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# HRA-Methodology Comparison on a Practical, Realistic-NPP Model Implementation: Sensitivity Analysis on a Plant-Level Risk Contribution

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This paper addresses the performance of human reliability analysis (HRA) as part of the development of a new plant-specific, full-scope industrial-scale L1/L2 PSA-model at the NPP Goesgen-Däniken (KKG), Switzerland. The focus of the paper is aimed at conducting sensitivity analysis on designated plant-level risk metric contribution (delta CDF) given two different HRA-methods for modelling the cognitive part of selected post-initiator operator actions (OA) – the Technique for Human Error Rate Prediction (THERP) and the Human Cognitive Reliability/Operator Reliability Experiments Method (HCR/ORE) method.

KKG, together with their supplier Framatome GmbH, embarked on the substantially thorough project – *PSASPECTRUM* – of migrating KKG`s existing PSA model from *Riskman*® to *RiskSpectrum*® environment. The conduction of an updated, plant-specific HRA using the *RiskSpectrum*® HRA Tool as well as a relatively new *RiskSpectrum*® feature – the Conditional Quantification tool – is one constituent part of this project. The preferred HRA-method, used for the internal events analysis, is the THERP practical method of predicting human reliability – both for the cognitive as well as for the execution part of the human error probability (HEP). Although this method is well established and being applied worldwide, it has its strengths and limitation. Especially, the use of simple, generic time reliability correlation (TRC) for addressing diagnosis errors is an over-simplification for addressing cognitive causes and failure rates for diagnosis errors when used, by itself. On the other hand, the HCR/ORE method would ideally use plant specific TRCs based on simulator measurement but may rely on expert judgement or generic data to derive the TRCs, hence making use of empirical data to support the HRA is a strength for this method. Once the relevant parameters have been identified, the derivation of the HEP using the TRC is straightforward and traceable.

Selected post-initiator OAs are used as basis for this comparative study. The results of the sensitivity analysis on the plant-level risk contributions are studied and discussed.

*Keywords*: PSA, HRA, event sequence diagrams, RiskSpectrum, HCR, OA, THERP.

## 1. Introduction

The focus of this conference contribution is the presentation of the results gained from a relatively rough sensitivity analysis given the application of two different HRA methods for the assessment of the cognitive part of various OAs.

Nowadays, there are at least a dozen various and well-established HRA methods, used both in the academia/research as well as the nuclear industry. Not surprisingly, the methods often differ in their underlying knowledge, data, and modeling approaches. Since all methods have strengths and limitations, this does not necessarily imply that one method is better than another, though it does mean that some methods are better suited to address certain types of issues associated with human performance than other methods. This reflects the positive evolution of HRA technology, as the area has improved its ability to address more complex and sophisticated aspects of human performance. There is an increased attention to the cognitive portion of human error in more recent methods, as compared to the modeling and analysis of cognitive error in earlier HRA methods (Forester et al. 2006).

The preferred HRA-method, used for the internal events analysis as part of the HRA update within the frames of the new KKG PSA project (*PSASPECTRUM*), is the THERP practical method of predicting human reliability – both for the cognitive as well as for the execution part of HEP – both for the cognitive as well as for the execution part of the human error probability (HEP). Although this method is well established and being applied world-wide, it has its strengths and limitation. Especially, the use of simple, generic time reliability correlation (TRC) for addressing diagnosis errors is an over-simplification for addressing cognitive causes and failure rates for diagnosis errors when used, by itself. On the other hand, the HCR/ORE-method would ideally use plant-specific TRCs based on simulator measurement but may rely on expert judgement or generic data to derive the TRCs, hence making use of empirical data to support the HRA is a strength for this method. Once the relevant parameters have been identified, the derivation of the HEP using the TRC is straightforward and traceable.

## 2. Methodology

### 2.1. *THERP*

THERP is a method for identifying, modelling, and quantifying HFEs in a PRA. As such, it is a reasonably complete approach to HRA, and has probably been used more than any other HRA technique (Swain et al. 1983). The THERP method does not provide guidance for screening of pre-initiator HFEs but does provide guidance for post-initiator screening. Nominal HEPs are being selected for tasks and subtasks, then modified by multiplicative performance shaping factor (PSF) model, five-level dependence model and recovery. Its underlying data includes judgement and sparse empirical data (largely 1960s vintage), mostly from non-nuclear experience (Forester et al. 2006). The quantification approach with the THERP method is such, that first a fixed set of PSFs and related descriptions are provided, which are then interpreted for the event being analyzed using analyst judgement. HEPs are then being "looked-up" in tables and curves, or a basic HEP is assigned in combination with multipliers to reflect the impact of PSFs. A TRC is used to quantify diagnosis HFEs based on available time and adjustments based on considering a few PSFs.

There are certain strengths and advantages in using the THERP method: given detailed task analysis are performed and available, quite a detailed and realistic assessment of the HEPs as well as insights for safety improvements are possible; The method is widely applied, across different industries, producing a wide pool of method knowledge, experts and benchmark applications; The method supports a five-level dependance model regarding an across-subtask dependence.

The THERP method has its limitations as well. This method is resource-intensive if performed as intended; Although the THERP method provides a good discussion of a broad set of PSFs, it explicitly uses only a limited set in its tables and curves and does not provide much guidance for how to handle a wider set of potentially important factors; The use of a simple, generic TRC for addressing diagnosis errors is an over-simplification for addressing cognitive causes and failure rates for diagnosis errors when used. Analysts may need to consider important PSFs besides the available time for diagnosis, that may significantly affect the diagnosis error rate. Moreover, using just the TRC is not very useful to understanding why such errors might be made (Forester et al. 2006). This last limitation of the THERP method is one of the motivations and the focus of the sensitivity study conducted within this conference contribution.

### 2.1. *HCR/ORE Method*

The HCR/ORE method was primarily developed to quantify post-initiator human actions (e.g., actions performed by control room crews associated with emergency and abnormal operating procedures) in a NPP PSA. The method uses a "simulator measurement-based" TRC to estimate the non-response probabilities for human actions (Parry et al. 1992). Given the HCR/ORE method, the non-response, i.e. error of omission (EOO), probability for a given event obtained from the TRC (which focuses on diagnosis and timely initiation of the correct response) is added to the probability of failure to execute the response to obtain the overall HEP. The error of commission (EOC), as well as the potential effects on plant dynamics thereof, are not explicitly addressed in the HCR/ORE method. Rather, the method only addresses the probability of not responding within a certain time period, based on data from simulator runs or analyst estimates with operator input and, therefore, an underlying assumption of the way the method gets applied is essentially that diagnosis will not fail given enough time (Forester et al. 2006).

The underlying model of the HCR/ORE method assumes lognormal distribution for the crew response time data, that has the two parameters of $T_{1/2}$ (median response time) and σ (sigma - logarithmic standard deviation of normalized time). The probability of EOO within a time window can, therefore, be obtained from the standard normal cumulative distribution. Its underlying data relies on obtaining estimates of crew response time data for use in the TRC using three potential approaches:

- Perform plant specific simulations of human events and accident scenarios;
- Use expert judgments from plant operators to estimate relevant parameters (i.e., when no appropriate data are available);
- Use data from EPRI ORE experiments and generalize to similar scenarios in similar plants.

The quantification approach with the HCR/ORE method is such, that analysts obtain estimates of critical parameters for inclusion in the TRC to estimate non-response probability. Other than the cue-response structure (temporal relationship between alarms and indications and the need to respond), it assumes that the influence of any other important plant specific factors will be implicitly included in the simulator-based, time-to-respond data collected at the plant and/or in the plant specific estimates obtained from operators (Forester et al. 2006).

There are certain strengths and advantages in using the HCR/ORE method: The use of empirical data to support HRA is a strength, especially in cases of realistic, real-life industrial model applications, in which such an application of the plant-specific empirics should be favorized given the thereof implicated best-estimate / realistic HEPs over the mainly "generic" ones, averaged over various decades and industries. Once the relevant parameters have been identified, the derivation of the HEP using the TRC is straightforward and traceable.

The HCR/ORE method has its limitations as well. Firstly, there are certain difficulties associated with implementing an adequate number of plant-specific simulator runs to address a range of plant conditions and PSFs, reasonably estimate model parameters, and identify potential problem areas; There is lack of guidance for the use of expert judgment to obtain estimates of crew response times while considering appropriate information and controlling biases is not provided; The experiments to plant-specific analyses may not always be appropriate; The simulator data from the ORE experiments supporting the assumptions made about the underlying distributions for the TRC are not publicly available and cannot be scrutinized.

## 3. Model

A set of OAs, as part of the complete HRA of the newly developed KKG PSA model, was selected as basis for this analysis. In particular, the preventive OAs from the accident scenarios part of the operator manual (OM), which in turn is symptom-based, are selected as basis for the analysis within this paper. It is a total of 25 OAs, covering the preventive spectrum of post-initiator human measures, ranging from starting the secondary depressurization, to initiation of cool-down, switching to RHR, feed-and-bleed, primary/secondary injection, starting recirculation / sump operation, initiating the PRZ-spray, etc.

In the nominal HRA model, all the OAs are modelled according to the THERP-methodology, both the diagnosis (Figure 1) and implementation part (Figure 2).

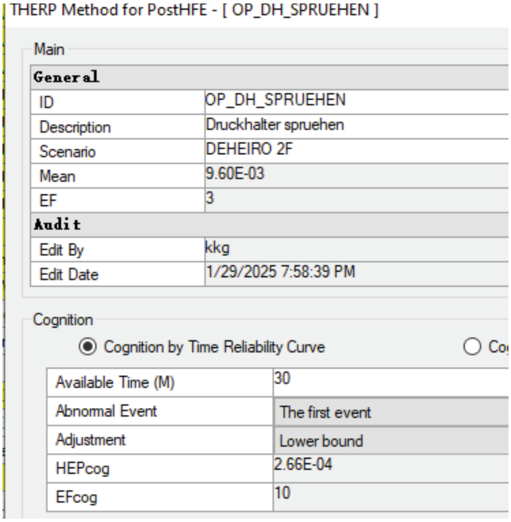


Fig. 1. Modelling of the cognitive (diagnosis) part with the *RiskSpectrum® HRA* tool, by using the THERP (TRC) method.

The TRC from THERP is used to evaluate the diagnosis, which means that the probability of a diagnostic error depends on the available diagnostic time. The probability of an incorrect diagnosis is also capped at 1.0E-04.

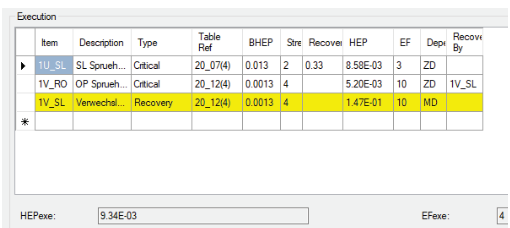


Fig. 2. Modelling of the implementation part with the *RiskSpectrum® HRA* tool, by using the THERP (TRC) method.

When using the lower diagnostic curve, a diagnostic time of 40 minutes results in exactly that probability of 1.0E-04. For more severe diagnoses, the mean value is appropriate and being used.

For the sensitivity analysis case, a second model is compiled based on the nominal one, such that the above-described set of 25 OAs are then modelled in the following way:

- The diagnosis part is being modelled according to the HCR/ORE method (Fig. 3);
- The implementation part remains modelled as in the nominal model, i.e. according to the THERP method.

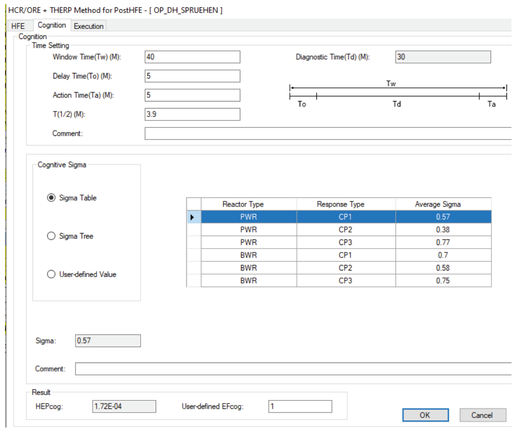


Fig. 3. Modelling of the diagnosis part with the *RiskSpectrum® HRA* tool, by using the HCR/ORE method.

The HCR/ORE model was derived from some simulator data collection studies, together with the SRK ideas of Rasmussen (Rasmussen, 1986) which divides all the human actions in a system into three categories of skill-base (S), rule-base (R) and knowledge-base (K). The HCR curves given in Figure 4 relate to SRK tasks.

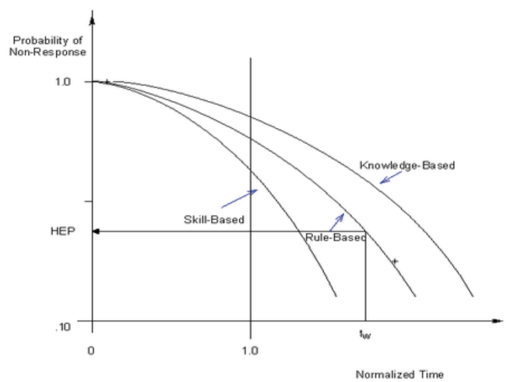


Fig. 4. Human Cognitive Reliability (HCR) Curve (Rasmussen, 1986; RiskSpectrum AB, 2022).

The HCR methodology can be broken down into a sequence of steps as given below:

- The first step is for the analyst to determine the situation in need of a human reliability

assessment. It is then determined whether this situation is governed by rule-based, skill-based or knowledge-based decision making.
- From the relevant literature, the appropriate HCR mathematical model or graphical curve is then selected.
- The median response time to perform the task in question is thereafter determined. This is commonly done by expert judgement, operator interview or simulator experiment. In much literature, this time is referred to as $T_{1/2}$ nominal.
- The median response time, ($T_{1/2}$), requires to be amended to make it specific to the situational context.

In RiskSpectrum HRA (RiskSpectrum AB, 2022) one could choose to use either SRK types or Cue Response types to decide the sigma (σ), both of these data are from ORE report. For the sake of the analysis presented in this paper, the second approach – the Cue Response types (as Figure 5) - is applied.

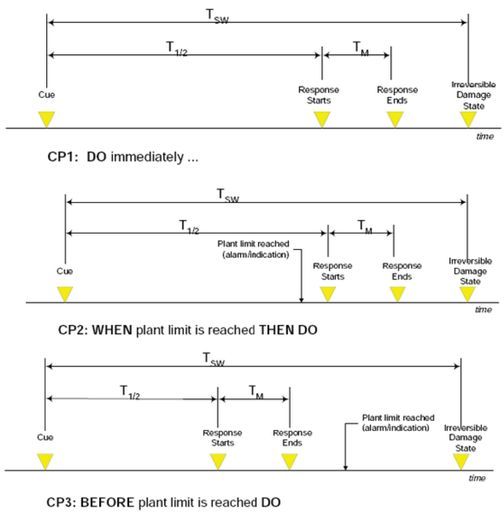


Fig. 5. Sigma values for the Cue-response groups (CP1, CP2, CP3) (Spurgin et al., 1990; RiskSpectrum AB, 2022).

The HCR model estimated crew median response times reflecting key plant- and task-specific PSFs (e.g., training level, man-machine interface quality). The model assumed that PSFs affect the response probability by changing the crew median response time $T_{1/2}$ (representing distribution location) but not the variability in response time (representing distribution shape) (Young et al., 2020). The following equation (Eq. 1) is suggested (Hannaman et al., 1984; 1988):

$$T_{1/2} = T_n \cdot (1 + k_1) \cdot (1 + k_2) \cdot (1 + k_3) \quad (1)$$

This represents the allowable time in which the operator must act to correctly resolve the situation. T1=2 is the median response time, n is the nominal response time, $k_1$; $k_2$; $k_3$ are PSF coefficients, defined as follows: $k_1$ represents operator experience, with parameter values of:

- Advanced (-0.22),
- Good (0), and
- Insufficient (0.44);

Parameter $k_2$ represents stress level, with parameter values of:

- Serious emergency (0.44),
- Heavy workload/Potential emergency (0.28),
- Excellent/Normal condition (0), and
- Vigilance problem (very low stress, -0.28);

Parameter $k_3$ represents operator/plant interface quality, with parameter values of:

- Excellent (-0.22),
- Good (0),
- Sufficient (0.44),
- Poor (0.78), and
- Extremely poor (0.92).

Table 1. Designation of the PSFs (k1; k2; k3) for each of the 25 OAs.

| # | ID | PSF | | | T1/2 _nominal (min) | T1/2 _median (min) |
|---|---|---|---|---|---|---|
| | | OP-experience | Stress-level | Interface quality | | |
| 1 | OA_1 | -0.22 | 0.28 | -0.22 | 2 | 1.6 |
| 2 | OA_2 | -0.22 | 0 | -0.22 | 2 | 1.2 |
| 3 | OA_3 | -0.22 | 0 | -0.22 | 2 | 1.2 |
| 4 | OA_4 | -0.22 | 0 | -0.22 | 2 | 1.2 |
| 5 | OA_5 | -0.22 | 0.28 | -0.22 | 2 | 1.6 |
| 6 | OA_6 | -0.22 | 0 | -0.22 | 2 | 1.2 |
| 7 | OA_7 | -0.22 | 0 | -0.22 | 2 | 1.2 |
| 8 | OA_8 | -0.22 | 0 | -0.22 | 2 | 1.2 |
| 9 | OA_9 | -0.22 | 0 | -0.22 | 2 | 1.2 |
| 10 | OA_10 | 0 | 0 | -0.22 | 5 | 3.9 |
| 11 | OA_11 | 0 | 0.28 | -0.22 | 5 | 5.0 |
| 12 | OA_12 | 0 | 0 | -0.22 | 5 | 3.9 |
| 13 | OA_13 | -0.22 | 0.28 | -0.22 | 15 | 11.7 |
| 14 | OA_14 | 0.44 | 0 | 0 | 5 | 7.2 |
| 15 | OA_15 | -0.22 | 0 | 0 | 5 | 3.9 |
| 16 | OA_16 | -0.22 | 0.28 | 0 | 5 | 5.0 |
| 17 | OA_17 | -0.22 | 0.28 | 0 | 5 | 5.0 |
| 18 | OA_18 | -0.22 | 0.28 | 0 | 2 | 2.0 |
| 19 | OA_19 | -0.22 | 0.28 | 0 | 3 | 3.0 |
| 20 | OA_20 | -0.22 | 0 | 0 | 2 | 1.6 |
| 21 | OA_21 | 0 | 0.28 | 0 | 10 | 12.8 |
| 22 | OA_22 | 0 | 0 | 0 | 5 | 5.0 |
| 23 | OA_23 | 0 | 0.28 | 0 | 5 | 6.4 |
| 24 | OA_24 | 0 | 0.28 | 0.44 | 5 | 9.2 |
| 25 | OA_25 | 0 | 0.28 | 0.44 | 60 | 110.6 |

Due to the partial or fully proprietary/confidential nature the exact qualitative descriptions of the analyzed OAs have or might have, these OAs are referred not according to their exact names/description herein, but simply as dummies, with forth numbered IDs, i.e. "OA_1", "OA_2" and so on.

Table 1 summarizes the application of the PSFs ($k_1$; $k_2$; $k_3$) for each of the 25 OAs.

## 4. Analysis and results

After designating the PSFs for the selected 25 OAs in relation to the HCR/ORE modelling for their corresponding diagnosis parts, their new HEPs are accordingly derived.

The following table (Table 2) presents the results of the implementation of the HCR/ORE method for the modelling of the diagnosis part of the HEP for the selected 25 OAs.

Table 2 summarizes the HEPs of the selected OAs for both models – the nominal model, in which these HEPs' both diagnosis and implementation parts are modelled according to the THERP method (columns designated with "THERP + THERP") as well as the new model, in which these HEPs' diagnosis parts are modelled according to the HCR/ORE method the and implementation parts are modelled according to the THERP method (columns designated with "HCR/ORE + THERP").

After applying the new HEPs to the 25 OAs, the model was re-quantified. The risk metric of interests for the sensitivity analysis in this paper is the L1-PSA measure (CDF) for plant operating states of full- and low-power operation.

The quantitative comparative analysis indicates ca. 33% CDF reduction in case of the new model ("HCR/ORE + THERP") versus the nominal model ("THERP + THERP").

Table 2. Implementation of the HCR/ORE method (diagnosis) to the selected set of 25 OAs.

| # | ID | THERP + THERP | | HCR/ORE + THERP | | Delta |
|---|---|---|---|---|---|---|
| | | HEP (mean) | EF | HEP (mean) | EF | HEP [%] |
| 1 | OA_1 | 5.7E-02 | 1 | 2.4E-02 | 1 | -65% |
| 2 | OA_2 | 1.4E-02 | 2 | 3.4E-03 | 7 | -89% |
| 3 | OA_3 | 6.7E-03 | 3 | 3.3E-03 | 7 | -68% |
| 4 | OA_4 | 1.5E-03 | 15 | 1.1E-03 | 19 | -19% |
| 5 | OA_5 | 5.7E-02 | 1 | 2.4E-02 | 1 | -65% |
| 6 | OA_6 | 1.4E-02 | 2 | 3.4E-03 | 7 | -89% |
| 7 | OA_7 | 6.7E-03 | 3 | 3.3E-03 | 7 | -68% |
| 8 | OA_8 | 1.5E-03 | 15 | 1.1E-03 | 19 | -19% |
| 9 | OA_9 | 5.6E-04 | 19 | 5.6E-04 | 19 | -15% |
| 10 | OA_10 | 1.2E-03 | 4 | 1.1E-03 | 4 | -8% |
| 11 | OA_11 | 4.7E-02 | 3 | 3.2E-01 | 1 | 492% |
| 12 | OA_12 | 4.0E-03 | 3 | 3.3E-03 | 3 | -45% |
| 13 | OA_13 | 1.8E-03 | 3 | 8.4E-03 | 3 | 301% |
| 14 | OA_14 | 2.2E-02 | 1 | 9.5E-02 | 1 | 220% |
| 15 | OA_15 | 9.7E-03 | 4 | 9.5E-03 | 4 | -1% |
| 16 | OA_16 | 1.3E-02 | 2 | 1.1E-01 | 1 | 295% |
| 17 | OA_17 | 3.4E-03 | 7 | 2.9E-02 | 1 | 509% |
| 18 | OA_18 | 5.2E-03 | 5 | 5.3E-03 | 5 | -56% |
| 19 | OA_19 | 1.1E-03 | 10 | 1.0E-03 | 11 | -9% |
| 20 | OA_20 | 1.1E-03 | 19 | 1.1E-03 | 19 | -19% |
| 21 | OA_21 | 3.6E-03 | 6 | 1.6E-02 | 2 | 344% |
| 22 | OA_22 | 8.2E-04 | 4 | 1.7E-03 | 2 | 53% |
| 23 | OA_23 | 1.7E-03 | 7 | 2.3E-03 | 5 | 31% |
| 24 | OA_24 | 1.1E-03 | 5 | 1.3E-03 | 5 | -19% |
| 25 | OA_25 | 4.5E-03 | 3 | 5.3E-02 | 1 | 1046% |


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## Disclaimer

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