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Protecting People and the Environment

Scoping Analysis of MACCS Modeling Improvements for the Study of Protective Action Recommendations (PARs)

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Outline

- Purpose and Objective
- Background: Original PAR Study
- Methodology
- MACCS Version Comparison
- Full Comparison
- Sensitivity Analyses
- Conclusions

Purpose and Objective

- U.S. NRC directed Sandia National Labs to conduct this analysis (SAND2022-3706).
  - Sandia authors: Mariah Smith, Fotini Walton, Jennifer Leute, Joshua Dise
  - NRC technical leads: AJ Nosek, Todd Smith, and Jonathan Barr
  - NRC project manager: Salman Haq
- Objective: Determine whether model and input parameter updates using the MACCS code result in changes when compared to the methodology of the original PAR study (NUREG/CR-6953).
- Originally this work was intended to be a first step in determining whether a new PAR study was warranted.
- This work has become an indication of how MACCS modeling has evolved, and it has become a case study that has helped identify important factors in consequence analysis.

Background: Original PAR Study

- The original PAR study (NUREG/CR-6953) contained many MACCS analyses that reflected various protective action strategies that radiological emergency response plans could implement.
- The protective action strategies that were identified and evaluated include:
  - Different types of evacuation (e.g., radial, lateral, staged)
  - Sheltering in typical housing
  - Sheltering in preferential shelters that offer greater shielding
  - Various combinations of both sheltering and evacuation
- The study evaluated strategies primarily on their ability to reduce potential health effects.

Background: Original PAR Study, Vol. 1

- Volume 1 of the original PAR study supports the following protective action strategies when appropriately selected for the incident:
  - Immediate evacuation;
  - Shelter-in-place;
  - Staged evacuation;
  - Preferential sheltering for special needs individuals;
  - Delayed evacuation, until traffic controls are in place;
  - Early closure of schools, parks, beaches, and government facilities at the Site Area Emergency;
  - Consideration of early protective actions within the 3.2-km (2-mile) radius surrounding the plant at Site Area Emergency; and
  - Early notification of the general population within the 10-mile EPZ to prepare for evacuation.
- Preferential sheltering affords better shielding than normal residence but deemed unfeasible and not significantly more protective than evacuation.
- Lateral evacuation can be an effective evacuation strategy when meteorologic conditions are such that wind direction does not change.

Background: Original PAR Study, Vol. 3

- Volume 3 provides a technical basis for decision criteria that can be used by licensees and offsite response organizations to enhance protective action strategy for nuclear power plant accidents **that progress rapidly**.
- The results show that for a rapidly progressing accident, shelter-in-place is more protective when evacuation cannot be accomplished within predetermined timeframes.
  - For the 0 to 2-mile area around a nuclear power plant: Evacuation is more protective when the evacuation time estimate (ETE) is less than 2 hours.
  - For the 2 to 5-mile area: Evacuation is more protective when the ETE is less than 3 hours.
  - For the 5 to 10-mile area: Shelter-in-place would likely be the initial protective action to allow a staged evacuation to proceed. If evacuation is the initial protective action for this area, it is more protective than shelter-in-place when the ETE is less than 3.2 hours.

Methodology

- This study (SAND2022-3706) selected one of the MACCS calculations from the original PAR study (NUREG/CR-6953, Vol. 3) known as “Scenario A.”
- The new analysis then applied more recent inputs and methods to evaluate how these changes may impact results.
- This was done in three steps:
  - The first step was a MACCS version comparison: “Scenario A” (v.2.4) was rerun using MACCS v4.1, with no other updates.
  - The second step was a full comparison: “Scenario A” (v2.4) was compared to a new analysis that applied a full set of new MACCS inputs and methods.
  - The final step was a set of one-way sensitivity analyses using “Scenario A” (v4.1) as the base case.

MACCS Version Comparison

- Compared to version 2.4, MACCS version 4.1 provides many additional modeling capabilities, but the original models remain largely intact.
- “Scenario A” using MACCS v4.1 was run with two weather models: “Non-uniform bin sampling” and “stratified random sampling.”
- Results show strong agreement between the two versions of MACCS. The small differences are likely from the random sampling of different weather sequences.

	MACCS Version 2.4.0.1	MACCS Version 4.1.0.2	
Radial Distance (mi)	Non-Uniform Bin Sampling	Non-Uniform Bin Sampling	Stratified Random Sampling
Latent Cancer Fatalities (mean weather results)			
0-2 mi	3.05E+01	3.17E+01	3.34E+01
2-5 mi	2.10E+02	2.07E+02	2.24E+02
5-10 mi	1.46E+02	1.57E+02	1.53E+02
Early Fatalities (mean weather results)			
0-2 mi	2.25E-01	7.96E-01	3.60E-01
2-5 mi	7.68E-02	4.95E-01	1.61E-01
5-10 mi	4.25E-05	5.58E-05	1.90E-04

Full Comparison: Summary Inputs

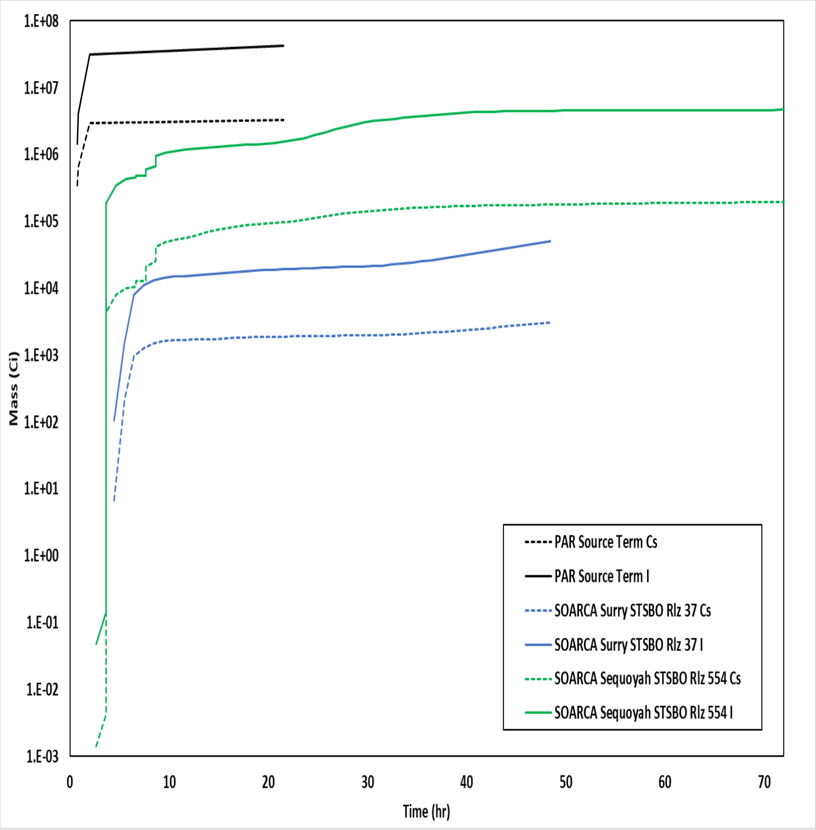
Scenario A, a representative calculation from the original PAR study, Vol. 3	Scoping analysis, using updated input/methodology
• Report publication: 2010 • MACCS v2.4.0.1	• Report publication: 2022 • MACCS v4.1.0.2
Site: • High population density • SecPop site file created using 2000 population data and 2002 economic data • 16 compass sectors	Site: • High population density • SecPop site file created using 2010 population data and 2007 economic data • 64 compass sectors
Source term: • Source term "A" (i.e., original PAR source term)	Source terms: • Source term "A" (i.e., original PAR source term) • SOARCA Surry STSBO Rlz 37 • SOARCA Sequoyah STSBO Rlz 554
Shielding and exposure values: NUREG-1150, Peach Bottom	Shielding and exposure values: from various sources
Emergency Response: • Circular evacuation (10-miles) • 1 mph evacuation speed • 0-2 miles: Immediate evacuation • 2-5 miles: Shelter-in-place (SIP) then evacuate • 5-10 miles: SIP then evacuate at 8 hours	Emergency Response: • Evacuation cohorts and speeds based on Evacuation Time Estimates (ETEs) and subject matter experts • Cohort-dependent evacuation modeling: • Mixture of circular evacuation, keyhole evacuation, and no evacuation
Dose coefficients: Federal Guidance Report 13 (FGR-13)	Dose coefficients: FGR-13 (with minor updates)

Full Comparison: Source Term Inputs

- The current scoping analysis includes:
  - A source term from the original PAR study (Source Term "A", Vol. 3)
  - Two additional source terms from a more recent research project known as "State-of-the-Art Reactor Consequence Analyses (SOARCA)".
- All source terms represent rapidly progressing accidents.
- The three source terms provide a range of release magnitudes.

Original PAR Source Term	SOARCA Surry STSBO Rlz 37	SOARCA Sequoyah STSBO Rlz 554
Release starts <1 hour after initiation Modeled release period of ~21 hours ~60% of Iodine released from inventory	Release starts ~2 hours and 45 minutes after initiation Modeled release period of ~48 hours ~0.11% of Iodine released from inventory	Release starts ~ 3 hours after initiation Modeled release period of ~72 hours ~5.1% of Iodine released from inventory

Cumulative release for the original PAR study source term and the two SOARCA source terms



Full Comparison: Shielding Inputs

	Activities	Cloudshine protection factor	Inhalation protection factor	Breathing rate (m^3/s)	Skin protection factor	Groundshine protection factor
Original PAR Study	Evacuation	1.00	0.98	2.66E-04	0.98	0.50
	Normal	0.75	0.41	2.66E-04	0.41	0.33
	Sheltering	0.60	0.33	2.66E-04	0.33	0.20
Current Scoping Analysis	Evacuation	1.00	0.98	2.66E-04	0.98	0.40
	Normal	0.68	0.46	2.66E-04	0.46	0.20
	Sheltering	0.60	0.25	2.66E-04	0.33	0.10

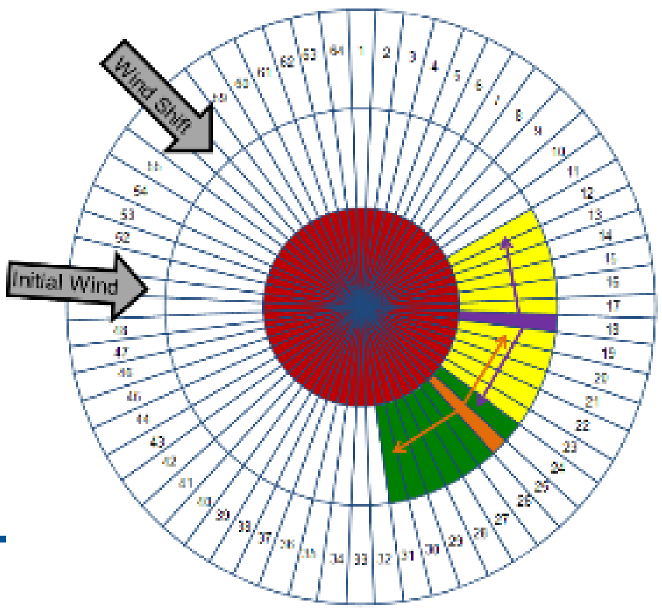
- For the original PAR study, the shielding and exposure parameters were taken directly from NUREG-1150 for Peach Bottom.
- For the current scoping analysis:
  - The cloudshine and skin protection factors were taken from the SOARCA Surry Integrated Analysis Study
  - The groundshine protection factors were taken from the Task 5 Letter Report: MACCS Uncertainty Analysis of EARLY Exposure Results
  - The inhalation protection factors were taken from EPA's Evacuation Risks: An Evaluation (EPA-520/6-74-002) study

A Primer on Evacuation Models

Circular Evacuation

- An evacuation region that is a 360-degree circle around the site.

Illustration of a Keyhole Evacuation Model



Keyhole Evacuation

- An evacuation region that has an inner circular area (red) and an outer downwind area (yellow).
- As wind shift is forecasted to occur, the outer area expands to include the new downwind areas (green).
- Allows for more targeted evacuation that focuses on areas of higher risk first.

Full Comparison:
Emergency Response Inputs (1/2)

Scenario "A" of the Original PAR Study

Scenario A	Evacuation Model	Population Distribution (0-10 miles)	0-2 Miles			2-5 Miles			5-10 Miles			Evacuation Speed (mph)
			Delay to Shelter (hr)	Delay to Evac (hr)	Depart (hr)	Delay to Shelter (hr)	Delay to Evac (hr)	Depart (hr)	Delay to Shelter (hr)	Delay to Evac (hr)	Depart (hr)	
Cohort 1	Circular	.909	0.5	0	0.5	0.5	0	0.5	0.5	8.0	8.5	1
Cohort 2	Circular	.909	0.5	0	0.5	0.5	0.5	1.0	0.5	8.0	8.5	1
Cohort 3	Circular	.909	0.5	0	0.5	0.5	1.0	1.5	0.5	8.0	8.5	1
Cohort 4	Circular	.909	0.5	0	0.5	0.5	1.5	2.0	0.5	8.0	8.5	1
Cohort 5	Circular	.909	0.5	0	0.5	0.5	2.0	2.5	0.5	8.0	8.5	1
Cohort 6	Circular	.909	0.5	0	0.5	0.5	2.5	3.0	0.5	8.0	8.5	1
Cohort 7	Circular	.909	0.5	0	0.5	0.5	3.0	3.5	0.5	8.0	8.5	1
Cohort 8	Circular	.909	0.5	0	0.5	0.5	3.5	4.0	0.5	8.0	8.5	1
Cohort 9	Circular	.909	0.5	0	0.5	0.5	4.0	4.5	0.5	8.0	8.5	1
Cohort 10	Circular	.909	0.5	0	0.5	0.5	4.5	5.0	0.5	8.0	8.5	1
Cohort 11	Circular	.909	0.5	0	0.5	0.5	5.0	5.5	0.5	8.0	8.5	1

Full Comparison: Emergency Response Inputs (1/2)

Current Scoping Analysis

	Description	Evacuation Model	Population Distribution (0-10 miles)	Notification Alarm (hr)	Delay to Shelter (hr)	Delay to Evacuation (hr)	Evacuation Start (hr)	Initial Evacuation Speed (mph)	Middle Evacuation Speed (mph)
Cohort 1	Early Public	Circular	0.055	1.50	0.25	0.25	2.00	20.0	10.0
Cohort 2	Middle Public	Keyhole	0.22	1.50	1.50	1.00	4.00	15.0	10.0
Cohort 3	Late Public	Keyhole	0.22	1.50	3.00	1.50	6.00	15.0	10.0
Cohort 4	Tail Public	Keyhole	0.1	1.50	6.50	1.50	9.50	20.0	20.0
Cohort 5	Schools	Circular	0.25	1.00	0.25	3.25	4.50	10.0	10.0
Cohort 6	Special Facilities	Keyhole	0.15	1.00	0.25	8.25	9.50	15.0	15.0
Cohort 7	Shadow Public (10-20 mi)	Circular	0	1.50	1.50	1.00	4.00	15.0	10.0
Cohort 8	Non-Evacuating Public	No Evacuation	0.005	1.50	N/A	N/A	N/A	N/A	N/A

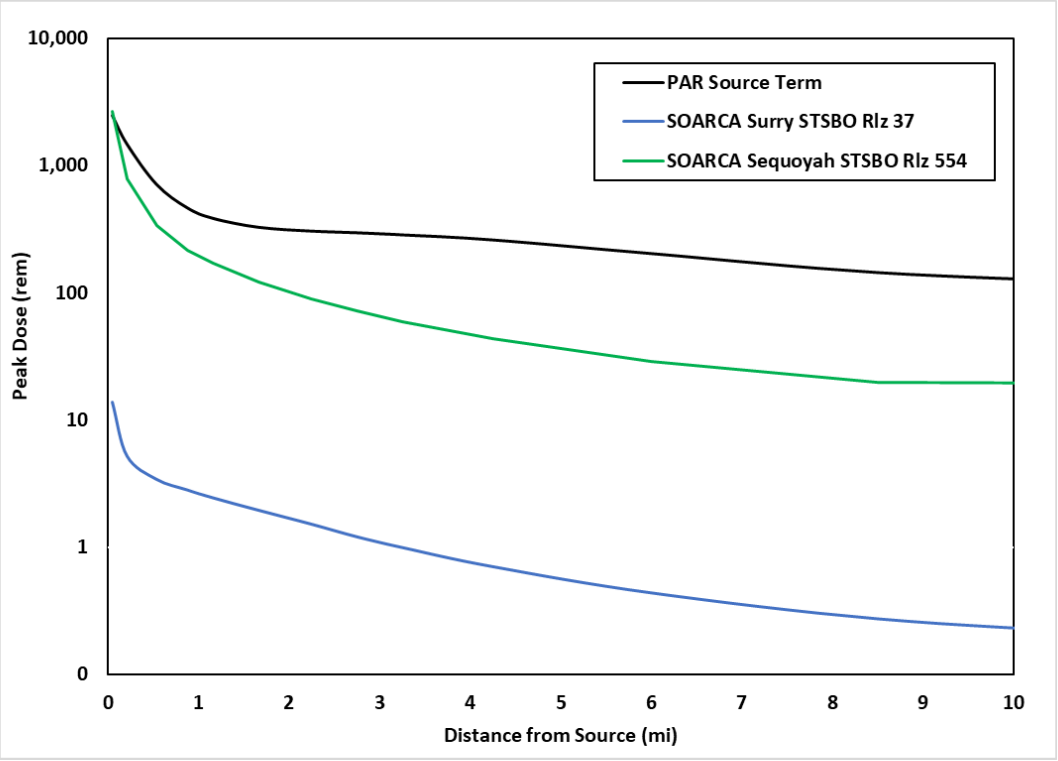
Results of Full Comparison

- Results show a notable decrease in latent cancer fatalities using the PAR source term of about a factor of 2.
- Significant decrease in latent cancer fatalities using the smaller source terms
- Significant decrease in early fatalities using the PAR source term.
- No early fatalities using smaller source terms.
- While the PAR source term certainly displaces more individuals in total, it displaces slightly fewer individuals in our 0–10-mile region of interest.

Radial Distance (mi)	Original PAR Version 2.4.0.1	Version 4.1.0.2 with Updates		
		PAR Source Term	SOARCA Surry STSBO Rlz 37	SOARCA Sequoyah STSBO Rlz 554
Latent cancer fatalities (mean weather results)				
0-2	3.35E+02	1.92E+02	2.06E+00	4.94E+01
2-5	1.67E+03	5.99E+02	3.10E+00	5.49E+01
5-10	1.61E+03	9.76E+02	2.65E+00	5.77E+01
0-10	N/A	1.77E+03	7.82E+00	1.62E+02
0-50	N/A	2.81E+04	5.17E+02	9.48E+03
Early fatalities (mean weather results)				
0-2	2.48E+00	7.19E-02	0.00E+00	0.00E+00
2-5	1.70E+00	5.40E-03	0.00E+00	0.00E+00
5-10	4.67E-04	1.18E-06	0.00E+00	0.00E+00
0-10	N/A	7.72E-02	0.00E+00	0.00E+00
0-50	N/A	7.72E-02	0.00E+00	0.00E+00
Displaced individuals (mean weather results)				
0-10	N/A	254,237	264,303	266,866

Scoping Analysis Results: Peak Dose Comparison

- Results show significant difference in peak dose among the source terms
- "Peak dose" represents the spatial element with the highest dose in a radial interval.
- Peak dose is closely related to centerline dose; however, centerline dose is not applicable for multiple plume segments.



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Scoping Analysis Results: Comparison of Source Terms

- Additional results comparing the source terms show the same trends

Mean population dose (person-rem) comparison

Radial Distance (mi)	Version 4.1.0.2 with Updates		
	PAR Source Term	SOARCA Surry STSBO Rlz 37	SOARCA Sequoyah STSBO Rlz 554
0-2	2.41E+05	3.83E+03	6.09E+04
2-5	7.77E+05	5.75E+03	8.93E+04
5-10	1.33E+06	4.90E+03	1.07E+05
0-10	2.34E+06	1.45E+04	2.57E+05
0-50	4.76E+07	9.55E+05	1.71E+07

99th percentile population-weighted individual risk of an early fatality comparison

Radial Distance (mi)	Version 4.1.0.2 with Updates		
	PAR Source Term	SOARCA Surry STSBO Rlz 37	SOARCA Sequoyah STSBO Rlz 554
0-10	2.89E-07	0.00E+00	0.00E+00

Mean population-weighted individual cancer fatality risk comparison

Radial Distance (mi)	Version 4.1.0.2 with Updates		
	PAR Source Term	SOARCA Surry STSBO Rlz 37	SOARCA Sequoyah STSBO Rlz 554
0-2	1.42E-02	1.56E-04	3.19E-03
2-5	9.01E-03	4.79E-05	6.71E-04
5-10	5.00E-03	1.40E-05	2.51E-04
0-10	6.43E-03	2.92E-05	4.98E-04

Sensitivity Analyses

- Other than for the source term input, the full comparison does not explain which updates in the current scoping analysis are responsible for the differences in the results.
- As such, the study conducted several one-way sensitivity analyses.
- Sensitivity analyses:
  - Circular vs. keyhole evacuation
  - Updated shielding inputs
  - Compass sector resolution
- All the sensitivity analyses use MACCS v4.1.0.2 and start with "Scenario A" of the original PAR study Vol. 3.

Sensitivity Analysis: Circular vs Keyhole Evacuation (1/2)

- Circular evacuation displaces entire 0–10-mile area.
- Keyhole evacuation displaces almost entire 0–10-mile area. Why?
  - Source terms release for tens of hours.
  - Wind shift is more likely during long release durations.
  - Therefore, long release durations expand the keyhole evacuation area.
- When the keyhole evacuation expands to half of the sectors, the model assumes decision-makers evacuate the full area.

Displaced Individuals During the Early Phase (All Cohorts)

Radial Distance (mi)	PAR Source Term	SOARCA Surry STSBO Rlz 37	SOARCA Sequoyah STSBO Rlz 554
Circular Evacuation (mean weather results)			
0-10	254,100	253,900	254,300
Keyhole Evacuation (mean weather results)			
0-10	232,100	249,600	253,800

Sensitivity Analysis:
Circular vs Keyhole Evacuation (1/2)

- Results show little difference in health effects between circular and keyhole evacuation model
- Since the keyhole model displaces almost as many people as the circular evacuation, this is expected.

Health Effects of Various Cohorts in 0-10 Mile Area

	PAR Source Term		SOARCA Surry STSBO Rlz 37		SOARCA Sequoyah STSBO Rlz 554	
	Early Fatality	Latent Cancer Fatality	Early Fatality	Latent Cancer Fatality	Early Fatality	Latent Cancer Fatality
Circular Evacuation Model (mean weather results)						
Cohort 1	1.29E+00	3.96E+02	0.00E+00	1.18E-01	0.00E+00	1.38E+02
Cohort 4	2.88E+00	3.85E+02	0.00E+00	1.29E-01	0.00E+00	1.47E+02
Cohort 7	1.15E+00	3.07E+02	0.00E+00	1.45E-01	0.00E+00	1.59E+02
Cohort 10	7.99E-01	2.90E+02	0.00E+00	1.70E-01	0.00E+00	1.74E+02
Keyhole Evacuation Model (mean weather results)						
Cohort 1	1.29E+00	3.96E+02	0.00E+00	1.29E-01	0.00E+00	1.39E+02
Cohort 4	2.88E+00	3.85E+02	0.00E+00	1.31E-01	0.00E+00	1.47E+02
Cohort 7	1.15E+00	3.07E+02	0.00E+00	1.48E-01	0.00E+00	1.59E+02
Cohort 10	7.99E-01	2.90E+02	0.00E+00	1.73E-01	0.00E+00	1.75E+02

Sensitivity Analysis: Updated Shielding Inputs

- Results show little difference in health effects between the original and updated shielding values
- The updated shielding values did not change significantly from the original PAR study.
- In general, shielding inputs are still expected to be important.

Health Effects of Various Cohorts in 0-10 Mile Area

	Original Shielding Values	Updated Shielding Values
Latent Cancer Fatalities (mean weather results)		
Cohort 1	3.96E+02	3.78E+02
Cohort 4	3.85E+02	3.65E+02
Cohort 7	3.07E+02	2.82E+02
Cohort 10	2.90E+02	2.63E+02
Early Fatalities (mean weather results)		
Cohort 1	1.29E+00	1.25E+00
Cohort 4	2.88E+00	2.81E+00
Cohort 7	1.15E+00	1.11E+00
Cohort 10	7.99E-01	7.74E-01

Sensitivity Analysis: Compass Sector Resolution

- A compass sector sensitivity requires updated external files.
- Both cases use:
  - A site file based on 2010 population data and 2007 economic data.
  - A meteorological file assuming 16 wind directions.
- Results show a notable difference in health effects.
  - The use of smaller spatial elements increases precision.
  - The use of a 64-sector site file more accurately represents the spatial population distribution.

Health Effects of Various Cohorts in 0-10 Mile Area

	16 Compass Sectors	64 Compass Sectors
Latent Cancer Fatalities (mean weather results)		
Cohort 1	4.05E+02	2.98E+02
Cohort 4	3.94E+02	2.92E+02
Cohort 7	3.21E+02	2.41E+02
Cohort 10	3.05E+02	2.31E+02
Early Fatalities (mean weather results)		
Cohort 1	1.48E+00	1.00E+00
Cohort 4	3.14E+00	2.30E+00
Cohort 7	1.25E+00	8.47E-01
Cohort 10	9.37E-01	6.12E-01

Conclusions (1/2)

- The current scoping analysis results in fewer health consequences than the original PAR study, indicating that the use of updated best practice modeling assumptions and capabilities are important.
- The choice of source term had the largest impact on the health consequences.
- The compass sector resolution update showed a significant difference.
- The use of the keyhole evacuation model may affect the number of displaced individuals, depending on the release duration and wind persistence.

Conclusions (2/2)

- The shielding values in the PAR study and this analysis are not significantly different and did not significantly change the results.
- Minimizing the potential harm from social disruption may also be important in determining which protective action strategies are best.
- This analysis considered the number of displaced individuals as a measure of social disruption. This measure can be used to inform guidance to help ensure that protective actions provide more benefit than harm.