EFFICIENT RISK ANALYSIS OF MULTI-UNIT ACCIDENT EFFECTS ON PUBLIC HEALTH AND SAFETY USING MODELS FROM THE STATE-OF-THE-ART REACTOR CONSEQUENCE ANALYSES (SOARCA) PROJECT

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USNRC SAFETY GOAL POLICY

How Safe is Safe Enough?

- USNRC safety goal policy broadly defines an acceptable level of radiological risk to public health and safety from commercial nuclear power plant (NPP) operations.
- In practice, it guides agency screening evaluations of proposed regulatory actions that would impose additional requirements beyond those needed to ensure public is adequately protected.
- Potentially cost-beneficial actions can be rejected if:
  - ➢ Safety benefits are not substantial enough.
  - ➢ Level of remaining risk deemed acceptable.

USNRC SAFETY GOAL POLICY STATEMENT

QUALITATIVE SAFETY GOALS

Individual Risk

Individuals bear no significant additional risk to life and health

Societal Risk

Comparable to or less than risks of generating electricity by viable competing technologies

QUANTITATIVE HEALTH OBJECTIVES (QHOs)

Individual Early Fatality Risk
(0-1.6 km [1 mi])
≤ 0.1% sum from other accidents

Individual Latent Cancer Fatality Risk
(0-16.1 km [10 mi])
≤ 0.1% sum from all other causes of cancer

USNRC Safety Goal Policy QHOs

- ➢ Measure attainment of corresponding high-level qualitative safety goals.
- ➢ Represent benchmarks or aiming points, not strict criteria.
- ➢ Designed for comparison against mean values from NPP probabilistic risk assessment (PRA) studies.

PROBLEM STATEMENT

Multi-Unit Accidents

- Safety goals and QHOs are applied to individual reactor units.
- Nearly 75% of operating reactors in the U.S. are located at sites with two or more units.
- Multi-unit accidents are not considered.

QHO Limitations

- Limited to measures of average individual risk of dying from accidental radiation exposure.
  - Do not address dominant public health risks from nuclear accidents.
  - Do not account for tradeoffs between radiological and non-radiological risks.
  - Are not able to detect different levels of accident severity.

Bottom Line

- Accident scenarios like the one that occurred at Fukushima in 2011— which resulted in no early fatalities and relatively insignificant increases in cancer fatality risk relative to the background cancer risk—contribute little to the QHO-based risk metrics used to evaluate proposed regulatory actions that aim to further enhance NPP safety.
- The level of remaining risk when adequate protection has been achieved and the potential safety benefits from proposed regulatory actions that aim to reduce the contribution to public risk from such scenarios may thus be UNDERESTIMATED or INCOMPLETELY CHARACTERIZED.
- Proposed safety enhancements may thus be prematurely rejected before performing detailed cost-benefit analyses to estimate their net benefit to society.

RESEARCH AIMS

Overall Aim

- To evaluate effects of expanding the scope and application of the safety goal policy to include:
  - Multi-unit accidents.
  - A broader set of public health risk metrics that go beyond measures of average individual radiological health risk.

Specific Aims

- *Aim 1: Base Case Analysis*
  - Evaluate effect of including multi-unit accident contributions under two key assumptions:
    1. Level of dependence between co-located reactor units (inter-unit dependence) assumed to be 10%.
    2. Concurrent accident scenarios in co-located units assumed to occur simultaneously.
- *Aims 2 and 3: Sensitivity Analyses*
  - Aim 2: Evaluate effect of variation in assumed inter-unit dependence.
  - Aim 3: Evaluate effect of variation in assumed timing offset between concurrent accident scenarios.

SELECTED RISK METRICS

Risk Perspective	Selected Risk Metric	Spatial Interval
Individual Radiological Health (for comparison to existing QHOs)	Average Individual Early Fatality Risk	0-1 mile [a]
	Average Individual Latent Cancer Fatality Risk	0-10 miles [a]
Societal Radiological Health	Total Number of Early Fatality Cases	0-50 miles [b]
	Total Number of Latent Cancer Fatality Cases	0-50 miles [b]
Societal Non-Radiological Health	Total Population Relocated During Emergency Phase [c]	0-50 miles [b]
	Total Population Relocated During Late (Recovery) Phase [c]	0-50 miles [b]

[a] The 0-1 mile and 0-10 miles spatial intervals were selected for average individual health risk metrics to be consistent with the region defined for each QHO specified in the USNRC safety goal policy statement.

[b] The 0-50 miles spatial interval was selected for societal health risk metrics to be consistent with USNRC guidance for estimating societal impacts as part of regulatory or environmental impact analyses.

[c] The total numbers of people relocated during the emergency and late (recovery) phases of accident response represent indirect, surrogate measures for adverse non-radiological health effects attributed to protective actions taken to avert radiological dose among the affected population.

POLICY ALTERNATIVES AND FIGURE OF MERIT

Policy Alternatives

- *Option 1: Status Quo*
  - Only single-unit accident contributions included in estimating mean values for selected risk metrics.
- *Option 2: Hypothetical Expansion in Scope of Safety Goal Policy*
  - Contributions from both single-unit and multi-unit accidents included in estimating mean values for selected risk metrics.

Figure of Merit (FOM)

- *Selected FOM*
  - Relative contribution of multi-unit accident scenarios to total mean value for each selected risk metric calculated under Option 2.
- *Criterion for Evaluation*
  - If $FOM \geq 10\%$, multi-unit accident scenarios represent a *non-negligible* contributor to total mean risk.

STUDY POPULATION

Peach Bottom Atomic Power Station Unit 2 and Unit 3

- Representative of NPP sites using boiling-water reactor (BWR)–Mark I containment design.
- Located 18 miles south of Lancaster, PA.
- Offsite population density within 10 miles of site boundary is below average for US NPP sites.

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 NPP sites using pressurized-water reactor (PWR)–large dry containment design.
- Located 17 miles northwest of Newport News, VA.
- Offsite population density within 10 miles of site boundary is about average for US NPP sites.

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

ACCIDENT SCENARIOS

Single-Unit Accident Scenarios

- Selected from SOARCA pilot study for Peach Bottom and Surry that leveraged decades of research and advanced analytical tools to:
  - Develop state-of-the-art models.
  - Estimate realistic consequences.
- PRA results and expert judgment used to identify important accident scenarios with respect to:
  - Likelihood of resulting in core damage.
  - Potential for causing adverse public health consequences.

Two-Unit Accident Scenarios

- MELCOR Accident Consequence Code System (MACCS) code was enhanced after Fukushima to include multi-source modeling capability.
- Two-unit accident scenarios modeled by combining single-unit accident scenarios and specifying value of timing offset parameter.

NPP Site	Single-Unit Accident Scenarios	Two-Unit Accident Scenarios
Representative BWR	3	9
Representative PWR	4	16
Total	7	25

KEY ASSUMPTIONS

- Single-unit accident scenario models from SOARCA pilot study assumed to be valid.
- Co-located units at each representative NPP site assumed to be identical.
- Modeled accident scenarios assumed to be representative of entire spectrum of possible scenarios with respect to potential consequences.

OVERVIEW OF METHODS

Limitations in Study Design

- Safety goal QHOs were developed for comparison to corresponding risk results from NPP PRAs that consider broad spectrum of possible accident scenarios.
- A limited set of accident scenarios judged to be important were modeled for this study.
  - Mean values of selected risk metrics will likely be *UNDERESTIMATED*.
  - Efficient risk estimation models were developed to compensate for this underestimation.

Efficient Risk Estimation Models

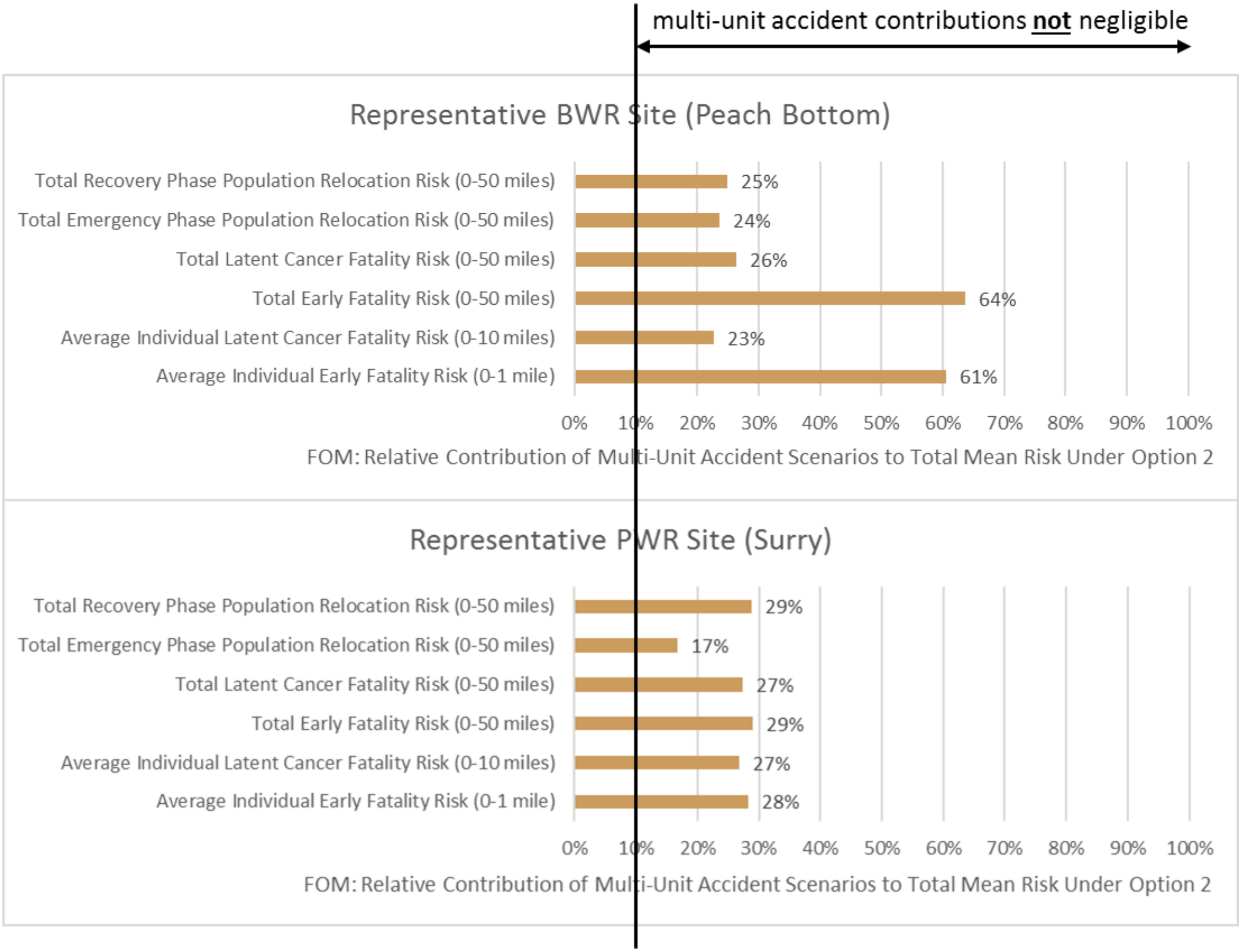
- ***Key Assumption:*** Modeled accident scenarios assumed to be representative of entire spectrum of possible accident scenarios with respect to potential consequences.
- Results from previous NPP PRAs used to calibrate results from this study by accounting for frequency contribution from excluded accident scenarios.
  - *Frequency adjustment factor* used to scale results to produce approximately equivalent NPP PRA results.
  - Approximation avoids having to perform a resource-intensive, complete NPP PRA.

AIM I: BASE CASE ANALYSIS

Findings

- Multi-unit accident scenarios contribute more than 10% to all selected risk metrics.
- Including multi-unit accident scenarios increases risk by non-negligible amount.
- Multi-unit accident scenarios dominate early fatality risk for the representative BWR site.

EFFECT OF INCLUDING MULTI-UNIT ACCIDENT SCENARIO CONTRIBUTIONS FIGURE OF MERIT (FOM)

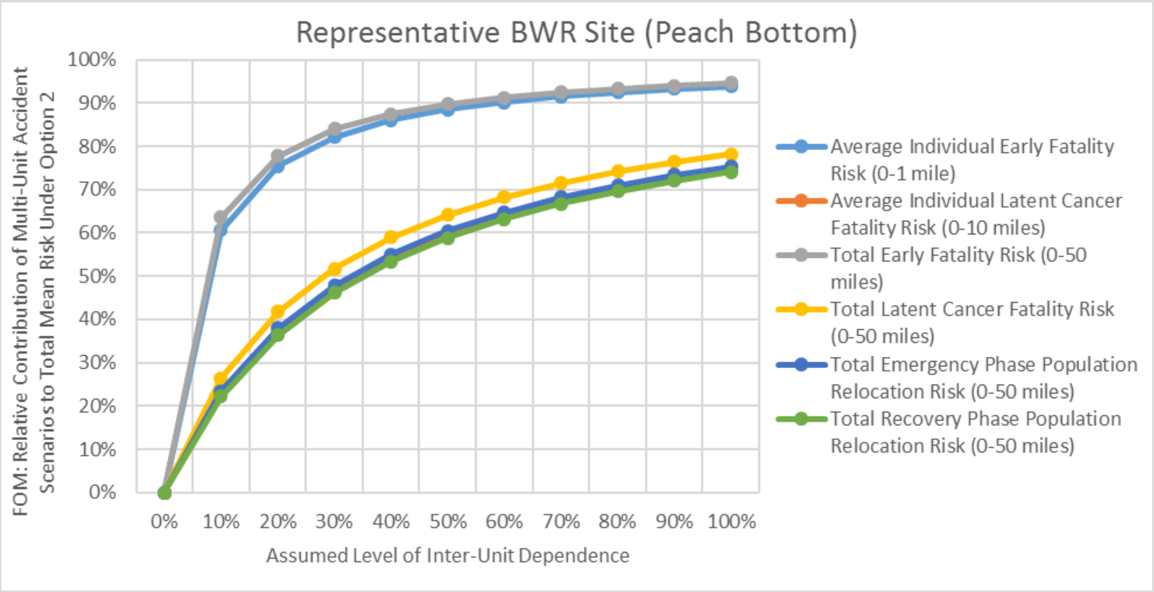


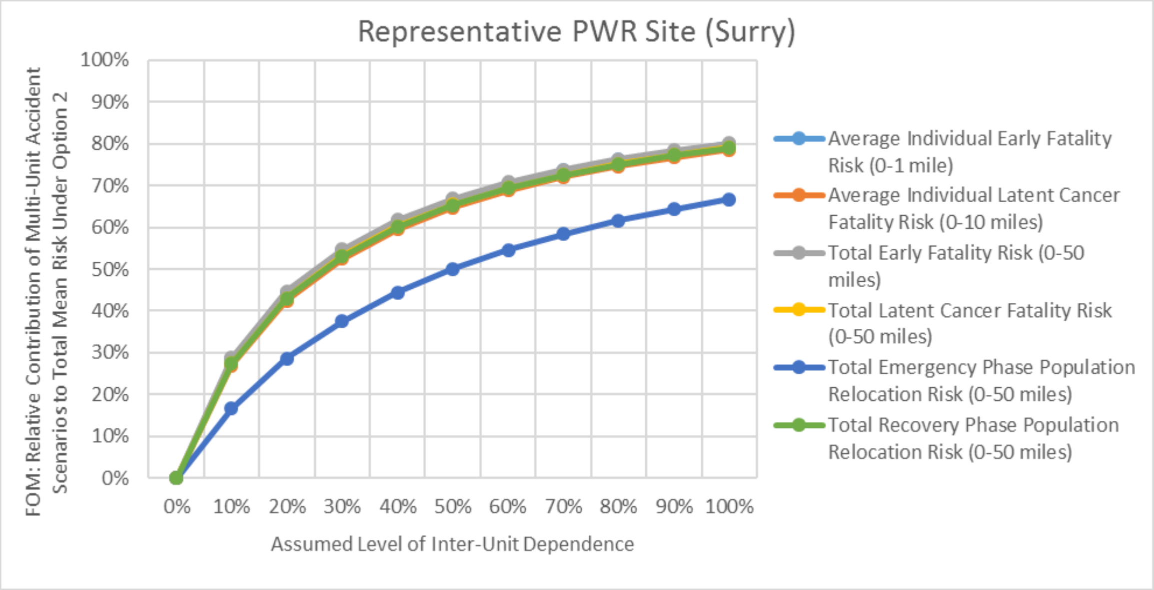
AIM 2: SENSITIVITY ANALYSIS

Findings

- Effect of including multi-unit accident scenarios increases as inter-unit dependence increases.
- Multi-unit accident scenarios dominate risk at higher assumed levels of inter-unit dependence.
- Sufficient margin to each QHO remains for even worst-case of complete inter-unit dependence.

EFFECT OF VARIATION IN ASSUMED LEVEL OF INTER-UNIT DEPENDENCE FIGURE OF MERIT (FOM)



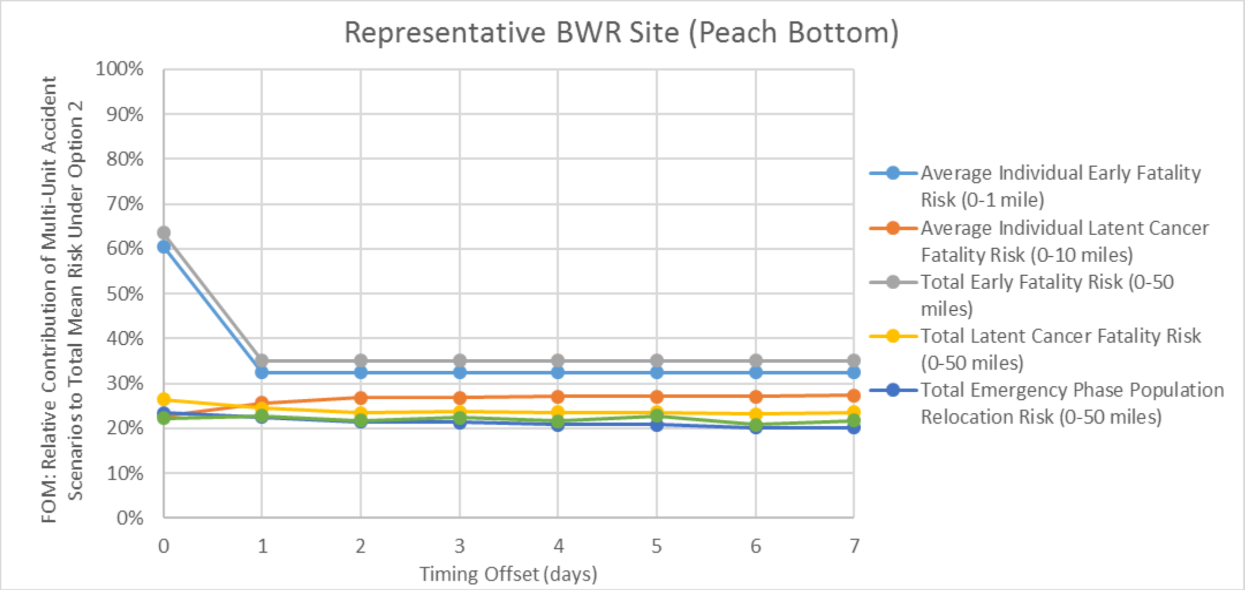


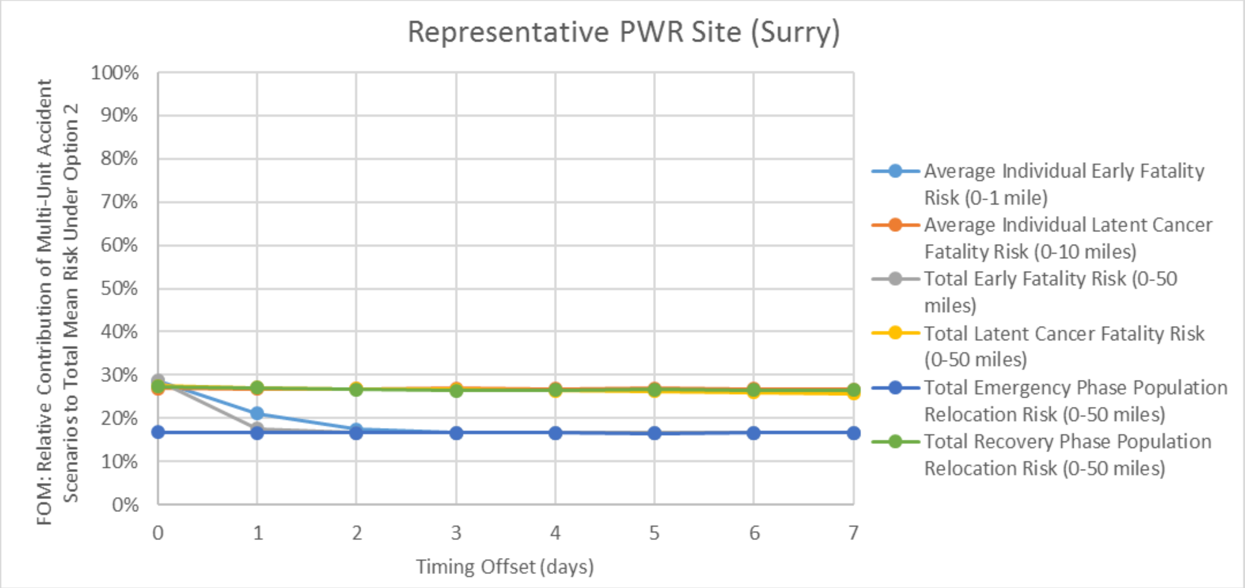
AIM 3: SENSITIVITY ANALYSIS

Findings

- Effect of multi-unit accident scenarios on early fatality risk is sensitive to timing offset.
- Assuming simultaneous multi-unit accident scenarios may not be conservative for all metrics.
- Findings may be due to interaction between timing offset and weather variability.

EFFECT OF VARIATION IN ASSUMED TIMING OFFSET FIGURE OF MERIT (FOM)





KEY CONCLUSIONS

- Including multi-unit accident scenarios increases risk by a non-negligible amount for all selected risk metrics.
  - Multi-unit accident scenarios dominate risk at higher levels of inter-unit dependence.
- Including multi-unit accident scenarios would likely not impact results of USNRC screening evaluations for proposed regulatory actions *using existing QHOs*.
  - Applies even under worst-case assumption of complete inter-unit dependence.
- Relying solely on risk insights for single-unit accident scenarios can lead to flawed risk management strategies for risk metrics that involve threshold effects (e.g., early fatality risk).
- Assuming simultaneous multi-unit accident scenarios may not be conservative for all risk metrics.
- Considering a broader set of public health risk metrics provides a more complete characterization of public risks from potential nuclear accident scenarios.

RECOMMENDATIONS

- Perform benchmarking studies to evaluate methods and key assumptions using results from contemporary full-scope NPP PRA studies.
- Apply methods and models developed for this study to additional reactor-containment designs and/or NPP sites.
- Gauge stakeholder interest in developing societal risk QHOs.
  - If sufficient interest exists, engage stakeholders to develop QHOs for societal risk metrics.
  - Perform follow-on studies to estimate societal risk metrics for comparison against developed QHOs for range of NPP sites.

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SUPPLEMENTARY INFORMATION

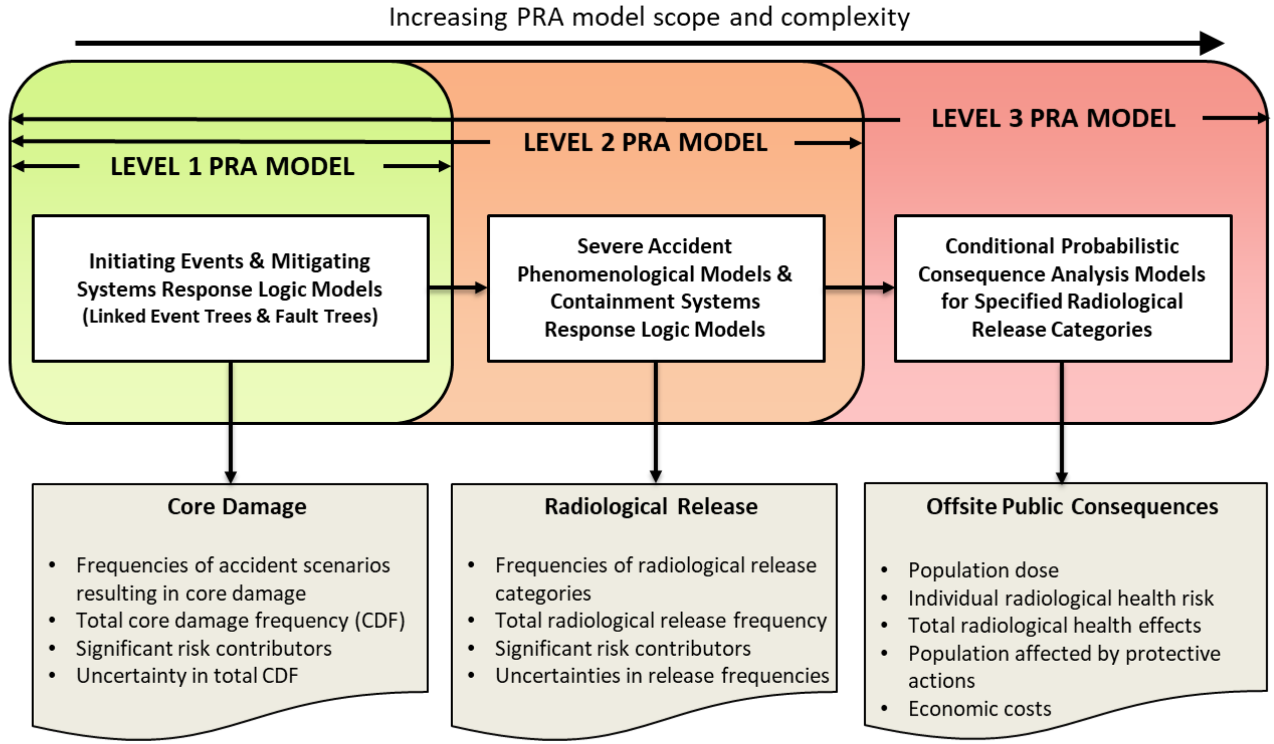
LOGIC AND STRUCTURE OF NPP PRA MODELS

- Subset of risk analysis techniques used to support safety-related decisions involving complex engineered systems.
- Traditional scenario-based approach involves systematic application of methods, models, data, and analytical tools to answer three questions underlying widely accepted quantitative definition of risk:

① What can occur (go wrong)?

② How likely is it to occur?

③ If it does occur, what are the consequences?



Risk Quantitatively Defined as a Set of Risk Triplets

$$R = \{< s_i, l_i, \boldsymbol{c}_i >\} \, \forall_i$$

R = total risk attributed to failure of engineered system.

i = index of accident scenarios (classes of accident scenarios).

s_i = accident scenario i (i^{th} class of accident scenarios).

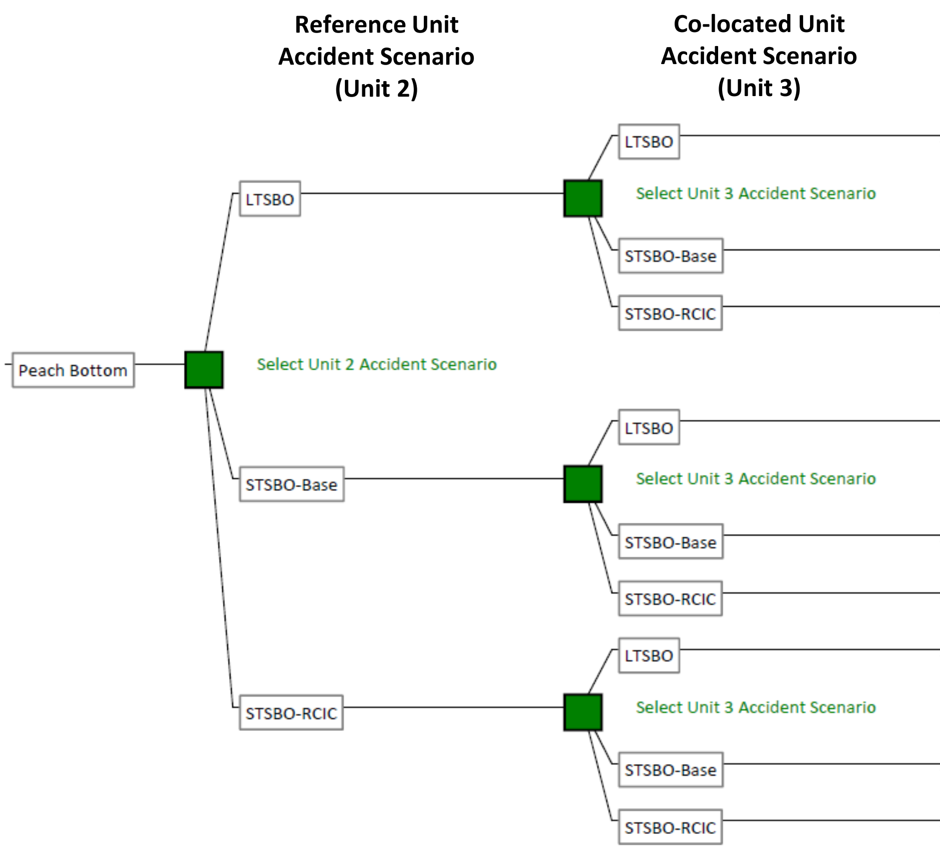
l_i = likelihood (frequency or probability) of accident scenario i.

$\boldsymbol{c}_i$ = vector of conditional consequences, assuming accident scenario i occurs.

SINGLE-UNIT ACCIDENT SCENARIO DESCRIPTIONS

Single-Unit Accident Scenario	Description Used in SOARCA Pilot Studies for Peach Bottom and Surry
Station Blackout (SBO)	NPP safety systems are powered by alternating current (AC) power. This ac power is normally supplied by offsite power sources via the electrical grid, but can be supplied by onsite backup power sources such as emergency diesel generators, if needed. An SBO involves the total loss of AC power that results when both offsite and onsite AC power sources fail. During an SBO, reactor cooling is temporarily provided by systems that do not rely on AC power, such as pumps driven by steam turbines. Onsite batteries can temporarily supply direct current (DC) power to control these turbine-driven pumps and to power instrumentation until battery depletion.
Long-Term Station Blackout (LTSBO)	An earthquake causes a loss of all AC power sources, but onsite batteries are able to supply DC power to safety systems for about 4-8 hours until battery depletion.
Short-Term Station Blackout – Base Case (STSBO-Base)	An earthquake more extreme than the LTSBO scenario earthquake causes a total loss of all AC and DC power sources, immediately rendering safety systems inoperable. As a result, onset of damage to nuclear fuel in the reactor core occurs in the “short-term.” This is the base case STSBO.
Short-Term Station Blackout with Reactor Core Isolation Cooling System Blackstart (STSBO-RCIC)	This scenario is a variation of the STSBO that applies only to BWR NPPs, which include the RCIC system. This scenario was selected for evaluation because the modeled NPP site (Peach Bottom) had explicit procedures for operating the RCIC system using portable electric generators in SBO conditions to provide reactor cooling.
Short-Term Station Blackout with Thermally-Induced Steam Generator Tube Rupture (STSBO-TISGTR)	This scenario is a lower probability variation of the STSBO that applies only to PWR NPPs, which include steam generators for steam production. While the reactor core is overheating and water available for heat transfer in the steam generators is boiling off, extremely hot steam and hydrogen circulating through the steam generator cause a tube to rupture. This creates a pathway for radiological materials to escape from the reactor coolant system to the NPP’s non-radiological systems, and potentially to the environment.
Interfacing Systems Loss-Of-Coolant Accident (ISLOCA)	A random failure of valves ruptures low-pressure system piping outside the containment building that connects with the high-pressure reactor coolant system piping that is inside the containment building. This failure bypasses the defense-in-depth layer of protection provided by the containment building, thereby resulting in a more rapid radiological release to the environment, with greater potential for causing fatalities among the offsite population.

TWO-UNIT ACCIDENT SCENARIOS REPRESENTATIVE BWR SITE (PEACH BOTTOM)



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

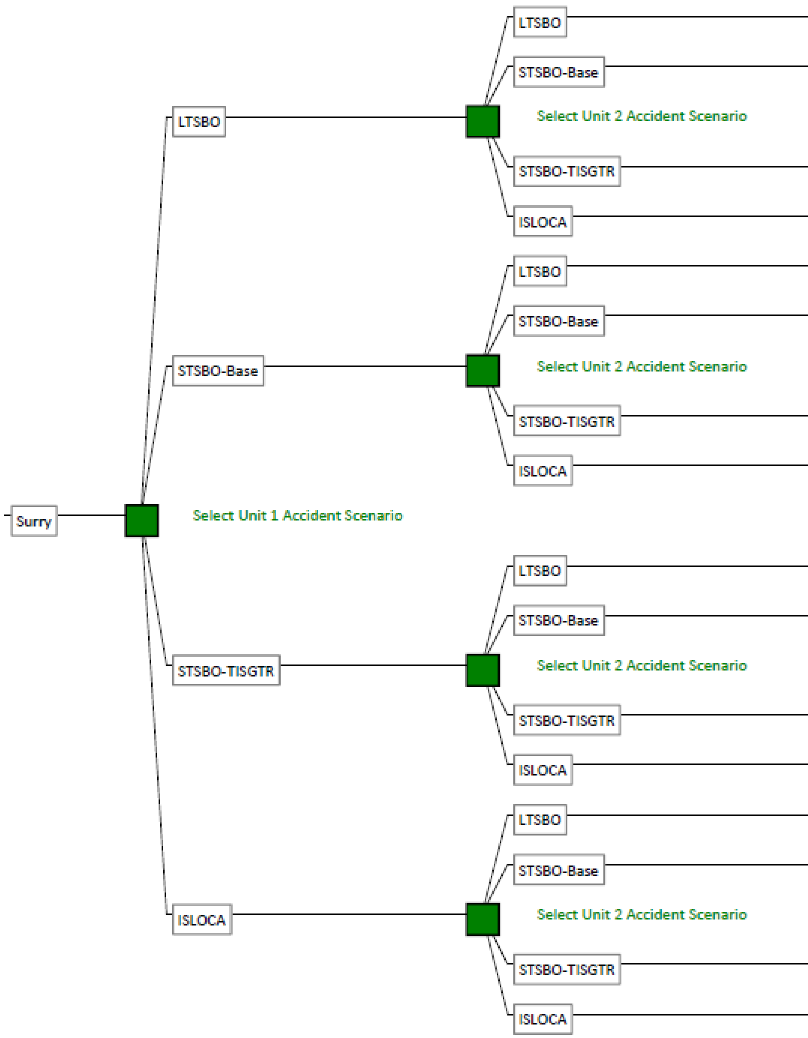
Two-Unit Accident Scenario Identification

Two-unit accident scenarios for both NPP sites were identified using all possible inter-unit permutations of the single-unit accident scenarios that were modeled and analyzed as part of the SOARCA project for each NPP site. Since permutations in which the co-located unit serves as the reference unit and vice versa are possible, the total number of two-unit accident scenarios for each NPP site is actually twice the number illustrated.

TWO-UNIT ACCIDENT SCENARIOS REPRESENTATIVE PWR SITE (SURRY)

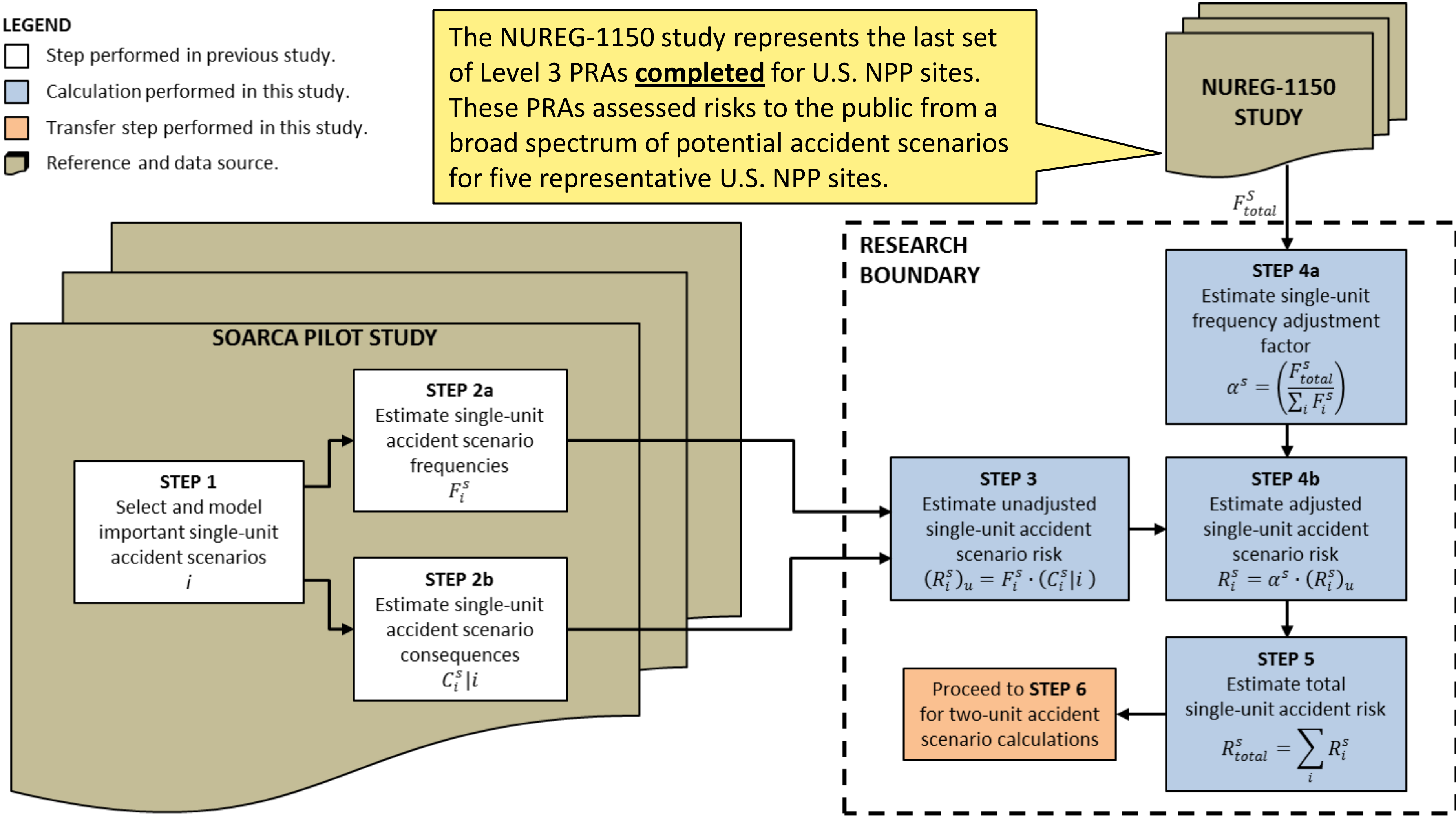
Reference Unit Accident Scenario (Unit 1)

Co-located Unit Accident Scenario (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

SINGLE-UNIT ACCIDENT RISK ESTIMATION



TWO-UNIT ACCIDENT RISK ESTIMATION

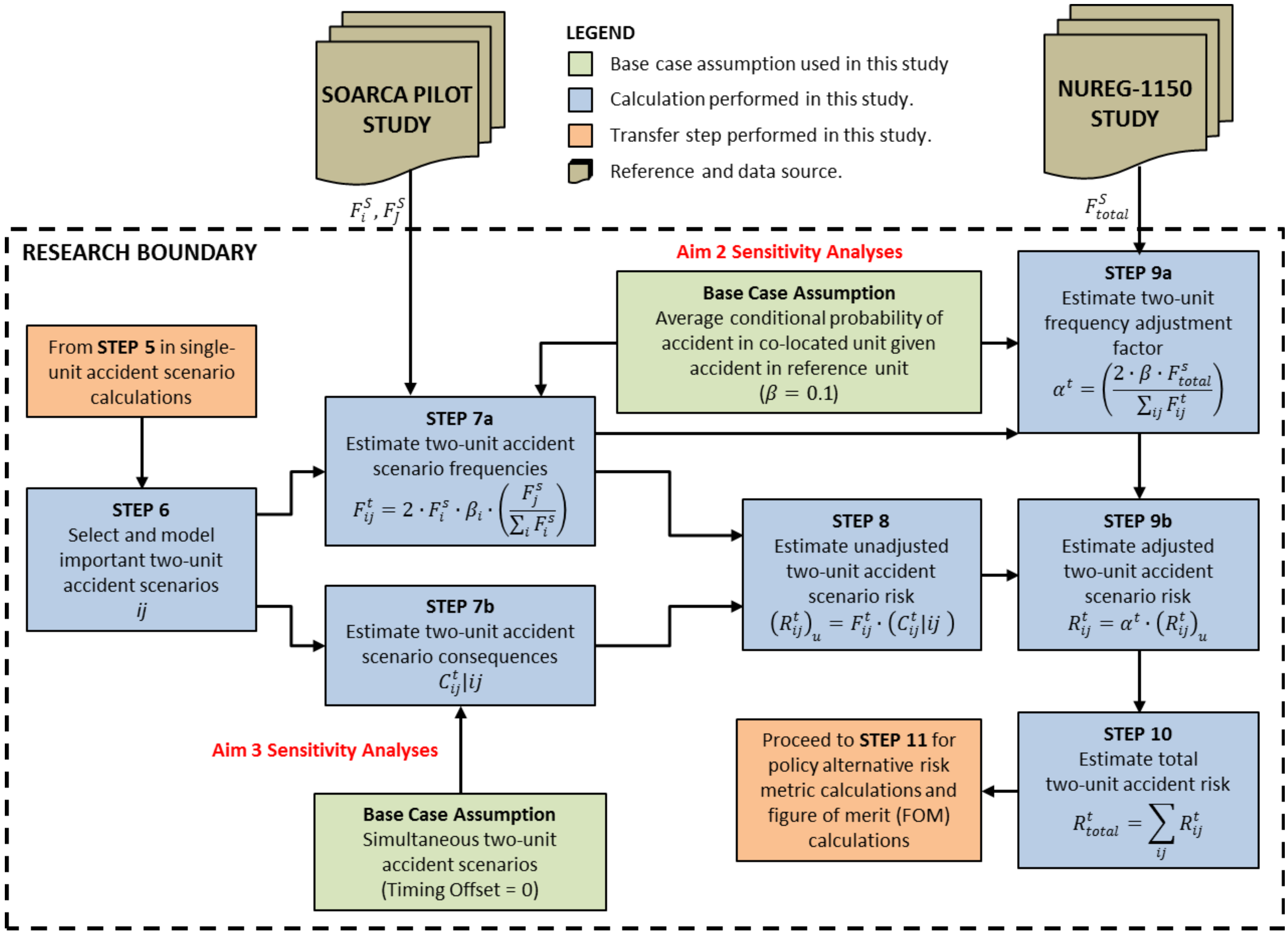
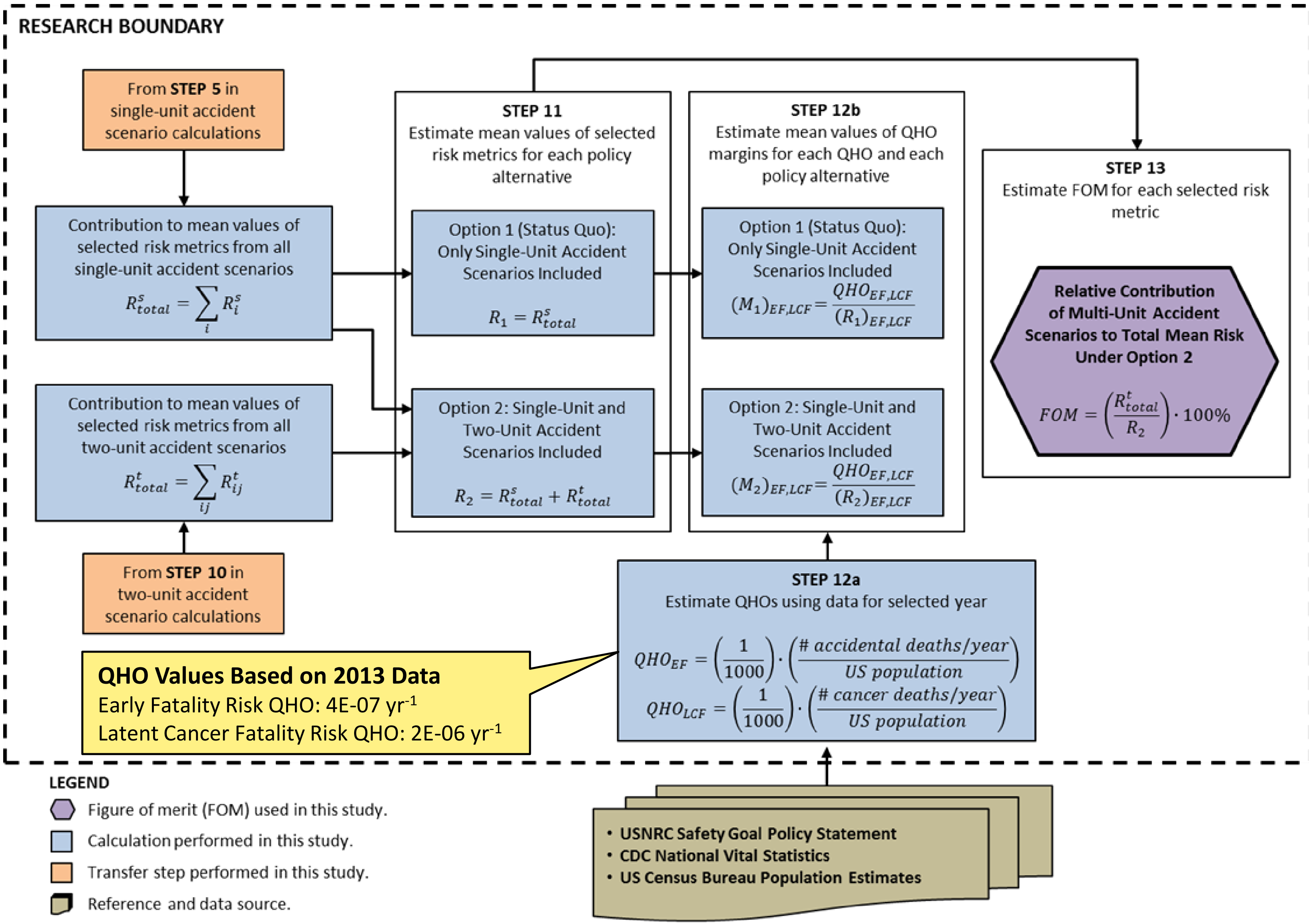


FIGURE OF MERIT AND QHO MARGIN ESTIMATION



ACRONYMS AND ABBREVIATIONS

AC	alternating current
BWR	boiling-water reactor
DC	direct current
FOM	figure of merit
ISLOCA	interfacing systems loss-of-coolant accident
LTSBO	long-term station blackout
MACCS	MELCOR Accident Consequence Code System
MELCOR	severe accident progression analysis computer code (not an acronym)
NPP	nuclear power plant
PRA	probabilistic risk assessment
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

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