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Original Article

A Method to Select Human–System Interfaces for Nuclear Power Plants

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ABSTRACT

The new generation of nuclear power plants (NPPs) will likely make use of state-of-the-art technologies in many areas of the plant. The analysis, design, and selection of advanced human–system interfaces (HSIs) constitute an important part of power plant engineering. Designers need to consider the new capabilities afforded by these technologies in the context of current regulations and new operational concepts, which is why they need a more rigorous method by which to plan the introduction of advanced HSIs in NPP work areas. Much of current human factors research stops at the user interface and fails to provide a definitive process for integration of end user devices with instrumentation and control and operational concepts. The current lack of a clear definition of HSI technology, including the process for integration, makes characterization and implementation of new and advanced HSIs difficult. This paper describes how new design concepts in the nuclear industry can be analyzed and how HSI technologies associated with new industrial processes might be considered. It also describes a basis for an understanding of human as well as technology characteristics that could be incorporated into a prioritization scheme for technology selection and deployment plans.

1. Introduction

The growing demand for clean and reliable energy has stimulated renewed interest in nuclear energy. At the same time, cheaper natural gas places energy utilities under increasing pressure to improve the competiveness of nuclear plants. Designers of the new generation of nuclear plants therefore need to implement new ways to reduce operating and maintenance (O&M) costs to help offset capital cost.

To meet this challenge, the nuclear industry is expected to invest billions of dollars over the next 10–20 years in the implementation of new technologies for use in power plant upgrades, modernization, and new construction. It is generally accepted that the new generation of nuclear power plants (NPPs), especially designs such as integral pressurized water reactors, liquid-metal cooled reactors, sodium fast reactors, molten salt reactors, high-temperature gas-cooled reactors, and other advanced reactor designs, will make use of state-of-

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the-art technologies in many areas of the plant, including the control room and other work spaces [1]. However, the number of available alternatives is making it increasingly difficult to identify the most appropriate technologies, especially those that may affect, and be affected by, human performance requirements. These new technologies are also growing more complex and sophisticated, even though they are intended to simplify operations. In addition, experience using them in the nuclear industry is limited. However, the correct selection of technologies is not only vital to ensure operational safety and effectiveness, it could also create significant competitive advantages for utilities and ensure that they remain successful in the energy economy. For example, it is well-known how easily the old type of analog human–system interfaces (HSIs) could become a potential source of human error. There is ample evidence of the critical importance of well-designed HSIs from the accidents at Three Mile Island (1979) and Fukushima Daiichi (2011), both of which had inefficient analog HSIs. The influence of HSI accuracy and availability on operator response continue to be key factors in NPP event response and mitigation and this has become the source of many decisions to upgrade plant systems and control rooms [2,3].

Because most new reactor designs will employ first-of-a-kind (FOAK) technology (i.e., technology that has not been used in the older generation of NPPs), they have the opportunity to avoid the problems of outdated instrumentation and control (I&C) and HSIs: obsolescence, unavailability, costly maintenance, fixed locations, and so on. However, there are still significant risks associated with FOAK designs. These risks include challenges of integration, inadequate consideration of the changing role of the operator, coupled with the possible need to define new models of human–automation collaboration, the need for integrated system validation, new concepts of operation, and many more. Advanced technologies cannot be placed in the hands of the operator without considering how this will affect task performance and safety. This means that designers should be intimately familiar with the characteristics of technologies, not only individual devices, but also devices coupled, integrated, or interfaced with other new as well as older devices. An understanding of how the introduction of new technologies may affect operator behavior and performance is crucial to the success of an NPP development project in the short term, and the safe and efficient operation of the plant in the long term.

Although future plants may be highly automated, there is little doubt that humans will continue to play an important role. Advances in digital I&C and HSI technologies will significantly change the nature of the interaction between operators and the system, while having the potential to enhance human reliability and control room safety. It is also expected that those technologies will contribute to lower O&M cost by reducing the need for human control. However, there is still very little evidence in the nuclear industry regarding the use of this type of technology, or indeed their ability to reduce dependence on humans or sensitivity to human error. Even recent evidence from replica, simulated environments is not yet perceived as sufficient proof [2–4]. As a result, the anticipated benefits of these new technologies may not be realized for several years. This situation will be exacerbated by the current lack of guidance for the selection and implementation of these technologies for upgraded plants or new builds. This will be a significant challenge for design engineers and human factors analysts because implicit in the adoption of different automation strategies is a change in the role of operators, coupled with new concepts of operation. These changes have yet to be defined, but safety and reliability requirements will require that operators be able to intervene when necessary and otherwise oversee automation in most aspects of plant operation.

New HSI technologies such as large, high-resolution displays, handheld and wearable devices, and augmented reality systems are already being introduced into other industries and can be expected to become important options for the nuclear industry as well, especially for new builds. These new technologies offer human support capabilities unheard of in existing conventional nuclear plants and this represents just one of the important design changes that will make the next generation of NPPs unique. However, to exploit these capabilities, designers need to consider various trade-offs associated with alternative perceptual and interaction modalities such as touch, voice, and gesture interaction. Technology selection will require accounting for mental and physical demands imposed, not only by the characteristics of the device, but also by the physical workspace and collaborative functions among crew members. This implies that human performance and operational safety and effectiveness are the deciding factors in choosing technologies. This in turn means that there is a need for guidance to support new power plant requirements, in particular, levels of automation, computational intelligence, operator support systems, and other methods of reducing complexity, to optimize human–automation interaction. Because there is currently no generally accepted guidance for HSI technology selection for the nuclear industry, designers are most often at the mercy of vendors who are more likely to promote the technical and functional features of technologies. The few human performance criteria and measures that do exist are limited primarily to the control room and conventional devices. The lack of a classification scheme for operational contexts and human factors requirements for specific work domains further complicates the decision.

The shortcomings described are best alleviated by providing approaches that permit the selection of the best available technologies that can be qualified for system operation, upgrades, maintenance, and replacement. With appropriate guidance, designers will be able to exploit the new technology capabilities to achieve enhanced monitoring, improved situation awareness, reduced human error, reduced workload, and more efficient response planning, coordination, and communication among human teams, some of whom may be remotely located, and also between humans and sophisticated automation systems. Because of the broad application potential of advanced HSIs, even small improvements in efficiency across the application domains can yield significant benefits for human and system reliability, resilience, usability, and productivity. The approaches described in this paper are offered to help ensure that the most suitable HSI technologies can be identified and deployed, and that strategies for upgrade and replacement are sound and meet regulatory guidance.

2. Learning from others

Despite all the requirements that will be imposed on designers of a new generation of nuclear plants to verify and validate their choice of technologies, there is already ample evidence in other industries regarding the benefits of advanced technologies in specific work environments and operational contexts. These other industries can be a starting point for Human Factors Engineering (HFE) guidance that analysts in the nuclear industry produce. HSIs currently in use in other domains offer support for substantial improvement in the safety and economics of all NPPs. The new and upgraded power plants and associated facilities that are the subject of research at several U.S. national laboratories promise to be safer and more economical plants that will reach the market in the next decade in various countries. That is just one reason why the adoption of the approach for selecting HSIs described in this paper is a logical evolutionary step that may be used in advanced control room design that will be evident in small modular reactors and other advanced designs. Furthermore, designers cannot simply assume that any new technology would contribute to better safety or better human performance. Addressing issues of automation, function allocation, error reduction, and overall operator efficiency is still a major challenge.

The following five complementary strategies derived from the experience in various industries (health care, military, transport, oil and gas, etc.) would help designers to address those challenges over the project life cycle [5]:

1. Designers should be familiar with the functional and technical characteristics of HSIs with potential for a new generation of NPPs and the human factors considerations associated with them. For example, large, high-resolution overview displays in the control room and mobile devices in the field have the potential to improve situational awareness, communication, and collaboration. However, the technical and functional characteristics of devices might affect their usability in different operational contexts. This leads to the need for the next strategy:
2. New technologies should be characterized for the plant in terms of the context of use, that is, the actual conditions under which a given product is likely to be used by plant personnel in a variety of working situations and environments. The characterization includes definitions of operational scenarios, a taxonomy of the families of input, output and hybrid devices, the context of operator interaction with devices in diverse environments, and the human performance characteristics and requirements with selected devices under various operating conditions.
3. Design and implementation strategies for advanced HSI technologies should form part of a general strategy to integrate human factors into the systems engineering process.
4. Designers should be encouraged to make extensive use of simulation, test beds, and prototypes as cost-effective methods to provide proof-of-concept evidence of the appropriate use of advanced HSIs prior to acceptance. The level of fidelity required for such trials should match the design maturity of the new plant, that is, low fidelity during conceptual design, and high fidelity during detail design.
5. Understand typical future trends, that is, how technologies are likely to develop over the next 10–15 years and how this will affect design and maintenance choices for the nuclear industry.

3. Definition and purpose of advanced HIS

Future successful implementation of new technologies will largely be determined by how the term “Advanced Human–System Interface Technology” is defined. Characterization of new and advanced HSIs is difficult due to the very broad nature of the terms “advanced” and “new technology.”

The U.S. Nuclear Regulatory Commission's (NRC) review guidance on HSIs (NUREG-0700 Rev 2) defines the HSI as “that part of the nuclear power plant through which personnel interact to perform their functions and tasks. Major HSIs include alarms, information displays, controls, and procedures” [6]. This definition and its accompanying guidance is generally valid for HSIs currently in use, but it does not take into account the latest advances in HSI hardware and software and it also does not make a distinction between advanced and more conventional HSIs.

In an attempt to define the boundaries for the guidance described in this paper, the following criteria were therefore applied:

1. “New technology” means devices and systems that are new to the nuclear industry, or new to specific nuclear power utilities.
2. “Advanced” means relatively mature technology that has only recently reached technology readiness levels (TRLs) of 8 or 9, and is still relatively unknown and not yet generally accepted by either the utilities or the regulator, or both. (The relationship between “advanced” and “technology readiness” is described in more detail later in this paper.)

The primary purpose of the HSI is to provide the operator with a means to monitor and control the plant and to restore it to a safe state when adverse conditions occur. To perform this task effectively, it must support human capabilities and limitations including cognitive as well as physical aspects necessary for supporting performance. The implementation of devices that successfully accomplish this objective would also satisfy six important human performance goals that all contribute to the safe and efficient operation of the plant: (1) reduce complexity, (2) reduce error and improve human reliability, (3) improve usability, (4) reduce operator workload, (5) support low variance among users, and (6) improve situation awareness.

An HSI is by definition a cross-cutting technology, that is, most general-purpose HSIs can be used in any environment where a human needs to interact with a controllable process or device. All HSIs are designed to serve as interface between the human and the process, and therefore, the HSI can be described as the user's “handle” on the device, the “front end,” or the “affordance.” This assumes, of course, that the HSI is well-designed and matched to the capabilities as well as the limitations of the user. The same principle also applies to special-purpose HSIs, which include a wide range of state-of-the-art display and control technologies that may be deployed in conjunction with advanced sensors and instrumentation to satisfy the needs of current NPP modernization efforts as well as new NPP designs. The "handle" of devices in this environment can be as simple as a control panel with a number of buttons and physical controllers, or it can be as complex as a device that detects and translates the user's brain waves into discrete commands that control one or more processes or machines.

This emphasizes again the need for designers to fully understand the characteristics of the technologies and their intended application.

4. Development of HSI selection guidance

The primary purpose of this guidance is the successful integration of advanced HSIs in modernized and new NPPs. As described earlier, the focus is on new technologies that are either new design concepts or technologies associated with new industrial processes within nuclear power. The basic approach is to provide a framework for new technology selection that is generic enough to enable comparison of any type of HSI technology and associated concepts. Second, the criteria in the framework should be technology-neutral enough to be able to deal with a degree of uncertainty, but it can only be realistically applied when there is enough information available about the possible technologies to enable designers to at least make an educated guess about certain criteria for comparison.

The recommended selection scheme described in the following sections consists of the following four criteria groups:

1. HSI technical characteristics, including architecture and functions, technology readiness, and regulatory considerations;
2. Context of use (work domain context and operational context);
3. Usability; and
4. Human performance and human–system interaction.

These four criteria sections are based on a logical sequence determined by the level of detail of analysis and dependency. While human performance is the most important criterion, it does not stand alone and is dependent on, and influenced by all other criteria.

4.1. *HSI technology characteristics*

The HSI in older NPPs has always been a complex system, but it is possible to describe it in fairly simple terms as consisting of control boards, panels, gauges, switches, controls, alarm annunciators, and so on. The advanced main control room with its digital HSIs is now a system with many functions, components, and interfaces to other systems and environments. The advanced HSI is in fact a hierarchy of high- and low-level components. It is possible to describe this structure from different viewpoints, for example, it could be safety or nonsafety related, it could be used in operations or in maintenance, and so on. It is important that the characterization cover these different perspectives and contexts, some of which are covered in other criteria in the following section. The terms "human–system interface" and "human–system interaction" suggest that a technology-centric as well as a human-centric classification is possible. This approach makes it possible to distinguish three classes of technology:

1. *Output technologies* for visual or auditory perception. This technology class includes visual as well as auditory and haptic devices. The use of these devices ranges from situational awareness displays in the control room to procedural and diagnostic support for maintenance work in the field. Typical examples are large display panels, desktop displays, handheld devices (e.g., tablets featuring multitouch interaction), audio devices (headphones, radios), printers, and force feedback devices (e.g., vibratory alerts). These devices are well-established in various industries and technology readiness is typically at level 9 (see the "Technology Readiness Levels" section).
2. Electromechanical control devices for *providing input* to a system. Typical devices include the conventional mouse, keyboard, stylus, touch pad, and control panels, but also more advanced multimodal input technologies such as touch screens, voice recognition systems, or wireless remote controls (infrared, ultrasonic, laser). The operational context for these devices varies and could range from inside the control room to any environment inside and outside the plant. The typical use of the more advanced devices is likely to be for maintenance, diagnostic, and monitoring functions.
3. Hybrid devices overlap both of the two classes because they *combine input as well as output* and provide a wide range of multimodal interaction options. Typical devices include multitouch tablets, smartphones, radios, touchscreens, gesture devices, barcode scanners, testing equipment, heads-up displays, augmented reality devices, etc. Many of these devices (e.g., tablets, smartphones, and wearable computers) are already in common use in various industries. They are especially suitable to support hands-free operations such as fieldwork requiring access to procedural or technical information while performing a task. However, more sophisticated devices such as head-mounted displays and augmented reality devices are still experimental and typically suffer from usability problems. They are still cumbersome and suffer from loss of "big picture" due to loss of peripheral visual cues. They also compete with other visual requirements. Some of these devices are still at a TRL 8 or even 7, and require careful consideration before they are implemented (see Hugo [7] for a more extensive discussion of advanced devices).

4.1.1. *HSI architecture and functions*

To reduce the complexity of the multidimensional structure of HSIs, a taxonomy was developed that explains the levels of the HSI physical architecture and the functional relationships between the devices at various levels. This serves as a reference to guide I&C designers and human factors engineers in their analyses and designs.

The taxonomy consists of two sections: the physical architecture and the functional architecture of the HSI. Because of space constrains, the full taxonomy could not be included here, but the readers can refer to Hugo [7] for the full list.

- The *physical architecture* includes the operating environment (control rooms and other workspaces as described in the "Work Domain Context" in the following section) and all the hardware within it. These physical components make it possible for the operating crew to perform all necessary tasks in the work environment:
    1. Physical work areas and control centers
    2. Input devices
    3. Output devices
    4. Hybrid input/output devices
- The *functional architecture* identifies the main HSI functions
    1. Plant, system, and process monitoring
    2. Process and system control (hard and soft controls)
    3. Alarm response
    4. Event recovery
    5. Procedure following
    6. Condition diagnosis
    7. Communication (operations, management, maintenance, grid)
    8. Routine reporting
    9. Exception reporting
    10. Other support functions

4.1.2. *Technology readiness levels*

Although there may be different approaches to determining the suitability of HSI devices, one of the most effective ways of evaluating devices considered for implementation in the control room or in the plant is to determine their status in terms of the U.S. Department of Energy's definition of TRLs. Technology readiness assessment aims to evaluate the proposed technology's maturity against a set of requisite technical, programmatic, and manufacturing indicators identified from relevant literature and experts to enable a successful and accelerated transition of the existing technologies from conceptualization, discovery, and development to eventual deployment [8].

There are nine levels, from TRL 1, where scientific research begins to be translated into applied research and development, to TRL 9, where the actual application of technology is in its final form and facilities, structures, systems, and components have been successfully operated for an acceptable amount of time. In general, it is not likely that any advanced HSI that has not reached at least TRL 8 would be considered for use in the nuclear industry, even for experimental purposes. It is possible, however, that a laboratory may consider TRL 7 devices (i.e., prototypes or near-operational systems) for research and demonstration purposes.

There is often risk associated with the adoption of new technology, and technology readiness assessment also provides the basis for risk assessment and uncertainty quantification. The recent consensus in various industries is that higher levels of technology readiness present lower risk, or at least lower perceived risk [9]. However, designers should not underestimate the challenge and possible subjectivity that can exist in assigning readiness levels. For example, the various subsystems comprising a system can have different TRLs and where significant impact on plant design is expected, it may be necessary to conduct a probabilistic risk assessment coupled with extensive field tests.

4.1.3. *Regulatory considerations*

Current NRC regulations were developed to support traditional large NPP light water reactor designs. Current requirements related to the human role in the plant deal primarily with avoiding human error and improving human reliability in normal and abnormal operational conditions. This includes requirements for control room staffing, criteria for evaluation of HSIs, and conducting human factors engineering activities in the power plant.

Although current NRC guidance such as NUREG-0800 [10], NUREG-0711 [11], and NUREG-0700 [6] provides a general framework for conducting design-specific reviews, the review of control room and HSI designs is expected to be challenging for future plants that plan to use advanced HSIs. This is because of the differences between the new reactor designs and previously licensed reactor designs, and also because of a lack of research and design data to provide an adequate technical basis for decisions. A starting point for the designer will be to identify tasks that could substantially affect operator workload and how these could be supported by advanced HSIs. Of particular importance will be new NRC requirements for minimum inventory, that is, the minimum number of indicators and controls needed for the operator to maintain situation awareness during upset conditions.

For the human factors engineer it is essential to resolve regulatory issues regarding the use of new HSIs as early as possible. This can only be accomplished through the development of appropriate Human Factors (HF) guidance. Supported by this guidance, it will be possible for designers to achieve an early resolution in HSI selection and to incorporate appropriate changes during the development and maturation of operational concepts, designs, task analyses, and staffing plans before submitting a design review or license application. This guidance will also support the NRC staff's review of the design and license applications.

4.2. *Context of use*

The nature of HSIs can be better understood if they are characterized in terms of the context of use, that is, the variety of actual working situations and environments under which a given product is used. This applies to HSIs intended for modernization as well as for new advanced reactor applications.

A clear definition of the context of use helps to determine unambiguous classifications of HSIs, which, in turn, help in the design and selection of technologies. This implies that the operator's interaction with devices under defined operational conditions must also be accounted for in the design and selection of advanced HSIs. A clear understanding of the aggregation of all these conditions helps to simplify the problem space.

The HSI technologies that designers will consider can be defined and classified in terms of two dimensions or contexts: the work domain and the operations performed within that domain:

4.2.1. *The work domain context*

The work domain context as described by Lintern [12], Naikar [13], and Vicente [14] focuses on the physical, structural, logical, or functional characteristics that distinguish different areas in the plant where work is performed and where humans interact with technology.

We suggest that when considering the communication, mobility, and general performance needs of workers in upgraded and new plants, nine distinct work domains can be identified where advanced HSIs will play an important role. Some of these are dedicated and enclosed areas; other areas inside or outside the plant have variable boundaries within which functions are performed:

1. *Main control room:* This is an enclosed area, often in close proximity to the reactor and turbine building.
2. Local control stations throughout the plant, typically consisting of one or more small control panels.
3. *Materials and waste fuel handling:* Forklifts, cranes, and similar tools are typically found in these domains.
4. Refueling operations, using specialized equipment to handle radioactive materials.
5. Outage control center, characterized by many desktop computers, large displays, printers, planning boards, and communication equipment.
6. Fuel processing installations, characterized by specialized equipment to handle hazardous materials, such as robotic manipulators.
7. *Technical support center*. This center is typically somewhere on-site and, like the outage control center, would have large displays, but also limited HSIs that provide access to some of the displays found in the control room.
8. *Emergency operations facility*. This facility is located at a more remote location outside the plant perimeter and would also have access to data from the control room.
9. Maintenance facilities inside and outside the plant, using a range of conventional and specialized tools.

Most of these work environments have a greater or lesser degree of interdependence (Fig. 1).

4.2.2. *The operational context*

As indicated before, the primary purpose of the HSI is to support the human user in any operational condition, that is, it must be usable for its assigned function during all plant operating modes such as start-up, shutdown, refueling operations, maintenance, and plant disturbances. The plant disturbances include anticipated operating occurrences (e.g., reactor scram, turbine trip, or loss of off-site power), design basis events (e.g., accident conditions such as steam generator tube rupture or large pipe break), and beyond design basis events (e.g., emergency conditions leading to radioactive releases and injury to workers or public). This context includes the tasks of the operator under those conditions, the environmental characteristics of the situation in which HSIs are used to operate the plant, and the use of procedures corresponding to the plant condition or the nature of the evolution.

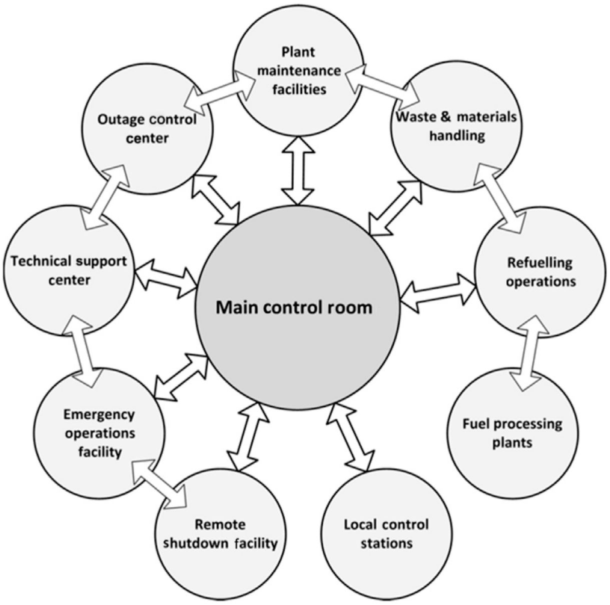

Fig. 1 – Human–system interface work domains in a typical large nuclear power plant. *Note*. From “Human-system interfaces in small modular reactors,” by J. Hugo, 2015, M. Carelli, D. Ingersoll (Eds.), *Handbook of Small Modular Reactors*, Woodhead Publishing, London (UK). Copyright 2015, *Elsevier*. Reprinted with permission.

4.3. *HSI usability criteria*

One of the most comprehensive methods to evaluate the usability of a device for an operational task is to apply the framework offered by ISO 9241-306:2008, which was originally numbered 9241-11 and titled “Guidance on Usability” [15]. This standard helps the designer to define usability in terms of the “safety, effectiveness, efficiency, and satisfaction with which a specific user can use a specific system in a defined context.” This approach would also require us to define “safety, effectiveness, efficiency, and satisfaction” in more precise human factors and contextual terms. That is, analysts could identify measures, assess the usability, and possibly compare between different options (“safety” is not regarded as a separate attribute, but rather as an outcome of the correct application of the other three attributes; in other words, a highly usable system helps to prevent adverse consequences in the event of user error or system malfunction). Usability assessment is thus an important tool to help identify where particular technologies might either provide benefits, or introduce problems from the user's perspective.

Designers should keep in mind that all advanced HSIs are supported by a software component that in itself represents advanced technology. This is especially important from an integration and interoperability point of view, because the main characteristic of a new HSI software platform in an NPP is that it will typically form part of the plant's distributed control system (DCS) software. The DCS is the system that is used for overall plant I&C integration and automation and the HSI forms part of the "front end" that enables the operator to interact with the plant through a hierarchy of controls and displays. This means that the entire integrated system should be subjected to usability evaluation.

The three attributes are defined as follows in the standard:

- *Effectiveness*: The accuracy and completeness with which users achieve specified goals.
- *Efficiency*: The resources expended in relation to the accuracy and completeness with which users achieve goals.
- *Satisfaction*: Freedom from discomfort, and positive attitudes toward the use of the product.

From this definition, it is now possible to examine the usability attributes and requirements of the technologies identified in the "HSI Architecture and Functions" section. All features of devices should be tested for effectiveness, efficiency, and satisfaction in the natural setting where they will be used, for example:

- The device must be accessible during all task-related operational conditions.
- Displays must be readable under all task-related environmental conditions (sunlight or other ambient lighting).
- The device must be usable for people wearing gloves, sweaty hands, etc.
- The device must be portable with ease when it needs to be carried by users.
- The design of the device must prevent error, damage, and injury.
- Use of the device must not interfere with safe operations or other tasks.
- Behavior when the device runs out of battery power or if the power is interrupted must be consistent with user expectation (e.g., provide a timely warning for almost empty battery, easy access to recharging facilities).
- If the device needs to be set up/installed, especially by untrained users, this phase should be tested prior to deployment.

The different contexts described before suggest that there will be significant variability and uncertainty when a new HSI device is considered for implementation in the plant. The fact that it might have been successfully applied in other environments is no guarantee that it will be successful in the target domain. This implies that it is often necessary to field test the device to verify its performance in a specific environment and operational condition. The National Institute for Standards and Technology has developed a tool named "System, Component and Operationally Relevant Evaluations (SCORE)" that can be used to test technology.

Fig. 2 illustrates the SCORE framework for technology evaluation. In this figure, the "value/usability assessment" dimension corresponds with the "utility" dimension described by Weiss and Schlenoff [16,17] where it refers to the value of the system to the user and includes usability assessment of attributes such as attitudes, flexibility, and learnability. This means that, to obtain an accurate impression of how a system will perform in the field, it is to be evaluated at the component

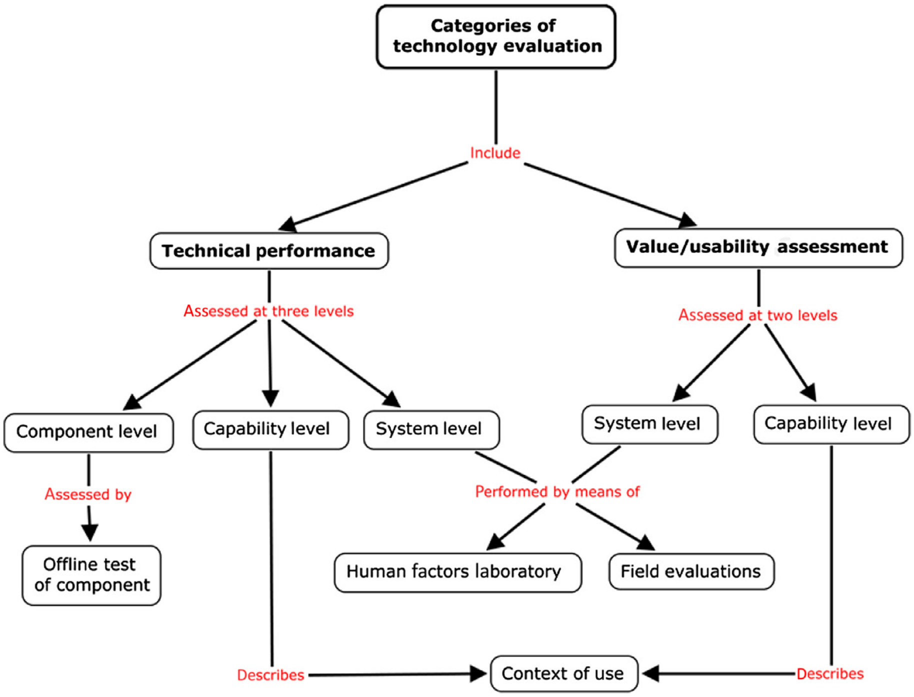

Fig. 2 – The System, Component and Operationally Relevant Evaluations emerging technology testing method. *Note*. From "Applying the system component and operationally relevant evaluation (SCORE) framework to evaluate advanced military technologies," ITEA Journal 2010; 31: 112–120. © 2010 by the International Test and Evaluation Association.

level, capability level, system level, and in an operationally relevant environment. This is indicated in Fig. 2 as "context of use," which could be regarded as an extension of the contexts described before.

Although SCORE represents a potentially useful approach to technology evaluation, we have not validated the framework in practice and do not necessarily endorse it as practical and useful in the contexts described in this paper.

4.4. *Human performance and human–system interaction*

Any of the operations or actions described in the previous section is performed by either a physical system, a human operator, or a collaborative combination of systems and humans. The physical objects would be any structure, system, or component, whereas the humans could be reactor operators, fieldworkers, maintenance technicians, etc. Each of the human workers could be characterized in terms of physical and cognitive abilities and limitations and assigned role.

It must be emphasized again that, although human performance is regarded as the most important decision factor before implementing new technologies, this cannot be assessed in isolation; all other criteria described here will ultimately influence human performance, and therefore, this whole scheme should be applied in the process of selecting HSIs. In addition, achieving these objectives requires a rational human–system function allocation and development of operator interfaces that would support accurate perception of and control over plant processes and systems, while also improving reliability and performance. With advanced plants, there is a high degree of complexity and associated data and information that, if not presented in a proper and meaningful way, can contribute to poor situational awareness. If the crew does not know how to navigate the system to find the right data, particularly during off-normal events, then stress, confusion, and error are likely to result.

Because implementation of some advanced technologies is not likely to significantly impact control rooms within the next 15 years, it is difficult to specify how interaction modalities such as voice actuation, augmented reality, and touch and gesture interfaces should be integrated to maintain or replace the benefits of pattern recognition supplied by alarms and other indicators in various locations on the control boards. One of the challenges for implementation of advanced HSIs in the short and longer term is to ensure that it supports collaboration and not implemented solely with the performance requirements of a single operator in mind. All advanced designs in one way or another will reduce, but not eliminate, the crew as a key operational element. Therefore, the implementation of advanced HSIs must also seek to support this collaboration. This is particularly important with devices such as large overview displays currently being promoted as collaborative workspaces.

To provide a human performance perspective to the selection of HSIs, a number of contributing factors must be addressed, including the following:

- The organizational mission and purpose of the plant (e.g., safe and economical production of electricity).
- The technical characteristics of the specific process (e.g., generation of nuclear heat, cooling and heat transport by means of liquid metal, conversion of thermal energy to mechanical energy).
- Environmental conditions of the process environment (temperature, noise, vibration, etc.).
- The level and qualifications of staff required for normal and abnormal plant conditions.
- Human–system function allocation and level of automation.
- Physical and cognitive workload (e.g., manual materials handling, or need for complex decision making).
- The technical, functional, and usability characteristics of HSIs that will be used.

Human performance can often be improved by removing, where possible, conditions or artifacts that negatively affect task performance, and by providing means to improve performance. For example, the mental and physical workload of the operator could be reduced and situation awareness could be improved by advanced HSIs that offer the following three major types of human–system interaction:

1. Just-in-time support that offers advanced features, such as the following:
    - Task support for all operational conditions, but especially nonroutine conditions that require dependence on long-term memory and performing little-used procedures. The most important feature would be the organization of the whole HSI as an operator-centric or task-based system with embedded operator support, including various levels of computer-based procedures. Because of the inherent complexity of advanced automation systems, the HSI must support intuitive navigation through a display architecture derived from a proper task analysis, coupled with a functional breakdown and rational function allocation.
    - Error-tolerant and resilient operation, adaptive automation schemes, and integrated multimedia communication;
    - Reduced visual and cognitive HSI complexity, for example, by intuitive information navigation schemes, abstraction hierarchies, and searchable technical and operational references and examples;
    - Cognitive support, such as diagnostic tools and data mining functions. This could also include expert operational advice and coaching on an as-needed basis, and procedural support such as modular computer-based procedures;
2. *Multimodal interactions:* Interaction with the work environment is possible through different, complementary senses (vision, hearing, touch), for example, touch screens, gesture interaction, speech recognition and synthesis, haptic input and output (i.e., technologies that use touch and tactile feedback to enhance human–system interaction), and even direct body–machine interfaces (biosensors). Advanced display and interaction features already commercially available or under development in mostly other industries make use of handheld devices, head-mounted displays, large overview displays, three-dimensional displays, and motion and position tracking.

To support such extensive interaction capabilities, the whole system is typically driven by high-performance processors for demanding applications such as high-resolution displays and computationally intensive applications such as real-time processing and trending of large amounts of plant data.

3. More sophisticated automation technologies are also emerging that in future will offer automated tools and functions embedded in the HSI and automation system, for example, intelligent software agents and predictive simulations that will enable operators to run "what-if" scenarios in preparation for event response.

A reliable method to measure the effect of these contributing factors on operator and team performance is provided by the Human Performance Process Evaluation Support System model [18,19]. This method evaluates six categories of measures to determine the impact on plant and human performance in the various operational contexts described earlier: plant performance requirements, operator task performance, cognitive workload, situational awareness, teamwork, and physiological factors (ergonomics and environment).

5. Practical application of the selection criteria

Typical examples of new technology for consideration in control rooms include digital control systems with a corresponding upgrade or change in the operator interface. Current efforts in the United States include modernization of existing control rooms where systems are being upgraded one by one, for example, turbine control system, feedwater system, alarm system, computerized procedures. A recent example is found in the International Atomic Energy Agency 2008 review of the Westinghouse AP1000 [20]. This design features some novel technologies and specific aspects of the design philosophy, including computerized procedures, soft controls, flexible methods of information presentation, the use of automated devices and robotics in support of maintenance, and wireless communications systems.

Many of the advanced designs mentioned in this paper have not yet migrated or are not likely to migrate soon from moderate maturity levels to acceptability for the control room. Large-screen displays are one of the technologies that, in our opinion, are most likely to be introduced first. The newer Korean-designed P1400 plants being planned for the United Arab Emirates incorporate this design feature. Flexible information presentation in the form of information-rich displays is being spearheaded by the design group at the Halden Reactor Program in Norway, and this information presentation model may be adopted in U.S. plants beginning first with nonsafety grade systems. However, operational guidelines for the use of the large screen as an organizing concept are scarce at best.

The selection process for designs that use familiar reactor technology is still relatively straightforward. However, the decision challenge is very different for an FOAK design. A simple hypothetical scenario will illustrate the practical application of this HSI selection method:

A nuclear engineering company is in the process of designing a reactor in which the primary coolant and the fuel itself is a molten salt mixture. There is minimal precedent for this kind of reactor, and therefore, the plant is considered a Generation IV AdvNPP. It will make extensive use of passive safety features and high levels of automation for most of its processes. This implies that there will be an important change in operational concepts and the traditional role of the control room operator. Under normal operating conditions, there will be little for the operator to do, except to monitor the status of the plant and its systems. Only when the automation system does not perform as expected will the operator be required to intervene.

The designers of this reactor know intuitively that analog HSIs that were common in older power plants cannot be used for this plant. The plant processes require a hierarchical DCS with a high level of integration, intelligent processing, and information aggregation at various levels. This requires HSIs that simplify the complexity of the plant and its systems, while still allowing the operator to know exactly how the plant is performing at all times. The designers realize that there are many factors to consider, in conjunction with the normal engineering process. They therefore implement an analysis and decision-making process as an integral part of the systems engineering process (Table 1).

An examination of the current state-of-the-art of emerging I&C and human interface technologies reveals improved reliability and resilience, greater precision in both control and monitoring, lower cost, easier maintenance, and reduced need for human operators for functions that can be achieved more efficiently through automation. In our opinion, the nuclear industry has yet to reap the full benefits of advanced technologies. It is generally accepted that modernization of existing power plants, and especially the design of FOAK plants, will require the use of technologies that are not common in the current fleet of reactors, many of which are older than 40 years. Current engineering practices typically do not provide for a human-centric approach to the classification of HSI technology. In addition, existing human performance criteria are limited primarily to the control room and conventional devices, and no formal guidance and decision criteria are available for technology selection. The lack of well-defined selection criteria hampers designers in their ability to ensure that displays and controls and "smart systems" adequately support operator job requirements and ensure operational safety. Guidance is also needed for higher-level operational and human performance issues, such as ensuring that chosen technologies support situation awareness, contribute to reduction of workload, and support balanced task allocation. Operational definitions and acceptable metrics for these technology attributes in support of optimizing human–system interaction also need to be determined. These definitions and metrics should be based on a combination of operating experience, human factors-based technology evaluations, training simulator trials, empirical field studies, and made available to the design community.

In response to this challenge, this paper described the basic principles and a framework for characterizing advanced HSI technology in relation to the human factors and contextual

Table 1 – Analysis and decision-making process in systems engineering process.

Phase	Method	Result
1. Trade study	Identify available technologies in three classes: input, output, and hybrid. Select only devices that are at least at TRL 8, but with high preference for TRL 9. Identify regulatory requirements that may affect technology choices. Develop an item list of technical characteristics for consistent categorization of technologies.	List of potential display devices for control room control desks and group view, portable and wearable devices for fieldwork, communication, monitoring, supervisory, and surveillance functions. List of potential devices for control of systems, including devices for all operator control desks, supervisors, maintainers, etc., and any regulatory requirements.
2. Contextual analysis	Identify and define all operational domains in terms of plant mission, purpose, measures of performance, and measures of effectiveness. Identify conceptual role of personnel in the various domains. Revisit list of potential devices and classify them in terms of target application domain (control room, field, etc.). Prioritize and rank all devices in all domains in terms of TRLs and operational objectives.	Prioritized list of identified technologies in various operational domains with list of personnel who will potentially be using the devices.
3. Usability analysis	Select the highest ranked devices and conduct usability tests to determine compliance with the common human factors criteria (see the "HSI Usability Criteria" section).	Prioritized list of technologies that comply with usability criteria.
4. Human performance requirements	Conduct a preliminary high-level task analysis to confirm the anticipated role of operational staff and generic human performance requirements in the target operational domains. Review results of Phases 1, 2, and 3 and consolidate with results of preliminary task analysis.	Summary of human performance requirements for each operational domain, including list of the most likely HSIs to be used for various generic tasks (e.g., monitoring, control, event response, surveillance, maintenance).
5. Field tests and verification	Conduct field tests in representative environments to verify human as well as system performance requirements. Where noncompliance is found, repeat previous phases as necessary.	Verification of performance requirements of selected devices as basis for request of approval for implementation from all engineering disciplines.

*TRL, technology readiness level.

aspects that would influence technology selection for NPPs. The potential benefits of this method are manifold: it would enable designers to make informed decisions that would reduce costly error and rework during the engineering process. This will ultimately allow optimization of human and system performance to levels unheard of in existing power plants. This includes enhanced monitoring, improved situation awareness, reduced human error, and reduced workload.

The paper also described a number of criteria that will have a significant influence on the successful implementation of advanced technologies. However, the limitation of this framework is that more field trials are needed to establish baselines and benchmarks that would formalize the criteria for specific application environments and project requirements. Nevertheless, experience gained to date in the application of these concepts in the U.S. nuclear industry suggests that there is a strong need for practical human factors guidance and implementation plans for technology selection and deployment. There are also indications that, due to the rapid development of technology, this effort should be ongoing and the guidance should be updated continually. This need will be the subject of follow-up research that will address development of a more formalized taxonomy with detailed criteria, and a detailed application case study.

Conflicts of interest

All authors have no conflicts of interest to declare.

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REFERENCES

[1] World Nuclear Organization [Internet]. Advanced Nuclear Power Reactors, World Nuclear Organization, London (UK), 2014 [cited 2015 Oct 21]. Available from: http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Power-Reactors/Advanced-Nuclear-Power-Reactors.

[2] J.V. Hugo, R.L. Boring, L. Hanes, O. Berg, M. Gibson, Functional Requirements Analysis (FRA) and Function Allocation (FA): Brunswick and Harris Plant Process Computer (PPC) and Turbine Control System (TCS) Modernizations (Project Report No. INL/MIS-13–28084), Idaho National Laboratory, Idaho Falls (ID), 2013.

[3] J.V. Hugo, R.L. Boring, L. Hanes, K. Thomas, A Reference Plan for Control Room Modernization: Planning and Analysis Phase (Project Report No. INL/EXT-13–30109), Idaho National Laboratory, Idaho Falls (ID), 2013.

[4] R.L. Boring, J.R. Lewis, T. Ulrich, J.C. Joe, Operator Performance Metrics for Control Room Modernization: A Practical Guide for Early Design Evaluation (Project Report No. INL/EXT-14–31511), Idaho National Laboratory, Idaho Falls (ID), 2014.

[5] J. Hugo, D. Gertman, M.S. Tawfik, Development of Human Factors Guidance for Human-system Interface Technology Selection and Implementation for Advanced NPP Control Rooms and Fuel Cycle Installations (Project Report No. INL/EXT-13-30118), Idaho National Laboratory, Idaho Falls (ID), 2013.

[6] J. O'Hara, J. Brown, P.M. Lewis, J. Persensky, Human System Design Review Guidelines (Regulatory No. NUREG-0700), Nuclear Regulatory Commission, Washington, DC, 2002.

[7] J. Hugo, Human-system interfaces in small modular reactors, in: M. Carelli, D. Ingersoll (Eds.), Handbook of Small Modular Reactors, Woodhead Publishing, London (UK), 2015.

[8] D.W. Engel, A.C. Dalton, K. Anderson, C. Sivaramakrishnan, C. Lansing, Development of Technology Readiness Level (TRL) Metrics and Risk Measures (Technical Report No. PNNL 21737), Pacific Northwest National Laboratory, Washington, DC, 2012.

[9] S. Mathews, Valuing risky projects with real options, Res. Technol. Manage 52 (2009) 32–41.

[10] Nuclear Regulatory Commission, Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition (Regulatory No. NUREG-0800), Nuclear Regulatory Commission, Washington, DC, 1981.

[11] J. O'Hara, J.C. Higgins, S.A. Fleger, P.A. Pieringer, Human Factors Engineering Program Review Model (No. NUREG-0711 Rev. 3), Nuclear Regulatory Commission, Washington, DC, 2012.

[12] G. Lintern, Work-focused analysis and design, Cogn. Technol. Work 14 (2010) 71–81.

[13] N. Naikar, Work Domain Analysis: Concepts, Guidelines and Cases, CRC Press, Boca Raton (FL), 2013.

[14] K. Vicente, Cognitive Work Analysis: Toward Safe, Productive, and Healthy Computer-based Work, first ed., CRC Press, Boca Raton (FL), 1999.

[15] International Organization for Standardization, Ergonomics of Human-system Interaction—field Assessment Methods for Electronic Visual Displays (International Standard No 9241-306), International Organization for Standardization, Geneva (Switzerland), 2008.

[16] C. Schlenoff, Applying the system component and operationally relevant evaluation (SCORE) framework to evaluate advanced military technologies, ITEA J. 31 (2010) 112–120.

[17] B. Weiss, C. Schlenoff, Evolution of the SCORE framework to enhance field-based performance evaluations for emerging technology, in: Proceedings of PerMIS'08, ACM, Gaithersburg (MD), 2008.

[18] J.S. Ha, P.H. Seong, Development of human performance measures for human factors validation in the advanced MCR of APR-1400, IEEE Trans. Nucl. Sci. 54 (2007) 2687–2700.

[19] J.S. Ha, P.H. Seong, HUPESS: human performance evaluation support system, in: P.H. Seong (Ed.), Reliability and Risk Issues in Large Scale Safety-critical Digital Control Systems, Springer, London (UK), 2009, pp. 197–229.

[20] IAEA/HSE, IAEA Generic Review for UK HSE of New Reactor Designs against IAEA Safety Standards (Regulatory Review), International Atomic Energy Agency, Vienna (Austria), 2008.