Human-System Interface (HSI) Challenges in Nuclear Power Plant Control Rooms

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Abstract. This study uses factor analysis to examine 30 errors due to human-system interface (HSI) in nuclear power plant control rooms. The results are used to validate the factor structure and the Decision-Action Model developed in this paper. Ten U.S. commercial operating nuclear plants, total of 18 units, participated in this study at the time this paper was written. The result is a five-factor structure: *Operations Uncertainties*, *Design Improvements*, *Misoperations*, *Equipment Control*, and *Human Factors Redesign*. The completed Decision-Action Model provides current operating plants with suggested corrective actions for each type of potential HSI errors.

Keywords: Human error, human-system interface, control room, human performance, factor analysis, corrective action.

1 Introduction

With the increasing demand for clean and reliable energy in recent years, there is much attention on new construction and increasing output for nuclear power plants in the United States. Concerns for nuclear safety have also risen in view of the numerous modifications current operating plants are installing.

This study aims to provide additional insights through operator experience on control room HSI. Human errors, when systematically analyzed and evaluated, provide information on the causes and correction methods. Among the human error analysis/evaluation methods, statistical analysis is effective in identifying error categories, occurrence patterns and trends, and revealing the hidden interrelationships between errors and their casual factors. Such knowledge can significantly improve human error prevention and corrective measure evaluation.

2 Background

Improving currently operating nuclear power plant control room design is a continuous effort. A review of recent operating experience (OE) from the Institute of Nuclear

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Table 1. Control Room Human-System Interface Hypothetical Factor Structure

Event	Item	Source
Operation Based	1. **Operation movements.** Operation requires small movements or jerking/unsmooth motion.	[4]
	2. **Simultaneous operation.** Operator required to multi task.	[5]
	3. **Control room/simulator discrepancies.** Trained actions are not applicable to real scenarios.	[6]
	4. **Operate equipment incorrectly.** Due to inattention to details/distractions.	[7]
	5. **Inappropriate compensation.** From lack of trust in equipment.	[8]
	6. **Over reliance.** From over trusting equipment.	[5]
	7. **Defeated safety features.** Manual override of safety feature.	[9]
	8. **Inexperience.** From lack of operating hours on equipment.	[10]
Controller Design Based	9. **Operate on wrong equipment.** Due to similarity.	[11]
	10. **Controls too far apart.** Need excess movement to operate consecutive actions.	[12]
	11. **Controls too close together.** Poor design leads to inadvertent operation.	[13]
	12. **Incorrect function allocation – Manual actions designed to be automated.**	[14]
	13. **Incorrect function allocation – Automated actions designed to be manual.**	[14]
	14. **Equipment allowing failures.** Allowing operation outside of design parameters.	[15]
	15. **Work-around's.** Known defects that require operators to take less direct action.	
	16. **Time limit to operation.** Operation cannot be completed within the allowed time.	[16]
	17. **No operator intervention allowed.** To abort or assume control as necessary.	[17]
Deficient Indication Based	18. **No alarm noting abnormal conditions and/or failures.**	[18]
	19. **Insufficient plant information.**	[19]
	20. **Boolean indication.** Indication without level of severity.	[20]
	21. **Unreliable indication.** Indication known to reflect plant condition imperfectly.	[21]
	22. **No feedback.** Action is performed with no confirmation.	[22]
	23. **No projection.** No indication on anticipated result from action.	
	24. **No trending.** No indication on equipment failing over a prolonged time period.	[17]
Ambiguous Indication Based	25. **Control panel visually crowded.** Cannot take in presented information at a glance.	[3]
	26. **Color/Sound coordination.** Many indications of the same color/sound or all indications having different colors/sounds.	[23]
	27. **Over-indication.** A single failure represented by more than one alarm.	
	28. **Non-intuitive control.**	
	29. **Display challenges.** Display font size/color or inconsistency in acronyms/labeling/terminology.	[24]
	30. **Data searching.** Extensive navigation needed to look for known existing data.	[17]

Power Operation (INPO) database shows that control room HSI design may still need to make improvements to increase safety and reduce cost of operation. Between 1991 and 2008, numerous plant events resulting in either a plant trip/transient or technical specification violation were still being reported to INPO. The cost of these errors could be as high as a million dollars per day for repairs and rework.

The United States Nuclear Regulatory Commission (USNRC) provided Human Factors Engineering (HFE) guidelines in NUREG-0700 [1] and identified different areas of HSI in both advanced and conventional control rooms. The HFE guideline provides the following categories: Information Display, User-System Interface, Process Control and Input Devices, Alarms, Analysis and Decision Aids, Inter-Personnel Communication, Workplace Design, and Local Control Stations.

The OE search conducted by the authors in August 2008 on the Institute of Nuclear Power Operations (INPO) OE database revealed 146 plant events between 12/3/1990 and 4/24/2008. These events were listed under control room operator work group and man-machine interface casual factor. Each plant event was reviewed for contributing factors; many were used in the hypothetical factor structure.

The hypothetical factor structure utilized the USNRC HFE categories as a starting point and items were expanded or deleted compared to the actual events found in OE. Categories developed for control centers in nuclear or other industries were also examined. Examples of these categories include Davey discussed factors important for structuring review criteria [2] and Grozdanovic's research on the control center of the railway traffic in Yugoslavia [3].

This study reviewed literature available on control room HSI and related issues to create the hypothetical factor structure listed in Table 1. This table lists one source for each item. For some of these items, the factors contributing to the errors are discussed in several different sources. For items such as these, a representative reference is selected and listed. Items that do not have a reference source listed are simplified or paraphrased from the literature review and cannot be pinpoint into a single source document.

3 Model Development

A review of recent plant events relating to control room HSI showed that the majority of the incidents, approximately 70%, did not lead to any immediate corrective actions. The focus of this study, in addition to developing a factor structure, is to provide corrective action guidelines for current operating plants. As such, a Decision-Action Model was developed (see Table 2) to offer current operating plants suggested corrective actions for each of the items in the purified factor structure, which effectively lists the causes of all OE submitted by operating plants. Future errors may

Table 2. Decision-Action Model

Group I (no incident) Correct Decision + Correct Action	Group II Incorrect Decision + Correct Action
Group III Correct Decision + Incorrect Action	Group IV Incorrect Decision + Incorrect Action

be associated with one or more of these items and the suggested corrective actions may help to effectively eliminate similar errors from reoccurring.

Decision, in this model, represents cognitive errors. These errors pertain to knowledge and judgment of the operator. This type of error is similar to the concept of "mistakes" described by Norman, 1981 [25]. It is described as representing defects in the formulation of strategy, generated only during the planning process as the result of inappropriate knowledge of the relations between parts of the plant or between physical quantities. Action, in this model, represents the physical errors, or "slips" in Norman's words, which are imperfections of attention monitoring or errors that occur while implementing intended plans [25].

This model is influenced by Chen-Wing and Davey [26], which illustrates that Designer, Operations, and Human/Technical Resources' roles on error reduction. Since the Decision-Action Model focuses on current operating plants, as opposed to designing new constructions, the Designer's role is eliminated. Suggested corrective actions are also based on the same study. These suggested actions are as follows:

- Group I Suggested Corrective Action: N/A
- Group II Suggested Corrective Action: Improvement to operations procedure, general guidelines, and pre-job briefing.
- Group III Suggested Corrective Action: Additional operator training, peer check, management oversight.
- Group IV Suggested Corrective Action: Control room modification with human factor re-evaluation to the extended condition.

4 Research Method

4.1 Procedure

A survey was developed based on the hypothetical factor structure shown in Table 1 to examine power plant operators' opinions on HSI errors. Each survey question consisted of two parts: a 7-point Likert scale ranging from *Strongly Disagree* (1) to *Strongly Agree* (7), and an option to select the contribution of the error from *Operator Decision*, *Operator Action*, or both. The survey contained 32 questions, which included two paired questions to estimate the internal consistency of participants' responses.

Ten commercially operating nuclear power plants, 18 units total, participated in this ongoing study at the time this paper was written. Several methods, e.g., telephone, email, and/or post, were used to contact the head of the Operations Department at each plant. Participants were directed to either forward the online survey URL to qualified licensed operators or mail back completed hard copies of the surveys. By the time when this paper was written, 138 responses were received, out of which eight were completed through paper surveys, and the remainder were collected online.

4.2 Profile of Participants

The first 138 responses were analyzed for this study. A single operating unit is expected to have around 20 licensed operators. The approximate number of operators at each unit was verified through operations training instructors at several plants.

From this information, the study's current participation rate is around 38%. As indicated above, surveys were distributed by the head of the Operations Department. While some plants sent the surveys to all operations personnel, others selected small groups of individuals to participate in this study. This accounts for the low participation rate of this study.

Out of the 138 responses, 14 were discarded due to low internal consistency. 3.8% of remaining 124 responses were from USNRC Region I, 21.5% was from USNRC Region II, 18.5% was from USNRC Region III, and 53.4% was from USNRC Region IV. The remaining responses did not provide enough plant information to identify their regions. These regions are designated by the USNRC to oversee the operation of power producing and non-power producing reactors in the United States [27].

Participants' ages ranged from 27 to 63 (mean = 47.0, standard deviation = 7.55). 18.1% had 1 to 10 years of operations experience, 20.3% had 11 to 20 years, and 61.7% had over 20 years.

4.3 Analysis

Descriptive Statistics. The overall internal consistency as estimated by Cronbach's alpha coefficient was 0.70, which indicates that the survey has acceptable internal consistency.

The general characteristics of the survey results on the items loaded on the purified factor structure (see discussion later in this section) were examined. The mean scores for each of the items were between 3.6 and 6.2 and the standard deviations were between 0.87 and 1.60. The overall mean of all the items in the purified factor structure is 5.1. Items scoring above the overall mean indicate relatively strong preferences of the participants and are in bold font. Item 12, incorrect function allocation – manual actions designed to be automated, has the lowest mean value. This suggests that operators believe that designing manual actions to be automated would reduce, rather than increase, the chances of making an error. Three-way ANOVA shows that there are no significant effects of age, experience, or plant of employment on all 18 loaded items.

Factor Analysis. Maximum likelihood factor analysis with varimax rotation was conducted to explore the hidden factor structure determined by the correlations among survey items. Five factors, whose eigenvalues are larger than 1.0, were retained (see Table 3).

Factor loadings are presented in Table 3. Items with loading higher than, or close to, 0.50 are considered significant. Items 29, 18, and 15 are very close to 0.50 and therefore considered significant as well.

The items loaded on Factor 1 pertain to errors caused by doubts in information presented on the job; thus, Factor 1 is classified as "Operations Uncertainties". Factor 2 contains items describing existing design with the need for improvements and is labeled "Design Improvements". Factor 3 includes operation-based errors and is categorized as "Misoperations". The two items loaded onto Factor 4 are equipment allowing failures and over reliance. As such, Factor 4 is labeled "Equipment Control". Factor 5 includes problems arising from basic human factor issues and is labeled "Human Factors Redesign".

Table 3. Descriptive Statistics and Rotated Factor Pattern

Item No.[a]	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Mean[b]	SD	Factor Mean	Decision-Action			
									Action (%)	Decision (%)	Both	$^2_1$
21	**0.69**	-0.01	0.23	0.33	0.09	**6.0**	1.02	5.6	11 (8.9)	85 (69.1)	27 (22.0)	57.04***
22	**0.66**	0.21	0.18	0.23	0.03	**5.4**	1.20		29 (23.6)	63 (51.2)	31 (25.2)	12.57**
28	**0.55**	0.17	0.20	0.03	0.12	**5.5**	1.20		47 (38.2)	40 (32.5)	36 (29.3)	0.56
19	**0.50**	0.24	0.28	0.32	0.10	**5.8**	0.99		12 (9.8)	79 (64.2)	32 (26.0)	49.33***
29	**0.49**	0.32	0.28	0.10	0.12	**5.2**	1.29		33 (26.8)	63 (51.2)	27 (22.0)	9.38**
18	**0.49**	0.28	0.33	0.12	0.16	**5.7**	1.14		44 (35.8)	54 (43.9)	25 (20.3)	1.02
24	0.26	**0.56**	0.32	0.29	-0.08	4.9	1.26	5.0	16 (13.0)	78 (63.4)	29 (23.6)	40.89***
16	0.09	**0.52**	0.09	0.14	0.12	5.0	1.11		44 (35.8)	40 (32.5)	39 (31.7)	0.19
26	0.11	**0.51**	0.19	0.04	0.15	5.0	1.23		32 (26.0)	57 (46.3)	34 (27.6)	7.02**
20	0.38	**0.50**	-0.06	0.42	0.12	4.9	1.34		17 (13.8)	91 (74.0)	15 (12.2)	50.70***
4	0.13	-0.06	**0.51**	0.17	0.12	**6.2**	0.87	5.5	30 (24.4)	50 (40.7)	43 (35.0)	5.00*
7	0.22	0.24	**0.50**	0.26	0.03	**5.3**	1.57		23 (18.7)	53 (43.1)	47 (38.2)	11.84**
25	0.32	0.42	**0.49**	0.14	0.30	5.1	1.19		58 (47.2)	37 (30.1)	28 (22.8)	4.64*
14	0.16	0.07	0.20	**0.57**	0.14	**5.2**	1.40	4.8	29 (23.6)	70 (56.9)	24 (19.5)	16.98***
6	0.04	0.11	0.17	**0.51**	0.21	4.3	1.46		15 (12.2)	90 (73.2)	18 (14.6)	53.57***
12	0.03	0.09	0.01	0.30	**0.69**	3.6	1.40	4.4	52 (42.3)	51 (41.5)	20 (16.3)	0.01
11	0.11	0.33	0.46	-0.04	**0.57**	4.9	1.37		87 (70.7)	22 (17.9)	14 (11.4)	38.76***
10	0.24	0.17	0.25	0.37	**0.54**	4.6	1.50		90 (73.2)	21 (17.1)	12 (9.8)	42.89***
Eigenvalve	20.0	2.7	2.4	1.9	1.6							
Variance explained by each factor	6.9	5.1	4.8	4.0	4.0							
% Variance explained by each factor	20.9	15.5	14.6	12.0	12.2							
Cumulative % total variance explained	20.9	36.4	51.0	63.0	75.2							

***: $p < 0.0001$; **: $p < 0.01$; *: $p < 0.05$

[a]: Reference Table 1 for Item Description

[b]: Means above the overall mean (5.1) are in bold type.

Factor loadings in bold type are considered to be significant. Five factors explained 75.2% of total variance.

Compared to the hypothetical factor structure in Table 1, Factors 1 and 2 in the purified factor structure include a shuffling of items from the original Deficient Indication and Ambiguous Indication categories. Factor 3 maps closely to the items in the Operation Based category and Factor 5 includes only items from the Controller Design Based category.

Model Population. Chi-square tests were performed to determine if the responses lean towards Operator Action or Operator Decision. Table 3 shows the number of responses that selected Action, Decision, or both for each loaded item. The Decision heavy items are populated into Group II of the Decision-Action Model, Action heavy items are populated into Group III, and the remaining items are populated into Group IV. The final model is shown in Table 4.

Table 4. Populated Decision-Action Model

Group I (no incident) **Correct Decision + Correct Action** **Suggested Corrective Action:** N/A	**Group II** **Incorrect Decision + Correct Action** • Unreliable indication. • No feedback • Insufficient plant information • Display challenges • No trending • Color/Sound coordination • Boolean indication • Operate equipment incorrectly • Defeated safety features • Equipment allowing failures • Over reliance **Suggested Corrective Action:** Improvement to operations procedures, general guidelines, and pre-job briefing.
Group III **Correct Decision + Incorrect Action** • Control panel visually crowded • Controls too close together • Controls too far apart **Suggested Corrective Action:** Additional operator training, peer check, management oversight.	**Group IV** **Incorrect Decision + Incorrect Action** • Non-intuitive control • No alarm noting abnormal conditions and/or failures • Time limit to operation • Incorrect function allocation – Manual actions designed to be automated **Suggested Corrective Action:** Control room modification with human factor re-evaluation to the extended condition.

5 Conclusion

This study collects nuclear power plant operator opinions on control room HSI errors. The factor means, shown in Table 3, indicate that the highest priority should be placed on the category of Operations Uncertainties. The remaining four factors, in the order of importance, are: Misoperations, Design Improvements, Equipment Control, and Human Factor Redesign.

The populated Decision-Action Model (Table 4) also provides some insight to control room design. A large number of items are populated in Group II. This may be interpreted as suggesting that improvements in the planning process will have better results in reducing HSI type errors.

Operating Experience was revisited to compare this study's finding to documented plant events. Out of the 106 plant events originally evaluated, 17% fall under Operations Uncertainties, 21% fall under Design Improvements, and 22% fall under Misoperations. No event strictly falls into the category of Equipment Control or Human Factor Redesign. This comparison confirms that this study's conclusion of category importance ranking is valid.

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