Multi-Unit Accident Contributions to U.S. Nuclear Regulatory Commission Quantitative Health Objectives



A Safety Goal Analysis Using Models from State-of-the-Art Reactor Consequence Analyses

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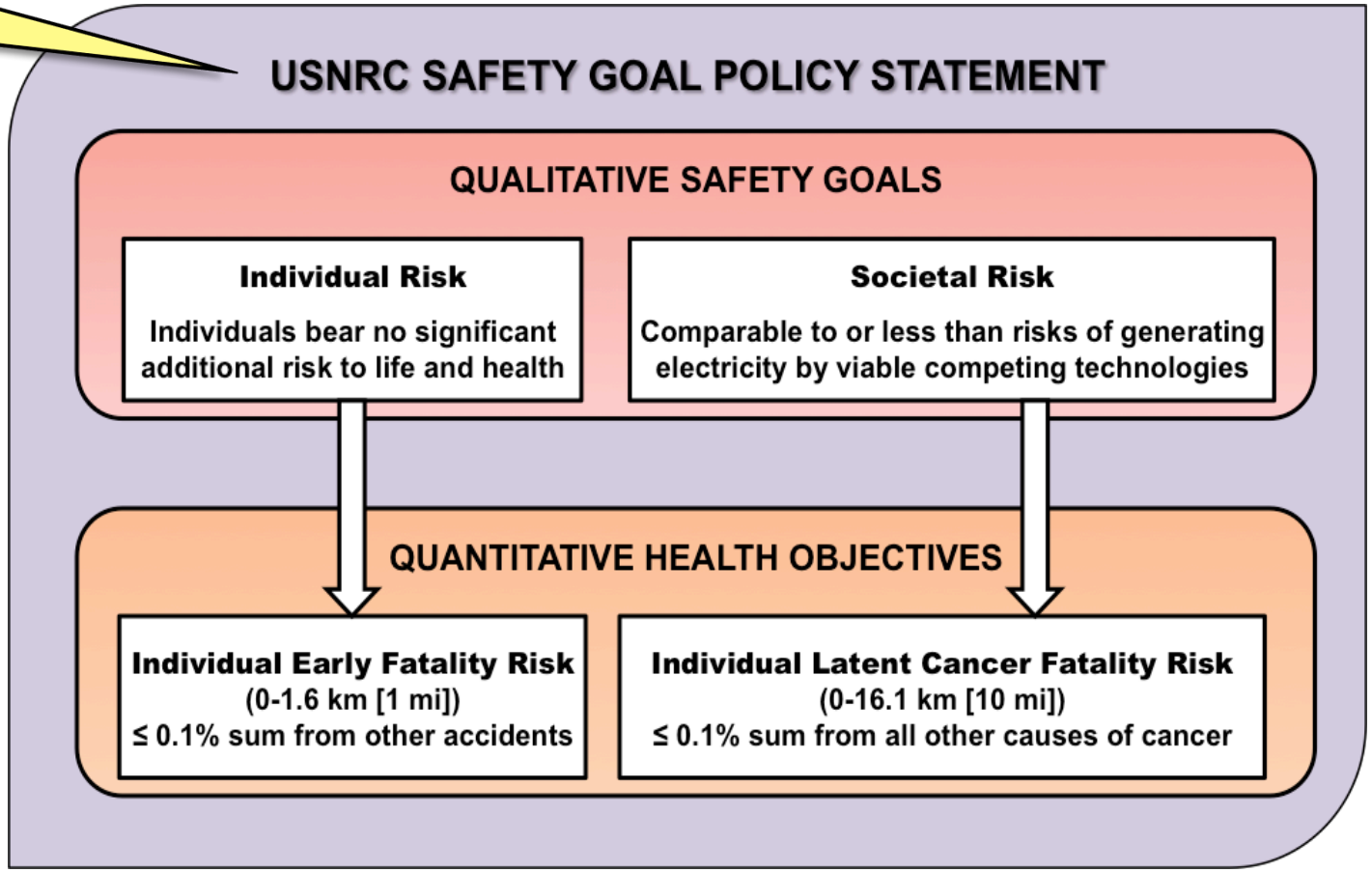
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BACKGROUND AND MOTIVATION

U.S. Nuclear Regulatory Commission Safety Goals

"How safe is safe enough?"



Probabilistic Risk Analysis (PRA) I: Overview

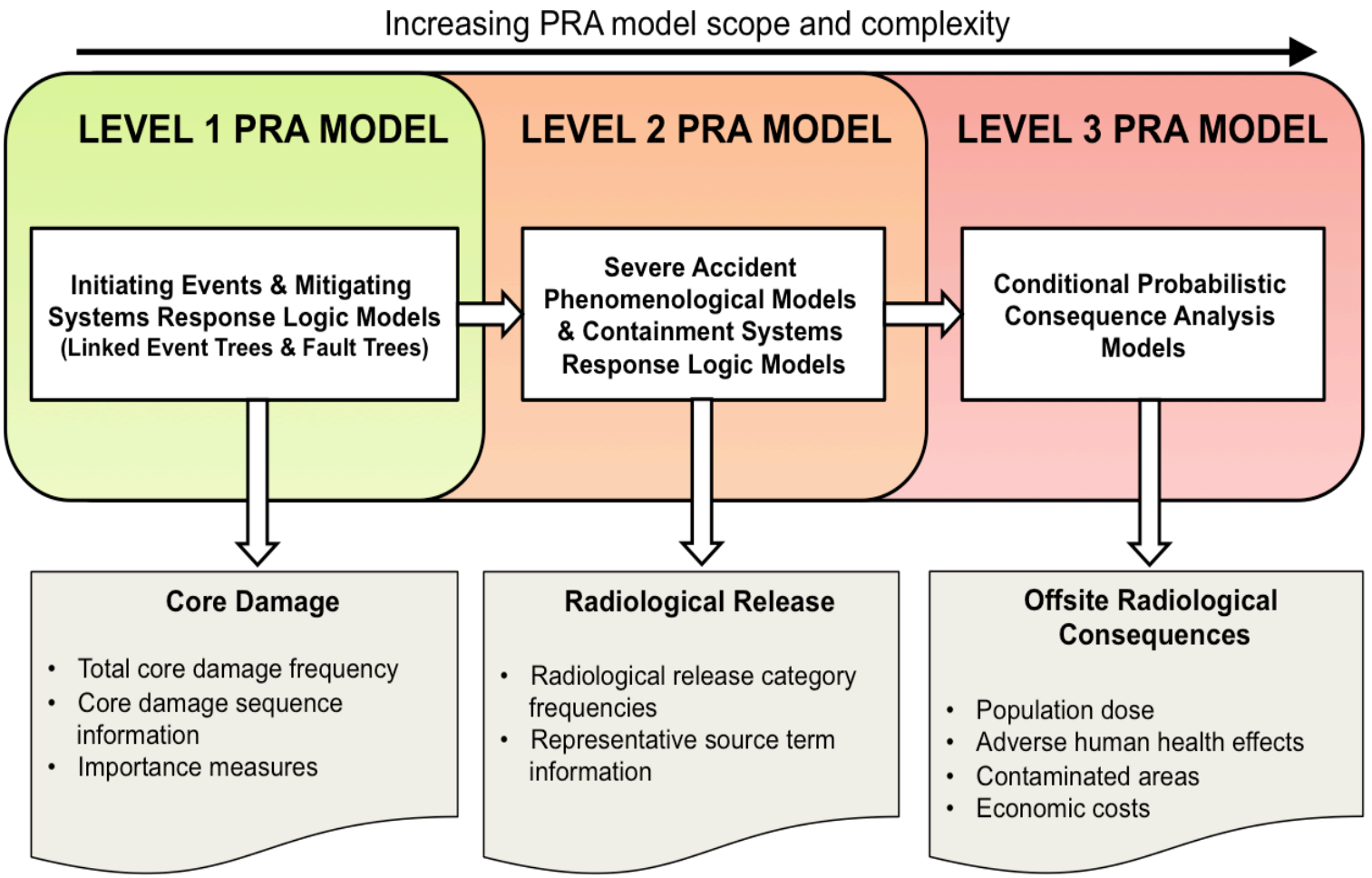
- Subset of risk analysis techniques used to support safety-related decisions involving complex engineered systems, including commercial nuclear power plants (NPPs).

- Systematic process of developing and applying methods, models, data, and analytical tools to answer three questions underlying scenario-based risk triplet:

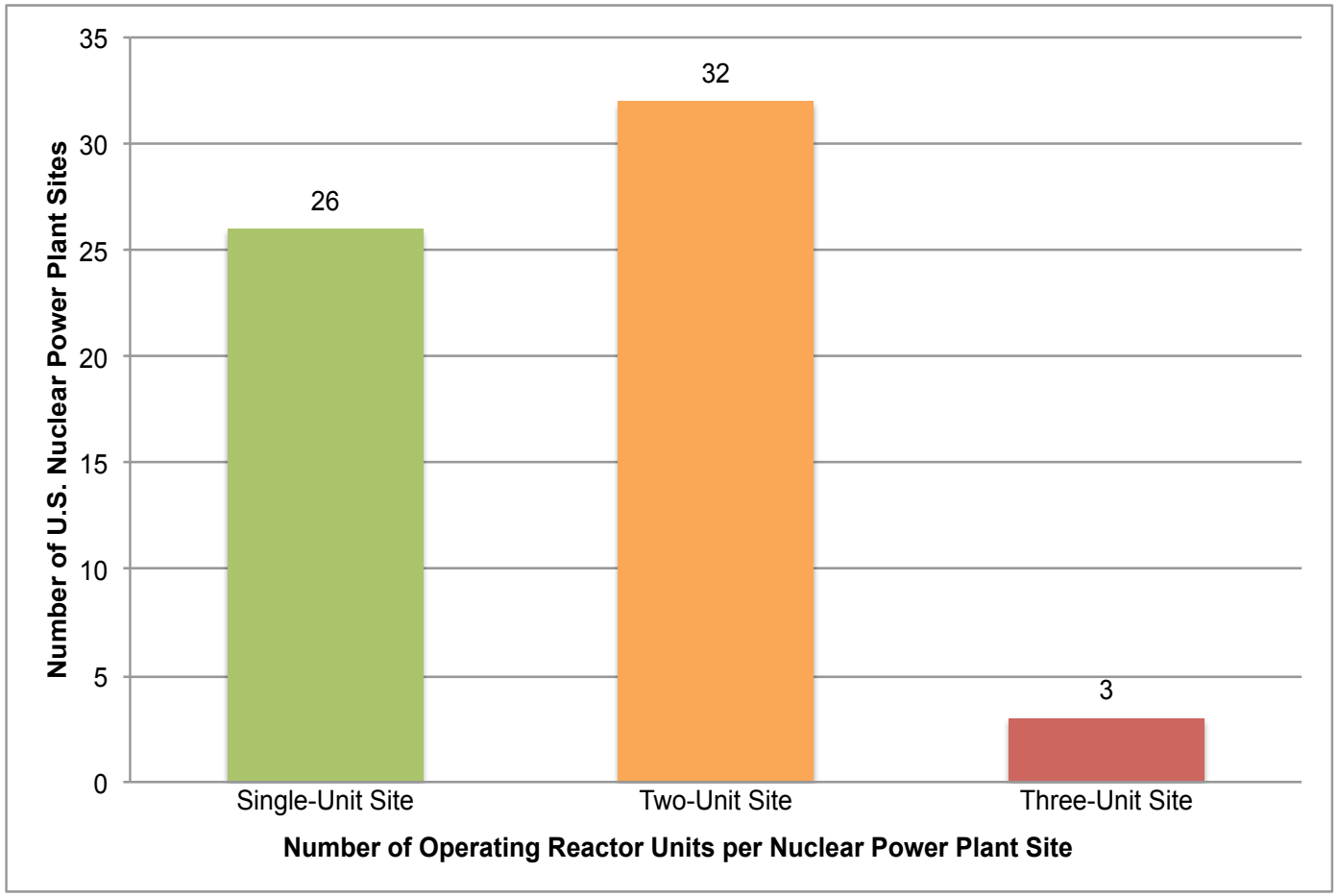
risk = < ① scenarios, ② frequencies, ③ consequences >

① What can happen (what can go wrong)?
② How likely is it to happen?
③ If it does happen, what are the consequences?

PRA II: Logic and Structure of NPP PRAs



Research Motivation I: Multi-Unit U.S. NPP Sites



Research Motivation II: Operational Experience



Image source: http://i.telegraph.co.uk/multimedia/archive/02081/Fukushima_2081985b.jpg

Research Motivation III

Poll Question:
If you live here, which type(s) of accidents are you at risk for being exposed to:

a. Single-unit accidents involving only one reactor unit or the other.
b. Two-unit accidents involving both reactor units.
c. All of the above.



Image source: http://www.pennenergy.com/content/dam/Pennenergy/online-articles/2015/September/Peach%20Bottom%20Atomic%20Power%20Station.JPG

Research Aims I: Overall Perspective

- Fundamental research question
  - What effect would expanding the scope of the safety goal policy to include contributions from multi-unit accidents have on risk metrics used to measure attainment of the safety goal quantitative health objectives (QHOs)?

- Overall research aim
  - Evaluate effect of expanding scope of safety goal policy to include multi-unit accident contributions to safety goal QHO risk metrics.

Research Aims II: Specific Aims

- Specific Aim 1: Base Case Analysis
  - Evaluate effect of including multi-unit accident contributions to safety goal QHO risk metrics under base case assumptions that affect two risk triplet elements:
    ① Frequency: Assumed 10% inter-unit dependence.
    ② Consequences: Assumed simultaneous multi-unit accidents.
- Specific Aims 2 & 3: One-Way Sensitivity Analyses
  - Aim 2: Evaluate effect of variation in assumed inter-unit dependence.
  - Aim 3: Evaluate effect of variation in assumed timing offset between accidents involving co-located units.

Study Design I: Policy Alternatives

- Option 1: Status Quo
  - Only single-unit accident contributions included in estimating risk metrics for comparison to QHOs.
- Option 2: Hypothetical Expansion in Scope of Safety Goal Policy
  - Contributions from both single-unit and multi-unit accidents included in estimating risk metrics for comparison to QHOs.
  - Assumes policy is still applied to individual reactor units, rather than the entire site.

Study Design II: Figures of Merit

- Figure of Merit 1 (FOM_1): Percent change in mean values for safety goal QHO risk metrics, comparing Option 2 relative to Option 1.
  - Quantifies the effect of including multi-unit accident contributions on safety goal QHO metrics.
- Figure of Merit 2 (FOM_2): Percent change in mean values for QHO margins, comparing Option 2 relative to Option 1.
  - Quantifies the effect of including multi-unit accident contributions on margins to the QHOs.

Study Design III: Study Population

Peach Bottom Atomic Power Station Unit 2 and Unit 3

- Representative of sites using boiling-water reactor (BWR)–Mark I containment design.
- Located 18 miles south of Lancaster, PA.
- Below average offsite population density within 10 miles of site boundary.



Image source: http://www.pennenergy.com/content/dam/Pennenergy/online-articles/2014/08/PeachBottom.jpg

Surry Power Station Unit 1 and Unit 2

- Representative of sites using pressurized-water reactor (PWR)–large dry containment design
- Located 17 miles northwest of Newport News, VA.
- Average offsite population density within 10 miles of site boundary.



Image source: http://apps.startribune.com/blogs/user_images/surry.jpg

Study Design IV: Single-Unit Accident Scenarios

The State-Of-the-Art Reactor Consequence Analyses (SOARCA) Project leveraged decades of research and advanced analytical tools to develop realistic consequence models for important single-unit accident scenarios.

Peach Bottom

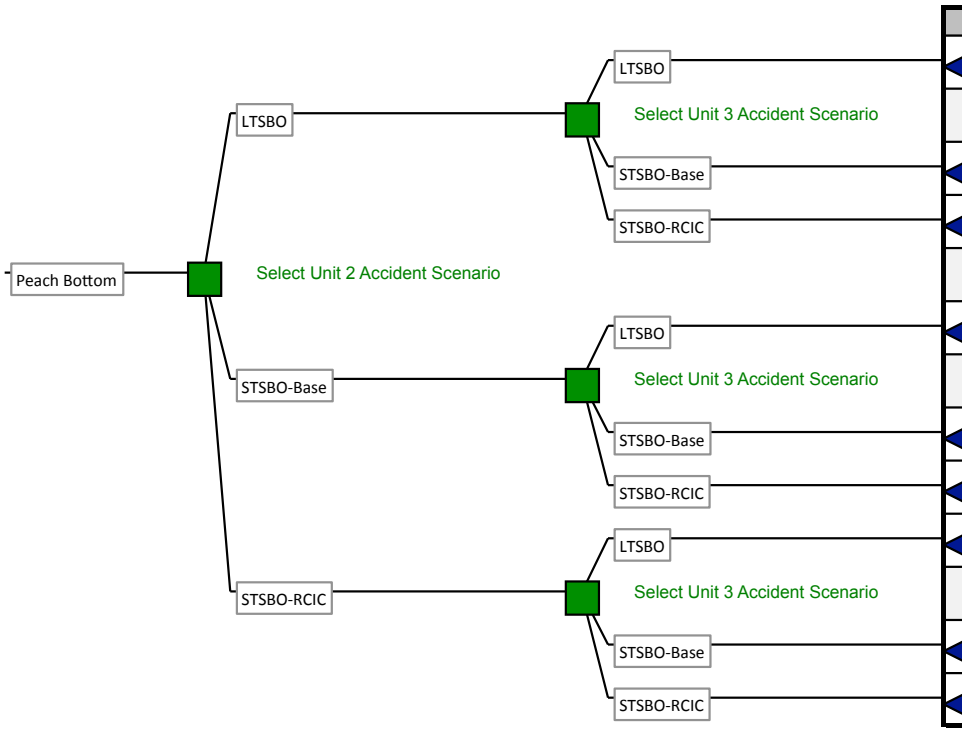
- Long-Term Station Blackout (LTSBO)
- Short-Term Station Blackout (STSBO-Base)
- Short-Term Station Blackout with Reactor Core Isolation Cooling System Operation (STSBO-RCIC)

Surry

- Long-Term Station Blackout (LTSBO)
- Short-Term Station Blackout (STSBO-Base)
- Short-Term Station Blackout with Thermally-Induced Steam Generator Tube Rupture (STSBO-TISGTR)
- Interfacing Systems Loss-Of-Coolant Accident (ISLOCA)

Study Design V: Two-Unit Accident Scenarios

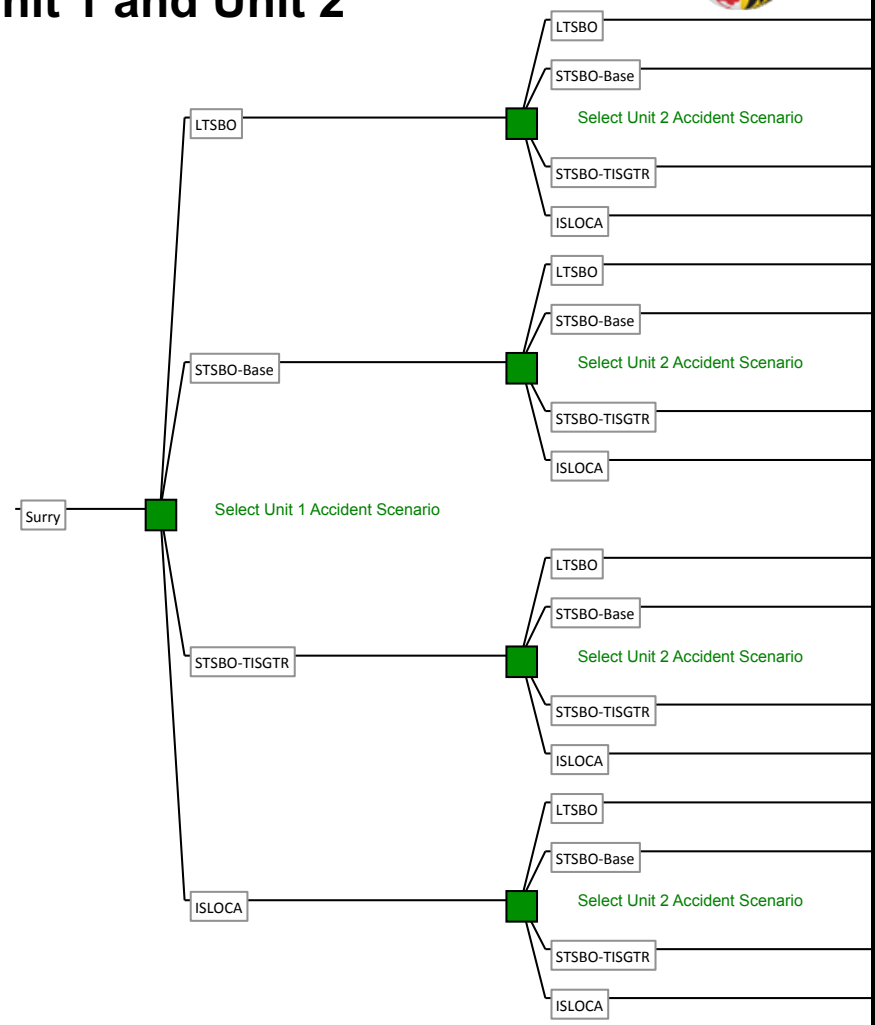
Peach Bottom Unit 2 and Unit 3



ID No.	Two-Unit Accident Scenario
BWR1	Unit 2: LTSBO, Unit 3: LTSBO
BWR2	Unit 2: LTSBO, Unit 3: STSBO-Base
BWR3	Unit 2: LTSBO, Unit 3: STSBO-RCIC
BWR4	Unit 2: STSBO-Base, Unit 3: LTSBO
BWR5	Unit 2: STSBO-Base, Unit 3: STSBO-Base
BWR6	Unit 2: STSBO-Base, Unit 3: STSBO-RCIC
BWR7	Unit 2: STSBO-RCIC, Unit 3: LTSBO
BWR8	Unit 2: STSBO-RCIC, Unit 3: STSBO-Base
BWR9	Unit 2: STSBO-RCIC, Unit 3: STSBO-RCIC

Study Design V: Two-Unit Accident Scenarios

Surry Unit 1 and Unit 2



ID No.	Two-Unit Accident Scenario
PWR1	Unit 1: LTSBO, Unit 2: LTSBO
PWR2	Unit 1: LTSBO, Unit 2: STSBO-Base
PWR3	Unit 1: LTSBO, Unit 2: STSBO-TISGTR
PWR4	Unit 1: LTSBO, Unit 2: ISLOCA
PWR5	Unit 1: STSBO-Base, Unit 2: LTSBO
PWR6	Unit 1: STSBO-Base, Unit 2: STSBO-Base
PWR7	Unit 1: STSBO-Base, Unit 2: STSBO-TISGTR
PWR8	Unit 1: STSBO-Base, Unit 2: ISLOCA
PWR9	Unit 1: STSBO-TISGTR, Unit 2: LTSBO
PWR10	Unit 1: STSBO-TISGTR, Unit 2: STSBO-Base
PWR11	Unit 1: STSBO-TISGTR, Unit 2: STSBO-TISGTR
PWR12	Unit 1: STSBO-TISGTR, Unit 2: ISLOCA
PWR13	Unit 1: ISLOCA, Unit 2: LTSBO
PWR14	Unit 1: ISLOCA, Unit 2: STSBO-Base
PWR15	Unit 1: ISLOCA, Unit 2: STSBO-TISGTR
PWR16	Unit 1: ISLOCA, Unit 2: ISLOCA

Study Design VI: Key Assumptions

- Modeled two-unit sites are representative of U.S. multi-unit NPP sites.
- Co-located units at each site are identical.
- One unit always serves as reference unit for two-unit accident scenarios.
- SOARCA consequence models and their technical bases are valid.
- Modeled accident scenarios are representative with respect to full-spectrum of consequences.

METHODS AND ANALYTICAL TOOLS

Methods I: The Need for a New Approach

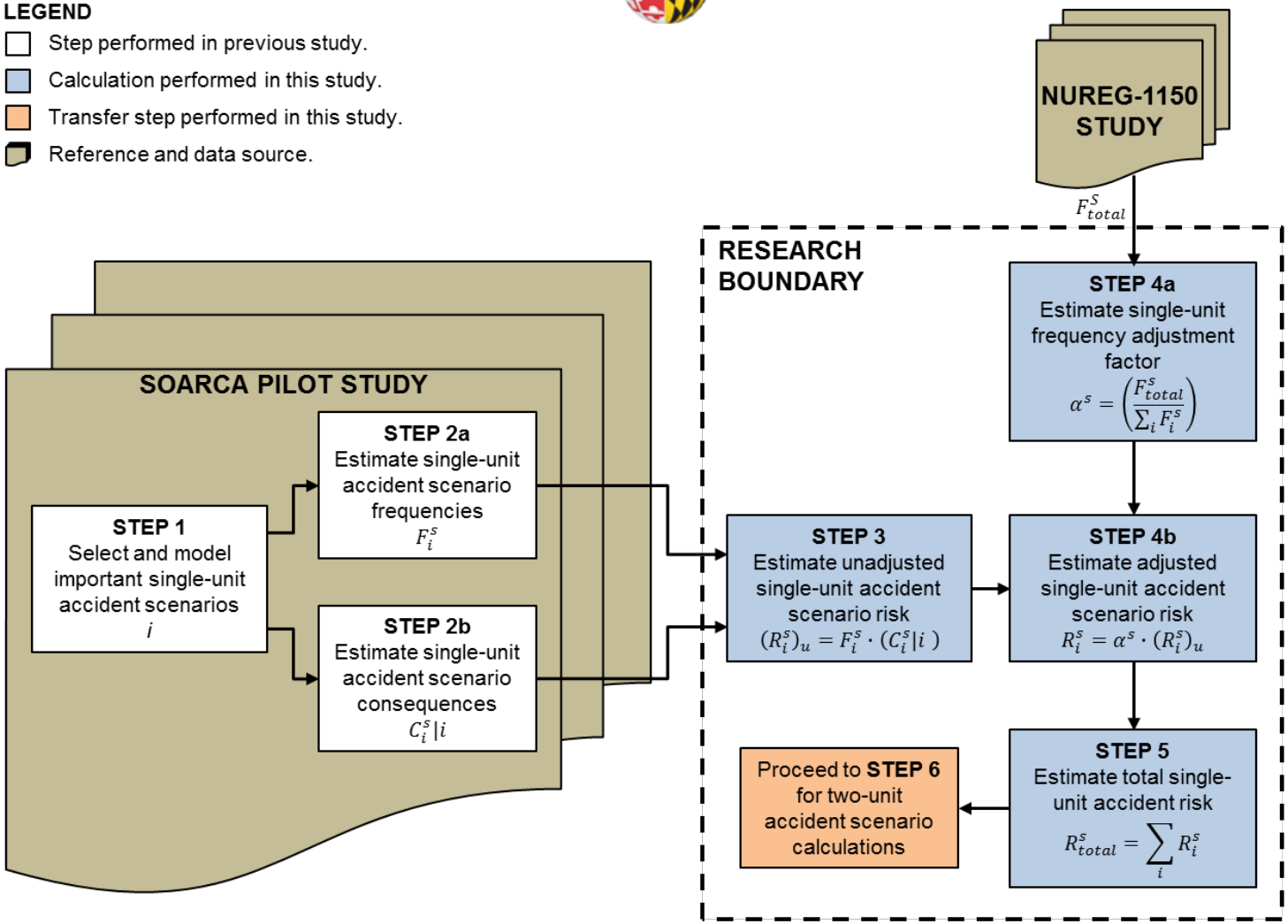
- SOARCA consequence models selected to leverage decades of research and advanced analytical tools that improved state of knowledge about severe accident progression and offsite radiological consequences.
- Consequence models developed for a small set of single-unit accident scenarios judged to be more important.
- Safety goal QHOs intended for comparison with risk results from full-scope NPP Level 3 PRAs.

Key issue: How can we translate SOARCA results into representative risk results for meaningful comparison to QHOs?

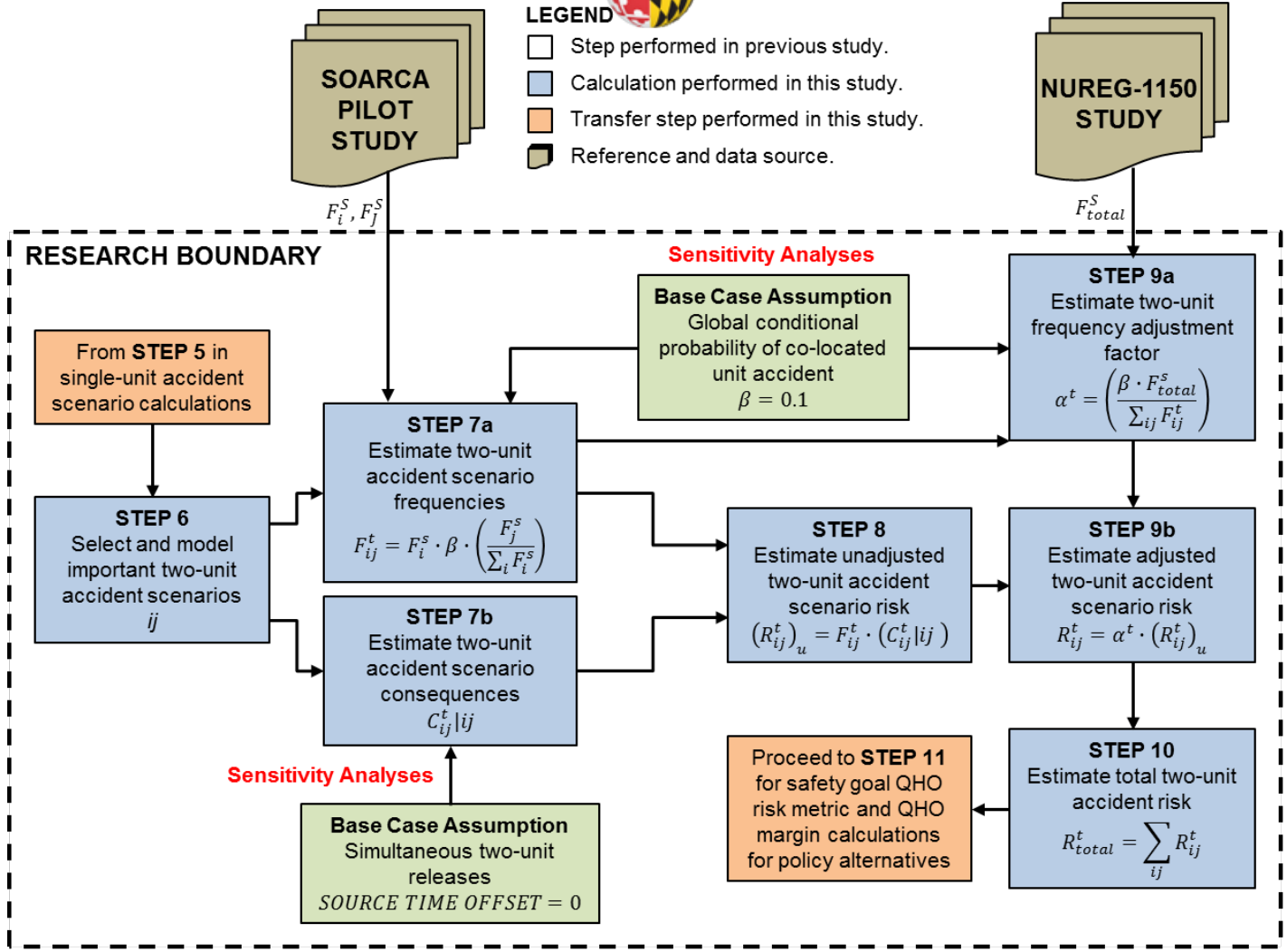
Methods II: Overview of Approach

- Part I: Estimate contribution from single-unit accidents to safety goal QHO risk metrics.
- Part II: Estimate contribution from multi-unit accidents to safety goal QHO risk metrics.
- Part III: Estimate safety goal QHO risk metrics for comparison to QHOs and figures of merit.

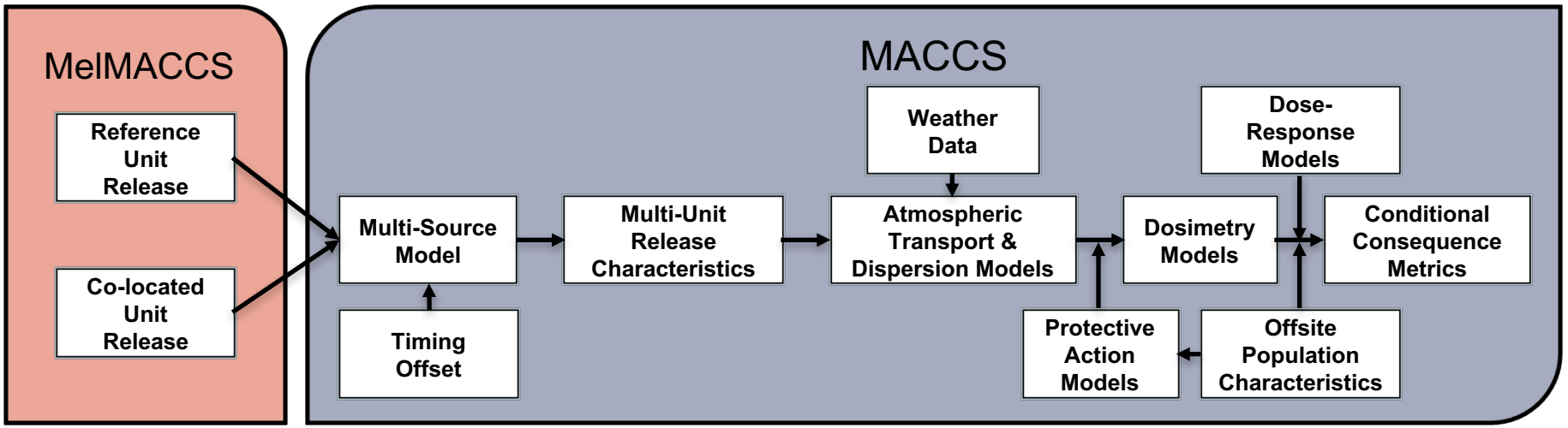
Methods III: Single-Unit Accident Contributions



Methods IV: Multi-Unit Accident Contributions



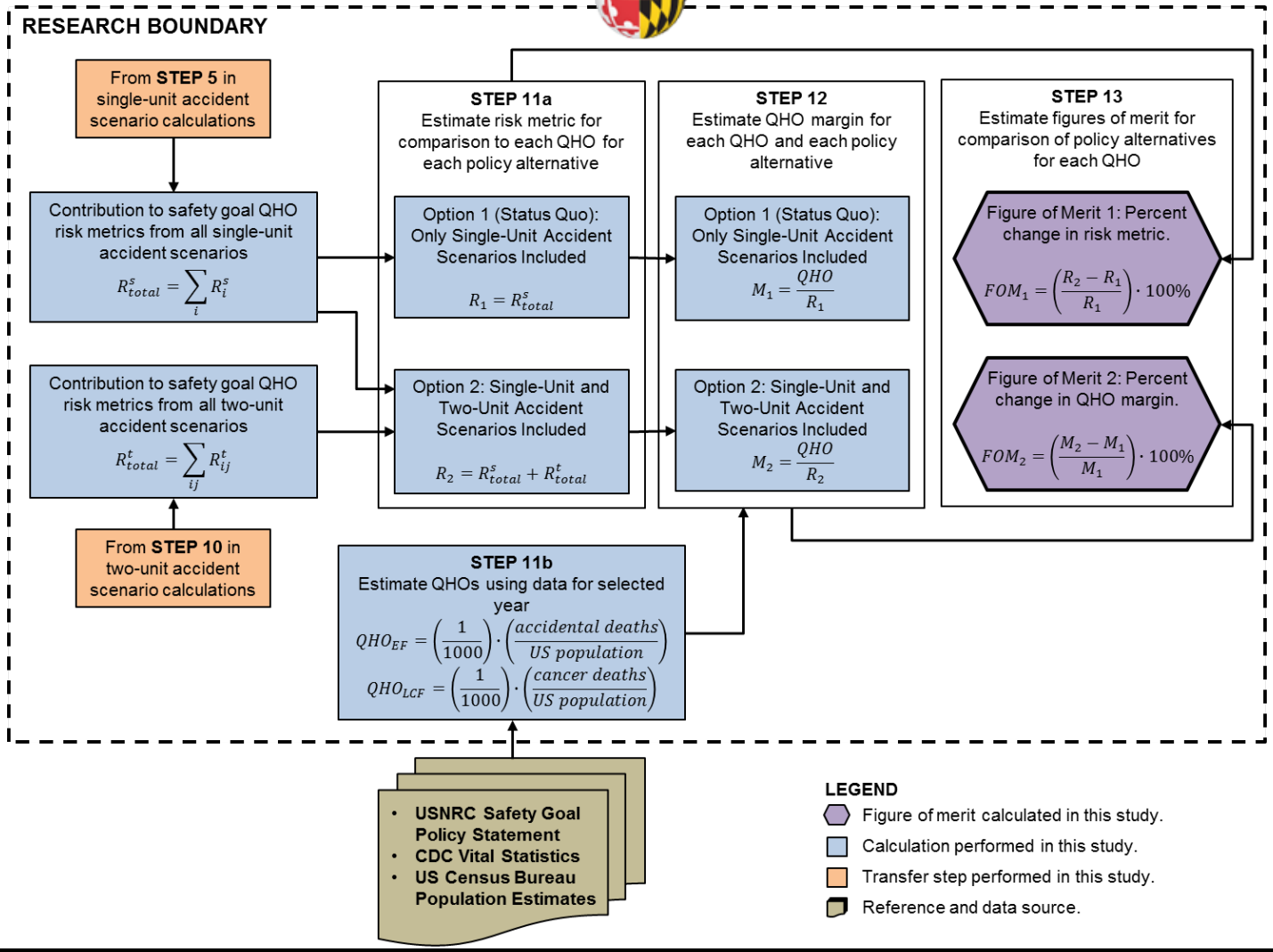
Methods IV(a): Multi-Unit Accident Consequences



Methods IV(b): Consequence Metric Options

- Average Individual Health Effect Risk
  - Averaging technique in effect assumes uniform population distribution.
  - Necessary for comparison with early fatality risk QHO when no individuals reside within one mile of the NPP site boundary.
  - Selected for comparison with early fatality risk QHO since no individuals reside within one mile of Surry.
- Population-Weighted Health Effect Risk
  - Can utilize site-specific population distribution data to calculate more realistic results.
  - Selected for comparison with latent cancer fatality risk QHO.

Methods V: Figures of Merit



RESULTS I: BASE CASE ANALYSIS

EFFECT OF INCLUDING CONTRIBUTION FROM MULTI-UNIT ACCIDENTS TO SAFETY GOAL QHO RISK METRICS

Conditions:

- Assumed $\beta = 0.1$.
- Assumed *SOURCE TIME OFFSET = 0*.

Results I(a): Figures of Merit Summary

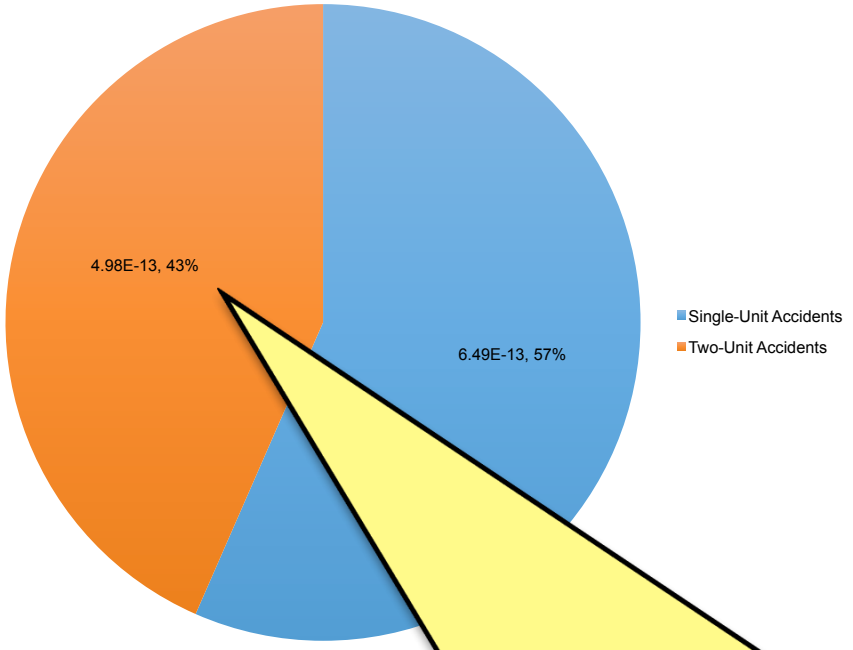
Safety Goal QHO and Reactor-Containment Design	Figure of Merit 1 Percent Change in Risk	Figure of Merit 2 Percent Change in QHO Margin
Representative BWR (Peach Bottom)		
Average Individual Early Fatality Risk QHO	77%	-43%
Average Individual Latent Cancer Fatality Risk QHO	15%	-13%
Representative PWR (Surry)		
Average Individual Early Fatality Risk QHO	20%	-17%
Average Individual Latent Cancer Fatality Risk QHO	18%	-16%

Key Findings

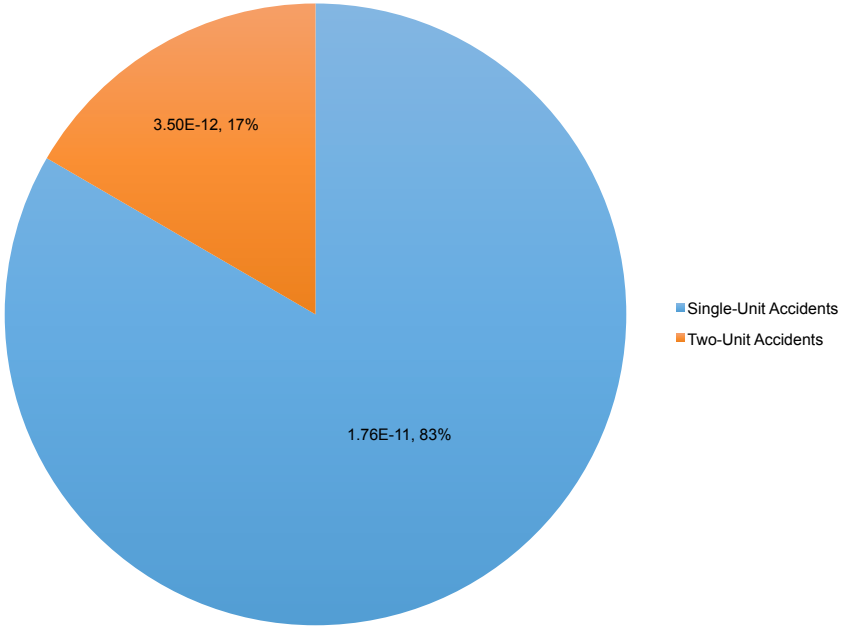
- Including contribution from two-unit accidents to safety goal QHO risk metrics results in non-negligible increases in risk and non-negligible reductions in QHO margins.
- Magnitude of effect depends on risk metric and reactor-containment design.

Results I(b): Early Fatality Risk Profiles

Representative BWR (Peach Bottom)



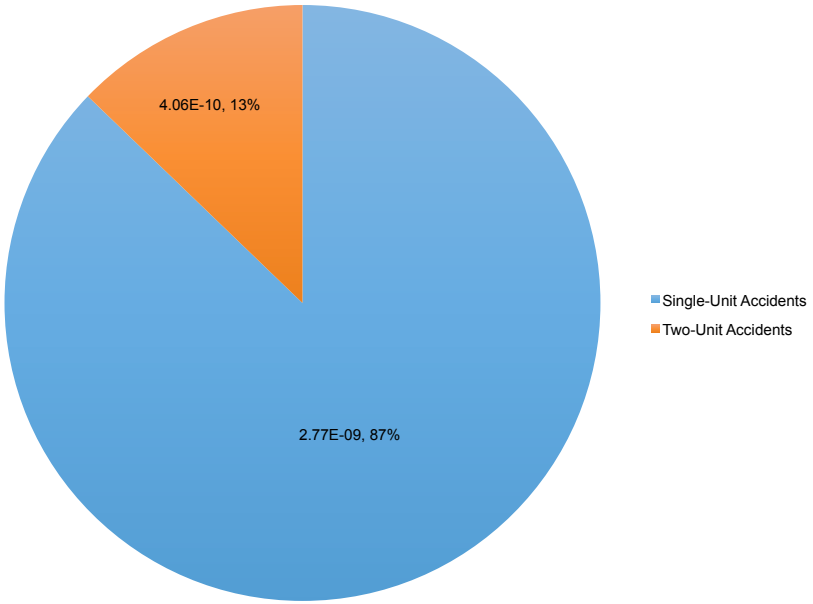
Representative PWR (Surry)



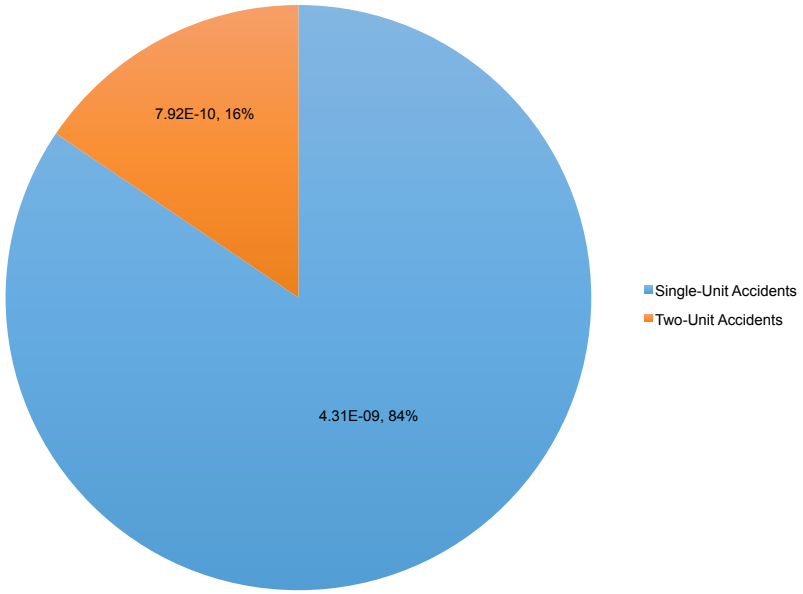
Two-unit accidents comprise a greater percentage of total early fatality risk for the representative BWR site (43%) than for the representative PWR site (17%).

Results I(c): Latent Cancer Fatality Risk Profiles

Representative BWR (Peach Bottom)



Representative PWR (Surry)



The relative contributions of two-unit accidents to latent cancer fatality risk are similar for both reactor-containment designs and NPP sites.

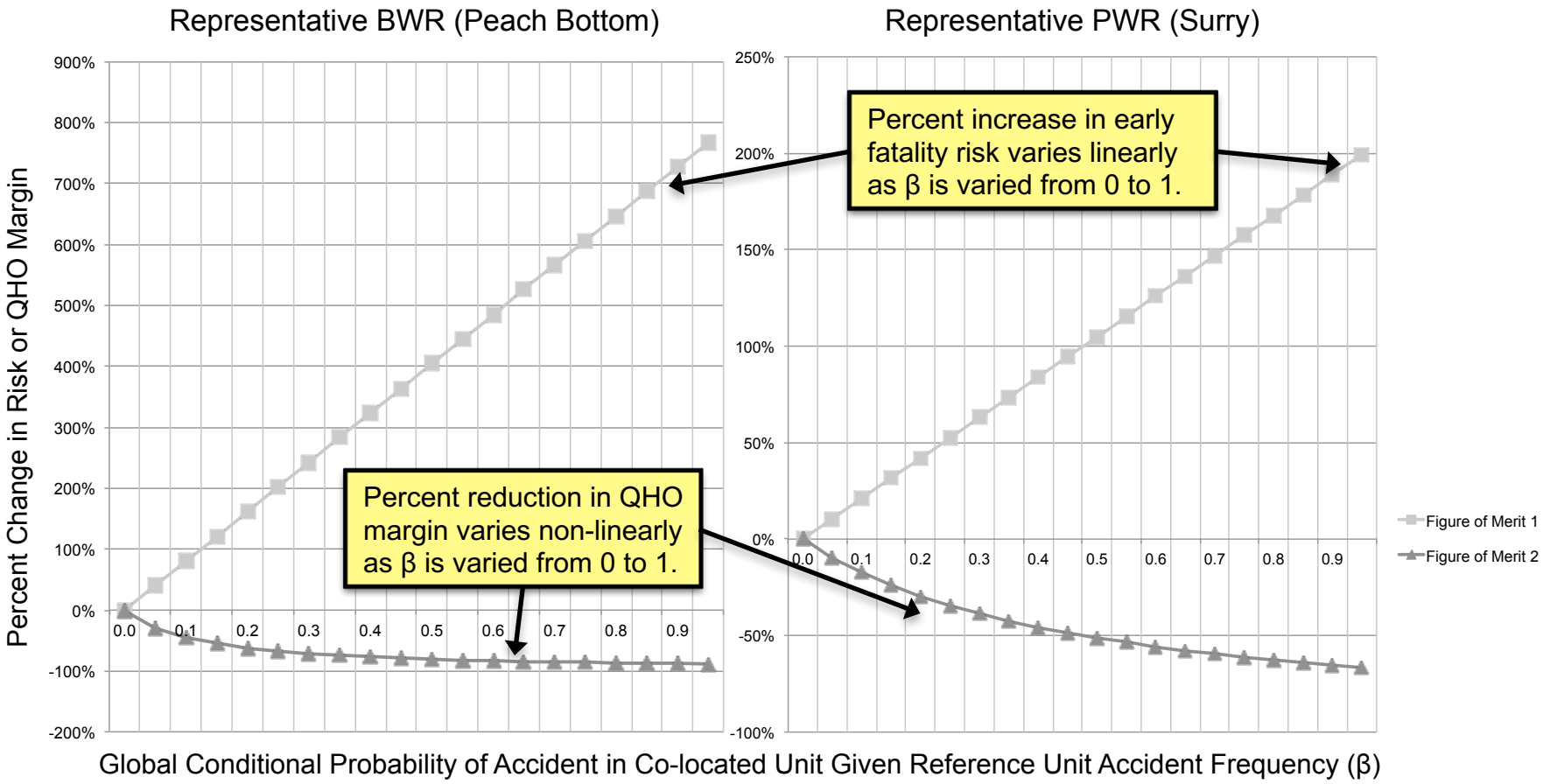
RESULTS II: ONE-WAY SENSITIVITY ANALYSIS

EFFECT OF VARIATION IN ASSUMED INTER-UNIT DEPENDENCE

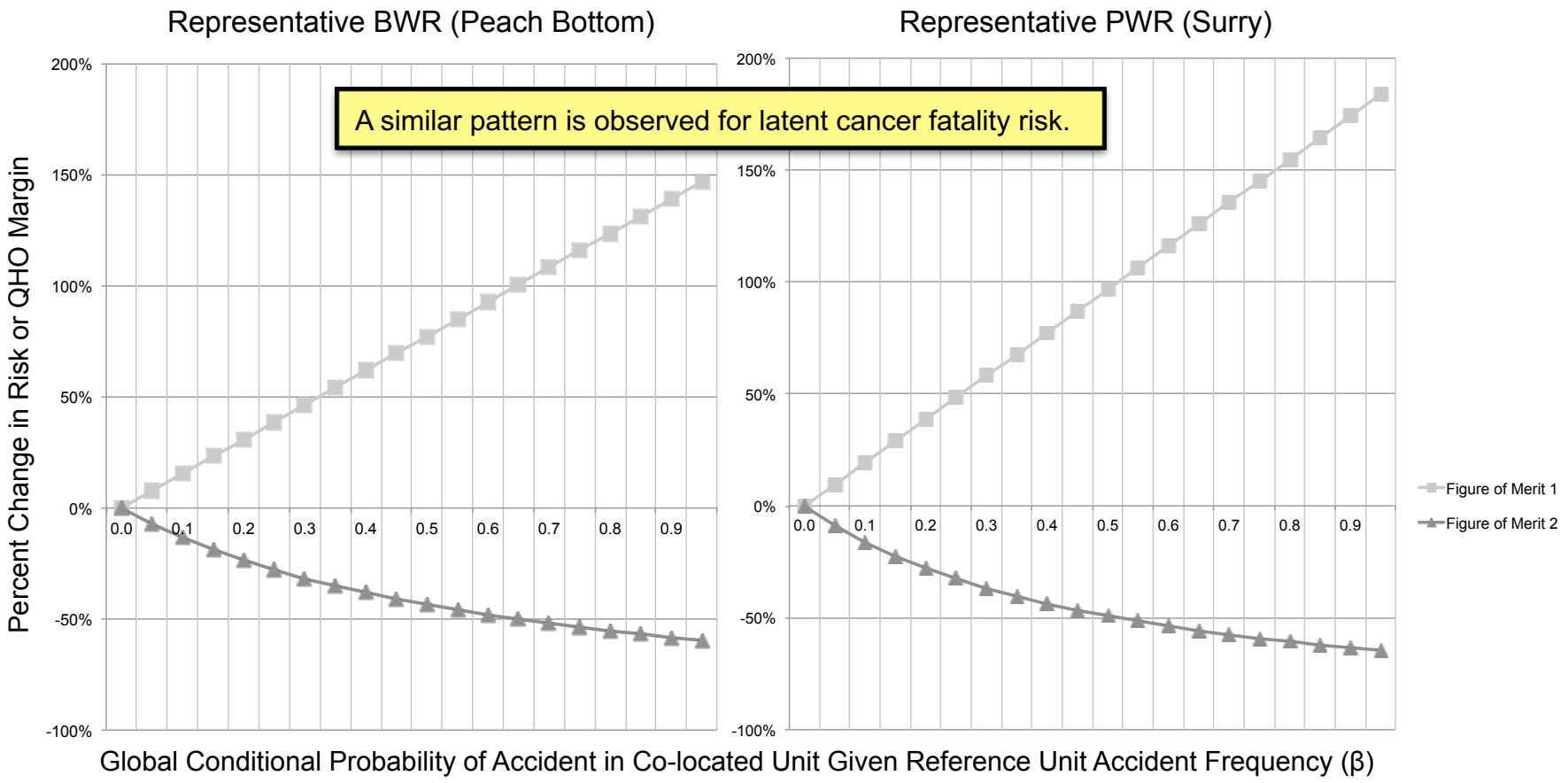
Conditions:

- Assumed *SOURCE TIME OFFSET = 0*.
- Assumed β varied from 0 to 1.

Results II(a): Early Fatality Risk



Results II(b): Latent Cancer Fatality Risk



Results II(c): Figures of Merit Summary

Safety Goal QHO and Reactor-Containment Design	Figure of Merit 1 Percent Change in Risk		Figure of Merit 2 Percent Change in QHO	
	Assumed Inter-Unit Dependence			
	β = 0.1	*β = 1*	*β = 0.1*	*β = 1*
Representative BWR (Peach Bottom)				
Average Individual Early Fatality Risk QHO	77%	770%	-43%	-89%
Average Individual Latent Cancer Fatality Risk QHO	15%	150%	-13%	-60%
Representative PWR (Surry)				
Average Individual Early Fatality Risk QHO	20%	200%	-17%	-67%
Average Individual Latent Cancer Fatality Risk QHO	18%	180%	-16%	-65%

For β = 0, which is equivalent to assuming there are no inter-unit dependencies that could give rise to multi-unit accidents, including the contribution from multi-unit accidents to safety goal QHO risk metrics has no effect. These trivial results are not displayed here to conserve space.

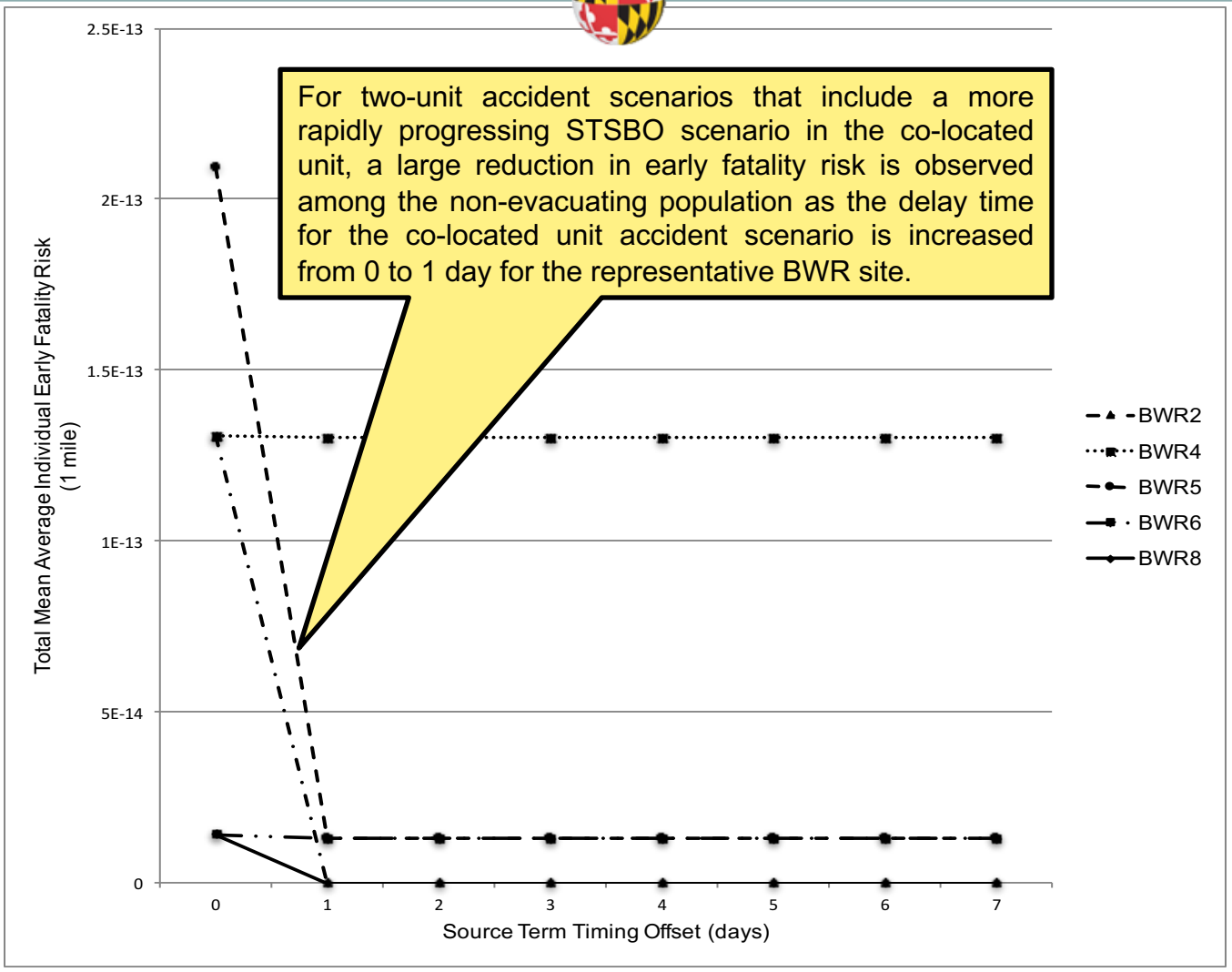
RESULTS III: ONE-WAY SENSITIVITY ANALYSIS

EFFECT OF VARIATION IN ASSUMED TIMING OFFSET BETWEEN CONCURRENT RELEASES

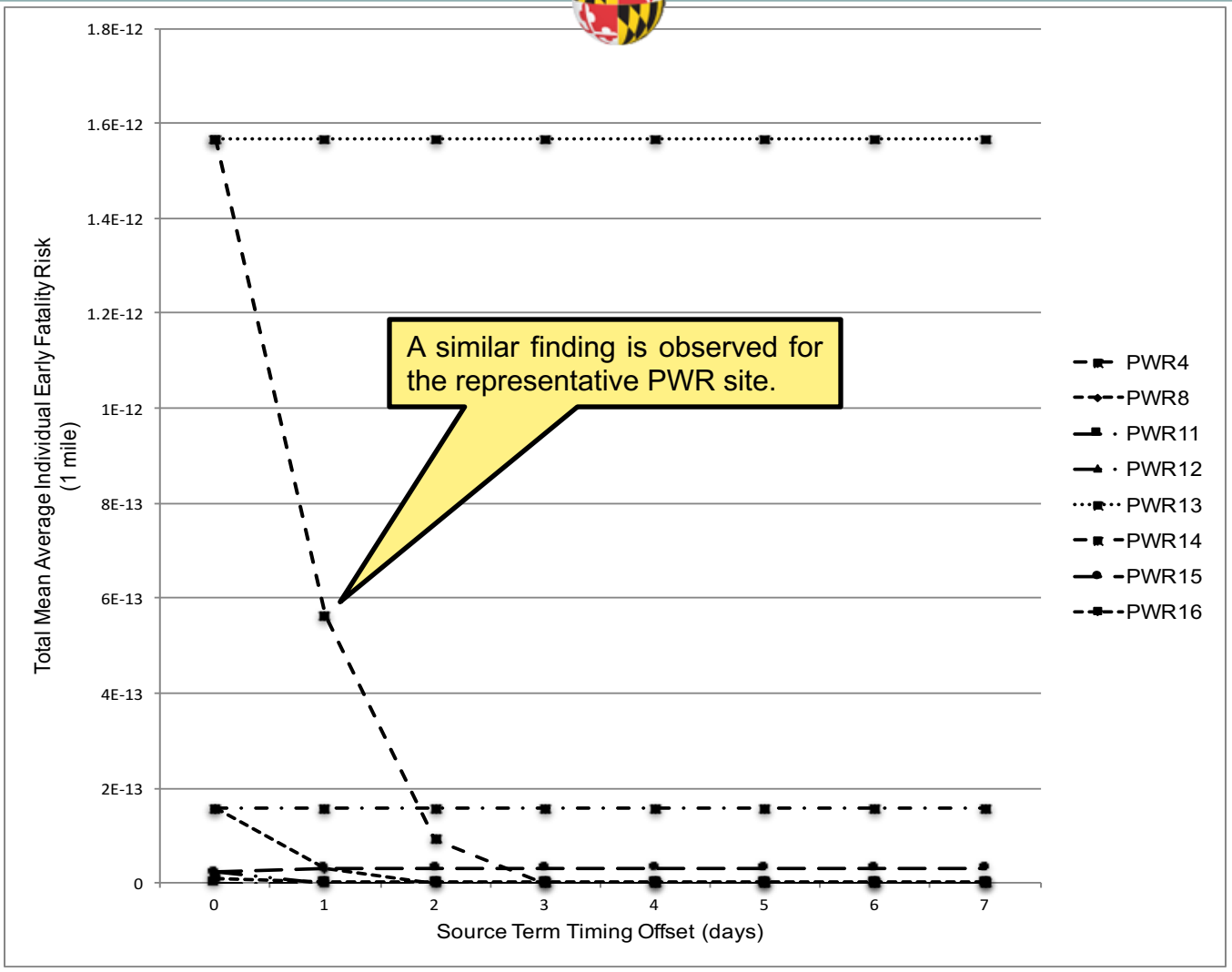
Conditions:

- Assumed $\beta = 0.1$.
- Assumed *SOURCE TIME OFFSET* varied from 0 to 7 days.

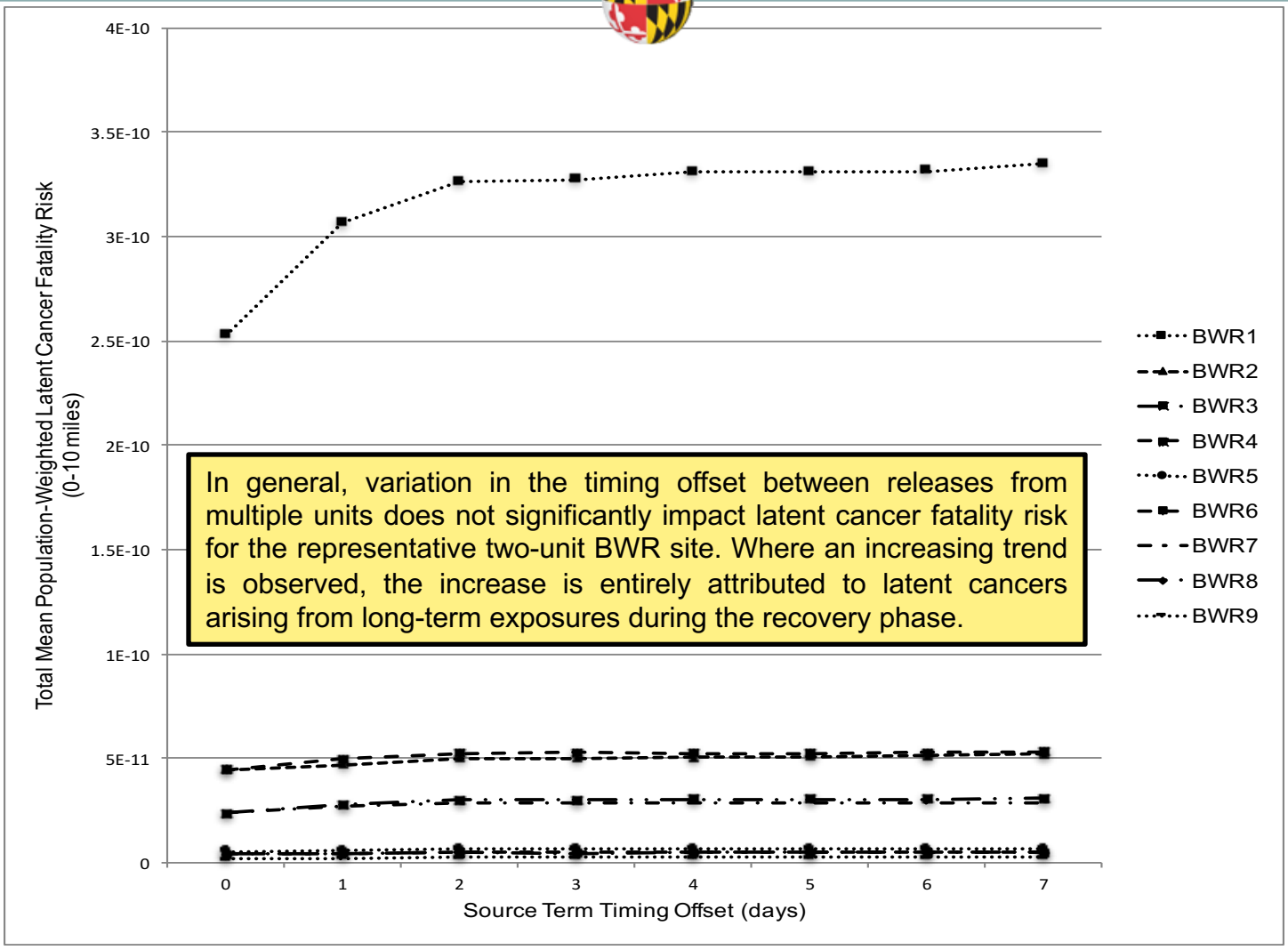
Results III(a): BWR Early Fatality Risk



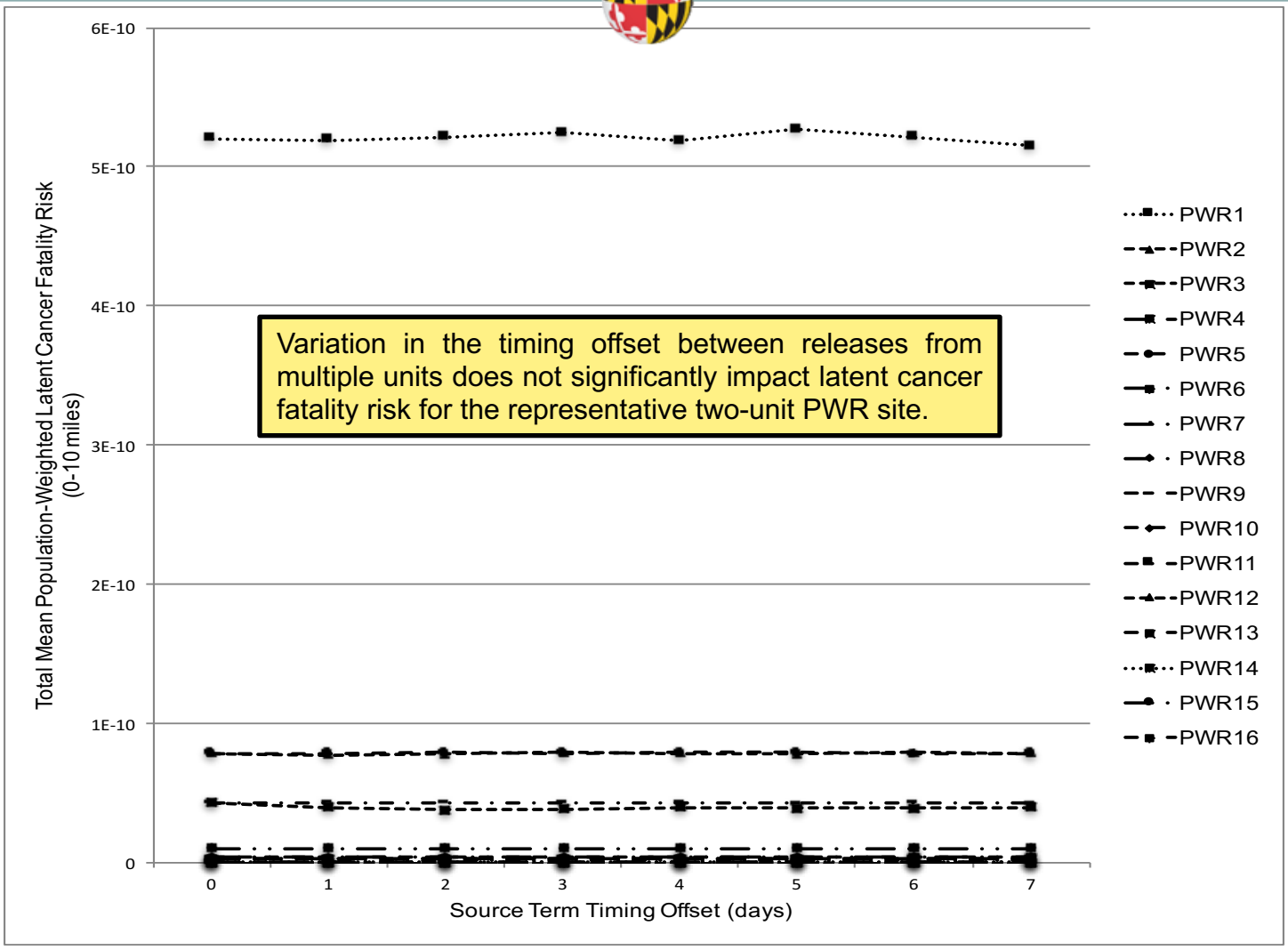
Results III(b): PWR Early Fatality Risk



Results III(c): BWR Latent Cancer Fatality Risk



Results III(d): PWR Latent Cancer Fatality Risk



CONCLUSIONS AND RECOMMENDATIONS

Conclusions I: Base Case Analysis

- Including the contribution from multi-unit accidents results in non-negligible increases in safety goal QHO risk metrics and non-negligible reductions in QHO margin.
- The magnitude of the effect depends on the safety goal QHO risk metric under consideration and reactor-containment design.
  - There were greater differences between the BWR and PWR designs with respect to early fatality risk than for latent cancer fatality risk.
  - Differences appear to be due to differences in the site-specific relative contributions of single-unit vs. multi-unit accidents to total early fatality risk.

Conclusions II: One-Way Sensitivity Analyses

- Variation of assumed inter-unit dependence with base case assumption of simultaneous releases reinforced conclusions from base case analysis.

- One additional conclusion was drawn:
  - Percent change in risk is more sensitive to assumptions about inter-unit dependence than percent change in QHO margin.
  - Several orders of magnitude in margin to both QHOs exist even for worst-case assumption of complete dependence.

Including the contribution from multi-unit accidents to safety goal QHO metrics may result in non-negligible changes in risk estimates, but may not result in different conclusions from safety goal evaluations.

Conclusions III: One-Way Sensitivity Analyses

- Variation of the timing offset between concurrent releases from co-located units with base case inter-unit dependence reinforced conclusions from base case analysis.

- Two additional conclusions from scenario-specific analyses:
  - Early fatality risk is more sensitive to assumptions about differences in timing for multi-unit accident scenarios in which the co-located unit experiences a more rapidly progressing accident.
  - Increasing the delay between concurrent accidents may cause latent cancer fatality risk to increase for some classes of scenarios.

There may be synergistic effects between the assumed timing offset between concurrent accident scenarios and other factors that influence offsite radiological consequences (e.g., statistical variability in weather conditions and protective actions taken to reduce radiological dose).

Recommendations

- Apply methods to additional reactor-containment designs and/or NPP sites.
- Benchmark methods and evaluate key assumptions using results from NPP Level 3 PRAs.
- Evaluate effect of including contributions from multi-unit accident scenarios to additional risk metrics.
  - Societal radiological risk
  - Numbers of people impacted by various protective actions
  - Land areas contaminated with various levels of radioactivity
  - Economic costs

Acronyms and Abbreviations

BWR	boiling-water reactor
ISLOCA	interfacing systems loss-of-coolant accident
LTSBO	long-term station blackout
MACCS	MELCOR Accident Consequence Code System
MELCOR	Methods for Estimation of Leakages and Consequences Of Releases
MELMACCS	MELCOR-MACCS software interface utility
NPP	nuclear power plant
PRA	probabilistic risk analysis
PWR	pressurized-water reactor
QHO	quantitative health objective
RCIC	Reactor Core Isolation Cooling System
SOARCA	State-Of-the-Art Reactor Consequence Analyses
STSBO	short-term station blackout
TISGTR	thermally-induced steam generator tube rupture
USNRC	U.S. Nuclear Regulatory Commission

References

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SUPPORTING INFORMATION

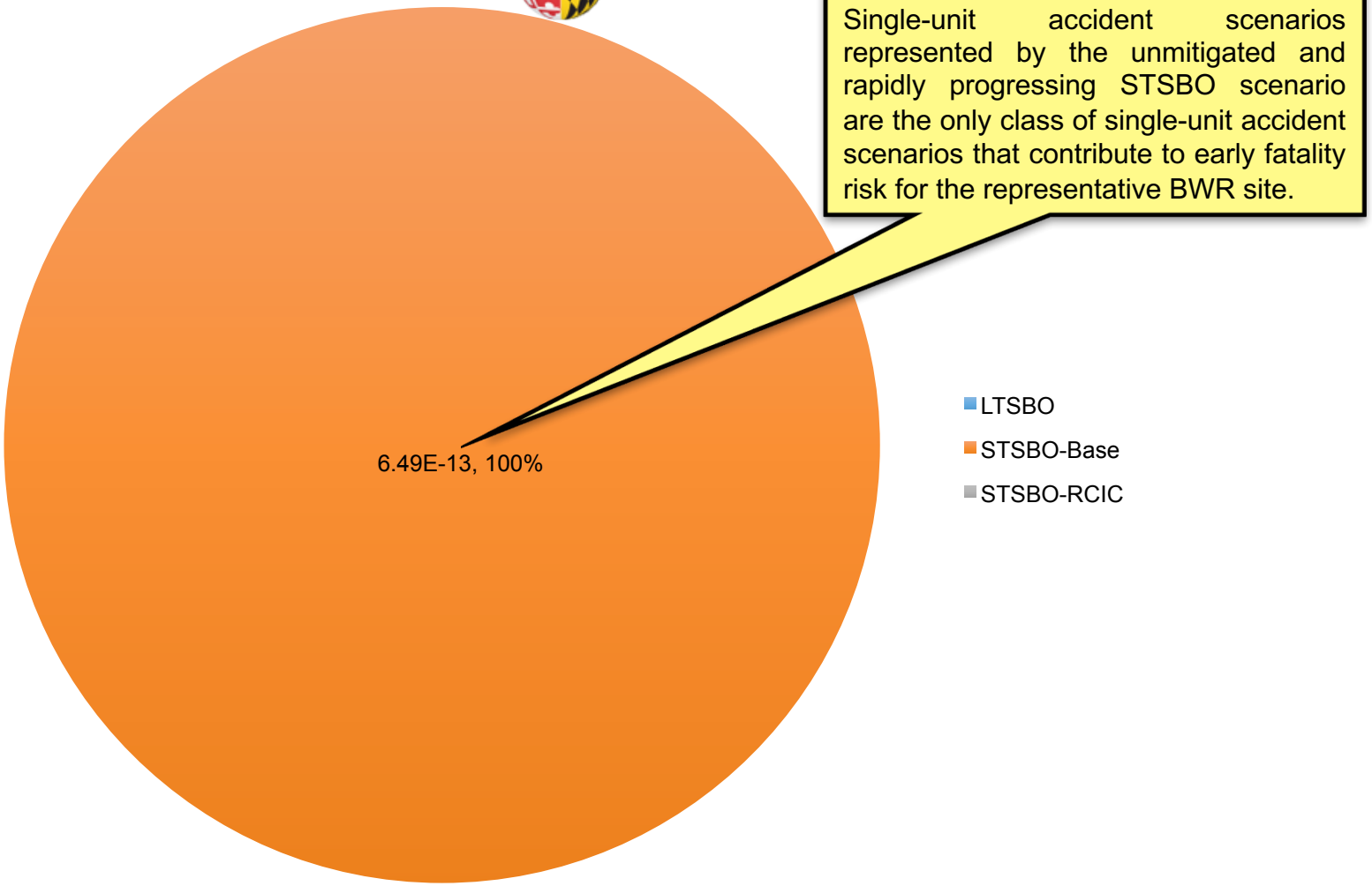
BASE CASE ANALYSIS RISK PROFILES

EARLY FATALITY RISK QHO

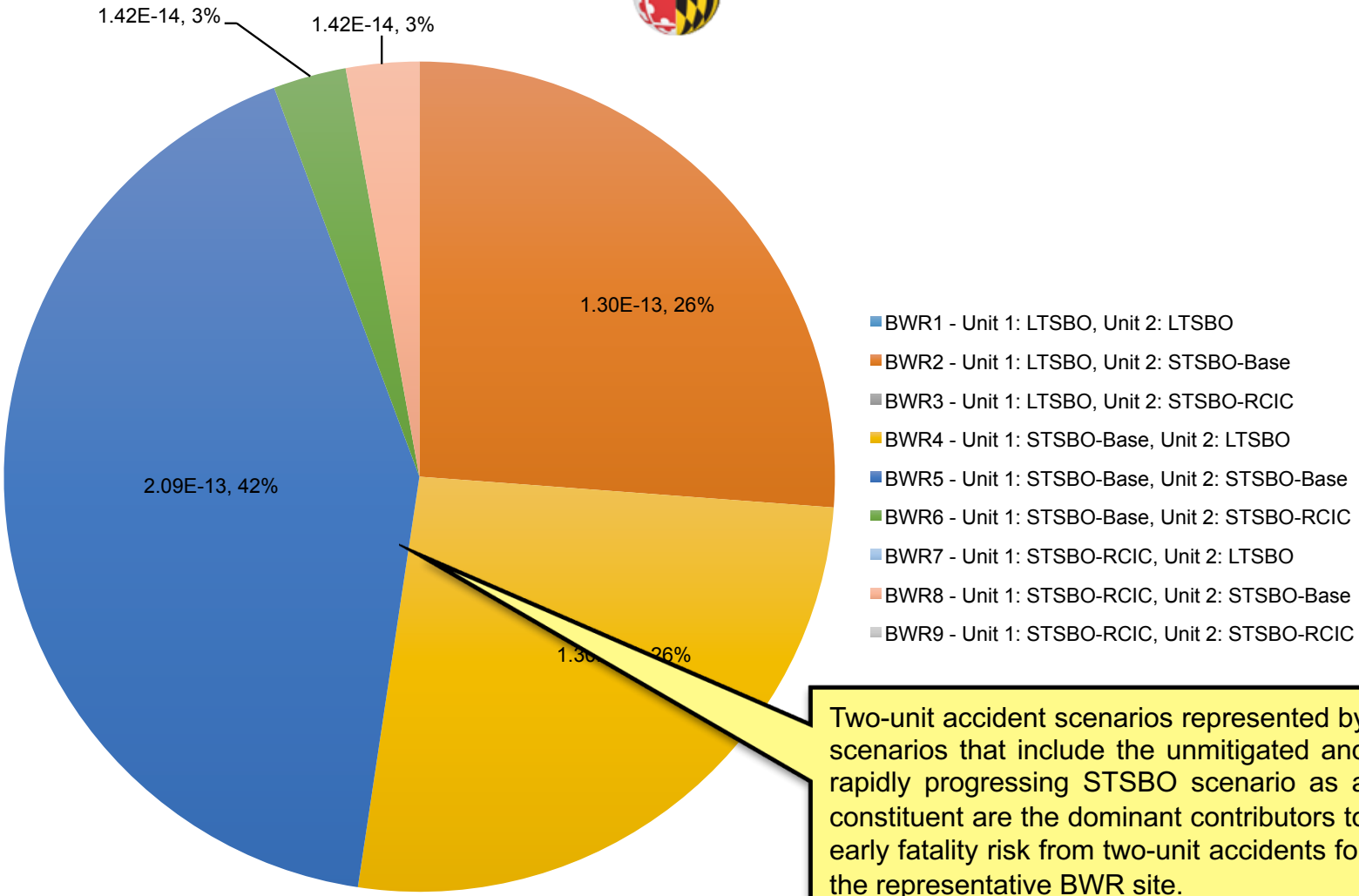
Conditions:

- Assumed $\beta = 0.1$.
- Assumed *SOURCE TIME OFFSET = 0*.

Risk Profile: BWR Single-Unit Accidents

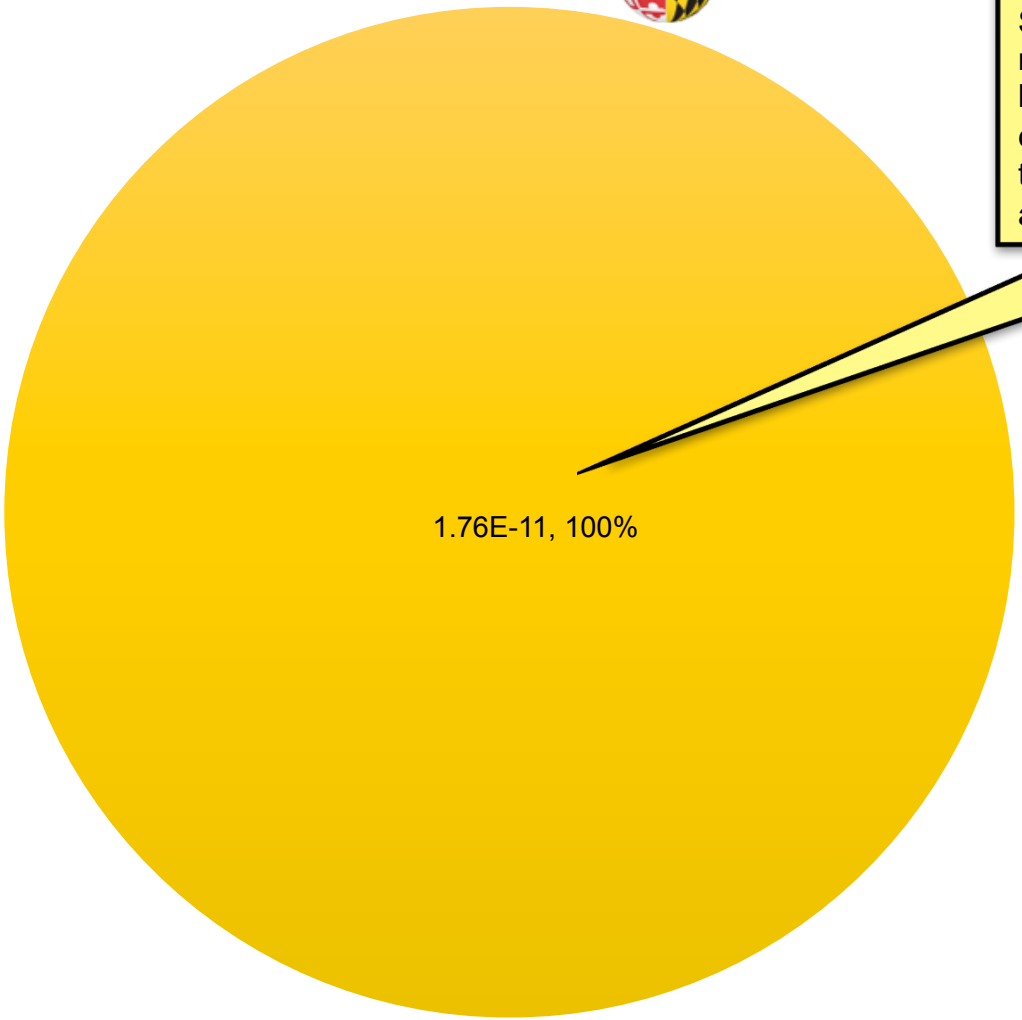


Risk Profile: BWR Two-Unit Accidents



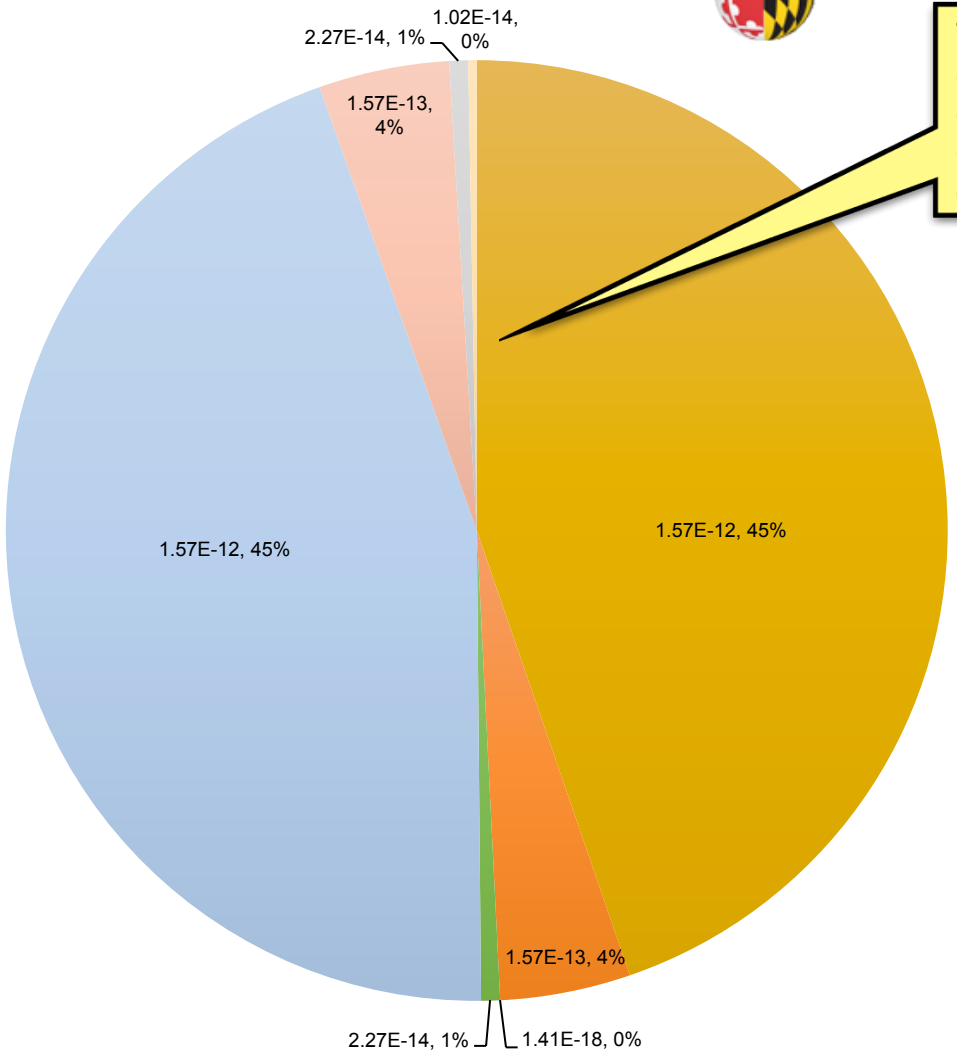
Two-unit accident scenarios represented by scenarios that include the unmitigated and rapidly progressing STSBO scenario as a constituent are the dominant contributors to early fatality risk from two-unit accidents for the representative BWR site.

Risk Profile: PWR Single-Unit Accidents



Single-unit accident scenarios represented by the containment bypass ISLOCA scenario are the only class of single-unit accident scenarios that contribute to early fatality risk for a representative two-unit PWR site.

Risk Profile: PWR Two-Unit Accidents



Two-unit accident scenarios represented by scenarios that include a containment bypass scenario as a constituent are the dominant contributors to early fatality risk from two-unit accidents for the representative PWR site.

- PWR1 - Unit 1 LTSBO, Unit 2: LTSBO
- PWR2 - Unit 1: LTSBO, Unit 2: STSBO-Base
- PWR3 - Unit 1: LTSBO, Unit 2: STSBO-TISGTR
- PWR4 - Unit 1: LTSBO, Unit 2: ISLOCA
- PWR5 - Unit 1: STSBO-Base, Unit 2: LTSBO
- PWR6 - Unit 1: STSBO-Base, Unit 2: STSBO-Base
- PWR7 - Unit 1: STSBO-Base, Unit 2: STSBO-TISGTR
- PWR8 - Unit 1: STSBO-Base, Unit 2: ISLOCA
- PWR9 - Unit 1: STSBO-TISGTR, Unit 2: LTSBO
- PWR10 - Unit 1: STSBO-TISGTR, Unit 2: STSBO-Base
- PWR11 - Unit 1: STSBO-TISGTR, Unit 2: STSBO-TISGTR
- PWR12 - Unit 1: STSBO-TISGTR, Unit 2: ISLOCA
- PWR13 - Unit 1: ISLOCA, Unit 2: LTSBO
- PWR14 - Unit 1: ISLOCA, Unit 2: STSBO-Base
- PWR15 - Unit 1: ISLOCA, Unit 2: STSBO-TISGTR
- PWR16 - Unit 1: ISLOCA, Unit 2: ISLOCA

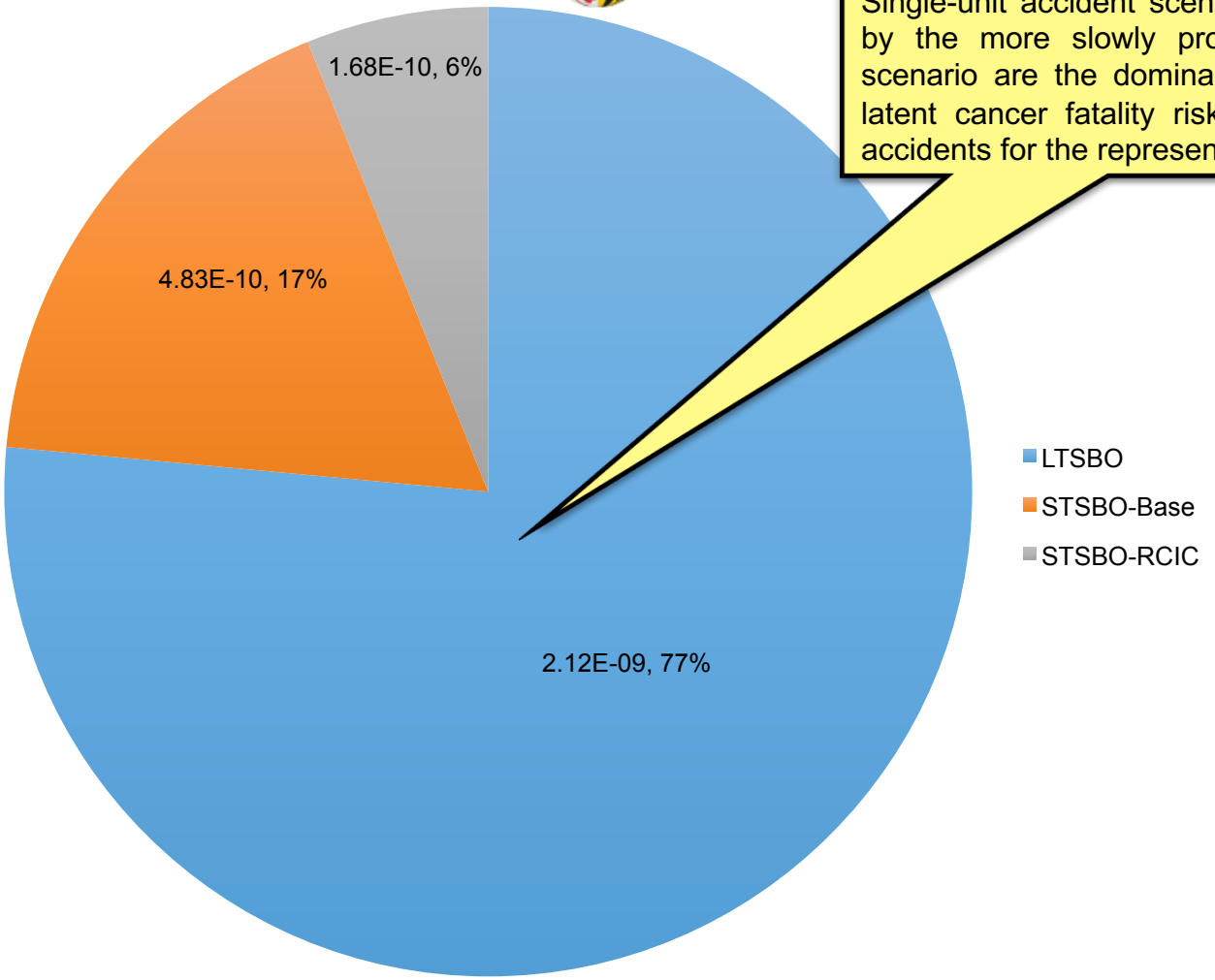
BASE CASE ANALYSIS RISK PROFILES

LATENT CANCER FATALITY RISK QHO

Conditions:

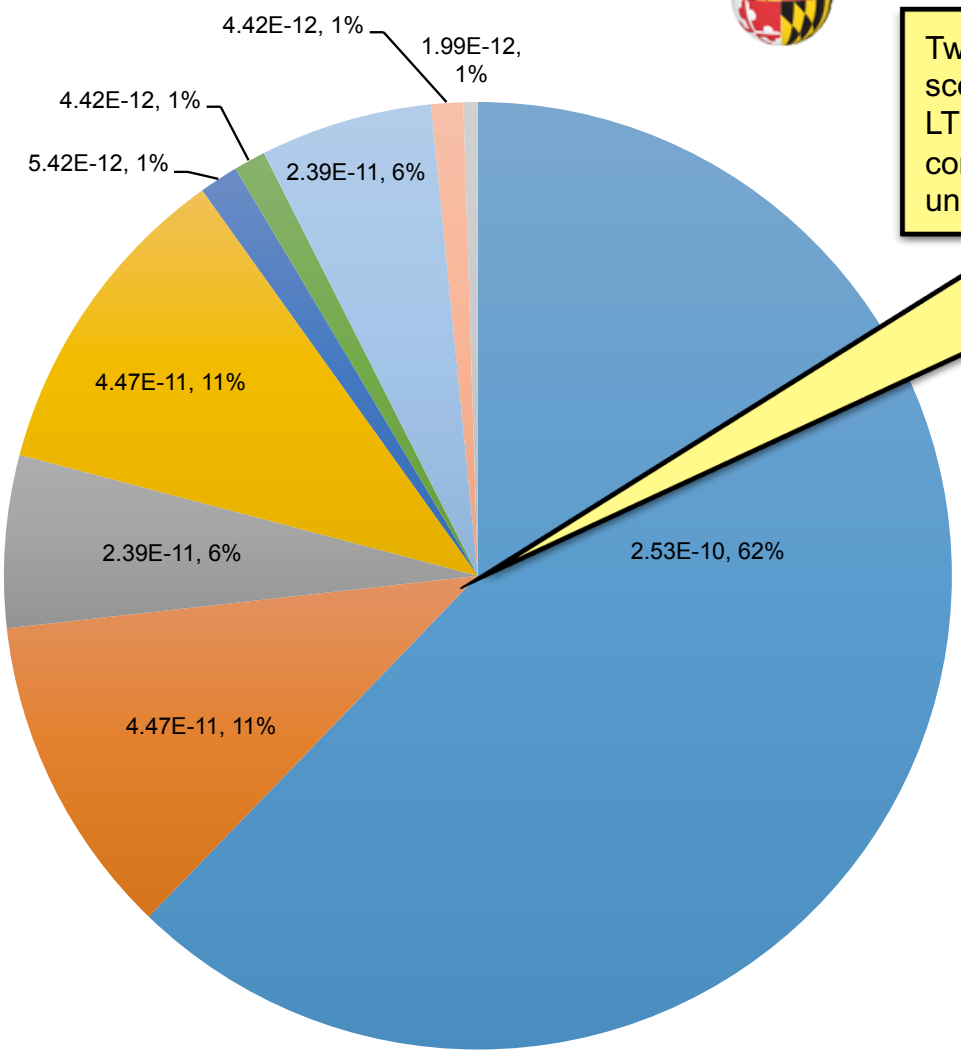
- Assumed $\beta = 0.1$.
- Assumed *SOURCE TIME OFFSET = 0*.

Risk Profile: BWR Single-Unit Accidents



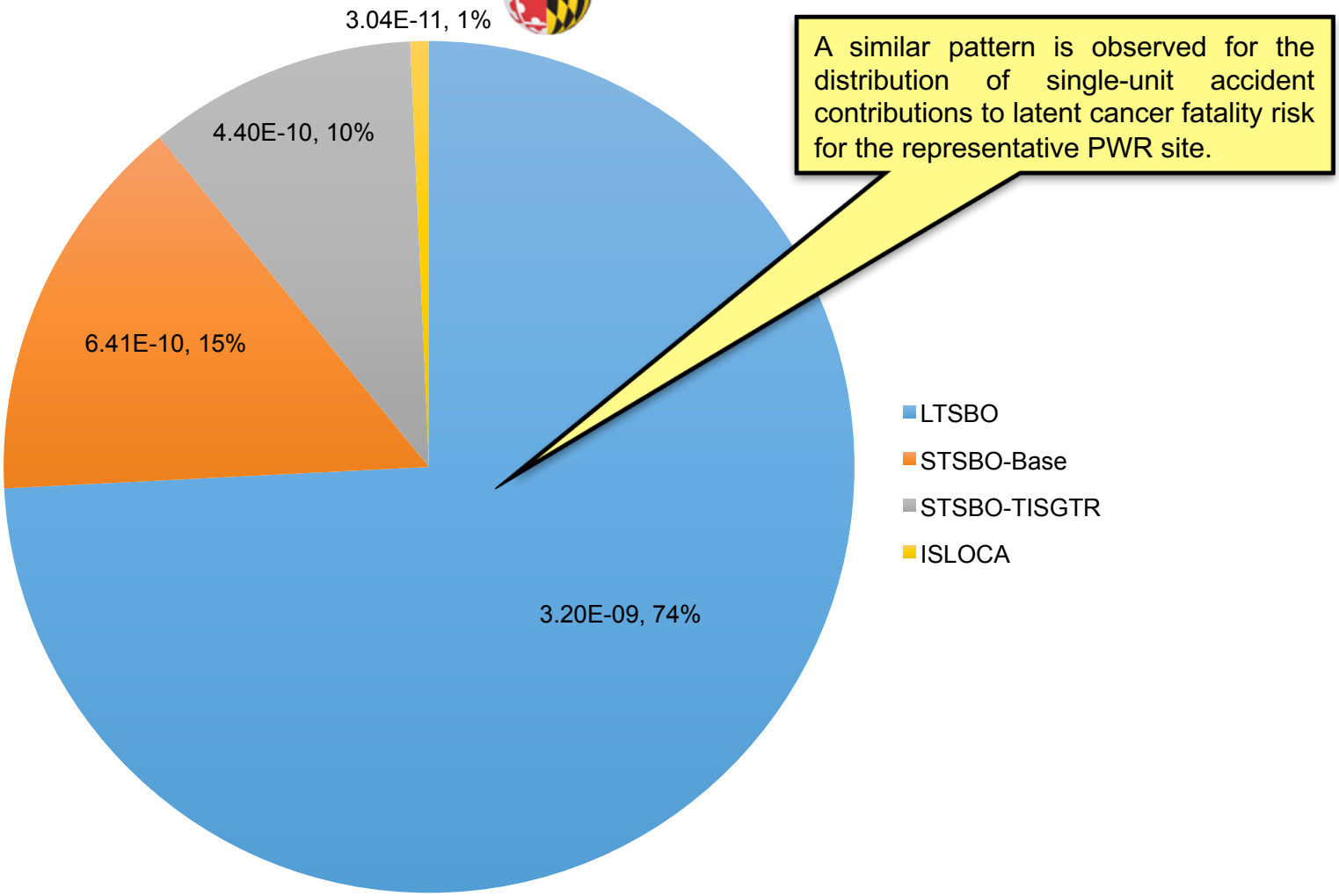
Single-unit accident scenarios represented by the more slowly progressing LTSBO scenario are the dominant contributors to latent cancer fatality risk from single-unit accidents for the representative BWR site.

Risk Profile: BWR Two-Unit Accidents



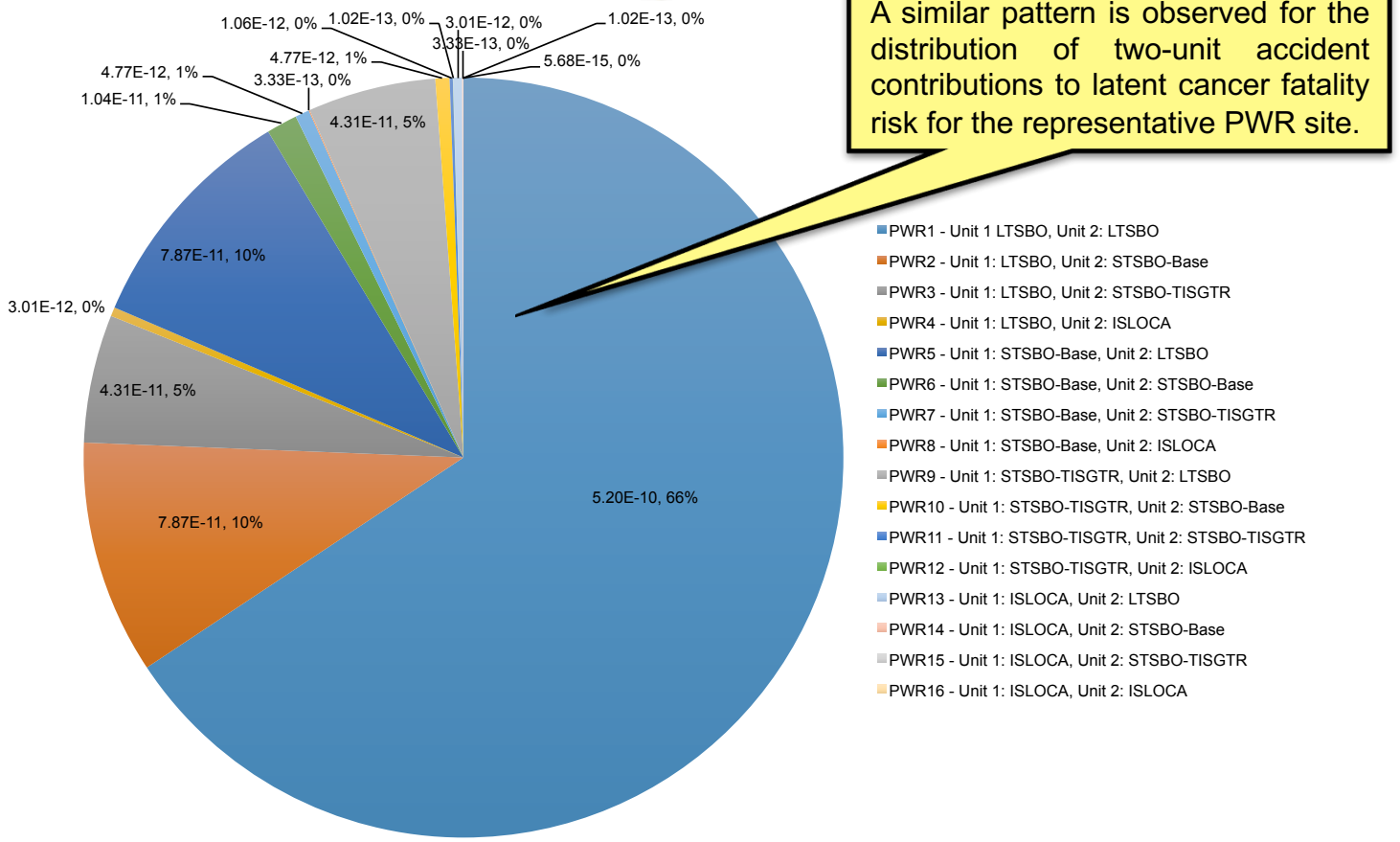
Two-unit accident scenarios represented by scenarios that include a more slowly progressing LTSBO scenario as a constituent are the dominant contributors to latent cancer fatality risk from two-unit accidents for the representative PWR site.

Risk Profile: PWR Single-Unit Accidents



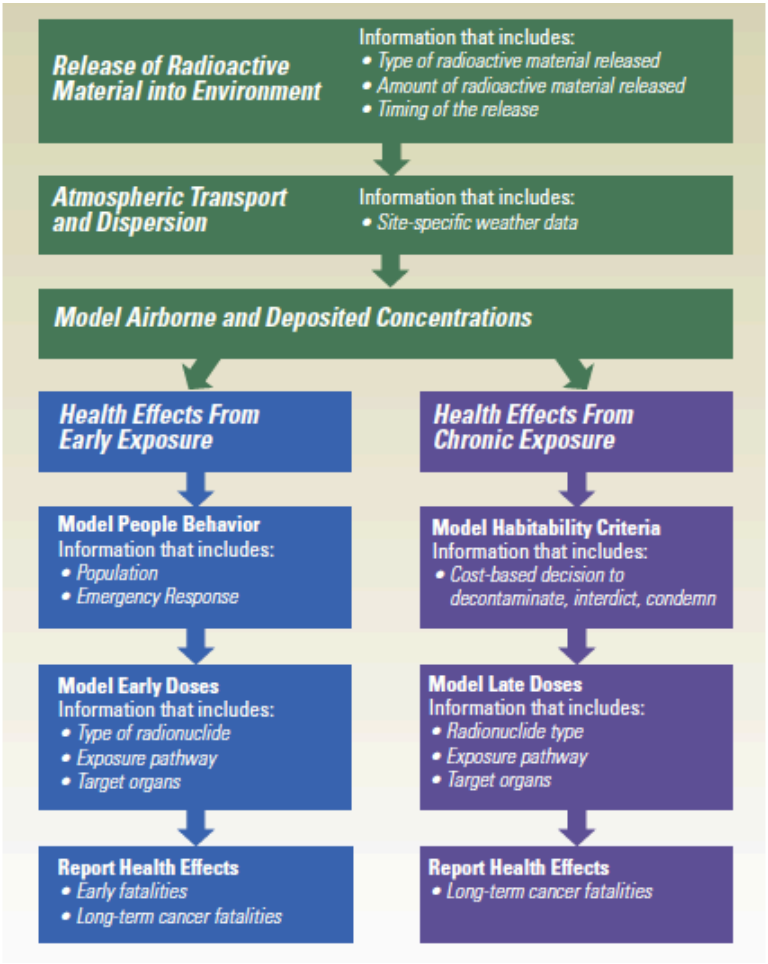
A similar pattern is observed for the distribution of single-unit accident contributions to latent cancer fatality risk for the representative PWR site.

Risk Profile: PWR Two-Unit Accidents



A similar pattern is observed for the distribution of two-unit accident contributions to latent cancer fatality risk for the representative PWR site.

SOARCA Consequence Analysis Process



Source: Figure reproduced from Reference 11 (NUREG/BR-0359, “Modeling Potential Reactor Accident Consequences”).

SOARCA Evacuation Cohorts

Evacuation Cohorts	
Schools	School populations within 10 miles of the site
General Public	People within 10 miles of the site who evacuate in response to the evacuation order
Special Facilities	Special-needs population, including residents of hospitals, nursing homes, assisted living communities, and prisons within 10 miles of the site
Nonevacuating Public	A portion of the public within 10 miles of the site who refuse to evacuate (assumed to be 0.5 percent of the population)
Shadow	Shadow evacuation occurs when members of the public evacuate from areas that are not under official evacuation orders, typically beginning when a large- scale evacuation is ordered
Tail	The last 10 percent of the public to evacuate from the 10-mile EPZ

Source: Figure adapted from Reference 11 (NUREG/BR-0359, “Modeling Potential Reactor Accident Consequences”).

SOARCA Accident Scenario Timing & Releases

Accident Progression Timing and Radiological Release Quantities				
	From the initiating event, about how long until radioactive material is released to the environment?		**About how much of the available radioactive material (Iodine-131 and Cesium-137) is released during the first 48 hours?**	
	Mitigated Case	Unmitigated	Mitigated Case	Unmitigated
Peach Bottom Long-Term Station Blackout	no release	20 hours	no release	Iodine: 2% Cesium: <1%
Peach Bottom Short-Term Station Blackout	no release	8 hours	no release	Iodine: 12% Cesium: 2%
Surry Long-Term Station Blackout	no release	45 hours	no release	Iodine: <1% Cesium: <1%
Surry Short-Term Station Blackout	no release modeled in MACCS2	25 hours	no release within 48 hours*	Iodine: 1% Cesium: <1%
Surry Thermally Induced Steam Generator Tube Rupture	3.5 hours	3.5 hours	Iodine: <1% Cesium: <1%	Iodine: 1% Cesium: <1%
Surry Interfacing Systems Loss–of-Coolant Accident	no release	13 hours	no release	Iodine: 16% Cesium: 2%

Source: Figure adapted from Reference 11 (NUREG/BR-0359, “Modeling Potential Reactor Accident Consequences”).

MACCS Multi-Source Model Parameters

Parameter	Description	Parameter Range		Units	Treatment
		Lower Limit	Upper Limit		
TOTREL	Defines number of plume segments released over all files specified for multi-source model.	2	500	N/A	Maintained number of plume segments defined in each of the SOARCA study source term files. Multi-source calculates TOTREL by summing the number of plume segments defined in each source term input file.
MS_LABELS	MelMACCS file name for source term input files.	1-255 characters		N/A	Defined when multi-source term file set specified in MACCS file specifications.
PLUME_DLY	Start time of plume release relative to MELCOR time frame.	0	2592000	seconds	Maintained plume delay timing defined each of the SOARCA study source term files.
NUM_SOURCES	Number of source term files specified. Defined when user specifies multi-source term file set.	2	500	N/A	Defined when multi-source term file set is specified in MACCS file specifications. Since both Peach Bottom and Surry are two-unit sites, this study was limited to modeling and analyzing multi-source accident scenarios involving exactly two source terms. (NUM_SOURCES=2)
SOURCE TIME OFFSET	Timing offset for each specified source term file.	0	2592000	seconds	Time offset for first source term file was set to 0 to coincide with modeled reference unit accident initiation. Time offset for co-located unit source term file was set to 0 for the base case assumption of simultaneous accident scenarios and varied from 1 to 7 days in one-day increments for sensitivity analyses to evaluate effects of variation in timing offet for concurrent accident scenarios.