^2 w/basement).
  - **Single-wide manufactured**, 101 m^2 livable space.

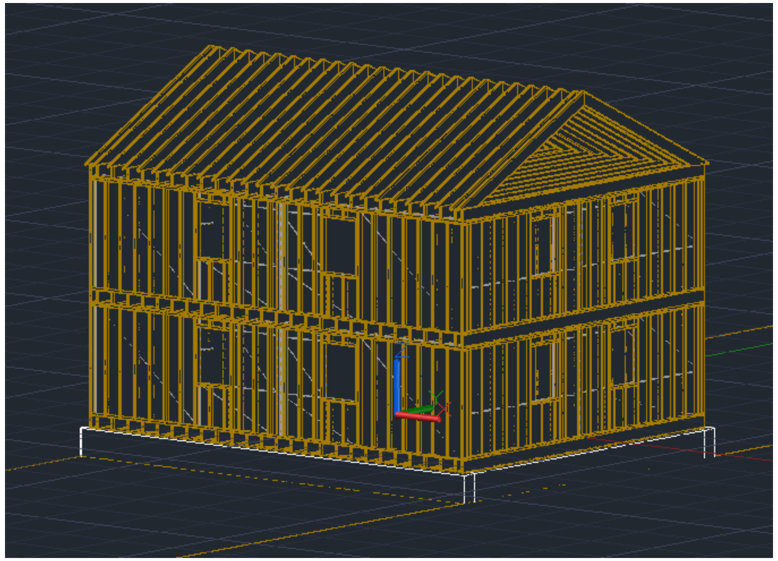
- Housing Construction Data Parameters
  - **All structural members modeled to general construction standards.**
    - Interior- and exterior walls, floor joists, flooring, rafters.
    - Interior room are 243.8 cm floor-to-ceiling .
  - Symmetrically designed, such that one side mirrors the other.
  - The one-story model is composed of the two floors of the two-story model side-by-side.
  - Foundation are either 20.32 or 33.07 cm thick and raise a standard 60.96 cm above the ground
  - Windows are modeled as generic 91.44 cm by 121.92 cm single-pane glass 0.508 cm thick.
  - No doors are modeled.

Data: 2009 American Housing Survey for the United States (HUD, 2009)

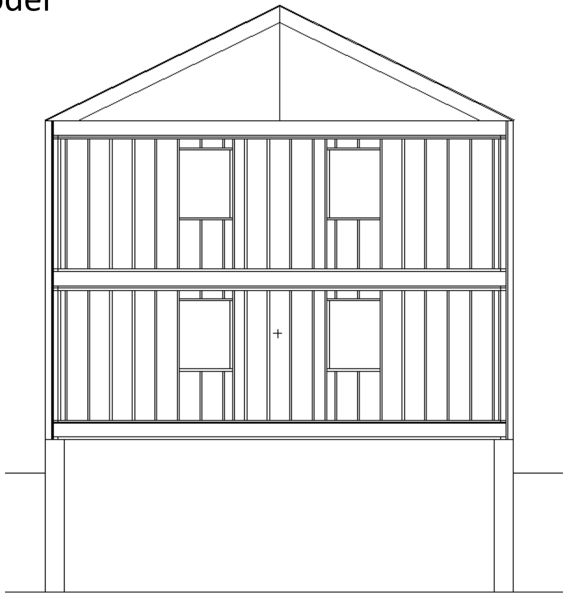
Technical Bases – Model Development (**Step 3 – House Models**)



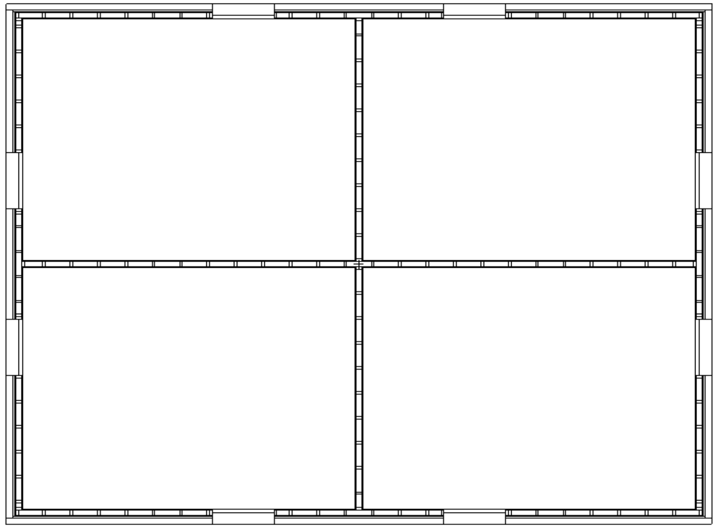
Isometric view of two-story clay brick and asphalt roof house model



Isometric view of two-story house model framing

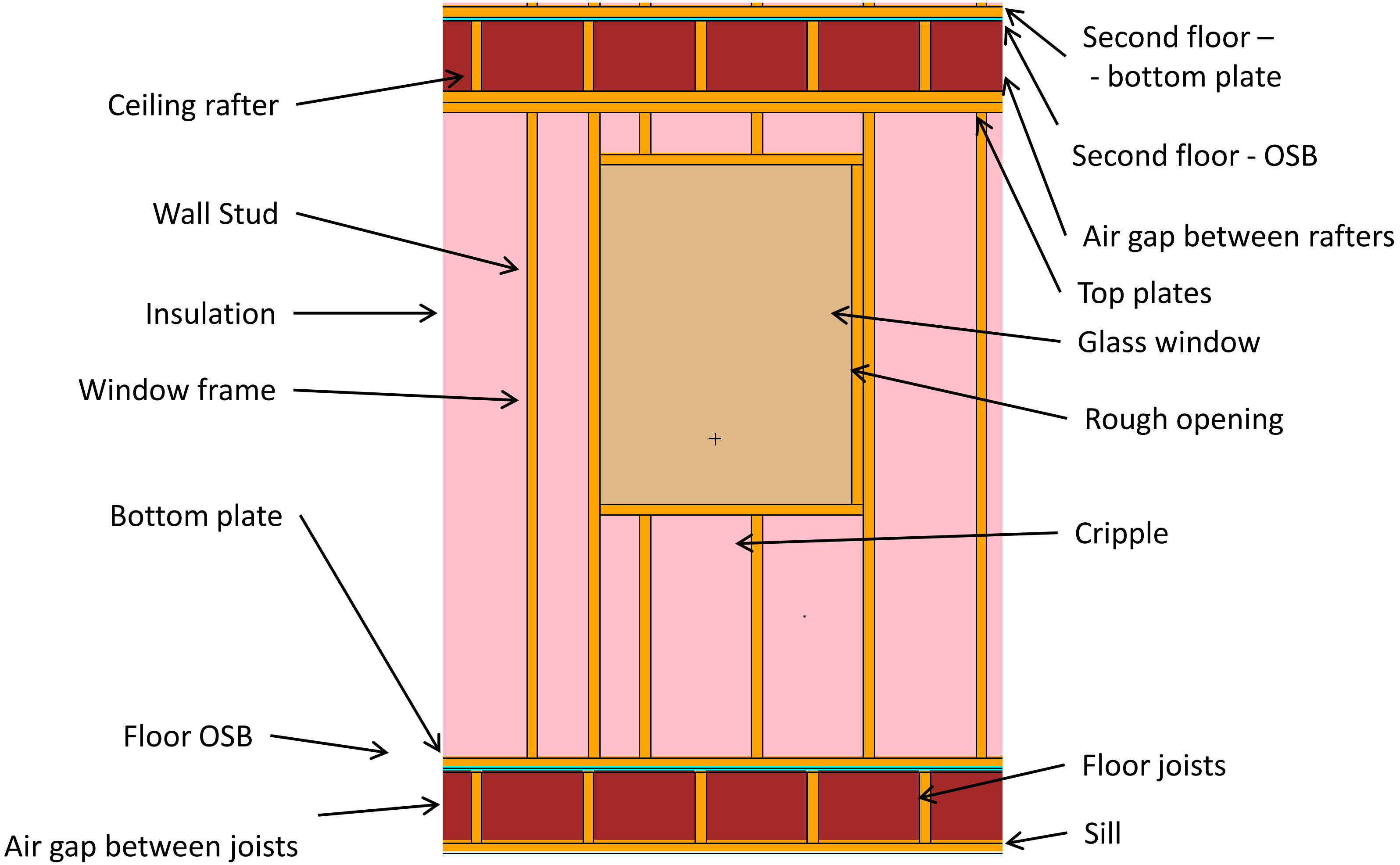


Two-story model Z/Y-axis view of right of unit exterior wall



Two-story model X/Y-axis view of first floor

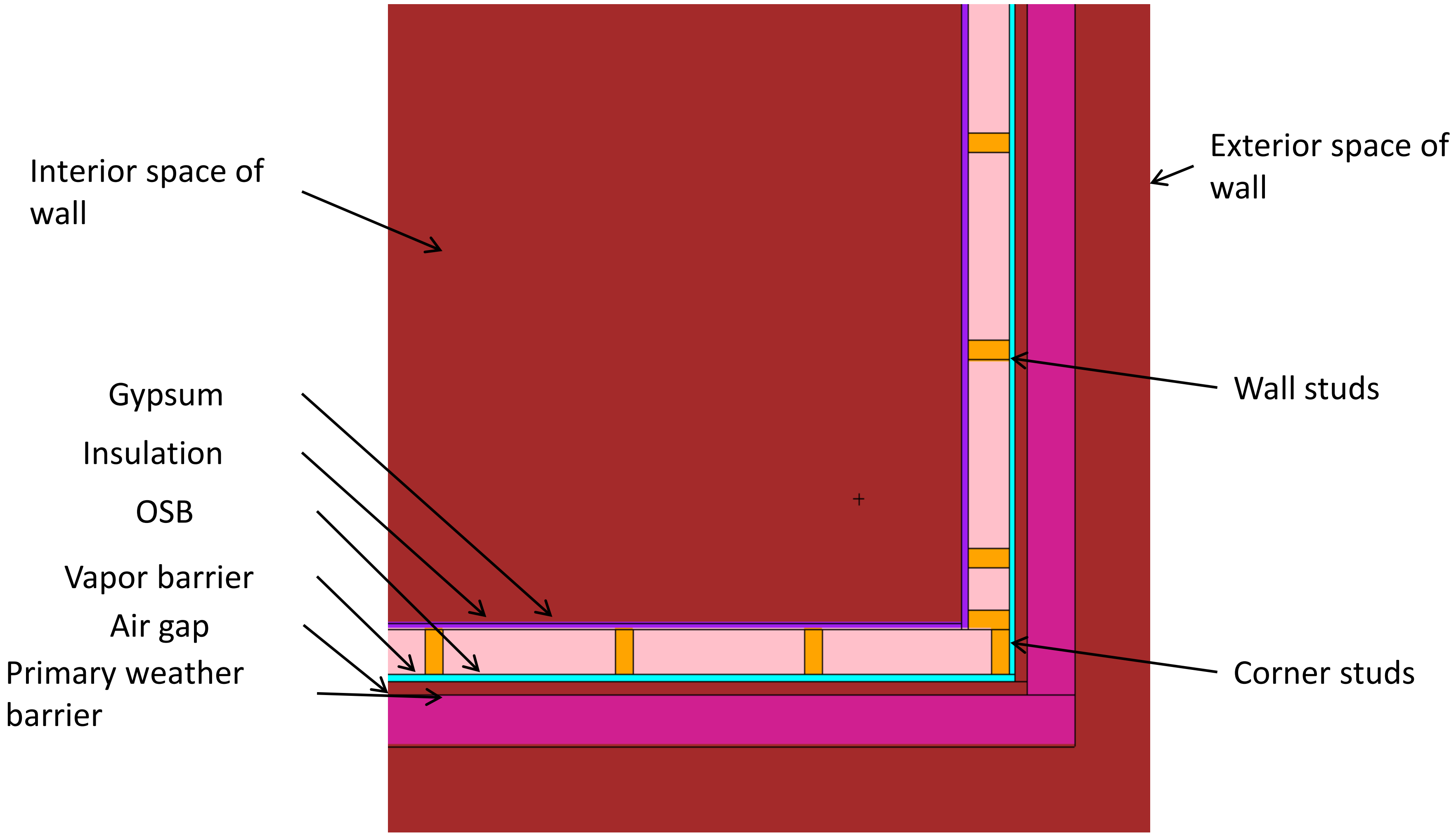
Technical Bases – Model Development (**Step 3 – House Models**)



Example of Exterior Wall partition

Source: guidance for the design and general construction of certain aspects came from Spence (1999)

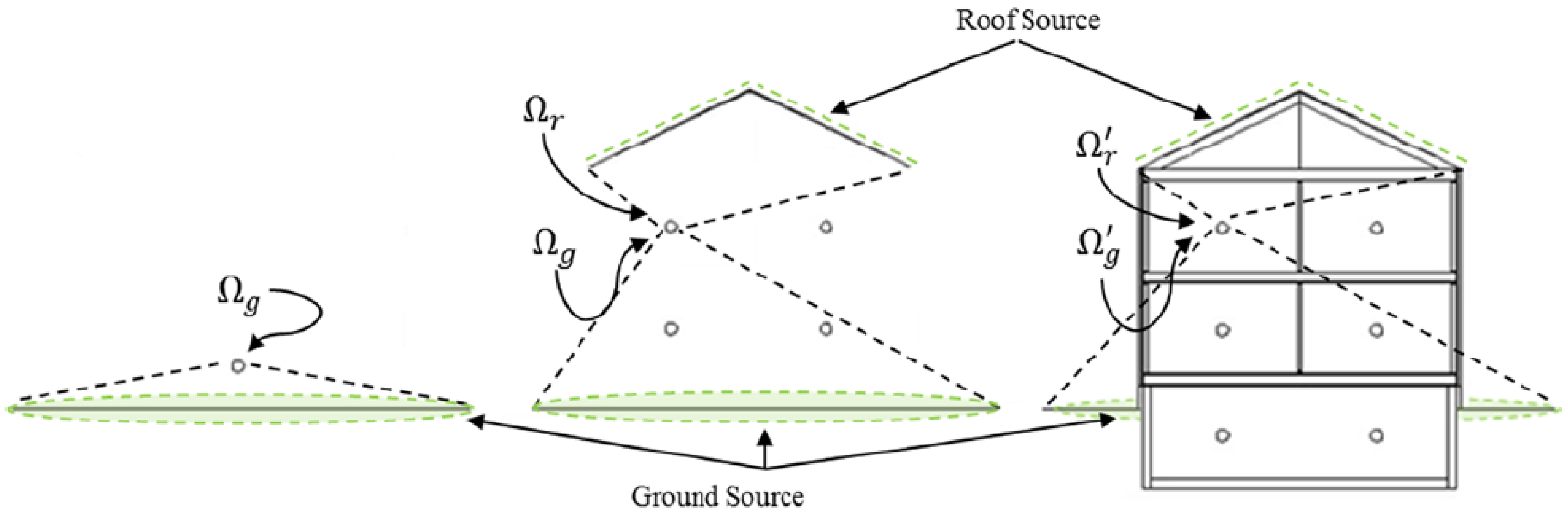
Technical Bases – Model Development (**Step 3 – House Models**)



Bird-eye view of exterior wall for brick and mortar home

Technical Bases – (Step 4 Factor and Function Development)

Illustrative representation of dose calculations…



(a) Standard Unprotection Position (D_0) (b) Unprotection Position (D) (c) Protection Position (D)

Building Protection factors -

P = Building Protection Factor

D_o = Standard Protected location

D = Unprotected Location

$$P = \frac{D}{D_o}$$

Technical Bases – (Step 4 Factor and Function Development)

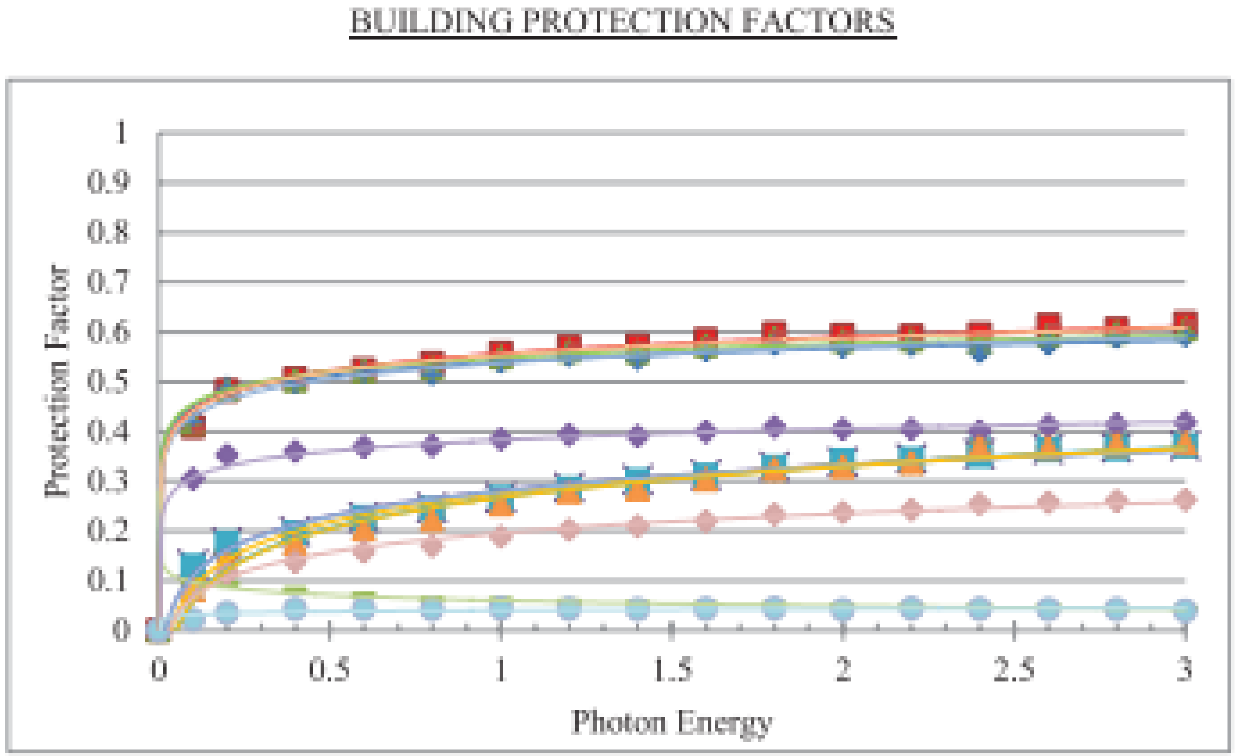
Results -

- Monte Carlo simulations for 16 monoenergetic photon energies from 0.10 to 3.0 MeV
    - Semi-infinite Cloud
    - Deposition

- Simulation results used to develop fitted logarithmic functions.
    - Correlate an estimated factor to photon energies between 0.10 and 3.0 MeV.

- Accident-specific PFs can be developed with mixed source terms with complicated spectra.
    - RDDs
    - Early-phase nuclear (fresh)
    - Late-phase nuclear (decayed)
    - decommissioning

Figure B3. Two-story housing-unit deposition protection factors versus monoenergetic photon energies.



Vinyl		
No Basement		
Second Floor	$PF = 0.0395\ln(x) + 0.5401$	$R^2 = 0.9946$
First Floor	$PF = 0.0491\ln(x) + 0.5557$	$R^2 = 0.9946$
Weighted Average	$PF = 0.0405\ln(x) + 0.5484$	$R^2 = 0.9922$
Basement		
Second Floor	$PF = 0.0466\ln(x) + 0.5378$	$R^2 = 0.9950$
First Floor	$PF = 0.0491\ln(x) + 0.5540$	$R^2 = 0.9934$
Basement	$PF = -0.0160\ln(x) + 0.0604$	$R^2 = 0.9631$
Weighted Average	$PF = 0.0333\ln(x) + 0.3900$	$R^2 = 0.9924$

Brick		
No Basement		
Second Floor	$PF = 0.0740\ln(x) + 0.2815$	$R^2 = 0.9727$
First Floor	$PF = 0.0905\ln(x) + 0.2683$	$R^2 = 0.9767$
Weighted Average	$PF = 0.0822\ln(x) + 0.2749$	$R^2 = 0.9761$
Basement		
Second Floor	$PF = 0.0740\ln(x) + 0.2803$	$R^2 = 0.9724$
First Floor	$PF = 0.0905\ln(x) + 0.2668$	$R^2 = 0.9755$
Basement	$PF = 0.0039\ln(x) + 0.0405$	$R^2 = 0.9198$
Weighted Average	$PF = 0.0570\ln(x) + 0.2009$	$R^2 = 0.9838$

References

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