DEPENDENCIES IN HRA – NPSAG PHASE I PROJECT

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Similar as the common cause failure between components, dependencies in human reliability analysis (HRA) is an important issue, which may heavily impact the results of probabilistic safety assessment (PSA). HRA dependencies appear in one human failure event (HFE), which includes multiple subtasks, and also among multiple HFEs which appear in the same event sequence or cut set. There is a need to establish a good practice in order to ensure HRA dependencies are considered in a systematic way throughout the entire PSA.

This paper presents the main results of the HRA dependencies project Phase I which has been funded by the Nordic PSA Group (NPSAG, with SSM, Ringhals, Forsmark and OKG as stakeholders) during 2015. The goal of the project has been to study how HRA dependencies should be accounted for in level 1 PSA during all plant operating modes. The performed work includes a literature review, an international survey, plant case studies and a final seminar to discuss the suggestions on HRA dependency evaluation. Understanding of the current industry practices in the different countries was gained through the international survey. Case studies were performed together with the plant PSA/HRA engineers, providing chances to understand the detailed HRA studies of the plants. Recommendations on how to perform HRA dependency analysis are provided for all categories of human actions in level 1 PSA. Specifically, rules are proposed to determine whether dependency exists among Category C actions.

I. INTRODUCTION OF THE PHASE I PROJECT

The HRA dependencies project Phase I, funded by the Nordic PSA Group (NPSAG, with SSM, Ringhals, Forsmark and OKG as stakeholders), was performed in 2015 (Ref. 1). The goal of the project has been to study how HRA dependencies should be accounted for in level 1 PSA during all plant operating modes. The performed work includes a literature review, an international survey, plant case studies and a final seminar to discuss the suggestions on HRA dependency evaluation. Good understanding of the current industry practices in the different countries was gained through the international survey. Case studies were performed for the Swedish plants together with the plant PSA/HRA engineers, providing chances to understand the detailed HRA studies of the plants. This paper presents the main results of the HRA dependencies project Phase I.

Phase I of the project has focused on how to evaluate the HRA dependency levels for human actions, considering the important factors and rules. Even though no new dependency decision tree has been developed, all the important dependency mechanisms/factors are listed and the existing methods/rules are discussed. Recommendations on how to perform HRA dependency analysis are provided for all categories of human actions in level 1 PSA. Specifically, rules are proposed to determine whether dependency exists among Category C actions. It is expected that the proper implementation of these rules will remove some of the unnecessary conservatism in the current PSA studies.

The identification of human actions for HRA dependency evaluations and the case studies for incorporation of the dependencies in the entire PSA are not included in Phase I of the project. They are currently being performed in the second phase of the project funded by NPSAG in 2016.

II. SUMMARY OF THE LITERATURE REVIEW

An extensive literature review was performed on the following documents related to HRA dependencies:

- International or national PSA/HRA requirements/guidelines, e.g. IAEA-TECDOC-1511 (Ref. 2), ASME PRA standard (Ref. 3), NUREG-1792 (Ref. 4), SKI 2003:48 (Ref. 5), YVL A.7 (Ref. 6), ENSI-A05/e (Ref. 7)
- HRA methods, e.g. THERP (Ref. 8), ASEP(Ref. 9), SPAR-H (Ref. 10), SHARP1 (Ref. 11), UK approach on human performance limit values (Ref. 12), NUREG-1921 (Ref. 13), as well as NUREG-1842 (Ref. 14)
- Some recent HRA projects, e.g. International HRA Empirical Study (Ref. 15),US HERA project (Ref. 16), EXAM-HRA project (Ref. 17)

There are clear requirements in reviewed documents about the treatment of HRA dependencies in a PSA model. However the state of the in HRA is such that the assessment of dependency is largely based on the analyst's judgement, as stated in ASME PRA standard.

Dependence is a continuum. For simplification, THERP proposes a five level dependency model for across subtask dependencies as well as for across human actions dependencies in a PRA sequence. THERP provides a good basis for the estimation of the appropriate degree of dependency, though analyst judgment is needed to assess the level of dependence. When the dependence level is assessed, THERP equations are provided to calculate the conditional HEP for a task based on the influence of the immediately preceding task. The five level dependency model and the equations are widely accepted by various HRA methods.

Some other HRA methods also provide ways to evaluate HRA dependencies, e.g. SHARP1 includes a thorough discussion of dependency issues, but does not include quantitative values. NUREG-1842 provides summaries of HRA methods on their dependency treatment.

The HRA good practice documented in NUREG-1792 proposes a number of good practices related to HRA dependencies including the commonality mechanisms for assessing the level of dependency, the range of conditional HEPs as well as the general limiting HEP for the joint probability.

EPRI developed a decision tree to assess the levels of HRA dependencies. The latest decision tree is presented in NUREG-1921 and it represents the state-of-practice in the US NRC and EPRI based methods. This decision tree is also implemented in EPRI's HRA Calculator Version 5.1.

In the International HRA Empirical Study, a diverse set of HRA methods was assessed based on reference data obtained in a dedicated simulator study. The benchmarking and assessment of each method involved comparing the empirical data with the predictions made under the method. Regarding the HRA dependency, it concluded that the treatment of dependency should be improved for most HRA methods, including SPAR-H method.

There was an interesting finding from the loss of feed water (LOFW) scenarios in the Empirical Study. In the simulation, all of the crews that failed to implement feed and bleed (F&B) before dry out (action 1B) subsequently succeeded to initiate F&B before core damage (action 2B). It seems that three things contributed to the success of the operating crews: (1) the crews had more time to analyze the situation; (2) the crews had additional cues, especially the flat steam generator level trend indications pointing to the indicators' unreliability; and (3) the situation after dryout was less complex to the crews because the concurrent goals and tasks of dealing with condensate pumps or feedwater pumps to feed the steam generator (SG) were no longer applicable.

However, most of the HRA teams analyzed the conditional HEP for action 2B and addressed potential dependencies with a THERP-based dependence model, and obtained HEPs for the conditional HEPs that were pessimistic (higher) compared to the empirical data (see Figure 2.6 in Ref. 15, most of the estimated HEPs for 2B are higher than the confidence bounds from the empirical HEPs). In considering potential dependencies, all the HRA teams were consistent with the industry common practice of accounting only for positive dependence, which refers in this case to the failure of a preceding task increasing the HEP of the subsequent task.

Thus the authors of Ref. 15 suggested that significant improvement in the treatment of dependence is needed for all methods. In particular, it would appear that analysts need to understand the dynamic nature of the plant status evolution and the information flow and procedural guidance that the evolution entails, rather than the current emphasis on factors like same crew, same procedure, or same location, which focus on more static aspects.

It should also be pointed out that experiment (B-scenario) is a special case which is not typically analyzed in PSA. But it clearly demonstrates that simulator results also provide good insights on the HRA dependencies among a sequence of human actions. Simulator could be a good source to check the reasonableness of the dependence level as well as the final conditional HEPs.

EXAM-HRA is a recently completed Nordic, Swiss and German project which assesses HRA applications in existing PSA studies. The overall project objective was to provide guidance for a state of the art HRA for purposes of PSA, to ensure that plant specific properties are properly taken into consideration in the analysis. In its practical guide report, Ref. 16, some general recommendations were also provided for HRA dependencies.

From the mechanism point of view, the HRA dependencies are introduced/caused by the situation/context/personnel factors. These factors need to be considered to evaluate the HRA dependencies levels. Table 1 summarizes the dependency factors described in the reviewed HRA guidelines/methods.

TABLE I. Summary of the Dependency Factors Considered in Various HRA Guidelines/Methods

Considered factors for Pre-initiating HFE													
Guidelines/Methods	Crew	Time	Location	Procedure	Stress	Cues	Instrumentation	Training	Functional relationships among events				
ASME	Y	Y		Y			Y						
Good practice	Y	Y	Y	Y		Y	Y	Y					
IAEA 1511	Y	Y		Y									
THERP	Y	Y	Y	Y	Y		Y	Y	Y				
SPAR-H	Y	Y	Y			Y							
Considered factors for Post-initiating HFE													
Guidelines/Methods	Crew	Time	Location	Procedure	Stress	Cues	Instrumentation	Training	Functional relationships among events	Action similarity	Adequate resources	Common cognitive	Intervening success
ASME	Y	Y		Y	Y		Y						
Good practice	Y	Y	Y	Y		Y				Y			
IAEA 1511	Y	Y		Y									
THERP	Y	Y	Y	Y	Y		Y	Y	Y				
SPAR-H	Y	Y	Y			Y							
HRA calculator	Y	Y	Y		Y						Y	Y	Y

III. FINDINGS FROM THE INTERNATIONAL SURVEY

During Phase I of the project, a survey on HRA dependencies was sent out internationally to contacts in nuclear power plants and associated organizations in March 2015. By September 2015, we received 16 replies from Europe, Asia, North and South America. The following nuclear power plants and technical organizations filled in the survey: Forsmark (Sweden), Ringhals (Sweden), Fortum (Finland), Eletronuclear (Brazil), MHI (Japan), Tepco (Japan), NEL (Japan), Karachi (Pakistan), CNPE (China), SNERDI (China), GNPC (China), Tractebel (Belgium), Jacobsen Analytics (UK, not plant specific), EPRI HRA user group (US, not plant specific), KAERI (South Korea, not plant specific), and OKG (Sweden).

An overview of the survey results is described in Table II.

The majority of the repliers have modelled HRA dependencies:

- Multiple post-initiating HFEs in one sequence, 94% of the repliers.
- One post-initiating HFE, 69% of the repliers.
- Multiple pre-initiating HFEs related to redundant trains in one function, 50% of the repliers.

None or only one reply has modelled HRA dependencies:

- Between pre-initiating HFEs and initiating HFE, none of the 16 repliers.
- Multiple pre-initiating HFEs related to multiple functions, one of the 16 repliers (The one who replied yes said they are studying this issue, but not yet implemented in any PSA project).
- Between pre-initiating HFEs and post-initiating HFEs, one of the 16 repliers.

TABLE II. Types of Human Dependencies Modelled In HRA

Types of human dependencies	Event(s)	Included in analysis
Dependency within one HFE which includes multiple parallel or subsequent subtasks	One pre-initiating HFE	44%
	One initiating HFE	38%
	One post-initiating HFE	69%
Dependency among multiple HFEs	Multiple pre-initiating HFEs related to multiple components in one train	44%
	Multiple pre-initiating HFEs related to redundant trains in one function	50%
	Multiple pre-initiating HFEs related to multiple functions	6% (One replied “yes”. They are studying this issue, but not yet implemented in any PSA)
	Multiple post-initiating HFEs in one sequence	94%
Dependency between different types of multiple HFEs	Between pre-initiating HFEs and initiating HFE	0%
	Between pre-initiating HFEs and post-initiating HFEs	6%
	Between initiating HFE and the following post-initiating HFEs	13%
Others	The same cognitive failure basic event is modelled as the factor of failure for several operations (complete dependence) when operations executed are based on same cognitive event*	

* This is a reply from one organization however we think it is common in HRA

With regard to the importance of the dependency in the PSA model, the majority of the respondents (8) consider it is important, some respondents (4) consider it depends on the model or not sure, few (2) respondents consider it is not important.

TABLE III. Importance of the Dependency in Your PSA Model(s)

Important	Not important	Not sure or it depends
57%	14%	29%

Note: 14 answers in total (= 100%)

IV. OVERVIEW OF THE NPSAG CASE STUDIES

Three case studies selected from the three Swedish nuclear power plants (see Table IV) were evaluated within the Phase I project. For each case, the following questions were evaluated to get an understanding of the HRA dependency treatment in their studies. Suggestions were provided if applicable for further improvements.

(1) What factors have been considered?
(2) Do you have clear rules to assign the dependency level?
(3) How do you quantify the conditional probability or joint probability?
(4) Do you have limiting value for a joint probability in one MCS?
(5) Justification of no dependency?
(6) Is the case study too conservative or too optimistic in the dependency treatment?

TABLE IV. Overview of the NPSAG case studies for three Swedish plants

Case No.	Type of HFE	Description
1	Multiple C actions	Dependency of human actions in shutdown LOCA event sequence
2	Multiple A actions	Misalignment errors
3	B action	Dependency within one B event which includes multiple human actions: LOCA during shutdown

In parallel with the Swedish case studies, two case studies were also performed by Finish counterparts for Finnish plants within the SAFIR project. They are documented in two separate SAFIR project reports, Ref. 18 and Ref. 19.

V. RECOMMENDATIONS ON HOW TO PERFORM HRA DEPENDENCY ASSESSMENT

From the literature review and case studies, recommendations were provided to evaluate the following HRA dependencies:

- Dependencies within a Category A HFE
- Dependencies within a manually induced initiating event (Category B)
- Dependencies within a Category C HFE
- Dependencies among Category A HFEs
- Dependencies between a Category B and the subsequent Category C HFEs within the same accident sequence
- Dependency among Category C HFEs, including recoveries
- Reasonable limiting value for the joint probability

This paper only summarizes some of the findings in Ref. 1 related to the dependency among Category C HFEs as well as the reasonable limiting values for the joint probability.

V.A. General Recommendations to Treat the Dependency among Category C HFEs

Some practical rules/models/methods have been proposed to evaluate the dependence level considering the various dependency factors in some of the reviewed HRA methods. Among them, a popular model is the decision tree proposed in the SPAR-H method. Another model is the decision tree used in the EPRI HRA Calculator. The decision tree in the EPRI HRA Calculator is in continuous development with insights from the U.S. nuclear practices.

It is considered that there is no thorough theoretical basis yet available to model all types of dependencies between multiple human interactions appearing in the same scenario. It is thus advisable to ensure that the approach to identity and evaluate such dependencies is self-consistent and well documented.

Following the findings from the recent studies, especially the lessons learned in the international HRA empirical study, it evolves that strictly following on the dependency rules (decision trees) might produce unreasonably conservative dependence level and thus produce a very pessimistic HEP estimation.

It is thus suggested to consider the context surrounding the events in question, determine whether dependencies exist between two human actions and then explain the factors or mechanisms that led to the dependency (i.e., describe the context).

V.B. Rules to Decide Whether Dependencies Exist among Category C HFEs

The following rules are proposed in the Phase I project as justification for zero dependence or independence between HFEs:

- Rule 1: separated by a successful action. The following literatures support this rule:
    - This rule is proposed in the NRC/EPRI Fire HRA guideline (NUREG-1921) which assumes that an HFE is independent of an immediate preceding success.
    - Cognitive connection between human actions is a crucial criterion for existence of dependencies between human actions. The presence of success may be able to indicate a break in the mind-set of the operators.
    - This is also supported by SHARP1 method.
    - Therefore, if two HFEs are identified in a cut set and a successful action can be identified between the two HFEs, the two HFEs in that cut set might be considered independent. Please be aware that in the PSA MCSs, the success might not be evident in the cut set (if no negated event is included in the MCSs), but will be seen by following the sequence in the event tree.
- Rule 2: separated by a long time interval. The following literatures support this rule:
    - human interactions separated by a long time interval with low stress (from SHARP1)
    - the required actions are separated sufficiently in the development of the accident sequence (IAEA-TECDOC-1511)

- Rule 3: distinct cues. The following literatures support this rule:
  - human interactions with distinct cues and low burden (from SHARP1)
  - the cues for subsequent actions are independent of those for prior actions (IAEA-TECDOC-1511)
- Rule 4: different crew. The following literatures support this rule:
  - Zero dependence can be assigned if two actions are performed by different people and under low stress level (NUREG-1921)
  - human interactions committed to memory (i.e. skill-based) and performed by different crew members (from SHARP1)
- Rule 5: The second action would be required whether or not the first were required. The workload is not significantly increased by virtue of the failure of the prior actions.
  - This is mentioned in IAEA-TECDOC-1511. This rule is judged not as effective as the previous rules.

V.C. Reasonable Limiting Values for the Joint Probability

It is recognized by many HRA experts that there should be some limiting values for the joint probability of multiple HFEs within the same cut set. These limiting values are in place to make sure the risk is not underestimated since there are many assumptions and uncertainties in the HEP estimation. When the joint probability goes to the extreme low values, the failure mechanisms that are usually negligible in the HEPs will become important, e.g. a heart attack to an operator, etc. The joint probability limiting values proposed in various sources are summarized in Table V.

TABLE V. Limiting Values in the Various Sources

HRA Guideline /Method	Proposed limiting value for the joint probability
SPAR-H	The lower bound on a single HEP in SPAR-H is suggested to be 1E-5. No limiting value for the joint probability is defined.
NUREG-1792 HRA Good Practices	Post-initiator HFEs: the total combined probability of all the HFEs in the same accident sequence/cut set should not be less than a justified value. It is suggested that the value not be below 1E-05.
ENSI-A05/e	The minimum joint failure probability for Category C actions within an accident sequence is 1E-05. For sequences that include actions that are supported by the emergency response team, the applicable minimum joint failure probability can be reduced to 1E-06.
THERP	Re-evaluate the level of dependence assumed if the joint probability of failure for two tasks is as low as 1E-06 in a case in which one person is checking the other. Likewise, if the joint probability of failure of two related tasks performed by one person is as low as 1E-05, re-evaluate the level of dependence assumed.
UK Approach	Human Performance Limiting Values (HPLVs): • Limiting value for a single operator 1E-4 • Limiting value for a team of operators 1E-5 Justify the optimizing factors if the HPLV could be lowered to 1E-6 or 1E-7 if significantly extended timescale (e.g. > 12 hours)

VI. CONCLUSIONS AND FUTURE WORKS

HRA dependency is an important issue in the PSA study. This is reflected in the industry PSA/HRA standards and the regulatory requirements. However the practices of the HRA dependencies are not systematic, consistent and quite often not well documented. Sometimes analysts have to assume conservative dependency levels because they don’t have available rules or theoretical background to support a lower judgement. One observation is that in many PSA studies, HRA dependencies are considered conservatively when they are evaluated but this is performed only for a limited scope of HFEs.

As discussed in the literature review, there have been quite a lot of findings recently in the industry about HRA dependencies. It is important to incorporate the findings in the HRA practices to derive a reasonable estimation and not to be over conservative during HRA dependency assessment. It is of course important to take all possible dependencies into account but it is equally important not to be over conservative by adding conservative approaches on top of each other.

The NPSAG Phase I project focuses on how to evaluate the HRA dependence levels for human actions, considering the important factors and rules. Even though there is no new decision trees developed in the current phase of the project, all the important factors have been listed and the existing methods/rules have been discussed. Recommendations on how to perform HRA dependency analysis are provided for all categories of human actions in level 1 PSA. Specifically, rules are proposed to determine whether dependency exists among Category C actions. It is expected that the proper implementation of these rules may remove some of the unnecessary conservatism in the current PSA studies.

It is also very important that a systematic and consistent approach is taken in the evaluation of HRA dependencies. In the same way as for the other elements of HRA, the importance of a good documentation should always be emphasized.

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REFERENCES

1. X. HE, *Dependencies in HRA*, NPSAG Report 41-001:01 (2015).
2. IAEA-TECDOC-1511, *Determining the quality of probabilistic safety assessment (PSA) for applications in nuclear power plants* (2006).
3. ASME/ANS RA-Sa-2009, *Standard for Level 1/Large Early Release Frequency Probabilistic Risk Assessment for Nuclear Power Plant Applications*. American Society of Mechanical Engineers (2009).
4. NUREG-1792, *Good Practices for Implementing Human Reliability Analysis (HRA).* U.S. Nuclear Regulatory Commission (2005).
5. SKI 2003:48, *Tillsynshandbok PSA*, Sweden Statens kärnkraftinspektion (2004).
6. YVL A.7, *Probabilistic Risk Assessment and Risk Management of a Nuclear Power Plant*, Finland STUK (2013).
7. ENSI-A05/e, *Probabilistic Safety Analysis (PSA): Quality and Scope*, Swiss Federal Nuclear Safety Inspectorate (2009).
8. A. D. SWAIN, H. E. GUTTMANN, *Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications*, NUREG/CR-1278/SAND80-0200, Sandia National Laboratories for the U.S. Nuclear Regulatory Commission, (1983).
9. A. D. SWAIN, *Accident Sequence Evaluation Program Human Reliability Analysis Procedure*, NUREG/CR-4772/SAND86-1996, Sandia National Laboratories for the U.S. Nuclear Regulatory Commission, (1987).
10. NUREG/CR-6883, *The SPAR-H Human Reliability Analysis Method*, U.S. Nuclear Regulatory Commission, (2005).
11. D. WAKEFIELD, G. PARRY, G. HANNAMAN, and A. SPURGIN, *SHARP1: A Revised Systematic Human Action Reliability Procedure*, EPRI TR-101711 Tier 2, Electric Power Research Institute, (1992).
12. B. KIRWAN, I. UMBERS, J. EDMUNDS, etc. "*Quantifying the unimaginable – the case for human performance limiting values*", PSAM9, Hong Kong, China, (2008)
13. NUREG-1921, *Fire Human Reliability Analysis Guidelines*, EPRI/NRC, (2012).
14. J. FORESTER, A. KOLACZKOWSKI, E. LOIS and D. KELLY, *Evaluation of Analysis Methods against Good Practices*, NUREG-1842, U.S. Nuclear Regulatory Commission, (2006).
15. NUREG-2127, *The International HRA Empirical Study, Lessons Learned from Comparing HRA Methods Predictions to HAMMLAB Simulator Data*, U.S. Nuclear Regulatory Commission, (2014)
16. A. M. WHALEY, R. L. BORING, H. S. BLACKMAN, et.al. "*Lessons Learned from Dependency Usage in HERA: Implications for THERP-Related HRA Methods*", Joint 8th Annual Conference on Human Factors and Power Plants and the 13th Annual Workshop on Human Performance / Root Cause / Trending /Operating Experience / and Self-Assessment (HPRCT), Monterey, USA, (2007).
17. G. JOHANSSON, S. JONSSON, K. BLADH, etc. *EXAM HRA A Practical Guide to HRA*, NPSAG Report 11-004-02, (2015).
18. J-E HOLMBERG, M. JACOBSSON, *Dependencies In Human Reliability Analysis - Case Study On Shutdown LOCA*, 14124_R001, Risk Pilot, Espoo (2015).
19. M. PORTHIN, *Methods for Handling of Dependencies in HRA: Fortum Case Study*, VTT Research report, VTT-R-05397-15 (2015).