Transforming Protective Action Strategies for Radiological Emergencies

Exacting the Science of Sheltering-in-Place

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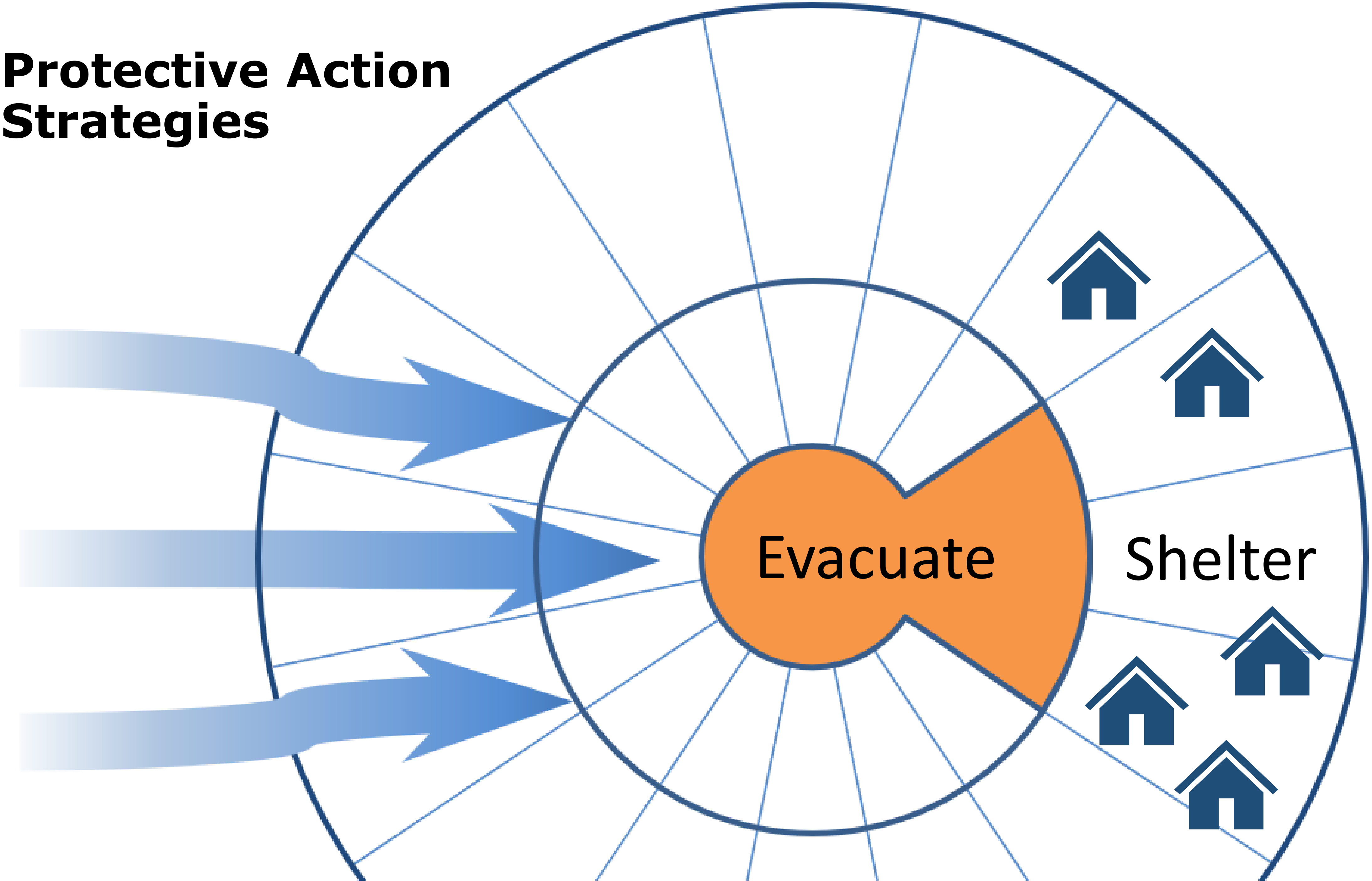
Protective Action Strategies



Deciding on Action

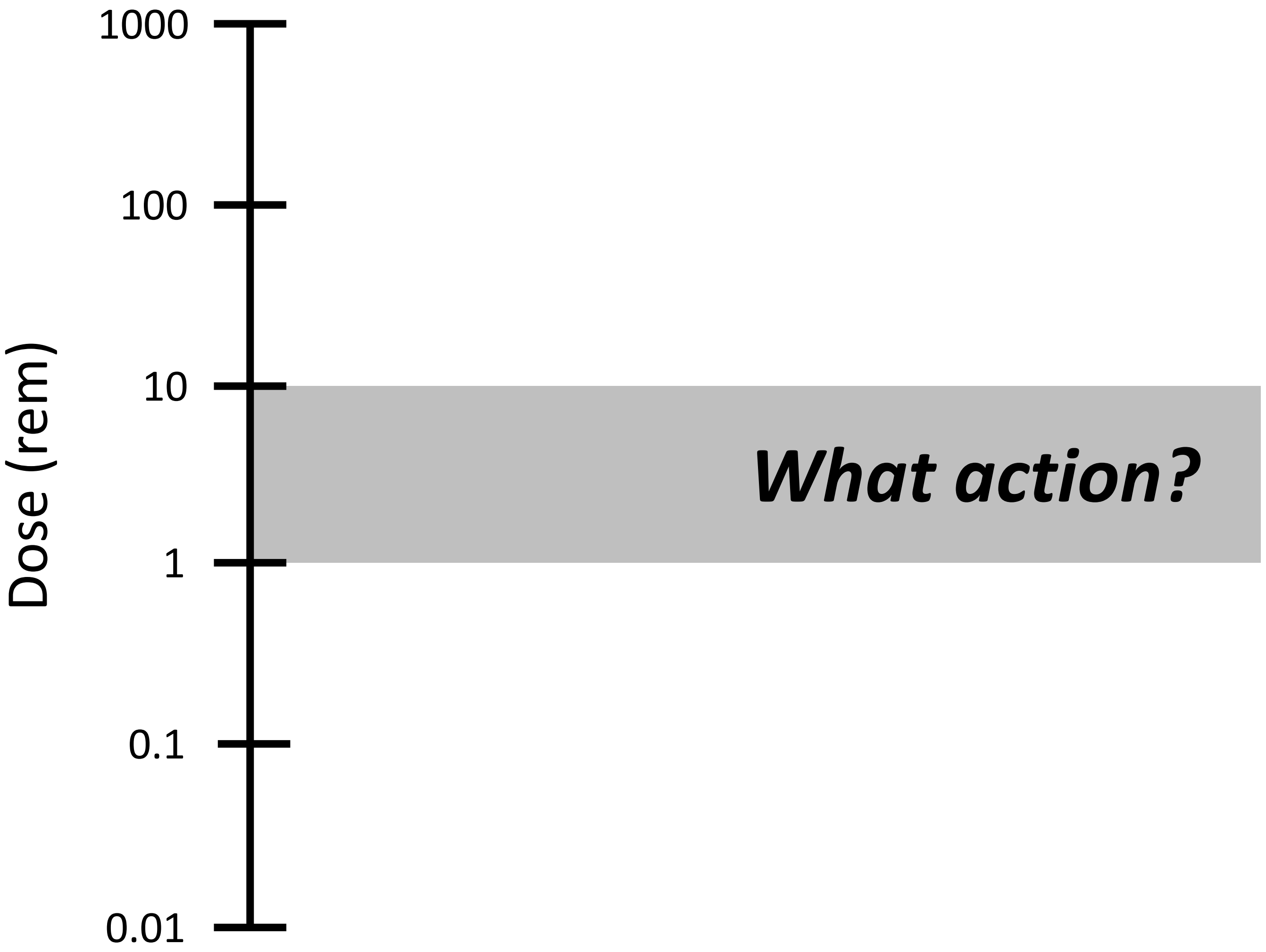
Protective Action Recommendation (PAR) – recommended protective measures from the nuclear power plant to offsite response organizations

Protective Action Decision (PAD) – measures taken in response to an actual or anticipated radiological release

Protective Action Guide (PAG) – a projected dose to an individual member of the public that warrants protective action

- trigger levels for action (e.g., early phase PAG 1-5 rem)
- balance the benefit of dose reduction against the risks of implementing the action

Balancing the Risk



Sheltering-in-place should be preferred to evacuation whenever it provides equal or greater protection.

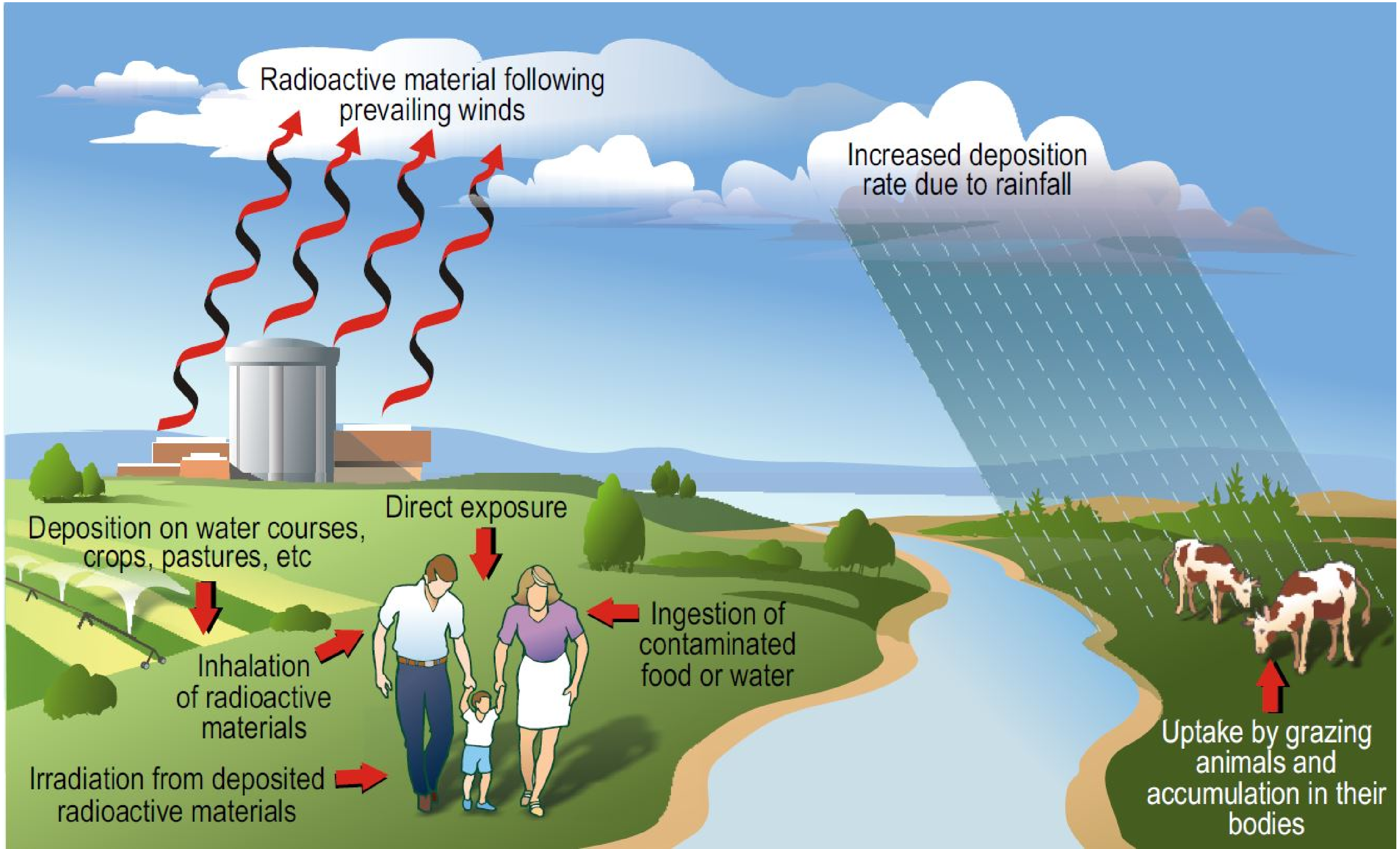
Sheltering-in-place followed by informed evacuation may be most protective.

“

Selection of evacuation or sheltering-in-place is far from an exact science...

—2017 EPA PAG Manual

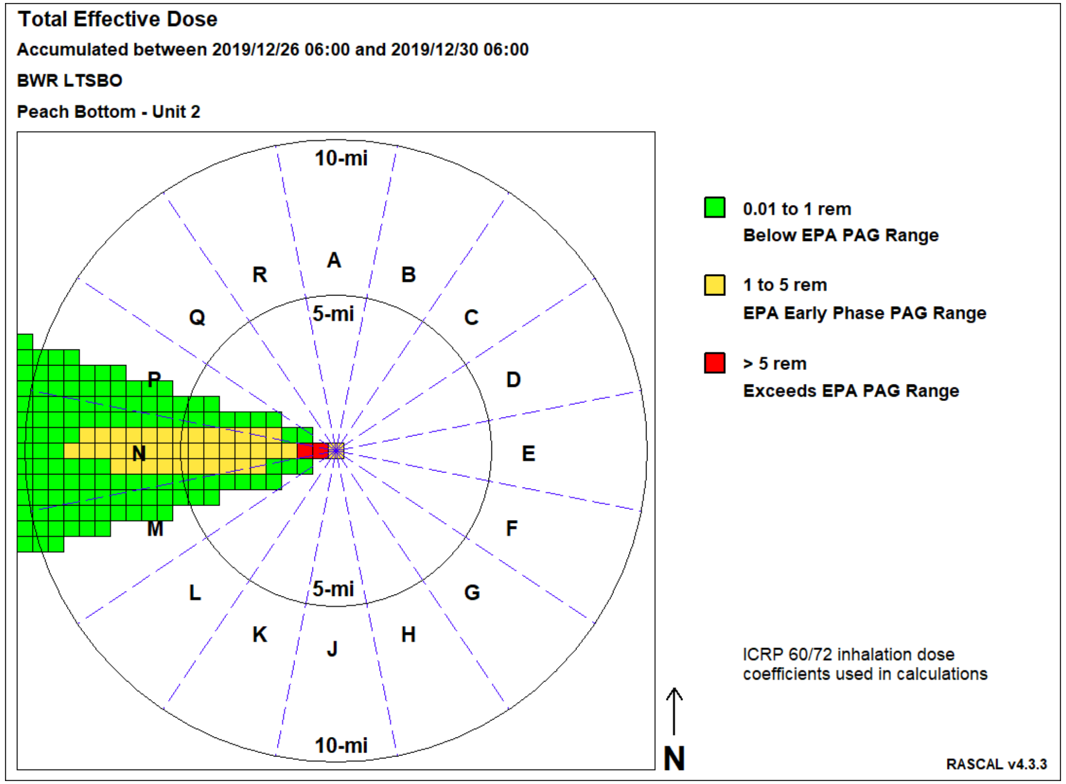
Exposure Pathways

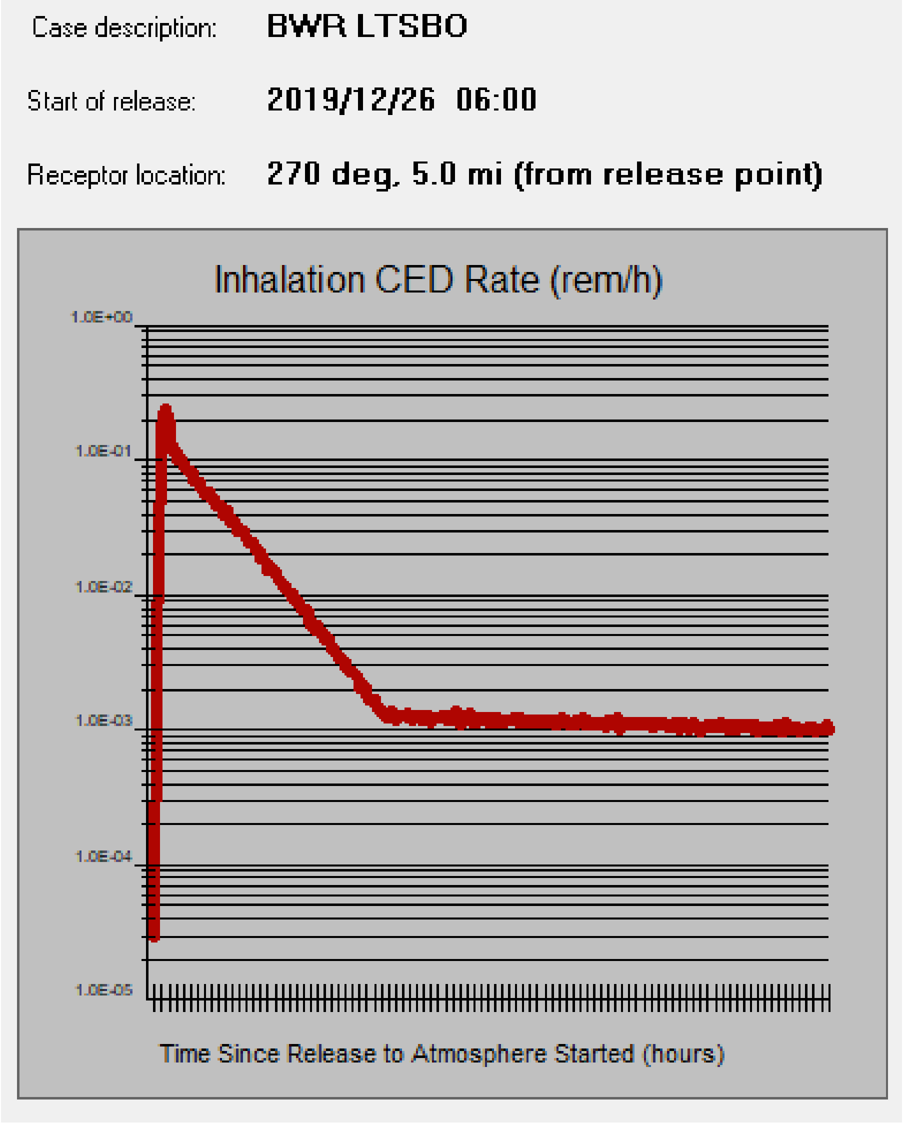


(Source: NRC)

RASCAL Source Terms

- BWR Long Term Station Blackout (LTSBO)
- PWR Loss of Coolant Accident (LOCA)
- SMR (250 MWth) LOCA

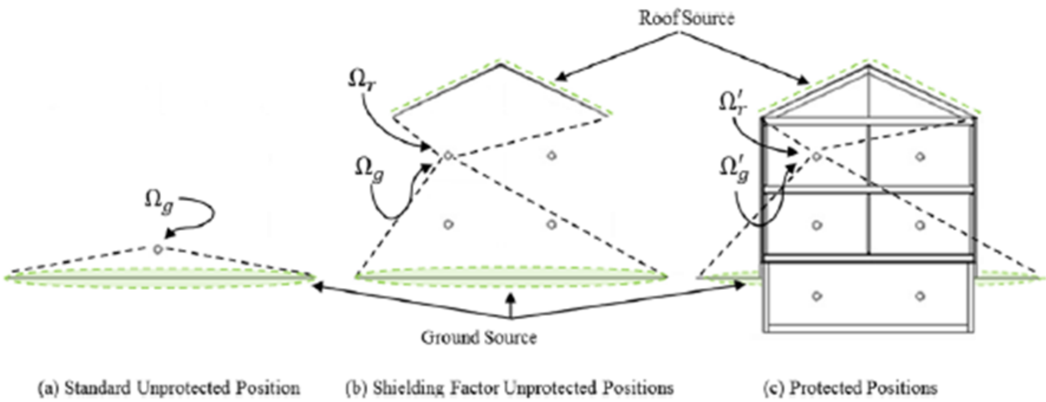




- Standard Meteorology: D stability 4 mph No precipitation 70 F 50% rh

Cloudshine and Groundshine Dose
Building Protection Factors

(*x* is photon energy in MeV)



Two Story Building Cloudshine Protection Factors

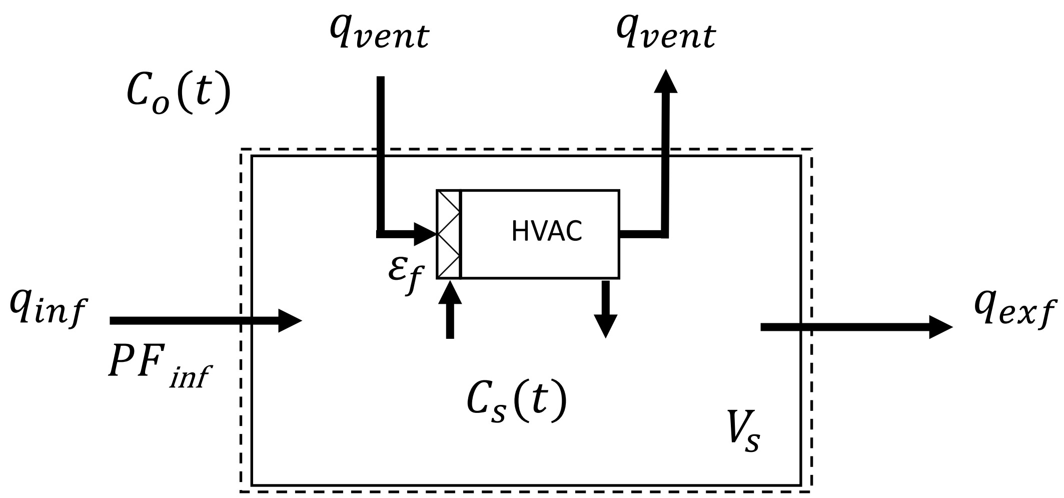
Vinyl		Brick	
No basement		No basement	
Second Floor	0.0936 ln(x) + 0.8741	Second Floor	0.1335 ln(x) + 0.6201
First Floor	0.0821 ln(x) + 0.7349	First Floor	0.1240 ln(x) + 0.4224
Weighted Average	0.0879 ln(x) + 0.8045	Weighted Average	0.1288 ln(x) + 0.5212
Basement		Basement	
Second Floor	0.0935 ln(x) + 0.8714	Second Floor	0.1336 ln(x) + 0.6186
First Floor	0.1028 ln(x) + 0.7217	First Floor	0.1240 ln(x) + 0.4176
Basement	0.0879 ln(x) + 0.4035	Basement	0.0730 ln(x) + 0.2070
Weighted Average	0.0950 ln(x) + 0.6654	Weighted Average	0.1102 ln(x) + 0.4144

Two Story Building Groundshine Protection Factors

Vinyl		Brick	
No basement		No basement	
Second Floor	0.0395 ln(x) + 0.5401	Second Floor	0.0740 ln(x) + 0.2815
First Floor	0.0491 ln(x) + 0.5557	First Floor	0.0905 ln(x) + 0.2683
Weighted Average	0.0405 ln(x) + 0.5484	Weighted Average	0.0822 ln(x) + 0.2749
Basement		Basement	
Second Floor	0.0466 ln(x) + 0.5378	Second Floor	0.0740 ln(x) + 0.2803
First Floor	0.0491 ln(x) + 0.5540	First Floor	0.0905 ln(x) + 0.2668
Basement	-0.016 ln(x) + 0.0604	Basement	0.0039 ln(x) + 0.0405
Weighted Average	0.0333 ln(x) + 0.3900	Weighted Average	0.0570 ln(x) + 0.2009

Dickson, E.D., Hamby, D.M, “Building protection- and shielding-factors for environmental exposure to radionuclides and monoenergetic photon emissions,” *J Radiol Prot.* 36, 27 July 2016, p. 579-615

Inhalation Dose
Shelter Control Volume Model



$$V_s \frac{dC_s}{dt} = rate\ in - rate\ out$$

$$V_s \frac{dC_s}{dt} = PF_{inf} q_{inf} C_o(t) + q_{vent}(1 - \varepsilon_f) C_o(t) - q_{exf} C_s(t) - q_{vent} C_s(t)$$

$$C_s(t_i) = C_s(t_{i-1}) + \Delta C_s(t_i)$$

$$\Delta C_s(t_i) = \left(PF_{inf} q_{inf} C_o(t_i) + q_{vent}(1 - \varepsilon_f) C_o(t_i) - q_{exf} C_s(t) - q_{vent} C_s(t_i)\right) \frac{\Delta t}{V_s}$$

Model Validation

This work:

$$\Delta C_s(t_i) = \left(PF_{inf}q_{inf}C_o(t_i) + q_{vent}(1-\varepsilon_f)C_o(t_i) - q_{exf}C_s(t) - q_{vent}C_s(t_i)\right)\frac{\Delta t}{V_s}$$

Kulmala et al., Validated Model:

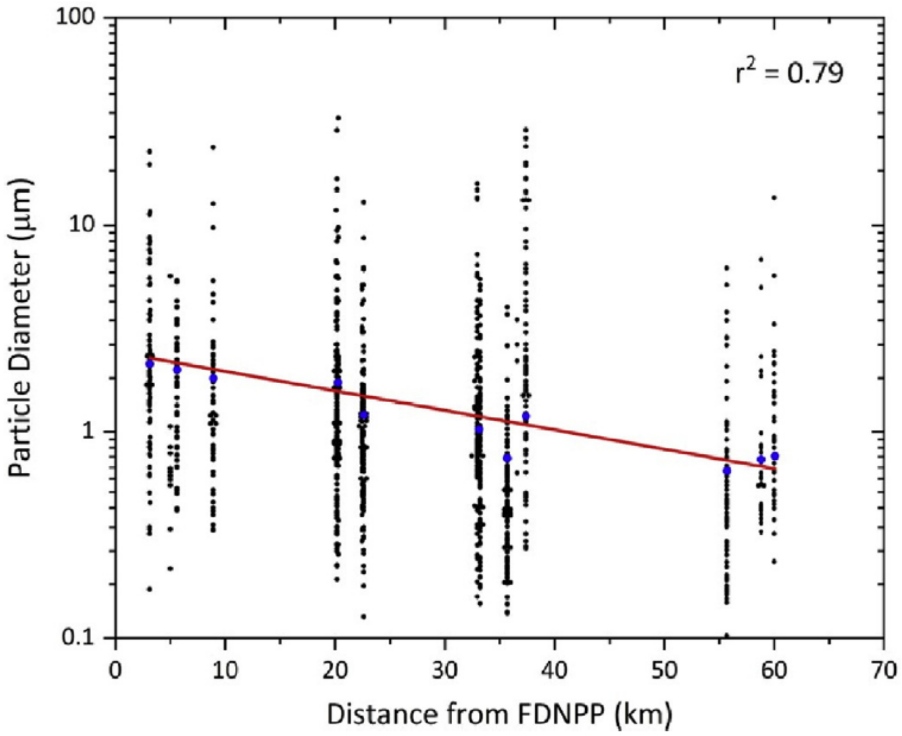
$$\Delta C_s(t_i) = \left(PF_{inf}q_{inf}C_o(t_i) + q_{vent}(1-\varepsilon_f)C_o(t_i) - q_{exf}C_s(t) - q_{vent}C_s(t_i) - q_{AC}E_{AC}C_s(t_i) - \beta V C_s(t_i) + G\right)\frac{\Delta t}{V_s}$$

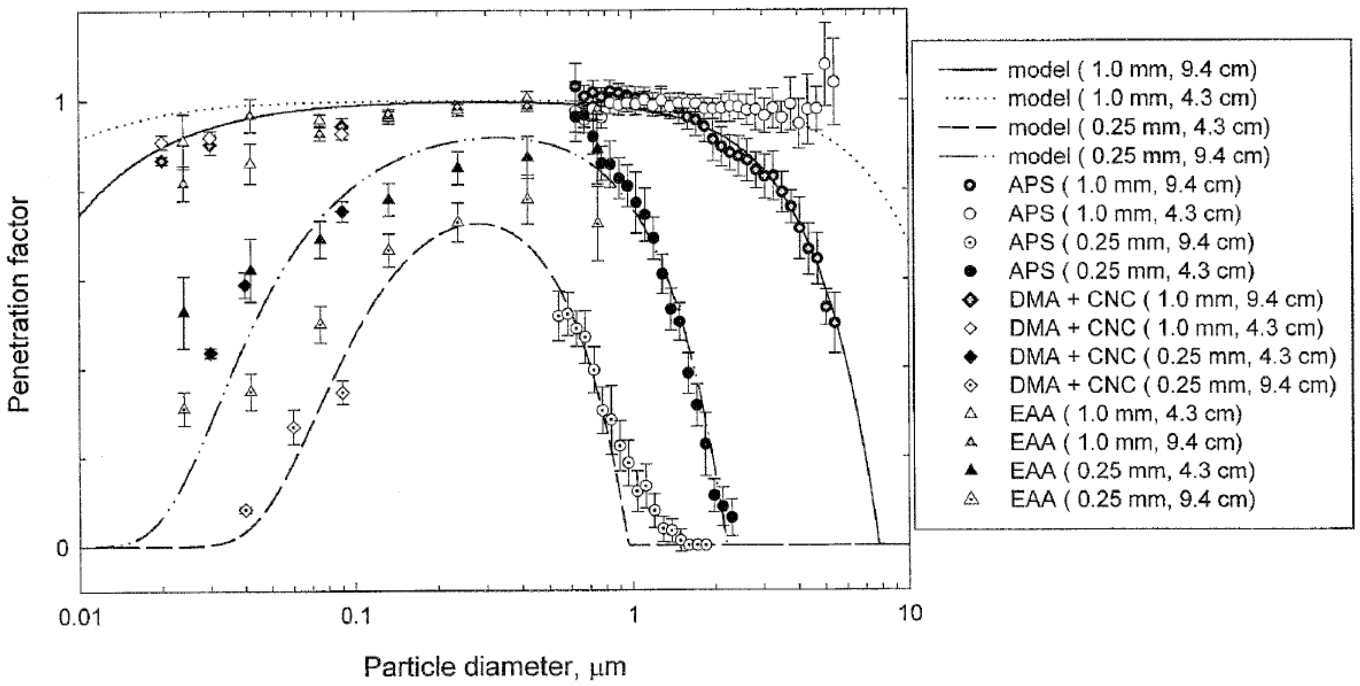
Minor and Inconsequential Differences:

- $q_{AC}E_{AC}C_s(t_i)$ is removal of contaminants by an air cleaner with flow rate q_{AC} and removal efficiency E_{AC}.
- $\beta V C_s(t_i)$ is the removal of contaminants by surface deposition at a deposition velocity of β. EPA study on shelter effectiveness showed to be very minor (EPA, 1978a; EPA, 1978b).
- G is the indoor contaminant generation rate. No radionuclides are generated indoors.

Kulmala, I., et al., "A tool for determining sheltering efficiency of mechanically ventilated buildings against outdoor hazardous agents," *Building and Environment*, 106, 2016, p. 245-253.

Penetration Factor





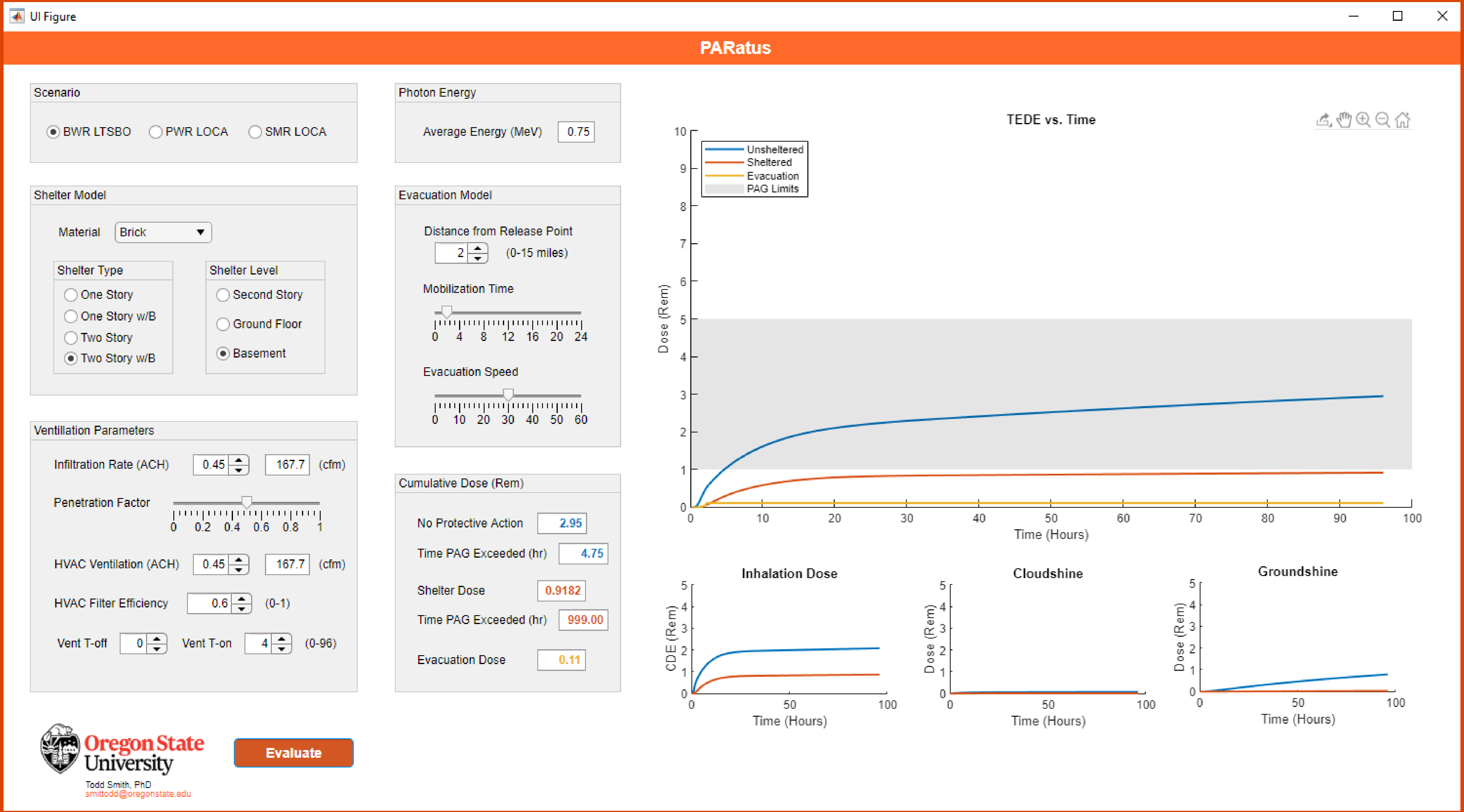
Martin, P.G., et al., “Analysis of particulate distributed across Fukushima Prefecture: Attributing provenance to the 2011 Fukushima Daiichi Nuclear Power Plant accident or an alternate emission source,” *Atmospheric Environment*, 212, 2019, pp. 142-152.

Liu, D., Nazaroff, W., “Particle Penetration Through Building Cracks,” *Aerosol Science & Technology*, 37:7, 2003, pp. 565-573.

HVAC Filter Efficiency

MERV Rating	Air Filter will trap Air Partiles size .3 to 1.0 microns	Air Filter will trap Air Particles size 1.0 to 3.0 microns	Air Filter will trap Air Particles size 3 to 10 microns	Filter Type ~ Removes These Particles
MERV 1	< 20%	< 20%	< 20%	Fiberglass & Aluminum Mesh
MERV 2	< 20%	< 20%	< 20%	~
MERV 3	< 20%	< 20%	< 20%	Pollen, Dust Mites, Spray Paint,
MERV 4	< 20%	< 20%	< 20%	Carpet Fibres
MERV 5	< 20%	< 20%	20% - 34%	Cheap Disposable Filters
MERV 6	< 20%	< 20%	35% - 49%	~
MERV 7	< 20%	< 20%	50% - 69%	Mold Spores, Cooking Dusts,
MERV 8	< 20%	< 20%	70% - 85%	Hair Spray, Furniture Polish
MERV 9	< 20%	Less than 50%	85% or Better	Better Home Box Filters
MERV10	< 20%	50% to 64%	85% or Better	~
MERV 11	< 20%	65% - 79%	85% or Better	Lead Dust, Flour, Auto
MERV 12	< 20%	80% - 90%	90% or Better	Fumes,Welding Fumes
MERV 13	Less than 75%	90% or Better	90% or Better	Superior Commercial Filters
MERV 14	75% - 84%	90% or Better	90% or Better	~
MERV 15	85% - 94%	95% or Better	90% or Better	Bacteria, Smoke, Sneezes
MERV 16	95% or Better	95% or Better	90% or Better	
*MERV 17 = HEPA 13	99.97%	99% or Better	99% or Better	HEPA & ULPA
*MERV 18 = HEPA 14	99.997%	99% or Better	99% or Better	~
*MERV 19 = U15	99.9997%	99% or Better	99% or Better	Viruses, Carbon Dust, < 0.3 µ
*MERV 20 = U16	99.99997%	99% or Better	99% or Better	*ASHRAE does not recognize Merv 17-20

Illustration Provided by LakeAir / www.lakeair.com


UI Figure
PARatus
Scenario
BWR LTSBO
PWR LOCA
SMR LOCA
Photon Energy
Average Energy (MeV)
0.75
Shelter Model
Material
Brick
Shelter Type
One Story
One Story w/B
Two Story
Two Story w/B
Shelter Level
Second Story
Ground Floor
Basement
Evacuation Model
Distance from Release Point
2
(0-15 miles)
Mobilization Time
0 4 8 12 16 20 24
Evacuation Speed
0 10 20 30 40 50 60
Ventillation Parameters
Infiltration Rate (ACH)
0.45
167.7
(cfm)
Penetration Factor
0 0.2 0.4 0.6 0.8 1
HVAC Ventilation (ACH)
0.45
167.7
(cfm)
HVAC Filter Efficiency
0.6
(0-1)
Vent T-off
0
Vent T-on
4
(0-96)
Cumulative Dose (Rem)
No Protective Action
2.95
Time PAG Exceeded (hr)
4.75
Shelter Dose
0.9182
Time PAG Exceeded (hr)
999.00
Evacuation Dose
0.11
TEDE vs. Time
Unsheltered
Sheltered
Evacuation
PAG Limits
Dose (Rem)
Time (Hours)
Inhalation Dose
CDE (Rem)
Time (Hours)
Cloudshine
Dose (Rem)
Time (Hours)
Groundshine
Dose (Rem)
Time (Hours)
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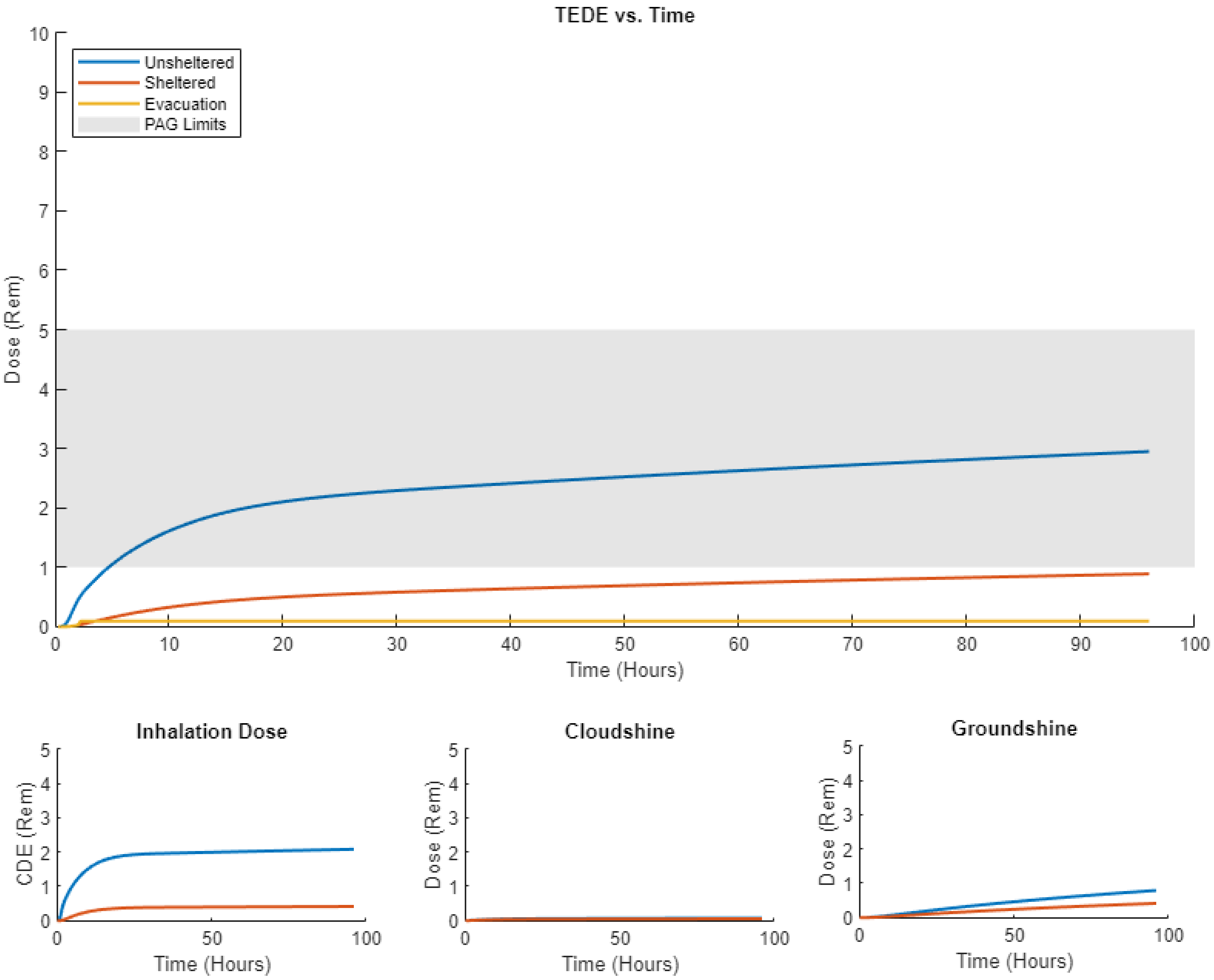
Evaluate

BWR LTSBO

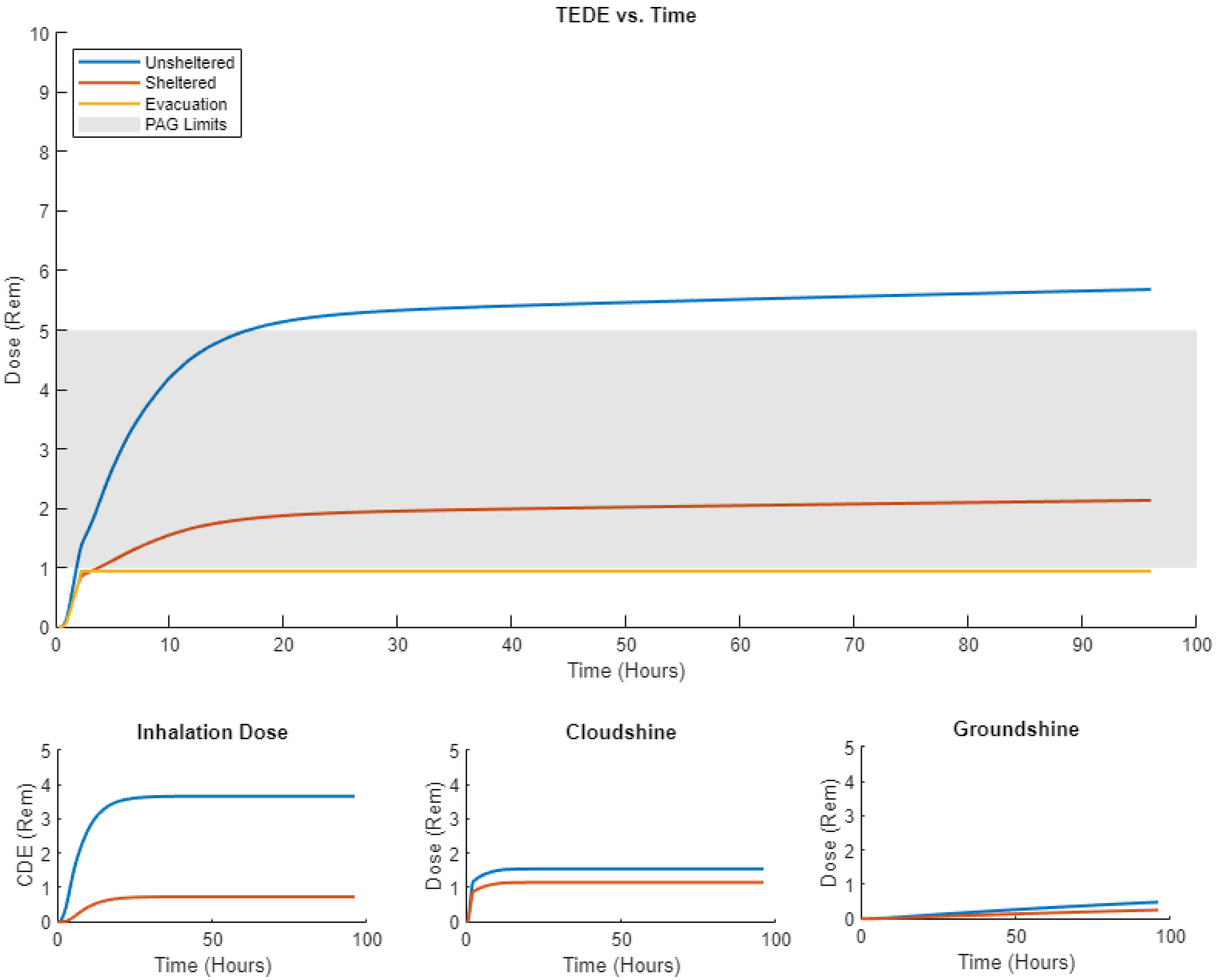
- Inhalation dominant early
- Groundshine builds up over time
- Shelter effective in maintaining dose below PAGs



<u>Model Parameters</u>
0.75 MeV average photon energy
2 miles downwind
One-story house
Vinyl siding
Ground floor
Natural infiltration 0.45 ACH, *PF* = 0.2
HVAC secured
2-hour mobilization time
30 mph evacuation speed

PWR LOCA

- Inhalation and cloudshine are dominant early
- Evacuation dose comparable to shelter



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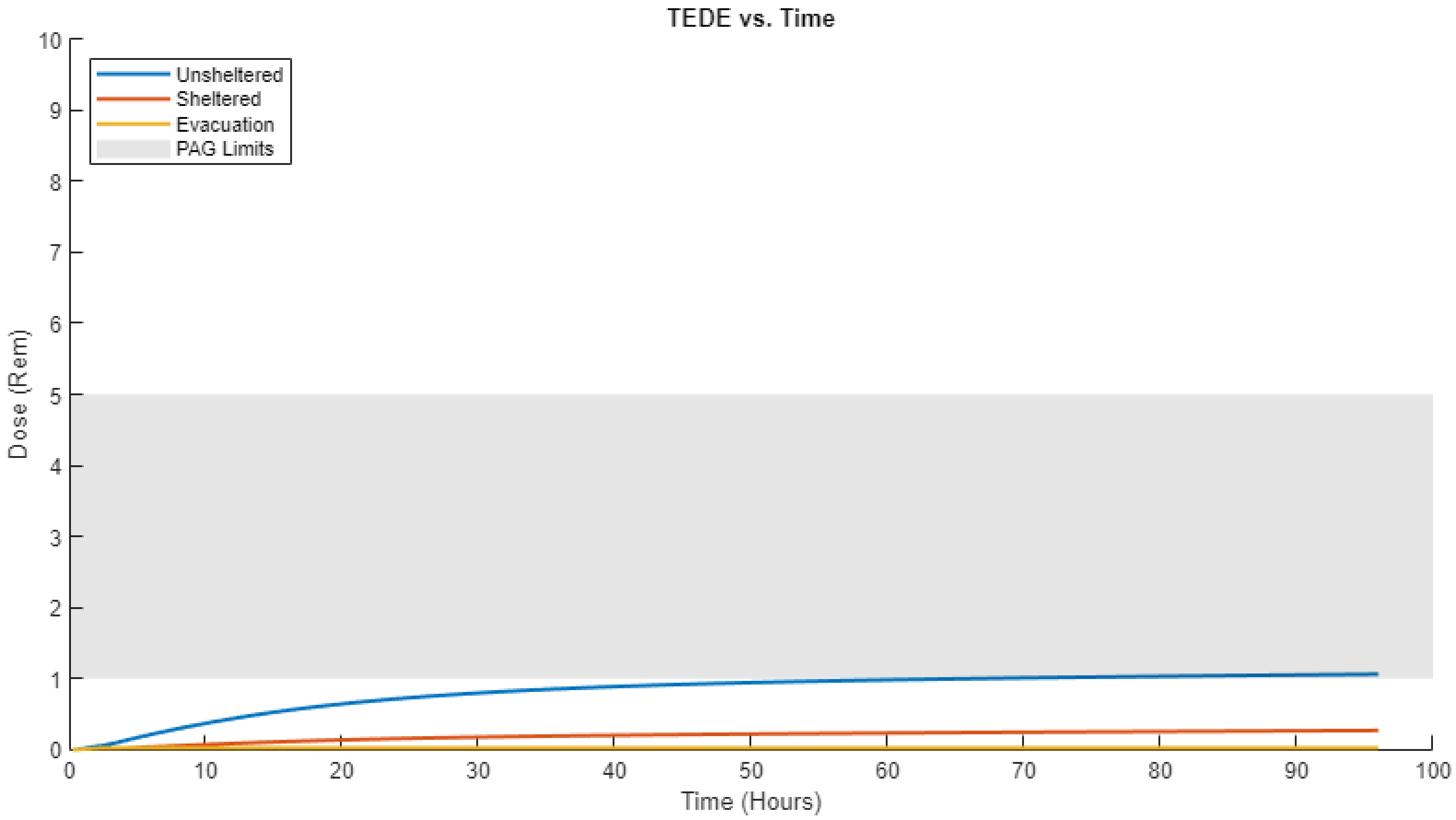
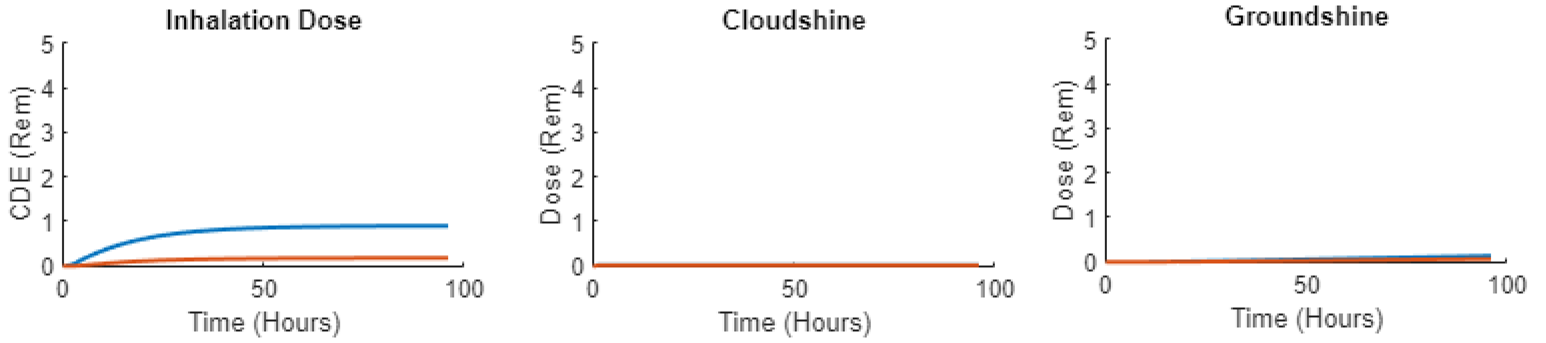
0.75 MeV average photon energy
2 miles downwind
One-story house
Vinyl siding
Ground floor
Natural infiltration 0.45 ACH, *PF* = 0.2
HVAC secured
2-hour mobilization time
30 mph evacuation speed

SMR LOCA

- Inhalation dominant
- Evacuation dose comparable to shelter
- Is evacuation even justified?





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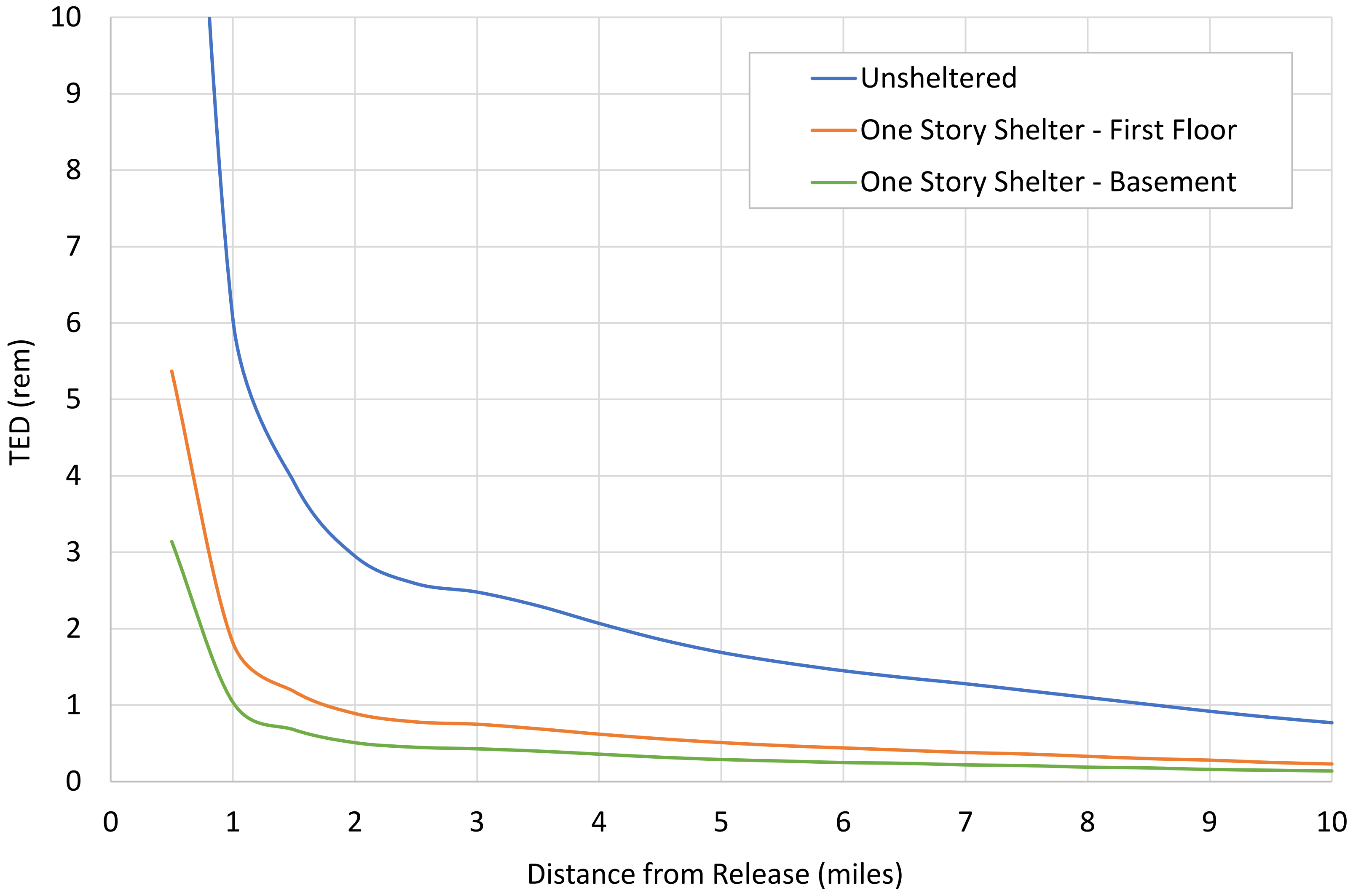
Shelter Effectiveness vs. Distance

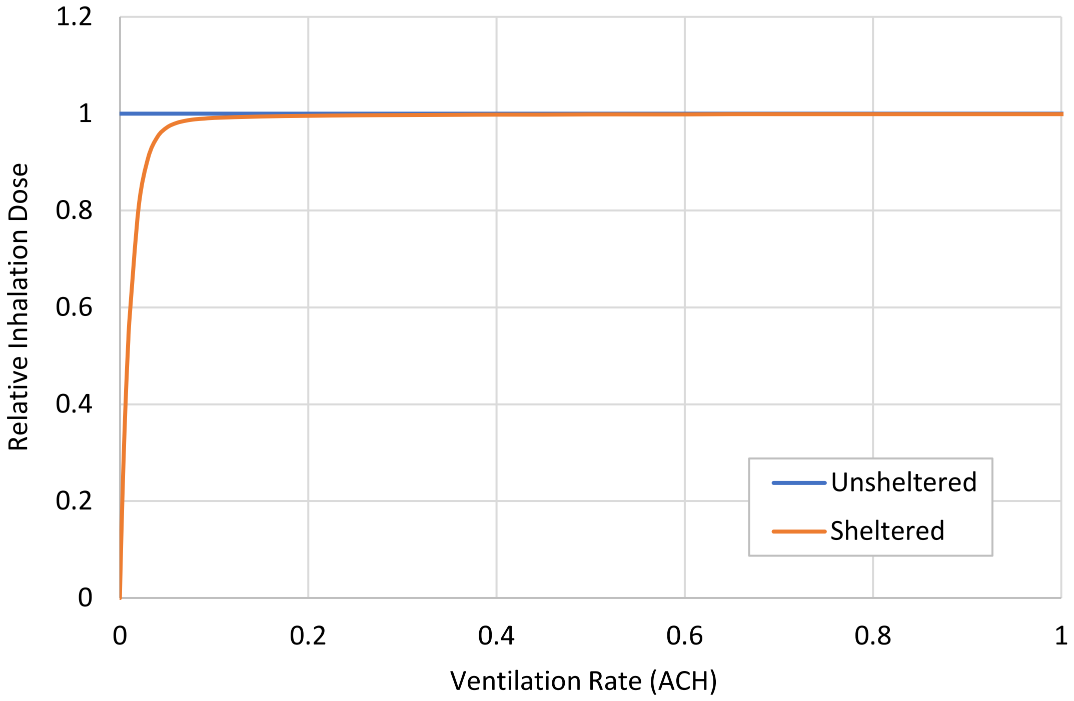


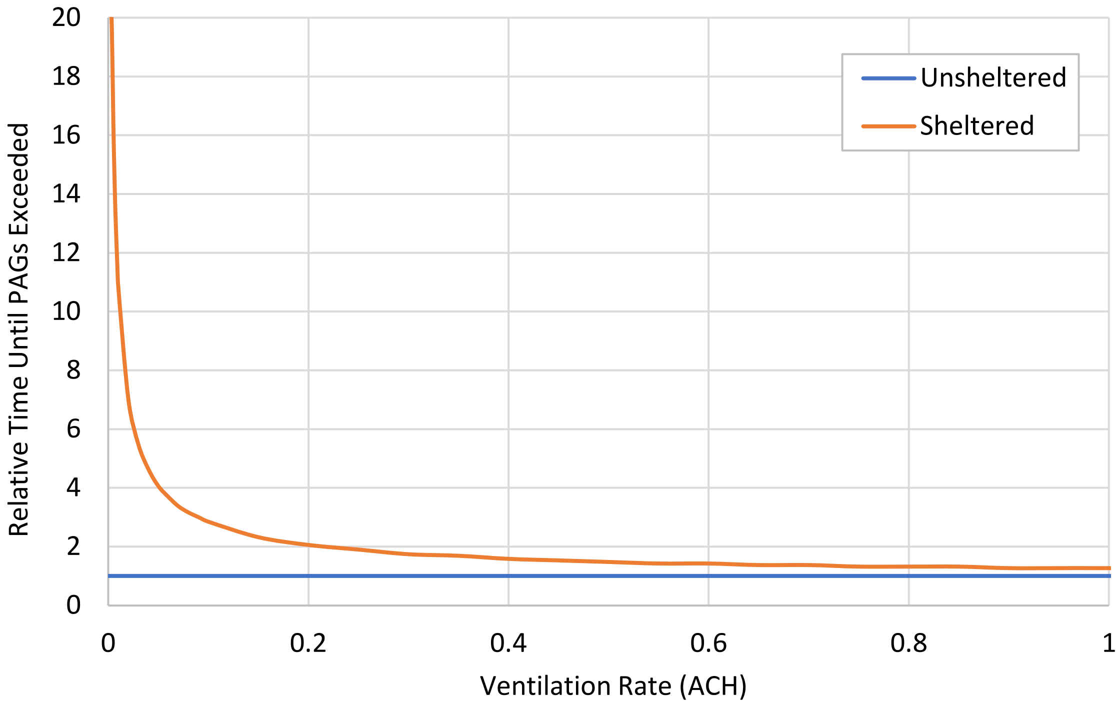
Protection Factor for Inhalation

Ventilation rate (ACH)	Duration of plume exposure (hr)	1992 EPA PAG Manual DRF (Table 3-4)	PARatus 0.5 miles DRF	PARatus 2 miles DRF
0.3	0.5	0.07	0.01	~ 0
	1	0.14	0.05	0.02
	2	**0.25**	**0.17**	**0.13**
	4	0.41	0.32	0.30
	6	**0.54**	**0.37**	**0.36**
	96	-	0.44	0.44
1.0	0.5	0.21	0.02	~ 0
	1	0.36	0.10	0.05
	2	**0.56**	**0.29**	**0.22**
	4	0.75	0.40	0.39
	6	**0.83**	**0.43**	**0.43**
	96	-	0.46	0.46

Effect of Air Exchange Rate (no filtration)

Requires very little air exchange to equilibrate dose

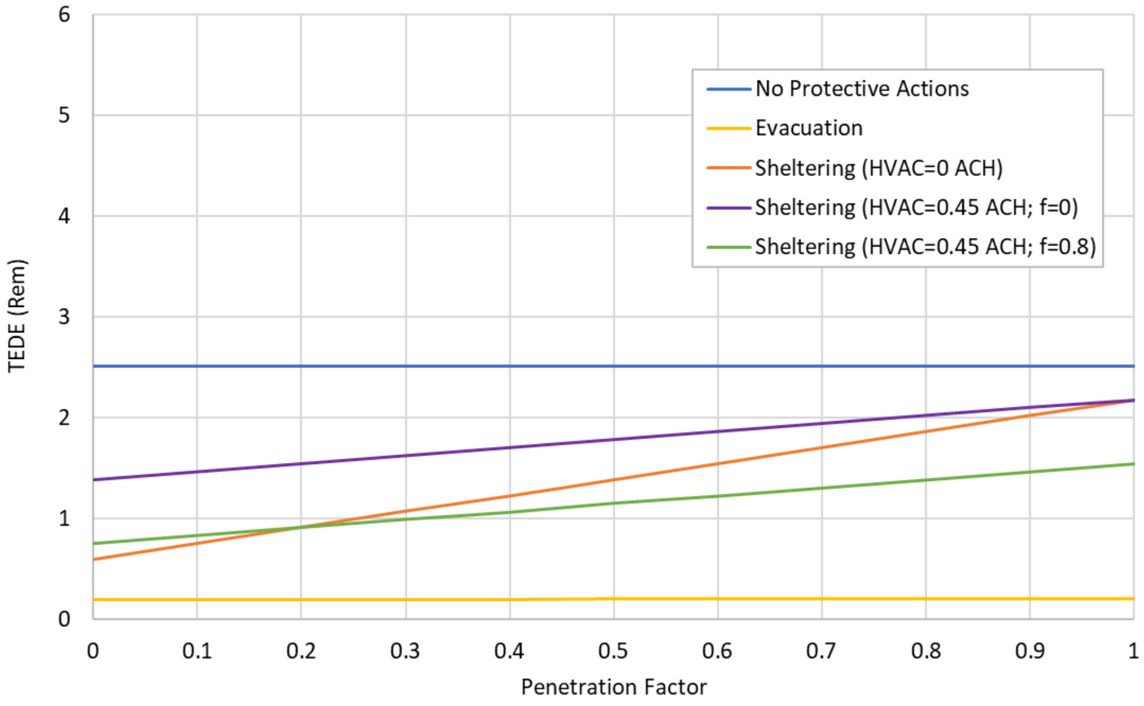


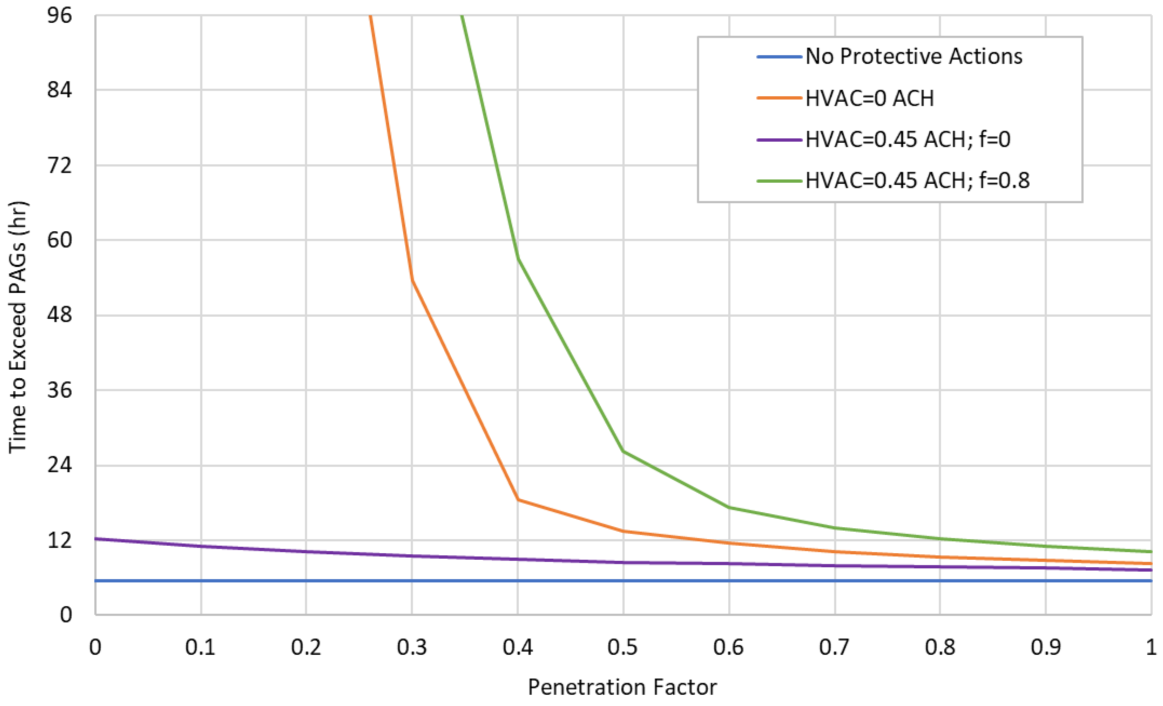


Reducing ACH increases time to exceed PAGs

Effect of Penetration Factor

PWR LOCA 5 miles downwind

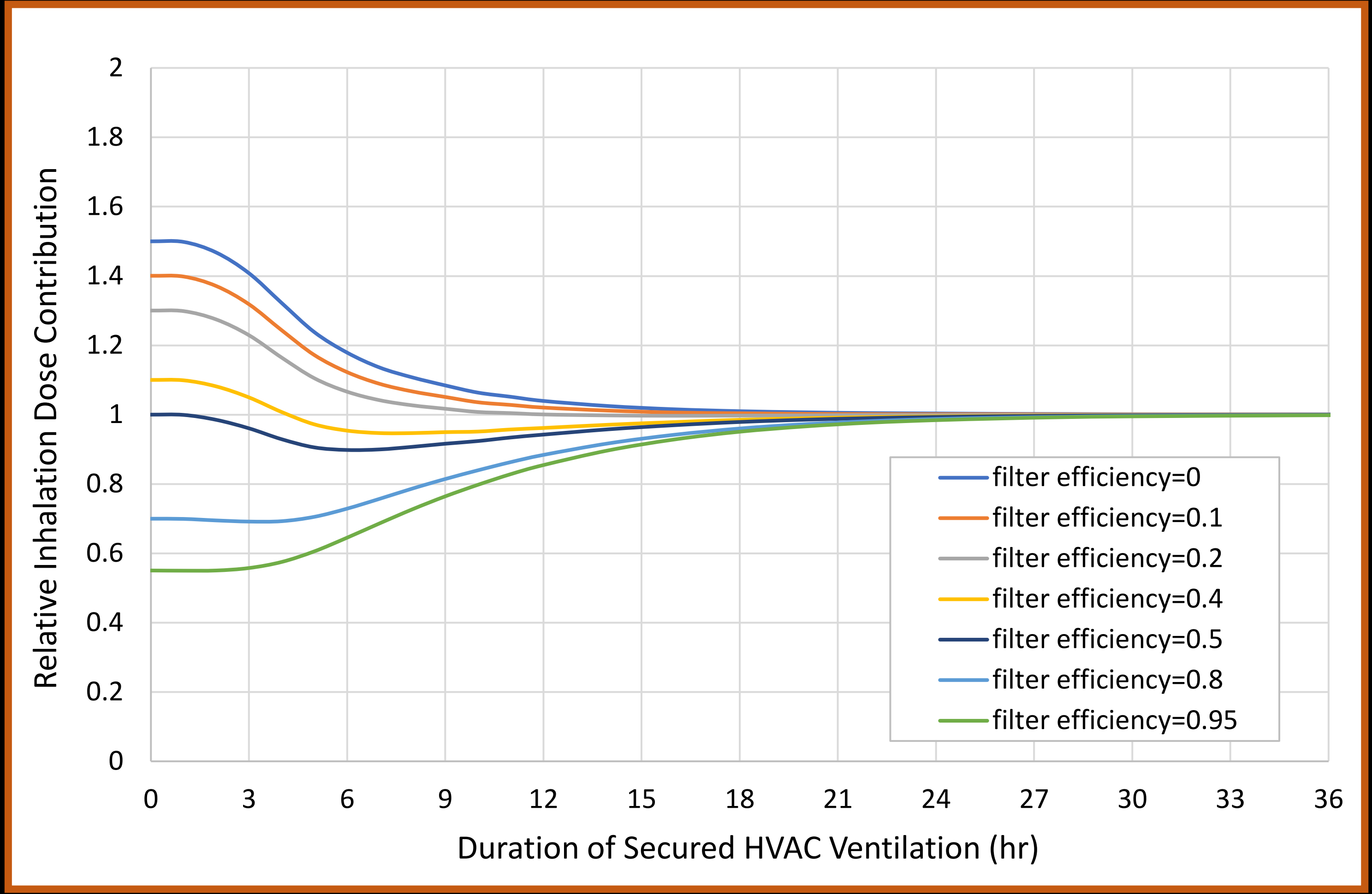




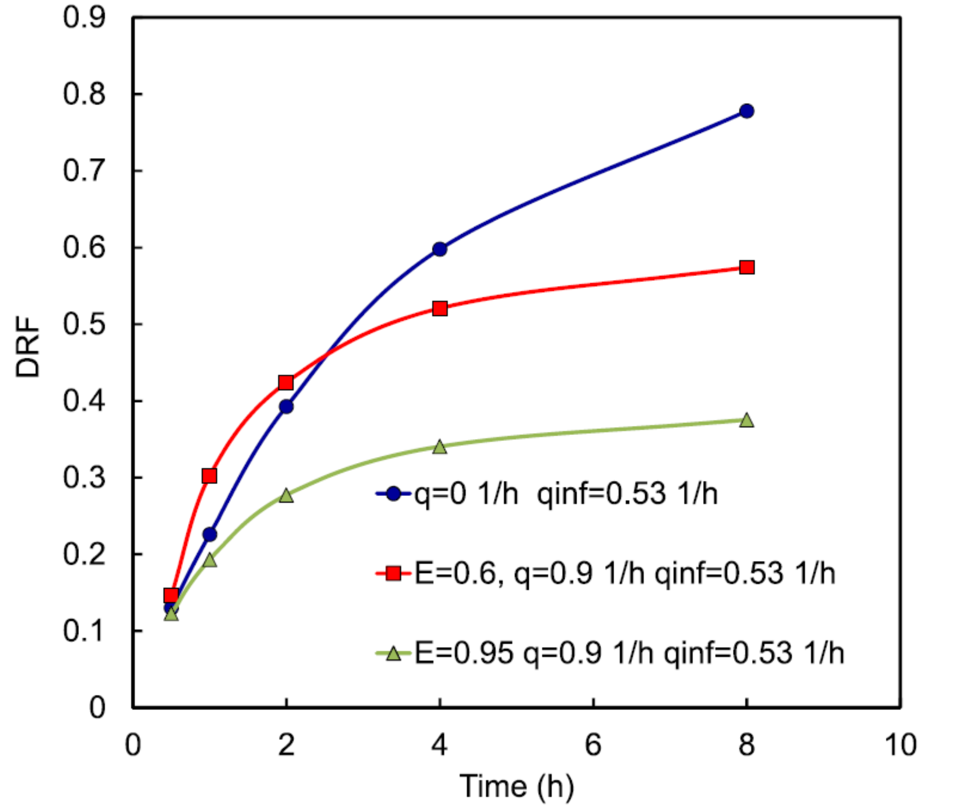
HVAC Considerations

How long should HVAC be secured?

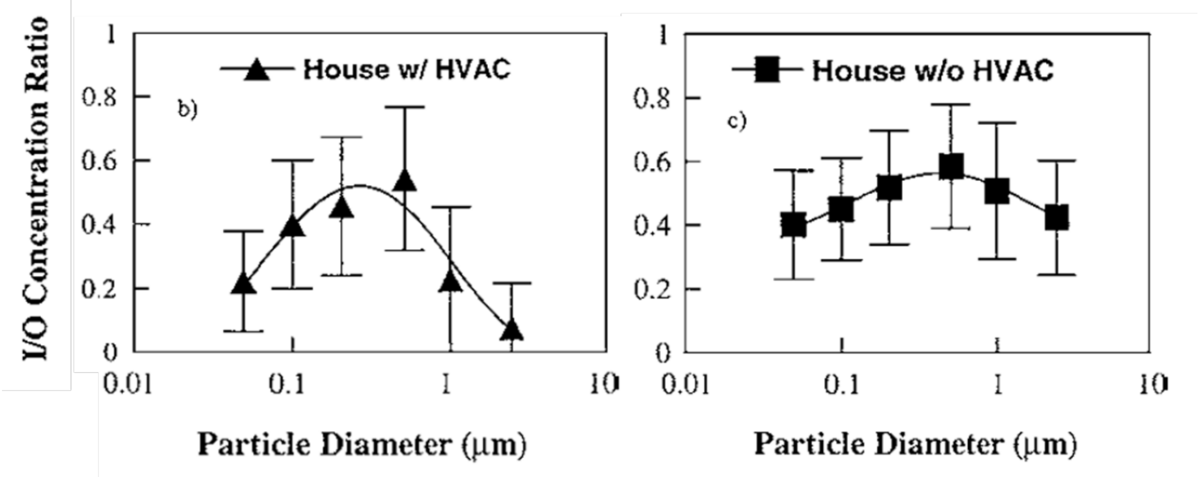
- Competing effects of increased air exchange and filtration efficiency
  - If filter efficiency is low, then secure ventilation
  - If filter efficiency is high, then operate ventilation
- Diminishing benefits to securing HVAC for prolonged periods of time in either case.



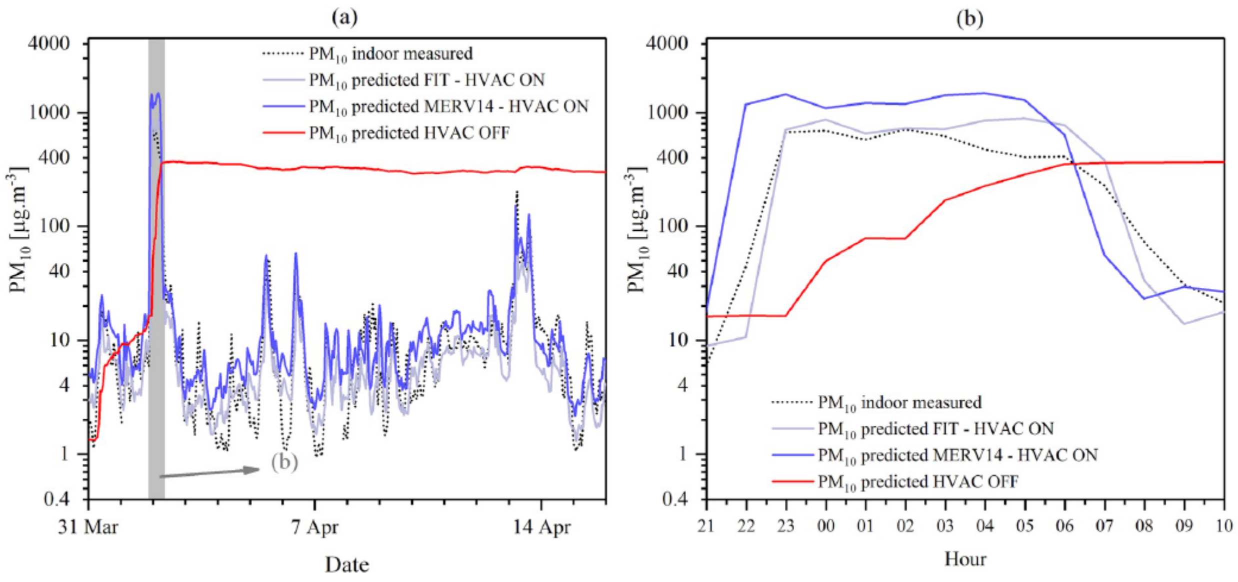
Benefits of HVAC



Modeled office building (Kulmala, 2016)



Monte Carlo simulations (Thornburg, 2001)



Dust storms (Argyropoulos, 2020)

APPLICATION

- Implementation strategies for sheltering-in-place can be informed by exacting the science considering:
  - Particle infiltration through building envelope
  - Air exchange rates
  - HVAC system operation
  - Plume timing considerations
  - Radionuclides released and dominant exposure pathways
  - Insights gained from other fields of study on shelter effectiveness
- Simple analysis tools can inform planning and response
  - Facilitate risk-informed protective action strategies
  - Examine strategies for advanced and small modular reactors
- Risks can be balanced to support protective action strategies that do more good than harm

Future Work

1. Reperform shelter analyses with realistic weather conditions
2. Conduct research to characterize the penetration factor for radiological releases
3. Examine implementation strategies for HVAC system use during a radiological release
4. Estimate the effect of particle deposition indoors on internal and external dose
5. Couple state-of-the-art shelter and evacuation models into consequence analysis codes
6. Perform protective action strategy studies using advanced reactor and small modular reactor source terms

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THANK YOU, RAMP

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