COMPARATIVE ANALYSIS OF COMMUNICATION AT MAIN CONTROL ROOMS OF NUCLEAR POWER PLANTS

Daihwan Min[1], Yun H. Chung[2], and Wan C. Yoon[3]

[1]*Dept. of MIS, Korea University,Jochiwon-Eup, Choongnam, 339-700, South Korea*
Tel: +82 41 860 1563, e-mail: mismdh@korea.ac.kr
[2]*Korea Institute of Nuclear Safety, 19 Guseong-dong, Yuseong-gu, Daejeon, 335-338, South Korea*
Tel: +82 42 868 0245, e-mail: yhchung@kins.re.kr
[3]*Dept. of Industrial Engineering, KAIST, 19 Guseong-dong, Yuseong-gu, Daejeon, 305-701, South Korea*
Tel: +82 42 869 3119, e-mail: wcyoon@kaist.ac.kr

Abstract: This paper investigates the difference between communications among the team members using a CBP system in an advanced MCR and communications using a paper-based procedure in a conventional MCR. Two training sessions with PBP and two test sessions with CBP are analyzed and compared. This study has found that the communication amount using a CBP is much lower than that using a PBP and suggests to develop a standard communication protocol in an MCR.

Keywords: Communications, Complex systems, Computer-aided work, Co-operation, Human error, Human-machine interface, Nuclear Plants, Socio-technical System

1. INTRODUCTION

An advanced MCR (Main Control Room) is planned for the next generation of nuclear power plants in Korea. The advanced MCR plans to utilize various display devices and computerized HMI (Human-Machine Interface) as well as many kinds of digitized instrumentation & control. Among the new features of the advanced MCR, a lot of controversies exist about CBP (computer-based procedures) systems.

In an MCR, a team of engineers including an SS (shift supervisor), an RO (reactor operator), a TO (turbine operator), and an EO (electric operator) carries out tasks by following various kinds of operating procedures. The purpose of the operating procedures is to guide operators' actions in order to increase the likelihood that the actions will safely achieve the task's goal. In a conventional MCR the operating crew uses the PBP (paper-based procedures), while in the advanced MCR the crew is going to use the CBP. Currently several nuclear power plants (e.g., Beznau, Chooz B, Civaux, Temelin) around the world are using various types of CBP systems.

New technology would bring some benefits through better interaction between humans and technical systems. However, when any new technology is introduced, it inevitably changes cognitive tasks of humans. Thus, before introducing new technology it is necessary to consider not only positive aspects, but also negative aspects of using the new technology. Especially in safety critical industries, it is crucial to check anticipated negative impacts as much as possible and to prepare appropriate ways to overcome all the negative impacts.

Communications among team members are important in complex systems. They work collaboratively to accomplish common goals. While a team task is performed, there exist inter-dependencies between operations by individual engineers. For example, EO's operation sequence may vary according to the information given by TO. An SS usually monitors overall situations and makes appropriate decisions while he observes every engineer's works to estimate current progress and to determine the following operation sequences. In spite of its importance in the nuclear power plant domain, there is little research on communications among the operating team members.

The purpose of this study is to examine possible effects of using the CBP system under development for the advanced MCR in Korea. This paper presents the result from a comparative evaluation. The evaluation compares communications among the team members in the advanced MCR using the CBP system with communications using a PBP in a conventional MCR.

2. LITERATURE REVIEW

Although there is only a little research on communication in the nuclear power industry, the aviation industry has an extensive literature on communication within the cockpit and between pilots and air traffic controller. This section reviews the previous literature and divides it into two groups of research. One group has studied the effect of communication on team performance and the other has focused on communication errors.

2.1. Effects of communication on team performance

The previous studies have found that the quantity and the quality of communication are related with team performance.

Several studies analyzed the relationship between the communication amount and aircrew performance. Foushee and Manos (1981), Orsanau (1990), and Mosier and Chidester (1991) found the positive relationship between the communication quantity and the performance. In other words, teams with more communications showed better performance. On the contrary, Thorton (1992) found that a team with more errors had more communications in relation with situation awareness. Combining these results suggests that the communication quantity alone does not determine the level of team performance.

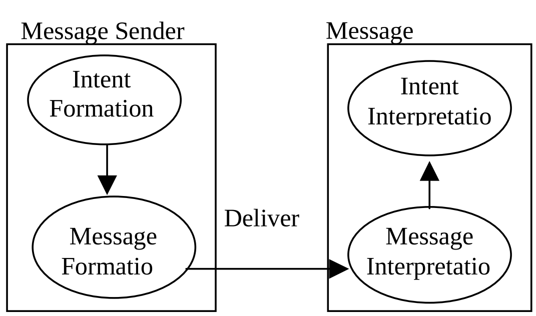

Fig. 1. Simplified one-way communication model

Other studies investigated the relationship between the communication quality and performance. Kanki et al. (1989) and Bowers et al. (1998) found that teams showing heterogeneous communication pattern made more errors than homogeneous teams. Jentsch et al. (1995) found that teams communicating with more standard phraseology were faster in finding a problem. The communication quality consisting of both content and pattern contributes to team performance.

2.2. Classification of communication errors

The previous literature also reports many types of errors in communication. In order to classify communication errors, this paper uses a simplified one-way communication model (See Figure 1).

There are three sources of communication errors, i.e., message sender, delivery, message receiver. Thus, communication errors can be classified into four groups, such as errors in the sender (A), errors in the delivery (B), errors in the receiver (C), and the others (D). Table 1 shows the classification of communication errors indicated by the previous research.
Although most of the literature is from the aviation domain, there are a few reports that point some communication issues in the nuclear power industry. O'Hara, et al. (2000) raised broad concerns with computer-based procedures. Hirotsu et al. (2001) reported that 25% of human error incidents at Japanese NPPs were due to communication problems. Chung et al. (2002) showed differences in communications with CBP and those with PBP. The present study attempts to extend the work of Chung et al.'s by carrying out more analysis and by adding more cases.

3. RESEARCH METHODOLOGY

3.1. Data collection

The procedures in a nuclear power plant are classified into normal operating procedures, abnormal operating procedures, and EOP (emergency operating procedures). This study selected an EOP called 'EOP-02 (LOCA: Loss Of Coolant Accident)' which consisted of 72 steps.

From May until July in 2003, a researcher observed and videotaped regular training sessions with the PBP at a training center. The training center has a conventional MCR with a simulator of Korea Standard Nuclear Powerplant.

Test sessions with CBP were videotaped at a laboratory in a research institute from time to time in 2001 and 2002. The laboratory has a mockup system of Advanced Power Reactor 1400.

Table 1. Classification of communication errors

Study	Communication Errors	Type
Grayson & Billings (1981)	Other inaccuracies in content	A
	Ambiguous phraseology	A
	Incomplete content	A
	Inaccurate (transposition)	A
	Misinterpretable(phonetic similarity)	A
	Absent (not sent)	B
	Untimely transmission	B
	Garbled phraseology	A
	Absent (equipment failure)	B
	Recipient not monitoring	C
Morrison & Wright (1989)	Clearance Composition	A
	Phraseology	A
	Delivery	B
	Readback/Hearback	B
Navarro (1989)	Transmission	B
	Detection	D
	Identification	C
	Interpretation	C
	Action	D
Prinzo & Britton (1995)	Grouped, Sequential, Omission	A
	Substitution, Transposition	A
	Excessive Verbiage	A
	Partial Readback	B
	Dysfluency, Misarticulation	A
Orasanu, Davidson & Fischer (1997)	Language/Accent	A
	Partial or Improper Readback	B
	Dual Language Switching	B
	Unfamiliar Terminology	A
	Speech Acts	A
	False Assumptions or Inference	C
	Homophony	A
	Unclear Hand-off	B
	Repetition across Languages	B
	Uncertain Inference	C
	Lexical Inference	C
	Lexical Confusion	C
	Mistakes (unexplained)	D
FAA ATC (2002)	Phraseology	A
	Transposition	A
	Misunderstanding	C
	Readback	B
	Acknowledgment	B
	Other	D
Hollnagel (1998)	Message not received	B
	Message misunderstood	C
	No information	B
	Incorrect information	A
	Misunderstanding	C

Participants to both conditions were off-duty teams who actually operate NPPs in Korea and the shift supervisor in each team has an SRO (Senior Reactor Operator) license. Two sessions with PBP and two sessions with CBP were selected for communication analysis. A process expert who had many years of experience in the operation at an MCR helped to transcribe all conversations in those sessions.

3.2. Data analysis

The previous literature in the aviation industry has found that both the quantity and the quality of communication affect team performance. This study analyzes communication in terms of the quantity and identifies differences between the two settings. This study employs a modified 'propositional analysis' method and a modified 'speech act' coding scheme in order to measure the communication quantity. However, communication quality and team performance were not measured.

Propositional analysis: Propositional analysis is a method to analyze information in text and has been applied to measure the level of text comprehension. The notion of a proposition has been adopted as a fundamental cognitive unit, because the information conveyed in one proposition is usually a self-contained and complete thought (Kintsch and van Dijk, 1983). A proposition expresses one action or event or state in a possible world. A proposition is usually a composite unit consisting of two or more concepts, one concept as a relation and the others as arguments. The relation is the central element in that the relation ties together its arguments in such a way that a single proposition results.

This study follows the original method in counting the number of propositions in most sentences. However, this study modifies the original method in making decisions on whether to separate a sentence with modifiers or circumstantial information into two or more propositions. The decision depends on the meaning and importance of those words in a sentence. For example, 'Open the valve V15.' has one proposition and 'What are the level and the pressure of the steam generator?' has two propositions.

Speech act coding scheme: In the aviation industry, a speech act coding scheme developed by Kanki and Foushee (1989) has been applied to the analysis of flight crew communications. In the nuclear industry, Kettunen and Pyy (2000) suggested a classification scheme for analyzing communication in a control room of an NPP.

This study modifies Kettunen and Pyy's scheme by adding more categories and by dividing a category into multiple sub-categories. 'Call' and 'judgment' types are added and 'command', 'inquiry', and 'reply' types are further divided into multiple types.

Commands are divided into twp types of 'command-manipulation' and 'command-others'. A 'command-manipulation' requires a manipulation of a device in the plant. For example, 'Stop one RCP (Reactor Coolant Pump) per loop.' is a 'command-manipulation' type. 'Record the current date and time.' is a 'command-others' type.

Inquiries are divided into two types of 'inquiry-identification' and 'inquiry-confirmation'. For instance, 'What is the pressure of Reactor Coolant System?'

Table 2. Speech act coding scheme

Types	Definitions	Examples
Command-manipulation	A specific assignment of responsibility by one group member to another to manipulate an object	"Open valve V15 now!"
Command-others	An order to do anything other than manipulating an object	"Record the current date and time."
Call	A call for a specific person as a target for communication	"RO"
Acknowledgement	A statement to indicate that a message was received	"Roger!"
Inquiry-identification	A deliberate and well defined request for information	"Does the flow measurement F001 show any increase?"
Inquiry-confirmation	A statement for asking confirmation.	"The status of RCP (Reactor Coolant Pump) 1A is ok, isn't it?"
Reply	A statement used to respond to an inquiry or other message that involves more information than a simple acknowledgement	"Yes, the current flow is 25 kg/s and it is slightly increasing."
Reply-Confirmation	A short statement representing agreement or disagreement	"Yes, that is right."
Reply-Report	A statement that reports the result of carrying out a command	"Valve V15 is opened."
Observation	A remark aimed at orienting other group members' attention to a specific aspect of operation	"Now it is 27 kg/s - the flow should be more than 40 kg/s."
Suggestion	A recommendation for a specific course of action or an introduction of an idea for consideration	"Should we try to move the valve, if it is stuck?"
Statement of intent	An announcement of an intended action	"Watch out, I'll try to move it now."
Judgment	An expression that announces one's decision	"This event seems to happen because of tube rupture."
Encouragement	A statement to build up team spirit	"Come on, let us clear this, guys!"
Non-task related	A statement that does not refer to any aspect of the present task or operation	"By the way, who can give me lift home?"
Uncodable	An ambiguous or unclear message	"Mmmmm …. Mmmm"

is an 'inquiry-identification' type. 'The status of RCP 1A is ok, isn't it?' is an 'inquiry-confirmation' type.

Replies are divided into three types of 'reply', 'reply-confirmation', and 'reply-report'. For example, 'Yes, the current flow is 25 kg/s and it is slightly increasing.' is a 'reply' type. 'Yes, that is right.' is a 'reply-confirmation' type. Table 2 provides a modified classification scheme this study has used to classify the type of communication among the operating crew.

Two raters independently counted the number of propositions and speech acts and inter-rater agreement was about 80% at first. After the two raters discussed the rationale for counting, the agreement reached 90%. Then, percentages to the total number were calculated in order to compare the three sessions.

4. RESULTS

This study has found some similarities and differences in communications between two PBP sessions and two CBP sessions.

First, the total amount of communications in the four sessions is summarized in Table 3. The measure is the number of propositions and speech actions verbalized by team members. The total amount of communication among the team members is reduced drastically when using a CBP.

Table 3. Summary of communication amount

	SS	RO	TO	EO	Others	Total
PBP1	43%	37%	12%	6%	2%	501
PBP2	39%	33%	17%	9%	2%	640
CBP1	55%	35%	9%	0%	1%	233
CBP2	54%	32%	9%	0%	5%	227

Second, the distribution of communication among the team members is also shown in Table 3. The percents in the table are the rates of each member's communication amount divided by the total amount of communication in each team. The asymmetric distribution of communication in all sessions reflects the position in the team and the LOCA scenario. An SS takes the responsibility for the operation of an NPP and plays the role of task leader. The other members of the operating team follow the supervisor's orders and play the role of task supporters. In the CBP sessions, the SS takes 54~55 percent of the team communication. This is higher than the percentage in the other PBP sessions. Among the board operators a RO takes the highest percentage, because most steps in the LOCA procedure requires the RO's actions.

Third, the composition of message types is different, as shown in Table 4.

Table 4. Composition of message types

Message Types	PBP 1	PBP 2	CBP1	CBP2
Command-manipulation	5%	7%	8%	8%
Command-others	2%	4%	2%	3%
Call	6%	14%	3%	5%
Acknowledgement	7%	14%	13%	13%
Inquiry-identification	25%	15%	13%	10%
Inquiry-confirmation	3%	1%	11%	9%
Reply	34%	19%	10%	8%
Reply-confirmation	2%	2%	11%	11%
Reply-report	0%	2%	2%	2%
Observation	4%	9%	10%	14%
Suggestion	2%	4%	2%	3%
Statement of intent	6%	4%	7%	11%
Judgment	1%	1%	5%	1%
Encouragement	0%	0%	0%	0%
Non-task related	0%	0%	0%	0%
Uncodable	3%	4%	3%	1%

There is one distinct difference between the CBP sessions and the two PBP sessions. The CBP sessions have much more percentage of inquiry-confirmation and reply-confirmation type messages than the PBP sessions. This result occurs because the SS gets a lot of plant information from the CBP. Thus, the supervisors in the CBP sessions tend to ask RO/TO very specific questions for confirmation, rather than asking for information on plant variables. In contrast, the supervisors in the PBP sessions have to ask board operators inquiry-identification type questions and the board operators have to give reply type answers.

Fourth, this study has also found a wide variation in communications between the two PBP sessions. The PBP 1 session has more inquire-identification and reply type messages, while the PBP 2 session has more call and acknowledgement type messages. Although it is not clear from Table 4, the observation during the training sessions and the review of videotapes reveals that the team at the session 2 has followed the conversation rules at MCR more closely than the team at the session 1.

5. DISCUSSION

The result of this study and a previous study (Chung et al., 2002) not only confirms recurring issues in communications at advanced MCRs, but also draws attention to communication at conventional MCRs.

The low level of communication with CBP raises serious concerns from the safety point of view. One reason might be an erroneous assumption that all members can share situation awareness with less communication because each member has the access to the same information from the same technical systems. Although more communications do not guarantee the safety, too low level of communication increases the possibility of error propagation. If a team member makes an error for any reason, the error should be detected and recovered as soon as possible. Without live and overt communication, it is hard to detect and recover from errors before it is too late. In one CBP session not included in the current analysis, a TO reported on the situation of a device to an SS, but did not receive any response from the SS. The TO manipulated the device incorrectly on the basis of his own judgment. This was not known to the SS and other operators until later.

A remedy for the low level of communication is to force communication at major steps of an operating procedure. At major steps, all members of a team should exchange not only information from CBP but also their judgement on the current situation before moving on to a next step. In Switzerland, a plant using a CBP system at a conventional MCR has this kind of communication [1] although the communication is not enforced.

The asymmetric distribution of communication with CBP is more salient than communication with PBP. In addition, the composition of message types shows differences between the CBP sessions and the PBP sessions. Both phenomena might be due to information provided by a CBP system. An SS with CBP can obtain information directly from the CBP system. Typically an SS with CBP asks long questions with the information from CBP and board operators give rather short answers. For example, an SS asks 'Both RCP 1A and 2A have high motor currents, aren't they?' and a RO answers 'Yes.' In contrast, an SS with PBP has to ask 'inquiry-identification type' questions in order to carry out steps in EOP-02. For example, an SS with PBP asks, 'What is the status of both RCP 1A and 2A?' and a RO answers 'Both RCP 1A and 2A have high motor currents.' The asymmetry is not unique in the nuclear industry. In the aviation industry, a captain and a first officer also show asymmetric communication (Kanki et al., 1989).
Asymmetry is inevitable because of the roles and positions of team members and given situation. However, too high level of asymmetry may not be desirable if it invokes a group-thinking mode. In a group-thinking mode, when a group leader makes an error it is hard for other members to find the error and to suggest corrections.

The composition of message types shows differences within two PBP sessions. The comparison of two PBP sessions points out that the PBP 2 session has better communication than the PBP 1 session. The PBP 2 session has more acknowledgement type messages than the PBP 1 session. Messages of acknowledgement type play an important role in effective communication, because they provide the message sender with feedback on whether a message has been received or not (Bowers et al., 1998). Another difference between PBP1 and PBP2 is that PBP2 session shows higher 'observation' type messages. This reflects more active role by board operators and contributes to better situation awareness.

Communications with PBP at a conventional MCR show wide variations in communication[2]. One reason might be the difference in personal characteristics of shift supervisors. Although the variation itself is not always bad, it certainly indicates a lack of standards in communication at an MCR. In contrast, communication in the aerospace environment has very standardized vocabulary and interactions with which crew members have to comply. Although it is not necessary to define standards in very specific ways like standard phraseology, there is a need for communication standards in order to improve the safety of nuclear power plants. Standard communication protocols would be very valuable in an advanced MCR with CBP, too.

[1] They call it a synchronized meeting.

[2] The researchers of this study made many observations of training sessions with PBP and testing sessions with CBP.

6. CONCLUSIONS

The purpose of this study is to invoke interests in communication in order to secure the safety of operation at nuclear power plants in Korea, even though communication is only one of many factors that affect team performance. This study follows and adapts an approach taken by previous research in the aviation industry. This study confirms recurring issues in communication using CBP and raises concerns with wide variations in communication using PBP.

This study has a serious limitation in terms of generalization in that this study has only four samples. However, the authors have observed many other training and testing sessions and found similar phenomena, although the other sessions have not been transcribed and analyzed yet because of enormous amount of time for transcription.
The communication issues have to be investigated quite extensively in the future. In future studies, the quality of communication can be measured in terms of content composition and communication pattern. It would be interesting to see which factors affect team performance in a nuclear power plant.

REFERENCES

Bowers, C.A., F. Jentsch, E. Salas, C. C. Braun (1998). Analyzing communication sequences for team training needs assessment. *Human Factors*, **40**(4), pp. 672-679.

Chung, Y. H., D. Min, and B. R. Kim (2002). Observations on Emergency Operations Using Computerized Procedure System. In: *Proceedings of the 2002 IEEE 7th Conference on Human Factors and Power Plants*, pp. 4-61~4-65, Scottsdale, AZ. U.S.A.

Federal Aviation Administration, (2002), Air Traffic Control Operational Error Report Form, FAA Order 7110.65N

Foushee, H. C., and K. Manos (1981). Information transfer within the cockpit: Problems in intracockpit communications. In: *Information Transfer Problems in the Aviation System*. (C. E. Billlings and E. S. Cheanet, (Eds)). NASA Technical Paper 1875, NASA-Ames Research Center. Moffett Field, CA, USA.

Grayson, R.L. and C.E. Billings (1981). Information transfer between air traffic control and aircraft: Communication problems in flight operations. In: *Information Transfer Problems in the Aviation System*. (C. E. Billlings and E. S. Cheanet, (Eds)). NASA Technical Paper 1875, NASA-Ames Research Center. Moffett Field, CA, USA.

Hirotsu, Y., K. Suzuki, M. Kojima, K. Takano (2001). Multivariate analysis of human error incidents occurring at nuclear power plants: Several occurrence patterns of observed human errors. *Cognition, Technology, & Work*, **3**(2), pp. 82-91.

Hollnagel, E. (1998). Cognitive Reliability and Error Analysis Method (CREAM), Elsevier, Oxford, UK

Jentsch, F. G., S. Sellin-Wolters, C. A. Bowers, and E. Salas (1995). Crew coordination behaviors as predictors of problem detection and decision making times. In: *Proceedings of the Human Factors and Ergonomics Society 39th Annual meeting*, pp. 1350-1353, Human Factors and Ergonomics Society, Santa Monica, CA.

Kanki, B.G., S. C. Lozito, and H. C. Foushee (1989). Communication indexes of crew coordination, *Aviation, Space, and Environmental Medicine*, **60**, pp. 56-60.

Kanki, B.G., and H. C. Foushee (1989). Communication as group process mediator of aircrew performance. *Aviation, Space, and Environmental Medicine*, **60**, pp. 402-410.

Kettunen, J. and P. Pyy (2000). Assessing communication practices and crew performance in a NPP control room environment – A prestudy, TAU-001/00.

Kintsch, W. and T. A. van Dijk (1983). Toward a model of text comprehension and production, *Psychological Review*, **85**(5), pp. 363-394.

Min, D., Y. H. Chung, and B. Kim (2001). An evaluation of computerized procedure system in nuclear power plant. In: *Proceedings of the 8th IFAC/IFIP/IFORS/IEA Symposium on Analysis, Design, and Evaluation of Human-Machine Systems*, pp. 597-602, IFAC, Kassel, Germany.

Morrison, R. and R. H. Wright (1989). ATC control and communication problems: An overview of recent ASRS data. In: *Proceedings of the Fifth International Symposium of Aviation Psychology*, Vol. 2, Columbus, Ohio.

Mosier, K. L., and T. R. Chidester (1991). Situation assessment and situation awareness in a team setting, in Designing for everyone. In: *Proceedings of the 11th Congress of the International Ergonomics Association*, pp. 798-800, Taylor & Francis, London

Navarro, C. (1989). A Method of studying errors in flight crew communications. *Perceptual and Motor Skills*, **69**, pp. 719-722.

O'Hara, J. M., J. C. Higgins, W. F. Stubler, and J. Kramer (2000). Computer-based procedure systems: Technical basis and human factors review guidance, NUREG/CR-6634, Washington, DC: US Nuclear Regulatory Commission.

Orsanau, J. (1990), Shared mental models and crew performance, Report No. CSLTR-46, Princeton University, Princeton, NJ, USA.

Orasanu, J., J. Davison, and U. Fisher (1997). What did he say? Culture and language barriers to efficient communications in global aviation. *International Symposium of Aviation Psychology*, pp. 673-678.

Prinzo, O.V. and T. W. Britton (1995). Development of a coding form for approach control/pilot voice communications. *DOT/FAA/AM-95/15*, U.S. Department of Transportation and Federal Aviation Administration.

Thorton, R. C. (1992). The effects of automation and task difficulty on crew coordination, workload, and performance, Unpublished doctoral dissertation, Old Dominion University, Norfolk, VA.