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Lessons Learned from Dependency Usage in HERA: Implications for THERP-Related HRA Methods

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April M. Whaley
Ronald L. Boring
Harold S. Blackman
Patrick H. McCabe
Bruce P. Hallbert

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April M. Whaley, Ronald L. Boring, Harold S. Blackman, Patrick H. McCabe, Bruce P. Hallbert
[1]Idaho National Laboratory, Idaho Falls, Idaho, USA
{april.whaley,ronald.boring,harold.blackman,patrick.mccabe,bruce.hallbert}@inl.gov

***Abstract*—Dependency occurs when the probability of success or failure on one action changes the probability of success or failure on a subsequent action. Dependency may serve as a modifier on the human error probabilities (HEPs) for successive actions in human reliability analysis (HRA) models. Discretion should be employed when determining whether or not a dependency calculation is warranted: dependency should not be assigned without strongly grounded reasons. Human reliability analysts may sometimes assign dependency in cases where it is unwarranted. This inappropriate assignment is attributed to a lack of clear guidance to encompass the range of scenarios human reliability analysts are addressing. Inappropriate assignment of dependency produces inappropriately elevated HEP values. Lessons learned about dependency usage in the Human Event Repository and Analysis (HERA) system may provide clarification and guidance for analysts using THERP-based dependency models. This paper presents the HERA approach to dependency assessment and discusses considerations for dependency usage in HRA, including the cognitive basis for dependency, direction for determining when dependency should be assessed, considerations for determining the dependency level, temporal issues to consider when assessing dependency, (e.g., considering task sequence versus overall event sequence, and dependency over long periods of time), and diagnosis and action influences on dependency.**

I. Introduction

The Human Event Repository and Analysis (HERA) system [1] is a tool developed to analyze and classify human performance information from nuclear power plant operating experience (e.g., event reports). The HERA system was specifically designed to be of a content and form useful to a variety of human reliability analysis (HRA) methods and the general discipline of human factors. As such, it consists of an analysis method that identifies information of interest to HRA, such as unsafe human actions, successful human actions including recoveries, performance shaping factors that contribute to human performance, and dependency between unsafe human actions.

A. Dependency Assessment in HRA

Dependency occurs when the probability of success or failure on one action changes the probability of success or failure on a subsequent action. The process of assessing dependency and incorporating dependency into the final human error probability (HEP) estimate varies by method. There is a wide variety of HRA methods available for use today; some explicitly model dependency, some assess dependency as part of the larger context surrounding human performance, and others do not consider dependency at all. The dependency model used in the Technique for Human Error Rate Prediction (THERP) [2] HRA method is widely used on its own and serves as the foundation for dependency modeling in other widely used methods such as SPAR-H [3] and ASEP [4].

Chapter 10 of THERP [2] provides an extensive discussion of dependency, including defining dependency levels ranging from zero dependence to complete dependence. The THERP process breaks down tasks into subtasks through task analysis, and provides explicit instructions for assessing dependencies among subtasks. It does not, however, provide guidance for considering dependency between different tasks. The subtask dependency model is often used to address dependency between tasks in THERP, which may not always be appropriate.

NUREG-1792, *Good Practices for Implementing Human Reliability Analysis (HRA)* [5], emphasizes examining human performance throughout the entire accident sequence for commonalities, similarities, and links among the actions, such as when involving the same crew members, occurring closely in time, sharing a common mindset, etc. In other words, the *Good Practices* document advocates considering the *context* of the actions in question when assessing dependency. The THERP dependency model only accounts for a small set of factors when calculating dependency, and therefore would not fully conform to the guidance established for dependency assessment in the *Good Practices* document. Because THERP does not fully consider context, using the THERP model of dependency may result in unrealistic HEP values.

Inappropriate dependency assignment may be attributed to a lack of clear guidance to encompass the range of scenarios human reliability analysts are addressing. Additionally, guidance regarding issues such as how to determine when dependency should be assessed, how to determine the factors or mechanisms that lead to dependency and how to consider those factors when assigning the dependency level, and how to properly consider temporal issues when assessing dependency is insufficient or absent [6]. Lessons learned about dependency usage in developing the HERA system and analyzing events within the HERA system may provide clarification and guidance about these issues.

II. HERA Guidance on Dependency Issues in HRA

A. The HERA Approach to Dependency

The HERA approach to dependency is based in part on the *Good Practices in HRA* document [5], but it differs slightly from the standard processes used in individual HRA methods, as it was designed to be informative to HRA in general, regardless of the specific method being employed. As HERA was being developed, it became clear that the approach to dependency offered by the many HRA methods was not appropriate for the data used in HERA. The information available in event reports does not lend itself easily to dependency calculation. In many cases, event reports offer a high-level overview of risk-significant activities that may omit risk-insignificant steps or contributors to the event sequence, therefore offering an account that may obscure any dependencies between human actions. Therefore, the HERA dependency assessment process was modified from traditional HRA dependency assessment to better suit the data being analyzed.

The HERA analysis process breaks down an event report into a timeline of *subevents*, individual human and equipment operations, and actions that contribute to an overall event. A human action that potentially decreases the safety of the event, such as an error, is classified as an "XHE" in HERA. The definition of dependency used in HERA is, "dependency exists between two subevents when an error on one subevent increases the probability that an error will occur on a subsequent subevent" [7].

HERA recognizes that dependency can exist between successful human actions and errors. However, because most HRA methods do not currently model the relationship between human errors and successful human actions, dependency is only completed for potentially unsafe human subevents, or XHEs. The approach to dependency assessment adopted in HERA does not attempt to quantify the level of dependency, nor does it limit the parameters that need apply. Instead, HERA analysts determine if dependency exists between two subevents and then identify the source of dependency (i.e., explain what dependence mechanisms were involved).

B. Determining Whether Dependency Should Be Assessed

The first step an analyst should take when considering dependency between human actions is to determine whether a dependency calculation is warranted. In practice, however, it is common for analysts performing an HRA to automatically perform a calculation of dependency level without first questioning whether dependency is actually present between the actions under consideration. The HERA analysis process instructs analysts to first consider whether there is any reason for dependency to occur between human actions.

The HERA authors believe that dependency between human actions is largely based in human cognition: dependency between human actions arises from the knowledge or lack of knowledge of the person involved in the second task regarding the occurrence and/or effect of the previous task. If an operator has no knowledge of a prior task, then it is not possible for that task to affect performance of a subsequent task.[1] More clearly stated, dependency arises from *mindset*. Mental models are updated by experience, so prior actions and errors can act as current cues and create expectancies and predispositions to behave in a certain manner. In other words, previous actions or experiences create a mindset that directs decision making [3].

The HERA dependency assessment process considers the multitude of situational, contextual, organizational, cognitive, and personal factors that can affect task dependency. HERA instructs analysts to ask the following questions to help them make an appropriate decision as to whether dependency exists between two human actions:

- Do the actions under consideration involve similar tasks?
- Are they part of a related sequence of actions?
- Do the personnel involved in each task share knowledge or a mindset that guides their actions?
- Is there any reason to expect that the first action influences the second?

If several subevents are all influenced by the same performance shaping factor (PSF), such as poor work processes, for example, it does not necessarily mean there is a dependency between them. If the PSF increases the likelihood of subsequent errors, then dependency exists. In other words, HERA asks analysts to fully consider the context of the actions under analysis and determine whether the situation is producing dependency between human actions.

In the case where multiple errors are made due to the same PSF but are otherwise unrelated to each other, HERA considers this to be a case of shared PSFs, not dependency, and identifies this information in the PSF assignment sections, not in the dependency section. HRA analysts also should consider these issues in the context of the method they are using before making a dependency calculation. An obvious example is that dependency is unlikely to occur between human actions that are a part of separate functions on an event tree, because the actions are unrelated to each other. Generally speaking, if there is no reason to predict that an error on one task or action makes a subsequent error more likely, then dependency does not exist between the two actions.

C. Determining Dependency Level: Dependency Factors

The traditional THERP [2] approach to dependency assessment uses several parameters to determine the level of dependency between subevents, including same or different crew, time, location, and cues. With these parameters came a scale that rated dependency from zero (no dependency) to a value representing complete dependency (see Table I). Following these criteria too rigidly, however, may lead to assignments of dependency levels that do not make sense given the situation under analysis, or are otherwise inappropriate. For example, not considering the possibility of zero dependency, even when all dependency factors do not apply, could

[1] The exception to this informal rule comes in cases when the operator should have been cognizant of a required action but failed to perform it. Such an error of omission may propagate itself, as the operator may continue not to realize the error, subsequently hindering successful recovery actions.

erroneously result in the assignment of low dependency using the guidance in Table I.

TABLE I. DEPENDENCY ASSIGNMENT FROM SPAR-H BASED ON THERP.

Dependency Level	Same Crew	Close in Time	Same Location	No Additional Cues	Dependency Modification
Complete	✓	✓	✓	✓	HEP = 1
	✓	✓	✓		
High	✓	✓		✓	$\frac{1+HEP}{2}$
	✓	✓			
	✓		✓	✓	
Moderate	✓		✓		$\frac{1+6 \times HEP}{7}$
	✓			✓	
		✓	✓	✓	
		✓	✓		
		✓		✓	
		✓			
Low	✓				$\frac{1+19 \times HEP}{20}$
			✓	✓	
			✓		
				✓	
Zero					HEP

HERA does not quantify the level of dependency, nor does it limit the parameters that can produce dependency. Instead, HERA analysts consider the context surrounding the subevents in question, determine whether dependency exists between two human actions and then explain the factors or mechanisms that led to the dependency (i.e., describe the context). HERA recognizes the THERP factors listed above (crew, time, location, and cues) as mechanisms for dependency, but these are only a subset of a much larger set of potential dependency mechanisms or contextual factors that can lead to dependency as well. A list of some possible contextual dependency factors that are included in HERA is presented in Table II below. Note that these mechanisms overlap one another and should not be considered orthogonal. Also note that this list is not exhaustive; HERA analysts are instructed to carefully consider any factor that reasonably triggers an increased likelihood of a negative outcome across subevents as a candidate dependency mechanism. It is important for HRA analysts to be aware that the factors presented in HRA methods as criteria for determining the dependency level are not absolute rules. Two actions can occur closely in time, be in the same location, and involve the same personnel, but be independent because the actions are part of unrelated tasks or functions. Similarly, moderate dependency can exist between two actions despite involving different personnel across a long period of time.

Currently the HERA system is designed primarily for retrospective analyses. Analysts performing a prospective HRA have to predict the most likely contributing factors and whether dependency is at play. Often, HRA analysts will set a high level of dependency as a screening value to determine the strongest possible or worst case effect of dependency on the total HEP. Our advice to HRA analysts performing prospective analyses is similar to that for retrospective analyses: analysts should carefully consider the situation under review, the tasks involved, the possible mechanisms for dependency, and the THERP definitions of the dependency levels, and then decide whether a dependency calculation is warranted and which level of dependency is most appropriate for the situation.

D. *Proper Consideration of Temporal Sequence*

HERA recognizes that dependency can occur between human actions that are not contiguous in time. It is possible for series of parallel activities to occur during an event. In such a case, the dependencies should reflect the proper track of occurrence, even when actions from different tracks co-mingle chronologically. HERA analysts consider dependency among subevents *within* tasks, rather than between subevents that are adjacent in the chronological order but are a part of separate tasks. For example, in Fig. 1 below, XHE 1 and XHE 3 are part of the same task sequence, and it is possible for XHE 3 to be dependent on XHE 1. XHE 2, however, represents a parallel activity that is unrelated to the task sequence including XHE 1 and XHE 3. Dependency occurs only between XHE 1 and XHE 3, even though XHE 2 occurs between them chronologically.

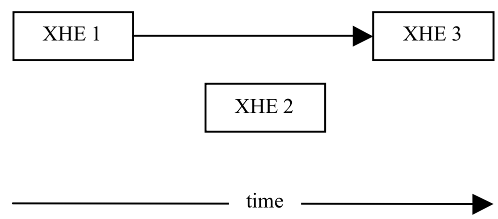

Figure 1. Task sequence vs. chronological sequence.

In order to properly consider possible dependencies between all XHEs, HERA analysts use the dependency matrix when determining whether dependency exists between two XHEs (see Fig. 2). Each XHE in the event under analysis is listed across the top row and down the left column, in chronological order. This allows HERA analysts to indicate whether dependency exists between the first XHE (listed in the column) and the second, the third, and so on (listed in the top row), by checking the box that intersects the two subevents. Using the list of possible dependency mechanisms (see Table II) as a guide, the HERA analyst moves to the second row and indicates any dependency between the second XHE and the third, the fourth, and so on, continuing down the rows until all subevents are accounted for.

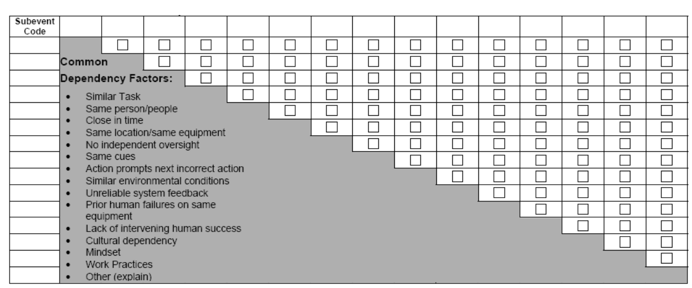

Figure 2. The HERA Dependency Matrix.

TABLE II. SELECTED HERA DEPENDENCE MECHANISMS

Dependence Mechanism	Discussion
Task	Task refers to the goal-driven activity performed by the crew. Each task represents different activities and corresponding different goals necessary to complete an action. A task may roughly correspond to a step of a procedure or may be defined at a finer grain corresponding to a series of actions required by each procedural step. If the second subevent involves a different task than the first, then dependency is very unlikely. If the two subevents involve the same or closely related tasks, however, dependency is possible. If, for example, an operator misreads a procedure step that causes him or her to go to the wrong subsequent procedure step, both actions share a common task of following procedures and could be considered dependent.
Crew / Person	Crew is broadly defined as those personnel who individually or as a team carry out plant activities. If the crew (or operator) involved in the first subevent is the same as is involved in the second subevent, there is a greater chance that dependency can exist between the subevents. This dependency may be related to the sub-optimal performance by a particular crew carrying forward to subsequent tasks. However, even if there is a different person or crew, if the culture or mindset is the same at the second subevent as the first, dependency is possible. Such would be the case for management sanctioned workarounds, in which two different crews have an established pattern of activity that does not differ between them and results in an undetected unsafe plant state. See also "Organizational/Team Culture" and "Mindset" below.
Time	If two subevents occur closely together in time, there is a greater possibility for dependency, as there is less opportunity for other factors (such as a different person or different cues) to intervene between the two subevents. When two subevents are close in time, there is less opportunity for recovery, as the ramifications of an error may not yet be apparent and there is inadequate time to recognize the problem. However, it is possible for dependency to exist between subevents that are far apart in time, even years, if other dependency mechanisms are at play, such as culture or mindset. Maintenance issues are examples of subevents that may span a large time but still be dependent.
Location	The location of a series of crew activities is an important consideration for dependency. If the second subevent takes place in the same location as the first subevent, there is a greater possibility for dependency between the two subevents. Proximate activities do not afford additional context that may enable the crew to diagnose and recover from an error.
Cues	Additional cues such as instrument readings, feedback from other personnel, or system performance introduce new information that thwarts the escalation of an error between two subevents. If additional cues are present during the second subevent in the sequence, dependency between subevents is less likely. If, however, no additional cues are available, then there is a greater possibility for dependency to exist between the subevents. The crew lacks additional information that may enable it to diagnose and recover from an error.
Independent oversight	Independent oversight refers to the presence of personnel in addition to the crew involved in completing plant tasks. Independent oversight can prevent dependency between subevents, often by providing additional cues. If a second checker is not truly independent (e.g., shares the same mindset as the operator), or if no second checker is involved, there is a greater likelihood that a negative outcome will go unmitigated and will have trickle-down negative effects on subsequent subevents. For example, a senior reactor operator's failure to notice a crew's faulty control setting can result in an unexpected plant transient and later difficulty determining the cause of that transient by the crew.
Organizational/ Team Culture	Organizational or team culture refers to the general worker attitudes and interactions that pervade activities at the plant. Culture is generally seen as a performance shaping factor (assessed in HERA through the Work Processes PSF), but it can be a mechanism for dependency, even over long periods of time. If the person or crew involved in a second subevent in sequence is operating under the same culture as the person or crew involved with the first subevent, then dependency is possible. Such would be the case for management sanctioned workarounds, in which two different crews have an established pattern of activity that does not differ between them and results in an undetected unsafe plant state. See also "Crew/Person" above and "Mindset" below. Organizational culture may also refer to factors such as the communication style of the crew. For example, a questioning crew may be more likely to detect a problem and hinder its progression than a crew that fears reprisal for questioning the course of actions during plant operation.
Mindset	Mindset refers to the attitudes toward aspects of plant operations, from attitudes toward safety to established patterns for performing activities in a specific fashion. It also refers to an understanding of the nature, cause, and consequences of a situation and the proper actions to take in response to the situation. Even if the person or crew involved in the second subevent is different from the person or crew involved in the first subevent, if the mindset is the same at both points, then dependency is possible between the two subevents. Such would be the case for a shared misunderstanding, for example, that certain degraded conditions are considered normal, and different crews have an established pattern of activity based on that misunderstanding that does not differ between them and results in an undetected unsafe plant state. A fresh perspective, be it from the same or a different person, can prevent the triggering of subsequent errors across subevents.
Work Practices	One way to look at work practices is in terms of safety culture. Work practices that strongly uphold safety are likely to have the necessary questioning mindset, second checking, and emphasis on individual safety to prevent human errors and, more importantly, detect and correct them before they escalate. Thus, safe work practices would tend to decrease the incidence of dependency between two subevents. Like Culture, Work Practices are usually seen as a PSF, and are assessed in HERA through the Work Processes PSF. It is also possible for work practices to be a mechanism for dependency. If the same poor work practices influence more than one subevent in a sequence *and* make a second error more likely, then dependence due to work practices exists. If, however, the work practices involved in the second subevent are different than the first action, dependency is less likely.
Intervening successes	Intervening successes or recovery can stop the escalation of negative subevents, often by introducing new cues or changing the crew mindset in a way that allows the crew to correct its course of action. A lack of intervening successes, on the other hand, can make dependency between subevents more likely. It is important to recognize that intervening successes do not necessarily prevent dependency between subevents, particularly if the success is unrelated to the subevent sequence in question.
Equipment / System	Equipment or system refers to those devices used by the crew to detect and control plant operations. It is important to recognize that the equipment or system is not synonymous with Location. Systems can be large and spread out over large areas, and equipment can, in some cases, be moved. If the equipment or system has an underlying characteristic (e.g., a stuck control valve) that causes the operators to perform a series of tasks incorrectly, then there is dependency between those tasks.
Unreliable system feedback	Unreliable system feedback (e.g., a misleading indicator or failed instrumentation) can contribute to dependency between actions in a task sequence by not allowing personnel to detect important underlying plant states or by leading personnel to a particular mindset (e.g., "do not trust the indicators"). Those faulty actions in response to the unreliable system feedback are dependent.
Action prompts next incorrect action	It is often the case that one error (often in judgment or diagnosis) leads the involved personnel down an incorrect path of action. In this case, dependency between actions in that path is very likely, as one error leads to subsequent errors. Additional cues or new personnel or mindset can break the path in such a situation.

Human reliability analysts often work from an event tree, in which case they are considering human actions within a task sequence. However, analysts typically only consider dependency between successive actions in a sequence (e.g., between XHE 1 and XHE 2, between XHE 2 and XHE 3, etc.). HERA allows consideration of dependency between XHE 1 and XHE 4, something that it not routinely performed in HRA currently (see Fig. 3). Whether working from an event tree or not, HRA analysts should be aware of the need to work within task sequences and to identify possible dependencies between human actions that they would not normally consider.

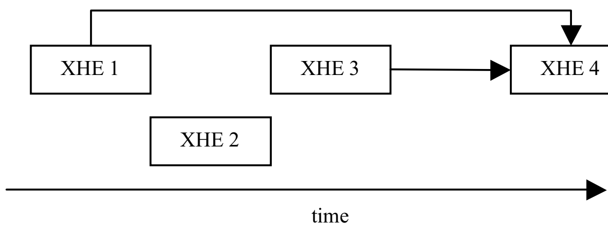

Figure 3. Dependency throughout an action sequence

Dependencies over very long timeframes are generally not addressed by current HRA methods. However, multiple HERA analyses have identified dependencies between subevents that occurred years apart. Such cases have often been due to instances of a shared organizational culture or mindset that led to increased unsafe actions across time. Latent errors—those that do not have an immediate impact but may affect system safety at a later time—almost invariably feature some degree of dependency over a long timeframe. The HERA approach to dependency allows analysts to identify and describe such cases of dependency over long periods of time. HRA analysts should remain aware of the possibility of dependency over long timeframes, and include such calculations in their analyses as appropriate.

E. Implications of Diagnosis and Action for Dependency Assessment

Some HRA methods such as SPAR-H [3] weight PSFs differently depending on whether the subevent under analysis involves *diagnosis* (a cognitive task such as decision making) or *action* (a behavioral response such as activating a switch), but there is little guidance available on how to properly consider diagnosis and action tasks when assessing dependency. Further research is needed to determine exactly how diagnosis and action tasks influence dependency. Insights gained from the HERA system may provide some clarification and serve to generate future exploration of this issue. The following argument is presented as a topic for further discussion.

HERA describes these four steps of human information processing or decision making [7]:

- Detection or recognition of a condition or change in situation (e.g., a problem or alarm)
- Interpretation of the condition or change in situation
- Planning a response to the situation
- Executing the response (action)

Diagnosis consists of the first three steps. Errors can occur at any of these steps and at more than one step in the sequence. In HERA, it is possible to see an XHE represent all of these steps, or for several XHEs to occur within one sequence.

One of the dependency mechanisms listed in Table II above is "Action prompts next incorrect action." This refers to the case where an error early on in the human information processing steps leads personnel down an incorrect path of actions. If an error is made in interpretation of the situation, subsequent planning and actions are more likely to be inappropriate; they are more likely to be dependent upon that error in interpretation. On the other hand, if the first error is an error in action implementation, any subsequent errors or unsafe actions are more likely to be unrelated to the first error. Recall the discussion above about dependency arising from mindset. The diagnosis steps of this process establish the mindset, and then the action follows. If the diagnosis is correct but an error occurs in response implementation, operators are likely to recognize the error and take actions to correct it. If however, the error is in diagnosis, actions taken as a result of the incorrect mindset are less likely to be recognized as inappropriate.

The HERA authors propose that when two actions under consideration for dependency are a part of the same detection-interpretation-planning-response sequence, then dependency is likely. If the two actions are part of separate, unrelated cognitive sequences, dependency is not likely. In many ways, this is similar or parallel to the THERP approach of considering dependency between subtasks within a task. Within the steps of the human information processing, or within a task, dependency is more likely than between separate cognitive sequences or tasks, respectively. The information processing process is something that is repeated iteratively. It is possible for two actions to be part of separate cognitive sequences that are related in a larger series of human actions. In such a case, dependency between the two actions is possible.

F. Dependency and HEP Calculations

Some HRA methods such as SPAR-H [3] provide explicit instructions on how to calculate dependency levels and include dependency in the HEP calculation. Other HRA methods leave assessing a dependency level and incorporating dependency calculation into the HEP estimate to analyst discretion [6]. HERA does not assign dependency levels, as discussed above, nor does it generate HEP values. For HRA methods that assign a dependency level, the HERA authors recommend that HRA analysts review the descriptions of the dependency levels provided in THERP [2], consider the factors and processes included in the HRA method being employed, consider the additional dependency mechanisms discussed in HERA, and consider the full context of the actions in question when assigning a dependency level. Our advice is similar for determining how to incorporate dependency into the overall HEP value: HRA analysts should give full consideration to the context of the actions under analysis within the process of the method being employed. Such a careful approach will enable analysts to avoid overestimating or underestimating the dependency level between two human actions.

III. Discussion

THERP-based dependency models lack consideration of some key contextual factors that are importance in today's HRA modeling. Yet they are still widely used. Issues relating to insufficient guidance regarding dependency assessment may result in inconsistent and/or inappropriate HEP values. Insights gained from the HERA system and approach to dependency provide additional clarification and guidance for dependency assessment in cases where existing information may not apply, and by bringing the consideration of context to THERP-based dependency models, may therefore improve the HRA dependency assessment process and resultant HEP values. HERA provides discussion for determining when dependency should be assessed, information about a variety of factors that lead to dependency between human actions to aid analysts in determining the proper dependency level, discussion about temporal issues that affect dependency calculations, and guidance for properly considering diagnosis and action when assessing dependency. Armed with guidance from the HRA *Good Practices* [5], and guidance from HERA [7], HRA analysts will be better prepared to appropriately and accurately characterize and include dependency in their HEP calculations.

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