Fukushima-Informed Recovery and Cost Assessment: A Proposed Approach to Offsite Consequence Analysis of Nuclear Disasters with Implications for Recovery Policy

2019 International MACCS User Group

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Outline

- Introduction
- The Fukushima-Informed Recovery and Cost Assessment (FIRCA) Approach
  - FIRCA Overview
  - FIRCA Post-accident Modeling Assumptions
  - FIRCA Cost Assessment
- Case Study Results
  - MACCS Conventional Approach vs FIRCA Approach
  - Current vs Expedited Recovery
  - Sensitivity Analyses: Credit for Shielding and Dose Criteria
- Conclusions and Recommendations

Introduction

- Research observations about MACCS
  - MACCS is useful at modeling how a nuclear accident will cause offsite contamination
  - However, the user cannot as easily control certain characteristics of how protective actions are applied
  - Likewise, the conventional use of MACCS could not predict Fukushima costs
- Research Goals
  - Create a new and more realistic approach to estimating nuclear disaster impacts that is more consistent with Fukushima experience and EPA guidance
  - Evaluate how different recovery strategies can affect the impacts of a nuclear power plant accident

FIRCA: A New Approach for Modeling Nuclear Disaster Impacts

FIRCA: A New Accident Modeling Approach

- "Fukushima-informed Recovery and Cost Assessment" is a new approach for modeling post-accident recovery actions and measuring nuclear disaster impacts
  - Alternative to the MACCS conventional approach
  - Still uses MACCS to generate offsite conditions
- Purpose of FIRCA:
  - Create a better (more complete) forecast of nuclear disaster impacts and associated costs with more realistic recovery and cost modeling
- The FIRCA approach is based on
  - A review of the recovery experience after the Fukushima nuclear disaster,
  - A review of current U.S. preparedness, and
  - An understanding of the MACCS conventional approach to modeling offsite consequences of nuclear disasters

FIRCA Post-accident Modeling Assumptions

Basis	Accident Modeling Assumptions	Description	MACCS Conventional Approach	FIRCA Approach	Effect on Interdiction / Evacuation Area	Effect on Dose
EPA	Relocation Dose Criteria	Long-term dose criterion	4 rem (5 years)	2 rem (1st year); 0.5 rem (2nd year)	Increase	Decrease
Fukushima	Relocation and Reoccupation Timeline	Emergency phase duration	7 (days)	40 (days)	Decrease	Increase
		Emergency phase 1 rem relocation	yes	no	Decrease	Increase
Fukushima	Decontamination Modeling	Cleanup dose reduction factors	3, 15	2	N/A	Increase
EPA	Emergency Phase Modeling	Emergency phase dose projection period	7 (days)	4 (days)	Decrease	Increase
EPA	Relocation and Shielding	Protective actions credit long-term shielding	yes	no	Increase	Decrease

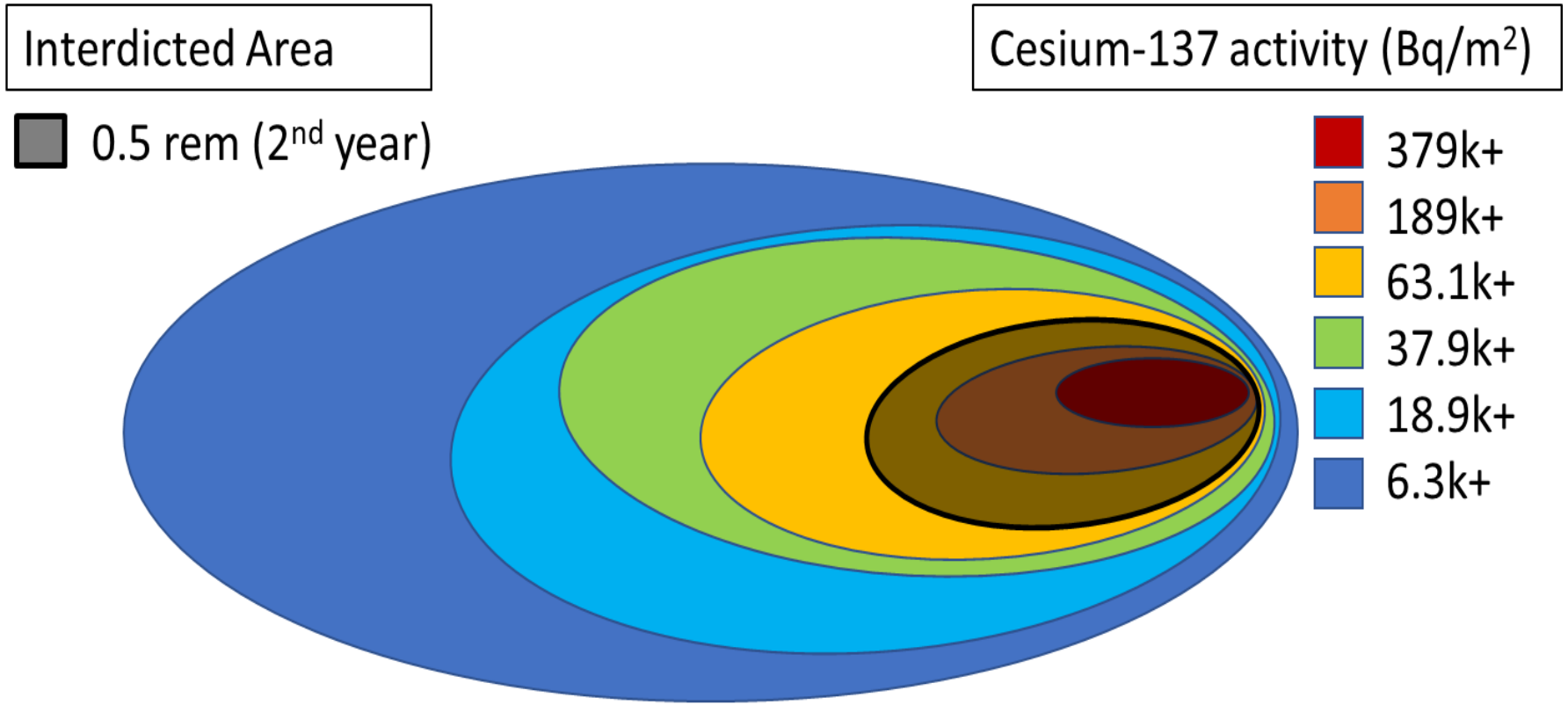
FIRCA Cost Assessment

- A more complete set of impacts than the MACCS conventional approach
- New methods to assess costs (not MACCS cost estimates), most based on Fukushima nuclear disaster experience
  - FIRCA includes a new method to assess burden of societal disruptions
- Performed in a post-processing step after the MACCS calculations
- Uses MACCS key results as the basis for determining the cost of various types of nuclear disaster impacts

FIRCA Cost Assessment: List of Inputs

List of Nuclear Disaster Costs	FIRCA Approach (MACCS Results / FIRCA Cost Inputs)
Market Consequences ($)	
Economic Disruptions (ED)	
• Income loss (inside interdicted area)	Displaced Individuals
Offsite Property Damage (OPD)	
• Property damage (inside interdicted area)	Value of Property Exceeding Dose Level
• Property damage (outside interdicted area)	Value of Property Exceeding Activity Level
Expenditures	
• Relocation Expenses (reoccurring)	Evacuees / Displaced Individuals
• Relocation Expenses (one-time)	Displaced Individuals
• Medical expenses	Cancer Fatalities
• Cleanup costs (non-farmland)	Displaced Individuals
• Cleanup costs (farmland)	Farmland Area
• Cleanup costs (outside interdicted area)	Affected Population
• Waste management (non-farmland)	Displaced Individuals
• Waste management (farmland)	Farmland Area
• Waste management (outside interdicted area)	Affected Population
• Compensation program	Displaced Individuals
Non-Market Consequences ($)	
• Radiation-induced Health Effects (i.e., cancer)	Collective Dose
• Burden of Societal Disruptions (inside interdicted area)	Displaced Individuals

FIRCA Cost Assessment: Offsite Property Damage



Decontamination Modeling: Comparison of Cleanup Cost Estimates

Land Use Category	MACCS Conventional Approach Cost-to-decontaminate Estimates (per unit; NRC, 2012)		Fukushima Cost-to-decontaminate Estimates (per unit; Dose Reduction Factor of 2)			Measure for disaster cleanup size
	Dose Reduction Factor of 3	Dose Reduction Factor of 15	Budget-based method (FIRCA)	Actual cost-based method (as of March 2017)	Unit cost-based method	
Interdicted Farmland	$1.33k	$2.96k	$493k	$358k	$133k	per hectare of decontaminated farmland
Interdicted Non-farmland	$7.11k	$19.0k	$210k	$153k	$56.6k	per displaced individual from decontaminated land
Extended Cleanup Zone	Not Included		$13.4k	$9.7k	-	per affected person

FIRCA Cost Assessment: Burden of Societal Disruption

Types of harms (Fukushima evacuees):

- Psychological distress (post-traumatic stress disorder: 20-23%, other disorders: 13-15%)
- Behavior and lifestyle changes (sleep issues: 60%; 1.3-1.6x for diabetes, dyslipidemia, and being overweight; significant substance abuse)
- Loss of livelihood (loss of homes, jobs, lifestyle)
- Dysfunction in families and communities (conflicts regarding risk perception, compensation, and stigma)
- Diminished standard of living (worse living conditions, severe health care issues, and social isolation have been major causes of death among elderly)

FIRCA Cost Assessment: Burden of Societal Disruption (continued)

- Interdicted Areas: Based on a value of statistical life-year methodology, using a value of $411k per life-year and a quality-of-life weighting of 80% for displaced individuals (based on the previous slide).
- Outside Interdicted Areas: Not included

FIRCA Cost Assessment Summary

Nuclear Disaster Cost	Description	Value
Offsite Property Damage (Inside Interdicted Area)	Annual Depreciation of Interdicted Area (straight-line)	16.7%
Offsite Property Damage (Outside Interdicted Area)	Property Value Loss (6.3-18.9 kBq/m^2 Cs-137)	2.91%
	Property Value Loss (18.9-37.9 kBq/m^2 Cs-137)	4.61%
	Property Value Loss (37.9-63.1 kBq/m^2 Cs-137)	5.82%
	Property Value Loss (63.1-86.3 kBq/m^2 Cs-137)	6.65%
Income Loss (Inside Interdicted Area)	GDP Per Capita (Pennsylvania)	$50,742
Relocation	Relocation Expenses ($/person-day)	$19
	Relocation Expenses (one time)	$12,000
Medical	Medical Cost ($/cancer fatality)	$146,000
Cleanup Costs	Non-farmland Cleanup Cost ($/displaced individual)	$210,435
	Farmland Cleanup Cost ($/hectare of Interdicted farmland)	$493,186
	Extended Cleanup Zone Cleanup Cost ($/affected person)	$13,440
Waste Costs	Non-farmland Waste Cost ($/displaced individual)	$95,105
	Farmland Waste Cost ($/hectare of Interdicted farmland)	$222,894
	Extended Cleanup Zone Waste Cost ($/affected person)	$4,724
Compensation	Compensation Program ($/displaced individual)	$12,000
Radiation-induced Health Effects	Value of Statistical Life ($/person-Sv)	$540,000
Burden of Societal Disruption	Value of Statistical Life-Year (VSLY)	$411,000
	Quality of Life (while dislocated)	0.8

Case Study Results

FIRCA Post-accident Modeling Assumptions

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EPA	Emergency Phase Modeling	Emergency phase dose projection period	7 (days)	4 (days)	Decrease	Increase
EPA	Relocation and Shielding	Protective actions credit long-term shielding	yes	no	Increase	Decrease

Key Results

Accident Modeling Impacts	MACCS Conventional Approach	FIRCA Approach	Ratio
Radiation-induced Health Impacts			
Early Fatalities	-	-	-
Collective Dose (person-Sv) (1-year recovery)	68,760	61,650	0.9
Collective Dose (person-Sv) (5.7-year recovery)	66,220	58,920	0.89
Cancer Fatalities (1-year recovery)	3,160	2,928	0.93
Cancer Fatalities (5.7-year recovery)	3,063	2,816	0.92
Countermeasure-related Impacts			
Emergency Phase Individuals (e.g., evacuees)	691,500	154,420	0.22
What is the limiting PAG criteria for relocation?	N/A	2nd year	N/A
Total Land in Interdicted Area (mi^2)	807	3,078	4
Farmland in Interdicted Area (mi^2)	289	1,111	3.84
Displaced Individuals	225,400	992,456	4.4
Population of Extended Cleanup Zone (between 0.1 rem and the limiting PAG criterion)	N/A	2,741,544	N/A
Reoccupation-related Impacts			
What is the limiting PAG criterion for reoccupation?	N/A	2nd year	N/A
“Able-to-Return” Population (5.7-year recovery)	225,277	904,800	4.02
“Able-to-Return” Fraction (5.7-year recovery)	99.90%	91%	0.91

Drivers of the Key Results

1. The EPA-based approach to long-term shielding (i.e., no credit for shielding in protective actions),
2. Fukushima-informed relocation timing (i.e., a 40-day delay before long-term relocation), and
3. The use of the EPA-based relocation criteria

- Relocation criteria and cleanup dose reduction factors can have a large effect on the ability to return.

Nuclear Disaster Costs (5.7 year Recovery)

	Main Results ($)		
Nuclear Disaster Costs	**RP Conventional Approach Model**	**FIRCA Model**	**Ratio**
Market Consequences ($)			
Offsite Property Damage (OPD) and			
Economic Disruptions (EC)			
*"Loss of Use" (i.e., combined income loss and depreciation of interdicted area)	$72.6B		7.45
*Income loss (Inside Interdicted Area)		$174B	
*Property damage (Inside Interdicted Area)		$367B	
*Income loss (Outside Interdicted Area)	Not Included	Not Included	-
*Property damage (Outside Interdicted Area)	Not Included	$56.3B	-
*Milk and Crop Disposal Costs	$0.51B	Not Included	-
EC / OPD Subtotal	**$73.1B**	**$597B**	8.2
Expenditures			
*Relocation Expenses (reoccurring)	$0.71B	$38.8B	55
*Relocation Expenses (one-time)	$2.70B	$11.9B	4.4
*Medical Expenses	Not Included	$0.41B	-
*Cleanup Costs (interdicted area: non-farmland)	$1.62B	$190B	117
*Cleanup Costs (interdicted area: farmland)	$0.096B	$51.5B	538
*Cleanup Costs (outside interdicted area)	Not Included	$36.8B	-
*Waste Management (inside interdicted area)	Not Included	$109B	-
*Waste Management (outside interdicted area)	Not Included	$13.0B	-
*Compensation program	Not Included	$41.1B	-
Market Total	**$78.3B**	**$1,090B**	13.9
Non-Market Consequences ($)			
*Radiation-induced Health Effects (i.e., cancer)**	$35.8B	$31.8B	0.89
*Burden of Societal Disruptions (inside interdicted area)	Not Included	$282B	-
*Burden of Societal Disruptions (outside interdicted area)	Not Included	Not Included	-
Non-Market Total	**$35.8B**	**$314B**	8.8
Grand Total	**$114B**	**$1,400B**	12.3

Sensitivity Analysis: Current vs. Expedited Recovery

	FIRCA Model				
Nuclear Disaster Costs	**Current Recovery (5.7 years)**		**Expedited Recovery (1 year)**		**Ratio**
Market Consequences ($)					
Offsite Property Damage					
*Inside Interdicted Area	$367B	25%	$251B	25%	0.68
*Outside Interdicted Area	$56.3B	4%	$56.3B	6%	1
Economic Disruptions (Income Loss)					
*Inside Interdicted Area	$174B	12%	$124B	12%	0.71
*Outside Interdicted Area	Not Included	-	Not Included	-	-
Expenditures					
*Relocation Expenses (reoccurring)	$38.8B	3%	$26.3B	6%	0.68
*Relocation Expenses (one-time)	$11.9B	1%	$11.9B	1%	1
*Medical Expenses	$0.41B	0%	$0.43B	0%	1.04
*Cleanup Costs (Inside Interdicted Area)	$242B	17%	$139B	14%	0.57
*Cleanup Costs (Outside Interdicted Area)	$36.8B	3%	$36.8B	4%	1
*Waste Management (Inside Interdicted Area)	$109B	8%	$62.6B	6%	0.57
*Waste Management (Outside Interdicted Area)	$13.0B	1%	$13.0B	1%	1
*Compensation Program	$41.1B	3%	$29.3B	2%	0.71
Market Total	$1,090B	**78%**	**$750B**	**77%**	0.69
Non-Market Consequences ($)					
*Radiation-induced Health Effects (i.e., cancer)	$31.8B	2%	$33.3B	3%	1.05
*Burden of Societal Disruptions	$282B	19%	$201B	20%	0.71
Non-Market Total	**$314B**	**22%**	**$234B**	**23%**	0.75
Grand Total	**$1,400B**	**100%**	**$984B**	**100%**	0.7

Sensitivity Analyses: Credit for Shielding and Dose Criteria

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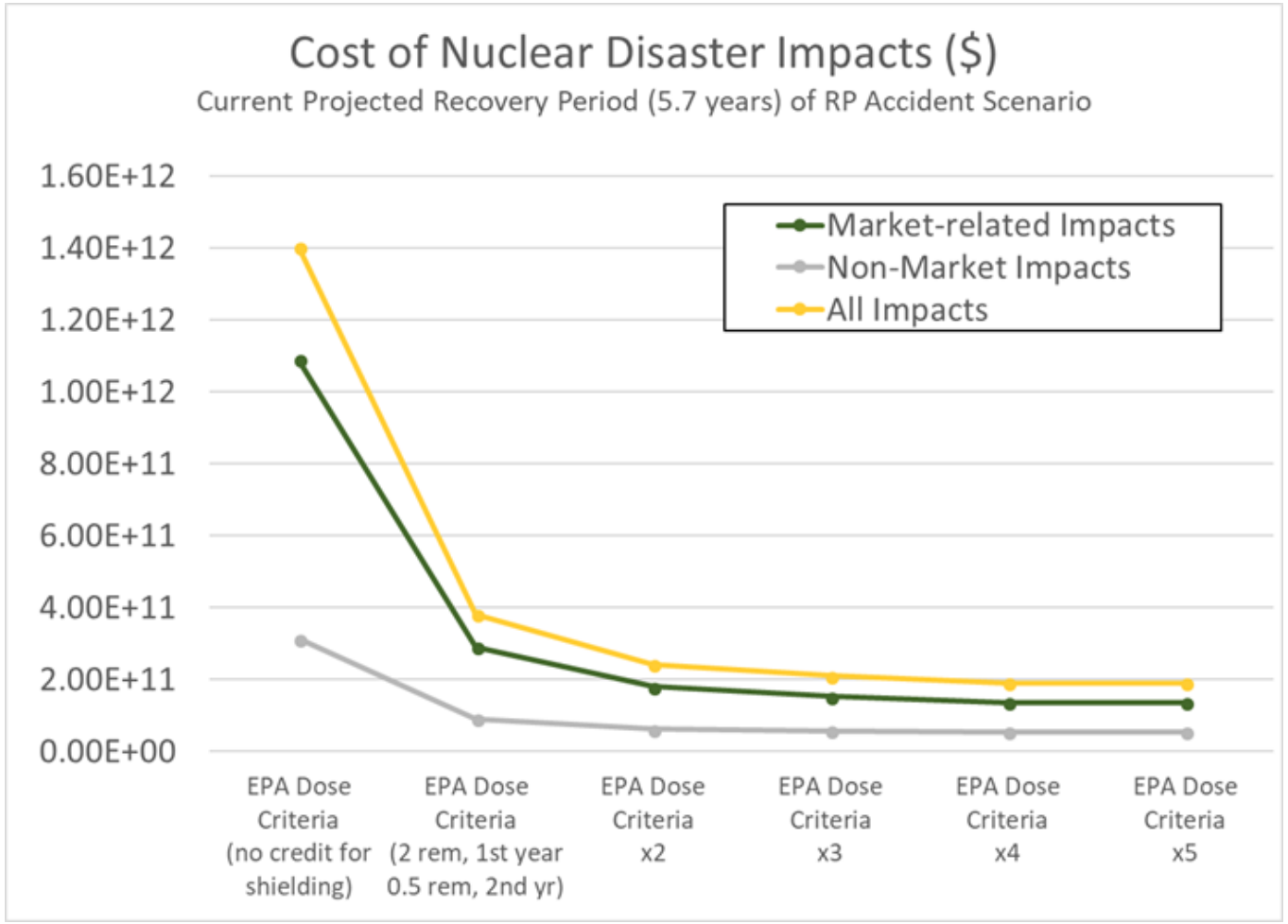

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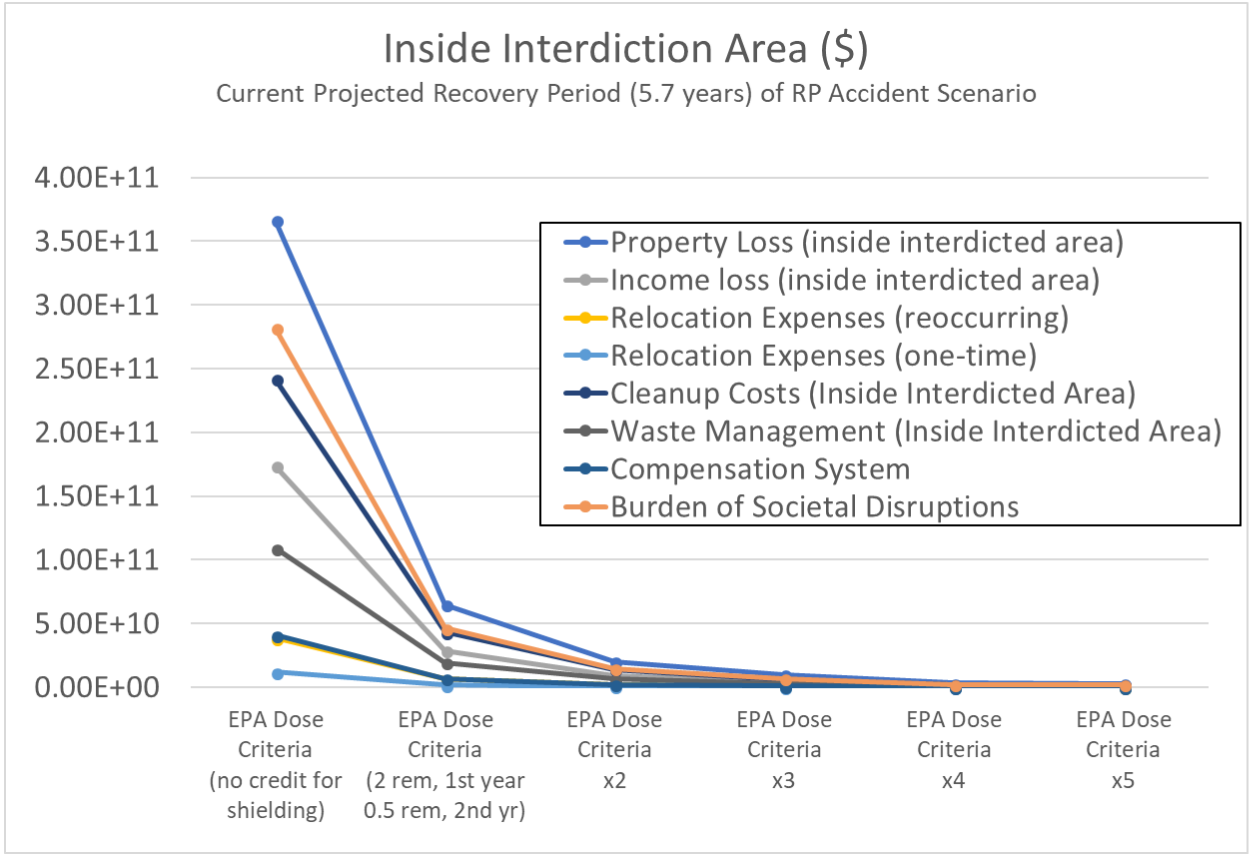
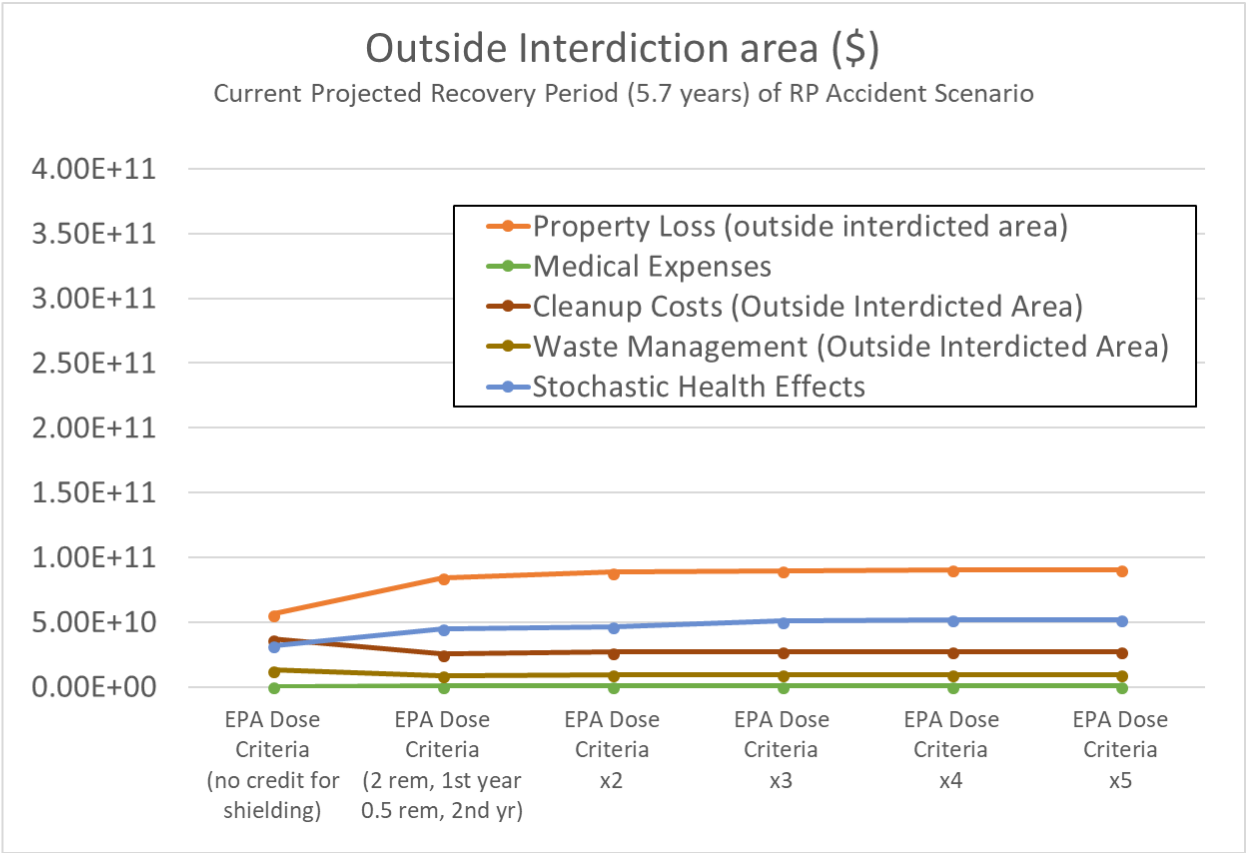




Conclusions and Recommendations

MACCS Recovery and Cost Assessment Capabilities and Limitations

- MACCS is useful at modeling how a nuclear accident will cause offsite contamination
- However, the user cannot as easily control certain characteristics of how protective actions are applied
- Likewise, the conventional use of MACCS could not predict Fukushima costs

FIRCA Provides an Improved Modeling Approach

FIRCA provides a significant improvement in nuclear accident consequence analysis from the MACCS conventional approach.

1. A more complete set of nuclear disaster impacts
2. New post-accident modeling assumptions (based on Fukushima recovery experience and EPA guidance)
3. A new cost assessment of impacts (based on Fukushima recovery experience)

Implications of More Comprehensive Impact Modeling

- NRC safety goals focus solely on health effects
- FIRCA results predict that health effects may only account for 2% of nuclear disaster impacts
- Could inform other areas as well, such as measures for “adequate protection” and “backfit analysis”

Relocation Delay and Credit for Shielding are Net Benefits

- Currently unclear if recovery strategies would delay relocation or credit shielding for relocation decisions
- A sensitivity analysis shows delaying the start of relocation (from 7 days to 40) decreases the interdiction size to 46% of its original value, leading to a significant net benefit.
- Another sensitivity shows that credit for a groundshine shielding factor (reducing groundshine dose from 100% to 18%) decreases the interdiction size to 20% of its original value.
  - Decreased nuclear disaster impacts from $1.40T to $382B (27% of its original value)
- Serious consideration should be given to both of these options

Raising the Relocation Dose Criteria is a Net Benefit

- Clear recommendation by the EPA to use specific dose criteria for relocation (i.e., 2 rem in the first year and 0.5 rem thereafter)
- Sensitivity analysis predicts impacts are minimized when dose criteria are x4-5 higher than EPA recommendation
  - Results still hold true when focusing only on impacts that include “health risks” (i.e., radiation induced health effects, and burden of societal disruption)
- In light of Fukushima experience surrounding the burdens of large relocations, this recommendation may be worth re-evaluating

Questions?

Thank you for your support!

Assessment of US Recovery Preparedness for a Nuclear Disaster

- Elements of Recovery
  - **Transition from the Emergency Phase (Roles and Responsibilities)**
  - Radiation Characterization and Monitoring
  - **Post-Emergency Zoning**
  - **Cleanup Planning**
  - **Cleanup Implementation**
  - Management of Radioactive Waste
  - Compensation Program

Assessment of US Recovery Preparedness for a Nuclear Disaster

- Recovery Preparedness Gaps
  - Transition from the Emergency Phase (Roles and Responsibilities)
    - No identified authority responsible for cleanup
  - Post-Emergency Zoning (i.e., relocation, cleanup, reoccupation)
    - Criteria for relocation not included in many radiological emergency plans
    - No process to determine where cleanup will occur
    - No process to determine if / when reoccupation of interdicted areas will be allowed
  - Cleanup Planning and Implementation
    - Objective, strategies, and guidelines are to be developed post-accident

Table 2: Comparison of Major Post-Emergency Zoning Considerations

Post-Emergency Zoning Comparison															
Protective Actions (Post Emergency Phase)			Basis of criteria	Annual Dose Criterion		Scenario assumptions						Derived Response Levels		
						Time indoors (hours / day)	Indoor shielding factor	Decay	Weathering	Contribution from inhalation	Contribution from ingestion	Evaluation time of dose rate measurement	Dose Rate (using scenario assumptions, 1 meter above ground)	
Japan - Fukushima (1)	Relocation zone (i.e. "Deliberate Evacuation Area")		Dose (ICRP-111)	20	mSv/yr	16	0.4	not credited	not credited	not credited	not credited	4/22/2011 (42 days)	3.8	uSv/hr
	Special Decontamination Area (SDA)	SDA 3 - (i.e. "Difficult to return" zone)	Dose (Pilot projects)	50	mSv/yr	16	0.4	not credited	not credited	not credited	not credited	Varies by region. Between 1-2 years after accident. (6)	9.5	uSv/hr
		SDA 2 - (i.e. "Residents not permitted to live" zone)	Dose (ICRP-111)	20	mSv/yr	16	0.4	not credited	not credited	not credited	not credited		3.8	uSv/hr
		SDA 1 - (i.e. "Evacuation orders ready to be lifted" zone)	Rest of evacuated / relocated zones	-									-	
	Intensive Contamination Survey Area (ICSA)		Dose (ICRP-111)	1	mSv/yr	16	0.4	not credited	not credited	not credited	not credited	Autumn, 2011 (7)	0.23	uSv/hr
	ICSA - cleanup goal		Dose / Dose rate (ICRP-111 + assumptions) (3)	1	mSv/yr	-	0.1	not credited	not credited	not credited	not credited	Ongoing. (Not used to establish zones.)	1.0	uSv/hr
	Return (from either evacuation or relocation)		Various (4)	-										
US (2)	Relocation (1st year)		Dose (PAG manual)	20	mSv	not credited	not credited	to be considered	to be considered	to be considered	not credited (5)	12 hours 42 days	49.7 2.99	uSv/hr (8)
	Relocation (2nd year+)		Dose (PAG manual)	5	mSv	not credited	not credited	to be considered	to be considered	to be considered	not credited (5)	12 hours 42 days 1.5 years	33.0 1.99 0.57	uSv/hr (8)
	Cleanup		TBD Post accident	-							not credited (5)	-		
	Return from evacuation		Below relocation dose (PAG manual)	See US relocation levels above (A gradual return is recommended)										
	Return from relocation		TBD Post accident	-										

1- According to IAEA (2015) - The Fukushima Daiichi Accident- Vol 5. Annex I

2- According to EPA PAG manual (2017).

3- Due to concern of using a 3.8 uSv/hr criterion for schools, MEXT proposed a stricter DRL of 1 uSv/hr, showing that this new DRL by can be justified by the ICRP-103 recommendation of 1 mSv/yr when using more optimistic assumptions. In Aug 2011, this DRL was adopted as a cleanup goal for all areas.

4- Below relocation dose, major completion of cleanup, community approval. For the towns' evacuation orders to be lifted, radiation must fall below 20 millisieverts per year. They must also have functioning utilities and telecoms systems, besides basic health, elderly care and postal services. http://www.asahi.com/ajw/articles/AJ201703110031.html

5- Exposure from ingestion of food and water is considered independently of decisions for relocation and decontamination. In rare instances, however, where withdrawal of food or water from use would pose a health risk in itself, relocation may be an appropriate protective action against exposure via ingestion. In this case, the dose from ingestion should be considered along with the projected dose from other exposure pathways for decisions on relocation.

6- Based on when the cleanup zone was established (between 4/2012-4/2013), MOE progress slideshow

7- IAEA (2015) - The Fukushima Daiichi Accident- Vol 5., page 17

8- Based on Turbo-FRMAC calculations for a nuclear power plant release 1 hour after shutdown and default assumptions

Types of Nuclear Disaster Impacts

Impacts	
Market	**Non-Market**
Onsite property damage (physical, contamination)	Environmental damage (radiation-induced)
Offsite property damage (contamination, deterioration)	Burden of societal disruptions (related to stigma and evacuation / displacement)
Economic interruptions (losses from business, wages, supply chain, electricity)	Health effects (radiation-induced)
Expenditures (e.g., response activities, decontamination, waste management)	
Nuclear industry impact (e.g., financial, regulatory, perception)	

Analysis Tools

- WinMACCS version 3.10 and version 3.11.2 (“MACCS”):
  - Offsite consequence analysis computer code
  - User inputs information to define accident scenario
    - Types of inputs: data for radiological release from site, meteorological data, demographic and economic data
  - Code calculates consequences of an atmospheric release
    - Types of outputs: collective dose, health effects, land interdiction, displaced individuals, costs for certain impacts, etc.

Analysis Approach: Process

- Section 5:
  - Select a reasonably severe but credible accident scenario (i.e., not worst case) appropriate for evaluation of different recovery strategies
  - Selected scenario: the PB-STSBO scenario from the 2011 SOARCA Study.
- Section 6:
  - Update the PB-STSBO model to “PB-STSBO 2016,” and analyze new results
- Section 7:
  - Develop “FIRCA,” A new accident modeling approach
- Section 8:
- All analyses have the same location, accident conditions and progression, environmental release, and short-term emergency response

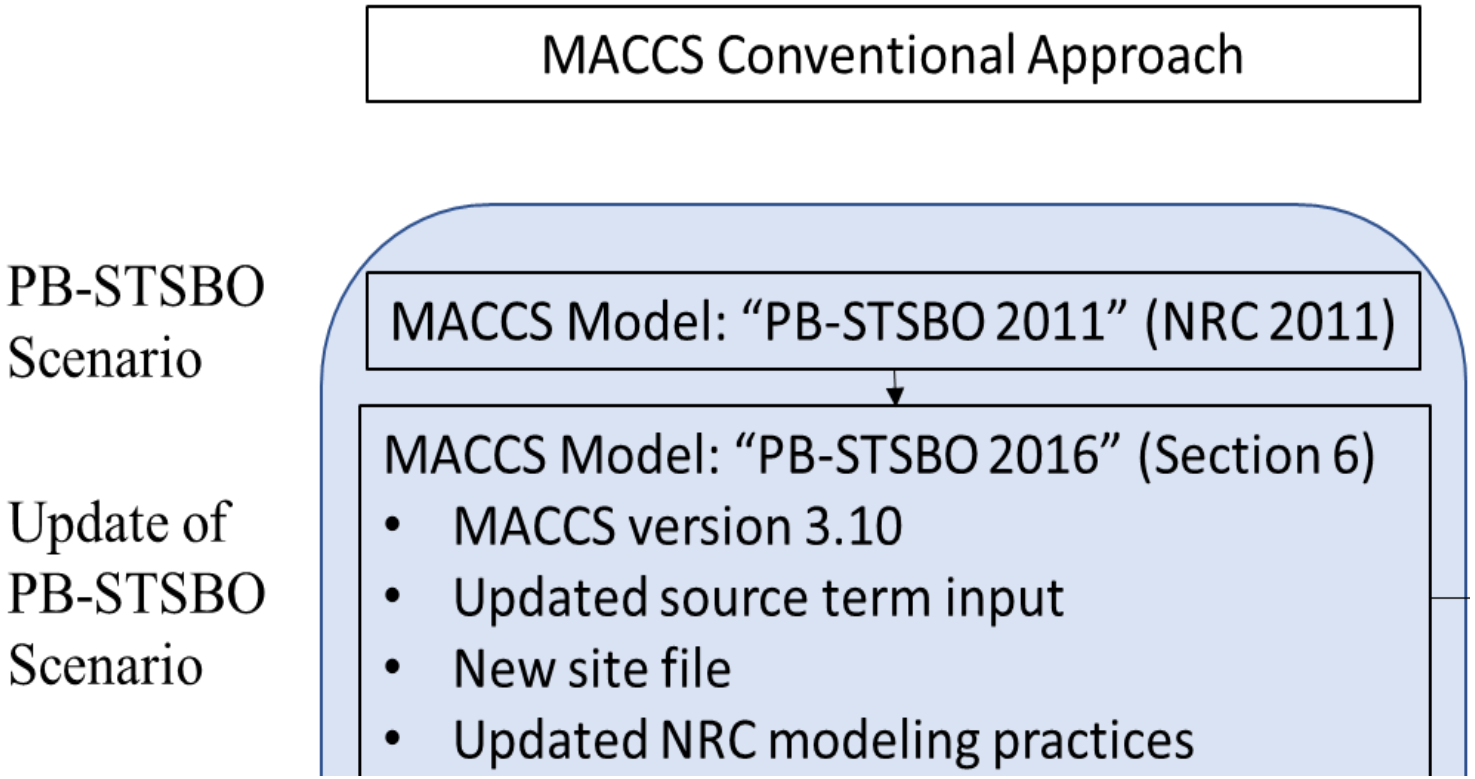
- Evaluate the impacts of a nuclear power plant accident with two different recovery speeds, to explore the benefit of enhanced recovery preparedness.
  - “Current” strategy: reflecting a Fukushima-like timeline (5-6 years)
  - “Expedited” scenario: TBD (likely ~6 to 12 months)

Section 6:
The PB-STSBO 2016 Model

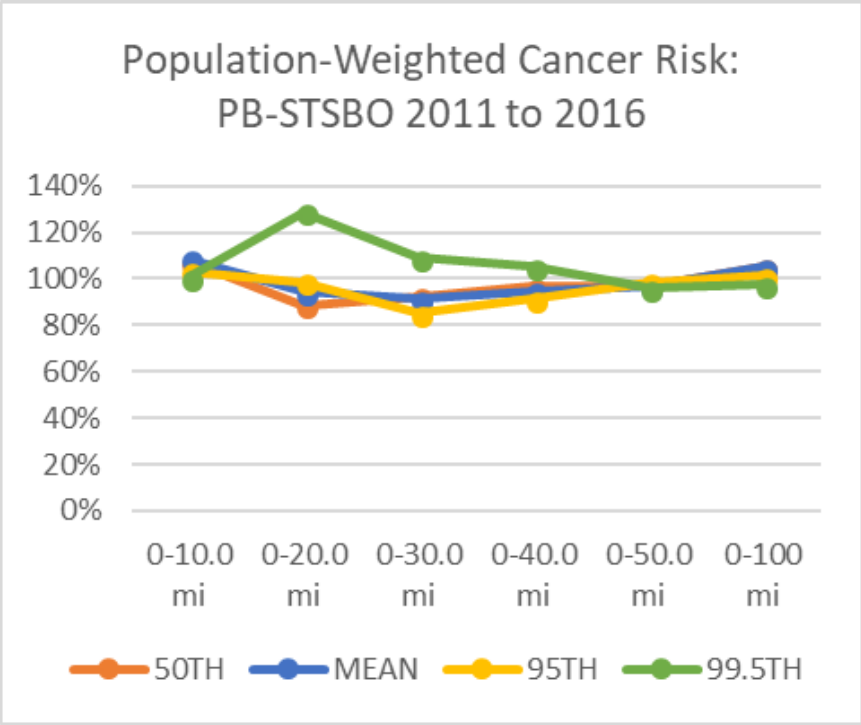
The PB-STSBO 2016 Model

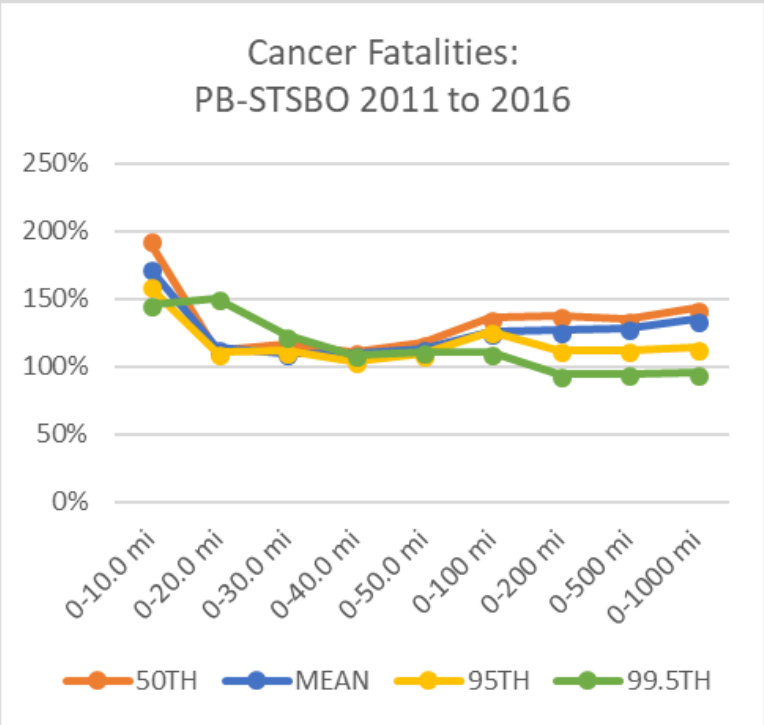
- The **P**each **B**ottom **S**hort-**t**erm **S**tation **B**lack**o**ut (PB-STSBO) accident scenario is a reasonably severe, yet credible event (not worst case)
- The PB-STSBO accident scenario is from the NRC research study called “State-of-the-Art Reactor Consequence Analyses (SOARCA)”
- Section 6 updates the MACCS PB-STSBO computer model (with a linear no-threshold dose response) using more current modeling practices based on publicly available information
- The new model is called “PB-STSBO 2016”
- The PB-STSBO results are for comparison and validation purposes

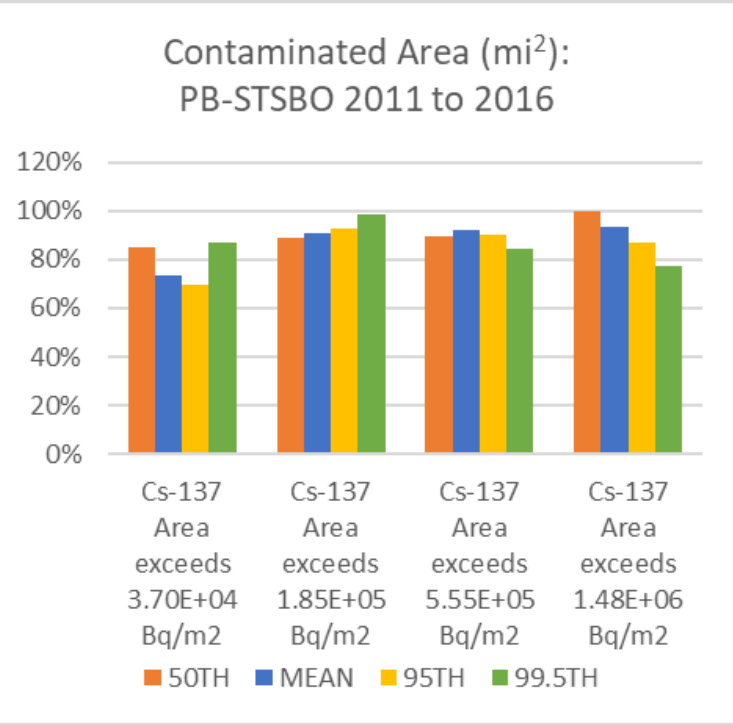
Development Path of MACCS Models



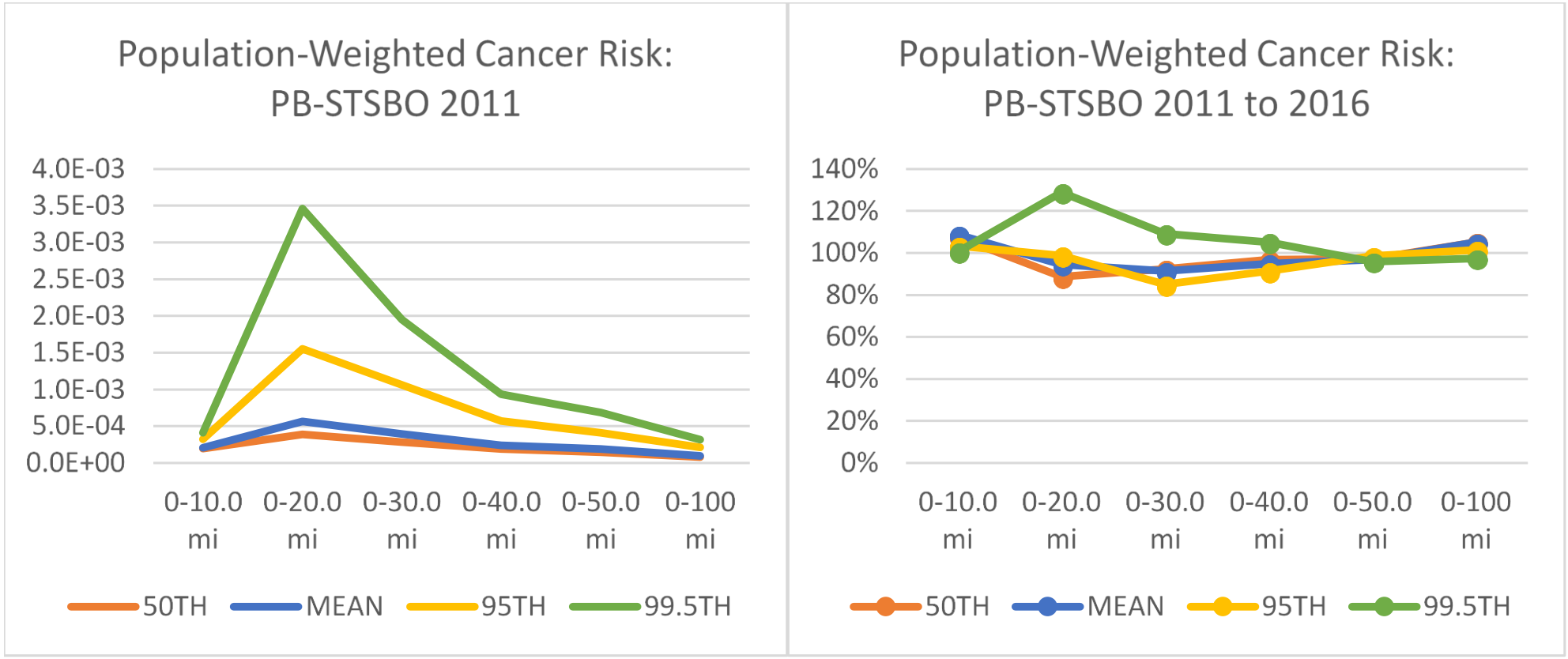
Updates to PB-STSBO Results



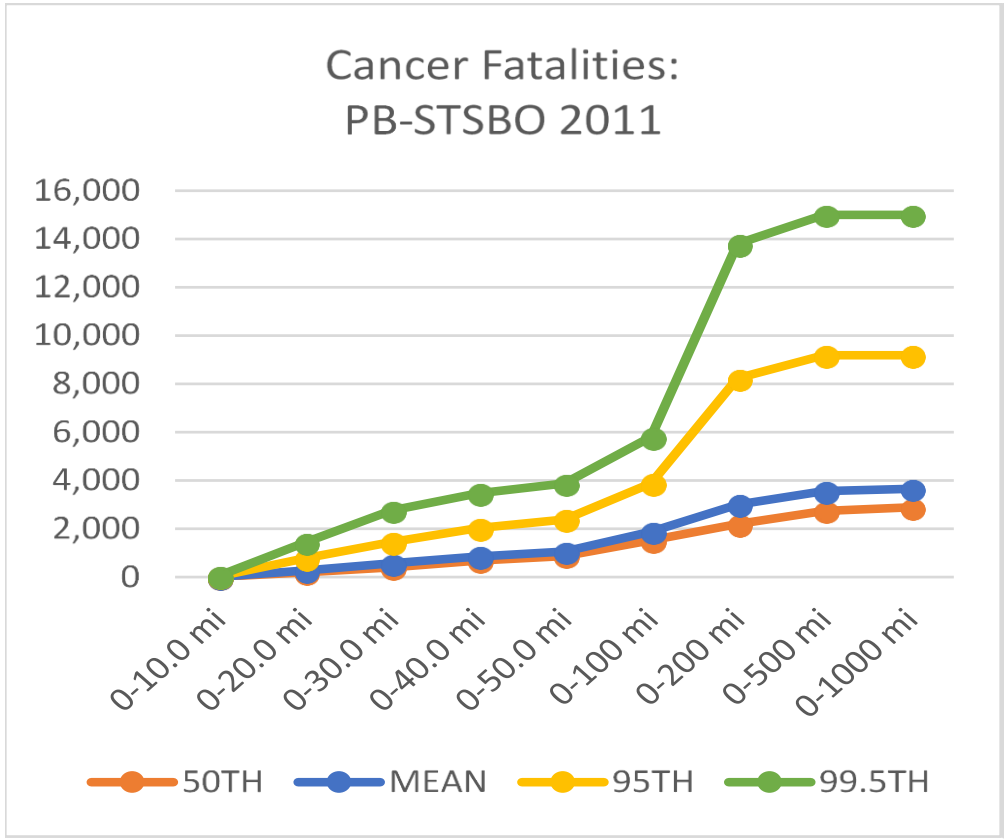


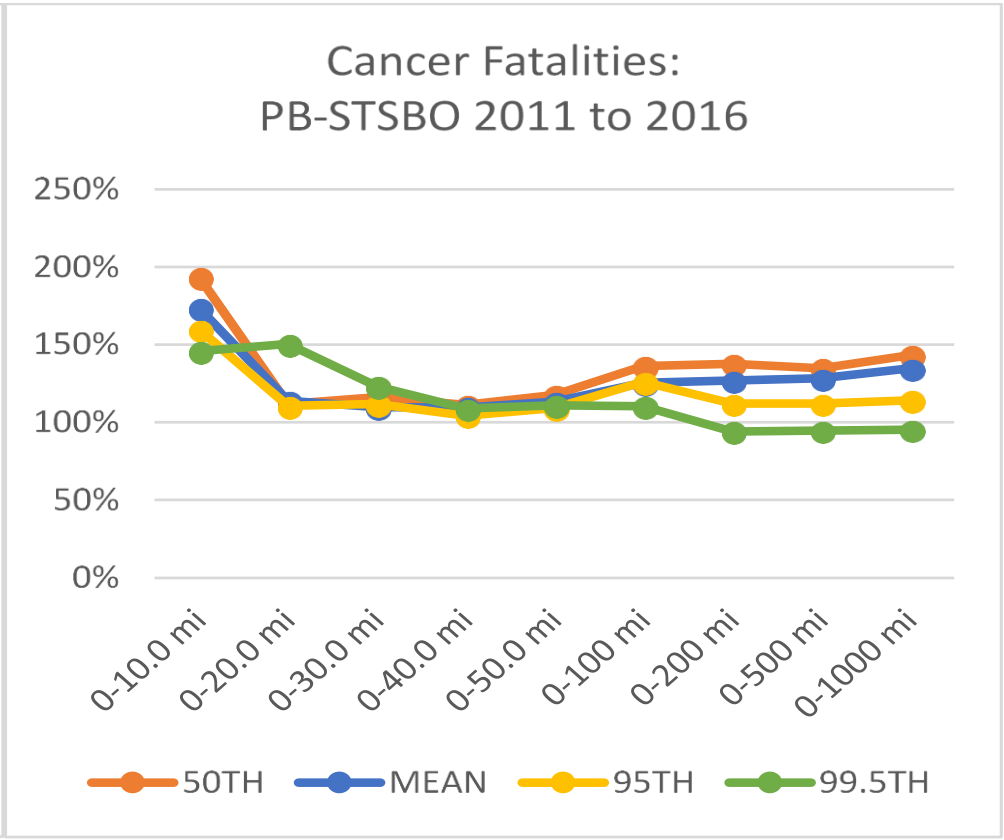


PB-STSBO - Cancer Fatality Risk, Conditional on the Accident Occurring (LNT)

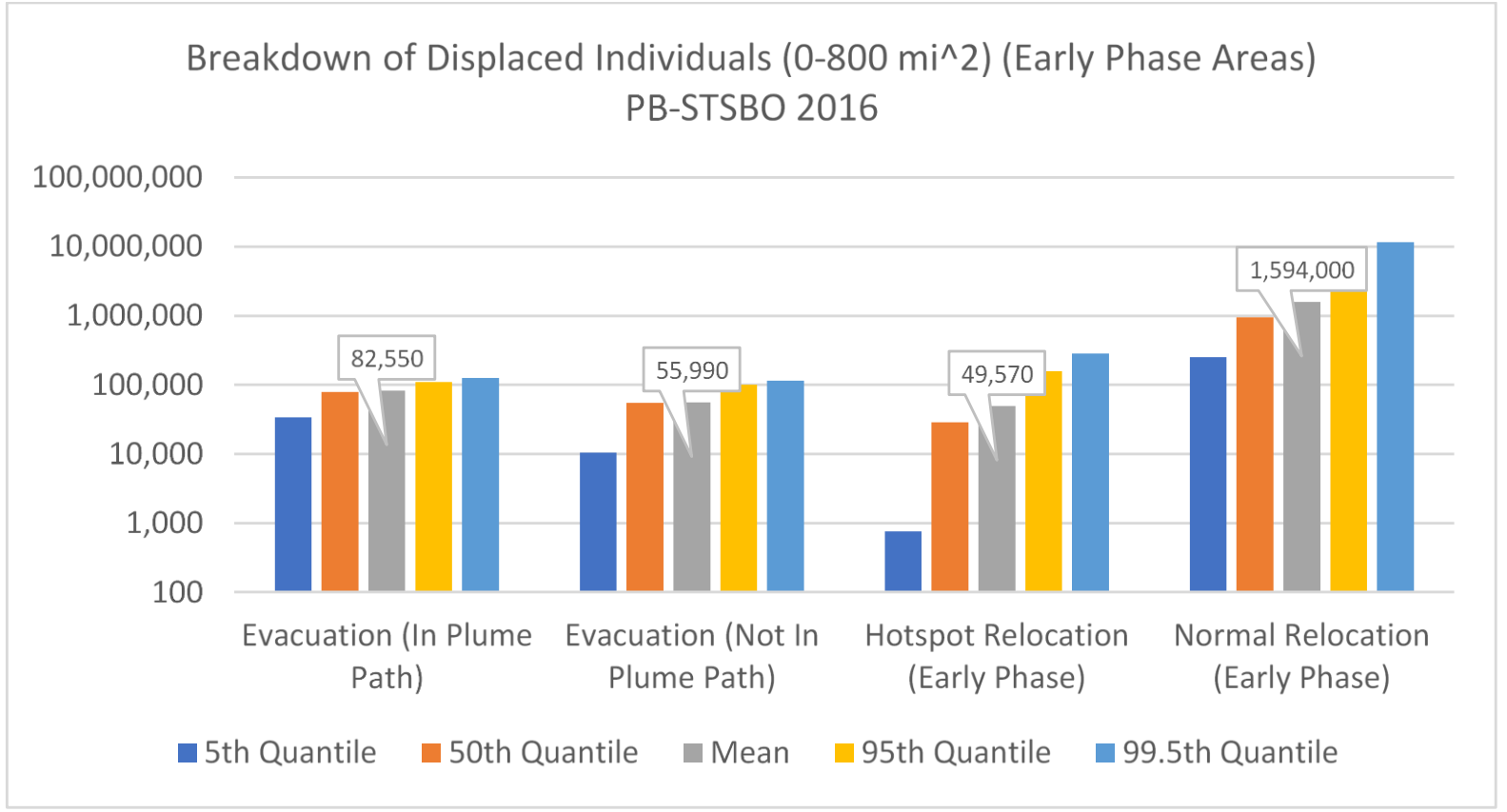


PB-STSBO - Cancer Fatalities (LNT)

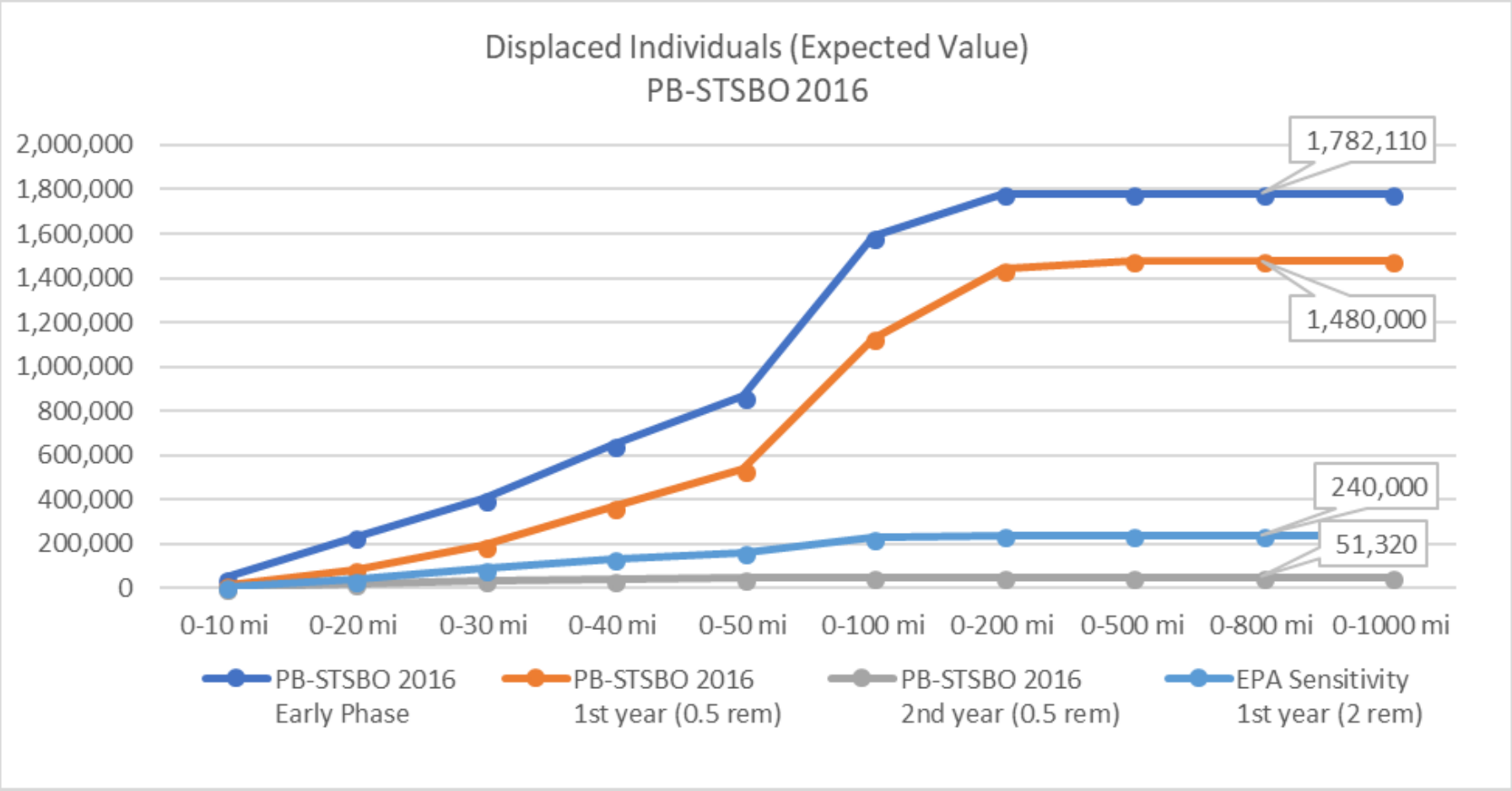




PB-STSBO – Breakdown of Displaced Individuals in the Emergency Phase



PB-STSBO – Displaced Individuals



“PB-STSBO 2016” - Displaced Individuals (average values)

- 1st week – 1,780,000 evacuees
  - 1,640,000 from “hotspot” relocation (0.5 rem; within 24 hours of plume)
- 1st year (0.5 rem) – 1,480,000 displaced individuals
- 2nd year (0.5 rem) – 51,000 displaced individuals

- EPA sensitivity
  - 1st year (2 rem) – 240,000 displaced individuals

List of Nuclear Disaster Costs	MACCS Conventional Approach (MACCS Results / MACCS Cost Inputs)	FIRCA Approach (MACCS Results / FIRCA Cost Inputs)
Market Consequences ($)		
Offsite Property Damage (OPD) and Economic Disruptions (ED)		
• "Loss of Use" (i.e., combined income loss and depreciation of interdicted area)	Value of Property Exceeding Dose Level	
○ Income loss (inside interdicted area)		Displaced Individuals
○ Property damage (inside interdicted area)		Value of Property Exceeding Dose Level
• Income loss (outside interdicted area)	**Not Included**	**Not Included**
• Property damage (outside interdicted area)	**Not Included**	Value of Property Exceeding Activity Level
• Milk and Crop Disposal Costs	Farmland Area	(Included in Cleanup Costs)
Expenditures		
• Relocation Expenses (reoccurring)	Evacuees / Displaced Individuals	Evacuees / Displaced Individuals
• Relocation Expenses (one-time)	Displaced Individuals	Displaced Individuals
• Medical expenses	**Not Included**	Cancer Fatalities
• Cleanup costs (non-farmland)	Displaced Individuals	Displaced Individuals
• Cleanup costs (farmland)	Farmland Area	Farmland Area
• Cleanup costs (outside interdicted area)	**Not Included**	Affected Population
• Waste management (non-farmland)	**Not Included**	Displaced Individuals
• Waste management (farmland)	**Not Included**	Farmland Area
• Waste management (outside interdicted area)	**Not Included**	Affected Population
• Compensation program	**Not Included**	Displaced Individuals
Non-Market Consequences ($)		
• Radiation-induced Health Effects (i.e., cancer)	Collective Dose	Collective Dose
• Burden of Societal Disruptions (inside interdicted area)	**Not Included**	Displaced Individuals
• Burden of Societal Disruptions (outside interdicted area)	**Not Included**	**Not Included**

FIRCA Cost Assessment: Offsite Property Damage

Approach	Region	Property Damages				
		from Contamination / Stigma	from lack of maintanence	from lack of income return	Period	Notes:
MACCS Conventional Approach	Inside Interdicted Area	Not Included	Exponential depreciation (20%) (structures only)	Exponential depreciation (12%)	Annual	Property damage and income loss are combined, limited to property value
	Outside Interdicted Area	Not considered			-	-
FIRCA Proposal	Inside Interdicted Area	Straight-line depreciation (16.7%)		Considered separately	Annual	Full loss after six years, based on Fukushima compensation estimates
	Outside Interdicted Area	Fixed (3-9%)	Not applicable		One-time	Amount of loss dependent on contamination level, according to Fukushima data

FIRCA Cost Assessment: Offsite Property Damage

MACCS conventional approach:

• Interdicted areas: Costs are based on unmaintained depreciation, for both farmland property and non-farmland property. (Altered market conditions from stigma and contamination are not considered. In MACCS, this depreciation is tied to economic disruptions, and is discussed more in section 7.2.3.)

• Outside interdicted areas: Not considered.

• Other: For affected farmland, there is an immediate loss of milk for three months, and an immediate loss of other products (e.g. crops) for a year.

FIRCA proposal:

• Interdicted areas: Costs are based on a straight-line depreciation with a one-sixth loss of the pre-accident property value annually, until a full loss is reached in year six.

• Outside interdicted areas: Costs are based on contamination levels determined by MACCS and the hedonic price relationship between residential land values and contamination developed from Fukushima data (Kawaguchi and Yukutake, 2017).

• Other: Not included.

FIRCA Cost Assessment: Economic Disruptions

MACCS conventional approach:

- Interdicted Areas: Lost income is based on tangible assets, the period of interruption, and a present value calculation.
  - Employee benefits, tax revenue, and consumer surplus not included
  - Wages may be considered in relocation expenses
  - A stricter "farmability" dose criteria applies to farmland, creating a larger area for farm income losses.
- Outside Interdicted Areas: Supply chain effects not included.

FIRCA proposal:

- Interdicted Areas: Income losses are based on GDP per capita of Pennsylvania ($50,742/capita), and the number of displaced individuals. GDP includes tax revenue and employee compensation.
  - Consumer surplus is indirectly considered in the burden of societal disruptions.
- Outside Interdicted Areas: Supply chain effects not included

FIRCA Cost Assessment: Relocation Expenses

- MACCS conventional approach:
  - Relocation expenses (reoccurring): $120 per person-day (EVACST), for a duration of the emergency phase (i.e., 7 days). No intermediate phase is modelled.
  - Relocation expenses (one time): $12,000 per person (POPCST).
- FIRCA proposal:
  - Relocation expenses (reoccurring): $19 per person-day, until displaced individuals are either “able-to-return” or six years, whichever comes first.
  - Relocation expenses (one time): $12,000 per person (same as above).

FIRCA Cost Assessment: Cleanup Costs

MACCS conventional approach:

- Interdicted Area: Cleanup produces dose reduction factors of 3 and 15, with farm cleanup costs of $1,330 and $2,960 per hectare, respectively, and non-farmland cleanup costs of $7,110 and $19,000 per capita, respectively.
- Outside Interdicted Area: Not included.

FIRCA proposal:

- Interdicted Area: Cleanup produces a dose reduction factor of 2, with farm cleanup costs of $493k per hectare of farmland to be decontaminated and non-farmland cleanup costs of $210k per displaced individual from land to be decontaminated. Costs are based on the recent Fukushima decontamination budget of the SDA in Japan (Dec. 2016).
- Outside Interdicted Area: The cost of cleanup outside the interdicted area (i.e., the extended cleanup zone) is $13.4k per affected person in the zone. Like the approach for cleanup costs inside the interdicted area, cleanup costs outside the interdicted area are based on the current Fukushima budget (albeit for the ICSA in Japan, Dec. 2016). The size of the extended cleanup zone is based on a 0.1 rem/yr dose criterion.

FIRCA Cost Assessment: Burden of Societal Disruption (continued)

Murakami et al. (2018b)			FIRCA Approach
Psychological Distress		All other factors that effect subjective well-being	All factors
K6 >= 13	20% loss	Not Included	20% loss
K6 < 13	0% loss		

- The Kessler Psychological Distress Scale (K6), scored from 0-24, is a survey for measuring serious mental illness

FIRCA Cost Assessment: Health Effects

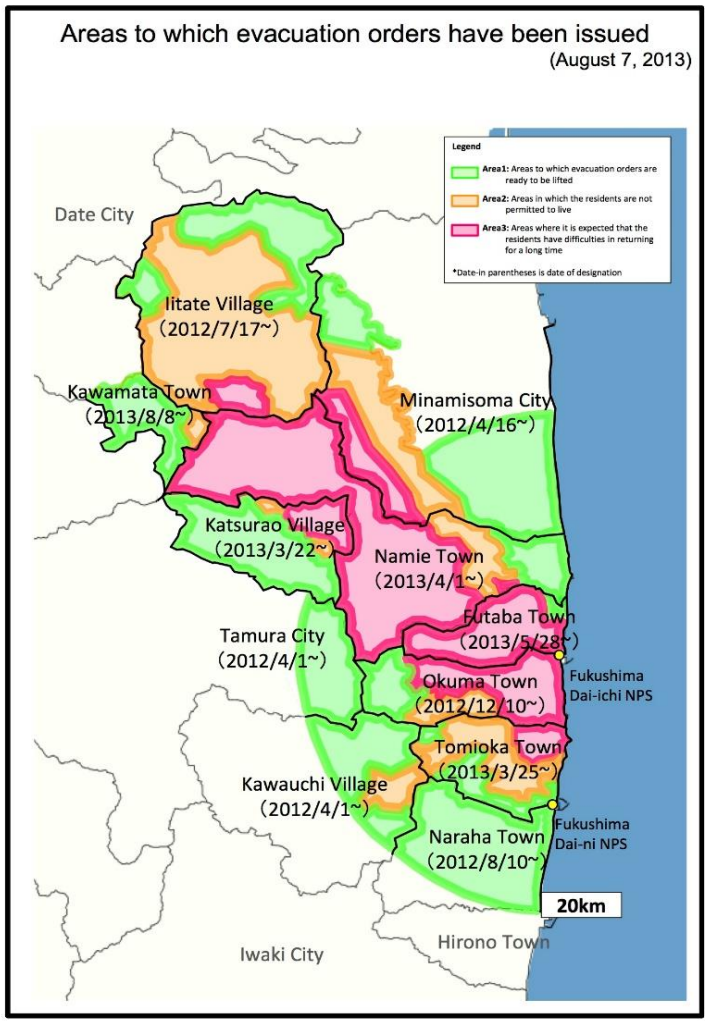
Current MACCS practice:

- Radiation-induced:
  - Stochastic health effects (e.g., cancer): $5400 / person-rem
  - Deterministic effects: Not included
- Health effects related to displacement: Not included
- Deaths during evacuation: Not included

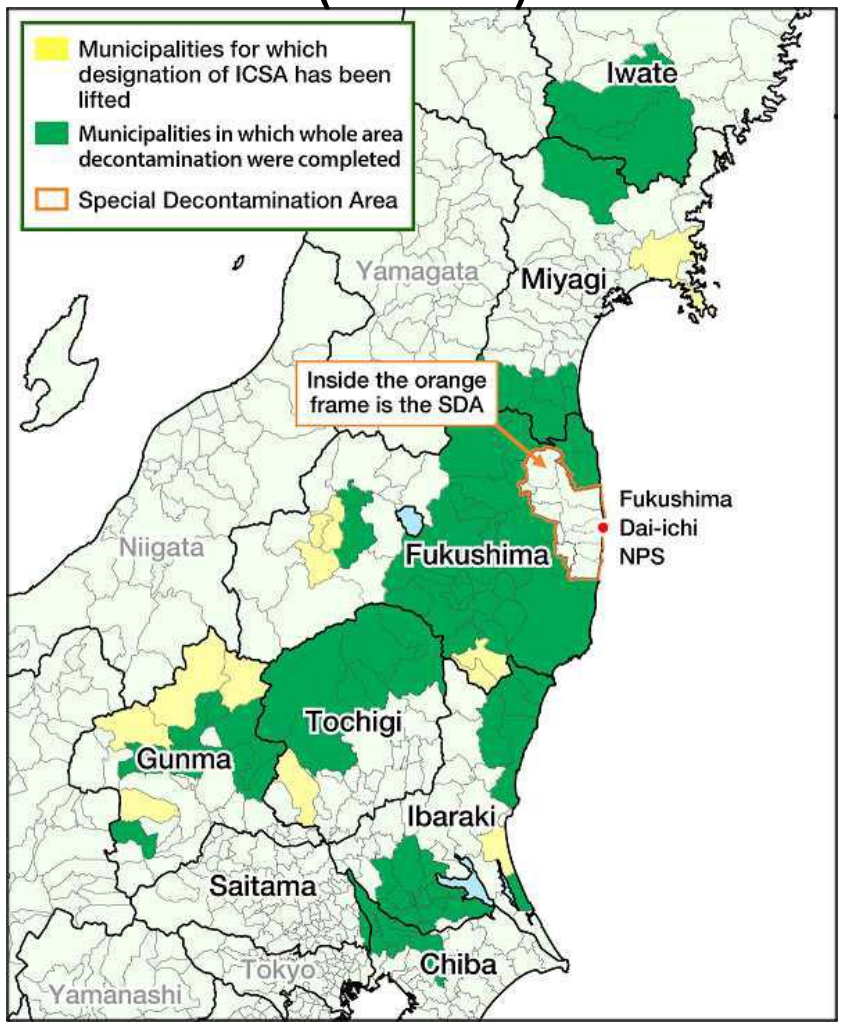
FIRCA proposal:

- Radiation-induced: Same as current practice.
- Health effects related to displacement: Indirectly considered in the burden of societal disruptions
- Deaths during evacuation: Not included

Fukushima Special Decontamination Area (SDA)



Japan Intensive Contamination Survey Area (ICSA)



Decontamination Modeling: Fukushima-informed Cleanup Costs

Land Use Category	Cleanup Cost	Cost-to-decontaminate Estimate (per unit)	Units of Measure for Cleanup Size
SDA farmland	¥0.47T ($4.2B)	¥55.8M ($493k)	Per displaced individual from decontaminated land
SDA non-farmland	¥1.46T ($12.9B)	¥23.8M ($210k)	Per hectares of decontaminated farmland
ICSA	¥2.07T ($18.3B)	¥1.52M ($13.4k)	Per affected person

Decontamination Modeling: Fukushima-informed Waste Costs

Land Use Category	Volume of waste (m^3)	Proportion of waste from area	Waste cost from area (yen)	Cost-of-waste Estimate (per unit)	Units of measure for disaster size
SDA Farmland*	2.21E+06	13.40%	¥214B	¥25.2M ($223k)	Per decontaminated hectare of farmland
SDA Non-Farmland*	6.79E+06	41.20%	¥658B	¥1.08M ($95.1k)	Per displaced individual from decontaminated land
ICSA	7.50E+06	45.50%	¥727B	¥0.53M ($4.72k)	Per affected person
Total	1.65E+07	100.00%	¥1600B	¥0.097M ($0.86k)	Per cubic meter

* Assumes 9 million m^3 of waste from SDA is distributed proportional to anticipated cleanup costs

FIRCA Cost Assessment: Management of Radioactive Waste Cost

- MACCS conventional approach: Not included.
- FIRCA proposal: 223k per hectare of interdicted farmland, $95.1k per displaced person, and $4.72k per affect person in the extended cleanup zone. Like the approach for cleanup costs, waste management costs are based on the current Fukushima budget (albeit for the ISF, Dec. 2016), and scaled based on the size of the cleanup area.

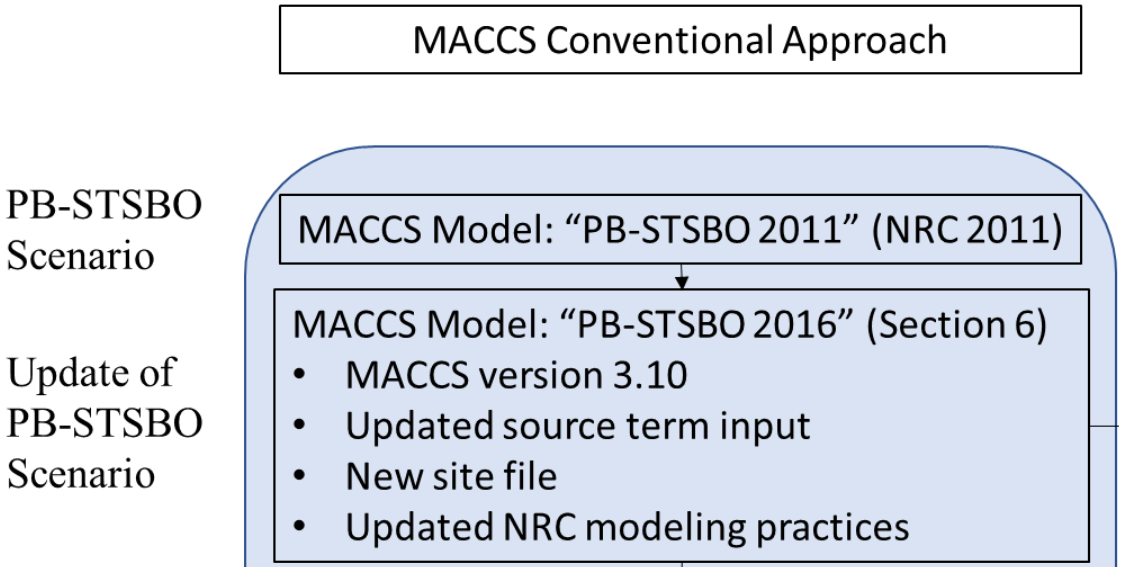
FIRCA Cost Assessment: Impacts Over Time

Nuclear Disaster Costs	MACCS Conventional Approach		FIRCA Approach	
	Loss Over Time	Max Impact Period	Loss Over Time	Max Impact Period
Market Consequences				
Offsite Property Damage (OPD) and Economic Disruptions (ED)				
• "Loss of Use" (i.e., combined income loss and depreciation of interdicted area)	Diminishing	N/A		
○ Income loss (Inside Interdicted Area)			Diminishing	6 years
○ Property damage (Inside Interdicted Area)			Constant	6 years
• Income loss (Outside Interdicted Area)	Not Included		Not Included	
• Property damage (Outside Interdicted Area)	Not Included		Fixed	N/A
• Milk and Crop Disposal Costs	Fixed	N/A	Not Included	
Expenditures				
• Relocation Expenses (reoccurring)	Constant	7 days	Constant	6 years
• Relocation Expenses (one-time)	Fixed	N/A	Fixed	N/A
• Medical Expenses	Not Included		Fixed	N/A
• Cleanup Costs	Fixed	N/A	Fixed	N/A
• Waste Management	Not Included		Fixed	N/A
• Compensation Program	Not Included		Diminishing	6 years
Non-Market Consequences				
• Radiation-induced Health Effects (i.e., cancer)	Fixed	N/A	Fixed	N/A
• Burden of Societal Disruptions (Inside Interdicted Area)	Not Included		Diminishing	6 years
• Burden of Societal Disruptions (Outside Interdicted Area)	Not Included		Not Included	

Analysis Approach: New Methods

- Two approaches for valuing disaster impacts:
  - MACCS conventional approach reflects recent NRC practices
  - FIRCA approach attempts to better capture some impacts

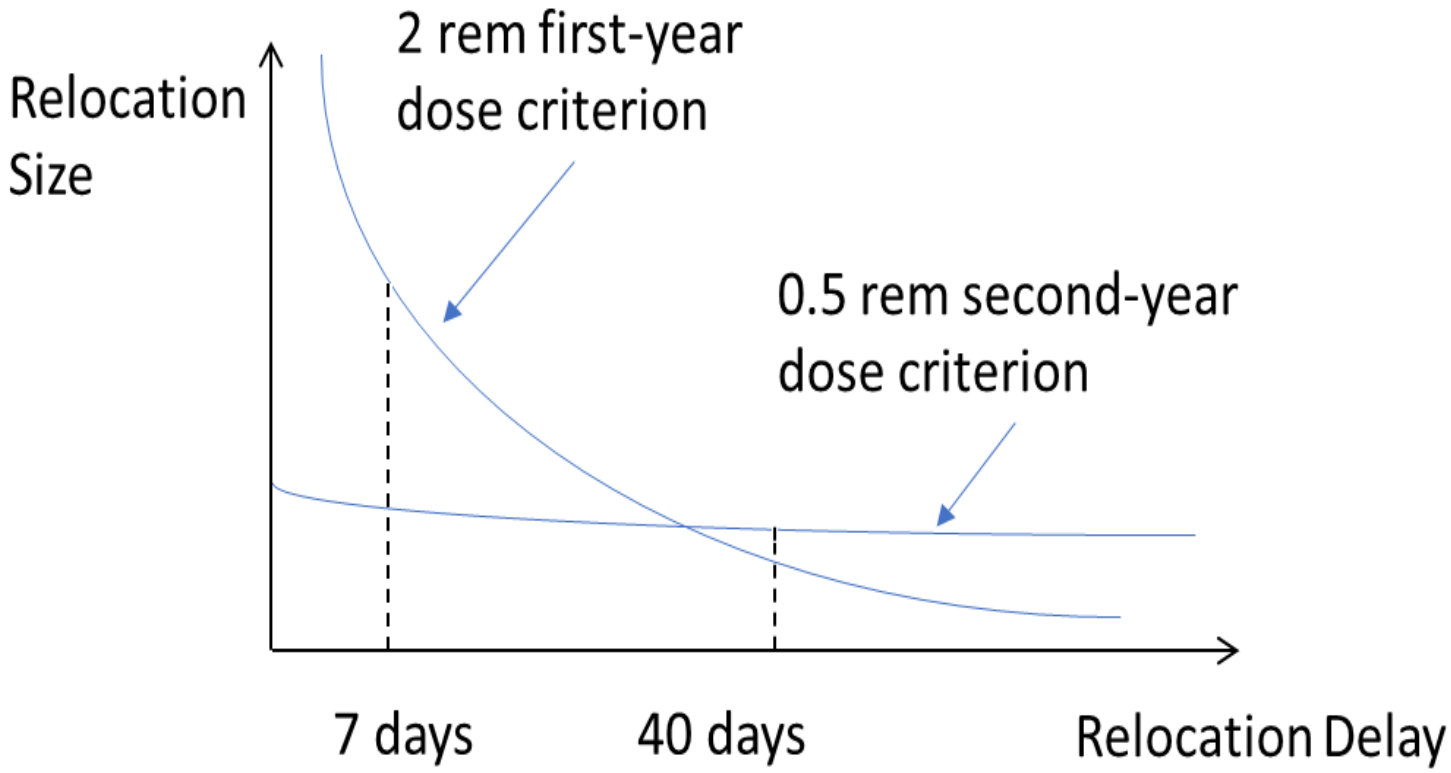
Development Path of MACCS Models



Accident Modeling Impacts (for RP Accident Scenario)

Accident Modeling Impacts	RP Conventional Approach Model	FIRCA Model	Ratio
Radiation-induced Health Impacts			
Early Fatalities	-	-	-
Collective Dose (person-Sv) (1-year recovery)	68,760	61,650	0.90
Collective Dose (person-Sv) (5.7-year recovery)	66,220	58,920	0.89
Cancer Fatalities (1-year recovery)	3,160	2,928	0.93
Cancer Fatalities (5.7-year recovery)	3,063	2,816	0.92
Countermeasure-related Impacts			
Emergency Phase Individuals (e.g., evacuees)	691,500	154,420	0.22
What is the limiting PAG criteria for relocation?	N/A	2nd year	N/A
Total Land in Interdicted Area (mi^2)	807	3,078	4
Farmland in Interdicted Area (mi^2)	289	1,111	3.84
Displaced Individuals	225,400	992,456	4.4
Population of Extended Cleanup Zone (between 0.1 rem and the limiting PAG criterion)	N/A	2,741,544	N/A
Reoccupation-related Impacts			
What is the limiting PAG criterion for reoccupation?	N/A	2nd year	N/A
"Able-to-Return" Population (1-year recovery)	224,550	413,500	1.84
"Able-to-Return" Population (5.7-year recovery)	225,277	904,800	4.02
"Able-to-Return" Fraction (1-year recovery)	99.6%	42%	0.42
"Able-to-Return" Fraction (5.7-year recovery)	99.9%	91%	0.91
Offsite Property-related Impacts			
Property Value between 6.3-18.9 kBq/m^2 Cs-137 ($)	N/A	6.40E+11	N/A
Property Value between 18.9-37.9 kBq/m^2 Cs-137 ($)	N/A	3.81E+11	N/A
Property Value between 37.9-63.1 kBq/m^2 Cs-137 ($)	N/A	1.96E+11	N/A
Property Value between 63.1-86.3 kBq/m^2 Cs-137 ($)	N/A	1.29E+11	N/A
Property Value of Interdicted area (~86.3+ kBq/m^2 Cs-137) ($)	N/A	3.85E+11	N/A

Accident Modeling Impacts: Relationship Between Relocation Delay and Relocation Size



Nuclear Disaster Costs	FIRCA Model		FIRCA.s Model		FIRCA.s.d2 Model		FIRCA.s.d3 Model		FIRCA.s.d4 Model		FIRCA.s.d5 Model	
Market Consequences ($)												
Offsite Property Damage												
*Inside Interdicted Area	3.67E+11	26%	6.49E+10	17%	2.03E+10	8%	1.02E+10	5%	3.31E+09	2%	3.11E+09	2%
*Outside Interdicted Area	5.63E+10	4%	8.43E+10	22%	8.87E+10	37%	8.97E+10	43%	9.04E+10	47%	9.04E+10	47%
Economic Disruptions (Income Loss)												
*Inside Interdicted Area	1.74E+11	12%	2.86E+10	8%	9.13E+09	4%	4.18E+09	2%	1.44E+09	1%	1.36E+09	1%
*Outside Interdicted Area	Not Included		Not Included		Not Included		Not Included		Not Included		Not Included	
Expenditures												
*Relocation Expenses (reoccurring)	3.88E+10	3%	6.47E+09	2%	2.15E+09	1%	1.05E+09	0%	4.39E+08	0%	4.21E+08	0%
*Relocation Expenses (one-time)	1.19E+10	1%	1.96E+09	1%	6.25E+08	0%	2.86E+08	0%	9.83E+07	0%	9.33E+07	0%
*Medical Expenses	4.11E+08	0%	5.71E+08	0%	5.86E+08	0%	6.28E+08	0%	6.39E+08	0%	6.40E+08	0%
*Cleanup Costs (Inside Interdicted Area)	2.42E+11	17%	4.32E+10	11%	1.40E+10	6%	6.13E+09	3%	2.02E+09	1%	2.09E+09	1%
*Cleanup Costs (Outside Interdicted Area)	3.68E+10	3%	2.53E+10	7%	2.68E+10	11%	2.72E+10	13%	2.74E+10	14%	2.74E+10	14%
*Waste Management (Inside Interdicted Area)	1.09E+11	8%	1.95E+10	5%	6.34E+09	3%	2.77E+09	1%	9.12E+08	0%	9.43E+08	0%
*Waste Management (Outside Interdicted Area)	1.30E+10	1%	8.90E+09	2%	9.42E+09	4%	9.56E+09	5%	9.63E+09	5%	9.63E+09	5%
*Compensation Program	4.11E+10	3%	6.77E+09	2%	2.16E+09	1%	9.89E+08	0%	3.40E+08	0%	3.22E+08	0%
Market Total	**1.09E+12**	**78%**	**2.91E+11**	**76%**	**1.80E+11**	**75%**	**1.53E+11**	**73%**	**1.37E+11**	**72%**	**1.36E+11**	**72%**
Non-Market Consequences ($)												
*Radiation-induced Health Effects (i.e., cancer)	3.18E+10	2%	4.49E+10	12%	4.66E+10	19%	5.08E+10	24%	5.20E+10	27%	5.21E+10	27%
*Burden of Societal Disruptions	2.82E+11	20%	4.64E+10	12%	1.48E+10	6%	6.78E+09	3%	2.33E+09	1%	2.21E+09	1%
Non-Market Total	**3.14E+11**	**22%**	**9.13E+10**	**24%**	**6.14E+10**	**25%**	**5.75E+10**	**27%**	**5.43E+10**	**28%**	**5.43E+10**	**28%**
Grand Total	**1.40E+12**	**100%**	**3.82E+11**	**100%**	**2.42E+11**	**100%**	**2.10E+11**	**100%**	**1.91E+11**	**100%**	**1.91E+11**	**100%**

Nuclear Disaster Costs	FIRCA Model		FIRCA.s Model		FIRCA.s.d2 Model		FIRCA.s.d3 Model		FIRCA.s.d4 Model		FIRCA.s.d5 Model	
Market Consequences ($)												
Offsite Property Damage												
*Inside Interdicted Area	3.67E+11	26%	6.49E+10	17%	2.03E+10	8%	1.02E+10	5%	3.31E+09	2%	3.11E+09	2%
*Outside Interdicted Area	5.63E+10	4%	8.43E+10	22%	8.87E+10	37%	8.97E+10	43%	9.04E+10	47%	9.04E+10	47%
Economic Disruptions (Income Loss)												
*Inside Interdicted Area	1.74E+11	12%	2.86E+10	8%	9.13E+09	4%	4.18E+09	2%	1.44E+09	1%	1.36E+09	1%
*Outside Interdicted Area	Not Included		Not Included		Not Included		Not Included		Not Included		Not Included	
Expenditures												
*Relocation Expenses (reoccurring)	3.88E+10	3%	6.47E+09	2%	2.15E+09	1%	1.05E+09	0%	4.39E+08	0%	4.21E+08	0%
*Relocation Expenses (one-time)	1.19E+10	1%	1.96E+09	1%	6.25E+08	0%	2.86E+08	0%	9.83E+07	0%	9.33E+07	0%
*Medical Expenses	4.11E+08	0%	5.71E+08	0%	5.86E+08	0%	6.28E+08	0%	6.39E+08	0%	6.40E+08	0%
*Cleanup Costs (Inside Interdicted Area)	2.42E+11	17%	4.32E+10	11%	1.40E+10	6%	6.13E+09	3%	2.02E+09	1%	2.09E+09	1%
*Cleanup Costs (Outside Interdicted Area)	3.68E+10	3%	2.53E+10	7%	2.68E+10	11%	2.72E+10	13%	2.74E+10	14%	2.74E+10	14%
*Waste Management (Inside Interdicted Area)	1.09E+11	8%	1.95E+10	5%	6.34E+09	3%	2.77E+09	1%	9.12E+08	0%	9.43E+08	0%
*Waste Management (Outside Interdicted Area)	1.30E+10	1%	8.90E+09	2%	9.42E+09	4%	9.56E+09	5%	9.63E+09	5%	9.63E+09	5%
*Compensation Program	4.11E+10	3%	6.77E+09	2%	2.16E+09	1%	9.89E+08	0%	3.40E+08	0%	3.22E+08	0%
Market Total	**1.09E+12**	**78%**	**2.91E+11**	**76%**	**1.80E+11**	**75%**	**1.53E+11**	**73%**	**1.37E+11**	**72%**	**1.36E+11**	**72%**
Non-Market Consequences ($)												
*Radiation-induced Health Effects (i.e., cancer)	3.18E+10	2%	4.49E+10	12%	4.66E+10	19%	5.08E+10	24%	5.20E+10	27%	5.21E+10	27%
*Burden of Societal Disruptions	2.82E+11	20%	4.64E+10	12%	1.48E+10	6%	6.78E+09	3%	2.33E+09	1%	2.21E+09	1%
Non-Market Total	**3.14E+11**	**22%**	**9.13E+10**	**24%**	**6.14E+10**	**25%**	**5.75E+10**	**27%**	**5.43E+10**	**28%**	**5.43E+10**	**28%**
Grand Total	**1.40E+12**	**100%**	**3.82E+11**	**100%**	**2.42E+11**	**100%**	**2.10E+11**	**100%**	**1.91E+11**	**100%**	**1.91E+11**	**100%**

	Main Results		One-way Sensitivity Analyses													
Accident Modeling Assumptions	**MACCS Conventional Approach**	**FIRCA Approach**	**1st year Relocation Dose Criterion**		**2nd year Relocation Dose Criterion**		**EPA-based Relocation Criteria (Combined Summary[1])**		**Fukushima-informed Relocation**		**Fukushima-informed Cleanup**		**EPA-based Emergency Phase Dose Projection Period**		**EPA-based long-term shielding**	
Intermediate phase / decontamination time[2] (years) (1-year recovery)	0 / 1	**1 / 0**	**0 / 1**		**1 / 0**		**Various**		*0 / 1*		*0 / 1*		*0 / 1*		*0 / 1*	
Intermediate phase / decontamination time[2] (years) (5.7-year recovery)	0 / 5.7	**1 / 4.7**	**0 / 5.7**		**1 / 4.7**		**1 / 4.7**		*0 / 5.7*		*0 / 5.7*		*0 / 5.7*		*0 / 5.7*	
Long-term dose criterion	4 rem (5 years)	**2 rem (1st year); 0.5 rem (2nd year)**	**2 rem**		**0.5 rem**		**2 rem (1st year); 0.5 rem (2nd year)**		*4 rem (5 years)*		*4 rem (5 years)*		*4 rem (5 years)*		*4 rem (5 years)*	
Emergency phase duration (days)	7	**40**	*7*		*7*		*7*		**40**		*7*		*7*		*7*	
Emergency phase 1 rem relocation	yes	**no**	*yes*		*yes*		*yes*		**no**		*yes*		*yes*		*yes*	
Cleanup dose reduction factors	3, 15	**2**	*3, 15*		*3, 15*		*3, 15*		*3, 15*		**2**		*3, 15*		*3, 15*	
Emergency phase dose projection period (days)	7	**4**	*7*		*7*		*7*		*7*		*7*		**4**		*7*	
Protective actions credit long-term shielding	yes	**no**	*yes*		*yes*		*yes*		*yes*		*yes*		*yes*		**no**	
Accident Modeling Impacts	**RP Conventional Approach Model**	**FIRCA Model**	**Value**	**Ratio**	**Value**	**Ratio**	**Value**	**Ratio**	**Value**	**Ratio**	**Value**	**Ratio**	**Value**	**Ratio**	**Value**	**Ratio**
Health Impacts (Radiation-induced)																
Early Fatalities	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Collective Dose (person-Sv) (1-year recovery)	68,760	61,650	*63,830*	*0.93*	62,510	0.91	62,510	0.91	87,080	1.27	70,380	1.02	69,510	1.01	42,250	0.61
Collective Dose (person-Sv) (5.7-year recovery)	66,550	58,920	*60,840*	*0.91*	61,200	0.92	61,200	0.92	85,860	1.29	67,260	1.01	66,970	1.01	38,030	0.57
Cancer Fatalities (1-year recovery)	3,160	2,928	*2,957*	*0.94*	2,813	0.89	2,813	0.89	4,056	1.28	3,195	1.01	3,200	1.01	1,930	0.61
Cancer Fatalities (5.7-year recovery)	3,076	2,816	*2,840*	*0.92*	2,762	0.90	2,762	0.90	4,014	1.30	3,086	1.00	3,104	1.01	1,738	0.57
Countermeasure-related Impacts																
Emergency phase Individuals (e.g. evacuees)	691,500	154,420	691,300	1.00	691,300	1.00	691,300	1.00	155,700	0.23	691,270	1.00	584,650	0.85	691,300	1.00
What is the limiting PAG criteria for relocation?	N/A	2nd year	1st year		*2nd year*		1st year		N/A		N/A		N/A		N/A	
Total Land in Interdicted Area (mi^2)	807	3,078	1,349	1.67	*468*	*0.6*	1,349	1.67	369	0.46	807	1.00	807	1.00	3,883	4.81
Farmland in Interdicted Area (mi^2)	289	1,111	460	1.59	*172*	*0.6*	460	1.59	133	0.46	289	1.00	289	1.00	1,372	4.75
Displaced Individuals	225,400	992,456	362,200	1.61	*121,642*	*0.5*	362,200	1.61	91,400	0.41	225,383	1.00	225,400	1.00	1,228,786	5.45
Reoccupation-related Impacts																
What is the limiting PAG criteria for reoccupation?	N/A	2nd year	*1st year*		2nd year		2nd year		N/A		N/A		N/A		N/A	
"Able-to-Return" Population (1-year recovery)	224,550	413,500	*361,562*	*2*	118,203	0.53	358,761	1.60	90,612	0.40	219,500	0.98	224,554	1.00	1,223,650	5.45
"Able-to-Return" Population (5.7-year recovery)	225,277	904,800	*362,186*	*1.61*	121,040	0.54	361,598	1.61	91,357	0.41	223,200	0.99	225,277	1.00	1,226,847	5.45
"Able-to-Return" Fraction (1-year recovery)	99.6%	42%	99.8%	1.00	97.2%	0.98	99.1%	0.99	99.1%	1.00	97.4%	0.98	99.6%	1.00	99.6%	1.00
"Able-to-Return" Fraction (5.7-year recovery)	99.9%	91%	100.0%	1.00	99.5%	1.00	99.8%	1.00	100.0%	1.00	99.0%	0.99	99.9%	1.00	99.8%	1.00

[1] The EPA-based relocation dose criteria sensitivity is based on two calculations, one for the 2 rem first-year criterion and one for the 0.5 rem second-year criterion, combined into one summary set of sensitivity results.

[2] The accident modeling assumption titled "Intermediate phase / decontamination time (years)" indicates the number of years allocated to the MACCS intermediate phase (DUR_INTPHAS) vs the MACCS decontamination time (TIMDEC). The combined value is the time that decontamination completes, however it is necessary to distribute some or all of this time to the intermediate phase when analyzing the second-year relocation dose criterion so that the criterion is correctly applied to the second year.

Nuclear Disaster Costs (5.7 year Recovery)

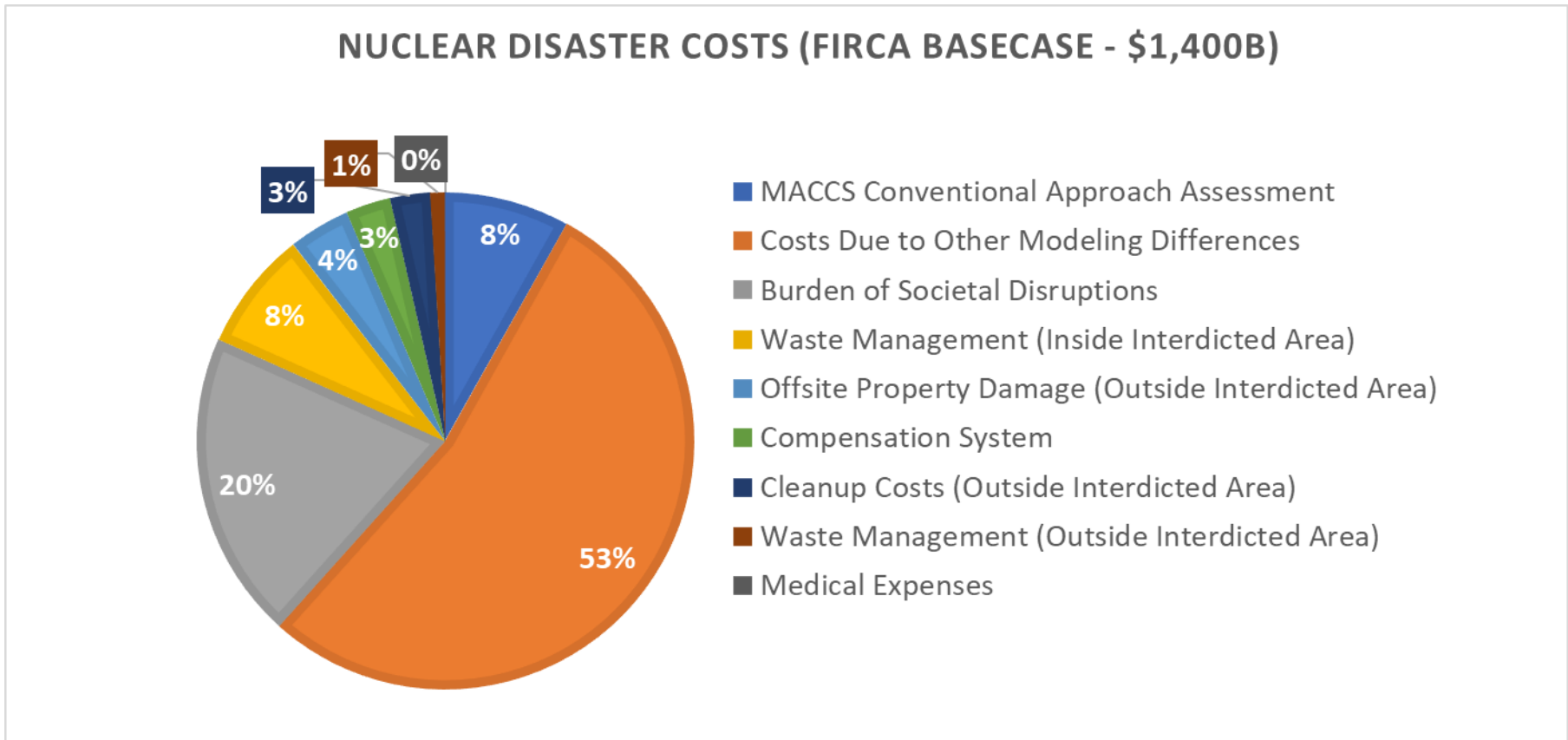
Nuclear Disaster Costs	RP Conventional Approach Model		FIRCA Model	
Market Consequences ($)				
Offsite Property Damage (OPD) and Economic Disruptions (ED)				
• "Loss of Use" (i.e., combined income loss and depreciation of interdicted area)	7.26E+10	64%		
○ Income Loss (inside interdicted area)			1.74E+11	10%
○ Property Damage (inside interdicted area)			3.67E+11	21%
• Income loss (outside interdicted area)	Not Included	-	Not Included	-
• Property damage (outside interdicted area)	Not Included	-	5.63E+10	3%
• Milk and crop disposal costs	5.12E+08	0%	Not Included	-
ED / OPD Subtotal	**7.31E+10**	**64%**	**5.97E+11**	**35%**
Expenditures				
• Relocation Expenses (reoccurring)	7.09E+08	1%	3.88E+10	5%
• Relocation Expenses (one-time)	2.70E+09	2%	1.19E+10	1%
• Medical Expenses	Not Included	-	4.11E+08	0%
• Cleanup Costs (inside interdicted area)	1.72E+09	2%	2.42E+11	17%
• Cleanup Costs (outside interdicted area)	Not Included	-	3.68E+10	3%
• Waste Management (inside interdicted area)	Not Included	-	1.09E+11	8%
• Waste Management (outside interdicted area)	Not Included	-	1.30E+10	1%
• Compensation program	Not Included	-	4.11E+10	3%
Market Total	**7.83E+10**	**69%**	**1.09E+12**	**78%**
Non-Market Consequences ($)				
• Radiation-induced Health Effects (i.e., cancer)	3.58E+10	31%	3.18E+10	2%
• Burden of Societal Disruptions (inside interdicted area)	Not Included	-	2.82E+11	19%
• Burden of Societal Disruptions (outside interdicted area)	Not Included	-	Not Included	-
Non-Market Total	**3.58E+10**	**31%**	**3.14E+11**	**22%**
Grand Total	**1.14E+11**	**100%**	**1.40E+12**	**100%**

Nuclear Disaster Costs (5.7 year Recovery)

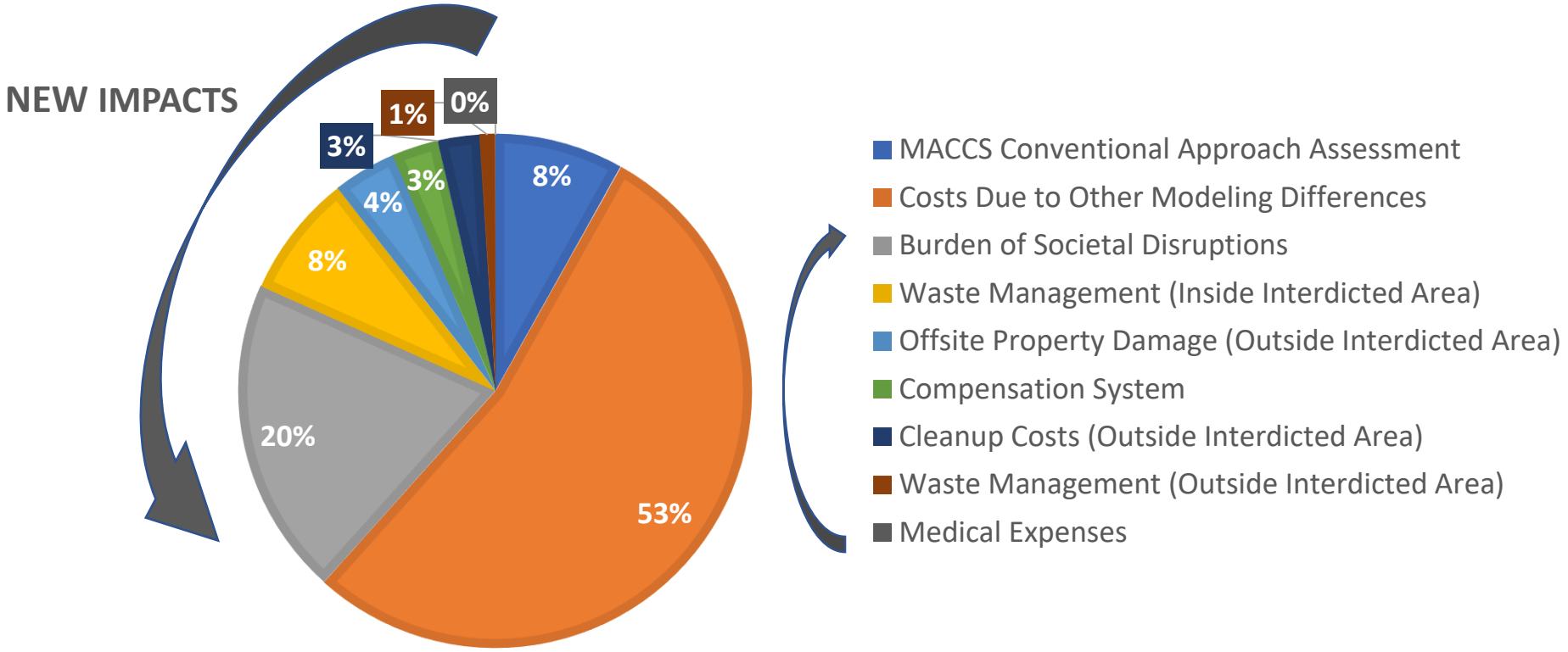
	Main Results ($)			Cost Difference ($)	
Nuclear Disaster Costs	**RP Conventional Approach Model**	**FIRCA Model**	**Ratio**	**New Nuclear Disaster Costs**	**Revised Cost and Modeling Assumptions**
Market Consequences ($)					
Offsite Property Damage (OPD) and Economic Disruptions (EC)					
*"Loss of Use" (i.e., combined income loss and depreciation of interdicted area)	7.26E+10		7.45		4.68E+11
*Income loss (Inside Interdicted Area)		1.74E+11			
*Property damage (Inside Interdicted Area)		3.67E+11			
*Income loss (Outside Interdicted Area)	Not Included	Not Included	-		
*Property damage (Outside Interdicted Area)	Not Included	5.63E+10	-	5.63E+10	
*Milk and Crop Disposal Costs	5.12E+08	Not Included	-	-5.12E+08	
EC / OPD Subtotal	**7.31E+10**	**5.97E+11**	8.2		
Expenditures					
*Relocation Expenses (reoccurring)	7.09E+08	3.88E+10	55		3.81E+10
*Relocation Expenses (one-time)	2.70E+09	1.19E+10	4.4		9.20E+09
*Medical Expenses	Not Included	4.11E+08	-	4.11E+08	
*Cleanup Costs (interdicted area: non-farmland)	1.62E+09	1.90E+11	117		1.89E+11
*Cleanup Costs (interdicted area: farmland)	9.59E+07	5.15E+10	538		5.14E+10
*Cleanup Costs (outside interdicted area)	Not Included	3.68E+10	-	3.68E+10	
*Waste Management (inside interdicted area)	Not Included	1.09E+11	-	1.09E+11	
*Waste Management (outside interdicted area)	Not Included	1.30E+10	-	1.30E+10	
*Compensation program	Not Included	4.11E+10	-	4.11E+10	
Market Total	**7.83E+10**	**1.09E+12**	13.9		
Non-Market Consequences ($)					
*Radiation-induced Health Effects (i.e., cancer)**	3.58E+10	3.18E+10	0.89		-3.94E+09
*Burden of Societal Disruptions (inside interdicted area)	Not Included	2.82E+11	-	2.82E+11	
*Burden of Societal Disruptions (outside interdicted area)	Not Included	Not Included	-		
Non-Market Total	**3.58E+10**	**3.14E+11**	8.8		
Grand Total	**1.14E+11**	**1.40E+12**	12.3	5.38E+11	7.52E+11
Total Difference				1.29E+12	

Current Recovery Preparedness Plans are Incomplete

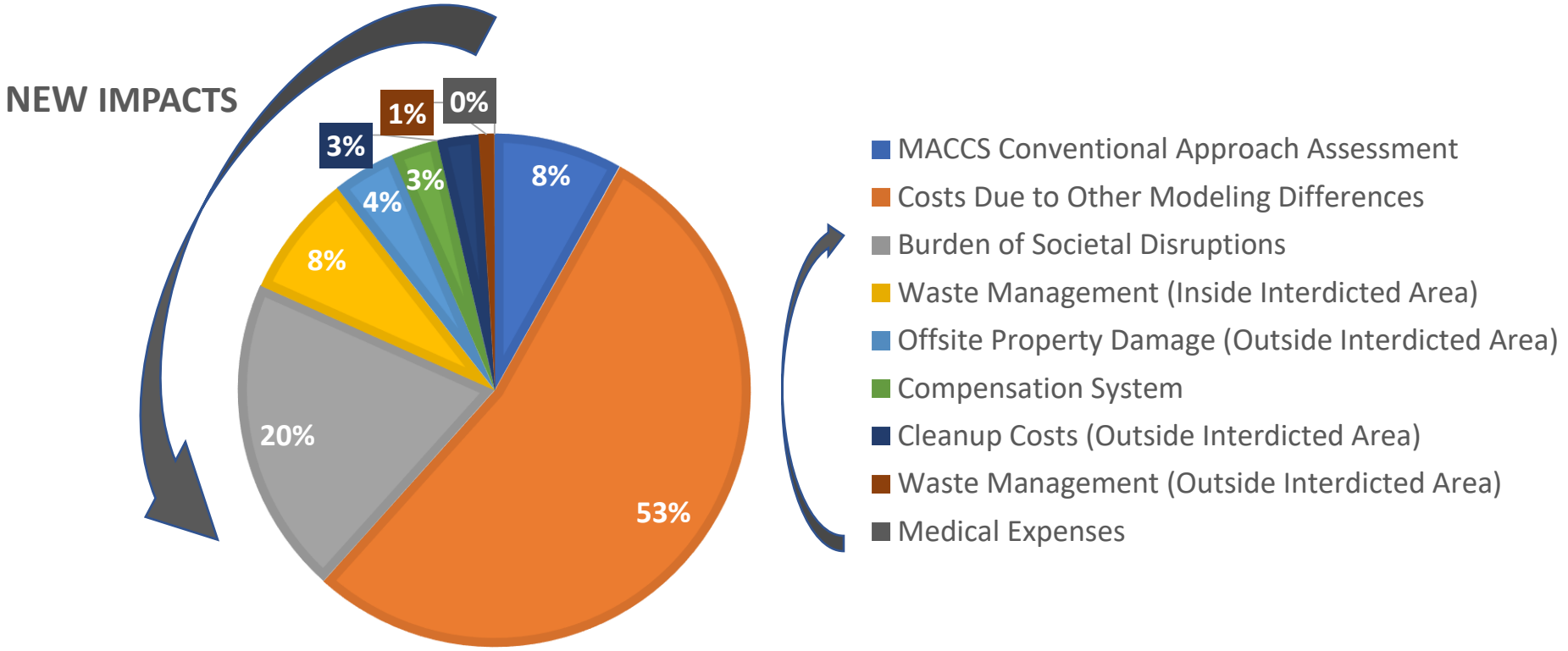
- Objective, strategies, and guidelines for recovery planning are instead intended to be developed post-accident
- Significant development of recovery preparedness could help speed the recovery process
- FIRCA predicts that expedited (one-year) recovery will reduce nuclear disaster impacts in the case study from $1.40T for a postulated 5.7-year recovery period (as at Fukushima) to $984B.
  - While a one-year recovery period may be optimistic, faster recovery can still provide a significant benefit.


NUCLEAR DISASTER COSTS (FIRCA BASECASE - $1,400B)
8%
53%
20%
8%
4%
3%
3%
1%
0%
MACCS Conventional Approach Assessment
Costs Due to Other Modeling Differences
Burden of Societal Disruptions
Waste Management (Inside Interdicted Area)
Offsite Property Damage (Outside Interdicted Area)
Compensation System
Cleanup Costs (Outside Interdicted Area)
Waste Management (Outside Interdicted Area)
Medical Expenses

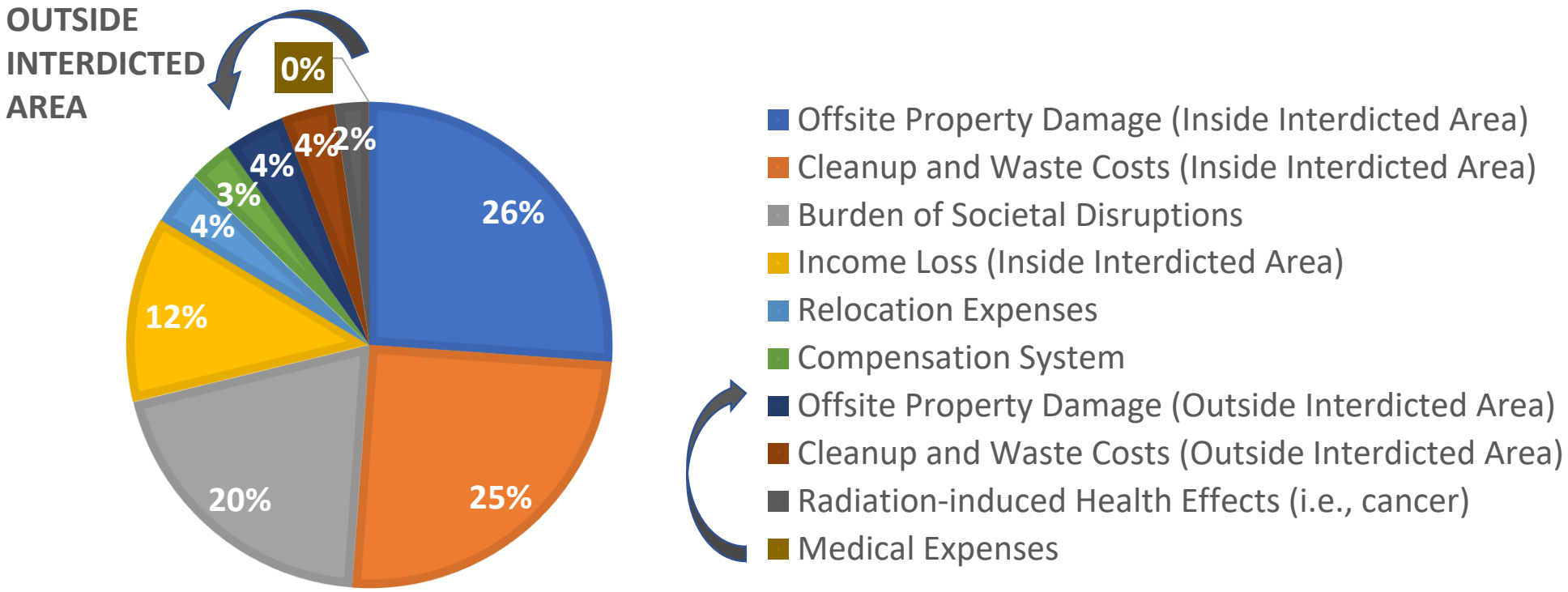
NUCLEAR DISASTER COSTS (FIRCA BASECASE - $1,400B)



NUCLEAR DISASTER COSTS (FIRCA BASECASE - $1,400B)

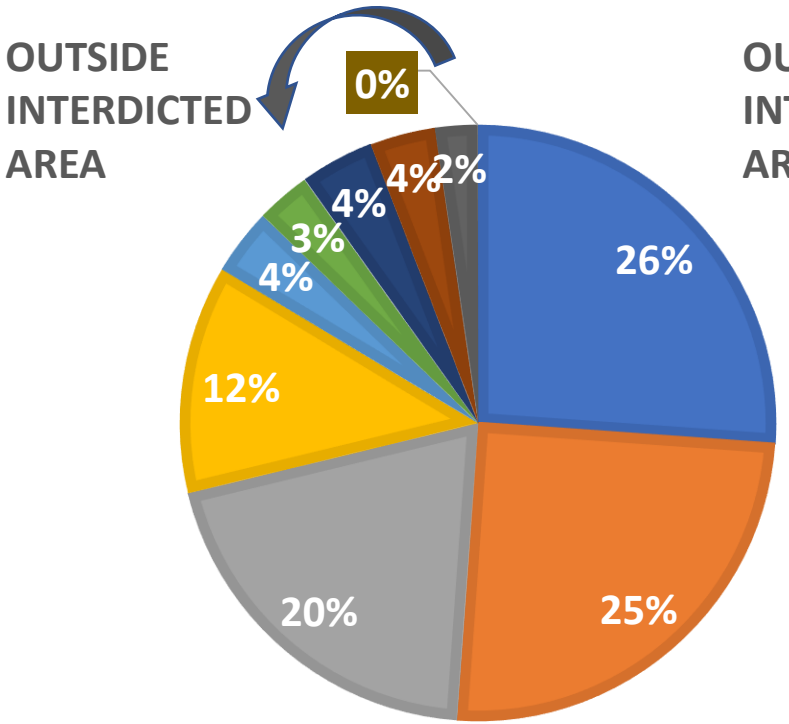
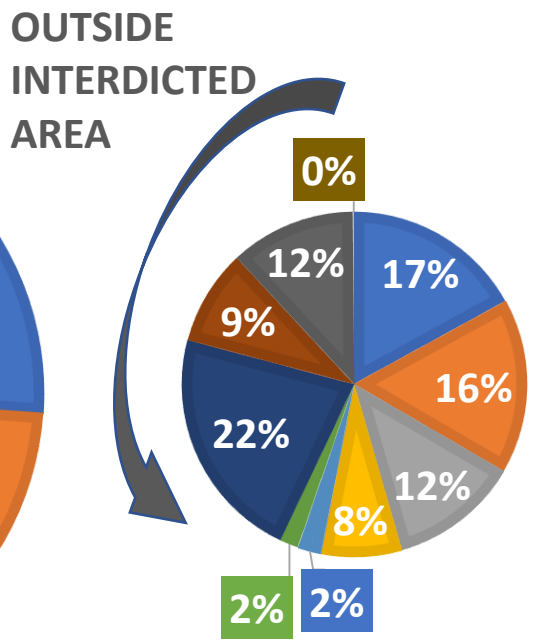
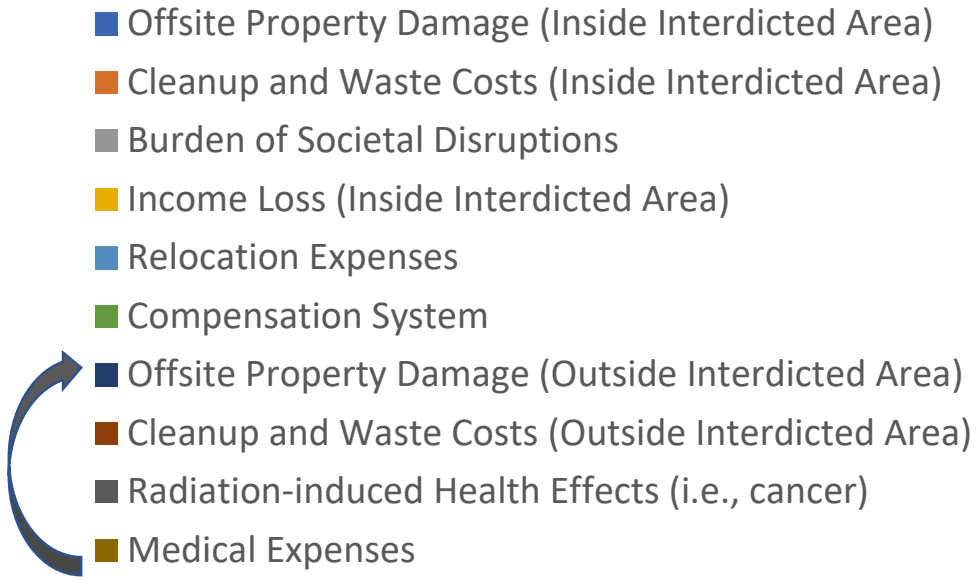


NUCLEAR DISASTER COSTS (FIRCA BASECASE - $1,400B)



NUCLEAR DISASTER COSTS (FIRCA W/ SHIELDING CREDIT - $382B)

FIRCA BASECASE – $1,400B)



FIRCA W/ SHIELDING CREDIT - $382B)