Exacting the Science of Emergency Preparedness

October 24, 2022

Todd Smith, PhD
U.S. Nuclear Regulatory Commission

Objective of Radiological EP

- The objective of emergency preparedness (EP) is to provide dose savings for a spectrum of accidents that could produce doses in excess of the Environment Protection Agency (EPA) protective action guides (PAG)
- Meeting NRC EP regulations provides reasonable assurance that adequate protective measures can and will be taken in the event of a radiological emergency
  - Reasonable assurance finding is made before a nuclear facility is licensed
  - Inspected over the lifetime of that facility

The NRC employs a graded approach to EP

- A graded approach is a process by which the safety requirements and criteria are set commensurate with several factors including magnitude of hazards involved, characteristics of a facility, the balance between radiological and nonradiological hazards.

- EP regulations employ a graded approach, which is a risk-informed process
  - Power reactors (low-power testing, power operations, decommissioning)
  - Research and test reactors
  - Fuel Fabrication Facilities
  - Independent Spent Fuel Storage Installations
  - Monitored Retrievable Storage

NUREG-0396 Planning Basis for EP

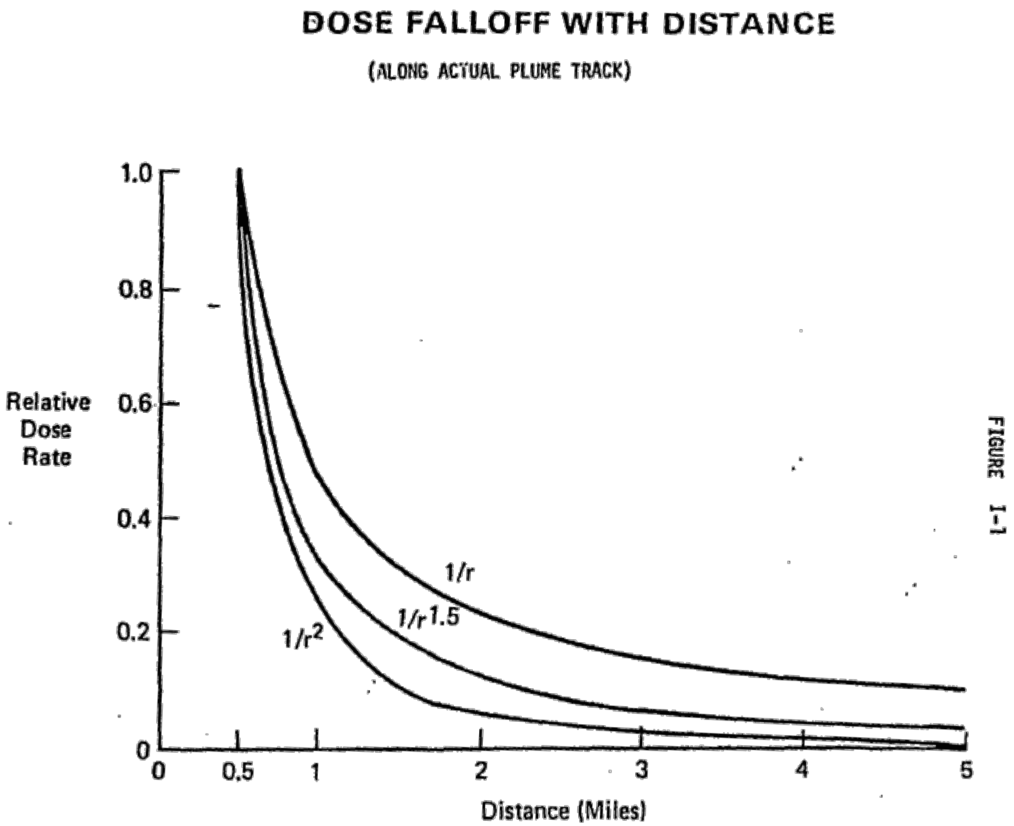
The consequences from a spectrum of accidents, tempered by probability considerations, should be considered to scope the planning efforts for:

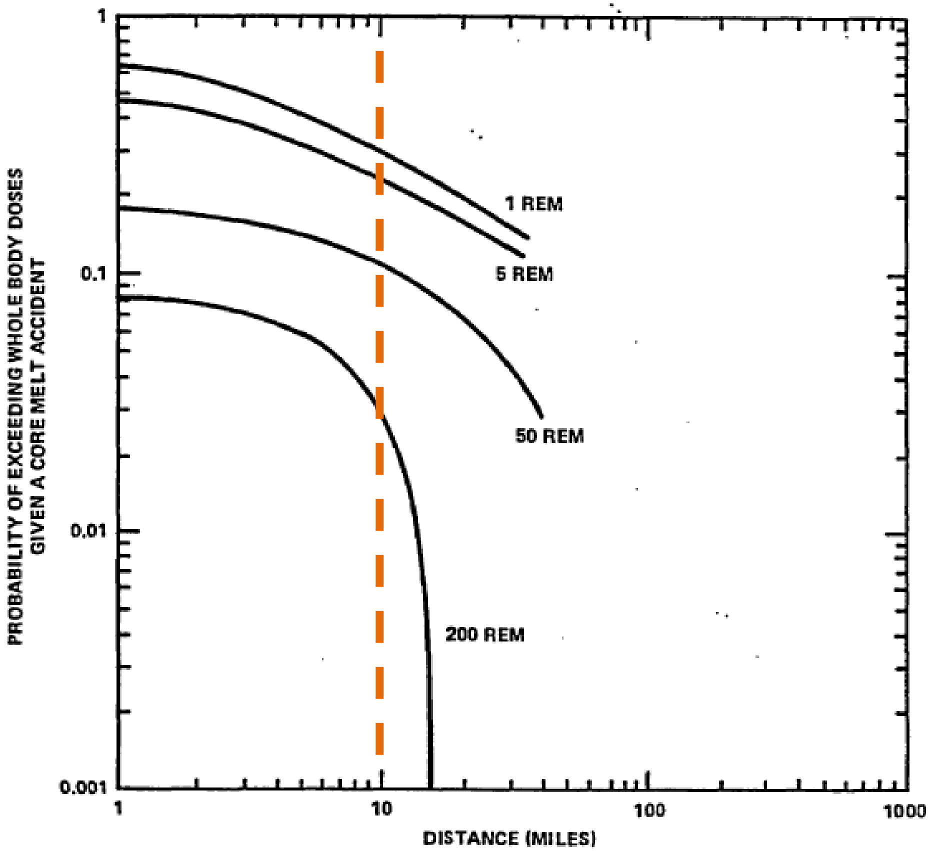
- *The **distance** to which planning for predetermined protective actions is warranted*
- *The **time** dependent characteristics of a potential release*
- *The type of radioactive **materials***

The planning basis included a recommended 10 mile plume exposure path emergency planning zone (EPZ) and a 50 mile ingestion pathway zone

NUREG-0396, "Planning Basis for the Development of State and Local Government Radiological Emergency Response Plans in Support of Light Water Nuclear Power Plants," November 1978

The EPZ size is risk-informed





Design Basis Accidents

Beyond Design Basis

NUREG-0396, "Planning Basis for the Development of State and Local Government Radiological Emergency Response Plans in Support of Light Water Nuclear Power Plants," November 1978

What's the likelihood of events considered?

TABLE V 2-1 SUMMARY OF ACCIDENTS INVOLVING CORE

RELEASE CATEGORY	PROBABILITY per Reactor-Yr	TIME OF RELEASE (Hr)	DURATION OF RELEASE (Hr)	WARNING TIME FOR EVACUATION (Hr)	ELEVATION OF RELEASE (Meters)	CONTAINMENT ENERGY RELEASE (10^6 Btu/Hr)	FRACTION OF CORE INVENTORY RELEASED[a] Xe-Kr	Org. I	I	Cs-Rb	Te-Sb	Ba-Sr	Ru[b]	La[c]
PWR 1	$9x10^{-7}$	2.5	0.5	1.0	25	520[d]	0.9	$6x10^{-3}$	0.7	0.4	0.4	0.05	0.4	$3x10^{-3}$
PWR 2	$8x10^{-6}$	2.5	0.5	1.0	0	170	0.9	$7x10^{-3}$	0.7	0.5	0.3	0.06	0.02	$4x10^{-3}$
PWR 3	$4x10^{-6}$	5.0	1.5	2.0	0	6	0.8	$6x10^{-3}$	0.2	0.2	0.3	0.02	0.03	$3x10^{-3}$
PWR 4	$5x10^{-7}$	2.0	3.0	2.0	0	1	0.6	$2x10^{-3}$	0.09	0.04	0.03	$5x10^{-3}$	$3x10^{-3}$	$4x10^{-4}$
PWR 5	$7x10^{-7}$	2.0	4.0	1.0	0	0.3	0.3	$2x10^{-3}$	0.03	$9x10^{-3}$	$5x10^{-3}$	$1x10^{-3}$	$6x10^{-4}$	$7x10^{-5}$
PWR 6	$6x10^{-6}$	12.0	10.0	1.0	0	N/A	0.3	$2x10^{-3}$	$8x10^{-4}$	$8x10^{-4}$	$1x10^{-3}$	$9x10^{-5}$	$7x10^{-5}$	$1x10^{-5}$
PWR 7	$4x10^{-5}$	10.0	10.0	1.0	0	N/A	$6x10^{-3}$	$2x10^{-5}$	$2x10^{-5}$	$1x10^{-5}$	$2x10^{-5}$	$1x10^{-6}$	$1x10^{-6}$	$2x10^{-7}$
PWR 8	$4x10^{-5}$	0.5	0.5	N/A	0	N/A	$2x10^{-3}$	$5x10^{-6}$	$1x10^{-4}$	$5x10^{-4}$	$1x10^{-6}$	$1x10^{-8}$	0	0
PWR 9	$4x10^{-4}$	0.5	0.5	N/A	0	N/A	$3x10^{-6}$	$7x10^{-9}$	$1x10^{-7}$	$6x10^{-7}$	$1x10^{-9}$	$1x10^{-11}$	0	0
BWR 1	$1x10^{-6}$	2.0	2.0	1.5	25	130	1.0	$7x10^{-3}$	0.40	0.40	0.70	0.05	0.5	$5x10^{-3}$
BWR 2	$6x10^{-6}$	30.0	3.0	2.0	0	30	1.0	$7x10^{-3}$	0.90	0.50	0.30	0.10	0.03	$4x10^{-3}$
BWR 3	$2x10^{-5}$	30.0	3.0	2.0	25	20	1.0	$7x10^{-3}$	0.10	0.10	0.30	0.01	0.02	$3x10^{-3}$
BWR 4	$2x10^{-6}$	5.0	2.0	2.0	25	N/A	0.6	$7x10^{-4}$	$8x10^{-4}$	$5x10^{-3}$	$4x10^{-3}$	$6x10^{-4}$	$6x10^{-4}$	$1x10^{-4}$
BWR 5	$1x10^{-4}$	3.5	5.0	N/A	150	N/A	$5x10^{-4}$	$2x10^{-9}$	$6x10^{-11}$	$4x10^{-9}$	$8x10^{-12}$	$8x10^{-14}$	0	0

NUREG-075/014 (WASH-1400), "Reactor Safety Study: An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants," October 1975

U.S.NRC United States Nuclear Regulatory Commission
Protecting People and the Environment

What’s the timing of events?

TABLE V 2-1 SUMMARY OF ACCIDENTS INVOLVING CORE

RELEASE CATEGORY	PROBABILITY per Reactor-Yr	TIME OF RELEASE (Hr)	DURATION OF RELEASE (Hr)	WARNING TIME FOR EVACUATION (Hr)	ELEVATION OF RELEASE (Meters)	CONTAINMENT ENERGY RELEASE (10^6 Btu/Hr)	FRACTION OF CORE INVENTORY RELEASED[a] Xe-Kr	Org. I	I	Cs-Rb	Te-Sb	Ba-Sr	Ru[b]	La[c]
PWR 1	$9x10^{-7}$	2.5	0.5	1.0	25	520[d]	0.9	$6x10^{-3}$	0.7	0.4	0.4	0.05	0.4	$3x10^{-3}$
PWR 2	$8x10^{-6}$	2.5	0.5	1.0	0	170	0.9	$7x10^{-3}$	0.7	0.5	0.3	0.06	0.02	$4x10^{-3}$
PWR 3	$4x10^{-6}$	5.0	1.5	2.0	0	6	0.8	$6x10^{-3}$	0.2	0.2	0.3	0.02	0.03	$3x10^{-3}$
PWR 4	$5x10^{-7}$	2.0	3.0	2.0	0	1	0.6	$2x10^{-3}$	0.09	0.04	0.03	$5x10^{-3}$	$3x10^{-3}$	$4x10^{-4}$
PWR 5	$7x10^{-7}$	2.0	4.0	1.0	0	0.3	0.3	$2x10^{-3}$	0.03	$9x10^{-3}$	$5x10^{-3}$	$1x10^{-3}$	$6x10^{-4}$	$7x10^{-5}$
PWR 6	$6x10^{-6}$	12.0	10.0	1.0	0	N/A	0.3	$2x10^{-3}$	$8x10^{-4}$	$8x10^{-4}$	$1x10^{-3}$	$9x10^{-5}$	$7x10^{-5}$	$1x10^{-5}$
PWR 7	$4x10^{-5}$	10.0	10.0	1.0	0	N/A	$6x10^{-3}$	$2x10^{-5}$	$2x10^{-5}$	$1x10^{-5}$	$2x10^{-5}$	$1x10^{-6}$	$1x10^{-6}$	$2x10^{-7}$
PWR 8	$4x10^{-5}$	0.5	0.5	N/A	0	N/A	$2x10^{-3}$	$5x10^{-6}$	$1x10^{-4}$	$5x10^{-4}$	$1x10^{-6}$	$1x10^{-8}$	0	0
PWR 9	$4x10^{-4}$	0.5	0.5	N/A	0	N/A	$3x10^{-6}$	$7x10^{-9}$	$1x10^{-7}$	$6x10^{-7}$	$1x10^{-9}$	$1x10^{-11}$	0	0
BWR 1	$1x10^{-6}$	2.0	2.0	1.5	25	130	1.0	$7x10^{-3}$	0.40	0.40	0.70	0.05	0.5	$5x10^{-3}$
BWR 2	$6x10^{-6}$	30.0	3.0	2.0	0	30	1.0	$7x10^{-3}$	0.90	0.50	0.30	0.10	0.03	$4x10^{-3}$
BWR 3	$2x10^{-5}$	30.0	3.0	2.0	25	20	1.0	$7x10^{-3}$	0.10	0.10	0.30	0.01	0.02	$3x10^{-3}$
BWR 4	$2x10^{-6}$	5.0	2.0	2.0	25	N/A	0.6	$7x10^{-4}$	$8x10^{-4}$	$5x10^{-3}$	$4x10^{-3}$	$6x10^{-4}$	$6x10^{-4}$	$1x10^{-4}$
BWR 5	$1x10^{-4}$	3.5	5.0	N/A	150	N/A	$5x10^{-4}$	$2x10^{-9}$	$6x10^{-11}$	$4x10^{-9}$	$8x10^{-12}$	$8x10^{-14}$	0	0

NUREG-075/014 (WASH-1400), “Reactor Safety Study: An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants,” October 1975

What can get released?

TABLE V 2-1 SUMMARY OF ACCIDENTS INVOLVING CORE

RELEASE CATEGORY	PROBABILITY per Reactor-Yr	TIME OF RELEASE (Hr)	DURATION OF RELEASE (Hr)	WARNING TIME FOR EVACUATION (Hr)	ELEVATION OF RELEASE (Meters)	CONTAINMENT ENERGY RELEASE (10^6 Btu/Hr)	FRACTION OF CORE INVENTORY RELEASED[a] Xe-Kr	Org. I	I	Cs-Rb	Te-Sb	Ba-Sr	Ru[b]	La[c]
PWR 1	$9x10^{-7}$	2.5	0.5	1.0	25	520[d]	0.9	$6x10^{-3}$	0.7	0.4	0.4	0.05	0.4	$3x10^{-3}$
PWR 2	$8x10^{-6}$	2.5	0.5	1.0	0	170	0.9	$7x10^{-3}$	0.7	0.5	0.3	0.06	0.02	$4x10^{-3}$
PWR 3	$4x10^{-6}$	5.0	1.5	2.0	0	6	0.8	$6x10^{-3}$	0.2	0.2	0.3	0.02	0.03	$3x10^{-3}$
PWR 4	$5x10^{-7}$	2.0	3.0	2.0	0	1	0.6	$2x10^{-3}$	0.09	0.04	0.03	$5x10^{-3}$	$3x10^{-3}$	$4x10^{-4}$
PWR 5	$7x10^{-7}$	2.0	4.0	1.0	0	0.3	0.3	$2x10^{-3}$	0.03	$9x10^{-3}$	$5x10^{-3}$	$1x10^{-3}$	$6x10^{-4}$	$7x10^{-5}$
PWR 6	$6x10^{-6}$	12.0	10.0	1.0	0	N/A	0.3	$2x10^{-3}$	$8x10^{-4}$	$8x10^{-4}$	$1x10^{-3}$	$9x10^{-5}$	$7x10^{-5}$	$1x10^{-5}$
PWR 7	$4x10^{-5}$	10.0	10.0	1.0	0	N/A	$6x10^{-3}$	$2x10^{-5}$	$2x10^{-5}$	$1x10^{-5}$	$2x10^{-5}$	$1x10^{-6}$	$1x10^{-6}$	$2x10^{-7}$
PWR 8	$4x10^{-5}$	0.5	0.5	N/A	0	N/A	$2x10^{-3}$	$5x10^{-6}$	$1x10^{-4}$	$5x10^{-4}$	$1x10^{-6}$	$1x10^{-8}$	0	0
PWR 9	$4x10^{-4}$	0.5	0.5	N/A	0	N/A	$3x10^{-6}$	$7x10^{-9}$	$1x10^{-7}$	$6x10^{-7}$	$1x10^{-9}$	$1x10^{-11}$	0	0
BWR 1	$1x10^{-6}$	2.0	2.0	1.5	25	130	1.0	$7x10^{-3}$	0.40	0.40	0.70	0.05	0.5	$5x10^{-3}$
BWR 2	$6x10^{-6}$	30.0	3.0	2.0	0	30	1.0	$7x10^{-3}$	0.90	0.50	0.30	0.10	0.03	$4x10^{-3}$
BWR 3	$2x10^{-5}$	30.0	3.0	2.0	25	20	1.0	$7x10^{-3}$	0.10	0.10	0.30	0.01	0.02	$3x10^{-3}$
BWR 4	$2x10^{-6}$	5.0	2.0	2.0	25	N/A	0.6	$7x10^{-4}$	$8x10^{-4}$	$5x10^{-3}$	$4x10^{-3}$	$6x10^{-4}$	$6x10^{-4}$	$1x10^{-4}$
BWR 5	$1x10^{-4}$	3.5	5.0	N/A	150	N/A	$5x10^{-4}$	$2x10^{-9}$	$6x10^{-11}$	$4x10^{-9}$	$8x10^{-12}$	$8x10^{-14}$	0	0

NUREG-075/014 (WASH-1400), "Reactor Safety Study: An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants," October 1975

The planning basis informs EP planning functions

Ensure capabilities exist to detect, classify, notify, assess, mitigate, and effectively respond to an emergency

Planning Basis		Emergency Planning Needs and Functions
Spectrum of Accidents	Distance	EPZ size, exposure pathways
	Time	Timeliness of classification and notification, protective action strategies, mitigation
	Materials	Detection and assessment capabilities, radiological protection, mitigation

Our understanding of accidents has evolved…

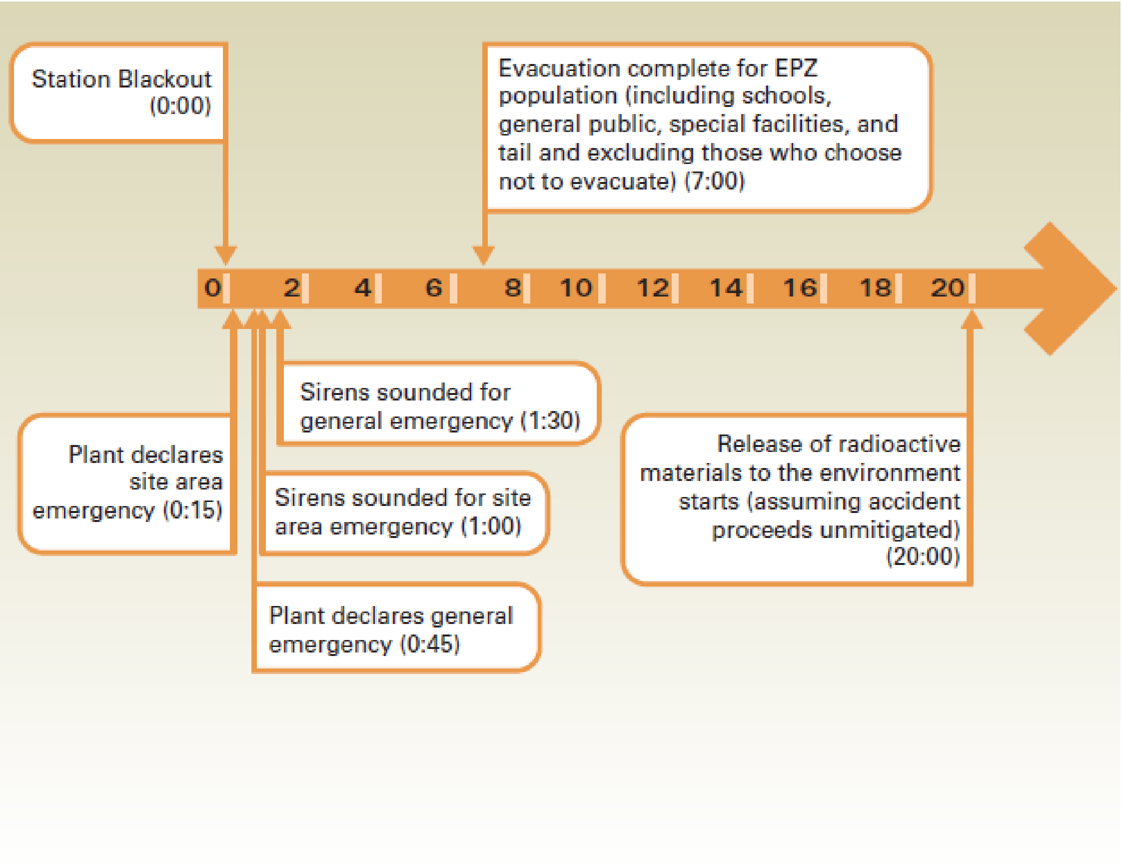
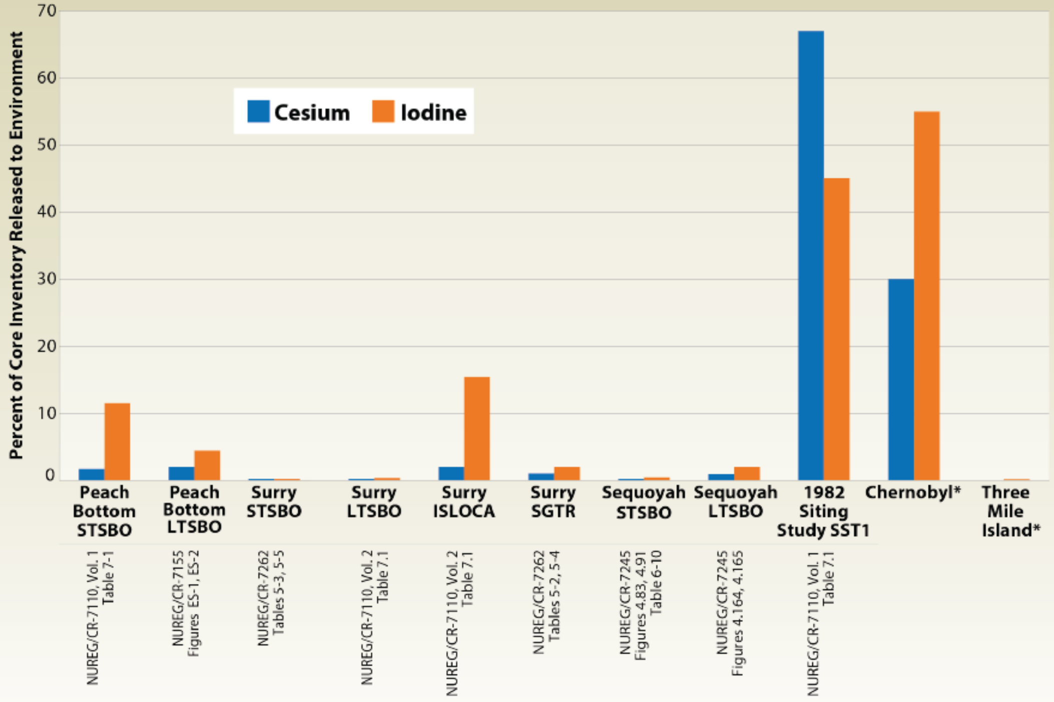


Figure 4.1 Percentages of Cesium and Iodine Released to the Environment for SOARCA Unmitigated Scenarios, 1982 Siting Study (SST1), and Historical Accidents

The SOARCA unmitigated release of Cesium-137 and Iodine-131, for each of the modelled scenarios, are much smaller than estimated in the earlier 1982 Siting Study Source Term 1 (SST1) case. Some of these releases develop over a period of time and are also much smaller than those from the Chernobyl accident.

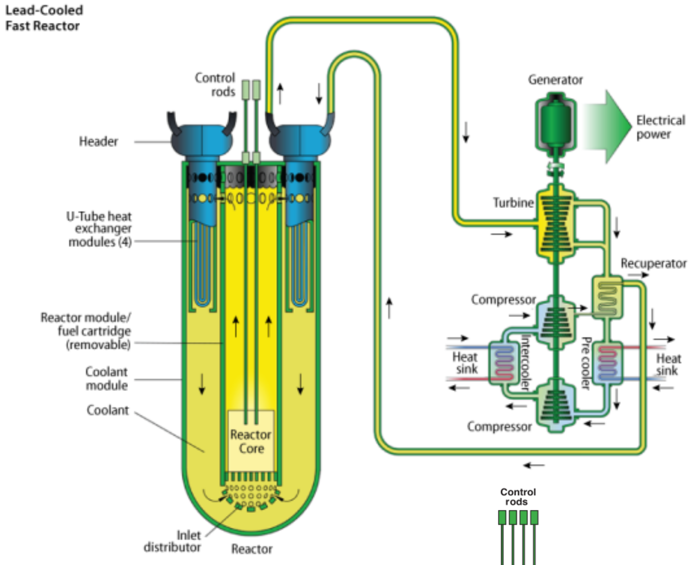


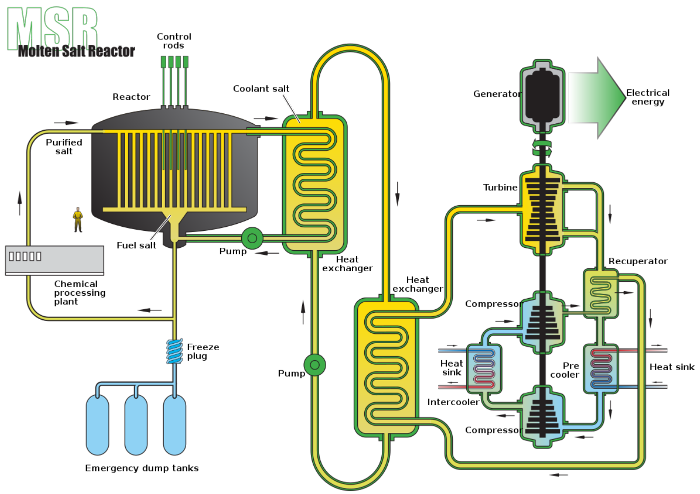
* Chernobyl release data is estimated at 20-40 percent for cesium-137 and 50-60 percent for iodine-131. Three Mile Island released an extremely small quantity of iodine-131 (~ 15 curies) and zero cesium-137. Fukushima releases are estimated to be approximately one-tenth of releases from Chernobyl [IAEA Report GC(59)/14].

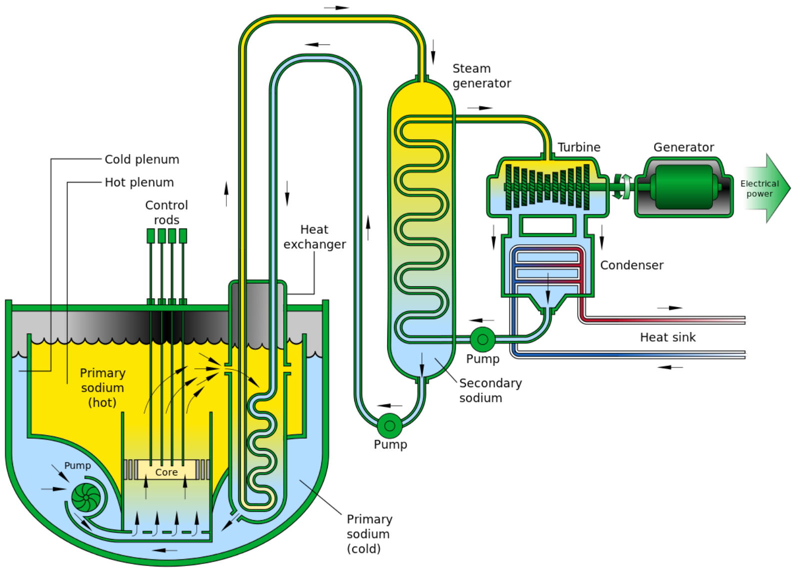
NUREG/BR-0359, Revision 3, "Modeling Potential Reactor Accident Consequences—State-of-the-Art Reactor Consequence Analyses: Using decades of research and experience to model accident progression, mitigation, emergency response, and health effects," October 2020

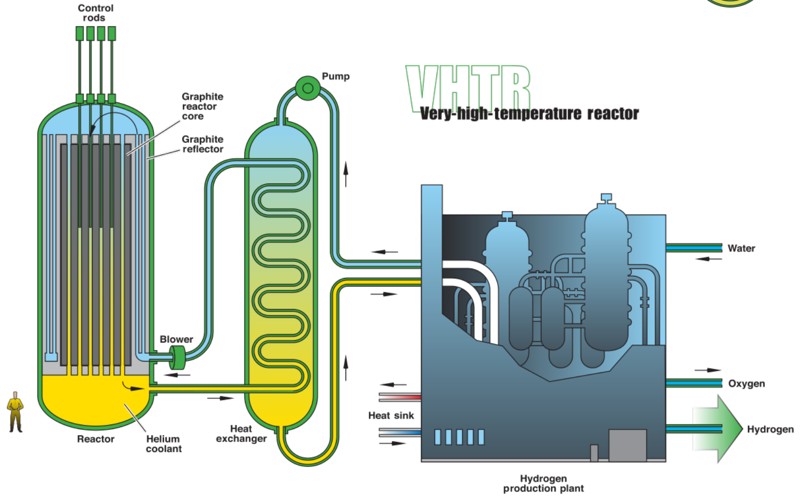
U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

...and will continue to evolve









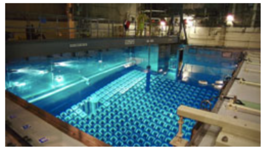
Accident Tolerant Fuel Technologies


Coated Cladding


Doped Pellets


FeCrAl Cladding


Increased Enrichment


Higher Burnup

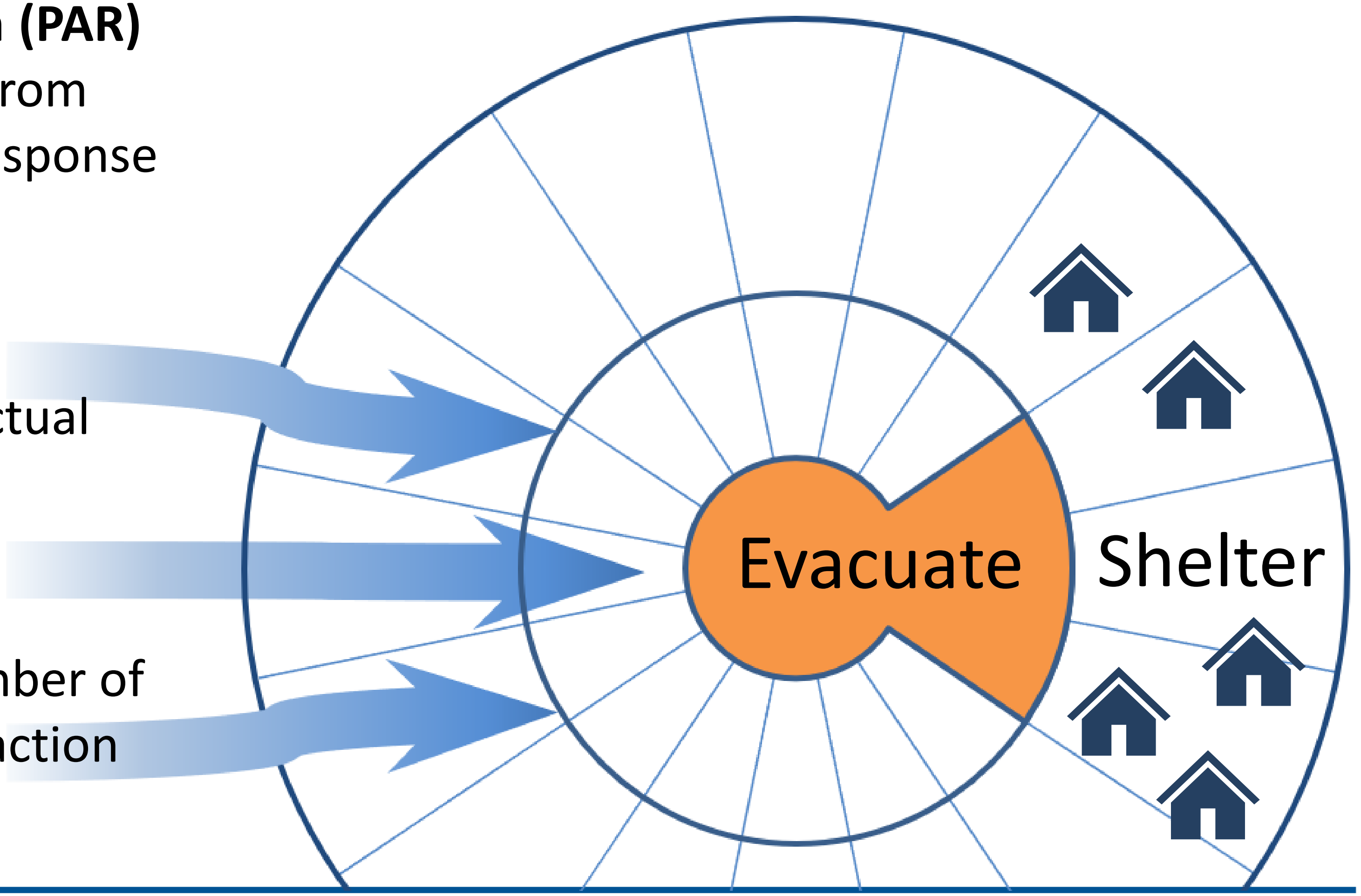

Longer Term Technologies

Deciding on action

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

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

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

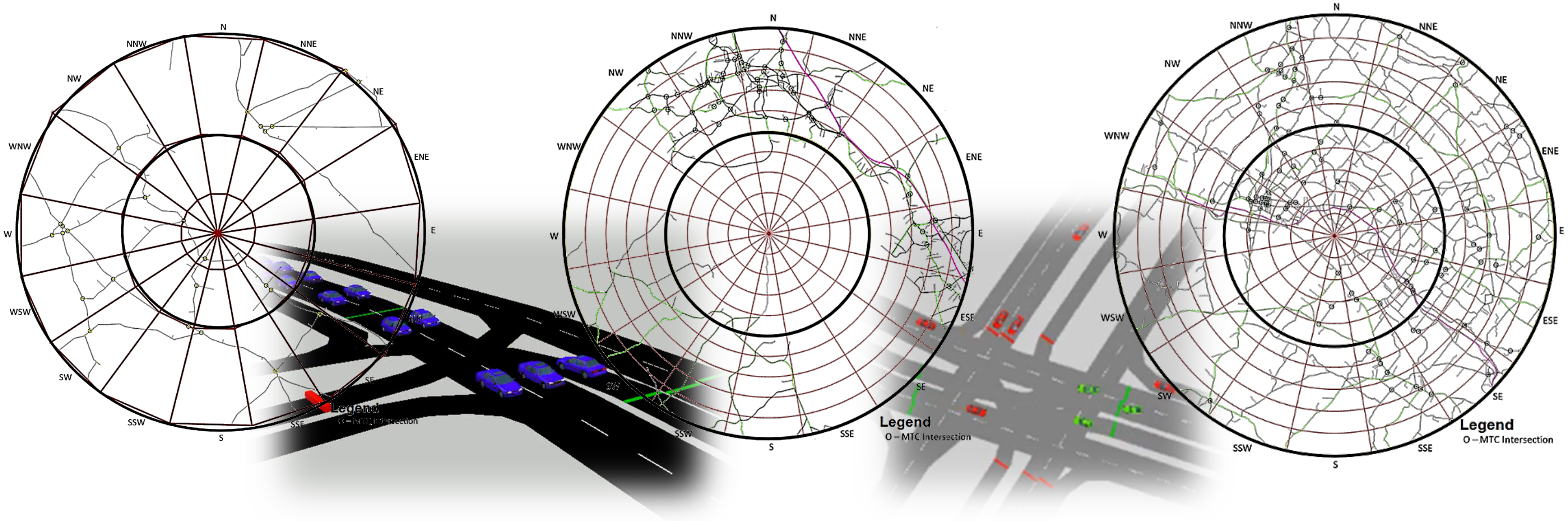


NRC research enhances emergency preparedness

- Protective Action Decisionmaking in the Intermediate Phase (NUREG/CR-7248)
- Evacuation Time Estimate Study (NUREG/CR-7269)
- Emergency Planning Zone (EPZ) Size Methodology
- Sensitivity of Dose Projections to Weather
- Analysis of the Effectiveness of Sheltering-in-Place
- Use of Heating and Ventilation Systems while Sheltering-in-Place
- Dose Reduction Effectiveness of Masks
- Nonradiological Health Impacts of Evacuations and Relocations (NUREG/CR-7285)
- MACCS Consequence Model Improvements Impact on Protective Action Strategies
- Development of a Machine Learning Tool for Predictive Emergency Response
  (to be published in *Transactions of the American Nuclear Society* for the 2022 ANS Winter Meeting)

Providing insights into effective evacuation

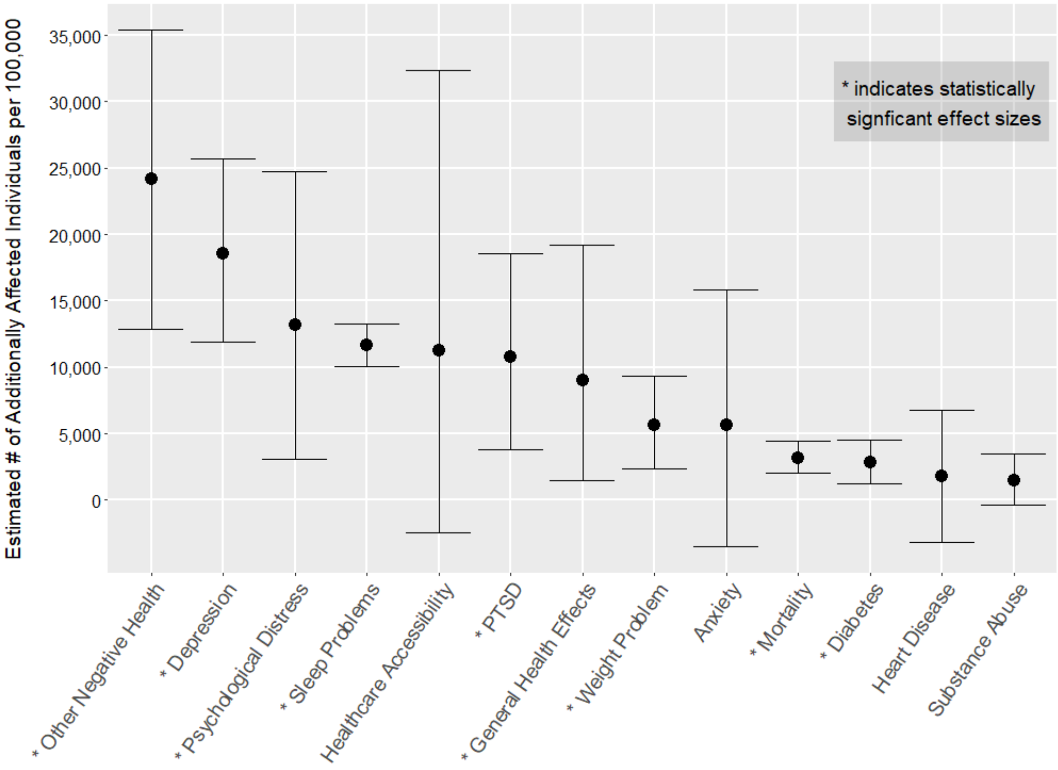
NUREG/CR-7269, "Enhancing Guidance for Evacuation Time Estimate Studies"
State-of-the-art traffic simulation models used to better understand evacuation dynamics and to develop insights for protecting the public and first responders



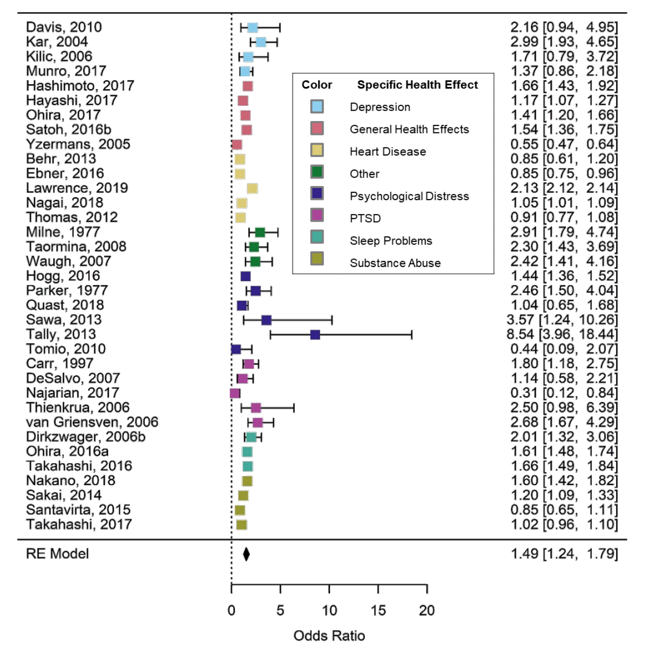
Assessing the balance of the risk

NUREG/CR-7285, "Nonradiological Health Consequences of Evacuation and Relocation"

Meta-analysis of the impact of prolonged displacement across all types of emergency events



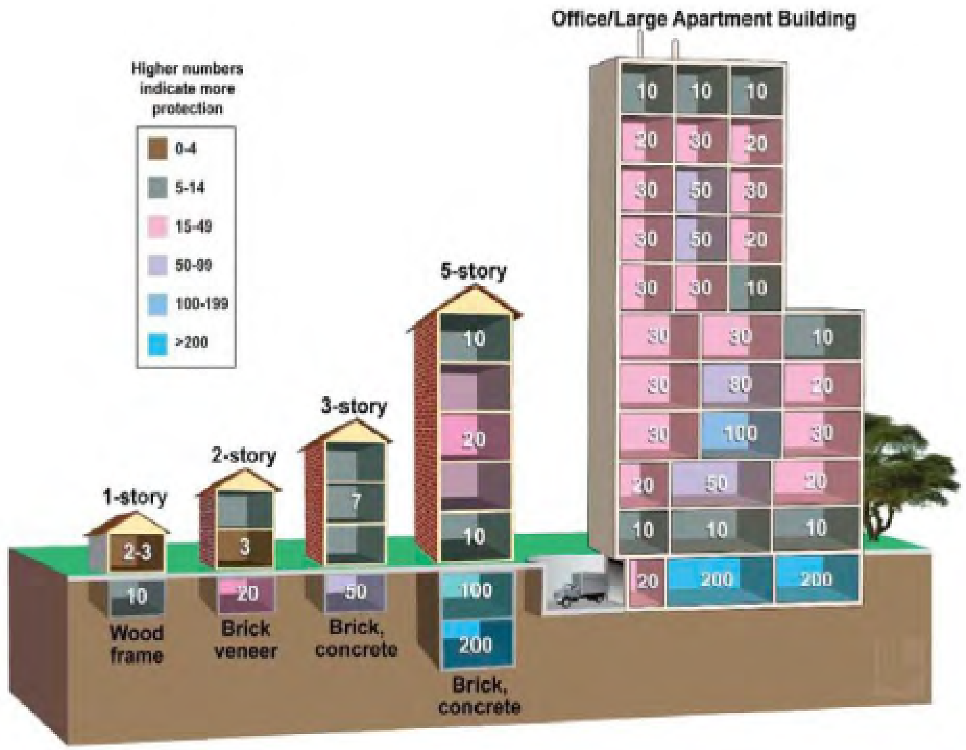
Meta-analysis of Odds Ratio for All Health Effects



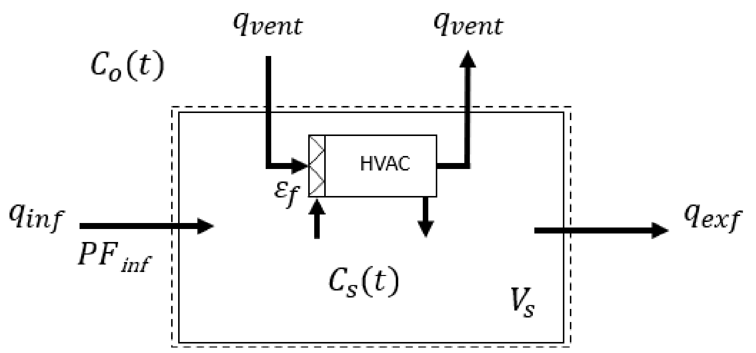
Health Outcome	Special Populations Included
Anxiety	
Depression	Children
Diabetes	Elderly
General Health Effects	Elderly, Males
Healthcare Accessibility	Elderly
Heart Disease	Elderly
Mortality	Hospital Patients, Nursing Home Residents
Other	Low-educated Mothers
Psychological Distress	Children, Hospitalized Patients
PTSD	University Students, Children
Respiratory Problem	Elderly
Sleep Problems	
Substance Abuse	Children
Weight Problem	

Analyzing the protection of shelters

Current dose reduction factors estimate shelter effectiveness



U.S. EPA. EPA-400/R-17/001, "PAG Manual: Protective Action Guides and Planning Guidance for Radiological Incidents," Office of Radiation and Indoor Air, January 2017.



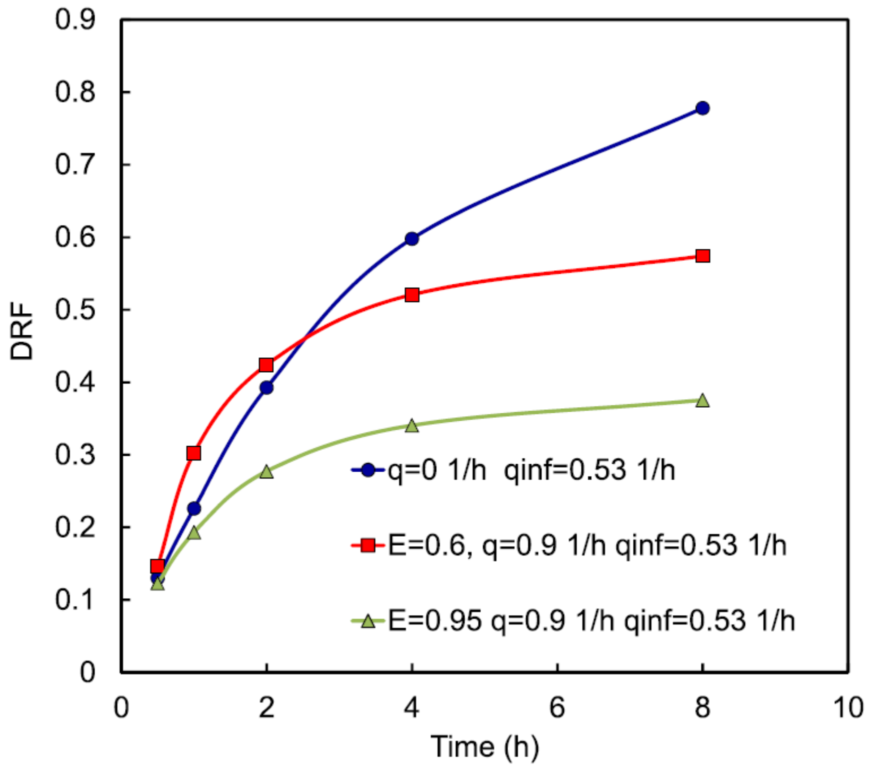
$$V_s \frac{dC_s}{dt} = rate\ in - rate\ out$$

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

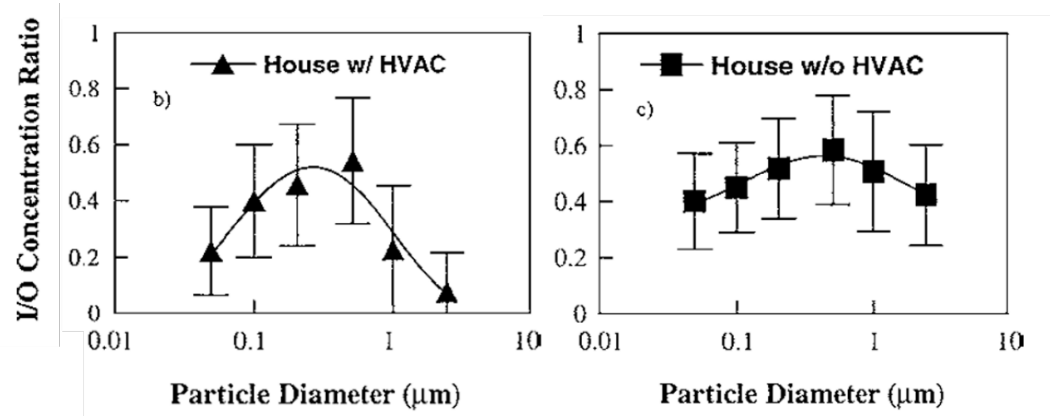
Shelter effectiveness can also be examined through dynamic models and lessons from other hazards to provide additional insight

Smith, Todd R. *Transforming Protective Action Strategies for Radiological Emergencies—Exacting the Science of Sheltering-in-Place.* Oregon State University, 2021.

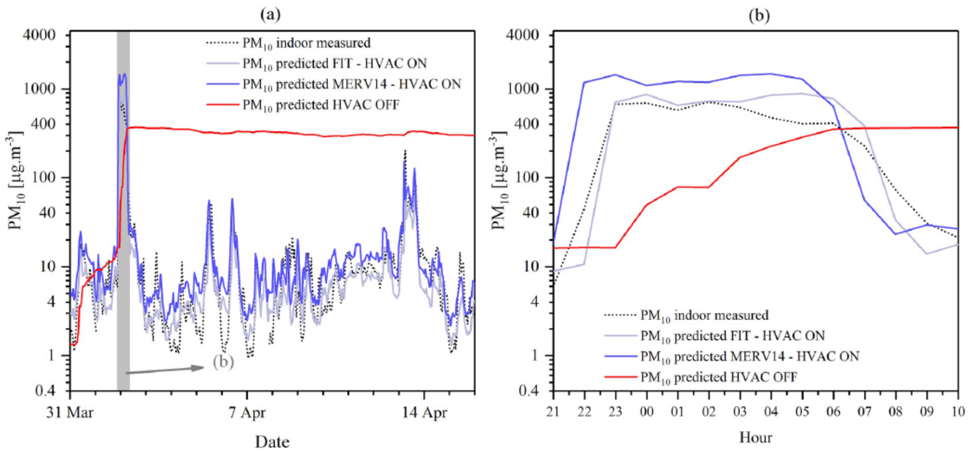
Exploring effective use of shelters and ventilation



Modeled office building (Kulmala, 2016)



Monte Carlo simulations (Thornburg, 2001)



Dust storms (Argyropoulos, 2020)

United States Nuclear Regulatory Commission

Protecting People and the Environment

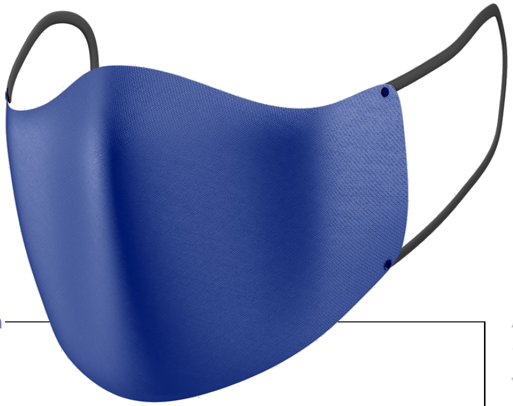
Quantifying the benefits of masks

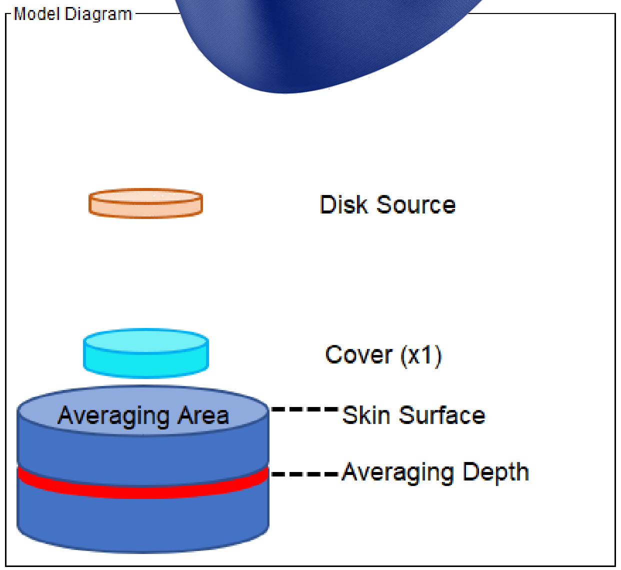
RASCAL

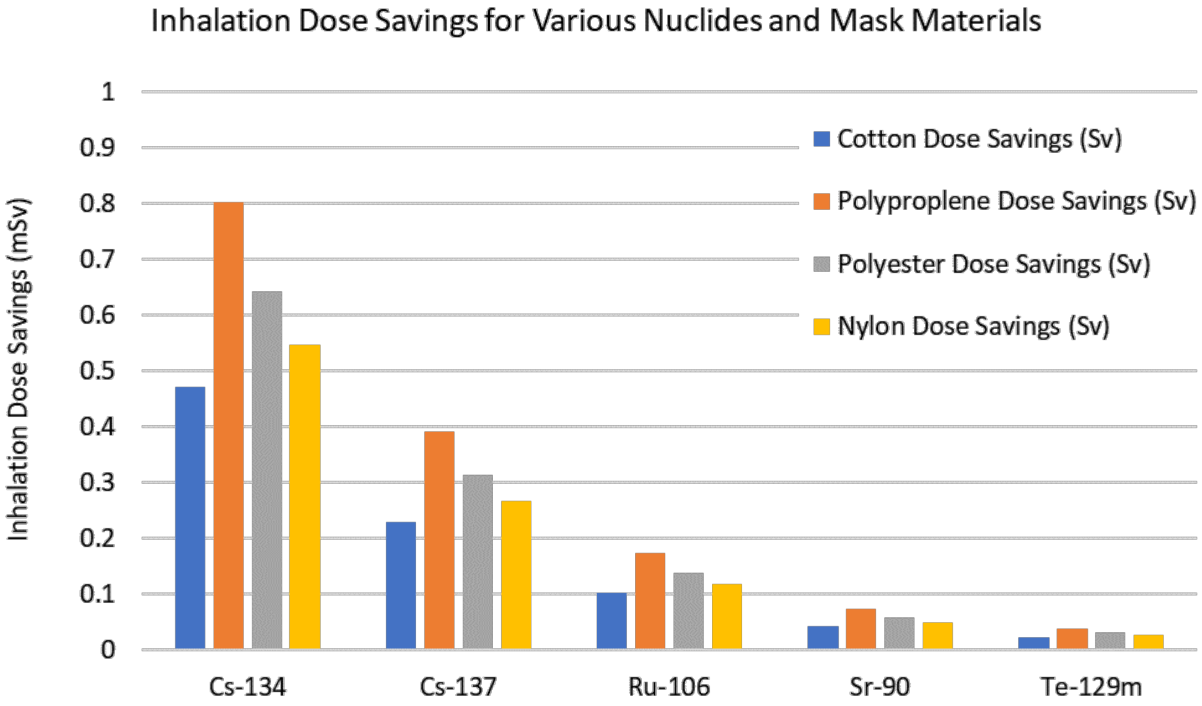
Radiological Assessment System for Consequence Analysis for radiological emergencies

VARSKIN

Dose calculation for skin contamination



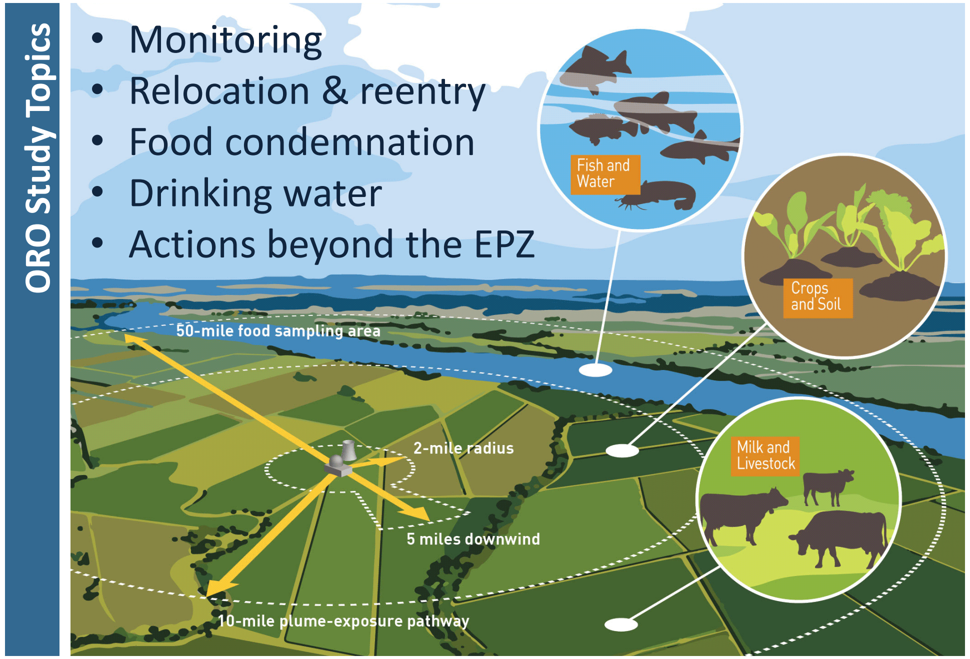




Gathering and sharing best practices

NUREG/CR-7248, "Capabilities and Practices of Offsite Response Organizations for Protective Actions in the Intermediate Phase of a Radiological Emergency Response"

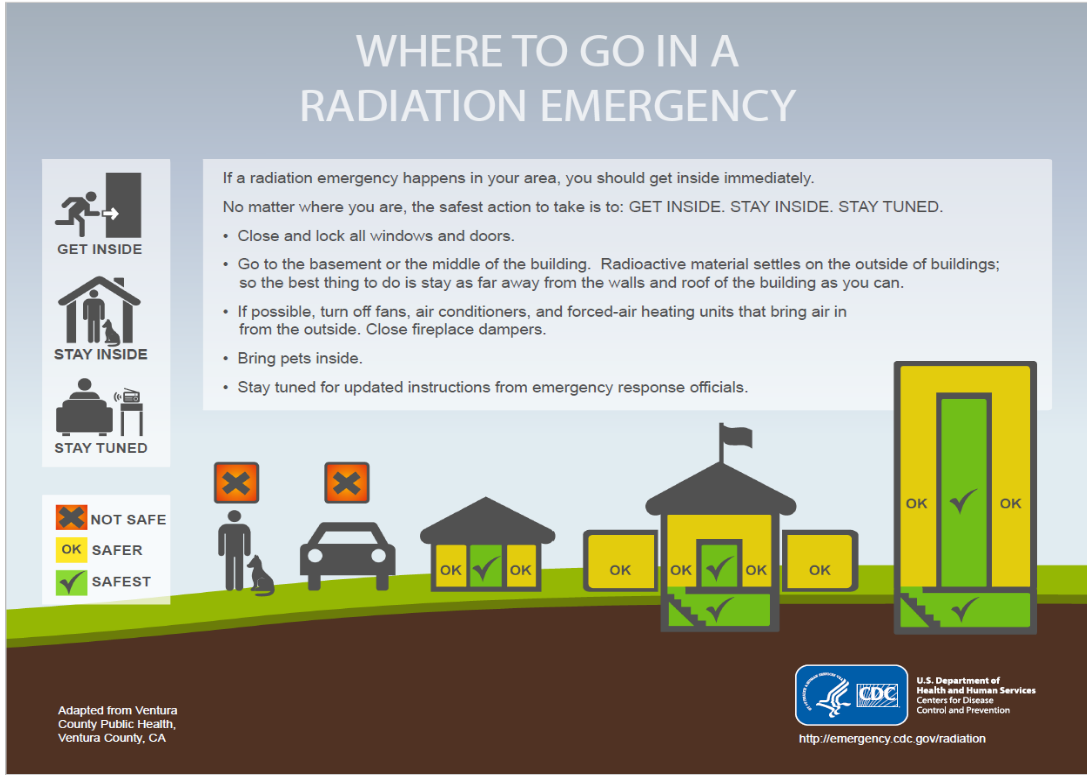
Shared understanding of offsite response organization capabilities and practices for protecting the public after the emergency phase. Data can inform MACCS modeling in intermediate phase.

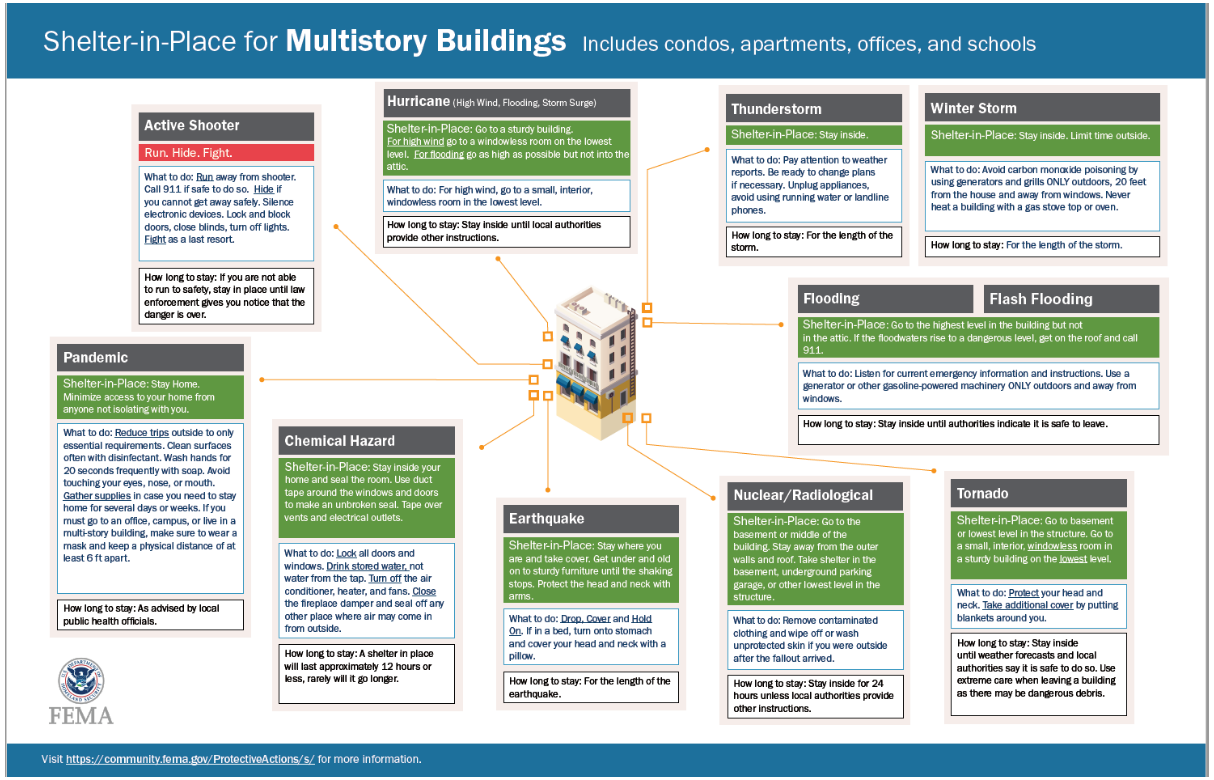


Best Practices identified for—

- Communicating with the public
- Developing partnerships and sharing resources for monitoring
- Making situation-dependent decisions based on science
- Leveraging technology
- Assisting vulnerable populations, livestock, and pets

Providing evidence to support protective actions





U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

RAMP — Radiation Protection Computer Code Analysis and Maintenance Program

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

RAMP *provides capabilities to exact the science of EP*

RASCAL

Radiological Assessment System for Consequence Analysis for radiological emergencies

RESRAD

Analyze potential human and biota radiation exposures from environmental contamination

Rad. Toolbox

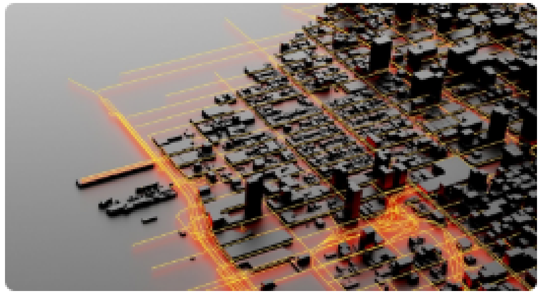
An electronic handbook of data for radiation protection

Turbo FRMAC

Assess radiological hazards during an emergency response

VARSKIN+

Dose calculation for skin contamination



VSP

Develop a defensible sampling plan based on statistical sampling theory

Thank you

For more information

Todd Smith, PhD
Senior Level Advisor for Emergency Preparedness and Incident Response
todd.smith@nrc.gov

References

1. U.S. NRC. NUREG/CR-7248, "Capabilities and Practices of Offsite Response Organizations for Protective Actions in the Intermediate Phase of a Radiological Emergency Response," June 2018. https://www.nrc.gov/reading-rm/doc-collections/nuregs/contract/cr7248/index.html
2. U.S. NRC. NUREG/CR-7269, "Enhancing Guidance for Evacuation Time Estimate Studies," January 2020. https://www.nrc.gov/reading-rm/doc-collections/nuregs/contract/cr7269/index.html
3. U.S. EPA. EPA-400/R-17/001, "PAG Manual: Protective Action Guides and Planning Guidance for Radiological Incidents," Office of Radiation and Indoor Air, January 2017. https://www.epa.gov/sites/default/files/2017-01/documents/epa_pag_manual_final_revisions_01-11-2017_cover_disclaimer_8.pdf
4. Smith, Todd R. *Transforming Protective Action Strategies for Radiological Emergencies—Exacting the Science of Sheltering-in-Place*. Oregon State University, 2021. https://ir.library.oregonstate.edu/concern/graduate_thesis_or_dissertations/pk02cj32m?locale=en
5. U.S. NRC. NUREG/CR-7285, "Nonradiological Health Consequences of Evacuation and Relocation," August 2021. https://www.nrc.gov/reading-rm/doc-collections/nuregs/contract/cr7285/index.html
6. U.S. Federal Emergency Management Agency. "Protective Actions Research," Web page, last accessed January 2022. https://community.fema.gov/ProtectiveActions/s/