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Nuclear Power Plant Maintenance and Commissioning Activities From the Perspective of HRA: A Comparative Study

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ABSTRACT

The recent Human Reliability Analysis (HRA) method developed by U.S. Nuclear Regulatory Commission, Integrated Human Event Analysis System (IDHEAS), provides a well-grounded model to analyze human errors as well as a promising interface for generalizing and integrating human error data from various sources. Nevertheless, the task context and human performance in different domains, even in different applications within one domain, manifest quite different features which make it elusive to draw an inter-sector or inter-application comparison. In light of this contradiction, one question arises: Can HRA in distinct applications be cross-referenced to one another? Motivated by this, an interview study was conducted as a preliminary attempt to figure out the similarities and differences between two typical activities in the nuclear domain, i.e., maintenance and commissioning, with respect to two vital HRA elements, i.e., error modes and performance shaping factors (PSFs). A total of 21 engineers in a nuclear power plant were recruited to participate in the interview about salient error modes and PSFs in maintenance activities as well as a comparison with commissioning activities. Results show that the two activities share analogous error modes and PSFs on the whole, but vary in the patterns and distributions of each individual PSFs. Hence, results of the present study indicate that human errors in these two comparable activities could be characterized by a unified taxonomy, affording positive evidence for the thrown question. However, the discrepancy in the PSF patterns should never be neglected, which could lead to the divergency of nominal PSF levels and nominal human error probabilities.

Keywords: Human reliability analysis, Nuclear power plant, Maintenance, Commissioning

INTRODUCTION

The cognitive-based Human Reliability Analysis (HRA), often classified as the second generation HRA, seems to provide a promising way to analyze human errors in different contexts and sectors. One example of such HRA methods is Cognitive Reliability and Error Analysis Method

(CREAM; Hollnagel, 1998), which has been applied in various sectors including nuclear industry (Marseguerra, Zio and Librizzi, 2006), oil and gas industry (Zhang and Tan, 2018), etc. Another method recently developed by U.S. Nuclear Regulatory Commission (NRC), Integrated Human Event Analysis System (IDHEAS), was also expected to be "applicable, but not limited, to all nuclear risk-informed applications" (Xing, Chang and DeJesus Segarra, 2022). The underlying cognitive model of IDHEAS, the macro-cognition model (Whaley et al., 2016), uses five macro-cognitive functions (i.e., detecting, understanding, decision-making, action, and teamwork) to characterize human activities. Each macro-cognitive function includes several cognitive processors which are driven by various cognitive mechanisms. Such general and technology-neutral model can enhance our understanding of human errors and provide an interface for generalizing and integrating human error data from various sources (Xing, Chang and DeJesus Segarra, 2020).

Although IDHEAS is expected to suit most nuclear applications, the divergent features of different nuclear applications are noteworthy, not to mention the divergence across different sectors. For example, Yin, Liu and Li (2021) highlighted the difference in contextual factors between control room and commissioning work. Obviously, the control room activities and ex-control room activities are quite distinct in that control room operators monitor the indicators and alarms of the plant and manipulate the plant through soft controls, while local operators outside the control room interact directly with the local equipment. In addition, different ex-control room activities also possess different characteristics. Two similar but distinct ex-control room activities are commissioning and maintenance (Yin et al., 2023). Note that such "ex-control room" is not that absolute in that some actions may also require operations in the control room. Commissioning and maintenance are two typical ex-control room activities in different stages of a Nuclear Power Plant (NPP). Commissioning is the last stage before the commercial operation of an NPP, serving as an important transition from engineering to operation. The main objective of commissioning is to validate that all components and systems can function normally and meet relevant criteria, and this is achieved through various functional tests. Maintenance happens during the whole operation stage of an NPP aiming at ensuring all components and systems to perform design functions, and mainly includes preventive and corrective maintenance. Although both belonging to ex-control room activities, commissioning and maintenance have salient differences with regard to several aspects such as objectives, working contents, risks, and contexts (Yin et al., 2023).

As a starting point, the present study tries to answer the question that whether HRA in commissioning and maintenance can be cross-referenced to one another. If so, the two activities might be assessed using a common HRA method, and human error data from the two sources could be better generalized and integrated. Remember that HRA aims at assessing the "reliability" of a task performed by humans in a certain context. Aligning with that, the feasibility of cross-reference would depend on meeting of several criteria:

(a) Tasks in the two activities should be comparable, so that the assessed objects of HRA are the same. This criterion is the most basic of cross-reference, as it makes limited sense to juxtapose one activity with another that exerts very different requirements on human information processing.
(b) Error modes in the two activities should be comparable. Error modes depend on the task type, and are the manifestation of how humans might fail to perform the task.
(c) Contexts in the two activities should be comparable. There should exist some shared contextual factors, so that the effects of such factors could be modeled and analyzed across activities.
(d) The effects of contextual factors on human errors should be homogeneous across activities. HRA models such effects as the quantitative relationship between contextual factors and Human Error Probabilities (HEPs).

In the present study, criteria (b) and (c) are addressed while the others are left for future work. Hence, two vital elements in HRA are specifically considered here: Error Modes (EMs) and contextual factors (i.e., Performance Shaping Factors, PSFs). These two variables are determinants of HEPs, and should therefore be treated carefully. Although existing studies (e.g., Kim et al., 2009; Yin, Liu and Li, 2021) have investigated relevant topics in commissioning and maintenance, there lacks an inter-activity comparison of EMs and PSFs. For this purpose, an interview study was designed to collect maintenance engineers' intuitive perception of EMs and PSFs in their daily work. In addition, most interviewees have also been involved in commissioning activities, making it possible to expose some comparative features of the two activities. The interview results reported by these interviewees are derived from their personal working experience in both maintenance and commissioning activities, and therefore provide direct and reliable information related with criteria (b) and (c). Based on the findings in this study and previous work, the question thrown before could be answered partly.

Interview of Maintenance Engineers

A total of 21 maintenance engineers from a domestic NPP were recruited to participate in face-to-face interviews. They have an average of 11.6-year (SD = 4.3) working experience in this NPP. Among the 21 participants, 19 have been involved in the commissioning and startup of this NPP, and therefore possess intuitive perception of comparative features of maintenance and commissioning activities. During the interview, the participant was required to answer the following three questions. Note that for the two participants who have not been involved in the commissioning work, only the first question was asked.

- Common human errors and contributing factors in maintenance.
- Common human errors and contributing factors in commissioning.

- Difference between these two activities, in terms of requirement on human, team structure, organization, target equipment or system, working environment, procedure and diagram, task, and risk.

The interview results are summarized in Tables 1–3. Tables 1 presents reported EMs of human errors in maintenance and commissioning. On the whole, the findings agree with those in previous studies. For example, EMs in test and maintenance reported in Kim et al. (2009), such as omission, inappropriate action (too fast, too long, too much, etc.), and wrong object, are also reported in Table 1. According to the findings in Table 1, those items shared by maintenance and commissioning reflect the commonality of the two activities, and those unshared items should be paid more attention to. In Table 1, EMs No. 1, 4, 7, 9, 11 & 13 are present only in maintenance. However, these EMs are judged not unique to maintenance but also applicable to commissioning. For example, it is reasonable to speculate that EM No. 9 (errors in following procedures) is also applicable to commissioning, since there are quite a lot of procedural tasks in commissioning. In Table 1, EMs No. 15 & 16 are present only in commissioning. The absence of these EMs in maintenance could be explained by technical differences. EM No. 15 (fail to check prerequisites such as the blocking status) can be explained by the fact that blocking in maintenance is strictly controlled and will be verified by several roles including the maintenance preparation engineer, blocking manager, maintenance task leader, etc.; EM No. 16 (temporary alterations are disrupted due to inadequate signs) can be explained by the fact that there are a few temporary alterations in maintenance which will be well controlled. Therefore, the presence of these two EMs depends highly on the technical conditions of NPPs but not differences in human information processing.

Table 1. Common human errors in maintenance and commissioning, comparable items placed in the same row.

No.	Maintenance	Commissioning
1	Perform tasks following one's own habits, memory or understanding, rather than the procedure and diagram (7*)	
2	Not aware of the change and risk in working conditions (3)	Not aware of the change in working conditions (1)
3	Operate on a wrong target (9)	Operate on a wrong target (2)
4	Accidental touch (4)	
5	Wrong operation due to lack of skills (3)	Wrong operation due to lack of skills (1)
6	Wrong operation by mistake (8)	Wrong operation by mistake (2)
7	Inadequate preparation, such as tools and procedures (4)	
8	Errors in using tools, such as multimeter (1)	Errors in using tools (1)
9	Errors in following procedures, such as skipping and omitting steps (5)	
10	Errors in preparing instructions (1)	Omit some points to be validated (1)
11	Fail to supervise (2)	

(Continued)

Table 1. Continued

No.	Maintenance	Commissioning
12	Forget to recover temporary alterations (2)	Forget to recover temporary alterations (2)
13	Errors in following administrative procedures, such as no-permit work (1)	
14	Errors in communication and handover (3)	Errors in communication (2)
15		Fail to check prerequisites such as the blocking status (2)
16		Temporary alterations are disrupted due to inadequate signs (1)

The number in the bracket represents for the frequency of this item being mentioned by interviewees. Same for the other tables.

Table 2 presents reported PSFs in maintenance and commissioning. Similar with Table 1, the unshared items deserve careful consideration. In Table 2, PSFs No. 3, 7–10, 12, 17, 19, 20, 22–24 are present only in maintenance. However, these PSFs are judged not unique to maintenance, some of which have been reported in the previous study on PSFs in commissioning (Yin, Liu and Li, 2021). Such PSFs (as well as those EMs in Table 1) are not mentioned in commissioning during the interview, partly because of the limited interview sample size. Besides, it had been years since the accomplishment of commissioning of this NPP, so the participants might fail to list some commissioning EMs and PSFs due to memory fades. In Table 2, PSFs No. 25–32 are present only in commissioning, reflecting some differences in contexts. For example, PSF No. 28 (high personnel mobility) is closely related with the flexible team structure in commissioning, and PSF No. 30 (concurrent work in the workplace) reflects the existence of lots of concurrent work (e.g., construction activities) during the commissioning stage.

Table 2. Common PSFs in maintenance and commissioning, comparable items placed in the same row.

No.	Maintenance	Commissioning
1	Lack of knowledge, experience, familiarity, and skills (9)	Lack of knowledge, experience, and skills (3)
2	Time and progress pressure (6)	Time and progress pressure (3)
3	Negative personality, such as impatience (1)	
4	Adverse mental and physical status, such as fatigue (8)	Fatigue (3) Negative emotion (1)
5	Distraction (4)	Irrelevant talks in the workplace (1)
6	Lack of responsibility (3)	Lack of responsibility (3)
7	Close to getting off work or holiday (2)	
8	Cutting corners (1)	
9	Empiricism (1)	
10	Habit in routing tasks causing habit intrusion (1)	

(Continued)

Table 2. Continued

No.	Maintenance	Commissioning
11	Inconsistency with behavioral norms (1)	Inconsistency with behavioral norms (1)
12	Taking a chance (1)	
13	Inadequate peer-check or supervision (4)	Inadequate supervision (1)
14	Inadequate preparation (1)	Inadequate preparation (2)
15	Technical system faults (1)	Installation errors in construction (1) Manufacturing errors (1) Poor equipment quality (1)
16	Inadequate procedures and documents (2)	Inadequate procedures and technical guides (1) Lack of test criteria (1)
17	Frequent upgradation of procedures (1)	
18	Incorrect procedures (1)	Incorrect procedures (2)
19	Mismatch of procedures and actual conditions (1)	
20	Harsh working conditions, such as radiation (3)	
21	Human error traps in working conditions and equipment, such as similar coding and chaos layout (7)	Human error traps in working conditions (1) Densely laid-out cables (1)
22	Narrow working space (1)	
23	Noise (1)	
24	Unclear task requirements (1)	
25		Lack of incentive (1)
26		Lack of vigilance due to low operation risk (2)
27		Poor ability to work with others (1)
28		High personnel mobility (1)
29		Complicated personnel constitution in a team (1)
30		Concurrent work in the workplace (5)
31		Dynamically changed working conditions (1)
32		Culture difference in design (1)

Table 3 focuses especially on the differences in contexts of the two activities, which should be considered carefully when we model the context. Findings in Table 3 highlight several meaningful concerns.

- Some differences cannot be adequately identified in current PSF frameworks. For example, the level of detail of maintenance procedures is lower than that of commissioning procedures. The effect on HEP needs to be clarified in further research. Another example is the risk faced during a task: There exist more plant operation risks during maintenance, which could influence operators' behavior. Though not modeled in PSF, the effect of such factors will contribute to HEP variability, which is less studied in HRA.
- Some differences cannot be adequately modeled using current PSF definition and level designs. For example, maintenance and commissioning exert different requirements on human knowledge. A simple distinction

of several knowledge levels (e.g., low, nominal, and high) seems to be incompetent to model such difference. This issue along with the aforementioned one constitutes the main source for within-category variability of HEP (Greco, Podofillini and Dang, 2021).

- The judgement criteria of PSF status or definitions of PSF levels in different activities may vary. A "complex" task in maintenance may be judged as a simple one from commissioning engineers' perspective, as in commissioning tasks there are more device and systems involved. This concern highlights the necessity of objective criteria for PSF evaluation.
- The distribution of single PSF status in different activities may vary. For example, commissioning teams are often loosely organized. Hence, the probability of the team structure being loosely organized in commissioning would be higher than that in maintenance.

Table 3. Comparison between maintenance and commissioning.

Aspects	Differences
Requirements on human	• In commissioning, one engineer is responsible for a plant system (e.g., Turbine Bypass System), and is therefore supposed to possess necessary knowledge on the whole system. In maintenance, one engineer is in charge of one or several types of equipment (e.g., valves), and the required knowledge is narrower but more in-depth (6) • Commissioning engineers' skills focus on the test of system functions, while maintenance engineers' skills focus on the defect handling of equipment (3) • In commissioning, engineers are expected to deal with more complex, unplanned, and dynamic conditions and control the entire test progress. This brings a higher requirement on skills. In maintenance, the working conditions are more standardized. Yet, some online maintenance tasks under emergency working conditions are also challenging (4) • Commissioning tasks are somewhat error-tolerant since the plant has not come into power operation. Maintenance engineers are strictly required to perform actions with determinate and predictable consequences (2) • Besides technical skills, there are also fair requirements on commissioning engineer's non-technical skills, such as coordination and project management (1)
Team structure	• There exist much more inter-team cooperation activities in commissioning. Many entities, such as architects, constructors, and the plant owner, are involved in. Hence, the team structure of commissioning teams is often more loosely organized and flexible, while the team structure of maintenance teams is often more compact and fixed (8)
Organization	• Various entities need to be coordinated in the organization of commissioning (2) • The progress of commissioning is controlled by the commissioning department, while the progress of maintenance is controlled by the operation schedule. The former is more loosely scheduled (4)

(Continued)

Table 3. Continued

Aspects	Differences
Target equipment or system	• Plant systems are independent during commissioning, but are strongly coupled during maintenance (2) • The plant is in power operation during maintenance, but not during commissioning. The different plant conditions lead to different error tolerances and different requirements for blocking (5) • Some systems are unavailable before they are tested during commissioning (2) • There are more uncertainties during commissioning such as temporary alterations (2)
Working environ-ment	• During commissioning, the noise and temperature in the factory buildings are lower since many machines are not running (1) • There exists concurrent work, especially construction work, during commissioning. After the plant comes into power operation, the cleanliness becomes better (13) • The nuclear fuel has not been loaded during commissioning, so there exists no radiation (5)
Procedure and diagram	• The level of detail of maintenance procedures is lower than that of commissioning procedures (10) • The procedures and diagrams in commissioning have more errors and changings, leading to frequent upgradation. The procedures and diagrams used in maintenance have been validated many times, and are therefore more accurate (14)
Task	• Commissioning tasks aim at testing and validating the functions of plant systems, while the objective of maintenance tasks is the maintenance and repair of equipment. Hence, the working contents of these two activities are very different. Some maintenance tasks like equipment tests are somewhat similar with commissioning tests, but the objective and criteria are still largely distinct. In addition, many tests would not be conducted ever since they have been done during commissioning (14) • There are more equipment and systems involved in commissioning tasks than in maintenance tasks. Many commissioning tasks would test the inter-operation of various systems, while most maintenance tasks only focus on single equipment (4) • The work intensity during commissioning is somewhat comparable with that during the major overhaul and higher than that during routine maintenance (10)
Risk	• There exist more industrial safety risks during commissioning, due to the concurrent construction work (2) • There are damage risks for equipment during commissioning, due to potential inappropriate tests (1) • There exist more plant-related and nuclear risks during maintenance (2)

DISCUSSIONS AND CONCLUSION

Tables 1–3 report the interview results with regard to the comparison of maintenance and commissioning activities. From the results, several meaningful insights can be summarized. Firstly, Maintenance and commissioning share very similar human error modes. It can be concluded from Table 1 that possible EMs in these two activities are quite similar. As discussed before, most EMs that are present only in maintenance are deemed as also applicable in commissioning. Hence, we can draw a conclusion that EMs in maintenance and commissioning are quite comparable. This implies the possibility of compiling a unified error taxonomy to analyze human errors in these two activities. To confirm this speculation, a comparative task analysis study is necessary to compare task characteristics in maintenance, commissioning, and other ex-control room activities, since EMs are closely related to the task.

With regard to PSF, Common PSFs in maintenance could also be found in commissioning. By comparing common PSFs presented Table 2 and the commissioning PSF list in Yin, Liu and Li (2021), it can be concluded that most PSFs in maintenance also exist in commissioning. Having said that, some unique commissioning PSFs in Table 2 are judged only applicable in commissioning such as "lack of vigilance due to low nuclear risk" and "high personnel mobility." This indicates the possibility of compiling a unified PSF framework, or at least different PSF frameworks with minor adjustment, to characterize task contexts in these two activities. In fact, Yin, Liu and Li (2021) have demonstrated that the PSFs in commissioning and in control room overlap heavily. A full set of PSFs that takes all control room and ex-control room activities into considertaion would benefit the generalization and integration of human error data in the nuclear industry. Nevertheless, it is noteworthy that the nominal PSF levels in maintenance and commissioning may be defined differently. Table 3 demonstrates typical differences of these two activities, which arise from different objectives and plant conditions. For example, the two activities have different requirements on human knowledge, with commissioning emphasizing knowledge on systems and maintenance emphasizing knowledge on equipment. How to define an appropriate nominal level for the PSF knowledge then becomes a problem. Although there exist some potential indicators such as the number of working years and training frequency, it is hard to say that maintenance and commissioning engineers with the same working years would commit errors with the same probability. Another example is task complexity. Table 3 indicates that commissioning tasks are more complex than maintenance tasks and have higher requirements on human knowledge and skills. Hence, a commissioning task with nominal task complexity might be evaluated as high task complexity using the criteria for maintenance. Then, a divergence in PSF levels occurs. In other words, the HEP of a commissioning task with all PSFs in nominal levels may equal to the HEP of a maintenance task with the task complexity PSF in high level. This would make the results of HEP generalizing and integrating (e.g., Xing, Chang and DeJesus Segarra, 2020) problematic. Besides the importance of a universal definition of PSF and PSF levels, the distribution of PSF levels could be divergent. As mentioned before, if commissioning and maintenance share a common PSF, the distribution of corresponding PSF levels, or the probabilities of this PSF locating at each level, could be divergent. Divergent distributions of PSF levels will lead to different expected probabilities of each PSF level and different expected HEPs finally. This issue should be considered in predictive HRA, especially when a PSF status is prospectively unknown.

In conclusion, the interview results show that commissioning and maintenance as two typical ex-control room activities share some commonalities in regard to EMs and PSFs. This implies that these two activities might be analyzed using the same HRA model. Having said that, the different objectives of these two activities and different plant conditions result in considerable differences in various context aspects, which can lead to potential discrepant definitions and distributions of PSF levels. Therefore, human error data from the two sources should be treated with caution. In future work, more efforts are in need to explore a comprehensive framework for recording human error information, so that human error data from various domains can be integrated.

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