



Exacting the Science of Emergency Preparedness

October 24, 2022

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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



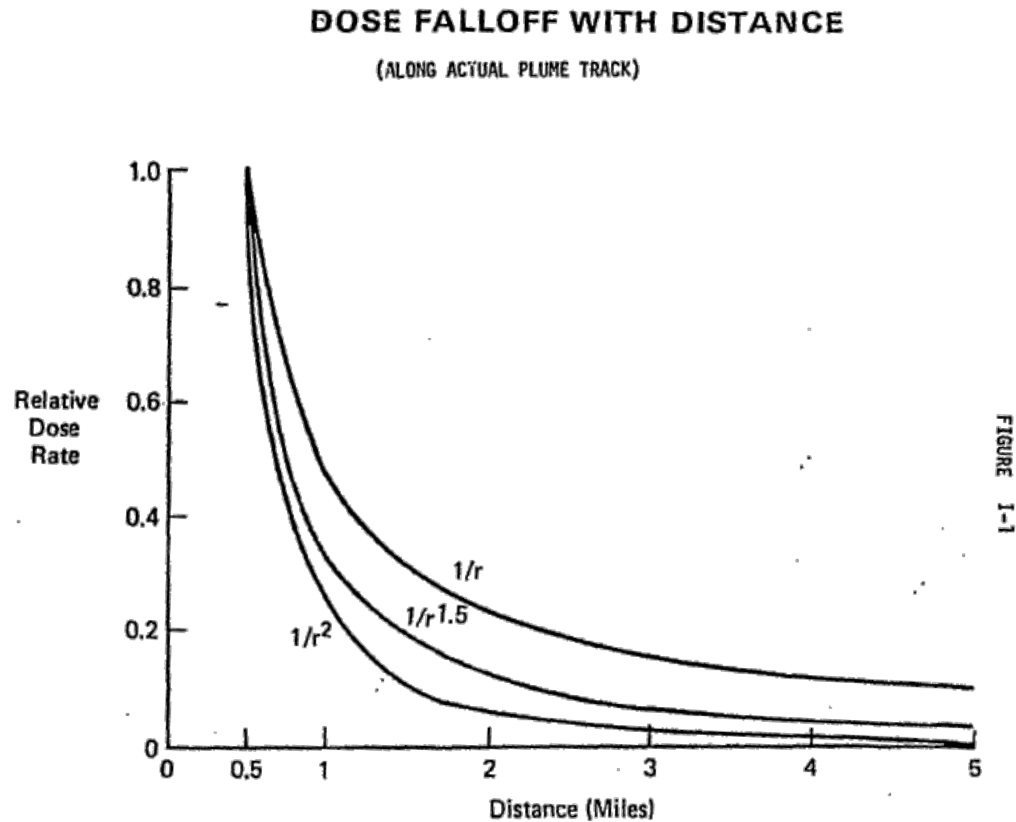
NUREG-0396 Planning Basis for EP

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

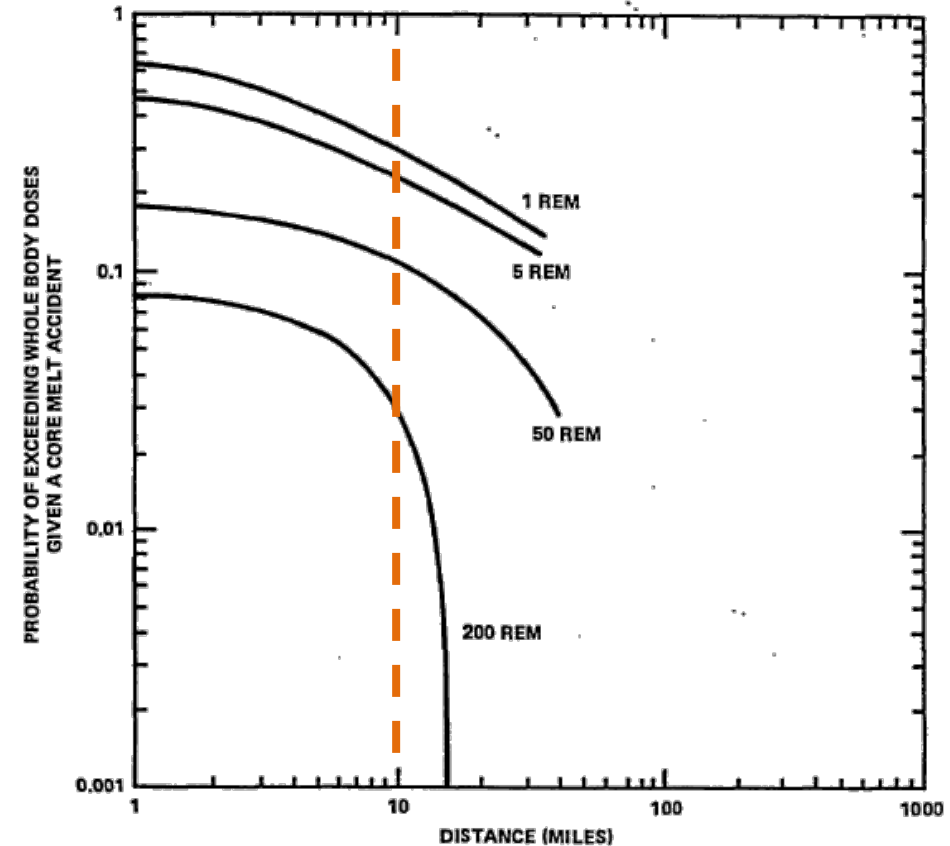
- *The **distance** to which planning for predetermined protective actions is warranted*
- *The **time** dependent characteristics of a potential release*
- *The type of radioactive **materials***

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

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



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)							
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PWR 1	9×10^{-7}	2.5	0.5	1.0	25	520 ^(d)	0.9	6×10^{-3}	0.7	0.4	0.4	0.05	0.4	3×10^{-3}
PWR 2	8×10^{-6}	2.5	0.5	1.0	0	170	0.9	7×10^{-3}	0.7	0.5	0.3	0.06	0.02	4×10^{-3}
PWR 3	4×10^{-6}	5.0	1.5	2.0	0	6	0.8	6×10^{-3}	0.2	0.2	0.3	0.02	0.03	3×10^{-3}
PWR 4	5×10^{-7}	2.0	3.0	2.0	0	1	0.6	2×10^{-3}	0.09	0.04	0.03	5×10^{-3}	3×10^{-3}	4×10^{-4}
PWR 5	7×10^{-7}	2.0	4.0	1.0	0	0.3	0.3	2×10^{-3}	0.03	9×10^{-3}	5×10^{-3}	1×10^{-3}	6×10^{-4}	7×10^{-5}
PWR 6	6×10^{-6}	12.0	10.0	1.0	0	N/A	0.3	2×10^{-3}	8×10^{-4}	8×10^{-4}	1×10^{-3}	9×10^{-5}	7×10^{-5}	1×10^{-5}
PWR 7	4×10^{-5}	10.0	10.0	1.0	0	N/A	6×10^{-3}	2×10^{-5}	2×10^{-5}	1×10^{-5}	2×10^{-5}	1×10^{-6}	1×10^{-6}	2×10^{-7}
PWR 8	4×10^{-5}	0.5	0.5	N/A	0	N/A	2×10^{-3}	5×10^{-6}	1×10^{-4}	5×10^{-4}	1×10^{-6}	1×10^{-8}	0	0
PWR 9	4×10^{-4}	0.5	0.5	N/A	0	N/A	3×10^{-6}	7×10^{-9}	1×10^{-7}	6×10^{-7}	1×10^{-9}	1×10^{-11}	0	0
BWR 1	1×10^{-6}	2.0	2.0	1.5	25	130	1.0	7×10^{-3}	0.40	0.40	0.70	0.05	0.5	5×10^{-3}
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BWR 4	2×10^{-6}	5.0	2.0	2.0	25	N/A	0.6	7×10^{-4}	8×10^{-4}	5×10^{-3}	4×10^{-3}	6×10^{-4}	6×10^{-4}	1×10^{-4}
BWR 5	1×10^{-4}	3.5	5.0	N/A	150	N/A	5×10^{-4}	2×10^{-9}	6×10^{-11}	4×10^{-9}	8×10^{-12}	8×10^{-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

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PWR 2	8×10^{-6}	2.5	0.5	1.0	0	170	0.9	7×10^{-3}	0.7	0.5	0.3	0.06	0.02	4×10^{-3}
PWR 3	4×10^{-6}	5.0	1.5	2.0	0	6	0.8	6×10^{-3}	0.2	0.2	0.3	0.02	0.03	3×10^{-3}
PWR 4	5×10^{-7}	2.0	3.0	2.0	0	1	0.6	2×10^{-3}	0.09	0.04	0.03	5×10^{-3}	3×10^{-3}	4×10^{-4}
PWR 5	7×10^{-7}	2.0	4.0	1.0	0	0.3	0.3	2×10^{-3}	0.03	9×10^{-3}	5×10^{-3}	1×10^{-3}	6×10^{-4}	7×10^{-5}
PWR 6	6×10^{-6}	12.0	10.0	1.0	0	N/A	0.3	2×10^{-3}	8×10^{-4}	8×10^{-4}	1×10^{-3}	9×10^{-5}	7×10^{-5}	1×10^{-5}
PWR 7	4×10^{-5}	10.0	10.0	1.0	0	N/A	6×10^{-3}	2×10^{-5}	2×10^{-5}	1×10^{-5}	2×10^{-5}	1×10^{-6}	1×10^{-6}	2×10^{-7}
PWR 8	4×10^{-5}	0.5	0.5	N/A	0	N/A	2×10^{-3}	5×10^{-6}	1×10^{-4}	5×10^{-4}	1×10^{-6}	1×10^{-8}	0	0
PWR 9	4×10^{-4}	0.5	0.5	N/A	0	N/A	3×10^{-6}	7×10^{-9}	1×10^{-7}	6×10^{-7}	1×10^{-9}	1×10^{-11}	0	0
BWR 1	1×10^{-6}	2.0	2.0	1.5	25	130	1.0	7×10^{-3}	0.40	0.40	0.70	0.05	0.5	5×10^{-3}
BWR 2	6×10^{-6}	30.0	3.0	2.0	0	30	1.0	7×10^{-3}	0.90	0.50	0.30	0.10	0.03	4×10^{-3}
BWR 3	2×10^{-5}	30.0	3.0	2.0	25	20	1.0	7×10^{-3}	0.10	0.10	0.30	0.01	0.02	3×10^{-3}
BWR 4	2×10^{-6}	5.0	2.0	2.0	25	N/A	0.6	7×10^{-4}	8×10^{-4}	5×10^{-3}	4×10^{-3}	6×10^{-4}	6×10^{-4}	1×10^{-4}
BWR 5	1×10^{-4}	3.5	5.0	N/A	150	N/A	5×10^{-4}	2×10^{-9}	6×10^{-11}	4×10^{-9}	8×10^{-12}	8×10^{-14}	0	0

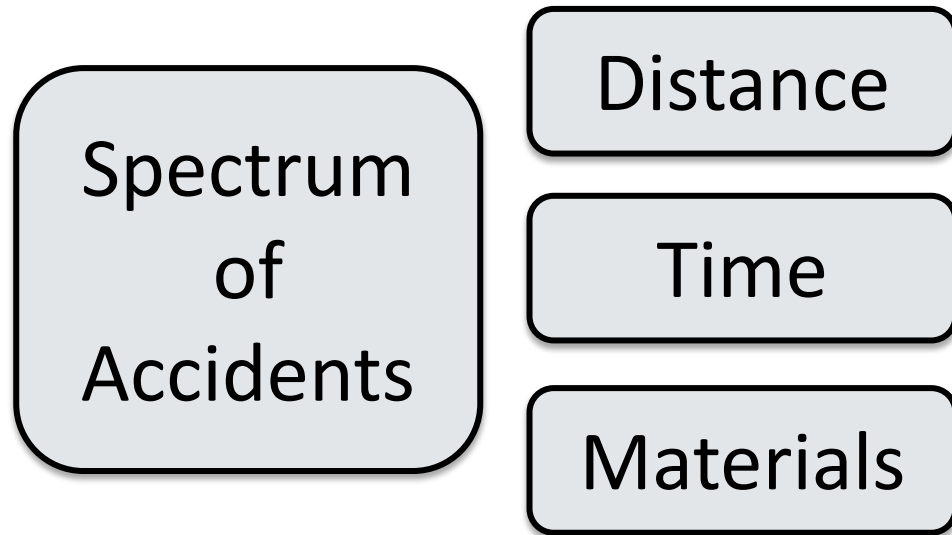
NUREG-075/014 (WASH-1400), "Reactor Safety Study: An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants," October 1975



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

EPZ size, exposure pathways

Timeliness of classification and notification, protective action strategies, mitigation

Detection and assessment capabilities, radiological protection, mitigation



Our understanding of accidents has evolved...

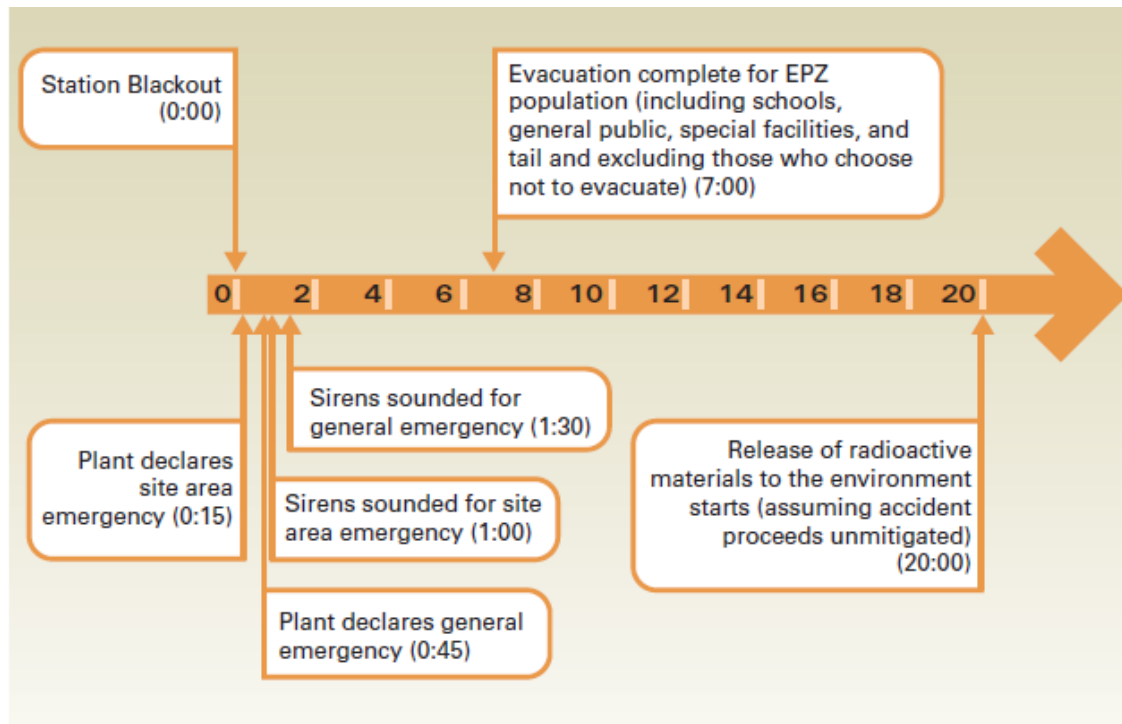
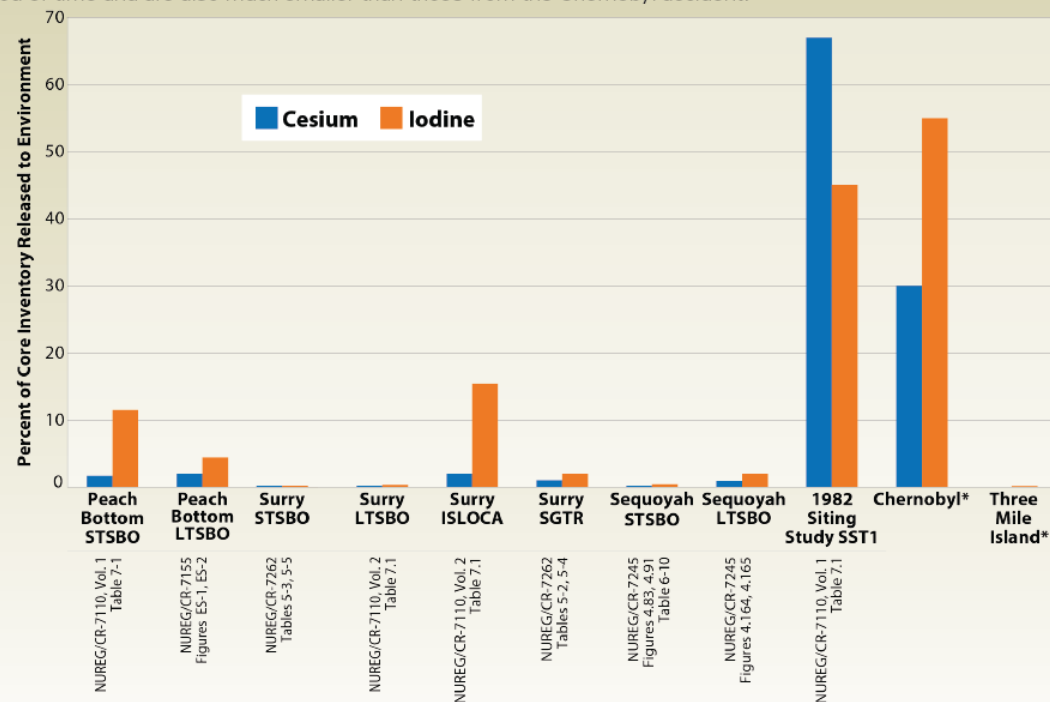


Figure 4.1 Percentages of Cesium and Iodine Released to the Environment for SOARCA Unmitigated Scenarios, 1982 Siting Study (SST1), and Historical Accidents

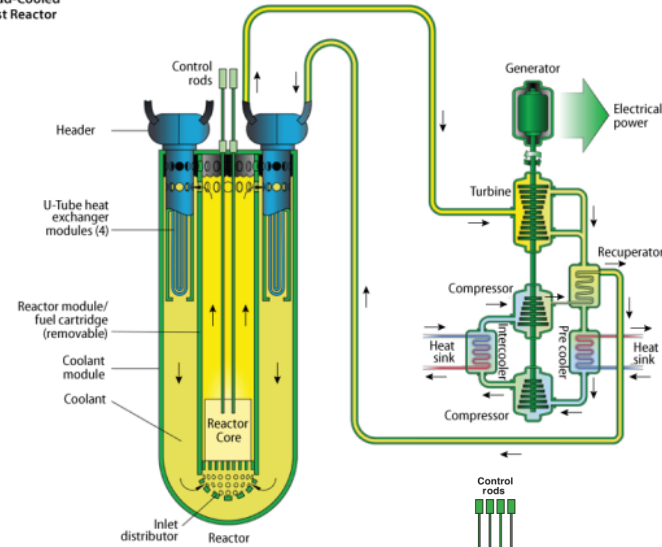
The SOARCA unmitigated release of Cesium-137 and Iodine-131, for each of the modelled scenarios, are much smaller than estimated in the earlier 1982 Siting Study Source Term 1 (SST1) case. Some of these releases develop over a period of time and are also much smaller than those from the Chernobyl accident.



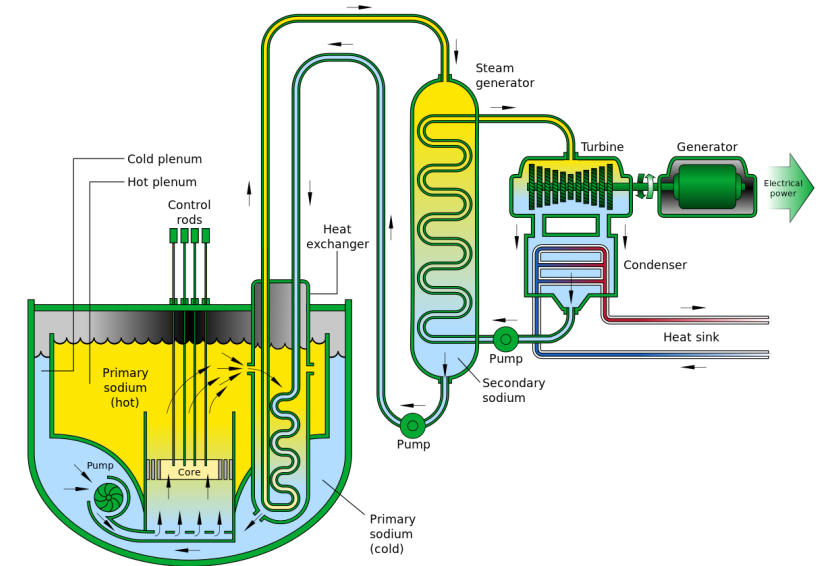
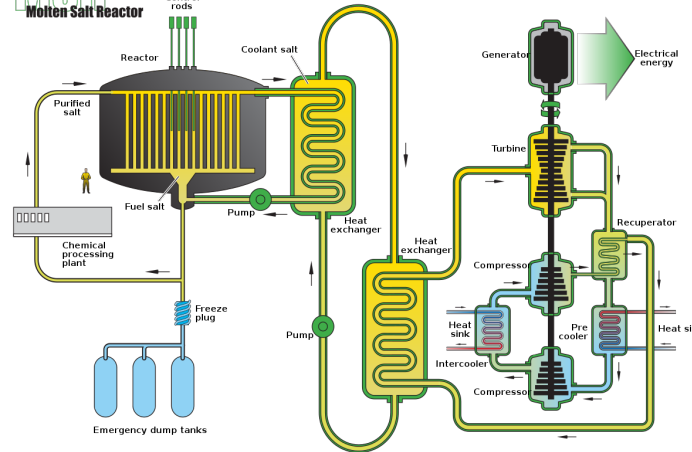
* Chernobyl release data is estimated at 20-40 percent for cesium-137 and 50-60 percent for iodine-131. Three Mile Island released an extremely small quantity of iodine-131 (~ 15 curies) and zero cesium-137. Fukushima releases are estimated to be approximately one-tenth of releases from Chernobyl [IAEA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

...and will continue to evolve

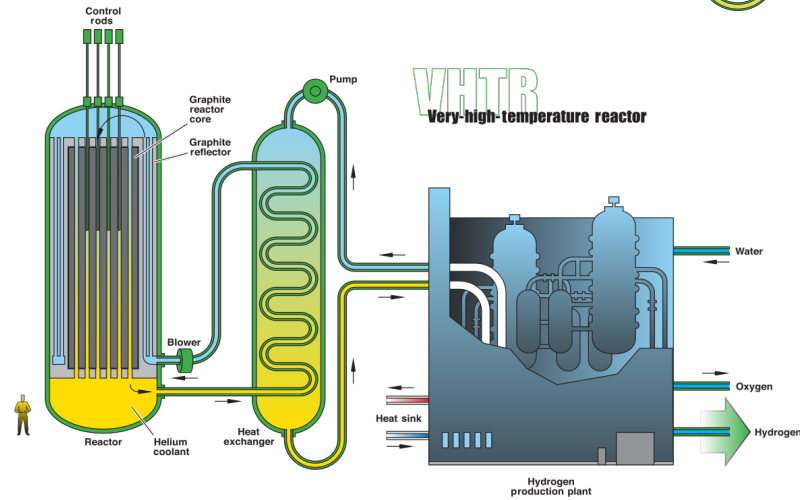
Lead-Cooled Fast Reactor



MSR
Molten Salt Reactor



VHTR
Very-high-temperature reactor



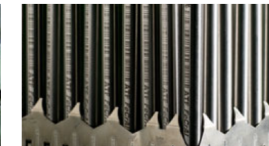
Accident Tolerant Fuel Technologies



Coated Cladding



Doped Pellets



FeCrAl Cladding



Increased Enrichment



Higher Burnup



Longer Term Technologies

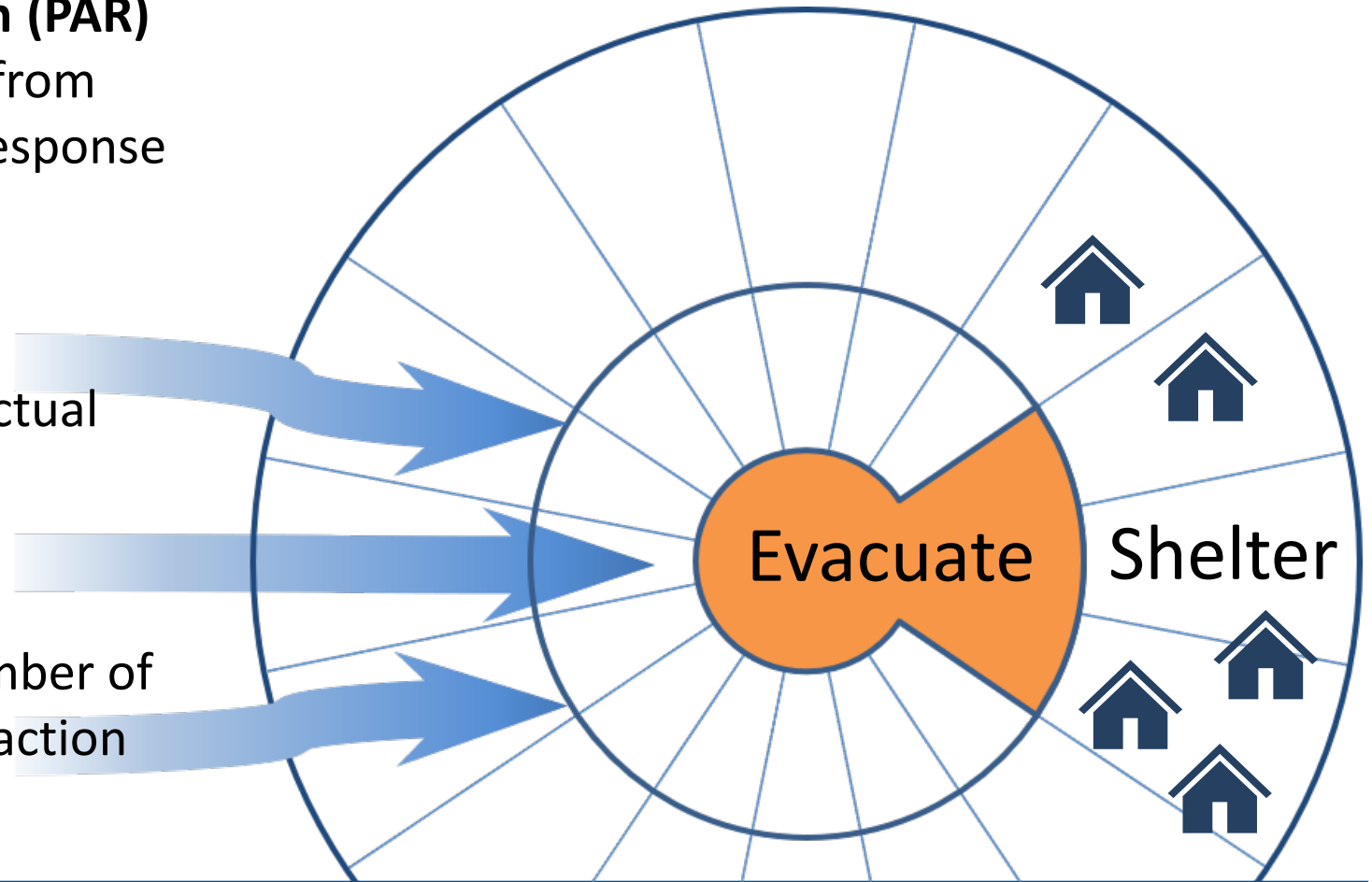


Deciding on action

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

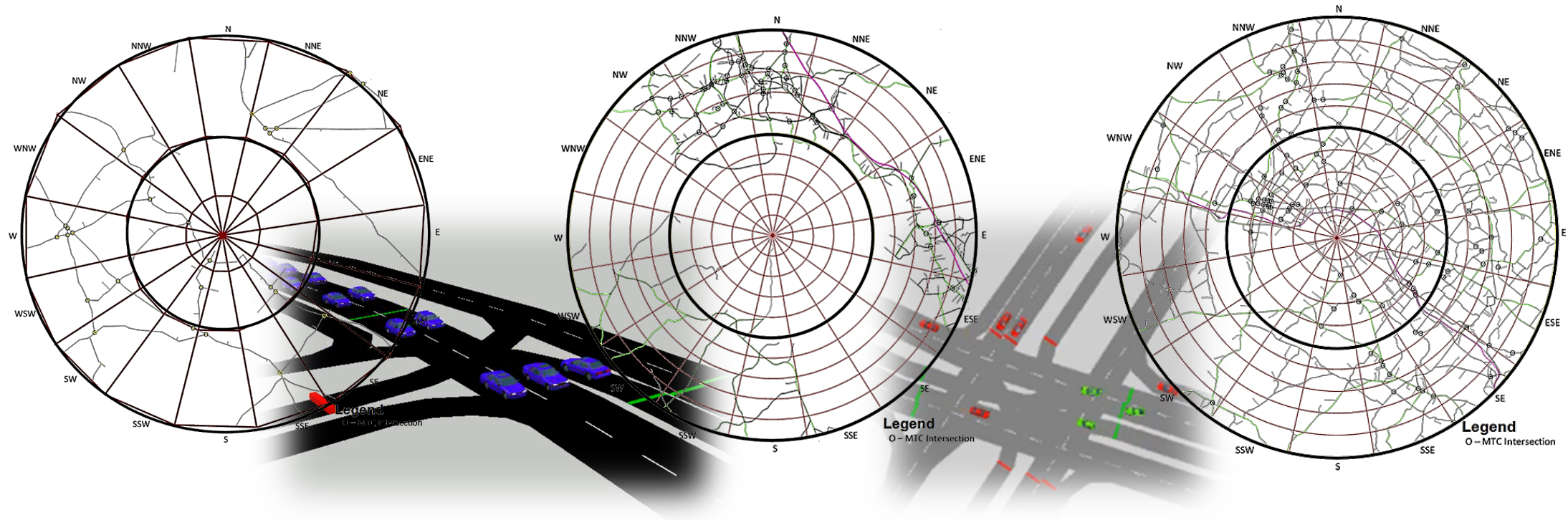
(to be published in *Transactions of the American Nuclear Society* for the 2022 ANS Winter Meeting)



Providing insights into effective evacuation

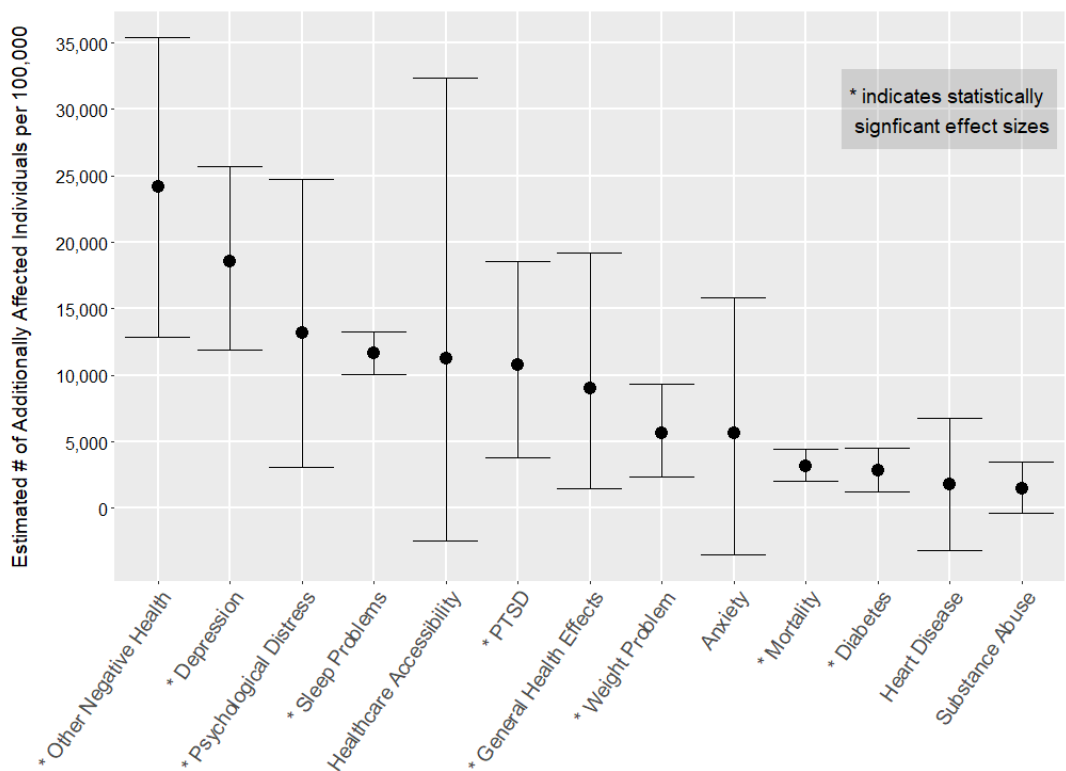
NUREG/CR-7269, “Enhancing Guidance for Evacuation Time Estimate Studies”

State-of-the-art traffic simulation models used to better understand evacuation dynamics and to develop insights for protecting the public and first responders

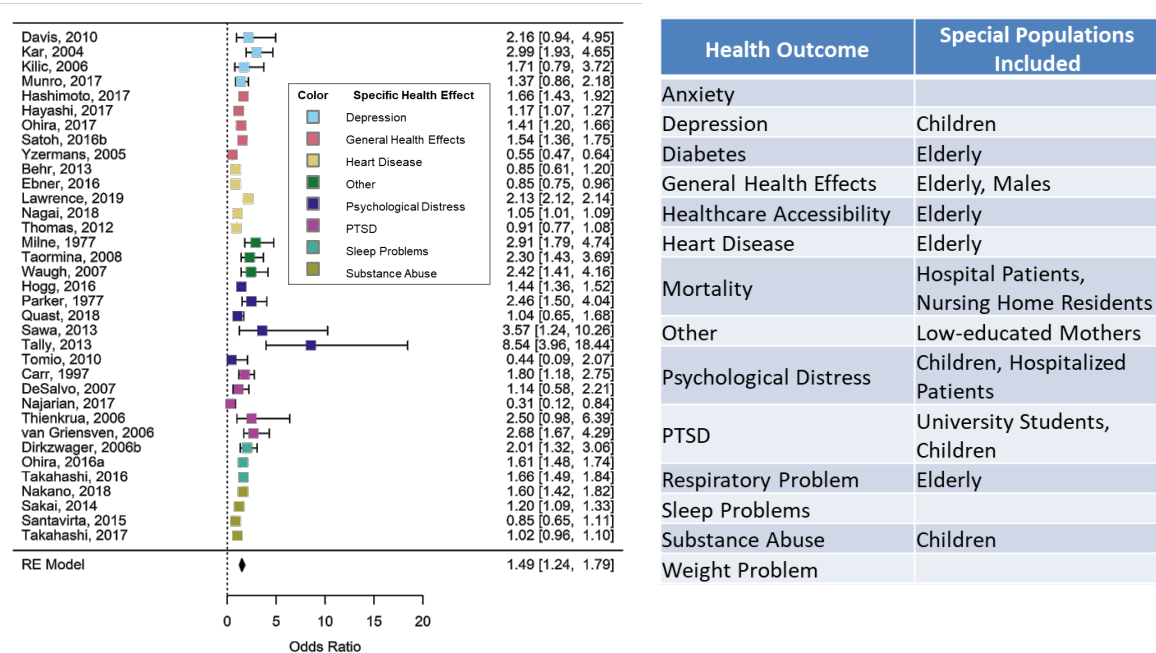


Assessing the balance of the risk

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



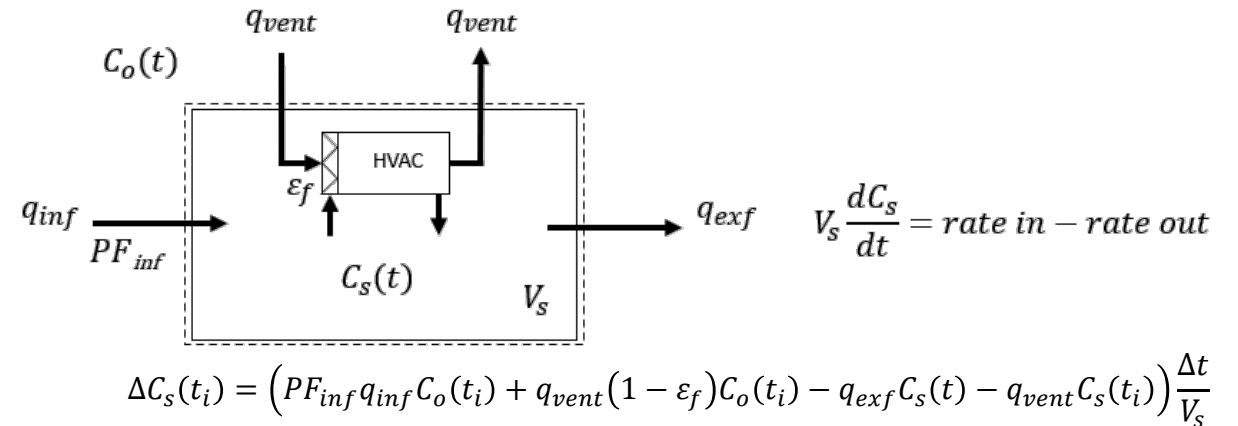
Health Outcome	Special Populations Included
Anxiety	
Depression	Children
Diabetes	Elderly
General Health Effects	Elderly, Males
Healthcare Accessibility	Elderly
Heart Disease	Elderly
Mortality	Hospital Patients, Nursing Home Residents
Other	Low-educated Mothers
Psychological Distress	Children, Hospitalized 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



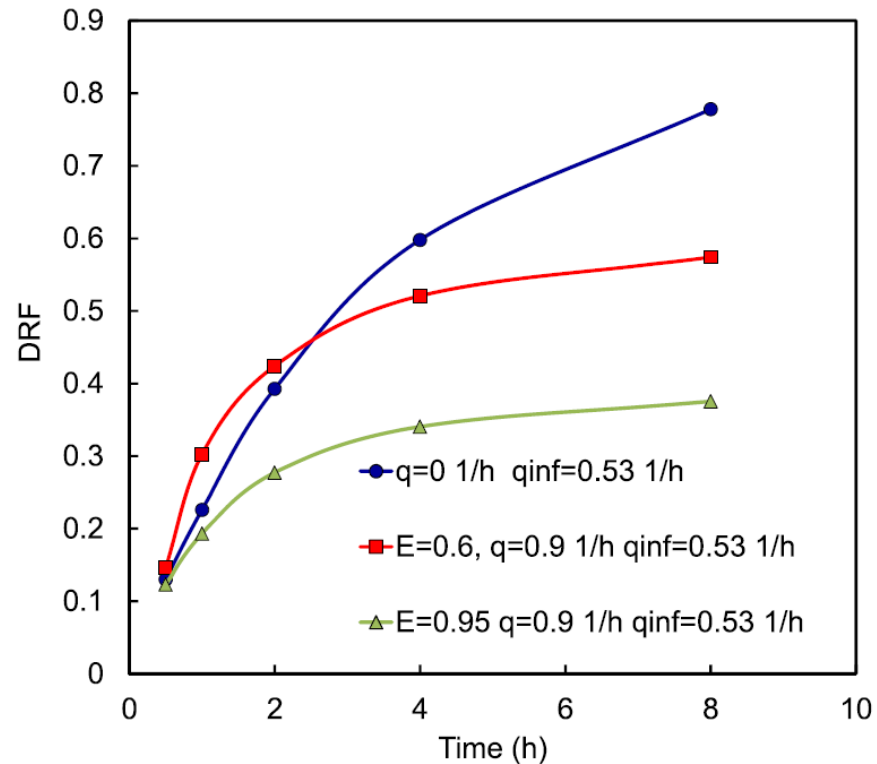
U.S. EPA. EPA-400/R-17/001, "PAG Manual: Protective Action Guides and Planning Guidance for Radiological Incidents," Office of Radiation and Indoor Air, January 2017.



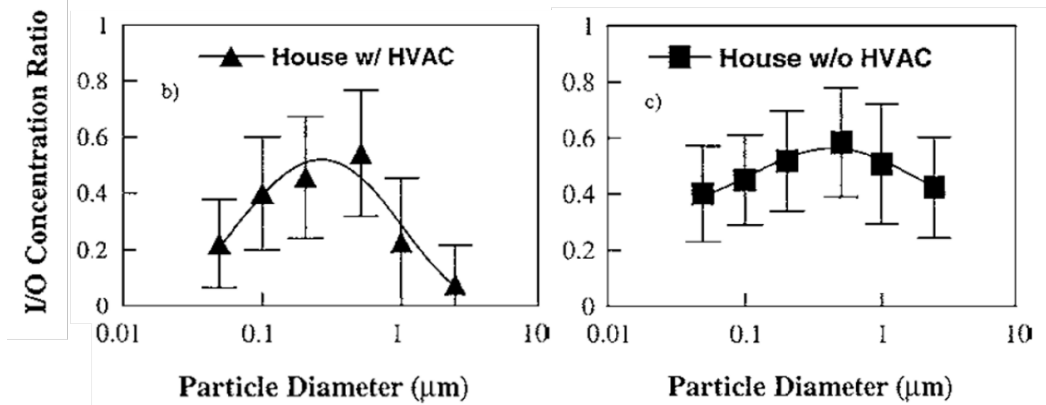
Shelter effectiveness can also be examined through dynamic models and lessons from other hazards to provide additional insight

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

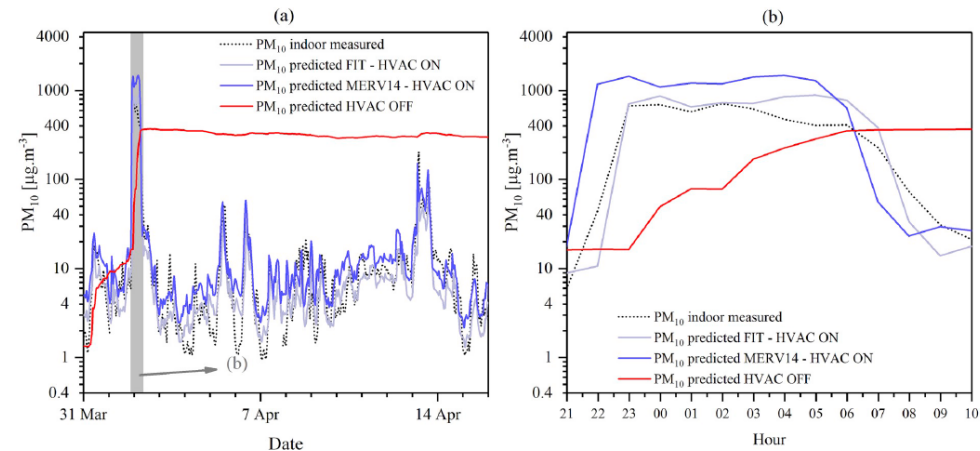
Exploring effective use of shelters and ventilation



Modeled office building (Kulmala, 2016)



Monte Carlo simulations (Thornburg, 2001)



Dust storms (Argyropoulos, 2020)

Quantifying the benefits of masks



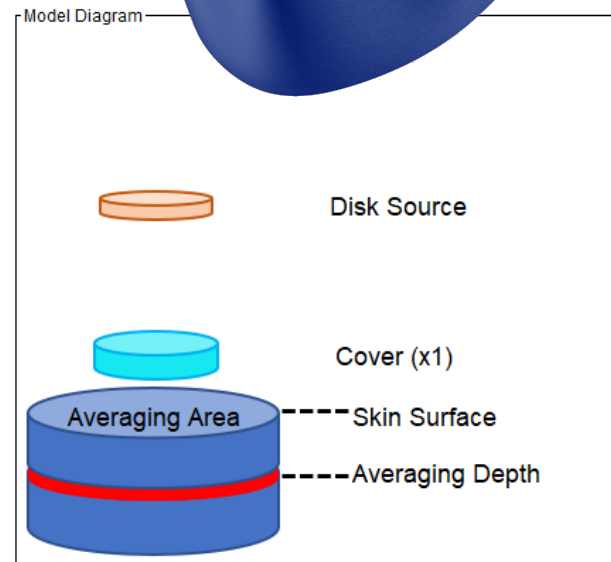
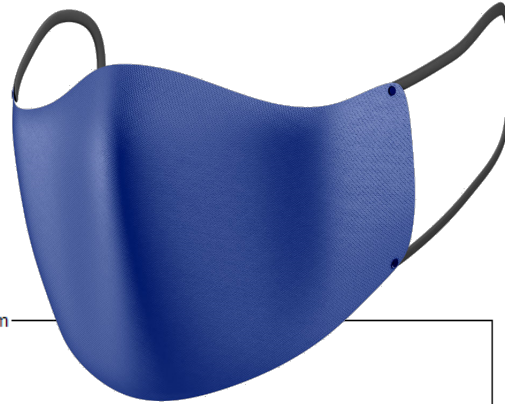
RASCAL

Radiological Assessment System for Consequence Analysis for radiological emergencies

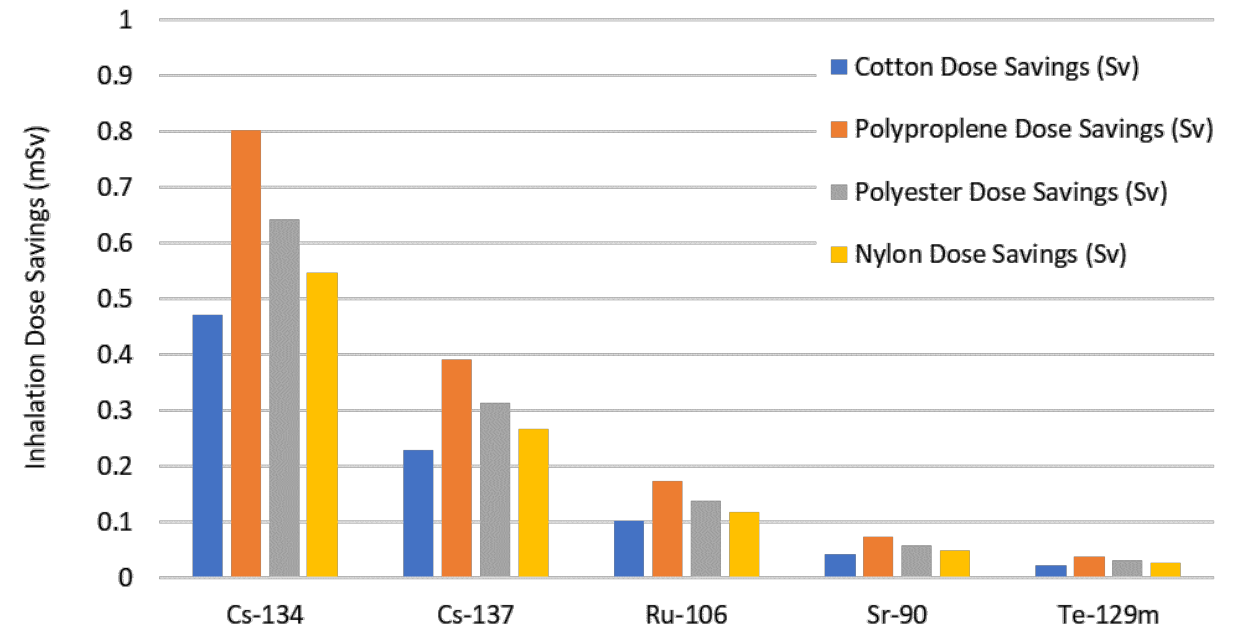


VARSKIN

Dose calculation for skin contamination



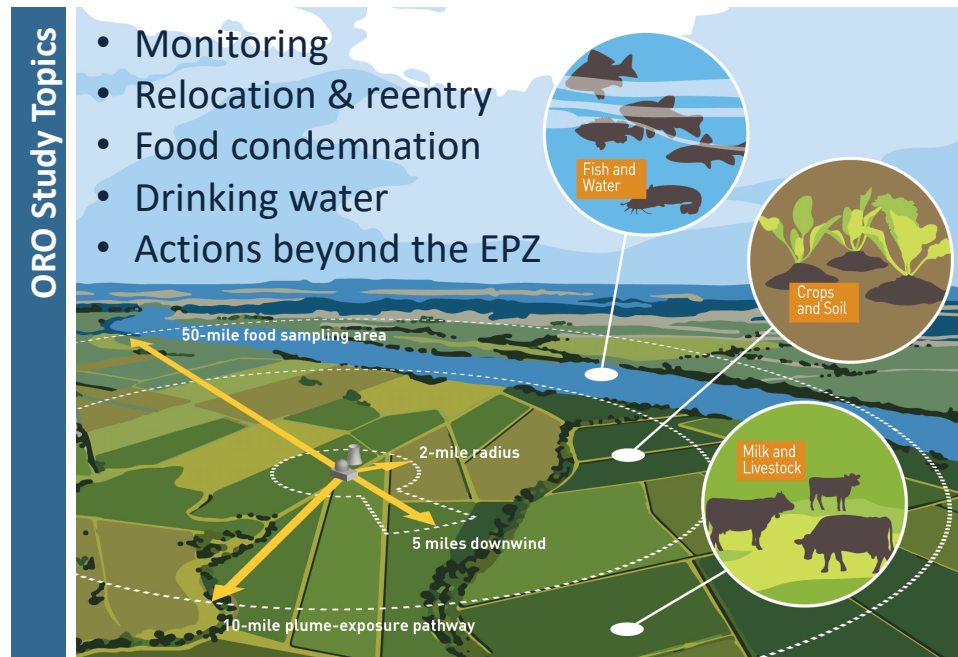
Inhalation Dose Savings for Various Nuclides and Mask Materials



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

WHERE TO GO IN A RADIATION EMERGENCY

If a radiation emergency happens in your area, you should get inside immediately.

No matter where you are, the safest action to take is to: **GET INSIDE. STAY INSIDE. STAY TUNED.**

- Close and lock all windows and doors.
- Go to the basement or the middle of the building. Radioactive material settles on the outside of buildings; so the best thing to do is stay as far away from the walls and roof of the building as you can.
- If possible, turn off fans, air conditioners, and forced-air heating units that bring air in from the outside. Close fireplace dampers.
- Bring pets inside.
- Stay tuned for updated instructions from emergency response officials.

Adapted from Ventura County Public Health, Ventura County, CA

U.S. Department of Health and Human Services
Centers for Disease Control and Prevention
<http://emergency.cdc.gov/radiation>

Shelter-in-Place for Multistory Buildings

Includes condos, apartments, offices, and schools

Active Shooter
Run. Hide. Fight.
What to do: Run away from shooter. Call 911 if safe to do so. Hide if you cannot get away safely. Silence electronic devices. Lock and block doors, close blinds, turn off lights. Fight as a last resort.
How long to stay: If you are not able to run to safety, stay in place until law enforcement gives you notice that the danger is over.

Hurricane (High Wind, Flooding, Storm Surge)
Shelter-in-Place: Go to a sturdy building. For high wind go to a windowless room on the lowest level. For flooding go as high as possible but not into the attic.
What to do: For high wind, go to a small, interior, windowless room in the lowest level.
How long to stay: Stay inside until local authorities provide other instructions.

Thunderstorm
Shelter-in-Place: Stay inside.
What to do: Pay attention to weather reports. Be ready to change plans if necessary. Unplug appliances, avoid using running water or landline phones.
How long to stay: For the length of the storm.

Winter Storm
Shelter-in-Place: Stay inside. Limit time outside.
What to do: Avoid carbon monoxide poisoning by using generators and grills ONLY outdoors, 20 feet from the house and away from windows. Never heat a building with a gas stove top or oven.
How long to stay: For the length of the storm.

Flooding
Shelter-in-Place: Go to the highest level in the building but not in the attic. If the floodwaters rise to a dangerous level, get on the roof and call 911.
What to do: Listen for current emergency information and instructions. Use a generator or other gasoline-powered machinery ONLY outdoors and away from windows.
How long to stay: Stay inside until authorities indicate it is safe to leave.

Flash Flooding
Shelter-in-Place: Go to the highest level in the building but not in the attic. If the floodwaters rise to a dangerous level, get on the roof and call 911.
What to do: Listen for current emergency information and instructions. Use a generator or other gasoline-powered machinery ONLY outdoors and away from windows.
How long to stay: Stay inside until authorities indicate it is safe to leave.

Pandemic
Shelter-in-Place: Stay Home. Minimize access to your home from anyone not isolating with you.
What to do: Reduce trips outside to only essential requirements. Clean surfaces often with disinfectant. Wash hands for 20 seconds frequently with soap. Avoid touching your eyes, nose, or mouth. Gather supplies in case you need to stay home for several days or weeks. If you must go to an office, campus, or live in a multi-story building, make sure to wear a mask and keep a physical distance of at least 6 ft apart.
How long to stay: As advised by local public health officials.

Chemical Hazard
Shelter-in-Place: Stay inside your home and seal the room. Use duct tape around the windows and doors to make an unbroken seal. Tape over vents and electrical outlets.
What to do: Lock all doors and windows. Drink stored water, not water from the tap. Turn off the air conditioner, heater, and fans. Close the fireplace damper and seal off any other place where air may come in from outside.
How long to stay: A shelter in place will last approximately 12 hours or less, rarely will it go longer.

Earthquake
Shelter-in-Place: Stay where you are and take cover. Get under and old on to sturdy furniture until the shaking stops. Protect the head and neck with arms.
What to do: Drop, Cover and Hold On. If in a bed, turn onto stomach and cover your head and neck with a pillow.
How long to stay: For the length of the earthquake.

Nuclear/Radiological
Shelter-in-Place: Go to the basement or middle of the building. Stay away from the outer walls and roof. Take shelter in the basement, underground parking garage, or other lowest level in the structure.
What to do: Remove contaminated clothing and wipe off or wash unprotected skin if you were outside after the fallout arrived.
How long to stay: Stay inside for 24 hours unless local authorities provide other instructions.

Tornado
Shelter-in-Place: Go to basement or lowest level in the structure. Go to a small, interior, windowless room in a sturdy building on the lowest level.
What to do: Protect your head and neck. Take additional cover by putting blankets around you.
How long to stay: Stay inside until weather forecasts and local authorities say it is safe to do so. Use extreme care when leaving a building as there may be dangerous debris.

Visit <https://community.fema.gov/ProtectiveActions/s/> for more information.





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

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