AN EXTENDED FRAMEWORK FOR ANALYSING TEAM COMMUNICATION IN ADVANCED NUCLEAR POWER PLANT

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

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
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
Dept. of MIS, Korea University,Jochiwon-Eup, Choongnam,
339-700, South Korea
Tel: +82 41 860 1563, e-mail: mismdh@korea.ac.kr

Abstract: Advanced human-machine interfaces rapidly change the co-working fashion between humans and systems. Among what are being changed are the abstraction level of presented information, human task characteristics, and the ways of communication. To accommodate the differences, an extended framework of communication is called for that includes and relates the tasks, verbal exchanges, and the information interface. This paper proposes an extended analytic framework, referred to as S-H-H (system-human-human), that helps understand the changing team communication under new working environments with highly processed information. The usefulness of the proposed framework is demonstrated by an in-depth comparison of the characteristics of communication in conventional and advanced main control rooms of nuclear power plants.

Keywords: Communication Analysis, Co-operation, Error Analysis, Human Error, Nuclear Plants, Training

1. INTRODUCTION

Communication among co-workers is an essential part of team operation in large-scale complex systems. In aviation and nuclear power industries, reliable communication has been emphasized for safety since problems in verbal communication often led to critical situations.

In the aviation industry, the communication error has been one of the biggest causes in aviation mishaps. A study found from the database of Aviation Safety Reporting System (ASRS) that the portion of verbal information transfer problems was approximately above 70% (Cornell, 1995). This led to extensive research on communication as a part of human error analysis. Communication errors have been classified from various viewpoints such as problem types, information processing models, and standard phraseology (Grayson and Billings, 1981; Navarro, 1989; Prinzo, 1996).

In contrast, in the nuclear power industry, communication issues have not been intensively dealt with until recently. However, the introduction of the digital instrumentation and control (I&C) technology and computerized systems, such as advanced monitoring systems and Computer-Based Procedures (CBPs), has raised new safety concerns related with communications (Roth and O'Hara, 1999; Min et al., 2001). An analysis on Japanese nuclear power plants showed that 25% of human error incidents were due to written or verbal communication problems (Hirotsu et al., 2001).

This paper introduces a framework for analysing the communication among team members during the operation of highly automated large-scale systems. The framework is based on the observation that human-human communication should not be analysed without taking the information into account since the communication is highly affected by the way of information representation by the technical systems.

2. ADVANCED CONTROL ROOMS AND COMMUNICATION

2.1 The Advanced Main Control Room and Its Characteristics

The advanced main control room (AMCR) is characterized by high level of information processing utilizing advanced information techniques and hardware, compared to the conventional MCR (CMCR) that basically relied on the concept of single-sensor single-display. This section describes how the AMCR is significantly different from the CMCR in the aspects that affect communication in it.

Firstly, the information presented by the technical system in the AMCR is different from that in the CMCR. The difference of information can be most succinctly explained in terms of the information level. Along the part-whole dimension, the information presented in MCR can be classified into that of component, sub-system, system, and inter-system levels. Table 1 shows some examples of data that belong to each information level in MCR. The AMCR presents information of all four levels in a necessary balance using information processing and advanced graphic displays. Even the component-level information may be presented after some processing such as representative value selection or alarm reduction. In contrast, most information in the CMCR belonged to component level until a few higher-level data (e.g., Safety Parameter Display System, Inadequate Core Cooling Monitoring System) were added after Three Mile Island accident.

However, CMCR does not completely lack high-level information. For instance, the grouped status lights of Bypassed and Inoperable Status Indication (BISI) and the group indication of isolation valves of containment provide information of inter-system level. Grouping individual status indicators can push the level of information upward because the group provides emergent patterns of system malfunction, instead of individual component status.

Table 1 Examples of information level in NPP

Level	Examples
Component	Level/pressure/temperature indicator of each process parameter
Sub-system	containment spray system, reactor coolant system, BISI, etc.
System	primary system, auxiliary system, secondary system, turbine generator system, electric system
Inter-system	safety functions like reactor coolant system inventory

The left-hand-side graph of Figure 1 shows different information profiles between CMCR and AMCR. While AMCR provides larger amount of information in general, it is most markedly abundant at the sub-system and system levels. The high-level information of AMCR is useful when a bird's-eye view of the system state is needed, although the navigation among information groups may add an extra degree of complexity.

Secondly, the human task characteristics in the two types of MCRs are distinct. The board operators (e.g., reactor operator, turbine operator, electric operator) in a CMCR have to observe process parameters, compare the values with the corresponding set-points, and report the results to Shift Supervisor (SS). Then SS integrates the results to assess the state of sub-systems or the system, and to determine if inter-system safety functions are satisfied. In contrast, in an AMCR, the board operators' tasks tend to be changed from observation and comparison to identification, because the operators directly obtain the transformed high-level information form the advanced display.

For instance, during Loss of Coolant Accident (LOCA) scenario, board operators of a CMCR have to observe various process parameters on several control boards to verify whether the conditions for LOCA entry are met. In an AMCR, operators can quickly grasp overall situation with high-level information on VDT (Visual Display Terminal) and confirm specified abnormal conditions on the basis of lower-level information. This level-by-level confirmation may continue until the operator acquires enough awareness of plant conditions.

The graph on the right in Figure 1 shows the different degrees of information processing at each level by operators in CMCRs and AMCRs. At the system and sub-system levels, operators in CMCR have to synthesize high-level account of the system state based on the low-level observations to fill up the gap between inter-system information and the observations. The workload of information processing in AMCR is lower than in CMCR at all information levels, because the tasks of operators are more of identification, instead of numerous observations and interpretation.

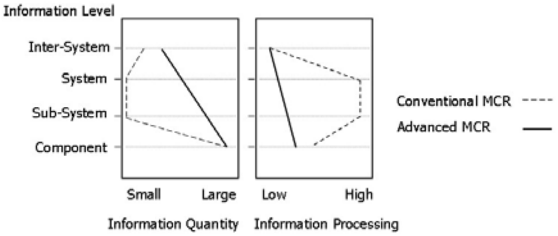

Fig. 1. The relationship of information quantity, information processing, and information level between conventional and advanced MCRs

One of the most important points regarding the difference in information activities in the two types of control rooms is the direction of human information processing. The above graphs suggest that the primary direction of operators' information processing is bottom-up in CMCR and top-down in AMCR. This was also very obvious in our own observations of team plant operations that were conducted for this study. This directional difference of information usage has great implications regarding the communication both among team members and between the human and the system.

2.2 The Need of a More Inclusive Perspective

Analysis of human-human communication alone can not reflect the above discussed effects of advanced information processing by the system. Therefore, we need a more inclusive framework that integrates human-human (H-H) communication and the information processing by the system that produces the common basis of the communication.

In general, communication stands for the information exchange among humans. Quite a lot of research in the aviation industry has focused on communication, because communication errors have been a major cause of air traffic accidents. The communication analyses in the aviation industry have investigated mainly the remote communication between air traffic controllers and pilots (Prinzo, 1996; Corradini and Cacciari, 2002). Although they have produced useful results to reduce aviation accidents, the research focus has remained on the information exchange among humans being confined to human-human communication.

Another group of research has dealt with the interaction between the human and the technical system under the titles of Human-Machine Interface (HMI), Human-System Interface (HSI), and Human-Computer Interaction (HCI). The main emphasis is on how to design interface features of the technical system, since the information presented by the technical system affects the cognitive processing of human users. As the information technology advances, the technical system becomes more intelligent with more sophisticated information processing capabilities as well as information presentation capabilities. The interaction between the human and system can now be viewed as information exchange, explicit or implicit, or human-system communication.

The studies in both lines of research have limitations in analysing information exchange in large-scale dynamic systems such as nuclear power plants (NPPs) due to the exclusion of inseparable participants. Studies of the human-human communication analyse the human conversation mainly with social perspectives. The results from the analyses tend to deliver superficial characteristics of communication without referring to the mental models or cognitive stages of workers and without considering the information processing capabilities of the technical system. In contrast, most studies with the HMI perspectives focus their attention to the cognition at the individual level. Although it is well known that changes in the design of HMI bring about changes in the cognitive process of individual users, few studies have yet tried to investigate the effect of the HMI design on the communication at the group level (Hutchins, 1995).

The role of the information presented to the humans who participate in communication is important since it provides externally perceivable and shareable basis of related communication. It would be pointless to embrace all the human-system interface issues. However, considering the whole path of information exchange through the system and humans appears to be an essential requirement, since the growing information processing capability of the modern systems takes more part of the path so that the communication between humans tends to deal with the remaining part. This rationale leads to the proposed analytic framework to study communication in technical environment introduced below.

3. THE S-H-H FRAMEWORK

We discussed the need for communication analysis to include the issues of information presentation by the technical system. We propose a framework for communication analysis, which is referred to as System-Human-Human (S-H-H) framework, for in-depth human performance analysis that encompasses not only human-human communication, but also the information processing and presentation by the technical system. In the framework, communication and information design are related as much as decision-making tasks and the latter have been related.

The usefulness of S-H-H framework can be demonstrated by that the framework has capability to account for two most important characteristic changes that are on-going in modern large-scale dynamic systems in relation with communication issues. The first is high level of information processing by the system and the second is the dynamic organization of communication.

3.1 Levels of Information Processing and H-H Communication

The S-H-H framework reflects the causal chain through which changes in HMI invokes changes in team communication. Firstly, changes in HMI technology typically bring changes in information that is presented by the technical system. In the opposite direction, desired changes in information require the adoption of new HMI technology. Secondly, changes in information provided by the system cause changes in task characteristics of individuals who directly interact with the system. Based on different information, an individual has to perform the same work through different cognitive processes and strategies. Thus, the information change may be planned for the purpose of enabling more reliable cognitive process. Since the information change usually involves partially automated information processing or integrated displays to facilitate the human information processing, allocation of information processing tasks between the human and the system becomes an important subject. Finally, changes in the operators' task characteristics and the displayed information they share lead to changes in communication among team members, even though the team task remains the same. This implies that, to understand the communication during system operation, not only tasks but also information presentation should be considered. Then, on the opposite direction, the design of tasks and information displays also need to consider the resulting characteristics of human communication. Throughout this causal chain, tracing back the causalities renders design issues.

A nuclear power plant provides a concrete and realistic example. In the MCR, several engineers form a team, which consist of a Shift Supervisor (SS), a Reactor Operator (RO), a Turbine Operator (TO), an Electric Operator (EO), and a Shift Technical Advisor (STA).

Communication in the MCR of a NPP contains various types of data. For instance, operating crew acquires and exchanges the values and status of process parameters. These are typical data of either quantitative or qualitative types. Synthetic data type is what we define as the third data type, which is normally produced by combining the other types of data and thus requires more mental effort. Synthetic data tend to represent more abstract system state than quantitative data,

Information processing by the computer alters the data types to be delivered to the human informational activity regarding the data. For instance, where the human operator had to compare a process parameter with its set-point, the advanced technical system can instead (or additively) provide an alarm sound or a flashing light as the indication of passing over the set-point. As the computer transforms the low-level quantitative value of the parameter into the higher-level qualitative state, the task of the operator is changed from the observation and calculation of quantitative values to mere identification of qualitative indications.

Figure 2 and 3 show how information is processed and flows at various levels among the system and crew members. These figures also explain the change of communication style and content. When information exchange between the RO and the SS needs to take place at a higher level than the level of original information acquisition by the RO, the RO has to integrate and/or abstract the observed information before communication.

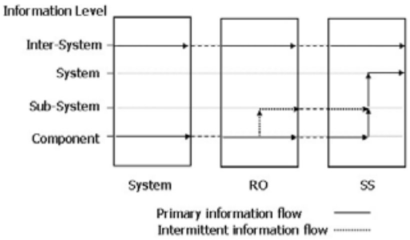

Fig. 2. Information flow of conventional MCR

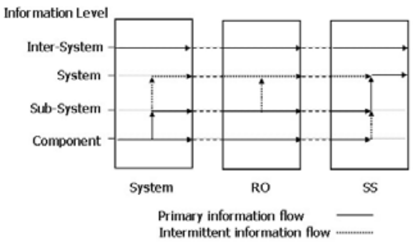

Fig. 3. Information flow of advanced MCR

When RO's task involves such abstraction gap, the communication between the SS and the RO, in both directions, reflects the needed (or performed) abstraction and becomes itself abstract. For example, the verb of the order from the SS is apt to be 'Judge' instead of simple 'Read' and the target information cannot be mapped onto a perceivable piece of information.

In typical S-H-H communication in AMCRs as depicted in Figure 3, a considerable portion of abstraction or integration of raw information is performed by the system, eliminating the need of further abstraction by the RO. Also, the target information, although abstract in its meaning, is no more invisible but correspondent to a displayed item. Due to the abstraction by the system, communication between the SS and the RO is reduced to orders or reports regarding mere indication of observable items.

The abstraction levels of communication messages between humans are accordingly affected as they have to use the presented form of information. A message that would report a judgment, which is based on lower-level elementary variables, can be changed to a message that reports a reading of an abstract, but visualized state.

As a general rule, when the abstraction of information was performed by the system and the abstracted information is explicitly presented, the abstraction level of human informational activities both with the system (e.g., reading and control) and with another human (e.g., verbal communication) is reduced. This 'shifting' phenomenon has a big implication to communication analysis since communication at different abstraction levels is prone to different types and causes of errors.

3.2 Two Types of Organization of Communication

The S-H-H co-working environments generally fall into two types of organization shown in Figure 4 and Figure 5. We call these two types S-H-H Type A and S-H-H Type B respectively.

The S-H-H Type A in Figure 4 represents the situation in which someone in a team does not acquire the information directly from the technical system. A typical example of Type A is CMCR operation where board operators directly interact with the technical system and a SS follows paper-based operating procedures getting system information from the board operators through human-human communication.

Fig. 4. Co-working environment Type A

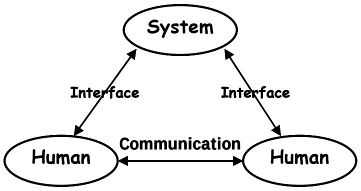

Fig. 5. Co-working environment Type B

In contrast, in the S-H-H Type B depicted in Figure 5, team members have access to the same technical system perhaps with the same interface. The information directly provided by the technical system does not have to be conveyed through verbal conversation. However, information exchange regarding the shared information may not be entirely omitted. Members assume that the others are also aware of important events and states displayed by the system and try to confirm this assumption in more implicit ways, such as monitoring intent or checking logical integrity during conversation that is not directly targeting those events or states. This situation, compared to traditional control rooms, looks very naturalistic. However, it may also be inviting many subtle miscommunications as can be found in naturalistic, everyday life situation. For instance, shared belief as a part of common ground of communication is much more implicit since they may have been never directly referred in the communication. AMCRs typically provide Type B environment, where each operator has access to the same system information and computer-based procedure via personal display.

4. OBSERVATIONS OF MCR COMMUNICATION IN THE S-H-H PERSPECTIVE

We observed and recorded the conversation in full-scale dynamic simulator during training sessions of Emergency Operation Procedure (EOP). The recorded communication was analysed according to the S-H-H framework. A scenario called 'EOP-02 Loss of Coolant Accident' was selected to be observed in two types of control rooms, KSNP[1] and APR 1400[2]. The LOCA training sessions of KSNP were mostly held from May to July in 2003 and the test sessions of APR-1400 were held in 2001 and 2002. The videotapes of the training sessions were used to make transcripts and verify the actual training situations when necessary for interpretation of the collected dialogues.

The communication analysis was performed to characterize the team work in AMCRs in terms of information exchange. The analysis was focused on the differentiation between S-H-H Type A and Type B configurations since we believed that they represented the fundamental socio-technical changes in modern NPPs.

For the communication analysis among the operating crew under the S-H-H framework, we used a modified version of Bowers's classification scheme (Bowers et al., 1995). Supervisors led conversation by 'inquiry' and 'command'. We further divided 'inquiry' into 'identification' type and 'confirmation' type. And according to the requested data types, we divided 'identification' into three sub-types (i.e., qualitative, quantitative, and synthetic type), which would tell the differences of interface and workload.

The team communication was observed proceeding very distinctively in S-H-H Type A and Type B systems. The style, amount, content, and roles of information exchange were all distinct. The S-H-H framework was useful to locate and describe those characteristic differences.

Firstly, the communication style differed. An inquiry by the SS in Type A preparing the start of Standard Post Trip Actions (SPTA) was as follows: "Is the reactor power decreasing and is the start-up rate minus?" That was from the corresponding step of the written procedure. However, the inquiry in the same situation in Type B was: "Now I see that the reactor power is decreasing and the start-up rate is minus. Is it correct?" It can be said that the expressions used in, Type A environment were more information-asking while those in Type B were more information-confirming, because the shift supervisor (SS) can also directly access the same information of board operators. Indeed, SS in Type B arrangement sometimes notified his own observations, when conditions changed, before the board operators' reported.

Secondly, the communication contents in Type A and Type B environments were different. In Type A, the SS requested the aforementioned three kinds of identification to the other operators. Then each board operator reported the status and values of process parameters as well as synthetic decisions from various parameters and their corresponding set-points. In contrast, the advanced information system of Type B, the 'synthetic' type inquiries for 'identification' were seldom found. The information that would be 'synthetic' type in Type A environment appeared as a 'qualitative' type in Type B environment. Moreover, there was a tendency that the frequency of 'inquiry-identification' decreased while 'inquiry-confirmation' was more frequent in Type B control room. As was discussed, this was the result of presentation of high-level information. The board operators could simply identify high-level information on the display and transferred it to the SS, who also was able to notice or confirm the same information on her/his own display. Supervisors seemed more comfortable when gathering information and determining system integrity based on the pre-processed information than in conventional environment.

---

[1] KSNP stands for the Korean Standard Nuclear Plant, which has rated electric power of 1,000MWe.

[2] APR 1400 stands for the Advanced Power Reactor 1400, which has rated electric power of 1,400MWe.

Thirdly, the communication amount was reduced. The verbal communication in Type B environment was drastically reduced because SS could use the same information and did not need to obtain detailed information from board operators. For instance, the verbal exchanges in Type B environment were reduced to about one third of those in Type A.

Fourthly, the roles of operators were distinguished. From the observations in Type A MCRs, we found that the SS, the exclusive reader of EOP, played the role of the task leader while the other operators played task supporters. Asymmetrical communication was obvious, where the conversation was primarily initiated by SS in the forms of inquiries and commands and ended with the responses or reports from board operators. Similar asymmetric property in communication between the captain and the first officer was also reported in an aviation study (Kanki et al., 1989). On the contrary, there existed a certain degree of role sharing between SS and RO in S-H-H Type B environment. The supervisors at times informed their own observations and the ROs actively raised their suggestions.

5. CONCLUSIOINS

The importance of communication for safe operation of plants is not an emerging issue. The experience in aviation industry continuously demonstrated its significance. The nuclear industry started to realize the importance of communication more recently with the advance of information-processing environment like computer-based procedure system.

This paper argued the need to extend the conventional framework for human-human communication analysis to include the information representation by the technical system. Advanced information processing in the part of system not only changes the characteristics of team communication, but makes it pointless to analyse the human-human communication separated from the system's information processing since the communication between humans is only a segment of the continuous information flow.

The S-H-H framework, that was proposed to answer the need, can account for the changes in advanced MCRs in terms of human task properties, communication styles, the content and amount verbal exchanges. The usefulness of the framework was further supported by an observational study applying the framework to a scenario of emergency operation of nuclear power plant.

While the AMCRs with Type B S-H-H communication environment were predicted and observed to provide better working conditions in terms of task workload and communication reliability, there may arise new communication issues. For instance, the shift supervisors were observed to use procedures and alarms as their primary task tools during emergency conditions, while the other operators of used alarms, indicators, and controls as main mediating tools. The shift supervisors handled plant conditions and symptoms as objects and the other operators regarded the status of meters and controls as their target objects. Such differences of instruments (i.e., objects and tools) can become a source of hampered communication. The common ground for communication that is assumed on the basis of shared information display may also turn out to be a false belief due to its nature of implicit sharing.

Proper communication is essential for safe and productive operation of nuclear power. The training of communication should be adapted to the advanced HMI in large-scale complex systems, because the new environment brings about new sorts of human performance problems, which are expected to be less structured and explicit than before.

REFERENCES

Bowers C., J. Deato, R. Oser, C. Prince, & M. Kolb (1995). Impact of Automation on Aircrew Communication and Decision-making Performance, *The International Journal of Aviation Psychology*, **5**(2), pp. 145-167.

Cornell, L. (1995). Pilot and controller communications issues. In: *Proceedings of the Methods and Metrics of Voice Communication Workshop* (B.G. Kanki and O.V. Prinzo. (Eds.). pp. 19-27.

Corradini, P., and C. Cacciari (2002), The Effect of Workload and Workshift on Air Traffic Control: A Taxonomy of Communication Problems. *Cognition, Technology & Work*, **4**(4), pp. 229-239.

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*. (Billlings C.E. and Cheanet, E.S. Eds). NASA Technical Paper 1875.

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.

Hutchins, E. (1995). Cognition in the Wild, MIT Press.

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.

Min, D., Y.H. Chung, and B.R. Kim (2001). An Evaluation of Computerized Procedure System in Nuclear Power Plant. *Proceedings of the 8th IFAC/IFIP/IFORS/IEA Symposium on Analysis, Design, and Evaluation of Human-Machine Systems*, Kassel, Germany, pp. 597-602

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

Prinzo, O.V (1996). An Analysis of Approach Control/Pilot Communications. *DOT/FAA/AM-96/26*, U.S. Department of Transportation and Federal Aviation Administration.

Roth, E. M. and J. M. O'Hara (1999). Exploring the Impact of Advanced Alarms, Displays, and Computerized Procedures on Teams, In: *Proceedings of the Human Factors, and Ergonomics Society*, *43rd Annual Meeting*, pp. 158-162.