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State-of-the-Art Reactor Consequence Analyses (SOARCA) Project: Sequoyah Integrated Deterministic and Uncertainty Analyses

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Outline

- Background
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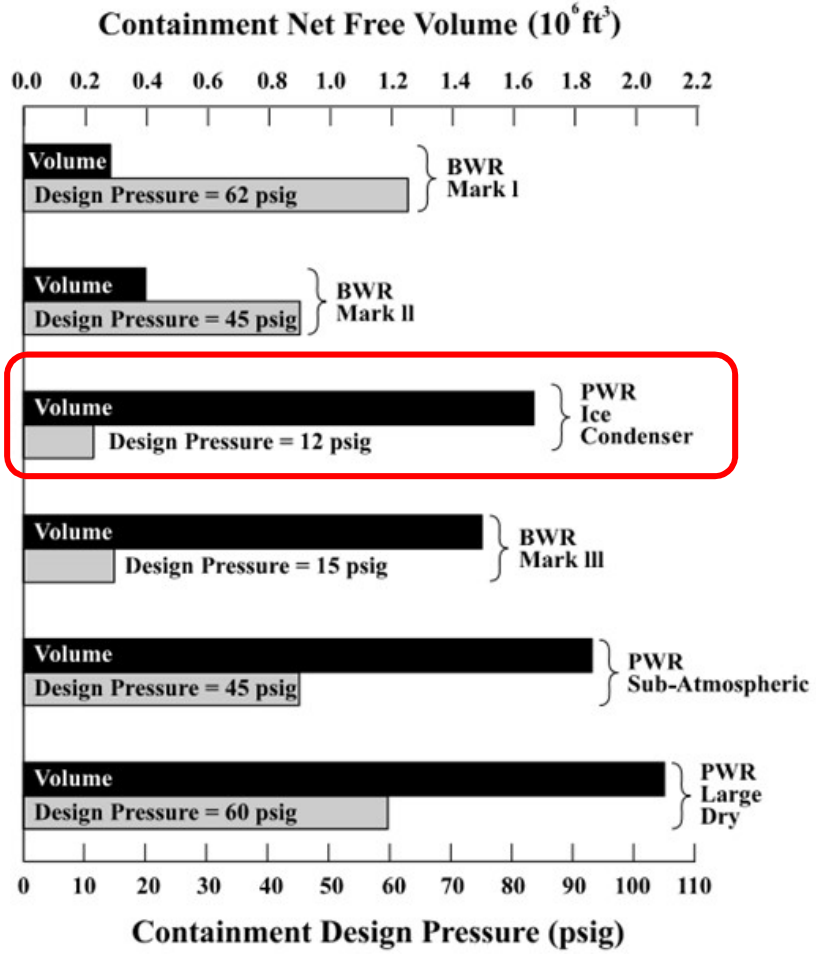
- Accident Progression Results
- Sequoyah Site and Region and MACCS Model Development
- MACCS Uncertainty Analysis Results
- Reference and Sensitivity Cases
- Offsite Consequence Analysis Summary
- Sequoyah SOARCA Conclusions

Background

- Relatively low design pressure and smaller volume leads to potential susceptibility to early failure from hydrogen combustion in a station blackout
- Analyzed in Generic Safety Issue program (GSI-189)
- Sequoyah SOARCA analyses supported closure of Fukushima Near Term Task Force (NTTF) activities 5.2 and 6 in SECY-15-0137 and SECY-16-0041

Source: NUREG/CR-6042, Rev. 2 (Figure 4.1-1)



SOARCA Sequoyah Study of Station Blackouts – STSBO MELCOR Uncertain Parameters

Sequence Issues

- Number of cycles to failure-to- close of pressurizer safety valves (SVs) – pri_SV_cycles
- Pressurizer SV flow area given failure to close – pri_SV_frac
- Number of cycles to failure-to-close of steam generator SVs – SG_SV_cycles
- Steam generator SV flow area given failure to close – SG_SV_frac
- Time in the burn-up cycle - cycle

In-Vessel Accident Progression

- Melting temperature of the eutectic formed between ZrO_2 and UO_2 – EU_Melt_T
- Oxidation kinetics model – H2_Ox_Corr

Ex-vessel Accident Progression and Containment Behavior

- Containment failure pressure - rupture
- Ice condenser inlet door stuck position following a forceful full opening - ajar
- Containment barrier seal failure differential pressure and area – Seal_Fail_Dp/Seal_Open_A

Hydrogen Combustion

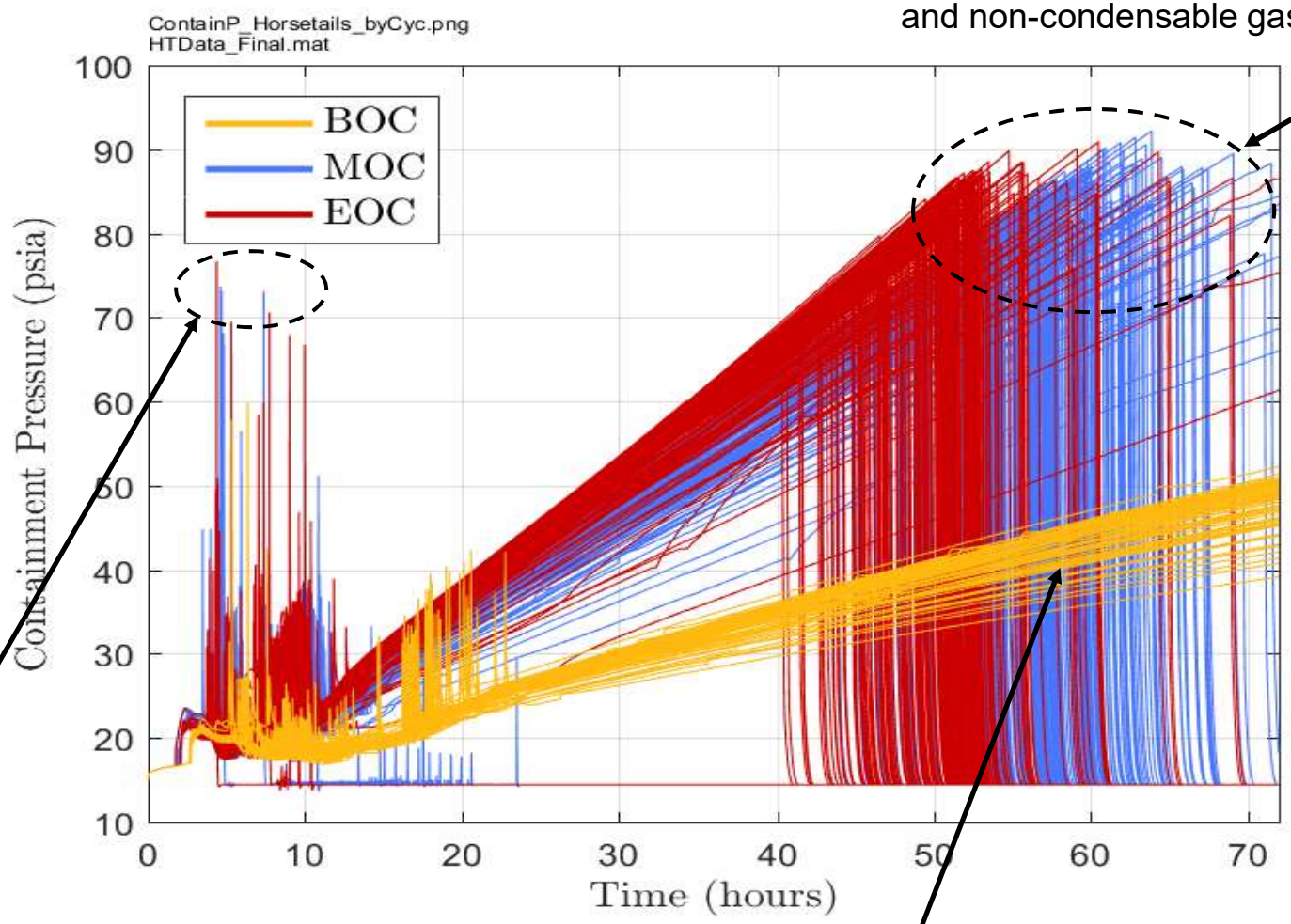
- Flammability (direction of flame propagation from an ignition source) – burn_dir

Aerosol Transport and Deposition

- Dynamic shape factor – shape_factor

Accident Progression Results

Long-tem containment over-pressurization failure due to prolonged steam production and non-condensable gas generation

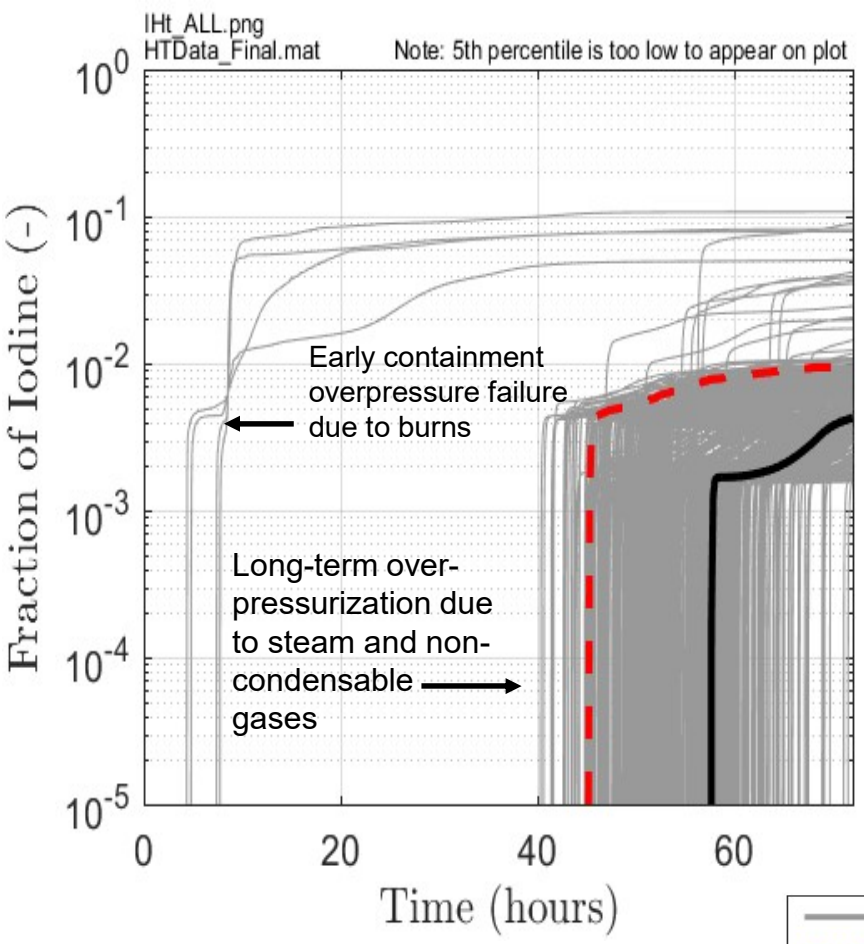


Early containment overpressure failures due to sufficiently large burns in containment

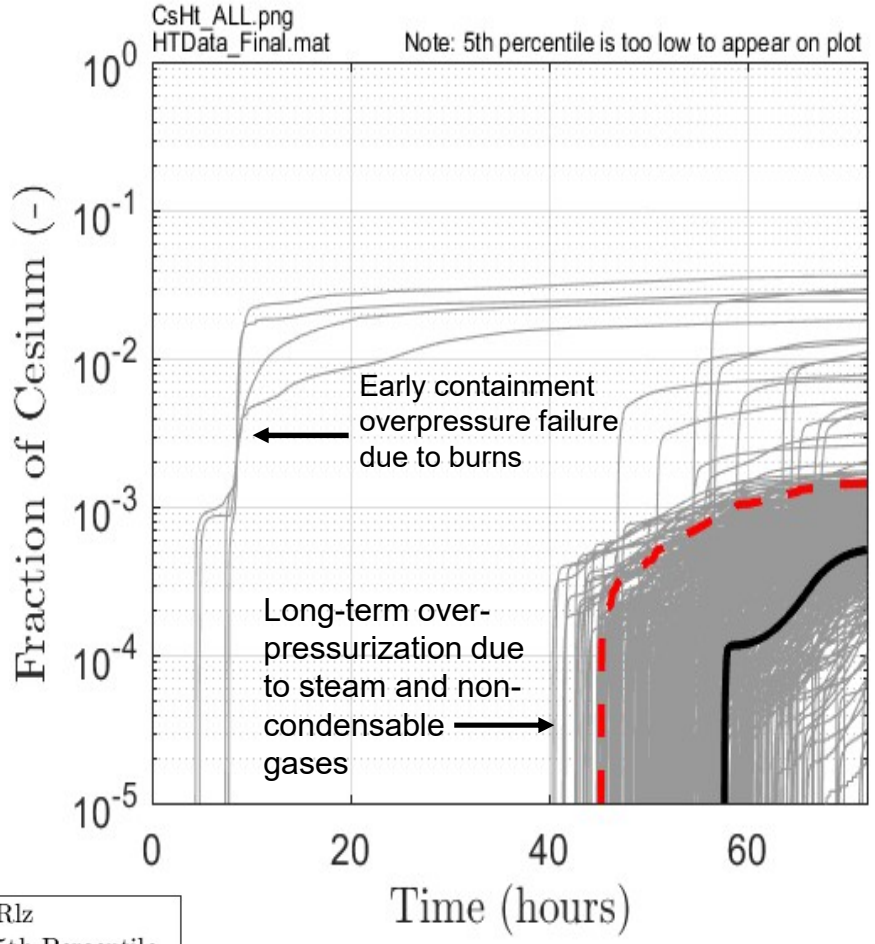
No BOC cases exhibit long-term overpressure failure before 72 hours

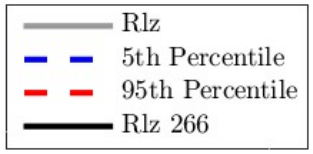
Accident Progression Results

All realizations - Iodine



All realizations - Cesium





Sequoyah Site and Region

https://www.flickr.com/photos/nrcgov/6517605543/

- Two-unit nuclear power plant site in Hamilton County, TN
  - Analysis assumes Short-term Station Blackout (STSBO) occurring at Unit 1
  - 18 miles NE of Chattanooga, TN
  - Approximately 98,000 people in 10-mile radius EPZ
  - Approximately 1,100,000 people in 50-mile radius EPZ
    - Population scaled from 2010 Census data to 2015

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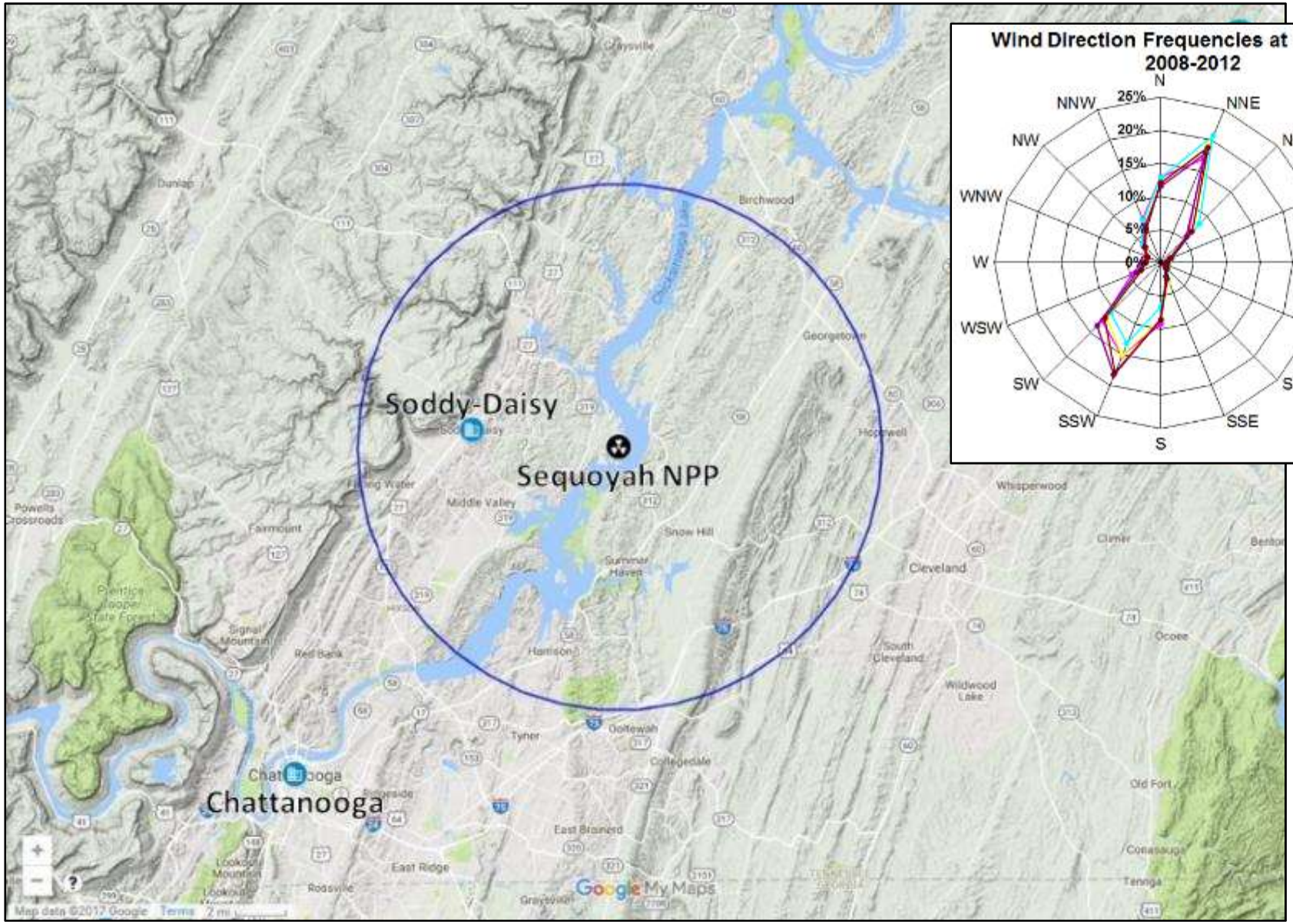
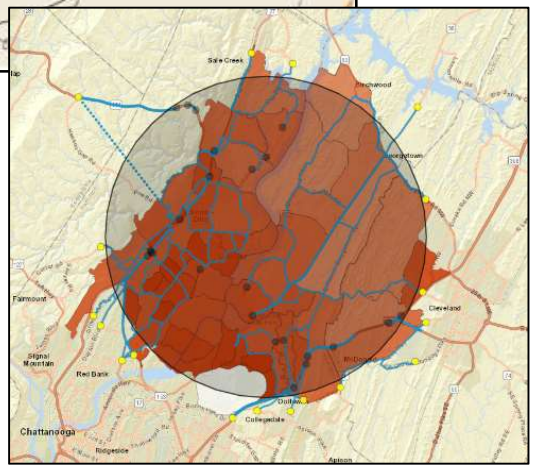
Sequoyah Site and Region



MACCS Model Development

10 mile EPZ



RtePM screenshot showing road network

- Nine evacuation cohorts defined
  - Includes schools, special facilities, transit-dependent, general public, shadow, non-evacuees
- Initiating event is a beyond-design-basis earthquake
- Analysis assumes bridges in 10-mile EPZ unusable ( )
- Calculate average evacuation time of ~ 9 hrs for base case
- Considering different characteristics of the 9 cohorts, EPZ evacuation completed about 17 hrs after accident initiation for base case (~14 hours after GE siren or emergency alerting)

MACCS Uncertain Parameter Groups

Deposition
- Wet Deposition
- Dry Deposition Velocities

Dispersion
- Crosswind Dispersion Linear Coefficient
- Vertical Dispersion Linear Coefficient
- Time-Based Crosswind Dispersion Coefficient

Latent Health Effects
- Dose and Dose Rate Effectiveness Factor
- Lifetime Cancer Fatality Risk Factors
- Long Term Inhalation Dose Coefficients

Early Health Effects
- Threshold Dose
- Lethal Dose to 50% of population
- Hazard Function Shape Factor

Shielding Factors
- Groundshine Shielding Factors
- Inhalation Protection Factors

Emergency Response
- Evacuation Delay
- Evacuation Speed
- Hotspot Relocation Time and Dose Criteria
- Normal Relocation Time and Dose Criteria
- Keyhole Forecast Time

Aleatory Uncertainty
- Weather Trials

MACCS Uncertainty Analysis Results – Distribution of Mean (over weather variation) Individual Latent Cancer Fatality Risk

	0-10 Miles	10-20 Miles	20-30 Miles	30-40 Miles	40-50 Miles	0-50 Miles
Mean	8.0E-05	9.7E-05	1.0E-04	8.2E-05	6.6E-05	8.8E-05
Median	6.7E-05	7.5E-05	9.1E-05	7.8E-05	6.2E-05	8.1E-05
5th Percentile	1.2E-08	2.7E-09	1.1E-09	4.2E-10	2.6E-10	2.3E-09
95th Percentile	2.0E-04	2.5E-04	2.4E-04	1.8E-04	1.4E-04	2.1E-04

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MACCS Uncertainty Analysis – Regression Results

0 – 10 Mile

	Rank Regression		Quadratic		Recursive Partitioning		MARS		Main Contribution	Conjoint Contribution
Final R^2	0.67		0.86		0.58		0.78			
Input	R^2 contr.	SRRC	S_i	T_i	S_i	T_i	S_i	T_i		
Cycle	0.36	0.58	0.23	0.29	0.40	0.60	0.20	0.20	0.237	0.056
priSVcyc	---	---	0.04	0.15	0.12	0.15	0.14	0.31	0.070	0.083
CFRISK(8)	0.09	0.29	0.07	0.12	0.08	0.23	0.10	0.09	0.068	0.042
Rupture	0.06	-0.24	0.06	0.08	0.07	0.18	0.09	0.15	0.054	0.046
CFRISK(7)	0.03	0.19	0.06	0.10	0.05	0.11	0.08	0.10	0.040	0.031
GSHFAC_6(2)	0.05	0.22	0.02	0.06	0.01	0.05	0.04	0.03	0.026	0.021
CFRISK(6)	0.01	0.09	0.04	0.11	---	---	0.04	0.07	0.018	0.029
CFRISK(3)	0.02	0.11	---	---	0.00	0.01	0.03	0.10	0.011	0.018
DDREFA(8)	0.01	-0.11	0.03	0.04	---	---	---	---	0.010	0.002

** highlighted if main contribution larger than 0.02 or conjoint contribution larger than 0.1*

0 – 50 Mile

	Rank Regression		Quadratic		Recursive Partitioning		MARS		Main Contribution	Conjoint Contribution
Final R^2	0.59		0.86		0.65		0.75			
Input	R^2 contr.	SRRC	S_i	T_i	S_i	T_i	S_i	T_i		
Cycle	0.23	0.52	0.24	0.31	0.36	0.44	0.21	0.21	0.208	0.038
CFRISK(8)	0.06	0.24	0.09	0.13	0.05	0.14	0.09	0.08	0.059	0.029
Rupture	0.05	-0.21	0.06	0.10	0.05	0.22	0.10	0.25	0.052	0.086
CFRISK(4)	0.05	0.23	0.07	0.10	0.04	0.15	0.08	0.09	0.048	0.037
CFRISK(7)	0.04	0.22	0.05	0.07	0.02	0.10	0.08	0.11	0.040	0.028
TIMNRM	0.04	0.22	0.04	0.07	0.06	0.30	0.05	0.06	0.038	0.061
CYSIGA(1)	0.03	0.19	0.03	0.04	0.01	0.05	---	---	0.015	0.013
DDREFA(4)	0.02	-0.13	0.02	0.02	0.00	0.04	0.02	0.02	0.013	0.011
CFRISK(6)	0.01	0.08	0.03	0.12	---	---	0.02	0.08	0.012	0.042

** highlighted if main contribution larger than 0.02 or conjoint contribution larger than 0.1*

Reference and Sensitivity Cases

- All cases assume seismic impact on evacuation network
- Reference case
  - Nominal shielding parameters
  - Evacuation order
  - Basis for uncertainty analysis
- Sensitivity cases
  - Shelter-in-place (SIP) while offsite response organization evaluates infrastructure
  - Shielding changes due to seismically degraded buildings
  - Weather year
  - Non-LNT dose response

Reference and Sensitivity Cases

MELCOR Realization	Scenario	Time in Cycle	Release Fraction		Released Activity (Bq)		Time (hr)	
			Cs	I	Cs-137	I-131	Start*	Increase**
266	STSBO Reference	MOC	0.001	0.004	1.4E+14	1.1E+16	3.4	57.6
554	STSBO Earliest Release	EOC	0.018	0.051	7.3E+15	1.6E+17	2.7	3.6
395	STSBO Highest Cs Release Mass	EOC	0.027	0.079	1.1E+16	2.6E+17	2.9	6.9
36	STSBO Highest Cs Release Fraction	MOC	0.036	0.107	9.7E+15	3.4E+17	3	7
146	Large Release at 56 hours	MOC	0.029	0.089	7.9E+15	2.4E+17	2.6	55.6
382	Release at 40 hours	EOC	0.001	0.008	4.0E+14	2.3E+16	3.3	40.3

*The “start” time indicates the timing of the first environmental release, no matter how small.
**The “increase” time indicates the timing of the first significant increase in the rate of release.

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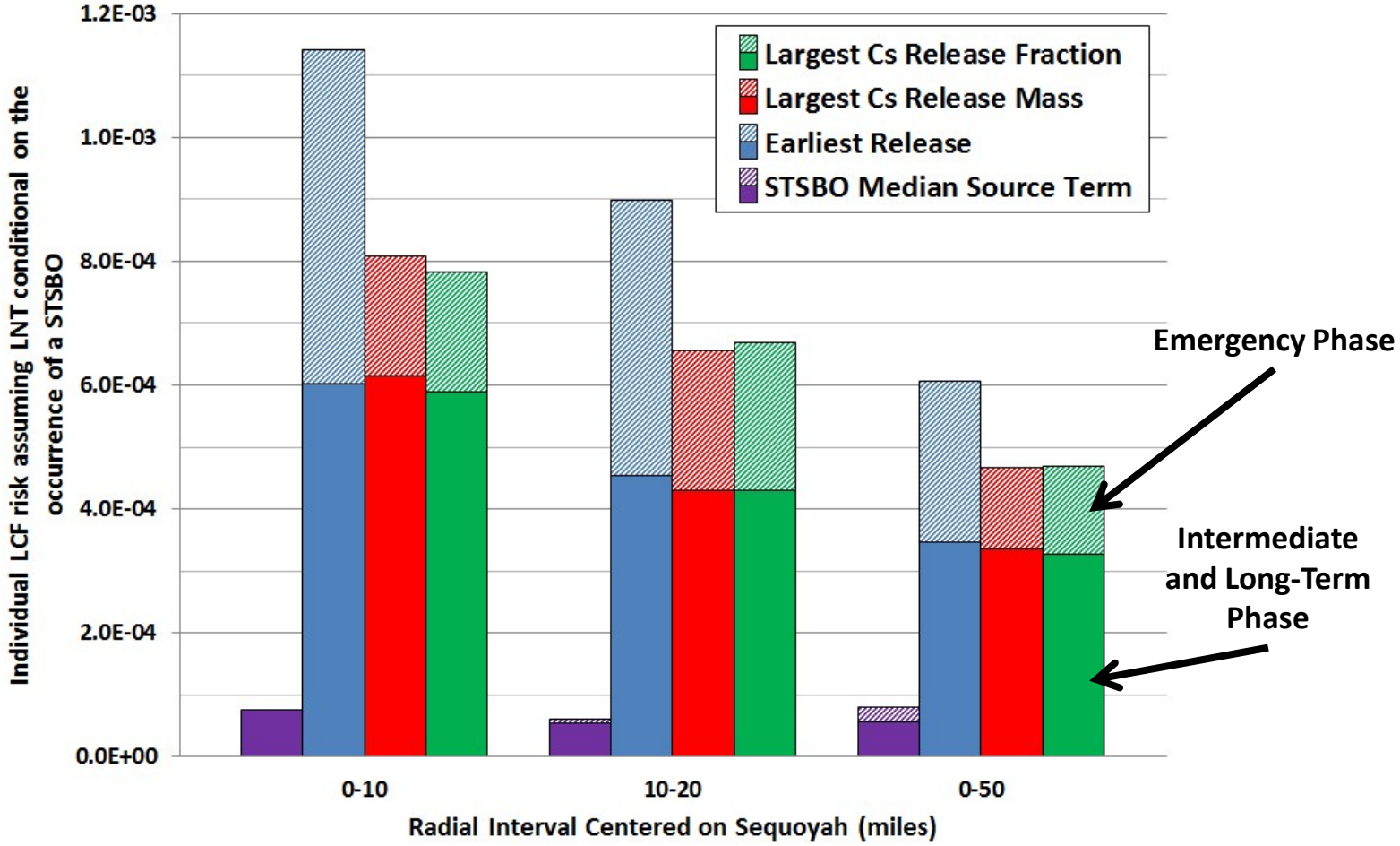
Reference and Sensitivity Cases: Results



- Conditional individual LCF risks generally decrease at longer distances

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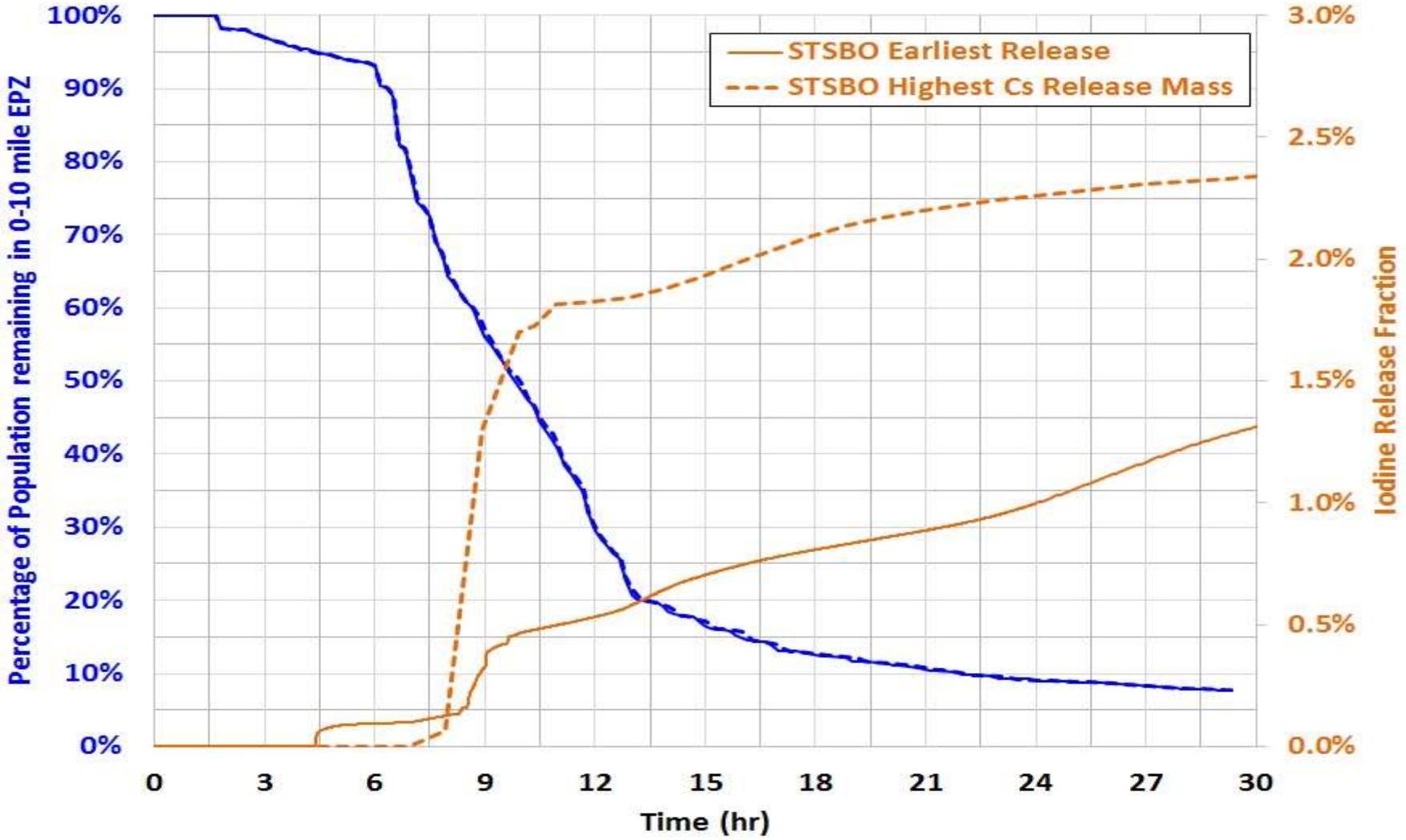
Reference and Sensitivity Cases: Population Movement Compared to Early Releases



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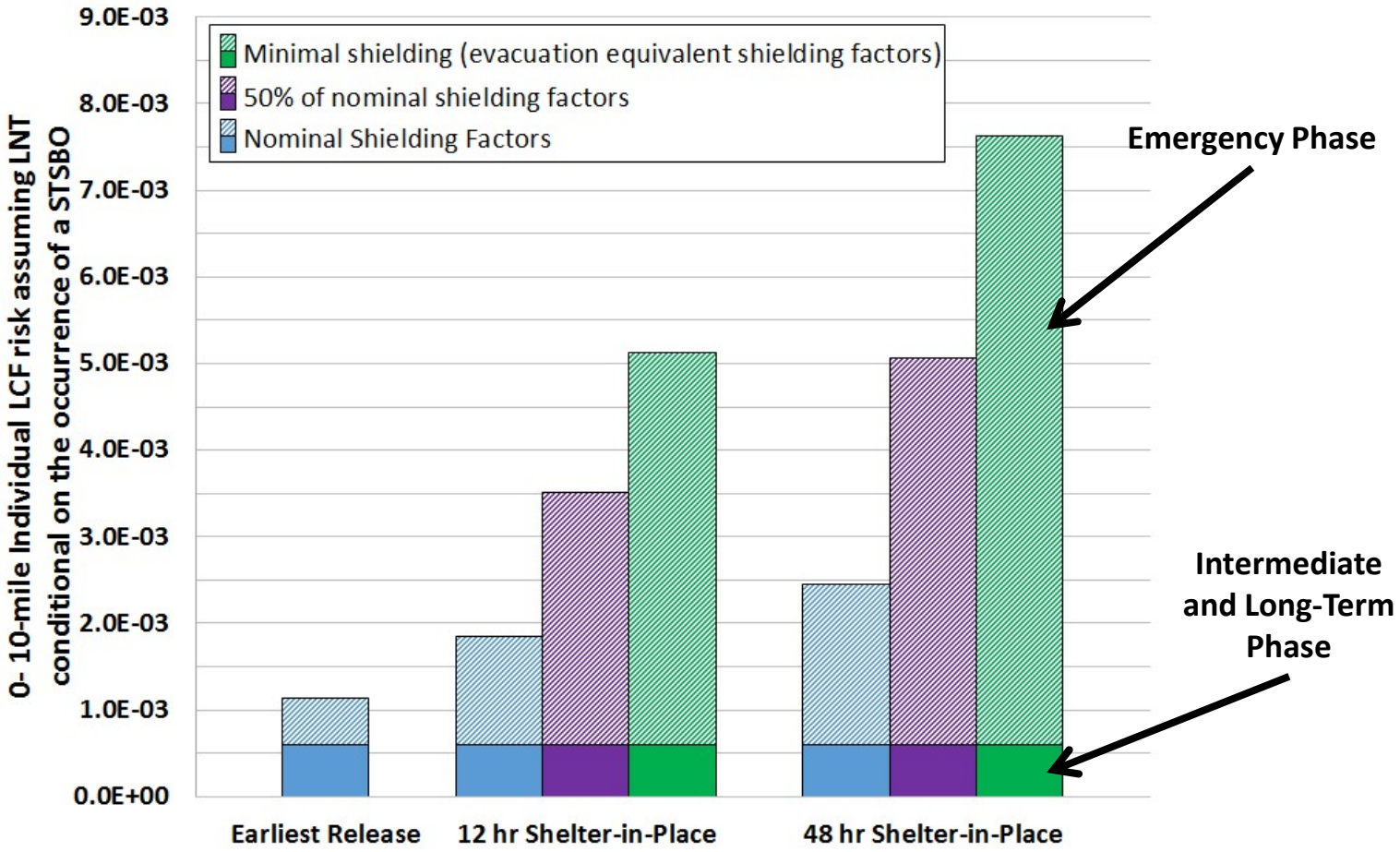
Reference and Sensitivity Cases: Sensitivity 1 and 2: SIP and shielding factor due to seismically degraded buildings (0-10 miles)



- Conditional individual LCF risks
  - Are roughly 1E-04 in 0- to 10-mile region for late releases
  - Are roughly 1E-03 in 0- to 10-mile region for early releases

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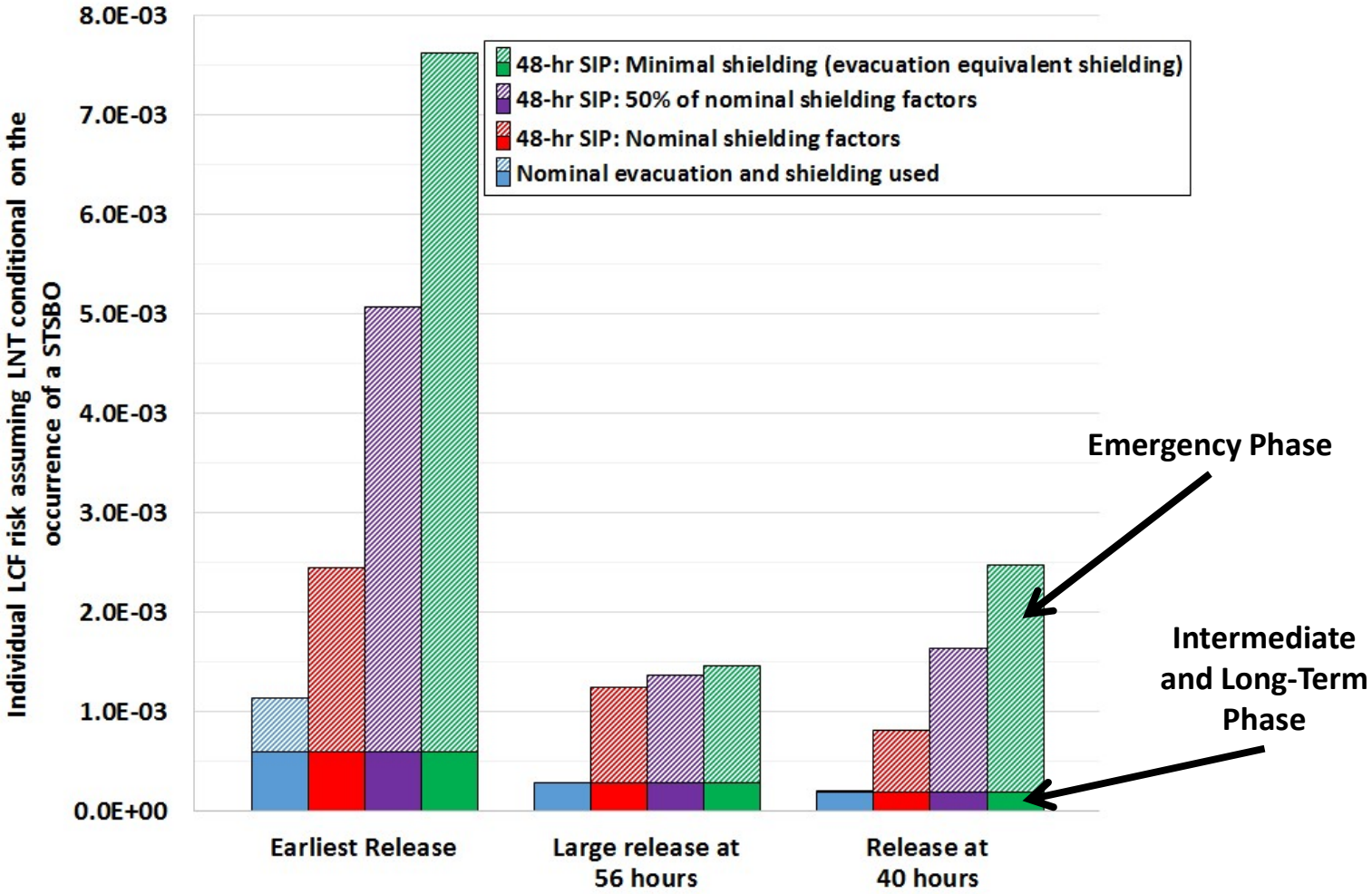
Reference and Sensitivity Cases: Sensitivities 1 and 2: Mean Conditional Individual LNT LCF Risks for SIP and Shielding Factor Variations



- 48-hour shelter-in-place increases 10-mile EPZ risks
  - By factor-of-2+ with nominal shielding factors
  - By factor-of-7+ with fully degraded shielding factors

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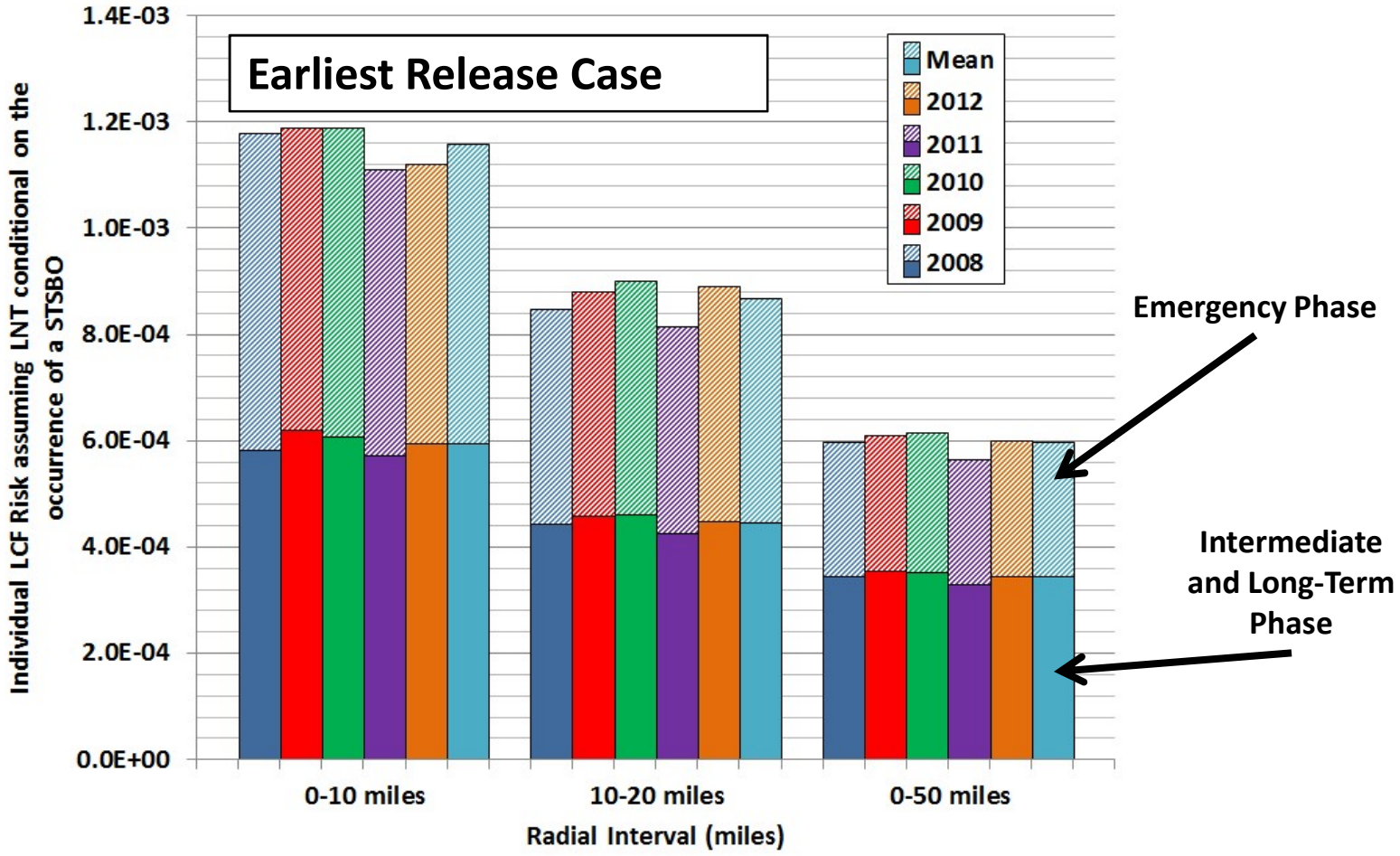
Reference and Sensitivity Cases
Sensitivity 3: Impact of Weather Year Risk



Conditional individual LCF risks are nearly independent of weather

Offsite Consequence Analysis Summary

- Individual, conditional LCF risks:
  - Range from about 1E-09 to 1E-03
  - Generally decrease at longer distances
  - Generally dominated by intermediate and long-term phase exposures compared to emergency phase exposures
  - Increase but by less than an order of magnitude for 48-hour shelter-in-place and degraded shielding factors
  - Nearly independent of weather year
  - Decrease with increasing dose-truncation level

- Parameters most important to uncertainty in individual LCF risk:
  - Time of accident during fuel cycle (most important at all distances)
  - Cancer fatality risk factors for “residual” organ, lungs, and colon
  - Containment rupture pressure
  - Number of safety valve cycles prior to failing open (more important at shorter distances)
  - Normal relocation time (more important beyond 10-mile EPZ)
  - Groundshine shielding factors (more important within 10-mile EPZ)

Sequoyah SOARCA Conclusions

- For unmitigated STSBO (without igniters), the two potential containment outcomes are either early or late failure
- Successful use of igniters averts early containment failure
- Essentially zero individual early fatality risk was calculated for Sequoyah STSBO
- Even for cases resulting in early release to environment, the conditional individual LCF risk is small
- Conditional individual latent cancer fatality risk results for Sequoyah are similar in magnitude to those from other SOARCA analyses

Acronyms & Abbreviations

AC	Alternating Current
BOC	Beginning of Cycle
CCDF	Complementary Cumulative Distribution Function
CCI	Core Concrete Interactions
CDF	Core Damage Frequency
CST	Condensate Storage Tank
DC	Direct Current
EOC	End of Cycle
EPZ	Emergency Planning Zone
EF	Early Fatality
HL	Hot Leg
FLEX	Diverse and Flexible Coping Strategies
FTC	Failure to Close
FTO	Failure to Open
LCF	Latent Cancer Fatality
LNT	Linear No Threshold
LTSBO	Long-Term Station Blackout
MACCS	MELCOR Accident Consequence System Code
MCR	Main Control Room
MELCOR	Not an acronym - accident progression code
MelMACCS	MELCOR to MACCS Source Term Converter
MOC	Middle of Cycle
MSIV	Main Steam Isolation Valve
NTTF	Fukushima Near-Term Task Force
PDF	Probability Density Function
PGA	Peak Ground Acceleration
PRA	Probabilistic Risk Assessment
PRT	Pressurizer Relief Tank
PZR	Pressurizer
RCP	Reactor Coolant Pump
RCS	Reactor Coolant System
RLZ	Realization
RPV	Reactor Pressure Vessel
RtePM	Real Time Evacuation Planning Model
SBO	Station Blackout
SG	Steam Generator
SIP	Shelter in Place
SNL	Sandia National Laboratories
SOARCA	State-of-the-Art Reactor Consequence Analysis
STSBO	Short-Term Station Blackout
SV	Safety Valve
TDAFW	Turbine Driven Auxiliary Feedwater System
TVA	Tennessee Valley Authority
UA	Uncertainty Analysis