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A Framework for Evaluating the Effects of Degraded Digital I&C Systems on Human Performance

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A FRAMEWORK FOR EVALUATING THE EFFECTS OF DEGRADED DIGITAL I&C SYSTEMS ON HUMAN PERFORMANCE

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ABSTRACT

New and advanced reactors will use integrated digital instrumentation and control (I&C) systems to support operators in their monitoring and control functions. Even though digital systems are typically highly reliable, their potential for degradation or failure could significantly affect operator situation awareness and performance and, consequently, impact plant safety. The U.S. Nuclear Regulatory Commission has initiated a research project to investigate the effects of degraded I&C systems on human performance and plant operations. The ultimate objective of this project is to develop the technical basis for human factors review guidance for conditions of degraded I&C, including complete failure. Based on the results of this effort, NRC will determine the need for developing new guidance or revising NUREG-0800, NUREG-0711, NUREG-0700 and other pertinent NRC review guidance. This paper reports on the first phase of the research, the development of a framework for linking degraded I&C system conditions to human performance. The framework consists of three levels: I&C subsystems, human-system interfaces, and human performance. Each level is composed of a number of discrete elements. This paper will describe the elements at each level and their integration. In the next phase of the research, the framework will be used to systematically investigate the human performance consequences of various classes of failures.

Key Words: Digital I&C, Human Performance, Degradation, Regulations

1 INTRODUCTION

To help ensure its human factors engineering (HFE) regulations and review guidance are up-to-date, the U.S. Nuclear Regulatory Commission (NRC) conducted research to identify potential human performance issues related to the introduction of emerging technologies in nuclear power plants. These issues were prioritized, and the technical bases needed to address them were developed [1, 2]. Sixty-four issues were defined of which 20 were ranked in the top priority category. One of the top priority issues is "Operations under conditions of degraded instrumentation and controls (I&C)." The I&C system senses basic parameters, monitors performance and system health, integrates information, and makes adjustments to plant operations as necessary. It also responds to failures and off-normal events, thus ensuring goals of efficient power production and safety. Because the I&C system is the primary means by which personnel monitor and control the plant, its degradation will have a significant impact on the operator's ability to monitor plant conditions, detect disturbances, assess the plant status, and take actions in response to unfolding conditions. Failure or degradation of I&C systems can pose additional challenges by causing abnormal operating conditions due to erroneous automatic action.

Prior NRC research on advanced reactors resulted in a draft report titled “Human Factors Considerations in New and Advanced Reactors.” Numerous issues were identified and subjected to a PIRT-like process for prioritization, based, in-part, on potential safety impact. One of the highest priority issues relates to operating under conditions of degraded I&C. The NRC Human Factors Engineering (HFE) reviews of advanced I&C technology issues may necessitate modification of existing guidance documents. The NRC therefore initiated a project to develop the technical basis for human factors review guidance for conditions of degraded I&C, including complete failure. Based on the results of this effort, NRC will determine the need for developing new guidance or revising NUREG-0800, NUREG-0711, NUREG-0700 and other pertinent NRC review guidance.

The research presented in this paper was undertaken to achieve this objective. It describes the first phase in the guidance development process, namely, the development of a framework for linking digital I&C systems to human performance. The framework described in this paper will be used in subsequent phases of the project to better understand the relationship between specific classes of I&C system degradation and human performance and to develop HFE review guidance that will help ensure that degraded I&C conditions can be effectively managed by plant personnel.

2 METHODOLOGY

As noted above, the objective of this phase in the guidance development process is to develop a framework for understanding the relationship of I&C systems and human performance. The purpose of the framework is to provide a means of linking degradations of the I&C system with human performance. Once developed, the framework will provide a tool to evaluate different I&C systems, studies of I&C degradations, operating experience involving I&C degradations, etc. in a common standardized language. This is necessary in order to develop broader generalizations in the form of lessons learned from a diverse set of information and analyses

The framework represents three essential levels of human-system integration: an I&C system characterization, a human-system interface (HSI) characterization, and a human performance characterization. A characterization refers to how each level of the framework is described. It includes the essential elements needed to describe the level. The development of the framework was accomplished through five activities, illustrated in Figure 1.

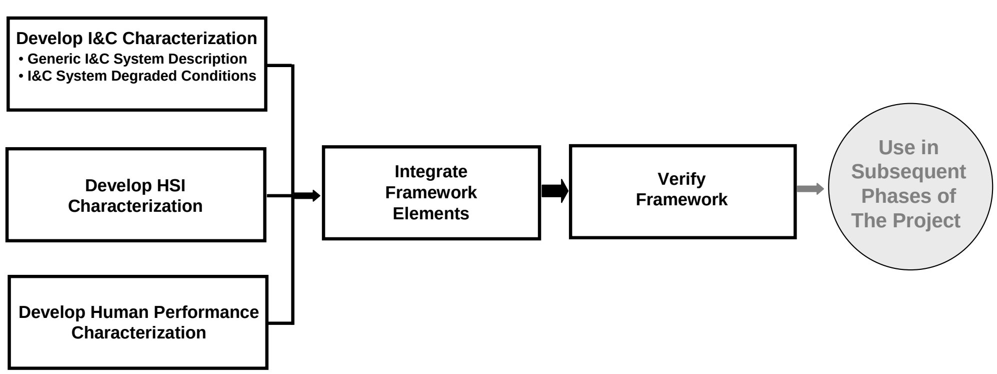

Figure 1. Framework development methodology

First, an I&C characterization was developed. In addition to reviewing the details of individual systems being proposed for advanced reactors, we reviewed recent efforts to characterize modern, digital I&C systems that have appeared in the literature, e.g., the Department of Energy (DOE) I&C roadmap [3]. Once a suitable I&C system characterization was developed, we sought to identify failure modes. The failure modes represent the set of degradation conditions whose effects on human performance we wish to determine. The availability of a fairly complete list of failure modes would ensure that our analysis is comprehensive. Our initial goal was to identify a generic classification for I&C system failure modes. However, no such taxonomy currently exists that is generally accepted in the I&C community. Thus, we examined two types of information: (1) studies of the risk impact of digital I&C system failures and (2) documented operating experience related to digital I&C failures.

The second activity was to develop an HSI characterization. This is needed because operations personnel perform their tasks associated with I&C systems using the available HSIs. It is through the HSI that the degraded I&C conditions are presented (or not presented) to the operator. It is also through the HSIs that operator actions impact plant systems and ultimately higher-level plant functions, including safety functions.

The third activity was to develop a human performance characterization. This is needed to describe how the degraded I&C conditions impact the performance of operators. Since it is quite likely that different types of degraded conditions may affect different aspects of human performance, the human performance characterization need to be sufficiently detailed to enable the effects to be determined.

The fourth activity was to construct an integrated framework that:

- provides a clear link between I&C systems to human performance,
- is characterized at a level of abstraction such that it can accommodate differences in the architecture of individual nuclear I&C vendor designs, and
- can be used to analyze a variety of theoretical and actual degraded conditions.

The final activity in this phase of the research was verification of the framework. Before proceeding to use the framework in subsequent phases of the research, we wanted some assurance that the framework makes technical sense and can be applied to the study of I&C degradation and failure conditions within the context of human performance. Verification was performed by using the framework to analyze operational events involving I&C degradation.

3 RESULTS

3.1 I&C Characterization

Following the evaluation of the I&C architectures of several current digital I&C systems being proposed in new reactor applications, we sought to identify a simple generic representation of an I&C system that characterized these different architectures. The characterization that seemed most suitable for our purposes was that developed for DOE's I&C roadmap for the advanced nuclear power plant programs [3]. The I&C system is divided into subsystem each having a specific function (see Figure 2) [4]. Note that the roadmap authors combine the I&C system and the Human System Interface, thus the acronym ICHSI. For our purposes, the HSI is considered separately (as its own layer) because, as noted earlier, the HSIs are the means by which information comes to plant personnel and through which actions are taken. The I&C layer is represented by four elements corresponding to I&C subsystems. A description of the I&C subsystems follows.

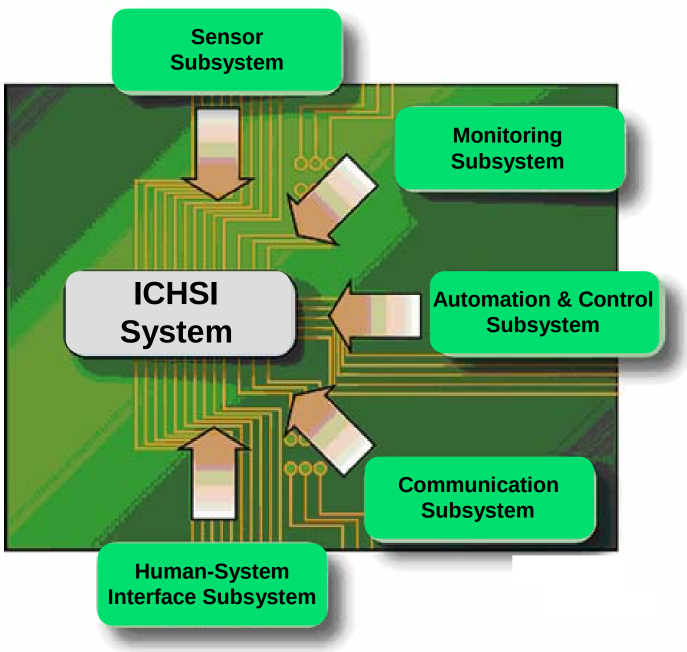

Figure 2. I&C subsystem representation (from [3])

Sensor subsystem - Nearly every plant process uses some form of physical measurement. These physical measurements are taken by sensors and instruments with signal conditioning that detect physical parameters in the plant, such as neutron flux, temperatures, pressures, flow, valve positions, electrical current levels, and radiation levels. Some new nuclear energy production technologies are using new and different types of sensors and instruments to measure physical processes. In some new reactor designs, these technologies include electronic sensors with imbedded software that will be required to work in high-temperature environments and measure and analyze process parameters that are quite different from those in light water reactors in operation today.

Monitoring subsystem - These subsystems monitor the signals and other information produced by sensors and evaluate that information to determine whether and what type of response may be needed. They can contain sophisticated diagnostic and prognostic functions. Diagnostics refers to techniques for identifying and determining the causes of deviations or faults in the plant systems or processes. Prognostics refers to methods for using sensor data to estimate the rate of physical degradation and the remaining useful life of systems, predicting time to failure, and applying this information to more effectively control plant processes.

Automation and Control subsystem - Digital control systems provide the capability to implement more advanced control algorithms than those that have been used in U.S. nuclear power plants to date. Current plants rely primarily on single-input, single-output, classical control schemes to automate individual control loops. Advanced control schemes include matrix techniques for optimal control, nonlinear control methods, fuzzy logic, neural networks, adaptive control (a control that modifies its behavior based on plant dynamics), expert systems, state-based control schemes, and other schemes that combine multiple control methods. Application of these advanced techniques will lead to more integrated control of plant systems and processes (versus separate, non-interacting control loops) and greater complexity. More modern control systems also provide the capability of more interaction and cooperation between automation and personnel, which essentially makes “man and machine” team players in the accomplishment of plant control functions.

Communications subsystem - Information flow throughout the I&C system and to devices being monitored and controlled is provided through a variety of communication systems that may include wireless technology. A classical I&C architecture provides point-to-point wiring of measured variables to the monitoring and control systems. The communications subsystems for a modern I&C system are configured in a flexible network architecture and have greatly expanded functionality, increasing the effectiveness of plant maintenance by providing field access to instruction manuals and diagnostics, and enabling “smart” transducers to signal their service condition to the plant engineering staff.

Next we sought to identify generic degradation/failure modes for the I&C system in order to understand how the subsystems can degrade. As noted above, we examined both risk studies and operating experience in developing a framework. With respect to the former, there are some generic types of digital I&C degradation that could become important considerations in evaluating operator performance during plant abnormal occurrences and, therefore, plant risk. Chu and colleagues conducted research on the risk importance of digital I&C system failures [5]. They identified ten failures as risk significant, e.g., spurious reactor protection system (RPS)/engineered safety function (ESF) actuation, failure to transfer from auto to manual control and back again, failure or degradation of displays causing anomalies, and general I&C communication failures. In many of these postulated events we were able to extract information about the need for effective interfaces between the I&C system and the operating personnel so that personnel awareness of its status is maximized. Understanding the failure modes from a risk analyst’s point of view was useful for understanding the potential operator interfaces and information needs that would also be important to consider in the overall research project. Operating experiences with digital I&C systems were examined to further our understanding of the relationship between the conditional risk significance of these failure modes with the means by which they are detected and propagated. Two of these events are briefly summarized to illustrate their human performance impacts.

- A zener diode failure on a circuit board caused an inadvertent safety injection which could not be reset. Safety protection signals could not be reset from the control room because of the degraded condition of the digital logic. Therefore the operating crew had to deviate from their shutdown procedures due to the lack of control of certain equipment from the control room (i.e., valves had to operated manually). [6]
- A power supply in a digital feedwater control system degraded to the point where it could not carry the required load. The degraded voltage condition disrupted feedwater operation, causing it to incorrectly start and stop automatically during the resulting transient. Several other issues were identified during a post-mortem analysis that affected the ability of the operator to assess the situation. This included a back-up system flow controller left in a manual mode following testing. [8]

The review of various sources of nuclear power plant operating experience identified examples of degradations of digital I&C systems that have affected human performance. Our review of these data indicate to us that: 1) failures of digital I&C systems occur regularly and have been on the rise over the past 20 years [9]; 2) these failures may have an important impact on nuclear power plant operations; and 3) the operating personnel are sometimes significantly challenged to restore the plant to a normal operating condition because of a lack of control or misleading information caused by the digital I&C system failure or degradation.

3.2 HSI Characterization

The HSIs are the parts of a nuclear power plant with which personnel interact in performing their functions and tasks. The HSIs are made up of hardware and software components and are characterized in terms of their important physical and functional characteristics. The NRC HSI review guidance contained in NUREG-0700 provides a detailed characterization of NPP HSIs [10]. Therefore, instead of developing a new HSI characterization, we adopted the NUREG-0700 characterization. However, for the purposes of this study, we combined several of the HSI elements. Thus, the HSI characterization includes the following six elements: Alarms, Information Systems, Computerized Operator Support Systems (COSSs), Controls, Communication Systems, and Workstations. For a description of the full set of HSI elements, see NUREG-0700.

3.3 Human Performance Characterization

To understand how I&C technology can impact plant safety, it is necessary to understand how human errors are caused and how technology impacts human performance. Thus, a characterization of human performance is needed. Such a characterization was developed when the NRC first began to focus research on advanced control room technology and developing guidance for its review [11]. Since its first publication, the characterization has been further developed and used as part of the technical basis in numerous research projects (see [1] for a summary). The characterization is summarized below.

The impact of operators on the plant is mediated by a causal chain as illustrated in Figure 3. The human-system interaction occurs when operations personnel perform their tasks using the HSIs provided. Operator tasks are supported by their physiological and cognitive processes. It is through the HSIs that operators interact with plant systems and components and ultimately higher-level plant functions, including safety functions.

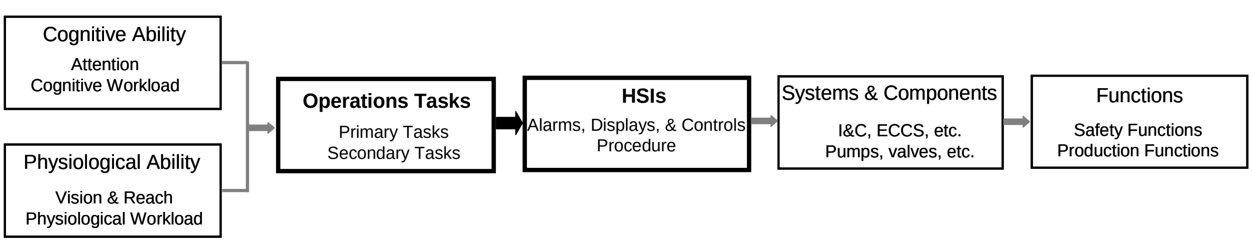

Figure 3. Operator impact on plant safety

In carrying out their roles and responsibilities, nuclear plant operators perform two types of tasks: primary tasks and secondary tasks. Primary tasks include activities such as monitoring plant parameters, following procedures, responding to alarms, starting pumps, and aligning valves. Secondary tasks are mainly “interface management tasks.” Primary tasks have a number of common cognitive elements. These common elements are monitoring and detection, situation assessment, response planning, and response implementation. Breakdowns in any of these generic primary tasks can lead to a human error.

The first primary task is monitoring and detection and involves extracting information from the environment, such as checking parameters on a control panel, monitoring parameters displayed on a computer screen, obtaining verbal reports from other personnel, and sending operators to areas of the plant to check on system components. This information is used to determine if the plant is operating as expected. In a highly automated plant, much of what operators do involves monitoring. Detection is the operator’s recognition that something has changed, e.g., a component is not operating correctly or the value of a parameter has increased or decreased. The alarm system is one of the primary means by which abnormalities and failures come to the attention of plant personnel.

The second primary task is situation assessment. It is the evaluation of current conditions to determine if they are within acceptable limits or to determine the underlying causes of abnormalities when they occur. Operators actively try to construct a coherent, logical explanation to account for their observations. This cognitive activity involves two related concepts: the situation model and the mental model. The “mental model” consists of the operator’s internal representation of the physical and functional characteristics of the plant and its operation as they understand it should be. The mental model is built up through formal education, training, and experience. Situation assessment occurs when operators use their mental model to understand information they obtain from the HSIs and other sources. The cognitive representation resulting from situation assessment is referred to as a “situation model,” the person’s understanding of the specific current situation. The term “situation awareness” is used to refer to the understanding that personnel have of the plant’s current situation; i.e., their current situation model. The alarms and displays are used to obtain information in support of situation assessment.

If operators have an accurate situation model, but mistakenly take a wrong action, they have a good chance of detecting it when the plant does not respond as expected. However, when an operator has a poor situation model, they may take many “wrong” actions because, while the actions are wrong for the plant state, they are correct for their current understanding of it.

The third primary task is response planning. It refers to deciding upon a course of action to address the current situation. In general, response planning involves operators using their situation model to identify goal states and the transformations required to achieve them. The goal state may be varied, such as to identify the proper procedure, assess the status of back-up systems, or diagnose a problem. To achieve the goals, operators generate alternative response plans, evaluate them, and select the one most appropriate to the current situation model. Response planning can be as simple as selecting an alarm response or it may involve developing a detailed plan when existing procedures have proved incomplete or ineffective.

The fourth primary task is response implementation. It is performing the actions specified by response planning. These actions include selecting a control, providing control input, and monitoring the system and process responses. There are a number of error types associated with controls, such as mode errors. Mode errors are a good example of a new error type associated with digital technology. A mode error occurs when operators take an action thinking the control system is in one mode when actually it is in another mode. Therefore, the system's response to the action is not what the operator intended.

To understand human performance, it is also important to consider the other class of tasks mentioned above - secondary tasks. To perform their primary tasks successfully, personnel must successfully perform secondary tasks or "interface management tasks." In a computer-based control room, secondary tasks include activities such as navigating or accessing information at workstations and arranging various pieces of information on the screen. In part, these tasks are necessitated by the fact that operators view only a small amount of information at any one time through the workstation displays. Therefore, they must perform interface management tasks to retrieve and arrange the information. These tasks are called secondary because they are not directly associated with monitoring and controlling the plant.

The distinction between primary and secondary tasks is important because of the ways they can interact. For example, secondary tasks create workload and may divert attention away from primary tasks and make them difficult to perform [12]. Thus, secondary tasks are important and need to be carefully addressed in design reviews, with particular attention to interface management tasks. Degraded I&C can increase interface management tasks, such as when operators need to navigate to additional displays when information on their current display is corrupted.

In actual plant operation, teamwork is required to perform these tasks. Important HFE aspects of teamwork include having common and coordinated goals, maintaining shared situation awareness, engaging in open communication, and cooperative planning. Successful teams monitor each other's status, back each other up, actively identify errors, and question improper procedures. [13]

Thus, the human performance characterization includes the following elements: Monitoring and Detection, Situation Assessment, Response Planning, Response Implementation, Interface Management, and Team Processes.

3.4 Development of an Integrated Framework

By integrating the I&C, HSI, and human performance layers, we developed the framework that links I&C degradations to human performance as mediated by the HSIs. This is shown in Figure 4. The left side of the Figure shows the framework, and the right side shows an example of how a sensor failure can impact human performance. The failed sensor degrades the sensor subsystem, which in turn impacts the information available to the alarm and information systems, which impairs the ability of the operators to monitor and detect disturbance. Table 1 provides examples of the possible human performance impacts of various degraded I&C subsystems. Thus for example, a failure that results in Communication subsystem degradation can potentially lead to a monitoring and detection error for the reasons shown in the table. The table is meant as an illustration of the methodology only. Actual analyses will be conducted in later phases of the research.

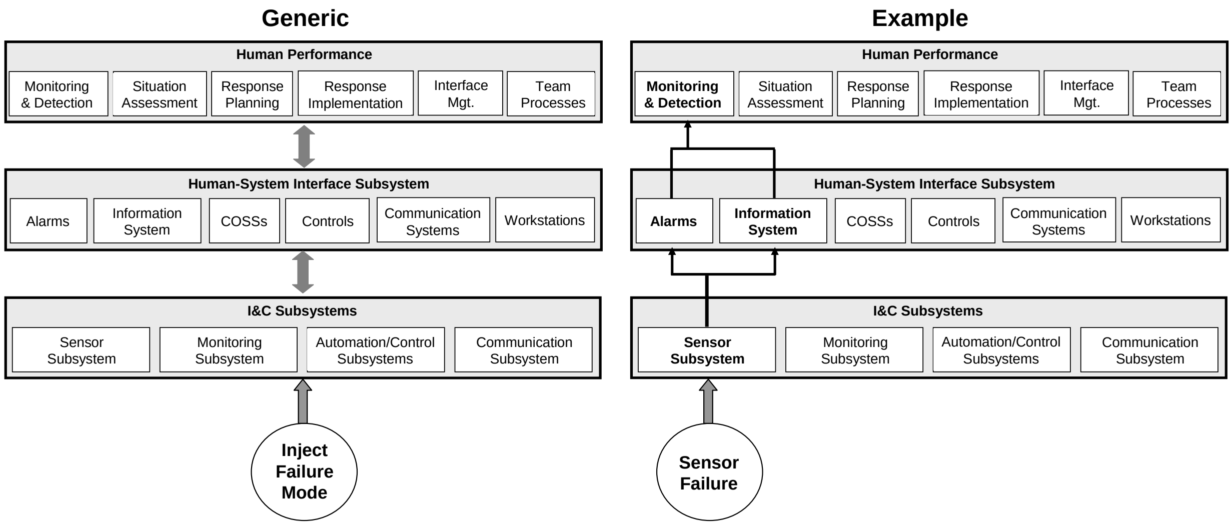

Figure 4. Framework for investigating the effects of degraded I&C on human performance

Table 1. Examples of I&C subsystem degradations and human performance impacts

I&C Subsystem Degradation	Impact on Human Performance
• Sensor subsystem • Monitoring subsystem • Communication subsystem	*Monitoring & Detection Error* • Needed information is not provided to the operator • Incorrect information is provided to the operator • Needed information is not provided to the operator in sufficient time
• Sensor subsystem • Monitoring subsystem • Communication subsystem	*Situation Assessment Error* • Needed information is not provided to the operator • Incorrect information is provided to the operator • Needed information is not provided to the operator in sufficient time
• Sensor subsystem	*Response Planning Error* • CBP not followed correctly
• Sensor subsystem • Monitoring subsystem • communication subsystem • Automation and control subsystem • Communication subsystem	*Response Implementation Error* • Needed action cannot be taken by the operator • The wrong action is taken by the operator • Needed action cannot be taken by the operator in sufficient time
• Communication subsystem	*Team Process Error* • Needed electronic communication from aux operator to main control room not completed

3.5 Framework Verification

Before proceeding to use the framework in subsequent phases of the research, we wanted some assurance that the framework makes technical sense and can be applied to the study of I&C degradations and failure conditions within the context of human performance. The usefulness of the framework was evaluated by analyzing several operating events to determine whether HFE insights can be derived. One example is the overloaded ethernet communication system event described in NRC Information Notice 2007-15 [7]. The nuance in this event is that this communication system also was linked to a recirculating pump control system. When the ethernet failed because of excessive data traffic, the recirculating pump speed control demand signal went to zero, causing the pump flow to decrease resulting in a plant scram due to a potentially high-power, low-flow condition.

Using the proposed framework for this occurrence, we determined that the communication subsystem was affected and consequently impacted the controls and information HSI subsystems. The Controls in this case were the recirculating pump speed controls. We linked to the Information System of the HSI subsystem because the operators had no indication that the ethernet was experiencing heavy data traffic and that it might be degraded. That affected the ability of the operating personnel to assess the situation (Situation Assessment) as important plant data were unavailable. The crew also lost the capability to implement the appropriate response since they had no control of the recirculating pump speed and flow (Response Implementation) The event is illustrated in Figure 5 using the integrated framework.

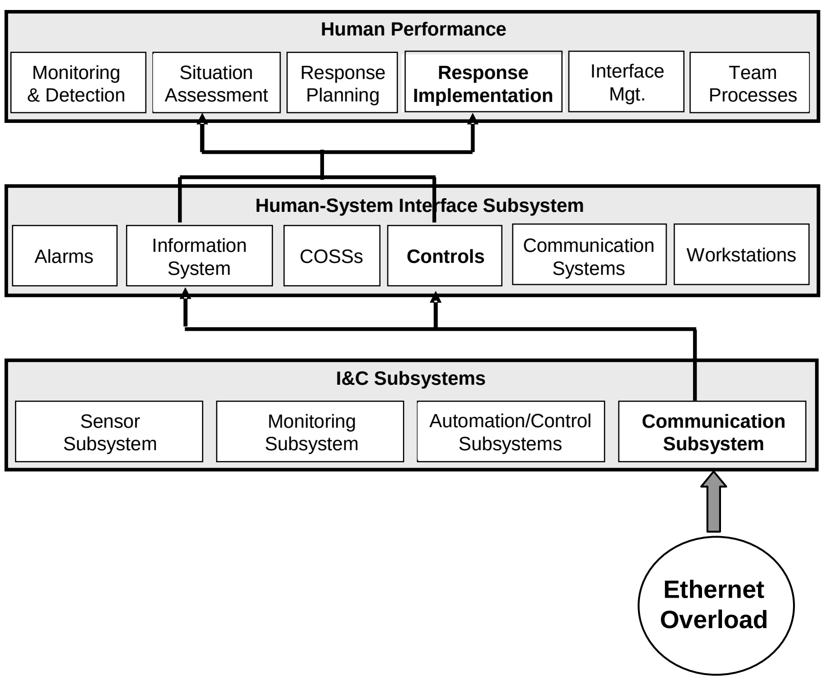

Figure 5. Framework representation of case study

4 CONCLUSIONS

A framework has been developed consisting of three layers representing the I&C system, HSIs, and human performance. Using the framework, failure and degradation modes of the I&C subsystems can be analyzed to show the propagation of the degradations to human performance as mediated by the HSIs. In addition, the framework provides a way of organizing the evaluation of other research, events, etc. into a standardized language for the purposes of developing more general insights.

The framework will be used in the next phase of the research to systematically investigate the human performance consequences of various types of degraded conditions. This will include previously published literature on I&C degradations, operational events involving I&C, and a detailed evaluation of a digital control system using the framework and failure modes. In the final phase of the research, we will use this technical basis to develop guidance for reviewing the HFE aspects of operating under degraded conditions.

5 ACKNOWLEDGMENTS

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