Research reactor operator performance based on the human error assessment and reduction technique (HEART)

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Abstract. This study is an attempt to apply the Human Error Assessment and Reduction Technique (HEART) method in order to quantify the human failure event (HFE) for probabilistic safety assessment (PSA) of a TRIGA Mark II reactor, situated at the Malaysia Nuclear Agency, Malaysia. This serves the qualitative part of the human reliability analysis (HRA) framework and HEART method is considered due to its potential applicability in quantifying human error probability (HEP) for other industries, beside nuclear power. This study addresses the application of HEART method in details: classification of selected research reactor human task into the Generic Task Type, the assignment of the nominal HEP, evaluation of Error Producing Condition and the resultant Assessed Proportion of Affect. The results of this study will be applied in the quantification of PSA's event sequence end state frequencies.

1. Introduction

Probabilistic Risk Assessment (PRA), or Probabilistic Safety Assessment (PSA) is a tool used to determine risk, and have been benefited much in the nuclear power industry[1], [2]. The risk can be defined as the product of a prescribed undesirable occurrences, i.e. consequences and their likelihood, i.e. frequency. Simply put, risk can be decreased by making the likelihood of a consequence lower, and/or by making the occurrences less severe. PSA uses event tree (ET) and fault tree (FT) in modelling postulated accident sequences that lead to the undesirable consequences and reliability of mitigations systems, respectively. The quantification of a consequence frequency in an accident sequence is eventually involve the conversion of the ET to a large FT[3].

Human contribution to the risk is incorporated in a PSA through the modelling of human action as the basic events in the mitigation systems’ FTs, similarly as to the modelling of hardware. The identification and evaluation of the human performance is accomplished in Human Reliability Analysis (HRA) which is one of the major tasks in PSA. The quality of a PSA relies heavily on many factors, including the input of the reliability data[1]. Contrary to hardware, the statistical human reliability data that could match a particular accident scenario/context of interest is not much available and alternative methods have been used to produce these data[4]. Although the general framework of HRA for PSA has been long established in the nuclear power industry domain, there are various
human error rate, i.e. human error probability (HEP) quantification methods which are available and yet, they are still continuously evolving[5–8].

Besides for the purpose of civil power generation, nuclear fuel is also utilized in other nuclear installation such as a research reactor (RR). A PSA is also applicable in assessing the possible radiological risk posed by RR due to the existence and the use of nuclear fuel in its operation. PSA for RR is unique owing to the inherent flexibility in the RR operation, in which a wide range of human interactions can be expected during either normal or abnormal condition[9], [10]. These various reasons have led to a numbers of PSA study on RR[11–16]. In the previous studies of HRA for RR PSA, HEP quantification methods that are being applied are: Technique for Human Error Rate Prediction (THERP)[15][17][11][18], Standardized Plant Analysis Risk-Human Reliability Analysis (SPAR-H)[19], A Technique for Human Event Analysis (ATHEANA)[20] and Empirical Technique to Estimate Operator Errors (TESEO)[18].

This study is an attempt to employ the Human Error Assessment and Reduction Technique (HEART)[21] method in order to quantify the human failure events (HFEs) for the PSA of the TRIGA Mark II research reactor, situated at the Malaysian Nuclear Agency, Malaysia. This would serve the qualitative part of the HRA framework and HEART method is considered due to its generic approaches that can be applied in quantifying HEP for other industries, beside the nuclear power[5]. The details on the methodology and results for quantitative part of the HRA can be found in our previous study[22]. The quantification of HFEs by HEART method in this study is limited only for those modelled in accident sequences postulated for reactivity insertion accident (RIA) initiating event[23]. Eventually, the HEART outputs in this study is verified with the SPAR-H method[24].

The next section of this paper describes the HEART methodology in details: classification of selected research reactor human task into the Generic Task Type, the assignment of the nominal HEP, evaluation of Error Producing Condition and the resulting Assessed Proportion of Affect. In section Result and Discussion, the quantified HEPs are presented and verified with those of from SPAR-H method, and insights obtained through the application of the HEART method for RR PSA are addressed. Finally, the summary of the methodology and results of the study are given in Conclusion.

2. Methodology

The approach of HEART[21] in deriving HEP of a task begins with selection of the generic task type (GTT) that match the description of the analysed task. There are nine GTTs (Table 1) defined within HEART:

The given nominal human unreliability values are the basic HEP values (mean) that are tend to be achieved by human when performing the prescribed generic tasks.

The value and the probabilistic limits are applied when the context within which the task is performed is in perfect condition. When there are circumstances that degrade the human performance, the perfect condition does no longer exist and the higher HEP value has to be applied. There are 38 circumstances that are defined as Error Producing Condition (EPC), each of which with maximum weighting factor that degrade the human performance (Table 3)[21]. The weighting factor of the EPCs can be adjusted by multiplying them with value ranging between (best, positive) to 1 (worst, negative). This step is termed as Assess Proportion of Affect (APAO). The final HEP of a task is calculated using Equation (1).

\[
\text{Final HEP} = \text{GTT} \times \prod_{i=1}^{n} (\text{EPC}_i - 1) \times \text{APAO}_i - 1
\]

(1)
In general, the HEART quantification process for a HFE can be illustrated as in Figure 1.

Select the Generic Task Type (GTT) that match the HFE

Identify the applicable Error Producing Conditions (EPCs)

Assess Proportion of Affect (APAO) on each identified EPCs

Calculate the final HEP, i.e. based on Equation (1)

Table 1. HEART GTTs and the corresponding mean HEP value.

| Item | Generic Task                                                                 | Proposed Nominal Human Unreliability (5th – 95th Percentile Bounds) |
|------|-----------------------------------------------------------------------------|---------------------------------------------------------------------|
| A    | Totally unfamiliar, performed at speed with no real idea of likely consequences | 0.55 (0.35 - 0.97)                                                  |
| B    | Shift or restore system to a new or original state on a single attempt without supervision or procedures | 0.26 (0.14 - 0.42)                                                  |
| C    | Complex task requiring high level of comprehension and skill                 | 0.16 (0.12 - 0.28)                                                  |
| D    | Fairly simple task performed rapidly or given scant attention               | 0.09 (0.06 - 0.13)                                                  |
| E    | Routine, highly-practiced, rapid task involving relatively low level of skill | 0.02 (7E-3 - 4.5E-2)                                                |
| F    | Restore or shift a system to original or new state following procedures, with some checking | 3E-3 (8E-4 - 7E-3)                                                  |
| G    | Completely familiar, well-designed, highly practiced, routine task occurring several times per hour, performed to highest possible standards, by highly-motivated, highly-trained and experienced person, totally aware of implications of failure, with time to correct potential error, but without the benefit of significant job aids | 4E-4 (8E-5 - 9E-3)                                                  |
| H    | Respond correctly to system command even when there is an augmented or automated supervisory system providing accurate interpretation of system state | 2E-5 (6E-6 - 9E-4)                                                  |
| I    | Miscellaneous task for which no description can be found                    | 0.03 (8E-3 - 0.11)                                                  |

In general, the HEART quantification process for a HFE can be illustrated as in Figure 1.

Figure 1. HEP quantification process based on HEART.
3. Results and discussion

The explanation in the next two paragraphs is regarding two HFEs postulated in RIA accident sequence. RIA is postulated to occur due to the existence of sample with positive reactivity which leads to excess reactivity of the core.

During RIA event, reactor safety channel will detect the excess reactivity and subsequently generate trip signal. Operators would have been attempting scram the reactor when realizing no reduction on the reactor power. The operators have to trip the reactor by improvisation. The operators would have to directly de-energize the control rods withdrawal mechanism by disconnecting its power supply: this task is identified as RIA-LOIC-H. The manual operators action within this HFE comprise of a simple turning a switch-off, which is able to be completed in a single second, once the decision is made. The operators then would attempt to push scram button a few times followed by physical field inspection to verify the control rods response. The diagnosis can be assumed to require maximal time of 20 minutes. The available time can be regarded as positive performance driver for the operators because it is estimated that the time until the complete depletion of pool water due to heat from fission reaction in the core is approximately 11 hours.

The reactor pool water has to be manually added when considering that all means to terminate the chain reaction have failed in order to prevent core uncover due to the water depletion. This human task is identified as PW-RIA-H. Again, with regard to the fact that pool water depletion up to the beginning of core uncover would take approximately 11 hours long, the available time can be regarded as positive performance driver for the operators.

This study identifies that the GTT that match RIA-LOIC-H task is Item F. The consideration of others GTT on this task is as addressed in Table 3. The task physically involves the changing of the instrument and control (I&C) system to a new state, and the checking by human redundancy. Although there is no formal procedure for this task specific for this abnormal condition, the operators are experience with the system since they perform the maintenance annually. This complements the unavailability of formal procedure. With regards to EPCs, the consideration is denoted in Table 3. As a result, the EPCs that are taken into account for the final HEP calculation are Item 1 and 34. A conservative approach is taken for APOA, by using the weighting factor 1. Putting these numerical values into Equation (1), the final HEP = 5.61E-2.

In classifying GTTs for a HFE, the one that is closely matching the task description is selected. The rest GTT which are not selected are provided with specific justifications. Intuitively, the result would be heavily depending on the task description, and therefore the familiarization of an analyst with the HFE should be in according to the HRA framework for PSA[25]. Likewise, the same explanation applied for the identification of EPCs. This study is unable to systematically perform the APOA, the part which is considerably relying on expert judgment[4]. Instead a conservative approach is used and yields HEP which is conservative. For the second human task postulated in RIA, i.e. PW-RIA-H, the context is similar as to the RIA-LOIC-H task and thus the same final HEP value is deduced.

The study using SPAR-H gave HEPs of 1.00E-2 for I&C-RIA-H and 2.55E-3 for PW-RIA-H [26]. The value of the former is considerably close to that calculated by HEART while the latter is an order of magnitude lower than that calculated by the HEART methodology in this study, due to the conservative approach taken with regards to its APAO.
**Table 2. HEART GTTs and the consideration for RIA-LOIC-H task.**

| Item | Generic Task | Consideration for RIA-LOIC-H task |
|------|--------------|-----------------------------------|
| A    | Totally unfamiliar, performed at speed with no real idea of likely consequences | The operators are familiar with the control system, and they know the consequence of the action |
| B    | Shift or restore system to a new or original state on a single attempt without supervision or procedures | Although there is no formal procedure for this task which is specific for this abnormal conditions, the operators are experience with the system: they perform the maintenance |
| C    | Complex task requiring high level of comprehension and skill | The action is not complex. The displays and annunciators provide the information for the operators to do diagnosis |
| D    | Fairly simple task performed rapidly or given scant attention | This is not directly a simple task such as the skilled-based action. It requires analysis on the reactor parameters |
| E    | Routine, highly-practiced, rapid task involving relatively low level of skill | This is not a routine task |
| F    | Restore or shift a system to original or new state following procedures, with some checking | - |
| G    | Completely familiar, well-designed, highly practiced, routine task occurring several times per hour, performed to highest possible standards, by highly-motivated, highly-trained and experienced person, totally aware of implications of failure, with time to correct potential error, but without the benefit of significant job aids | This task only demanded during abnormal condition (not hourly), which is never been occurred |
| H    | Respond correctly to system command even when there is an augmented or automated supervisory system providing accurate interpretation of system state | The augmented or automated supervisory system specific for this case does not available |
| I    | Miscellaneous task for which no description can be found | The task is identified with respect to the postulated accident sequence |
### Table 3.1 HEART EPCs and the corresponding maximum weighting factors. For task RIA-LOIC-H’s GTT Type F, applicable EPCs are denoted as: A, not applicable (out of the context) : NA, and opposite to the context in which the task is performed: O.

| Item | Error Producing Conditions (EPCs)                                                                 | Maximum predicted nominal amount by which unreliability might change going from ‘good’ condition to ‘bad’ | Consideration for RIA-LOIC-H’s GTT Type F |
|------|----------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------|------------------------------------------|
| 1    | Unfamiliarity with a situation which is potentially important, but which only occurs infrequently, or which is novel | 17                                                                                              | A                                        |
| 2    | Time shortage                                                                                                  | 11                                                                                               | O                                        |
| 3    | Low Signal/Noise ratio                                                                                        | 10                                                                                               | NA                                       |
| 4    | Features override allowed                                                                                      | 9                                                                                                | NA                                       |
| 5    | Spatial and functional incompatibility                                                                       | 8                                                                                                | NA                                       |
| 6    | A mismatch between an operator's model of the world and that imagined by a designer                           | 8                                                                                                | NA                                       |
| 7    | No obvious means of reversing an unintended action                                                           | 8                                                                                                | O                                        |
| 8    | A channel capacity overload, particularly one caused by simultaneous presentation of non-redundant information | 6                                                                                                | NA                                       |
| 9    | A need to unlearn a technique and apply one which requires the application of an opposing philosophy          | 6                                                                                                | NA                                       |
| 10   | The need to transfer specific knowledge from task to task without loss                                        | 5.5                                                               | NA                                       |
| 11   | Ambiguity in the required performance standards                                                               | 5                                                                                                | NA                                       |
| 12   | A mismatch between perceived and real risk                                                                    | 4                                                                                                | NA                                       |
| 13   | Poor, ambiguous or ill-matched system feedback                                                                | 4                                                                                                | O                                        |
| 14   | No clear direct and timely confirmation of an intended action from the portion of the system over which control is to be exerted | 4                                                                                                | O                                        |
| 15   | Operator inexperience (e.g. a newly-qualified tradesman, but not an "expert")                                 | 3                                                                                                | O                                        |
| 16   | An impoverished quality of information conveyed by procedures and person/person interaction                   | 3                                                                                                | O                                        |
| 17   | Little or no independent checking or testing of output                                                        | 3                                                                                                | O                                        |
| 18   | A conflict between immediate and long-term objectives                                                         | 2.5                                                               | NA                                       |
| 19   | No diversity of information input for veracity checks                                                         | 2.5                                                               | O                                        |
| 20   | A mismatch between the educational achievement level of an individual and the requirements of the task       | 2                                                                                                | NA                                       |
4. Conclusion
In this paper, we demonstrate the application of HEART method for the quantification of HEP for two selected HFEs modelled in a TRIGA research reactor. The process involves the classification of GTTs, identification of EPCS and APAO. A conservative approach is taken in dealing with APOA so that there would be no unnecessary optimism when interpreting the overall risk at this stage. HEPS

Table 3.2 HEART EPCs and the corresponding maximum weighting factors. For task RIA-LOIC-H’s GTT Type F, applicable EPCs are denoted as: A, not applicable (out of the context): NA, and opposite to the context in which the task is performed: O (continue).

| Error Producing Conditions (EPCs) | Maximum predicted nominal amount by which unreliability might change going from ‘good’ condition to ‘bad’ | Consideration for RIA-LOIC-H’s GTT Type F |
|----------------------------------|-------------------------------------------------|---------------------------------------|
| 21  An incentive to use other more dangerous procedures | 2  | NA |
| 22  Little opportunity to exercise mind and body outside the immediate confines of a job | 1.8  | NA |
| 23  Unreliable instrumentation (enough that it is noticed) | 1.6  | NA |
| 24  A need for absolute judgments which are beyond the capabilities or experience of an operator | 1.6  | O |
| 25  Unclear allocation of function and responsibility | 1.6  | NA |
| 26  No obvious way to keep track of progress during an activity | 1.4  | NA |
| 27  A danger that finite physical capabilities will be exceeded | 1.4  | NA |
| 28  Little or no intrinsic meaning in a task  
29  High-level emotional stress | 1.4  | O  
1.3  | NA |
| 30  Evidence of ill-health amongst operatives, especially fever | 1.2  | NA |
| 31  Low workforce morale | 1.2  | NA |
| 32  Inconsistency of meaning of displays and procedures | 1.2  | NA |
| 33  A poor or hostile environment (below 75% of health or life-threatening severity) | 1.15  | NA |
| 34  Prolonged inactivity or highly repetitious cycling of low mental workload tasks | 1.1  | A |
| 35  Disruption of normal work-sleep cycles | 1.1  | NA |
| 36  Task pacing caused by the intervention of others | 1.06  | NA |
| 37  Additional team members over and above those necessary to perform task normally and satisfactorily | 1.03  | NA |
| 38  Age of personnel performing perceptual tasks | 1.02  | NA |
calculated in this study are verified by the results from the previous study that has employed SPAR-H method, and therefore they would be used as input parameter for human basic events of the PSA logic models. In addition, remedial measures related to each EPCs can be proposed into the reactor operation and management so that a better operator performance and hence the more risk reduction can be achieved. The future work of this study requires the development of a systematic scheme for rating the APAO specifically for the context of the RR PSA.

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