Effects of Environmental Factors on Manual Actions for Flood Protection and Mitigation at Nuclear Power Plants

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The 2nd Annual NRC PFHA Research Program Workshop
January 23-25, 2017

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Scope and Objectives

- **Project scope**
  - Review technical literature on effects of environmental conditions (ECs) on human performance
  - An extension of NUREG/CR-5680, The Impact of Environmental Conditions on Human Performance, Volumes 1 and 2 (1994)
  - Consider environmental conditions that could occur during a flood and the manual actions taken to prepare/respond

- **Research objectives**
  - Develop a framework for assessing the impact of ECs on human performance of manual actions for flood protection and mitigation
  - Develop a technical literature review on effects of ECs on human performance
  - Develop a proof-of-concept method for EC impact assessment
  - Identify approaches to using literature review results in the EC impact assessment method

Impact Assessment Framework

FRAMEWORK

Decomposition of Manual Actions into Generic Actions (GAs)

(1) Identify Manual Actions from procedures and reports
(2) Decompose Manual Actions into Tasks and Sub-tasks
(3) Use subject matter experts and literature review to decompose Tasks and Sub-Tasks into GAs. For example:
- Walking
- Operating vehicles
- Opening/closing doors
- Operating hoists
- Loading equipment
- Communicating

Identification of Environmental Conditions that Impact Generic Actions

	EVIRONMENTAL CONDTIONS											
GENERIC ACTIONS	Heat	Cold	Noise	Vibration	Light	Humidity	Wind	Precipitation	Slippery surface	Condensation	Debris	Etc.
Walking	X	X				X		X	X		X	
Operating forklift	X	X	X		X	X		X		X	X	
Driving vehicle	X	X			X	X		X		X	X	
Using hand tools	X	X				X	X	X				
Operating hoist	X	X		X	X	X		X		X		
Setup of equipment	X	X				X	X	X	X			
Loading equipment	X	X				X	X	X	X			
Etc.												

Determination of ECs from Flood Causing Mechanisms (FCMs)

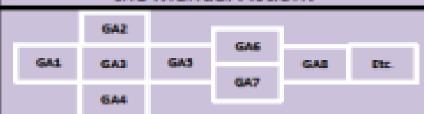
(1) Identify FCMs
(2) Identify Environmental Factors (EFs) from FCMs
(3) Identify EFs from ECs. For example:

Primary
- Heat
- Cold
- Noise
- Precipitation
- Humidity

Secondary
- Slippery surface
- Condensation
- Windborne debris

Literature search on the measurable impact of ECs on GAs and associated Performance Demands

How do GAs fit together to accomplish the Manual Action?



Importance of each GAs the overall Manual Action

Generic Action Performance Demands (PDs)

	GA1	GA2	GA3	GA4	Etc.
PERFORMANCE DEMANDS (PD)	% CONTRIBUTION				
Detecting and Noticing	30	10	10	20	-
Understanding	30	10	20	-	20
Deciding	40	-	-	-	-
Action – Fine Motor	-	-	60	-	50
Action - Course Motor	-	80		40	-
Teamwork – Read/Write	-	-	10	-	-
Teamwork – Oral Communication	-	-		-	30
Teamwork – Crew Interaction	-	-		20	

Impact of Environmental Conditions on PDs/GAs

	EC1	EC2	EC3	EC4	Etc.	TOTAL IMPACT ON GA
MANUAL ACTION GAs	EXTENT OF IMPACT					
GA1 – PD1	Hi	Med	Hi	Low		GA1 - Impact given weighting of different PDs Med
GA1 – PD2	Low	Med	Med	Med		
GA1 – PD3	Low	Med	Med	Hi		
GA2 – PD1	Low	Low	Low	Low		GA2 - Impact given weighting of different PDs Low
GA2 – PD2	Hi	Low	Low	Low		
GA2 – PD3	Low	Med	Low	Med		
Etc.						

Quantitative impact of ECs on Manual Action based on quantitative variables such as **Extension of Completion Time** or **Increase in Failure Probability**

Characterization of Manual Actions

- Manual actions (MAs) are actions taken away from the Main Control Room.
  - We define and MA as a distinct group of inter-related tasks that are performed outside the main control room to achieve an operational goal.
  - MAs were compiled from
    - NRC Staff Assessments of licensees' Flooding Walkdown Reports
    - Available site-specific Flood Protection and Mitigation procedures
- Key assumptions
  1. Differences between/among individuals are minimal
  2. Staffing levels are appropriate and adequate
  3. Procedures are established and appropriate
  4. Staff are provided with and know how to use necessary equipment
  5. Staff are trained
  6. Staff are fit for duty

Decomposing Manual Actions

- MAs are often complex, consisting of multiple steps, involving sequential movements or a combination of motor and cognitive functions and processes, and requiring more than one task location and varying levels of automation and/or need for tools or equipment.

Manual Actions
Information Source:
- Staff Assessments
- Plant Flood Procedures

→

Tasks and Sub-Tasks
Information Source:
- Expert Judgment
- Plant Flood Procedures

→

Generic Actions (GAs)
- Walking
- Operating vehicles
- Opening/closing doors
- Operating hoists
- Loading equipment
- Communicating
- ……

Approach:
- Expert judgment
- Literature review

- MAs are decomposed into tasks/sub-tasks, and then generic actions (GAs).
- EC impact is assessed at the level of GAs.

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Characterizing GAs with Performance Demands

- Performance demands are the physical and/or cognitive exertions required for performing a GA by an operator.

- We developed a taxonomy of performance demands by integrating performance capabilities from NUREG/CR-5680 (Echeverria et al. 1994), taxons (O'Brien et al. 1992), and cognitive functions in NUREG-2114 (Whaley et al. 2013).

- We used performance demands to characterize GAs for assessing the impact of ECs on operator performance.

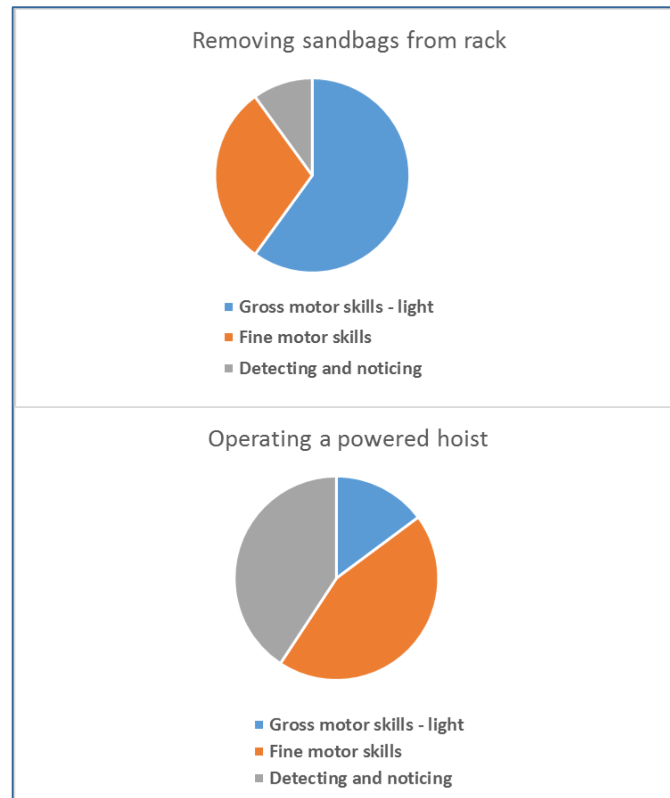
Performance Demands

- **Detecting and Noticing**
- **Understanding**
- **Decision Making**
- **Action**
  - Fine motor
  - Gross motor
  - Other neurophysiological functions
- **Teamwork**
  - Read/Write
  - Oral communication
  - Crew interaction

Representing GAs with Performance Demands

- Each GA can be represented as a combination of one or more performance demands.
- The % contribution represents the weight associated with a performance demand. Different GAs require different varying types and magnitudes of performance demands.
- For each GA, the total contributions from its constituent performance demands should be 100%.

Generic Action Performance Demands (PDs)					
	GA1	GA2	GA3	GA4	……
Performance Demands (PD)	**% CONTRIBUTION**				
Detecting and Noticing	30	10	10	20	-
Understanding	30	10	20	-	20
Decision Making	40	-	-	-	-
Action – Fine Motor	-	-	60	-	50
Action – Gross Motor	-	80		40	-
Action – Other	-	-	-	-	-
Teamwork – Read/Write	-	-	10	-	-
Teamwork – Oral Communication	-	-		-	30
Teamwork – Crew Interaction	-	-		20	
Sum of Contributions	100	100	100	100	100



Environmental Conditions (ECs)

Flood-Causing Mechanisms	Environmental Factors that Could Co-Occur with Floods of Interest	Environmental Conditions that Could Affect Manual Actions
		Primary Environmental Conditions
Local Intense Precipitation	Cold	Cold
Streams and Rivers	Heat	Heat
Dam or water-storage structure failure	Humidity	Relative Humidity
Storm surges and seiches	Precipitation (rain, sleet, hail, snow)	Precipitation Type and Intensity
Tsunamis	Wind	Wind Velocity
Ice dams or jams	Thunder	Noise Level
Channel diversion or migration	Lightning	Water Depth
	Standing water	Water Velocity
Conditions Contributing to Combinations of Flooding Mechanisms	Moving water	Vibration Frequency and Intensity
	Waves	Lighting Level / Low Visibility
Concurrent wind-induced wave activity	Outdoor light level	Presence of Ice
Antecedent or subsequent precipitation	Ice	Snow Depth
Snowpack	Snow	Presence of Lightning
Dam failure concurrent with riverine flood		**Secondary Environmental Conditions**
Earthquakes		Slippery/muddy surfaces
Concurrent high tides		Condensation
		Windborne debris
		Waterborne debris

Technical Literature Review on ECs

- A key component of the project is the development of a comprehensive technical literature review on ECs pertinent to flood protection and mitigation.
- The literature review updated the information on ECs included in NUREG/CR-5680 and included additional ECs:
  1. Vibration
  2. Noise
  3. Heat
  4. Cold
  5. Lighting
  6. Humidity
  7. Wind
  8. Precipitation
  9. Standing and moving water
  10. Ice
  11. Snowpack
  12. Lightning

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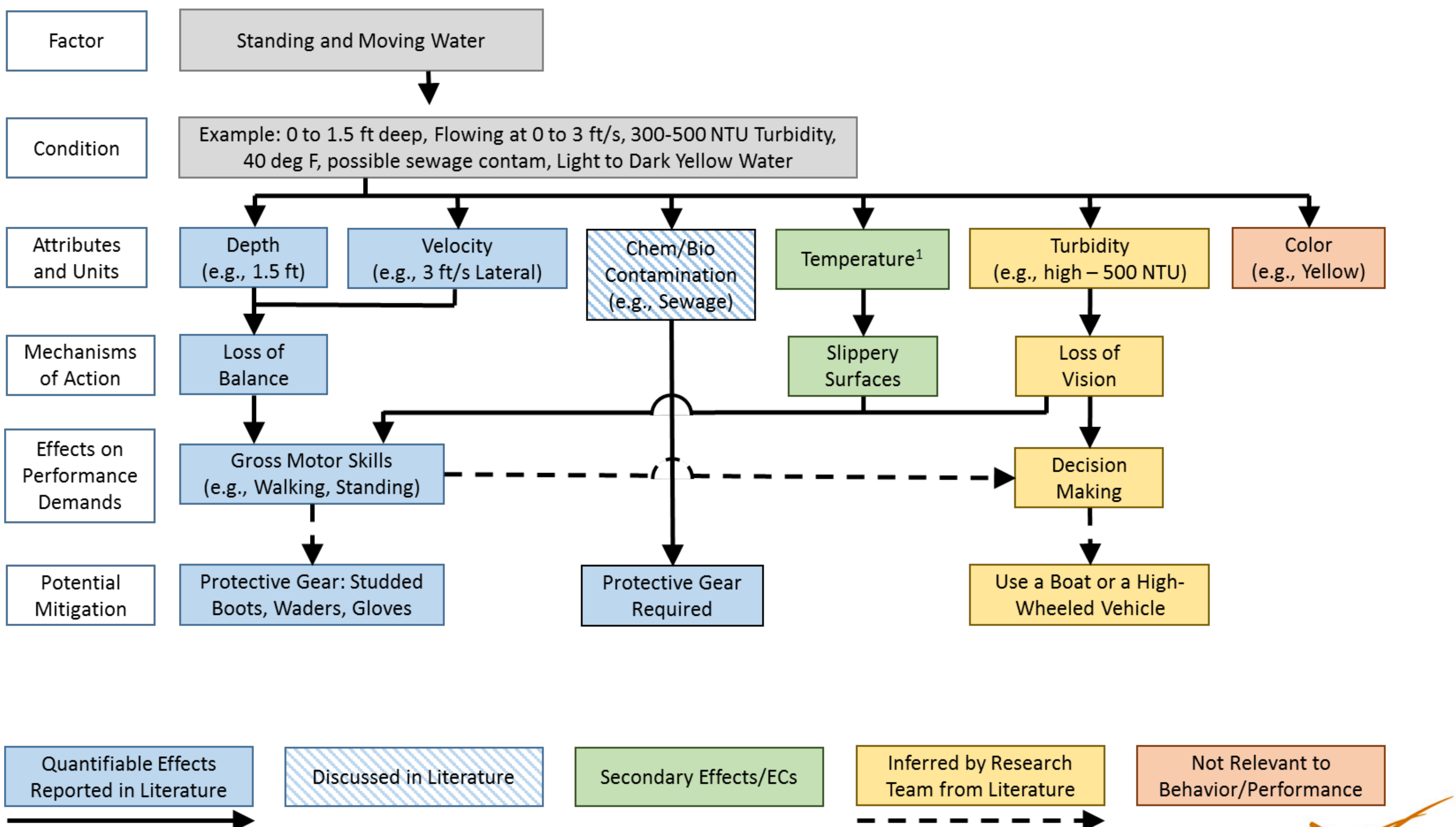
Literature Review Approach: Example of Standing and Moving Water

EF: Standing and Moving Water, EC: Water Depth and Flow Velocity



[1] See COLD and HEAT EC Figures.

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Leveraging Literature Review for Impact Assessment

- Information identified from the literature review was classified into 4 categories in terms of what level of information is available and how it might be used in impact assessment.

Four Levels of Information

1. **Quantitative information that is directly applicable** to determining the quantitative impact of an EC on a performance demand and can be directly used to support the proof-of-concept approach.

2. **Quantitative information** that is of some applicability in determining the degree impact of an EC on a performance demand (e.g., in some cases, EC severity limits may be available - below a lower limit, there is no discernible impact and above an upper limit, an operator cannot perform an activity at all). Under certain assumptions regarding the variation of impacts with changing severity between the two limits, this information might be used with the proof-of-concept model to provide useable information.

3. **Qualitative information**. General agreement exists that the EC affects a performance demand, but the measured impacts are not reported in literature, not even for limits. A performance demand may also be affected because a critical cognitive function is primarily impaired. This information might be used to inform a sensitivity analysis using the proof-of-concept model.

4. **No information** (i.e., a literature gap).

Example of EC Literature Review Summary Table – Standing and Moving Water

- For each EC, the available literature was summarized by performance demands and coded based on the 4 levels of information.

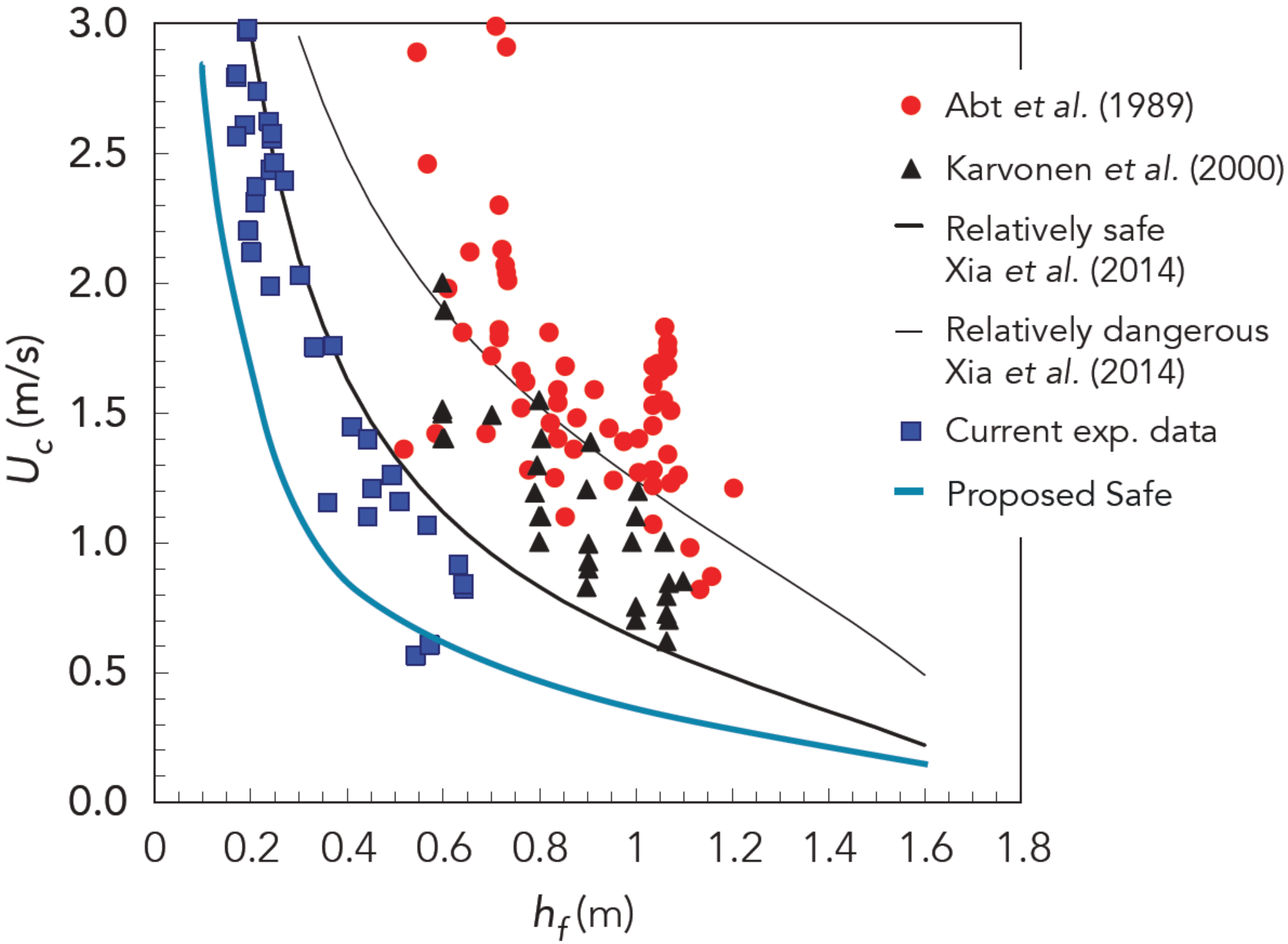
Performance Requirements for Standing/Moving Water	Level of Information Related to Impacts	Assumptions and Limitations on Applicability
Detection and Noticing		
Attention, memory, vigilance, switching, acuity, perception and threshold perception	3	(b)
Sensation and visual recognition	3	(b)
Understanding		
Pattern recognition, discrimination, understanding, evaluating, hypothesizing, diagnosing, and integrating	3	(b)
Decision Making		
Reasoning, computation, interpreting, classifying, goal setting, planning, adapting, and evaluating and selecting options	3	(b)
Action		
Fine motor skills - discrete and motor continuous, and manual dexterity	3	(b)
Gross motor skills - heavy and light	1	(a)
Other neurophysiological functions	3	(b)
Teamwork		
Reading and writing	3	(b)
Oral face-to-face and electronic communication	3	(b)
Cooperation, crew interaction, and command and control	3	(b)

(a) Toppling risk is very quantifiable for models, but any individual's toppling tendency may depend on additional factors including fitness, loose or form fitting clothing, shoe gripping abilities, etc.
(b) It can be assumed that once an individual topples in moving water, none of the other manual or cognitive tasks will be possible.

- Information levels were not cleanly cut and expert judgment was used to make coding decisions.

1 = Quantitative information that is directly applicable to determining the quantitative impact of an EC on a performance demand and can be directly used to support the proof-of-concept approach.
3 = Qualitative information

Example of Level 1 EC Information in Literature – Standing and Moving Water



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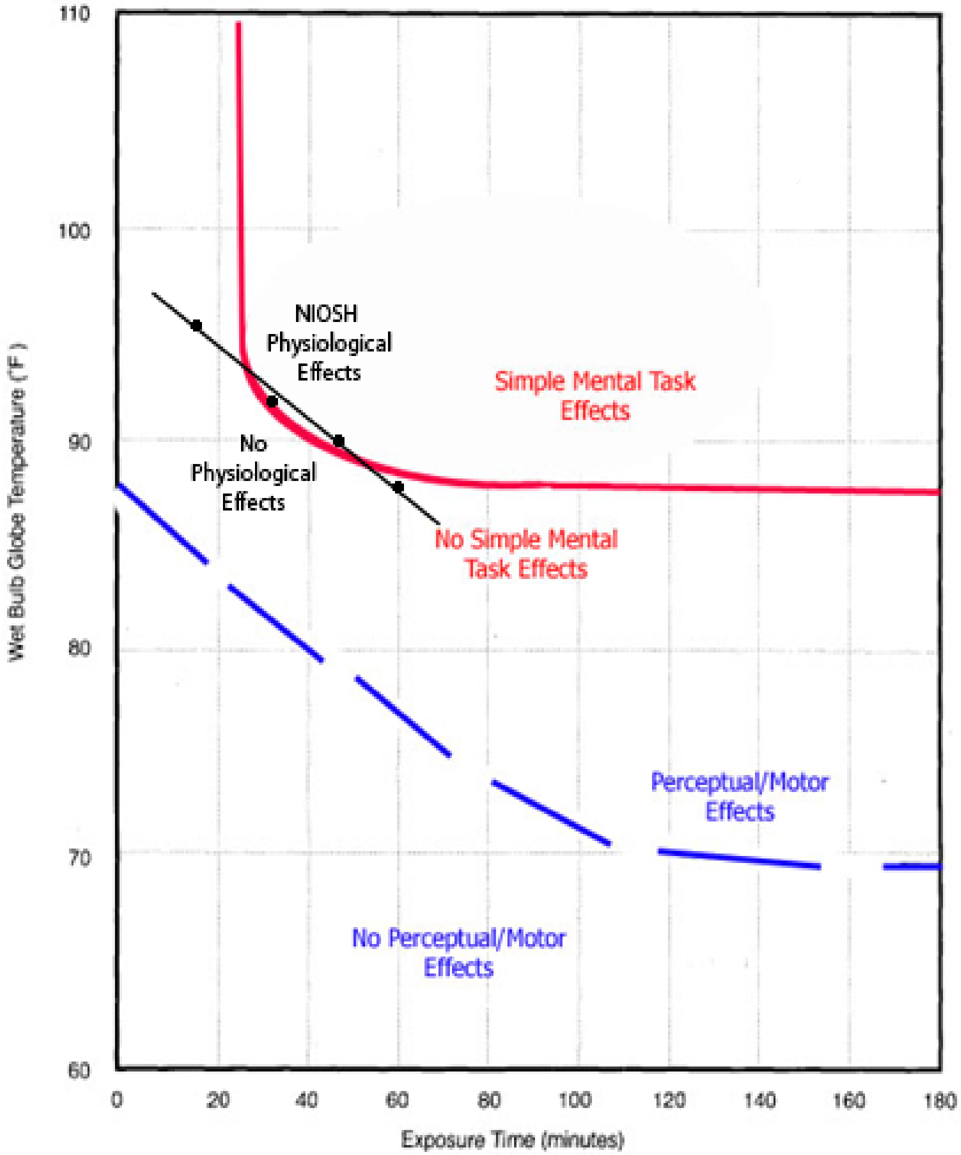
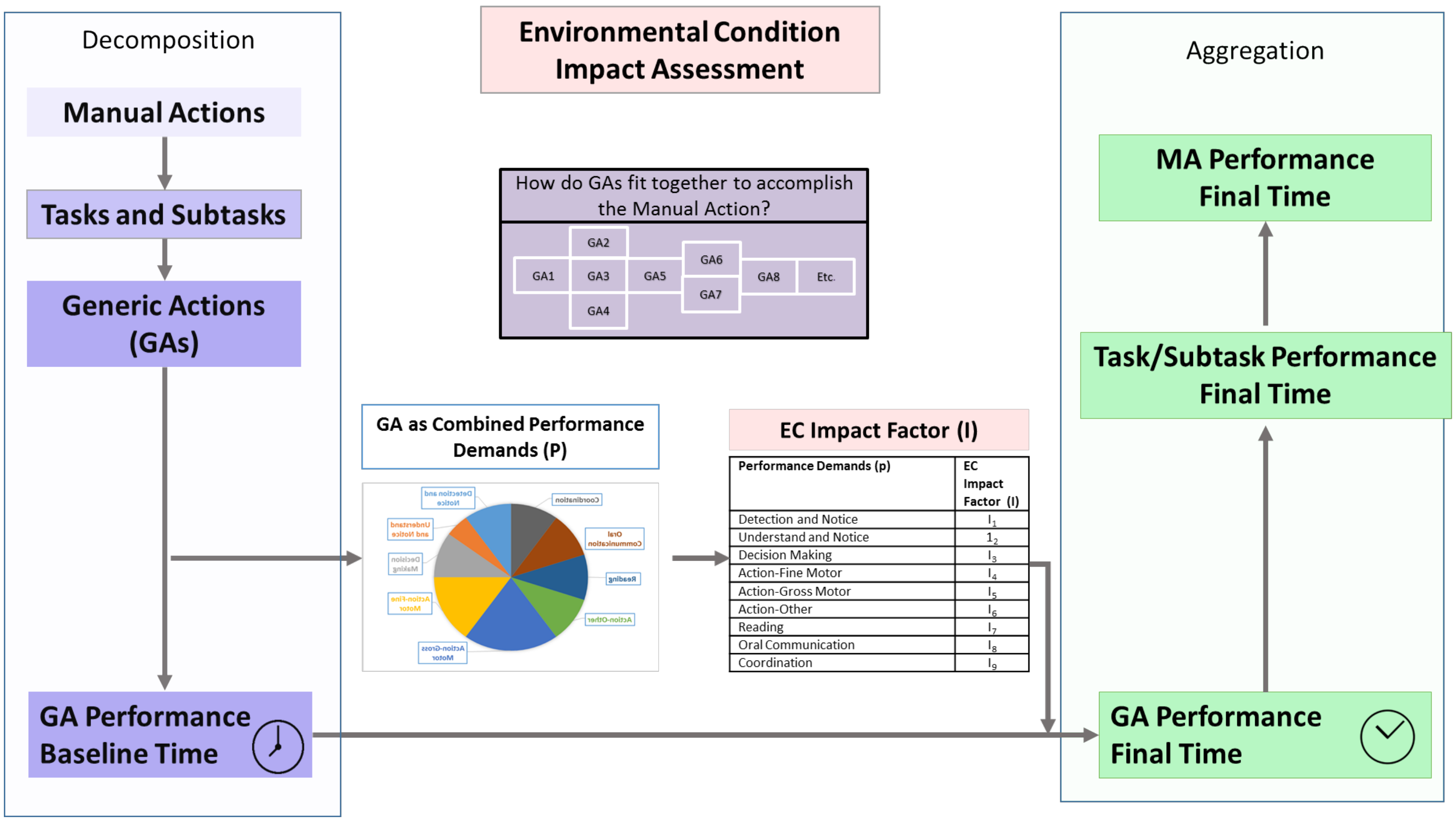
Example of Level 2 EC Information in Literature – Heat



Assessing Impacts of ECs on Performance of MAs

- Developed a method to leverage the decomposition approach and assess EC impact on GAs via performance demands. The resulting GA-level impact is aggregated up to the MA level.
- The method focused on time as the primary performance measure but accuracy and other measures can also be assessed.



Overview of Impact Assessment Approaches

- In Human Reliability Analysis, ECs have been used as Performance Shaping or Influencing Factors (PSFs/PIFs), and function as multipliers affecting Human Error Probabilities for varying levels of stress (e.g., extreme, high, and nominal).

$HEP_{overall} = HEP_{nominal} * PSF$	$0 < PSF < 1$	$HEP_{overall} < HEP_{nominal}$	**Enhancing reliability**
	$PSF = 1$	$HEP_{overall} = HEP_{nominal}$	**No impact on reliability**
	$PSF > 1$	$HEP_{overall} > HEP_{nominal}$	**Reducing reliability**

- In IMPRINT, ECs are Performance Degradation Factors (PDFs) affecting performance time/accuracy through their impact on taxons.

Time/Accuracy adjustment = (PDF associated with a taxon – 1) x weight assigned to the taxon
Final time/accuracy = (1 + time/accuracy adjustment) x baseline time/accuracy

- **IMPRINT includes nine taxons**: (1) visual cognition/visual discrimination, (2) numerical analysis, (3) information processing/problem solving, (4) fine motor discrete, (5) fine motor continuous, (6) gross motor light, (7) gross motor-heavy, (8) oral communication, and (9) written communication

A Proof-of-Concept Method for Impact Assessment: Conceptual Representation

- For each GA, performance time is assumed to be longer than the baseline if an EC adversely impacts performance.
- Among the performance demands required by a GA, an EC could impact different performance demands differently.
- For performing each GA,

Affected Time = (1 + Combined Time Adjustment) * Baseline Time

- For each performance demand within a GA,

Combined Time Adjustment = Sum of Time Adjustments across all performance demands encompassed in a GA

Time Adjustment = (EC Impact Factor -1) * Performance Demand Weight

- Baseline Time can be estimated from flood protection procedures and/or expert opinion.
- EC Impact Factor is a quantitative measure representing the magnitude of the impact on a performance demand resulting from a specific EC. It can be estimated from relevant literature and/or by expert judgment.
- Performance Demand Weight is the relative contribution of a performance demand toward completing a GA that comprises the performance demand.

A Proof-of-Concept Method for Impact Assessment: Single Prevailing EC

The impact of an EC E_j on the GA G_k, as measured by time, is the difference between affected time (TG_k^*) and baseline time (TG_k).

$$TG_k = \sum_{i=1}^{9} T_{i,k}$$

the affected time for G_k, given only one prevailing EC E_j, is:

$$TG_k^* = \sum_{i=1}^{9} T_{i,k}^* = \sum_{i=1}^{9} (1 + \Delta_{i,j,k}) T_{i,k}$$

Where

G_k = a GA, where $k = 1,2,3, \ldots n_G$

i = a performance demand required by G_k, where $_i$ ranges from 1 to 9

w_i = weight for performance demand $_i$, where $w_i \in [0,1]$ and $\sum_{i=1}^{9} w_i = 1$

E_j = an EC, where $j = 1,2,3, \ldots n_E$

$I_{i,j,k}$ = impact factor for performance demand $_i$ from prevailing E_j within G_k

TG_k= baseline time for performing G_k

$T_{i,k}$= baseline time associated with performance demand $_i$ within G_k (which is $w_i TG_k$)

$\Delta_{i,j,k}$= time adjustment for performance demand $_i$ from prevailing E_j within G_k ($\Delta_{i,j,k} = I_{i,j,k} - 1$)

TG_k^*= affected time for performing G_k

$T_{i,k}^*$= affected time associated with performance demand $_i$ within G_k

A Proof-of-Concept Method for Impact Assessment: Multiple Prevailing ECs

- To account for the impact of multiple ECs, the impact factor $I_{i,j,k}$ could be combined (three examples):

a) Simple additive combination, where n_E is the number of prevailing ECs while performing G_k

$$I_{i,k} = \sum_{j=1}^{n_E} I_{i,j,k}$$

b) Multiplicative combination, where n_E is the number of prevailing ECs while performing G_k

$$I_{i,k} = \prod_{j=1}^{n_E} I_{i,j,k}$$

c) Power function combination, where $\alpha_j, j = 1,2,3, \ldots n_E$ are the different exponents for prevailing ECs' impacts while performing G_k

$$I_{i,k} = \prod_{j=1}^{n_E} (I_{i,j,k})^{\alpha_j}$$

- Thus, the affected time for G_k, given multiple prevailing ECs, is expressed below, where I_k^* is the impact factor for the kth GA, appropriately weighted by performance demand weights.

$$TG_k^* = \sum_{i=1}^{9} T_{i,k}^* = \sum_{i=1}^{9} (1 + \Delta_{i,k}) T_{i,k} = \sum_{i=1}^{9} I_{i,k} w_i TG_k = I_k^* \, TG_k$$

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A Proof-of-Concept Method for Impact Assessment: Aggregation from GA to MA

- Based on the affected time for GAs, affected times for tasks/subtasks and MAs can be estimated:

  - **Task/Subtask**: a task or subtask S_l can consist of one more GAs, (i.e., $S_l = \{G_k\}, k = 1,2,3 \dots n_G$), baseline time TS_l and affected time TS_l^* for a task S_l are, assuming GAs are performed sequentially

$$TS_l = \sum_{k=1}^{n_G} TG_k \qquad TS_l{}^* = \sum_{k=1}^{n_G} TG_k{}^* = \sum_{k=1}^{n_G}\sum_{i=1}^{9}\left(1+\Delta_{i,k}\right) T_{i,k} = \sum_{k=1}^{n_G}\sum_{i=1}^{9} I_{i,k}\, T_{i,k} = \sum_{k=1}^{n_G} I_k^*\, TG_k$$

  - **MAs:** a manual action M_o typically consists of one or more tasks (and subtasks), (i.e., $M_o = \{S_l\}, l = 1, 2, 3 \dots n_S$), baseline time TA_o and affected time TA_o^* for M_o are, assuming tasks are performed sequentially

$$TA_o = \sum_{l=1}^{n_S} TS_l \qquad TA_o{}^* = \sum_{l=1}^{n_S} TS_l^*$$

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Method Application: an example

Example MA: Fastening Barriers onto Intake Structure Walls

Task 1. Fabricate steel plates

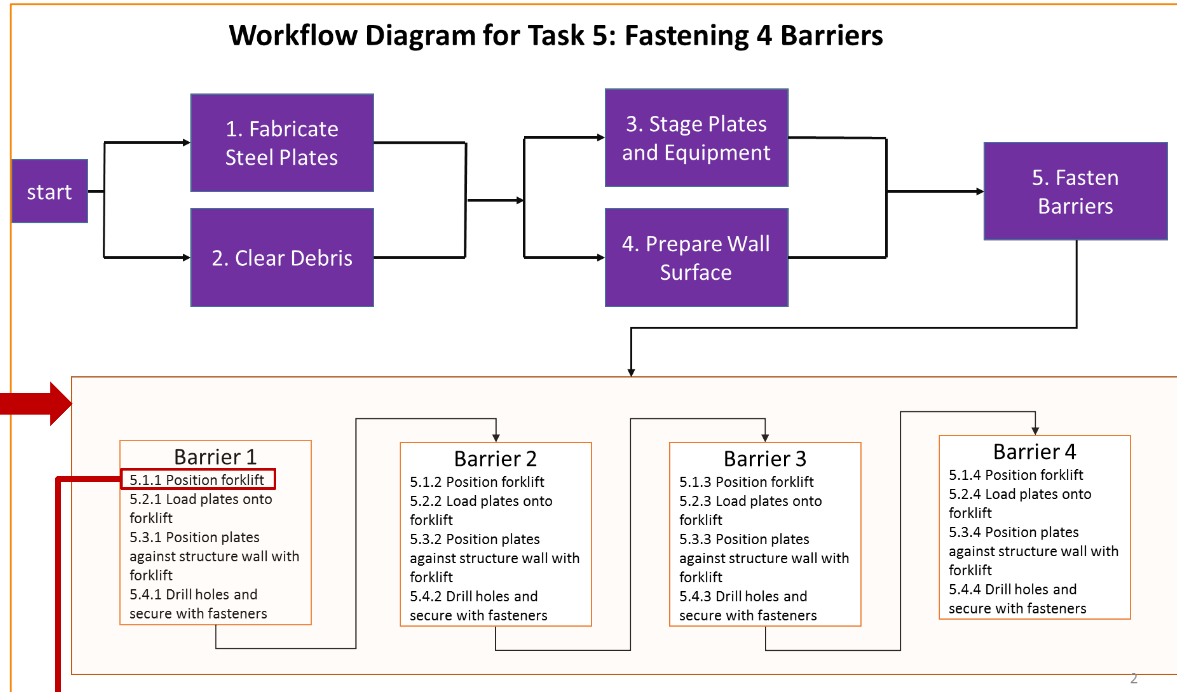
Task 2. Clear debris – could be done parallel to #1

Task 3. Stage plates and equipment – must be done sequential with # 1 and # 2

Task 4. Prepare wall surface – could be parallel to # 3

Task 5. Fasten 4 Barriers

- Subtask 5.1 Position Forklift
  - *GA 5.1.a Walking*
  - *GA 5.1.b Getting forklift*
  - *GA 5.1.c Driving forklift*
- Subtask 5.2 Load plates onto forklift
  - *GA 5.2.a Operating forklift (picking up)*
- Subtask 5.3 Position plates against structure wall with forklift
  - *GA 5.3.a Operate forklift (lifting the plate)*
  - *GA 5.3.b Communicate and coordinate*
  - *GA 5.3.c Operate forklift (pinning the plate)*
  - *GA 5.3.d Manually adjust plate position against wall*
- Subtask 5.4 Drill holes and secure with fasteners
  - *GA 5.4.a Hand tools (drill)*
  - *GA 5.4.b Hand tools (concrete bolts)*



5.1.1 Position Forklift

5.1.a Walking

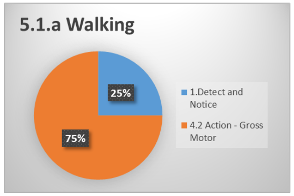
1.Detect and Notice	4.2 Action – Gross Motor
0.25	0.75

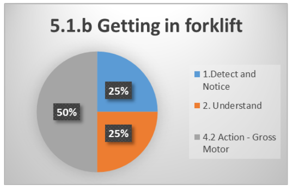
5.1.b. Getting in forklift

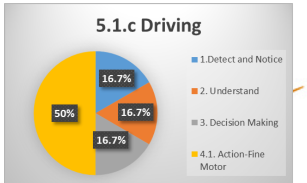
1. Detect and Notice	2. Understand	4.2 Action - Gross Motor
0.25	0.25	0.5

5.1.c. Driving

1. Detect and Notice	2. Understand	3. Decision Making	4.1. Action- Fine Motor
0.167	0.167	0.167	0.5







Method Application: an example (cont'd)

Performance Demands Associated with Each GA under Task 5

S_5: Task 5. Fasten 4 Barriers		Performance Demand Weights (w)								
		w_1 1. Detection and Noticing	w_2 2. Understanding	w_3 3. Decision Making	4. Action			5. Teamwork		
Subtask	**GAs**				w_4 4.1 Fine Motor	w_5 4.2 Gross Motor	w_6 4.3 Other	w_7 5.1 Reading'/writing	w_8 5.2 Oral Comm.	w_9 5.3 Crew Interaction
B_1: 5.1 Position forklift	G_1: 5.1.a. walking	0.25	0	0	0	0.75	0	0	0	0
	G_2: 5.1.b. getting in forklift	0.25	0.25	0	0	0.5	0	0	0	0
	G_3: 5.1.c. driving	0.17	0.17	0.17	0.5	0	0	0	0	0
B_2: 5.2 Load plates onto forklift	G_1: 5.2.a loading plates	0.17	0.17	0.17	0.5	0	0	0	0	0
B_3: 5.3 Position plates against structure wall with forklift	G_1: 5.3.a. Position plates/driving	0.17	0.17	0.17	0.5	0	0	0	0	0
	G_2: 5.3.b. communicating the position	0	0	0	0	0	0	0	0.5	0.5
	G_3: 5.3.c. pinning with forklift	0.17	0.17	0.17	0.5	0	0	0	0	0
	G_4: 5.3.d. manual adjustment	0.33	0	0	0.33	0.33	0	0	0	0
B_4: 5.4 Drill holes and secure with fasteners	G_1: 5.4.a drilling (hand tool)	0.33	0.33	0	0.33	0	0	0	0	0
	G_2: 5.4.b. bolting (hand tool)	0.33	0.33	0	0.33	0	0	0	0	0

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Method Application: an example (cont'd)

GA Baseline Times, Impact Factors, and Affected Times

Task 5. Fasten 4 Barriers		Baseline Time TG_k (min)	Nominal GA Impact Factor I_k^* (Primary EC only)	Affected Time TG_k^* (Primary EC Only)
Sub-Tasks	**GAs**			
5.1 Position forklift	5.1.a. walking	5	1.15	5.75
	5.1.b. getting in forklift	1	1.15	1.15
	5.1.c. driving	9	1.23	11.10
5.2 Load plates onto forklift	5.2.a loading plates	15	1.23	18.50
5.3 Position plates against structure wall with forklift	5.3.a. Position plates/driving	10	1.23	12.33
	5.3.b. communicating the position	10	1.25	12.50
	5.3.c. pinning with forklift	20	1.23	24.67
	5.3.d. manual adjustment	20	1.23	24.67
5.4 Drill holes and secure with fasteners	5.4.a drilling (hand tool)	15	1.23	18.50
	5.4.b. bolting (hand tool)	15	1.23	18.50
Total Time		**120**		**147.67**

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Limitations of Method

- Mapping between each GA and performance demands could be influenced by the by analysts' knowledge, experience, and professional biases.
- The proof-of-concept method does not address the potential occurrence of secondary ECs and their associated impacts. Combining primary and secondary EC impacts on performance demands needs further development.
- The proof-of-concept method did not fully address the complexity in task sequence and configuration.
- The method could be expanded to address how recovery time stemming from operator errors could also contribute to the time required to complete a manual action.
- The effects of dynamic (time-varying) ECs and combinations of ECs during the performance of manual actions, as well as uncertainties are not incorporated into the current method.

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Conclusion

- Existing research findings can be leveraged to provide the technical basis for impact quantification despite gaps and limitations in the research literature
- The proof-of-concept method, notwithstanding limitations, is theoretically and computationally tractable
- The proof-of-concept method is conceptually and operationally consistent with the decomposition-aggregation methodology and supports the implementation of the EC impact assessment framework.

Directions for Future Research

- Adapting the model to account for both primary and secondary EC impacts on performance
- Modeling complexity in task sequence and crew performance;
- Expanding the approach to model the time it takes to recover from critical operator errors Modeling effects of multiple, simultaneously-occurring ECs
- Modeling the effects of dynamic ECs;
- Address uncertainties in model parameters
- Addressing additional factors (e.g., fatigue, stress, and learning) that might influence performance.

Questions?

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