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Multi-unit Operations in Non-nuclear Systems: Lessons Learned for Small Modular Reactors

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ABSTRACT

The nuclear-power community has reached the stage of proposing advanced reactor designs to support power generation for decades to come. Small modular reactors (SMRs) are one approach to meet these energy needs. While the power output of individual reactor modules is relatively small, they can be grouped to produce reactor sites with different outputs. Also, they can be designed to generate hydrogen, or to process heat. Many characteristics of SMRs are quite different from those of current plants and they may be operated quite differently. One difference is that multiple units may be operated by a single crew (or a single operator) from one control room. The U.S. Nuclear Regulatory Commission (NRC) is examining the human factors engineering (HFE) aspects of SMRs to support licensing reviews. While we reviewed information on SMR designs to obtain information, the designs are not completed and all of the design and operational information is not yet available. Nor is there information on multi-unit operations as envisioned for SMRs available in operating experience. Thus, to gain a better understanding of multi-unit operations we sought lessons learned from non-nuclear systems that have experience in multi-unit operations, specifically refineries, unmanned aerial vehicles and tele-intensive care units. In this paper we report the lessons learned from these systems and the implications for SMRs.

Key Words: human factors engineering, small modular reactors, safety reviews

1 INTRODUCTION

Small modular reactors (SMRs) are a promising approach to meeting future energy needs. Although the electrical output of an individual SMR is relatively small compared to that of typical commercial nuclear plants, they can be grouped to produce as much energy as a utility demands. Furthermore, SMRs can be used for other purposes, such as producing hydrogen and generating process heat. Many characteristics of SMRs are quite different from those of current plants and may be operated quite differently. The U.S. Nuclear Regulatory Commission (NRC) is examining the human factors engineering (HFE) and the operational aspects of SMRs. Our main objective is to identify potential issues in human performance related to the design and operations of SMRs. These issues have been previously discussed (O'Hara et al., 2010; O'Hara et al., 2012). One important issue identified is the operation of multiple SMR units from a single control room and possibly by a single operator. While we reviewed information on SMR designs, the designs are not completed and all of the design and operational information is not yet available. Nor is there information on multi-unit operations as envisioned for SMRs available in operating experience. Thus we examined several non-nuclear systems where multi-unit operations are performed. Although there are important differences between SMRs and these surrogates, there also are similarities that afford us an opportunity to learn about the design and operation of multiple units, and the resulting demands on human performance.

2 LESSONS LEARNED FROM NON-NUCLEAR SYSTEMS

In this section, we will review the lessons learned from surrogate systems to gain a fuller understanding of potential HFE issues related to SMRs. Information about the surrogates came from a variety of sources including published literature, site visits, and conference calls. In addition, we visited selected facilities to observe and discuss multi-unit operations and related challenges with their staffs.

2.1 Unmanned Aircraft Systems

Unmanned aircraft systems (UASs) consist of an unmanned aerial vehicle (UAV) and the operators located in a remote control room to undertake meeting the goals of flight and mission operations. Perhaps the best known UAS to the general public is the Predator; equipped with various sensors and payloads, it is used extensively in military operations. Although some UASs are fully autonomous, most of them are flown remotely by crews of varying sizes from control rooms where the vehicle is monitored and controlled at workstations that support mission planning, navigation, aircraft control, and management systems. A two-person crew operates the Predator.

In 2005, the U.S. Department of Defense (DoD) published a UAS Roadmap (DoD, 2005) offering their vision of UAS operations over the next 25 years; the overall goal is to expand their use to new missions and identify the capability infrastructure needed to accomplish them. One such future direction is "multi-vehicle control" i.e., to change the ratio of crew members to vehicles from many-to-one to that of a single person controlling multiple aircraft (one-to-many).

In general, the DoD's goals for UASs is analogous to those of SMR designers: To reduce staffing requirements, in part, through increased automation. The DoD initiated a research program to address the technological developments needed to change the operator-vehicle ratio, and to detail its impact on mission and human performance. The approach being taken to meet this goal may offer lessons learned for SMR operations.

We reviewed the UAS literature, concentrating on the DoD's efforts to achieve their vision for UASs, especially the operator-vehicle ratio. We supplemented the research literature with information gleaned from discussions with DoD personnel from the U.S. Army Research Laboratory (ARL). They provided information on their unmanned-vehicle research, developmental efforts, and field experience. The ARL team has published many articles, and two have noteworthy summaries (Barnes & Jentsch, 2010; Barnes, Jentsch, Chen, Haas & Cosenzo, 2010).

In this paper we summarize the results. The reader is referred to the full report for detailed information (O'Hara et al., 2012). We organized the results into the following aspects of UAS design and performance: UAV team characteristics, automation design, task allocation to crew members, HSI design and performance measures.

<u>UAV Team Characteristics</u>

A principal objective of much of the research was to investigate the size of the UAV team (i.e., the number of UAVs), its impact on performance, and technologies for enabling operators and crews to manage large teams of UAVs. This is a major factor of interest to our work since team size is analogous to number of SMR units that an operator manages.

Nearly all studies found notable effects of team size. As the size of the UAV team increased, task performance declined and workload rose. It also impacted other factors such as vehicle "neglect," which rose as team size increased. "Neglect" means that a vehicle is underutilized or ignored. Another important characteristic of teams is their degree of team homogeneity; generally, as the differences between the vehicles in the teams increased, it becomes more difficult for operators to manage.

Automation Design

Automation is deemed a key enabling technology for increasing team size. The aspects of automation examined are summarized below.

Functions automated - The studies reviewed verified the successful application of automation to a variety of UAS functions, such as vehicle monitoring and control functions. More abstract functions, such as mission coordination (supervision), are more difficult to automate.

Level of automation (LOA) - Many studies considered the LOA; i.e., the degree to which a function is automated ranging from no automation (manually performed by personnel) to full automation (no direct personnel involvement). In general, increasing the LOA led to better task performance. However, the effects were not universal for all measures (discussed further under performance measures below).

Static versus flexible LOA - LOAs can be implemented statically or flexibly. When "static," the LOA never changes. When flexible, the LOA changes based on situational considerations, such as personnel's overall workload. The latter is called adaptive automation (AA). Static LOA frequently did not significantly impact workload or SA, though most studies did not evaluate SA. AA was associated with better task performance and lower workload. Increasing the automation options available to operators may have helped them manage their workload.

Transparency of automation's processes - Increasing the transparency of the processes of automation proved an important factor supporting the ability of operators to understand its workings. To assure its optimization, communication features should be and inherent part of the HSI allowing operators to interact with automation to better understand its behavior.

Automation's reliability - In general, lower reliability led to declines in task performance, and a lower level of operator trust in the automation. Because the reliability of real-world systems is imperfect, their effect on operator- and system-performance is a major consideration.

Cummings et al. (2007) cautioned against over-automation; namely, it is not a good strategy to automate anything that can be due to human-performance concerns associated with high degrees of automation. Determining when and how to automate is the key consideration to success. ARL researchers echoed this same consideration, stating that their experience shows that some higher-levels of automation may be difficult to achieve. Cummings expressed the same concern about automating mission-planning functions that depend on decision making, judgment, and experience. Thus, there are both technical concerns (difficulty automating a function) and HFE concerns (negative effects on operators of high-levels of automation) that set constraints on the achievable crew-vehicle ratio.

Task Allocation to Crew Members

Performance was affected by task allocation between crew members. It was better when specific UAVs were assigned to specific crew members rather than shared between them. Lee et al. (2010) postulated that sharing diffused responsibility, leaving some vehicles underutilized (neglected); i.e., each crew member thought the other was responsible. Thus, an alternative explanation may be that, in the sharing condition, the operators were not effectively functioning as human teams, and did not clearly allocate their tasks or maintain awareness of each other's responsibilities.

HSI Design

The design of the HSI is a key factor. The HSI should incorporate communication features enabling operators to better understand the automation's processes. Other important considerations for HSI design include:

- providing HSI features so operators can effectively monitor multiple UAVs and gain accurate situation awareness (SA)
- managing the workload for coordinating and controlling multiple vehicles, e.g., via using intelligent agents and of predefined "plays"
- managing the interface management workload because high workload can lead to the operators' disuse of automation, and can distract them, thereby impairing their performance

Performance Measures

UAS research illustrated the importance of performance measures. Measures of primary task performance must be selected carefully. Many studies found effects on one performance measure but not another. Thus, important aspects of the primary task should be measured to avoid the possibility of committing a Type 2 error, i.e., failing to identify significant effects when they exist.

Designers and researchers should carefully choose measures that are sensitive to the expected variations in performance. That is, the measures selected should avoid floor and ceiling effects. For example, in studying the effects of automation on search and rescue task performance, primary task measures might include number of targets retrieved and response time. If most operators retrieve all the targets, then that measure will not be sensitive to changes in automation. Thus the measure will exhibit a ceiling effect, in which case, response time may be a more sensitive one.

The studies also illustrate the need for comprehensive performance measures that encompass primary task measures, and measures of SA, workload, and trust. These cognitive measures were found to be viable constructs essential to understanding and predicting human-system performance in complex systems, especially those employing extensive automation (Parasuraman, Sheridan, & Wickens, 2008). For example, Wickens et al. (2010) noted that SA was a critical factor in dealing with automaton failure, and tended to mitigate the poor handling of disturbances often associated with high LOAs. They indicated that designers need to focus on increasing the operators' SA for automation by finding its right level for tasks, improving the HSI for automation, and training. Furthermore, the benefits of automation can be offset when operators do not trust it. Then, they may not use it, or may increase their workload significantly by overly verifying the automation's behavior. Similarly, failures of automation can remain undetected if operators trust it too much and hence, become complacent. Thus, constructs such as these are important to assess as part of developing and evaluating a system.

Finally, the studies identified some additional measures that may be important considerations for multi-unit operations: Neglect time (Crandall & Cummings (2007), and change detection/blindness (Parasuraman et al., 2009). The latter refers to the phenomenon of failing to see large, salient changes in the environment (Simons & Ambinder, 2005).

In summary, the lessons learned from UAS development that are relevant to SMRs include the following:

1. The characteristics of the UAS team proved important, especially its size (number of vehicles monitored and controlled by an operator or crew), and the degree of homogeneity of the vehicles assigned to an operator (vehicular differences compound the difficulty operators have managing the team). Both these issues are significant to SMR operations. SMR designers will have to identify the manageable number of units; wherein unit differences may play a role in determining the specific number. We expect the SMR units at a site generally to be the same, but some differences likely will develop over time.
2. Increasing the number of UAVs assigned to an operator (or crew) depends on the automation's design. SMR designers recognize the need to increase automation; similar to UAS designers, they are likely to apply automation to more than monitoring and control. As its usage extends to diagnostics, situation assessment, prognostics, and other support aids, the systems' reliability will be a key issue.

UAS researchers found that as automation's reliability declines, operator's performance and trust is degraded. As we noted earlier, the reliability of real-world systems is imperfect. Therefore, it is vital to quantify the reliability of automation in general, and of decision support systems in particular. A further consideration is assessing the effects of differences in automation's reliability on SMR operators.

3. UAS designers found that increasing the LOA generally improves performance and providing flexibility over the level, such as adaptive automation, supports workload management. They are evaluating the use of different LOAs and LOA flexibility to achieve the benefits of automation, while minimizing the negative effects of very high levels on human performance. These considerations must be examined in designing SMR automation, finding the proper mix of automation and human involvement to ensure the safety of SMR operations.
4. Applying automation to SMR operations needs to be carefully tested. UAS researchers encountered difficulties achieving the levels of automation needed to improve the operator-to-vehicle ratio. Careful evaluations considering the performance of the entire system will assure the success of automated systems in achieving their functions and their acceptable integration into the human-automation team.
5. UAS researchers reported that the allocation of tasks between crew members affected performance, which will be an important consideration in developing SMR operations. For example, at a site with four SMR units and two operators, each might monitor two reactors along with their balance of plant (BOP) systems. Alternatively, one operator might manage all four reactors, while the other operator manages the BOP systems. The advantages and disadvantages of different task allocations must be assessed, while also considering the impacts on teamwork and supervision.
6. UAS researchers highlighted the importance of HSI design when managing multiple vehicles; this also is applicable for SMR operators managing multiple units.
7. The UAS research emphasizes the importance of measuring performance. A comprehensive set of measures is needed to address, at a minimum, important aspects of primary task performance, teamwork, SA, trust (in automation), and workload; the same considerations are needed in developing and evaluating SMRs. The UAS studies suggest some additional measures, such as unit neglect time and change blindness, may be useful as well. In addition to selecting the right aspects of performance to measure, the measures should be sensitive to the expected reasonable variation in performance. Measures with restricted ranges, such as ceiling and floor effects, should be avoided because they produce misleading results.

2.2 Oil Refineries

An oil refinery comprises a series of processes that convert crude oil into different petroleum products. Many refineries are made up of multiple units. In new and modernized facilities, these units are monitored and controlled from a single central control room. We visited a refinery to observe the control room while operators were performing their tasks. We also interviewed them to obtain specific information about their approach to operations.

The plant was built in 1955 and was expanded and upgraded over the years. Its overall mission is to process crude oil into products such as gasoline, diesel, propane, and butane. It also manufactures asphalt, heating fuels, and sulfur for fertilizers. The facility accomplishes its mission through nine processes: Sulfur, Crude, Naphtha I and Naphtha II, Distillate, Coker, Gas Oil (GO), Alky, and Fluid Catalytic Cracker (FCC). Some of the processes have three units (e. g., crude, distillate, hydrogen units, and GO have three units each). The units, however, are not identical.

Operations are performed in a modern, digital, centralized control room (CCR) from where operators monitor and control multiple process units with operational demands similar to those anticipated for

SMRs. The processes are highly automated, so that the operating staff's main role is to oversee them and make any needed adjustments. There also are local operators out in the plant whose main responsibility is ensuring the equipment's reliability. Two key areas not automated are the startup and shutdown of the various units; these evolutions are performed manually, requiring additional staff to accomplish all the needed tasks.

In the CCR, one operator, the project lead (PL), is assigned to each of the nine processes. There also is a control room supervisor and a day shift "bench lead" for each process who fills in where needed. For each process, there also are three to five local personnel consisting of at least one local lead and two auxiliary operators. Figure 1 shows the layout of the CCR, consisting of three "pods" and nine "consoles."

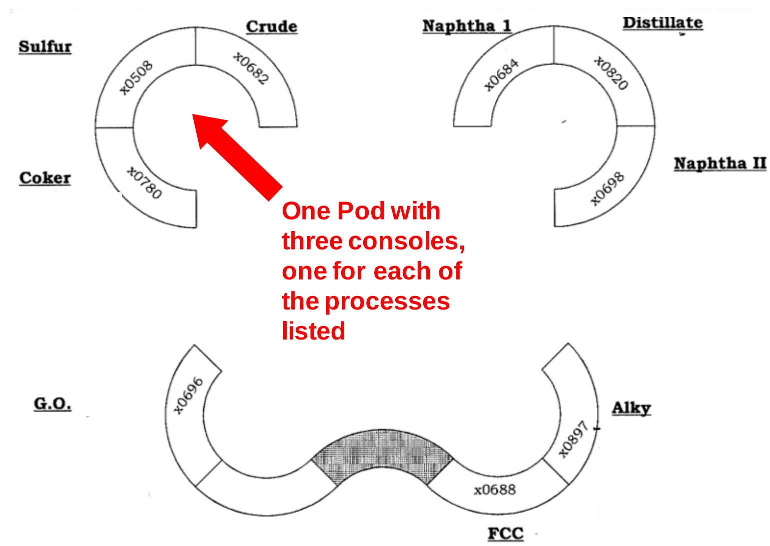

Figure 1. Layout of the refinery control room
(Figure provided by refinery staff and annotated by the authors)

A console is a workstation, one for each process, and a pod is a group of connected consoles. The figure identifies which process is controlled from which console. The consoles are sit-down workstations manned by one PL; they have sufficient room for additional staff when needed.

Processes can involve up to three units and are monitored and controlled from a single console by a single PL; about 250 controls and 2000 indicators are available at the console. Workload is a key consideration in evaluating the assignment of units to PLs. For each PL, engineering analyses ensure that the workload is acceptable, and the required tasks can be successfully performed. Evaluations of task loads determined the number of controls and indicators that the PL can manage. Engineers can reassign parts of a process or secondary functions to another PL, should the workload prove too high. Facility management also brings in additional staff when they anticipate high workload, such as during startup, shutdown, or major transients.

Workstation screens display almost all of the information and controls. Each console has approximately three monitors for the distributed control system (DCS), and five to seven monitors for other purposes. The DCS is the most important I&C system; it is used to monitor and control key process parameters and identify critical alarms. Facility personnel stated that the design of the alarms is critical to operations. Each alarm must be identified carefully. The criterion determining whether a parameter should be an alarm is that it must be unique information requiring an achievable action. An alarm is considered critical when immediate action by operations is needed. The facility receives an estimated two critical alarms per shift across all nine processes. The secondary alarms, also called Console Action Plan alarms, are non-critical alarms.

When PLs monitor three units, the alarms for all three are integrated; that is, they are presented together, so that PLs only have to look at one screen to see them all. However, the information displays for each unit are separate. The two primary types of displays are process (mimic) displays, and trend displays, using fairly standard display formats for modern digital systems. The crude process, for example, contains three crude units, numbered 1, 2 and 3. Unit 1 has a small capacity, while Units 2 and 3 are large capacity. Both the inputs to and the outputs of the process for each of the units differ, as do, the number and sizes of their components. The PLs indicated that these differences made it easier for them to distinguish between the units, i.e., they look different on the displays so they are easily distinguished. These differences between multiple units within one process are addressed in training. Soft controls (on-screen controls), also called faceplates, are used to control the equipment.

Procedures guide personnel action. PLs must follow them and sign off upon completing a step. However, there is a formal deviation sheet if needed. The refinery undertakes an annual review of the accuracy of procedures, noting any improvements.

In summary, the lessons learned from refinery operations that are relevant to SMRs include the following.

1. Operators can monitor and control multiple units, and the refinery's operating experience supported this conclusion. Keys to making this possible include
   - careful analyses of workload to ensure operators are not overloaded
   - automation, so operators can focus on monitoring and managing processes
2. Careful attention to designing the alarm system is essential so the number of alarms is manageable, each alarm is unique, and each is associated with an achievable action. In the refinery, alarms for different units are integrated into a single display rather than being presented separately for each unit.
3. Unit differences, as depicted in the HSIs, supported operators in maintaining awareness of the status of individual units.
4. Organizational changes are needed during emergencies to manage events occurring at one unit. The availability of additional staff during periods of high workload (such as startup/shutdown and to manage major off-normal conditions) is necessary for the refinery's multi-unit operations.

2.3 Tele-Intensive Care Units

Tele-intensive care units (tele-ICUs) are emerging as an alternative to and backup for traditional hospital ICUs (Lilly & Thomas, 2009). Tele-ICUs are facilities that remotely monitor intensive-care patients and notify on-site hospital staff when conditions warrant medical intervention. They share many characteristics with other high-risk, high-reliability organizations; that is, a critical mission, wherein the consequences of error can be unacceptable, is accomplished by a formalized organization of highly trained experts, using pre-established procedures, supported by state-of-the-art computer technology.

The need for such facilities arose from the dearth of physicians specializing in critical-care medicine (so-called intensivists). The shortage is especially acute during overnight hours when smaller hospitals may not have intensivists on shift, and at rural hospitals where such specialists may not be available.

Tele-ICUs have a control room from where the tele-ICU staff can monitor many more patients in hospitals remote from the facility than can the on-site hospital staff. For example, an ICU nurse in the hospital may monitor two patients, while a tele-ICU nurse may monitor as many as 30 patients. One hospital's intensivist may administer to 10 ICU patients in a hospital, while a tele-ICU intensivist is available to over 100 patients located at many different hospitals.

Studies of patients monitored by tele-ICUs found reductions in patient mortality, length of stay, and cost compared with traditional ICU methods (Kohl et al., 2007; Lilly & Thomas, 2009; Heightman, 2009). Further, the availability of tele-ICUs has improved critical care services in small rural hospitals and reduced patient transfers to larger ones (Zawada et al., 2009).

While patient monitoring is clearly different from reactor monitoring, the remote monitoring of patients at multiple hospitals places demands on human performance that have some similarities with those that SMR operators may face:

- monitor multiple independent "units" (patients or reactors)
- monitor the same multiple parameters of those independent units
- maintain SA of multiple independent units
- deal with differences in information available across "sites" (it may vary from one hospital to another)
- deal with differences in the presentation of information across "sites" (it may vary from one hospital to another)
- manage events that may arise and cope with the workload of emergency management
- manage multiple events occurring among independent units when such situations arise
- coordinate shifts in staff responsibilities to manage emergencies
- manage increased communication demands during emergencies
- deal with bringing new independent units on-line

The project staff visited a tele-ICU to observe control-room operations and interview staff to obtain specific information about their operations. The tele-ICU has operated for over 5 years and provides a remote ICU monitoring control room for four hospitals (one major hospital and four rural ones).

The high-level functions that tele-ICU staff performs involve:

- *Patient monitoring* – Tele-ICU staff monitor the vital signs and medications of each patient, classified into one of three categories: Red (most serious), yellow, and green (least serious). This classification guides the extent of monitoring of individual patients.

- *Assessment of conditions* – When an abnormal vital sign is identified, assessment of conditions requires access to the patient's data, charts, test results, X-rays, and visual observation of the patient. For example, the tele-ICU nurse may communicate with on-site staff to check a lead on measuring equipment to determine if an abnormal heartbeat is due to a loose connection.

- *Responding to events* – If the facility's staff determines that intervention is required, they need communication equipment to contact on-site staff to take necessary actions. Common information displays for the tele-ICU staff and the local hospital's staff support their communication.

The facility is staffed to include: one intensivist (night shift only), three ICU nurses (providing round-the-clock coverage), and two clerks providing round-the-clock coverage. As noted above, the on-shift staff emphasized the importance of communication with in-hospital staff on patient interventions.

The tele-ICU we visited has one experienced nurse (at least 5 years of work experience) for every 30 patients. The ideal patient-to-physician ratio still is being determined, but facility staff estimate it to be between 120 to 150 patients per physician.

The control room layout includes a workstation for each of the nurses and the doctor. Each workstation has five monitors, keyboard, mouse, camera controls, and telephone. The data displayed for each patient includes: demographic data (including names of patient and their physician); vital signs (heart rate, heart rhythm, blood pressure, respiratory rate, and oxygen saturation); laboratory tests; and X-rays. Monitoring is supported by alarms and signal processing of the patient's vital signs. Cameras enable the tele-ICU staff to observe patients, and with the communication equipment, interact with on-site staff.

The lessons learned from tele-ICU operations that are relevant to SMRs include the following.

1. Monitoring individual patients can be viewed as analogous to monitoring individual reactor units. The tele-ICU staff indicated that monitoring and intervention can be complicated by the differences between hospitals. For example, different hospitals' chart formats create higher workload and slow the physician's response. If the SMR units monitored by the control room staff are at different sites, site differences may impose additional complications, as do different hospitals. Also, there may be variations in the design between units and/or their HSIs at one site.
2. A related issue concerns differences in the I&C system when new units are brought on-line. When hospitals are brought on-line, new ones may have more recent versions of the patient monitoring software, entailing differences in data and data presentation between new and old hospitals. This problem may arise as new reactors are brought on-line. Indeed, the development of I&C systems is so rapid that reactors brought on-line a decade apart may have different I&C systems, different levels of data processing, and might measure different parameters.
3. Organizational changes are needed during emergencies to manage events occurring at one unit. For example, when a nurse is intervening with a critical patient, a particular specialist may have to be called in, and the monitoring of less critical patients delegated to other nurses. A similar flexible adaptability to emergency events might be used in operating modular reactors.
4. Some aspects of the HSI are not well suited to monitoring multiple "units," e.g., the tele-ICU lacks a flexible means simultaneously to display the vital information for many patients. The approach to HSI design for monitoring multiple SMR units will be a key aspect of safe operations, and may involve novel approaches to HSI design.
5. HSI support is needed for monitoring multiple "units." The tele-ICU gives patient criticality codes to guide where to focus monitoring attention ("red" patients). Alarms and signal-processing aid personnel to monitor individual parameters. HSI designs for SMRs must consider HSI support for the workload associated with monitoring multiple units.

3 CONCLUSIONS

Based on the lessons learned from these three different non-nuclear systems, we summarize the general lessons learned that are potentially applicable to SMRs:

1. Monitoring and controlling multiple units can be accomplished by a single operator or crew in a single control room, and is part of the normal operations in refineries and tele-ICUs. The DoD is developing this capability for UASs, and it's proving to be a challenge to designers.
2. Enabling technologies that support operators to monitor multiple units include:
   - extensive use of automation
   - advanced designs of HSIs and alarm systems
   - design of control room that fosters teamwork and communication
   - procedures and HSIs that support the transition from normal operation to off-normal/emergency management
   - extensive information technology support for troubleshooting the problems that personnel encounter

3. The effect of unit differences (heterogeneity) on performance is unresolved. At the refinery, such differences were helpful in monitoring and distinguishing between units; while for tele-ICUs and UAS operators, differences complicated operations.
4. As noted in 2 above, automation is a key enabling technology. Concerns about over-automation and its potentially negative effects on human performance have led designers to develop more interactive and flexible approaches to automation. Adaptive automation, for example, may be valuable in assisting operators to manage the workload in supervising multiple plants. Training improves operators' understanding and use of automation.
5. Clear staffing responsibilities are defined for personnel at the refinery and tele-ICU, and are being defined for UAS staff. Allocating tasks to crew members is vital in terms of the performance of the overall team and integrated system.
6. Crew flexibility is a key to managing off-normal situations. At refineries and tele-ICUs, significant organizational changes are made to manage them. The availability of additional staff for the off-normal unit was necessary. Additional staff also were used for some transitions, such as unit start-up or shut-down at the refinery. Having a way to transfer responsibilities for reactors in off-normal states to a person or team specialized in dealing with them may be beneficial to SMR operations. Communication between personnel is crucial. Maintaining SA during off-normal situations is easier when operators have a simple means to communicate with other personnel.
7. Designing the control room and HSI for multi-unit monitoring and control is challenging. HSIs must enable monitoring of the overall status of multiple units, and the easy retrieval of detailed information on an individual unit. The design of alarms particularly must ensure operators are aware of important disturbances, thus minimizing the effects of change blindness and neglect. The organization of information is another critical HSI consideration, e.g., deciding on what information crew members need to access, both individually and as a crew, to support teamwork. HSIs also must support the transfer of operations between crew members.
8. The design for multi-unit management is aided by detailed HFE analyses of staffing and operator tasks, via task analysis, human-performance modeling, and operator-in-the-loop simulations.

Thus monitoring and control of multi-unit facilities by a single operator or crew in a single control room is possible. However, the successful accomplishment by a single crew of multi-unit operations in the commercial nuclear industry is yet to be demonstrated. First, the unique operational demands of different systems need to be addressed before we can formulate conclusions about multi-unit NPP operations. The special demands of one industrial application may limit our making generalizations to another. For example, while multi-unit operations may be routine in the petrochemical industry, it is proving a difficult challenge for unmanned vehicle operations. We recommend conducting more research on surrogate systems to answer questions, such as the impact of unit differences on monitoring, and to verify our findings, thereby expanding the technical basis of information pertaining to multi-unit control.

The information obtained from these non-nuclear systems will help the NRC to better understand the issues and human performance challenges associated with multi-unit operations and to provide a technical basis, along with the other information obtained from our research, to develop guidance to support the safety review of the HFE aspects of SMRs.

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