Characteristics and Modeling Considerations of Multi-Unit Level 3 PSA

Sung-yeop Kim

sungyeop@kaeri.re.kr

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Korea Atomic Energy Research Institute

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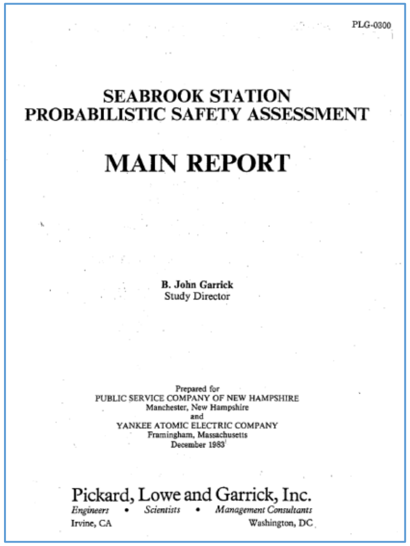
Korea Atomic Energy Research Institute

Existing Studies on Multi-Unit Level 3 PSA

- **Seabrook Station Probabilistic Safety Assessment**, B. J. Garrick, PLG-0300, Pickard, Lowe and Garrick, Inc., December 1983.
- **Multiunit Accident Contributions to Quantitative Health Objectives: A Safety Goal Policy Analysis**, D. W. Hudson and M. Modarres, Nuclear Technology Vol 197, pp. 227-247, March 2017.
- **Development of the Integrated Risk Assessment Technology for Multiple Units**, KAERI/RR-4225/2016, 2017.


PLG-0300

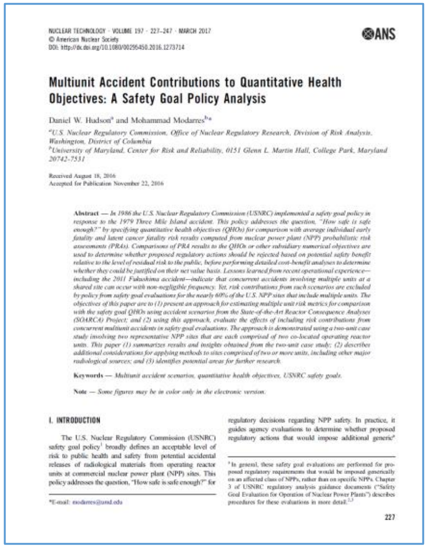
SEABROOK STATION
PROBABILISTIC SAFETY ASSESSMENT

MAIN REPORT

B. John Garrick
Study Director

Prepared for
PUBLIC SERVICE COMPANY OF NEW HAMPSHIRE
Manchester, New Hampshire
and
YANKEE ATOMIC ELECTRIC COMPANY
Framingham, Massachusetts
December 1983

Pickard, Lowe and Garrick, Inc.
Engineers • Scientists • Management Consultants
Irvine, CA Washington, DC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ANS

Multiunit Accident Contributions to Quantitative Health Objectives: A Safety Goal Policy Analysis

Daniel W. Hudson[a] and Mohammad Modarres[b]*
[a]U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, Division of Risk Analysis, Washington, District of Columbia
[b]University of Maryland, Center for Risk and Reliability, 0151 Glenn L. Martin Hall, College Park, Maryland 20742-7531

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Abstract — In 1986 the U.S. Nuclear Regulatory Commission (USNRC) implemented a safety goal policy in response to the 1979 Three Mile Island accident. This policy addresses the question, "How safe is safe enough?" by specifying quantitative health objectives (QHOs) for comparison with average individual early fatality and latent cancer fatality risk results computed from nuclear power plant (NPP) probabilistic risk assessments (PRAs). Comparisons of PRA results to the QHOs or other subsidiary numerical objectives are used to determine whether proposed regulatory actions should be rejected based on potential safety benefit relative to the level of residual risk to the public, before performing detailed cost-benefit analyses to determine ...

I. INTRODUCTION

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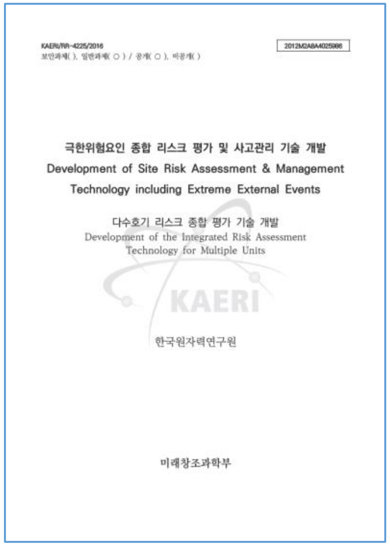

KAERI/RR-4225/2016
보안과제( ), 일반과제(○) / 공개(○), 비공개( )

2012M2A8A4025986

극한위험요인 종합 리스크 평가 및 사고관리 기술 개발
Development of Site Risk Assessment & Management Technology including Extreme External Events

다수호기 리스크 종합 평가 기술 개발
Development of the Integrated Risk Assessment Technology for Multiple Units

KAERI

한국원자력연구원

미래창조과학부

Characteristics of MU Level 3 PSA

- Accident Occurrences at Multiple Units
  - **Different source term** released **from each NPP unit**
  - Exponentially increasing number of multi-unit accident scenarios (combinations) with the number of units on a site:

    when
    n: number of source term categories
    k: number of units comprising a site

    - Number of accident scenarios (General): Power

    $$n^k$$

    - Number of accident scenarios when every accident is assumed to occur at the same place (One point): Combination with repetition

    $$_nH_k = {}_{n+k-1}C_k$$

    - Ex) If 21 STCs can released from 6 units

    $$_{21}H_6 = {}_{21+6-1}C_6 = 230{,}230 \qquad n^k = 21^6 = 85{,}766{,}121$$

Characteristics of MU Level 3 PSA (cont')

- Inclusion of "No Accident" Case

No. of Units Where Accident Happens	0	1	2	3	4	5	6	Total
Combination with repetition	${}_{21}H_0$ 1	${}_{21}H_1$ 21	${}_{21}H_2$ 231	${}_{21}H_3$ 1,771	${}_{21}H_4$ 10,626	${}_{21}H_5$ 53,130	${}_{21}H_6$ 230,230	296,010
Combination with repetition Including "No Release" as a STC								${}_{22}H_6$ 296,010

Possible Approaches to Perform MU Level 3 PSA

- *Major difficulty lies in the exponentially increasing number of multi-unit accident scenarios.*
  - **Frequency of each multi-unit accident scenarios**: possibly obtained from the result of multi-unit Level 1 and 2 PSA
  - **Consequence of each multi-unit accident scenarios**: should be obtained by consequence analysis
    1) **Building millions of consequence analysis model**
    2) **Reducing the cases** of the consideration (Applying **cut-off** method):
       Cut-off what is expected to have negligible risk (frequency × consequence) and then perform 1)
       - Scenario which has very low frequency can be decided from the results of Level 1, 2 PSA
       - Scenario which has very low consequence?
    3) **Developing innovative approach** to perform multi-unit consequence analysis with a **practical amount of effort**

Existing Method: Tool for Multi-Unit Consequence Analysis

- **Multi-Unit Consequence Analysis Tool Installed in Recent Version of WinMACCS**

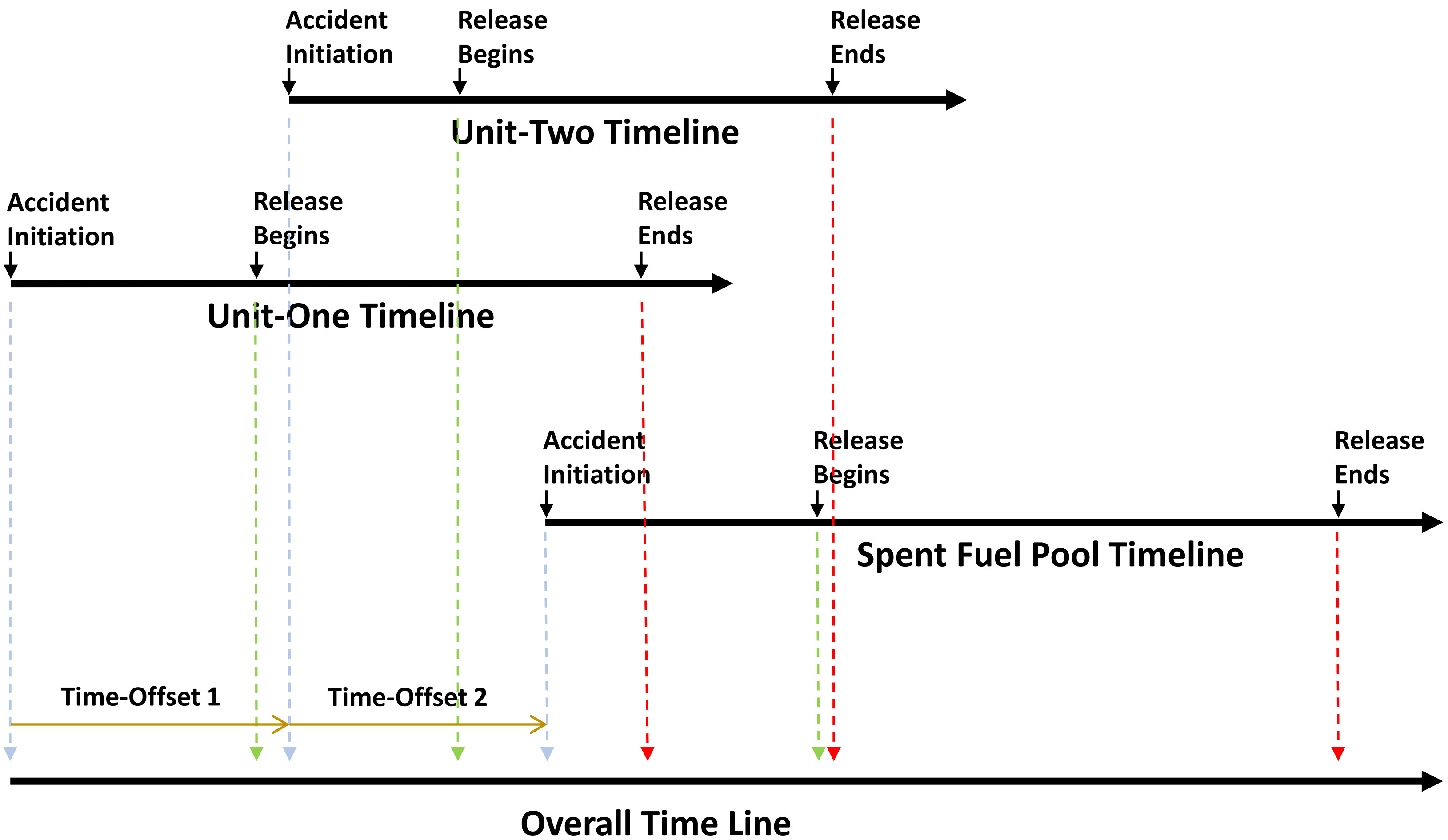


*Image from "Performing Consequence Analysis for Multi-Unit/Spent Fuel Pool Source Terms," N. Bixler, MACCS Users' Workshop 2017

Existing Method: Seabrook Station PRA

- Quantification of Consequences of **Double-Reactor Accident**
  - No assurance that the same event sequences will be followed in the respective accidents, even when the particular cause of the accident is common to both
    - Progression of events which can be substantially different at the two units resulting in different plant damage states and release categories
    - Single-unit analysis: 39 plant damage states(PDSs) and 13 release categories

      $13^2 = 169$ release category combinations for two-unit accidents

      "However, such an approach is clearly impractical."
  - A much simpler approach
    - Full use of the detailed results for single-unit events: Minimize need for additional consequence analysis

Existing Method: Seabrook Station PRA (cont')

- Quantification of Consequences of **Double-Reactor Accident**
  - Distribution of accident sequence frequency among the various PDS for each IE analyzed in the two-unit accident model

Initiating Event	Plant Damage State Type (percent contribution)			
	A	D	FP	F
Seismic Events	2	33	63	2
Loss of Offsite Power	2	98	< 1	< 1
Truck Crash	3	97	< 1	< 1
External Flood	< 1	99+	< 1	< 1

A: Isolated containment with spray working
D: Isolated containment with no sprays
FP: Failure to isolate a small containment penetration
F: Large, unisolated penetration

Existing Method: Seabrook Station PRA (cont')

- Quantification of Consequences of **Double-Reactor Accident**
  - PDS would be highly correlated for two concurrent accidents
    - Dominant contributor to accident frequency: common cause failures (CCF) of similar or identical component in the analysis of the double-core damage frequency
    - Exception: Only in the case of a truck crash into the transmission lines was the frequency contribution of independent concurrent accidents found to be significant
  - Therefore, reasonable and definitely conservative assumption: All double-reactor accidents resulting in the same PDS
    - Occurrence of different plant states → Reduced probability of concurrent releases → Reduced early health effect

Existing Method: Seabrook Station PRA (cont')

- Quantification of Consequences of **Double-Reactor Accident**
  - Strong correspondence of PDS to release categories
    - Risk significant sequences in PDS type A: $S5$ (predominantly benign consequences)
    - Those in PDS type D: $\overline{S3}V$ or $\overline{S4}V$ (similar consequences; i.e., latent health effects and negligible potential for early health effects)
    - Those in PDS type FP: $\overline{S2}V$ (latent health effects and small number of early health effects)
    - Those in PDS type F: $\overline{S6}V$ (dominant release category for early health effects)

Initiating Event	Percentage of Double-Unit Accident Frequency Assigned to Release Categories		
	$\overline{S3}V_2$	$\overline{S2}V_2$	$\overline{S6}V_2$
Seismic Events	35	63	2
Loss of Offsite Power	100	0	0
Truck Crash	100	0	0
External Flood	<100	0	0

Designator indicates a double release.

Existing Method: Seabrook Station PRA (cont')

- Quantification of Consequences of **Double-Reactor Accident**

Initiating Event	Plant Damage State Type (percent contribution)			
	A ($S5$)	D ($\overline{S3}V$)	FP ($\overline{S2}V$)	F ($\overline{S6}V$)
Seismic Events	2	33	63	2
Loss of Offsite Power	2	98	< 1	< 1
Truck Crash	3	97	< 1	< 1
External Flood	< 1	99+	< 1	< 1

Initiating Event	Percentage of Double-Unit Accident Frequency Assigned to Release Categories		
	$\overline{S3}V_2$	$\overline{S2}V_2$	$\overline{S6}V_2$
Seismic Events	35	63	2
Loss of Offsite Power	100	0	0
Truck Crash	100	0	0
External Flood	<100	0	0

Designator indicates a double release.

Existing Method: Seabrook Station PRA (cont')

- Quantification of Consequences of **Double-Reactor Accident**
  - Consequence analyses of the double releases for $\overline{S3}V_2$, $\overline{S2}V_2$, and $\overline{S6}V_2$
    - Early fatalities
    - Latent cancer fatalities

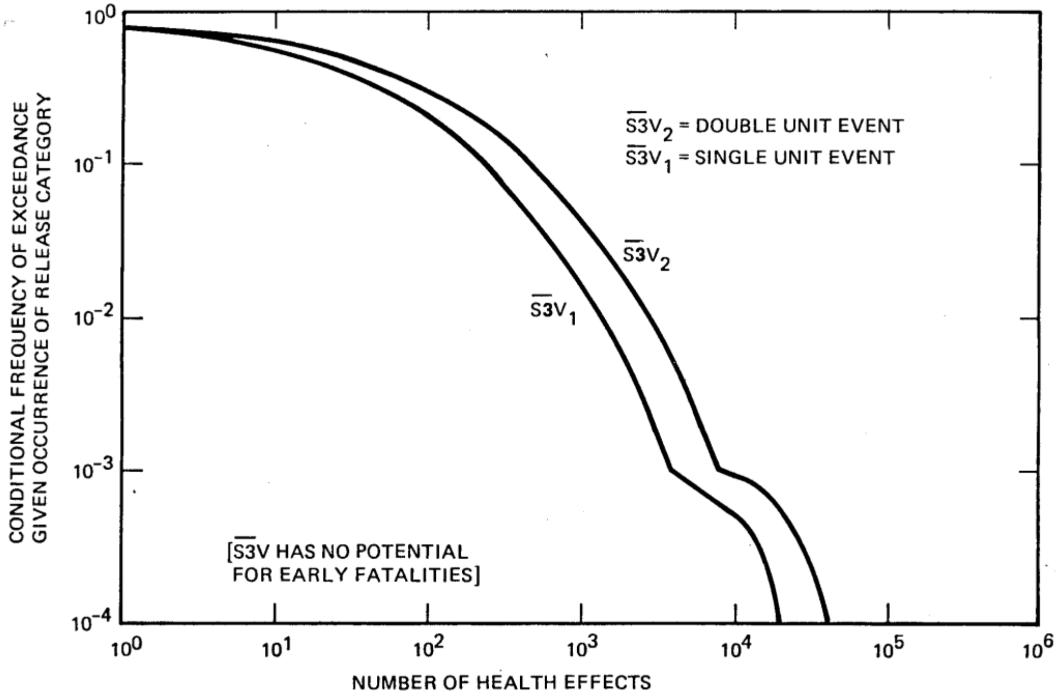
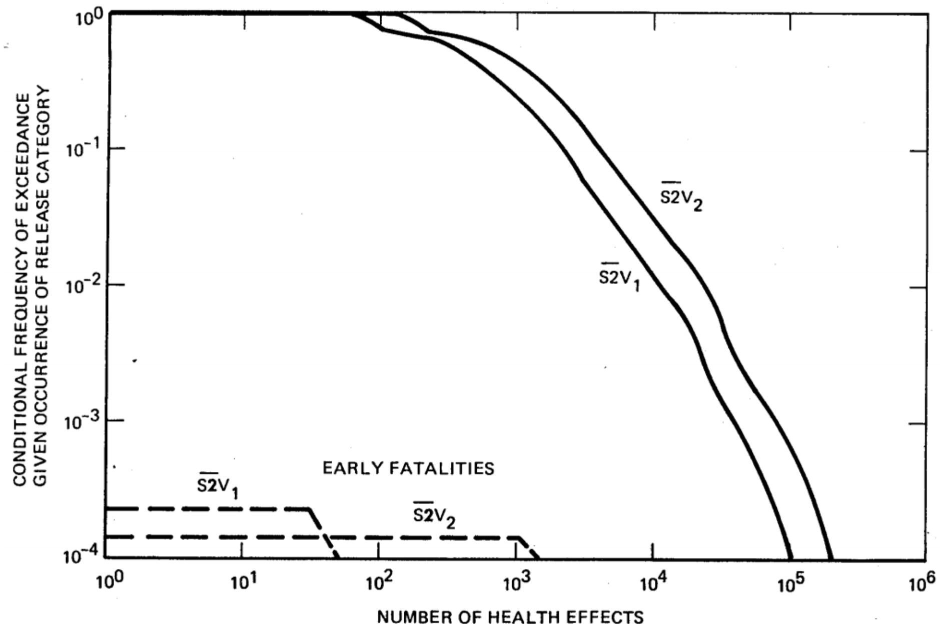
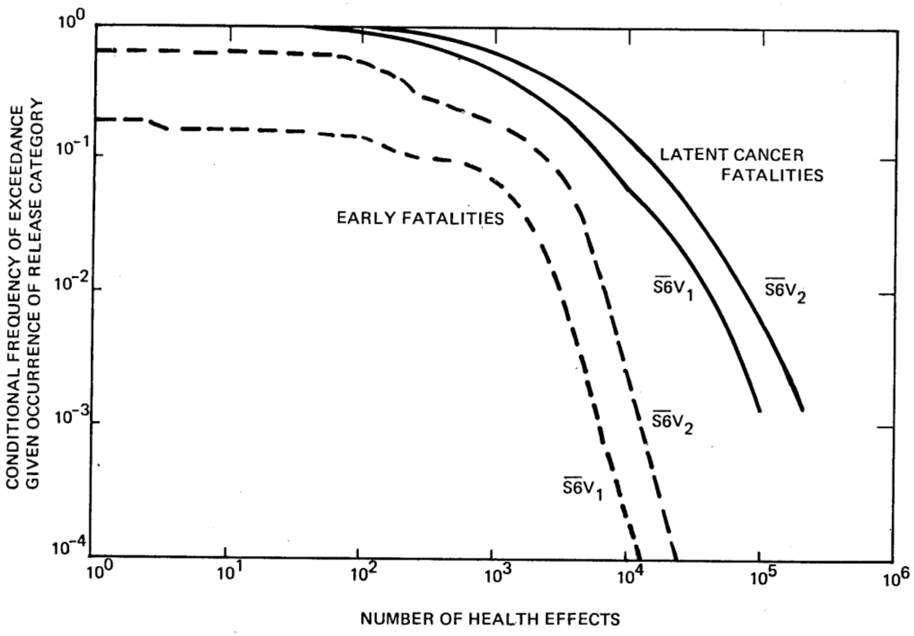


FIGURE 13.3-4. COMPARISON OF CONDITIONAL RISK CURVES FOR SINGLE AND DOUBLE RELEASES IN CATEGORY $\overline{S3}V$ (LATENT CANCER FATALITIES)

Existing Method: Seabrook Station PRA (cont')

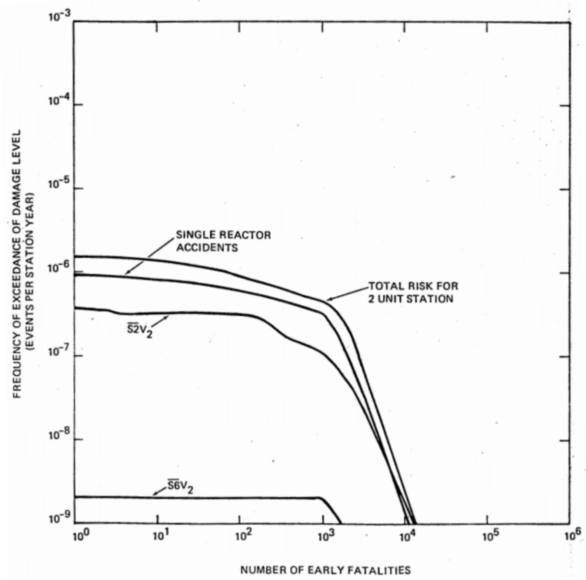
- Quantification of Consequences of **Double-Reactor Accident**
  - Consequence analyses of the double releases for $\overline{S3}V_2$, $\overline{S2}V_2$, and $\overline{S6}V_2$
    - Early fatalities
    - Latent cancer fatalities

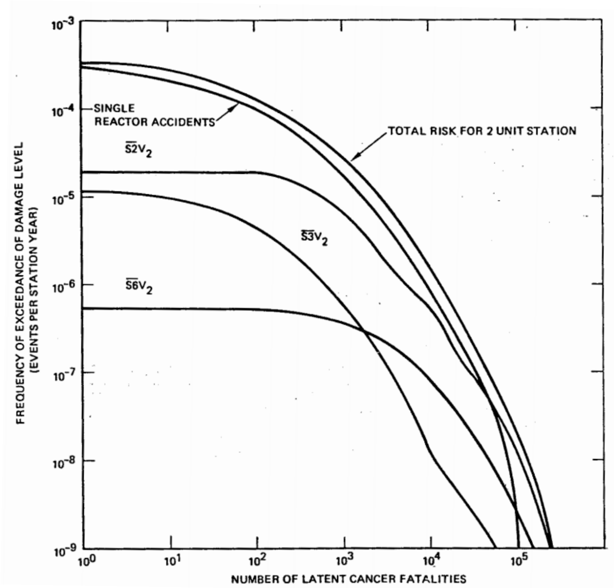




Existing Method: Seabrook Station PRA (cont')

- Quantification of Consequences of **Double-Reactor Accident**
  - A set of mean conditional risk curves was obtained by scaling up the mean S matrix damage scale by a factor of 2
    - Mean S Matrix results: mean values (probability weighted averages) of the results from 12 different CRACIT analyses that were performed for each release category in the single-unit analyses
    - Using this approach, it was possible to incorporate the full spectrum of CRACIT cases without having to rerun all of them using a different source term





Existing Method: MU Accident Contribution to QHO

- **Multiunit Accident Contributions to Quantitative Health Objectives: A Safety Goal Policy Analysis**, D. W. Hudson and M. Modarres, Nuclear Technology Vol 197, pp. 227-247, March 2017.
  - Consequence analyses of two-unit accident combinations based on SOARCA source term
    - Peach Bottom: Unit 2 & 3
    - Surry: Unit 1 & 2

TABLE I

Two-Unit Accident Scenario Models Constructed by Combining Single-Unit Accident Scenario Models from the SOARCA Pilot Study for Peach Bottom and Surry*

Peach Bottom		Unit 3			Surry		Unit 2			
		LTSBO	STSBO-Base	STSBO-RCIC			LTSBO	STSBO-Base	STSBO-TISGTR	ISLOCA
Unit 2	LTSBO	BWR1	BWR2	BWR3	Unit 1	LTSBO	PWR1	PWR2	PWR3	PWR4
	STSBO-Base	BWR4	BWR5	BWR6		STSBO-Base	PWR5	PWR6	PWR7	PWR8
	STSBO-RCIC	BWR7	BWR8	BWR9		STSBO-TISGTR	PWR9	PWR10	PWR11	PWR12
						ISLOCA	PWR13	PWR14	PWR15	PWR16

*ISLOCA = interfacing systems loss-of-coolant accident; LTSBO = long-term station blackout; STSBO-Base = unmitigated short-term station blackout; STSBO-RCIC = short-term station blackout with reactor core isolation cooling system operation; STSBO-TISGTR = short-term station blackout with thermally-induced steam generator tube rupture.

Existing Method: MU Accident Contribution to QHO (cont')

- **Multiunit Accident Contributions to Quantitative Health Objectives: A Safety Goal Policy Analysis**, D. W. Hudson and M. Modarres, Nuclear Technology Vol 197, pp. 227-247, March 2017.

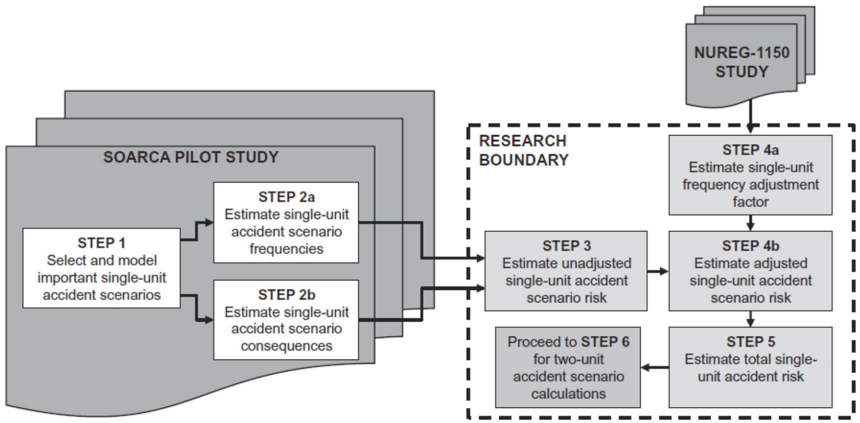


Fig. 2. A two-unit case is used to demonstrate the process for estimating the contribution from single-unit accident scenarios to QHO risk metrics.

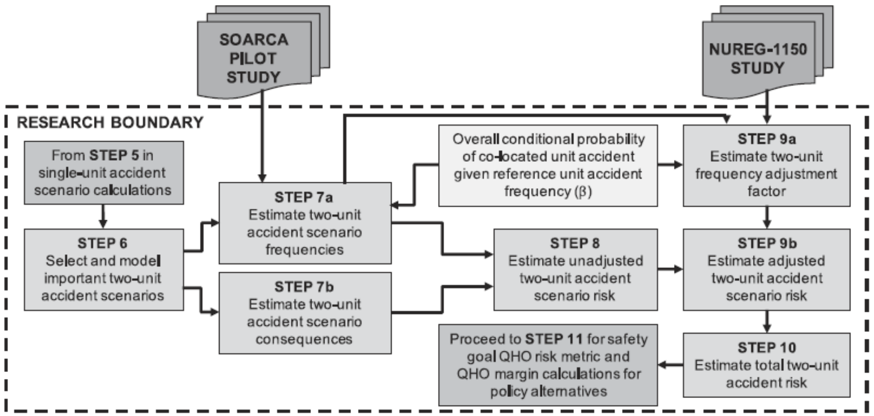


Fig. 3. A two-unit case is used to demonstrate the process for estimating the contribution from multiunit accident scenarios to QHO risk metrics.

New Approach: Correspond to Strategy 3)

- **Development of the Integrated Risk Assessment Technology for Multiple Units**, KAERI/RR-4225/2016, 2017.

Index No.	SUM CDF %								
10,000	100.0%								

Index No.	CDF %	# of CD Units	Top1	Top2	Top3	Top4	Top5	Top6	Top7
1	15.0%	1	#GIE-TS-L-5-P34-S12						
2	12.9%	1	#GIE-TS-L-5-P34-S8						
3	12.1%	1	#GIE-TS-L-5-P34-S2						
4	10.5%	1	#GIE-TS-L-5-P34-S14						
5	9.5%	1	#GIE-TS-L-5-P34-S10						
6	6.6%	1	#GIE-TS-L-3-P19-S2						
7	1.3%	1	#GIE-TS-L-5-P34-S6						
8	0.9%	1	#GIE-TS-L-5-P34-S4						
9	0.8%	1	#GIE-TS-L-3-P19-S10						
10	0.7%	1	#GIE-TS-L-3-P19-S14						
11	0.7%	1	#GIE-TS-L-5-P34-S15						
12	0.6%	1	#GIE-TS-L-5-P34-S21						
13	0.4%	1	#GIE-TS-L-3-P19-S15						
14	0.3%	4	#GIE-TS-H-07-P32-S2	#GIE-TS-H-07-P32-S2	#GIE-TS-H-07-P32-S2	#GIE-TS-H-07-P32-S2			
15	0.2%	1	#GIE-TS-L-3-P19-S8						
16	0.1%	1	#GIE-TS-L-3-P19-S12						
17	0.1%	1	#GIE-TS-L-5-P34-S16						
18	0.1%	1	#GIE-TS-H-11-P34-S12						
19	0.1%	6	#GIE-TS-H-02-P32-S2	#GIE-TS-H-02-P32-S2	#GIE-TS-H-05-P32-S2	#GIE-TS-H-05-P32-S2	#GIE-TS-H-05-P32-S2	#GIE-TS-H-05-P32-S2	
20	0.1%	1	#GIE-TS-L-3-P19-S16						
21	0.1%	1	#GIE-TS-H-11-P34-S8						
22	0.1%	4	#GIE-TS-H-07-P32-S2	#GIE-TS-H-07-P32-S2	#GIE-TS-H-07-P32-S2	#GIE-TS-H-07-P32-S8			
23	0.1%	4	#GIE-TS-H-07-P32-S2	#GIE-TS-H-07-P32-S2	#GIE-TS-H-07-P32-S8	#GIE-TS-H-07-P32-S2			
24	0.1%	4	#GIE-TS-H-07-P32-S2	#GIE-TS-H-07-P32-S8	#GIE-TS-H-07-P32-S2	#GIE-TS-H-07-P32-S2			
25	0.1%	4	#GIE-TS-H-07-P32-S8	#GIE-TS-H-07-P32-S2	#GIE-TS-H-07-P32-S2	#GIE-TS-H-07-P32-S2			
26	0.1%	1	#GIE-TS-H-11-P34-S2						
27	0.1%	2	#GIE-TS-L-5-P34-S12	#GIE-TS-L-5-P34-S12					
28	0.1%	1	#GIE-TS-H-11-P34-S14						
29	0.0%	2	#GIE-TS-L-5-P34-S8	#GIE-TS-L-5-P34-S12					
30	0.0%	2	#GIE-TS-L-5-P34-S12	#GIE-TS-L-5-P34-S8					
31	0.0%	1	#GIE-TS-H-11-P34-S10						
32	0.0%	2	#GIE-TS-L-5-P34-S2	#GIE-TS-L-5-P34-S12					
33	0.0%	2	#GIE-TS-L-5-P34-S12	#GIE-TS-L-5-P34-S2					
34	0.0%	4	#GIE-TS-H-07-P32-S2	#GIE-TS-H-07-P32-S2	#GIE-TS-H-07-P32-S2	#GIE-TS-H-07-P32-S12			
35	0.0%	4	#GIE-TS-H-07-P32-S2	#GIE-TS-H-07-P32-S2	#GIE-TS-H-07-P32-S12	#GIE-TS-H-07-P32-S2			
36	0.0%	4	#GIE-TS-H-07-P32-S2	#GIE-TS-H-07-P32-S12	#GIE-TS-H-07-P32-S2	#GIE-TS-H-07-P32-S2			
37	0.0%	4	#GIE-TS-H-07-P32-S12	#GIE-TS-H-07-P32-S2	#GIE-TS-H-07-P32-S2	#GIE-TS-H-07-P32-S2			
38	0.0%	2	#GIE-TS-L-5-P34-S8	#GIE-TS-L-5-P34-S8					
39	0.0%	4	#GIE-TS-H-07-P32-S2	#GIE-TS-H-07-P32-S2	#GIE-TS-H-07-P32-S2	#GIE-TS-H-07-P32-S10			
40	0.0%	4	#GIE-TS-H-07-P32-S2	#GIE-TS-H-07-P32-S2	#GIE-TS-H-07-P32-S10	#GIE-TS-H-07-P32-S2			
41	0.0%	4	#GIE-TS-H-07-P32-S2	#GIE-TS-H-07-P32-S10	#GIE-TS-H-07-P32-S2	#GIE-TS-H-07-P32-S2			
42	0.0%	4	#GIE-TS-H-07-P32-S10	#GIE-TS-H-07-P32-S2	#GIE-TS-H-07-P32-S2	#GIE-TS-H-07-P32-S2			
43	0.0%	2	#GIE-TS-L-5-P34-S12	#GIE-TS-L-5-P34-S14					
44	0.0%	2	#GIE-TS-L-5-P34-S14	#GIE-TS-L-5-P34-S12					
45	0.0%	2	#GIE-TS-L-5-P34-S2	#GIE-TS-L-5-P34-S8					
46	0.0%	2	#GIE-TS-L-5-P34-S8	#GIE-TS-L-5-P34-S2					
47	0.0%	2	#GIE-TS-L-5-P34-S2	#GIE-TS-L-5-P34-S2					
48	0.0%	2	#GIE-TS-L-5-P34-S10	#GIE-TS-L-5-P34-S12					
49	0.0%	2	#GIE-TS-L-5-P34-S12	#GIE-TS-L-5-P34-S10					
50	0.0%	2	#GIE-TS-L-5-P34-S8	#GIE-TS-L-5-P34-S14					
51	0.0%	2	#GIE-TS-L-5-P34-S14	#GIE-TS-L-5-P34-S8					
52	0.0%	1	#GIE-TS-H-09-P19-S2						
53	0.0%	1	#GIE-TS-L-3-P19-S6						
54	0.0%	2	#GIE-TS-L-5-P34-S2	#GIE-TS-L-5-P34-S14					
55	0.0%	2	#GIE-TS-L-5-P34-S14	#GIE-TS-L-5-P34-S2					
56	0.0%	4	#GIE-TS-H-07-P32-S2	#GIE-TS-H-07-P32-S2	#GIE-TS-H-07-P32-S2	#GIE-TS-H-07			

Mapping between Frequency and Consequence

Consequence Table Established with a Practical Amount of Effort

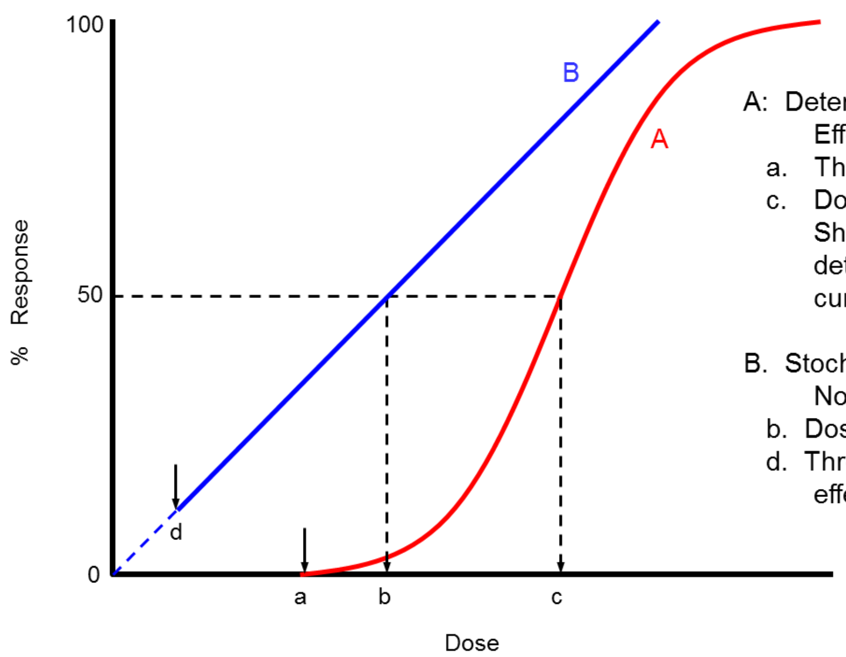
Site Risk of an Initiating Event Can Be Estimated by Total Sum of the Risk of Each Scenarios

Frequency Estimated from Level 1&2 PSA

Common Question on Multi-Unit Accident

- Health Effect Expected from Multiple Release?
  - **Early fatality and cancer fatality**

Dose-Response Curves



A: Deterministic (Acute) Effect:
- a. Threshold dose
- c. Dose → 50% incidence Shape factor that determines width of curve

B. Stochastic Effect (Linear No-Threshold) :
- b. Dose → 50% incidence
- d. Threshold of observable effects

*Image from “EARLY-Phase Health Effects,” M. Dennis, MACCS Users’ Workshop 2017

Common Question on Multi-Unit Accident (cont')

- Health Effect Expected from Multiple Release?

  - **Early fatality**

    - Average individual risk of early fatality from dose D

$$r = 1 - exp(-H)$$

    - H, the cumulative hazard, is given by

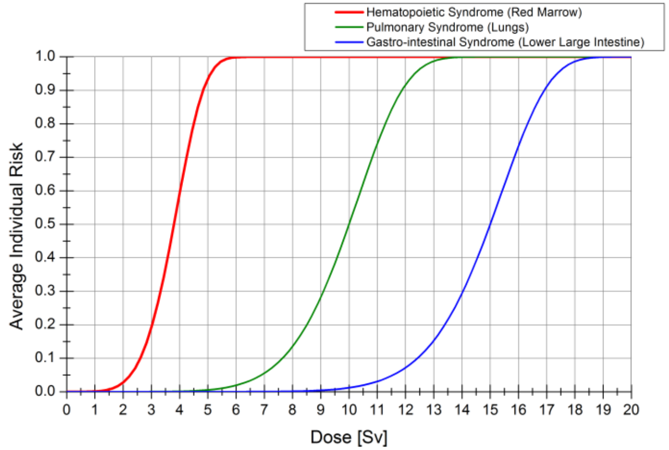
      $H = \ln_2(D/D_{50})^{\beta}$ for $D > T$

      » D : average absorbed dose to the relevant organ

      » D_{50} : dose which causes the effect in 50% of the exposed population

      » β : shape factor, which characterizes the slope of the dose-risk function

      » T : threshold dose



Common Question on Multi-Unit Accident (cont')

- Health Effect Expected from Multiple Release?
  - **Latent cancer fatality**
    - Average individual risk of latent cancer fatality from dose D: Linear No-Threshold (LNT) or linear-quadratic dose response function:

$$r = aD(b + cD)$$

- D : the observed dose to the organ of interest
- a, b, c : effect specific model parameters that quantify risk per unit dose (risk coefficients)

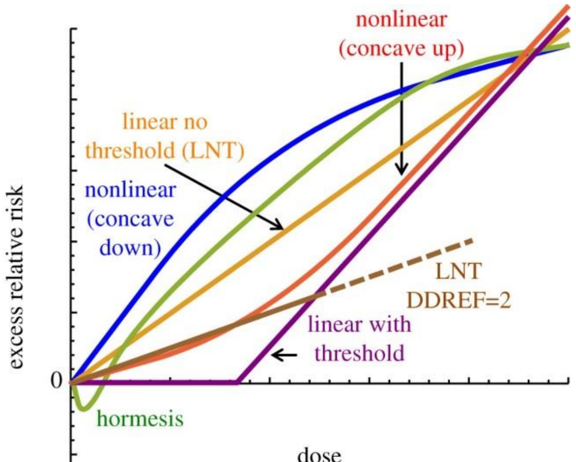


*Image from "A restatement of the natural science evidence base concerning the health effects of low-level ionizing radiation, R. Angela et al., Proc. Of the Royal Society B, 2017

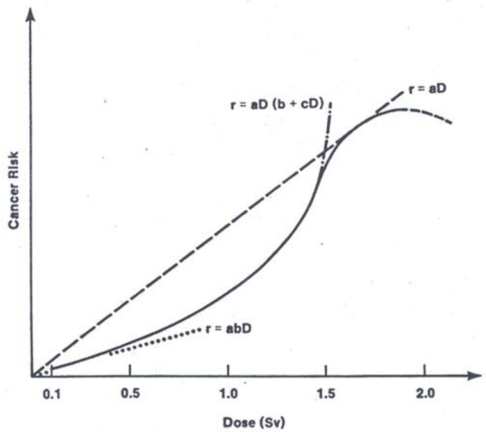


*Image from "MACCS Model Description," H-N Jaw et al., 1990

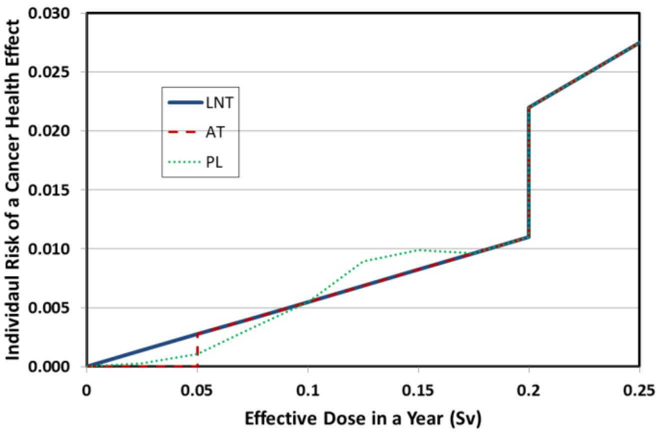


*Image from "EARLY-Phase Health Effects," M. Dennis, MACCS Users' Workshop 2017

Summary

- Few existing studies on multi-unit Level 3 PSA
- Major difficulty to perform MU Level 3 PSA
  - Exponentially increasing number of multi-unit accident combinations as different source terms can be released from each NPP unit → Impractical to build consequence models for the astronomical number of accident scenarios
- Three kinds of strategies
  - Building millions of consequence analysis model one by one
  - Reducing the cases of consideration (applying cut-off method)
  - Developing a approach to reduce the amount of effort to be practical
- Seabrook
  - Probability-weighted average of CRACIT results for each release category in the single-unit analyses and scaling up by a factor of 2 (Double-reactor accident)
- QHO Study
  - Analyses of selected accident scenarios by importance for two units

Thank you for your attention.

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