Multi-Attribute Utility Analysis for Proliferation Resistance Assessment

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MAUA Facts

• a well-established decision analysis methodology

• evolved since its first publication in 1978

• method to compile several factors to make a decision
MAU Function

(Additive form)

\[ u(x_1, x_2 \ldots x_i) = \sum_{i=1}^{n} (k_i u_i(x_i)) \]

- \( k_i \): the weight assigned to a utility value \( u_i \)
- \( x_i \): attribute

\[ 0 \leq k_i \leq 1 \quad 0 \leq u_i \leq 1 \quad \sum_{i=1}^{n} k_i = 1 \]
MAU Function
(Multiplicative form)

\[ 1 + Ku(x_1, x_2...x_i) = \prod_{i}^{n} (1 + Kk_i u_i(x_i)) \]

Equation to arrive at the scaling parameter, $K$

\[ 1 + K = \prod_{i}^{n} (1 + Kk_i) \]

Conditions

\[ \sum_{1}^{n} k_i > 1 \]

-1 < $K$ < 0

0 < $u_i$ ≤ 1
Four Stages of PR Assessment

- Material Diversion
- Material Transportation
- Material Transformation
- Weapons Fabrication
List of Attributes

**Diversion Stage**

*Material handling difficulty during diversion*
1. Mass/SQ of nuclear material
2. Volume/SQ of nuclear material
3. Number of items/SQ
4. Material Form
5. Radiation level in terms of dose
6. Chemical reactivity
7. Temperature of Source Process
8. Heat load of material

*Difficulty of evading detection by the accounting system*
9. Uncertainty in accountancy measurements
10. Expected vs. Actual MUF
11. Frequency of measurement
12. Amount of Material Available

*Difficulty of evading detection by the material control system*
13. Probability of detection

*Difficulty of covertly making facility modifications*
14. Is there enough physical space to make modifications?
15. Number of People for Modifications
16. Remote handling tools required?
17. Specialized tools required?
18. Requirement for the process to be halted for modifications
19. Risk of Modification (safety)
20. Risk of penetrating containment

*Difficulty of evading IAEA with covert facility modifications*
21. Probability of getting caught

*Off normal detection system*
22. Probability of detection by process monitoring
List of Attributes

**Transportation Stage**

*Material handling difficulty during transportation*
- 23. Mass/SQ of nuclear material
- 24. Volume/SQ of nuclear material
- 25. Material Form
- 26. Radiation level in terms of dose
- 27. Heat load of material
- 28. Chemical reactivity
- 29. Immediate Chemical toxicity
- 30. Time Average Chemical toxicity

*Difficulty of evading detection during transport*
- 31. Mass of material and transportation container
- 32. Volume of material and transportation container
- 33. Heat load of material
- 34. Shield thickness to reduce radiation to 10 mR/hr
- 35. Host country size
- 36. Number of declared nuclear facilities
- 37. IAEA imagery analysis rate

**Transformation Stage**

*Facilities and equipment needed to process diverted materials*
- 38. Number of process steps to metallic form
- 39. Number of export controlled/equipment/materials
- 40. Minimum electrical requirement

*Work force required for transformation*
- 41. Number of unskilled workers required (e.g. construction)
- 42. Number of skilled workers required (e.g. electrician)
- 43. Number of advanced degree work (e.g. Grad Student Work)
- 44. Number of Technical Experts (e.g. Adams on Transport)

*Difficulty of evading detection of transformation activities*
- 45. Additional Protocol in force?
- 46. Environmental sampling rate
- 47. Sensitivity of IAEA equipment
- 48. Isotopic signatures
- 49. Facility size
- 50. Heat load of transformation process
- 51. Sonic load
- 52. Radiation load
- 53. Volume of non-naturally occurring gases emitted
- 54. Undiluted volume liquid emissions
List of Attributes

**Weapons Stage**

*Difficulty associated with design*
- 55. Spontaneous fission production Rate
- 56. Radiation exposure at one meter
- 57. Heating rate of weapons material
- 58. Can use ballistic assembly methods?
- 59. Number of phases in the phase diagram

*Handling difficulties*
- 60. Radiation level in terms of dose
- 61. Chemical reactivity
- 62. Radio-toxicity

*Knowledge and skills needed to design and fabricate*
- 63. Knowledge and skill level for material/weapon type alternatives
Essentials for MAUA methodology

- Break the assessment into sub-steps
- List of attributes defining a system for each sub-step
- Map the attribute to a utility value using a defined function
- Assigning weights for each utility value
- Aggregation scheme
Example Utility Function

Material handling difficulty

\[ u_1(x_1) = e^{-25\left(\frac{x_{1\text{min}}}{x_1}\right)} \]

Utility Value

Weight/SQ (kg)
MAUA Aggregation Scheme

**First Tier**
- \( u_1 \) (mass per SQ)
- \( u_2 \) (volume per SQ)
- \( u_3 \) (heat per SQ)
- \( u_4 \) (dose per SQ)
- \( u_i \) (\( x_i \))
- \( k_1 \)
- \( k_2 \)
- \( k_3 \)
- \( k_4 \)
- \( k_i \)

**Second Tier**
- \( u_{11} \): material handling difficulty
- \( u_{12} \): detection through NMA
- \( u_{13} \): facility modification difficulty
- \( u_i \)
- \( k_{11} \)
- \( k_{12} \)
- \( k_{13} \)
- \( k_{1i} \)

**Third Tier**
- \( k_{21} = 0.327 \)
- \( k_{22} = 0.183 \)
- \( k_{23} = 0.272 \)
- \( k_{24} = 0.218 \)

**Overall FOM**
- \( U: \) Overall FOM
- \( u_{21} \): diversion
- \( u_{22} \): transportation
- \( u_{23} \): transformation
- \( u_{24} \): weaponization
- \( k_{21} \)
- \( k_{22} \)
- \( k_{23} \)
- \( k_{24} \)
A Typical FBR Fuel Cycle

FUEL:
$^{239}\text{Pu}$, $^{240}\text{Pu}$, $^{241}\text{Pu}$, $^{242}\text{Pu}$ wt% (fresh): 69, 25, 5, 1
(irradiated): 65, 28, 5, 2

Blanket:
$^{239}\text{Pu}$, $^{240}\text{Pu}$, $^{241}\text{Pu}$, $^{242}\text{Pu}$ wt% (fresh): 0, 0, 0, 0
(irradiated): 98, 2, 0, 0

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Information from FBR Fuel Cycle

FBR Fueling Scheme

Number of SA Refuelled During 3 Cycles of Operation

<table>
<thead>
<tr>
<th>Cycle No.</th>
<th>Total SA Refuelled</th>
<th>Assembly Type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Core-1</td>
</tr>
<tr>
<td>1</td>
<td>97</td>
<td>31</td>
</tr>
<tr>
<td>2</td>
<td>109</td>
<td>27</td>
</tr>
<tr>
<td>3</td>
<td>101</td>
<td>27</td>
</tr>
</tbody>
</table>

Core SA Details at the Beginning of Each Cycle

<table>
<thead>
<tr>
<th>Cycle Name</th>
<th>Core 1</th>
<th>Core 2</th>
<th>RB</th>
<th>Diluents</th>
<th>ICSA</th>
</tr>
</thead>
<tbody>
<tr>
<td>BOC-1</td>
<td>88</td>
<td>90</td>
<td>114</td>
<td>8</td>
<td>1</td>
</tr>
<tr>
<td>BOC-2</td>
<td>95</td>
<td>90</td>
<td>114</td>
<td>2</td>
<td>0</td>
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<tr>
<td>BOC-3</td>
<td>85</td>
<td>96</td>
<td>120</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>BOC-4</td>
<td>85</td>
<td>96</td>
<td>120</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Fuel Assembly

(ALPHA,N) NEUTRON SOURCE, NEUTRONS/SEC

Pu238 0.000E+00 5.191E+04
Pu239 3.812E+05 3.127E+05
Pu240 5.220E+05 5.528E+05
Am241 0.000E+00 1.187E+05
Cm242 0.000E+00 9.167E+06
Am242 0.000E+00 1.203E+05

SPONTANEOUS FISSION NEUTRON SOURCE, NEUTRONS/SEC

UO2 (tons)

FBR Fueling Data
(Fast Breeder Reactor)

<table>
<thead>
<tr>
<th>Material</th>
<th>Inner core Fuel Subassembly (kg)</th>
<th>Outer core Fuel Subassembly (kg)</th>
<th>Radial Blanket Subassembly (kg)</th>
<th>Nominal Reactor Loading (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UO2 (active core)</td>
<td>40.15</td>
<td>36.71</td>
<td>132.2</td>
<td>287.45</td>
</tr>
<tr>
<td>UO2 (ax. blanket)</td>
<td>32.84</td>
<td>32.84</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PuO2</td>
<td>10.46</td>
<td>14.07</td>
<td>-</td>
<td>2242</td>
</tr>
</tbody>
</table>

FBR assemblies refuelled per year

<table>
<thead>
<tr>
<th>Total SA Refueled</th>
<th>Assembly Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equilibrium cycle</td>
<td>151</td>
</tr>
<tr>
<td>PuO2 weight (tons)</td>
<td>0.42 0.68 0</td>
</tr>
<tr>
<td>UO2 (tons)</td>
<td>2.92 3.34 8.33</td>
</tr>
</tbody>
</table>

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Schematic of the MBAs for the FBR Fuel Reprocessing Facility

1. **MBA-1**
   - FBR
   - Spent fuel Storage

2. **MBA-2**
   - Mechanical De-cladding
   - Fuel Dissolution

3. **MBA-3**
   - Fission Product Removal
   - Fission Product Storage

4. **MBAs-4**
   - U/Pu Partitioning
   - U Purification
   - U Conversion

5. **KMP**
   - Hulls and Metal Waste Storage
   - Pu Conversion
   - Pu Purification
   - U and Pu Storage

**Additional Processes:**
- Input Accountability tank
- Low Level Waste Storage
- U and Pu Storage
- U Conversion
- U/Pu Partitioning
PRAETOR results obtained for PR of the diversion sub-step for different SNM diversion scenarios within the FBRFC facilities with and without safeguards.
PRAETOR results overall PR for diversion, transportation, transformation and weaponization with SNM diverted from FBRFC facilities with and without safeguards
Schematic of MBAs for the FRFRF using PRAETOR Risk Informed Safeguards Approach
Spent Fuel Assembly Diversion from FBR & PWR
Linear Vs. Multiplicative

Mat. Handl. Diff. during diversion
Diff. of evading dete. by the acc. system
Diff. of covertly making facility modif.
Mat. Handl. diffi. during transp.
Off. Normal Detec. System
Diff. of evading dete. during transp.
Facil. and equip. needed to process diverted mat.
Workforce required for transformation
Diffi. of evading dete. of transf. activities
Knowl. and skills needed to design
Handling diffi.
Second Tier-Transformation
Second Tier-Weapon Fabrication
Final U

LINEAR
MULTIPLICATIVE
Future Research Planned

- Sensitivity analysis with respect to weighting schemes
- Suitability of Multiplicative & Additive MAUA model to different scenarios
- Analysis of new nuclear fuel cycles

ACKNOWLEDGEMENT
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