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Multi-Criteria FLEX Benefit Evaluation - Slide Package

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Changing the World's Energy Future

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Multi-Criteria Benefit Evaluation of FLEX Strategies

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Presentation Outline

- Motivation and Objective
- Proposed Methodology
- Case Study
- Near-Term Work Plan

Multi-Criteria Benefit Evaluation: Motivation and Objective

Motivation

- **Existing evaluations of FLEX benefits leave room for improvement**
  - Usually focus on a limited scope of benefits
  - Usually examine benefits in a “one-at-a-time” manner
  - Seldom consider how different types of benefits are related

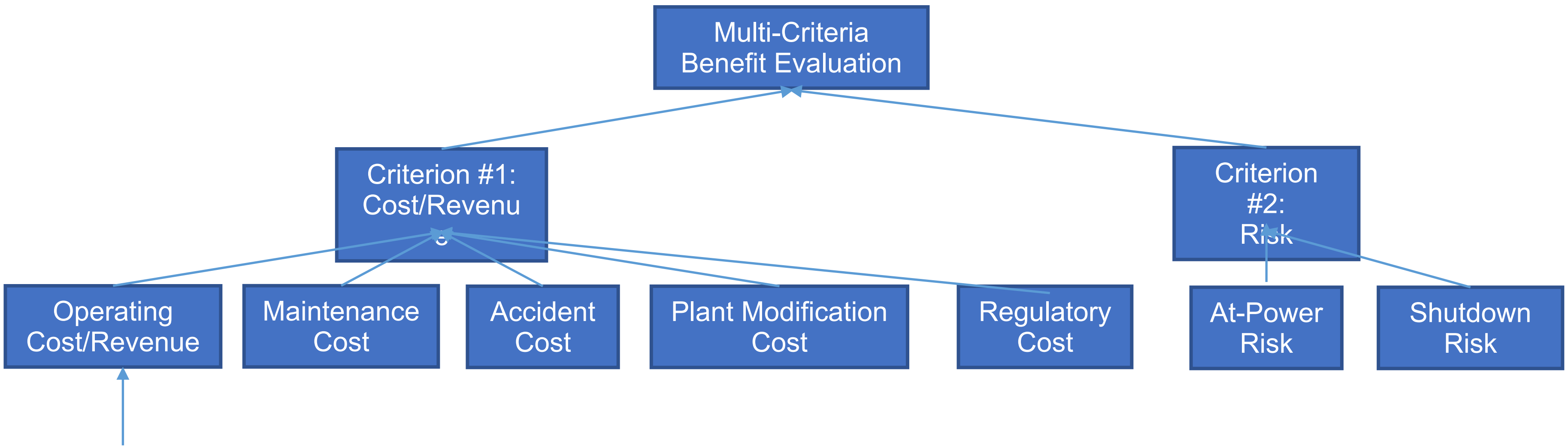
Objective

- **Develop a multi-criteria benefit evaluation methodology**
  - Grounded in causal modeling with explicit inter-criteria relationships
  - Could expand the evaluation scope and improve evaluation accuracy
  - Applicable to FLEX strategies as a case study
  - Expected to be applicable to non-FLEX features (e.g., accident tolerant fuel designs, passive cooling designs)

Multi-Criteria Benefit Evaluation: Proposed Methodology

- Step 1:
  - Select and define evaluation criteria (i.e., metrics that measure FLEX impact).
- Step 2:
  - Develop a causal model for quantifying the selected criteria.
- Step 3:
  - Identify FLEX deployment options (i.e., circumstance(s) determining what FLEX equipment is deployed and where). The baseline option is set as non-deployment of FLEX equipment.
- Step 4:
  - For each deployment option, (i) quantify each of the criteria and (ii) evaluate the impact through comparison with the baseline case.
- Step 5:
  - Compare deployment options (e.g., via multi-criteria decision analysis [MCDA]).

Multi-Criteria Benefit Evaluation: Step 1: Evaluation Criteria



- Increase revenue by reducing downtime
  - Planned outages
  - Unplanned outages
    - TS-required shutdowns

- Optimize maintenance schedule
  - SSC categorization
  - SSC conditions

- Reduce expected post-accident compensations
  - For impacted health
  - For societal impact

- FLEX cost
  - Historical cost
  - Potential future cost

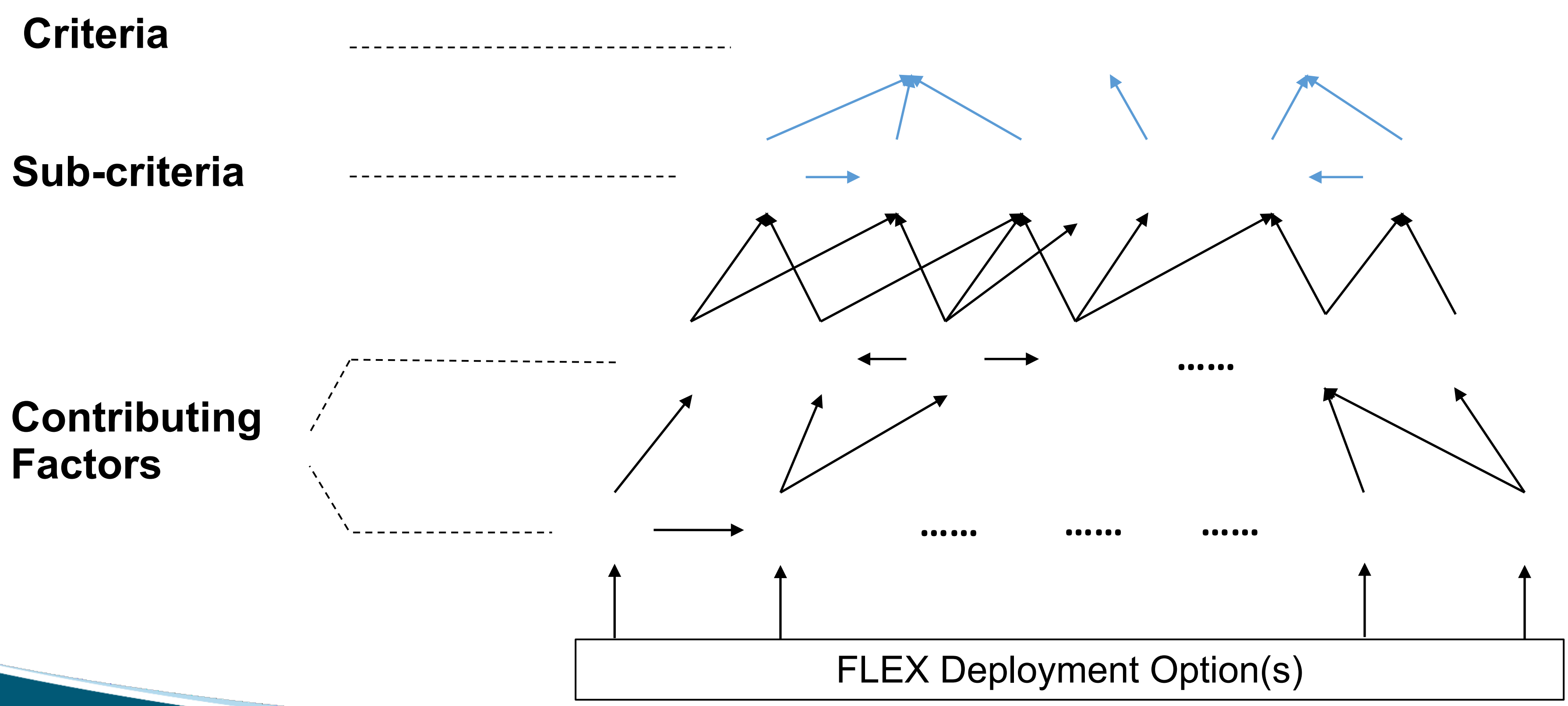
- Reduce risk
  - Initiating event frequency
  - SSC reliability and availability
  - Mitigation systems design
  - Accident consequences

- Reduce external efforts (regulators)
  - Conduct inspections and/or investigations per SDP results
  - Review and issue NOEDs

- Reduce internal efforts (plant personnel)
  - Preparing for NOEDs

Multi-Criteria Benefit Evaluation: Step 2: Causal Modeling

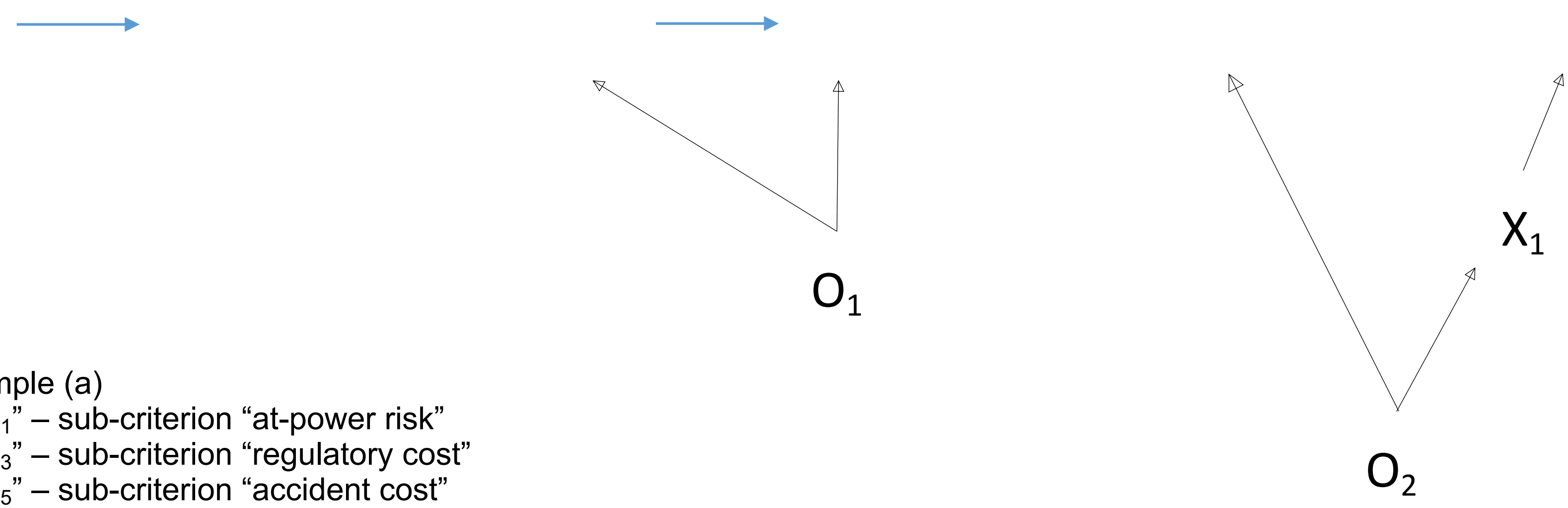
- A causal model consists of (i) criteria and sub-criteria, (ii) underlying contributing factors, and (iii) causal relationships.



Multi-Criteria Benefit Evaluation: Step 2: Causal Modeling (cont.)

- Examples of causal relationships (represented by the line arrows)

(a) (b) (c)



Example (a)
- "R_1" – sub-criterion "at-power risk"
- "C_3" – sub-criterion "regulatory cost"
- "C_5" – sub-criterion "accident cost"

Example (b)
- "R_1" – sub-criterion "at-power risk"
- "C_3" – sub-criterion "regulatory cost"
- "C_5" – sub-criterion "accident cost"
- "O_1" – "crediting FLEX equipment in accident mitigation"

Example (c)
- "R_1" – sub-criterion "at-power risk"
- "C_1" – sub-criterion "operating cost/revenue"
- "X_1" – "reliability of FLEX equipment"
- "O_2" – "utilizing FLEX equipment in reducing outage time"

Multi-Criteria Benefit Evaluation: Step 3: FLEX Deployment Options

LWRS LIGHT WATER REACTOR SUSTAINABILITY

- Single-Context FLEX Deployment Options

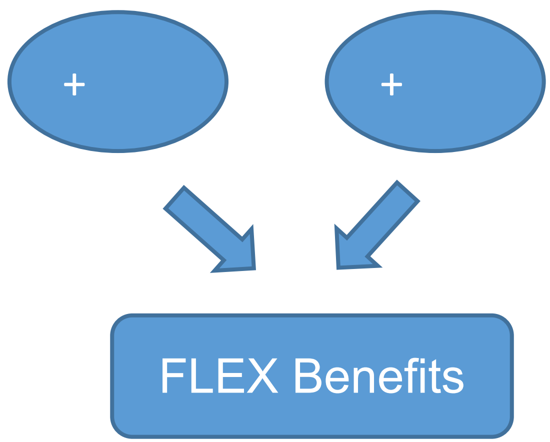
Option #	Context	Description
1	Accidents	Utilizing FLEX equipment in accident mitigation
2	Incidents	Utilizing FLEX equipment to back up inoperable equipment during an incident
3	Planned outages	Utilizing FLEX equipment to expedite scheduled activities during a planned outage
4	Planned maintenance	Utilizing FLEX equipment to back up a component being maintained, either online (i.e., during plant operation) or offline (i.e., during a plant outage)

- Multi-Context FLEX Deployment Options (Examples)

Option #	Context
1	Accidents
2	Accidents and incidents
3	Accident, incidents, and planned outages
4	Accident, incidents, planned outages, and planned maintenance

Multi-Criteria Benefit Evaluation: Step 4: Benefit Quantification

Cost of option # *i*
Risk of option # *i*
Cost of baseline option
Risk of baseline option

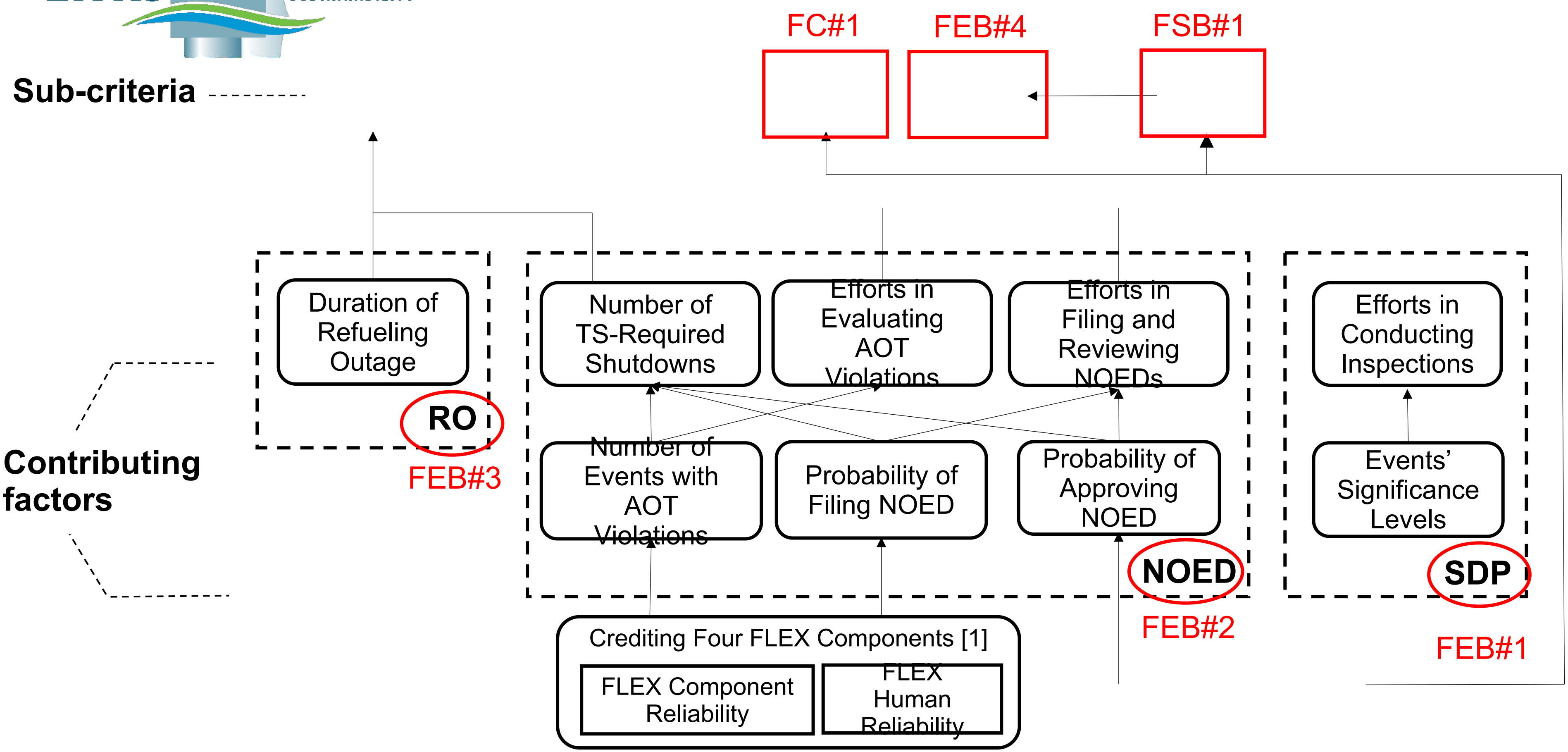


Multi-Criteria Benefit Evaluation: Step 5: Option Comparison

- Reasons to conduct:
  - There is a need to compare different FLEX deployment options
  - The number of deployment options is quite large (even infinite).
    - Example 1: single context, 5 FLEX components, formulating options
    - Example 2: involve continuous variables (e.g., hours of FLEX component usage).

- Candidate technique:
  - Multi-Criteria Decision Analysis (MCDA)
    - A structured decision-making process for evaluating conflicting decision criteria
    - Previous nuclear-based applications include NPP siting, waste management, etc.

Multi-Criteria Benefit Evaluation: Case Study



FC - FLEX Cost
FEB - FLEX Economic Benefit
FSB - FLEX Safety Benefit

R_1 - At-Power Risk
R_2 - Shutdown Risk

C_1 - Operating Cost/Revenue
C_2 - Maintenance Cost
C_3 - Regulatory Cost
C_4 - Plant Modification Cost
C_5 - Accident Cost

AOT - Allowed Outage Time
NOED - Notice of Enforcement Discretion
RO - Refueling Outage
SDP - Significance Determination Process
TS - Technical Specification

Case Study – Economic Benefit #1: SDP-Associated Cost Savings

- **Overview**
  - **By crediting FLEX equipment:**
    - Assume the significance of each SDP finding is reduced a level (e.g., a finding in the red zone is moved to the yellow zone).
  - **Potential economic benefit for NPPs:**
    - Reduce regulatory costs by saving NRC inspection efforts in response to SDP findings.

Case Study – Economic Benefit #1: SDP-Associated Cost Savings

Model

Equation	No.
	(1)
	(2)
	(3)

Annual regulatory costs associated with SDP

(B = before crediting FLEX; FLEX = after crediting FLEX)

Color index of SDP zones (R = Red, Y = Yellow, W = White)

Frequency of inspections in response to findings in color zone *i*

Factor of work for associated plant personnel vs. NRC inspections

Inspection cost per inspection in response to a finding in color zone *i*

Preparation cost per inspection in response to a finding in color zone *i*

Assessment & documentation cost per inspection for a finding in color zone *i*

Case Study – Economic Benefit #1: SDP-Associated Cost Savings

Model (cont.)

Equation	No.
	(4)*
	(5)
	(6)

* Based on an assumed relationship

Average inspection cost per professional staff hour
Team size for an inspection in response to a finding in color zone *i*
Duration of inspection in response to a finding in color zone *i*
Time horizon of SDP finding statistics
Number of operating reactor units within time horizon
Number of SDP findings in color zone *i* within time horizon

Case Study – Economic Benefit #1: SDP-Associated Cost Savings

Input Parameters

Parameter	Unit	Value	Reference
	year	24 (start: 1996, end: 2019)	NRC [2]
	reactor	109	NRC [2]
	-	7 Red, 17 Yellow, 218 White	NRC [2]
	-	0 Red, 7 Yellow, 17 White	Assumed
	$ per staff hour	280.52*	NRC [3]
	staff	15 Red, 10 Yellow, 5 White	Assumed
	hour	40 Red, 24 Yellow, 16 White	Assumed
	-	5	Assumed

* Updated from August 2018 U.S. dollars to November 2019 U.S. dollars (the most recent data in an inflation calculator provided by the U.S. Bureau of Labor Statistics)

Results

Parameter	Unit	Value
	$ per reactor year	2.92E+04

Case Study – Economic Benefit #2: NOED-Associated Cost Savings

- **Overview**
  - **By crediting FLEX equipment:**
    - Assumed reduction in the annual average number of events with violated AOTs
    - Given an AOT violation event, assumed increase in the conditional probability of qualifying and filing an NOED request.
    - Given a filed NOED request, assumed increase in the conditional probability of granting an NOED.
  - **Potential economic benefit for NPPs:**
    - Reduced loss of revenue due to reactor shutdowns required by TSs.
    - Reduced regulatory costs through eliminated effort in reviewing events with violated AOTs or preparing for and reviewing NOED requests.

Case Study – Economic Benefit #2: NOED-Associated Cost Savings

- **Model**

Equation	No.
	(7)
	(8)
	(9)

Avoided annual revenue loss from TS-req. shutdowns by crediting FLEX
Frequency of TS-required reactor shutdowns
Average reactor downtime per TS-required shutdown
Reactor electrical capacity
Unit electricity sales revenue
Time horizon of NOED statistics
Number of operating reactor units within
Number of TS-required reactor shutdowns within

Case Study – Economic Benefit #2: NOED-Associated Cost Savings

➢ Model (cont.)

Equation	No.
	(10)
	(11)
	(12)
	(13)
	(14)

Number of events with violated AOTs within

Number of issued NOEDs within time horizon

Number of TS-required reactor shutdowns within time horizon

Number of TS-required shutdowns with approved NOEDs within

Reduction factor of events with violated AOTs by crediting FLEX

Fraction of shutdowns without filing NOED in all TS-required shutdowns

Conditional prob. of filing a NOED, given an event with violated AOT

Conditional prob. of approving a received NOED request

Case Study – Economic Benefit #2: NOED-Associated Cost Savings

- **Model (cont.)**

Equation	No.
	(15)
	(16)
	(17)
	(18)

Improvement factor of filing NOED conditional prob. after crediting FLEX
Improvement factor of approving NOED conditional prob. after crediting FLEX

Case Study – Economic Benefit #2: NOED-Associated Cost Savings

➢ **Model (cont.)**

Equation	No.
	(19)
	(20)
	(21)
	(22)
	(23)

Annual regulatory cost savings associated with NOEDs by crediting FLEX
Frequency of events with violated AOTs
Frequency of filing NOEDs
Cost of evaluating an event with a violated AOT
Cost of filing an NOED request
Cost of reviewing an NOED request

Case Study – Economic Benefit #2: NOED-Associated Cost Savings

Input Parameters

Parameter	Unit	Value	Reference
	hour	72	Assumed
	MWe per reactor	1000	Assumed
	$ per MWh	106.4*	U.S. Energy Information Administration [4]
	year	19	NRC [5] (start: 2000, end: 2018)
	reactor	103	NRC [5]
	-	169	NRC [5]
	-	209	NRC [6]
	-	4	NRC [6]
	-	0.5	Assumed

* Average price of electricity to ultimate customers by end-use sector, all sectors (residential, commercial, industrial, transportation)

Case Study – Economic Benefit #2: NOED-Associated Cost Savings

- **Input Parameters (cont.)**

Parameter	Unit	Value	Reference
	-	0.5	Assumed
	-	1.2	Assumed
	-	1.2	Assumed
	$ per AOT violation event	5.00E+03	Assumed
	$ per NOED request	5.00E+03	Assumed
	$ per NOED request	5.00E+03	Assumed

- **Results**

Parameter	Unit	Value
	$ per reactor year	5.53E+05
	$ per reactor year	1.14E+03

Case Study – Economic Benefit #3: Cost Savings from Shorter Refueling Outage

- **Overview**
  - **By crediting FLEX equipment:**
    - Duration of refueling outage directly shortened (e.g., FLEX equipment accelerates cooldown at the beginning of the outage [7]).
    - Duration of refueling outage indirectly shortened (e.g., FLEX equipment facilitates online maintenance).
  - **Potential economic benefit to NPPs:**
    - Reduced revenue loss due to reactor shutdowns during refueling outages.

Case Study – Economic Benefit #3: Cost Savings from Shorter Refueling Outage

Model

Equation	No.
	(24)

Reduced duration of a refueling outage by crediting FLEX
Refueling interval

Input Parameters

Parameter	Unit	Value	Reference
	Day	2	Assumed
	Year	1.5	World Nuclear Association [8]

Results

Parameter	Unit	Value
	$ per reactor year	3.40E+06

Case Study – Safety Benefit #1: Plant At-Power Risk Reductions

Overview

- Crediting FLEX equipment reduces plant at-power risk, as determined by core damage frequency (CDF).

Model

Equation	No.
	(25)

CDF before crediting FLEX

CDF after crediting FLEX

Input Parameters

Parameter	Unit	Value	Reference
	per reactor year	3.12E-05	INL/EXT-19-53556 [1]
	per reactor year	3.06E-05	INL/EXT-19-53556 [1]

Results

Parameter	Unit	Value
	per reactor year	6.00E-07

Case Study – Economic Benefit #4: Accident Cost Savings

- **Overview**
  - **By crediting FLEX equipment:**
    - Reduced plant baseline risk, as determined by CDF.
  - **Potential economic benefit for NPPs:**
    - Reduced expected compensation costs for adversely impacted health by lowering CDF.
    - Reduced expected compensation costs for adverse societal impact by lowering CDF.

Case Study – Economic Benefit #4: Accident Cost Savings

- **Model**

Equation	No.
	(26)
	(27)*
	(28)*
	(29)
	(30)

* Cited from NUREG-1530, Rev.1 [9]

Accident cost savings by crediting FLEX
Cost of compensating for adversely impacted health
Cost of compensating for adverse societal impact
Conditional prob. of large early release, given core damage
Unit cost of compensating for adversely impacted health
Population doses within ten miles of an NPP
Unit cost of compensating for adverse societal impact

Case Study – Economic Benefit #4: Accident Cost Savings

Input Parameters (cont.)

Parameter	Unit	Value	Reference
	-	0.1	Assumed
	-	0.1	Assumed
	$ per person rem	5.50E+03*	NUREG-1530, Rev.1 [9]
	Person rem	3.68E+05	NUREG/CR-6349 [10]
	$ per accident	4.26E+10**	Denning and Mubayi [11]
	per reactor year	3.12E-05	INL/EXT-19-53556 [1]
	per reactor year	3.06E-05	INL/EXT-19-53556 [1]

* Updated from August 2015 U.S. dollars to November 2019 U.S. dollars
** Updated from June 2012 U.S. dollars to November 2019 U.S. dollars

Results

Parameter	Unit	Value
	$ per reactor year	2.57E+03

Case Study: Preliminary Results

➢ One-Time Cost of Crediting FLEX

Criteria	Parameter	Value ($ million per reactor lifetime)	Reference
Plant Modification Cost	FC#1	25.000	Assumed

➢ Annual Economic Benefits of Crediting FLEX

Criteria	Parameter	Value ($ million per reactor year)
Regulatory Cost	FEB#1	0.030
Regulatory Cost	FEB#2	0.001
Operating Cost/Revenue	FEB#2	0.553
Operating Cost/Revenue	FEB#3	3.400
Accident Cost	FEB#4	0.003
Sum		3.987
Fraction of Expected Cost Savings		14.7[illegible]%

(Cost)

(Benefit)

Benefit-Cost Ratio #1: 2.17

*Converted to present value by assuming interest rate = 4% and remaining reactor lifetime = 20 years

Benefit-Cost Ratio #2: 3.16

*Converted to present value by assuming interest rate = 4% and remaining reactor lifetime = 40 years

➢ Annual Safety Benefits of Crediting FLEX

Criteria	Parameter	Value (per reactor year)
At-Power Risk	FSB#1	6.00E-07

Multi-Criteria Benefit Evaluation: Near-Term Work Plan

Near-Term Efforts

- Refine the current model by:
  - **Obtaining more accurate estimates of key input parameters**
    - Improved parameter estimates from industry experience and available databases
    - Sensitivity analyses to identify critical inputs
  - **Further considering evaluation criteria**
    - Additional criteria such as worker safety
  - **Developing and incorporating additional sub-models**
    - e.g., the effects of FLEX equipment degradation & maintenance
- Extend the current model by:
  - **Developing a FLEX HRA method and applying it in FLEX PRA**
    - A practical method that compromises between static and dynamic methods
      - Takes the form of static, PSF-based HRA method
      - Seeks to incorporate dynamic effects in a parametric manner
      - Seeks to facilitate scenario-specific human error probability estimation

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