Effects of an Advanced Reactor's Design, Use of Automation, and Mission on Human Operators

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Abstract: The roles, functions, and tasks of the human operator in existing light water nuclear power plants (NPPs) are based on sound nuclear and human factors engineering (HFE) principles, are well defined by the plant's conduct of operations, and have been validated by years of operating experience. However, advanced NPPs whose engineering designs differ from existing light-water reactors (LWRs) will impose changes on the roles, functions, and tasks of the human operators. The plans to increase the use of automation, reduce staffing levels, and add to the mission of these advanced NPPs will also affect the operator's roles, functions, and tasks. We assert that these factors, which do not appear to have received a lot of attention by the design engineers of advanced NPPs relative to the attention given to conceptual design of these reactors, can have significant risk implications for the operators and overall plant safety if not mitigated appropriately. This paper presents a high-level analysis of a specific advanced NPP and how its engineered design, its plan to use greater levels of automation, and its expanded mission have risk significant implications on operator performance and overall plant safety.

Keywords: Human Factor Engineering, Advanced NPPs, Automation, Human Reliability Analysis

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1. INTRODUCTION

Since the construction of the first commercial nuclear power plants (NPPs) in the United States (U.S.), there has been considerable variability in the amount of interest and momentum behind the development of new NPPs. Economic and political factors (e.g., the fluctuating cost of producing energy from fossil fuels, and the political stalemate over Yucca Mountain), as well as high profile events (e.g., Deepwater Horizon and Fukushima Daiichi) and the debate over climate change appear to cause interest in nuclear power to wax and wane over time. Despite these externalities, a number of entities have worked ardently to develop new and advanced NPPs, including small modular liquid-metal cooled reactors, and have prepared their designs for licensing review by the U.S. Nuclear Regulatory Commission (NRC).

General Electric-Hitachi is one such entity developing an advanced sodium cooled small modular reactor (SMR), called the Power Reactor Inherently Safe Module reactor (PRISM) [1]. Other entities have also been pursuing their own advanced NPP designs [2, 3, 4], but as of the writing of this paper, PRISM is, to our knowledge, the only sodium cooled SMR design that has both human factors engineering (HFE) and risk related information (e.g., probabilistic risk assessment) publicly available in an unredacted form, thereby allowing us to perform this analysis. Specifically, General Electric (GE), prior to partnering with Hitachi, submitted a preliminary safety information document [5] to the NRC as part of its license application. The NRC reviewed GE's submission [6], and notably included the following comment, "On the basis of the review performed, the staff, with the ACRS [Advisory Committee on Reactor Safeguards] in agreement, concludes that no obvious impediments to licensing the PRISM design have been identified." (pg. xxiv) However, [6] also specified that the NRC reviewed only a conceptual design of PRISM, and that their review, "did not, nor was it intended to, result in an approval of the design". (pg. C-1). Given the conceptual state of design for this reactor, and other advanced reactors, we believe there are a number of HFE issues (as well as other design related questions), which have not been considered in sufficient detail from a risk analysis perspective.

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That is, advanced NPPs whose engineering designs differ considerably from existing light-water reactors (LWRs) will affect the conduct of operations and operator performance in ways that may not be adequately addressed without an explicit HFE analysis. Changes to the engineered design of the reactor, however, are only one of a number of factors that can affect human performance in advanced NPPs. Some advanced NPPs are designed to operate with more automation in their digital instrumentation and control (I&C) system, and a reduced operating staff in one central control room operating multiple units. More automation will make the operator's role more supervisory in nature, but controlling multiple modules or units may introduce additional workload challenges. Similarly, some advanced reactors are touted as being capable of producing other commodities in addition to electricity in an economically competitive manner. These changes to the mission of the advanced NPP will also likely affect the operator's performance. In short, the role the operator(s) play (e.g., their function and the tasks they perform) are slated to change, given changes to the engineered design, planned use of automation, and change in plant mission for advanced NPPs. In our view, it is unlikely that suitable solutions to mitigate the risk significance of these issues will be found easily, such as by adopting best practices from operational experience of existing LWRs. Rather, a new HFE technical basis for the human performance requirements for advanced NPP operators will need to be established.

Other researchers, in particular O'Hara, Higgins, and Pena [7], studying human performance issues related to the design and operation of SMRs have made this point previously in their study of multiple classes of advanced NPPs. In this paper, however, we are explicating some risk implications for a specific advanced reactor design. We will show how specific changes in reactor design, such as the core design and type of coolant used, and other aspects (e.g., greater use of automation and change in plant mission) change the safety and risk impacts on the operator. By doing this, we will explicate what some of the human performance issues operators will face given a specific design.

This paper presents a high-level analysis of the PRISM SMR, and how its engineered design, its anticipated use of greater levels of automation, and its expanded mission have significant risk implications on the human operator's roles, functions, and tasks. From this analysis we further conclude that formal HFE approaches, such as Functional Requirements Analysis (FRA) and cognitive work analysis (CWA), as well as human reliability analysis (HRA), are helpful in considering how to mitigate the risk impacts of these changes on human performance, particularly because these approaches are helpful in understanding the complex interactions of these factors.

2. DIFFERENCES BETWEEN PWRs AND PRISM

2.1. Design

PRISM is an example of an advanced NPP in that its engineered design differs from LWRs in a number of important ways, including but not limited to, the type of coolant and fuel it uses, and its core design. PRISM is a sodium cooled, metallic fuel, pool-type, fast breeder reactor. By way of comparison, pressurized light water reactors (PWRs) in the U.S. are water-cooled, oxide fuel, loop-type, thermal reactors. Perhaps the most important difference is the fact that the design of PRISM's reactor core and the use of metallic fuel are designed not to require operators or automation to intervene in order to shut down safely given certain initiating events (i.e., passive safety features). Upon reactor trip, a PWR operator must be actively involved in performing certain actions (e.g., performing decay heat removal actions) that a PRISM operator would not. Clearly, these differences have significant implications on the operator and their role (e.g., what functions and tasks operators perform). There are also a number of important differences, and associated advantages and disadvantages, in using sodium versus water as the primary coolant. Some of these differences are highlighted in Table 1, which was adapted from Bays, Piet, Soelberg, Lineberry, and Dixon [8].

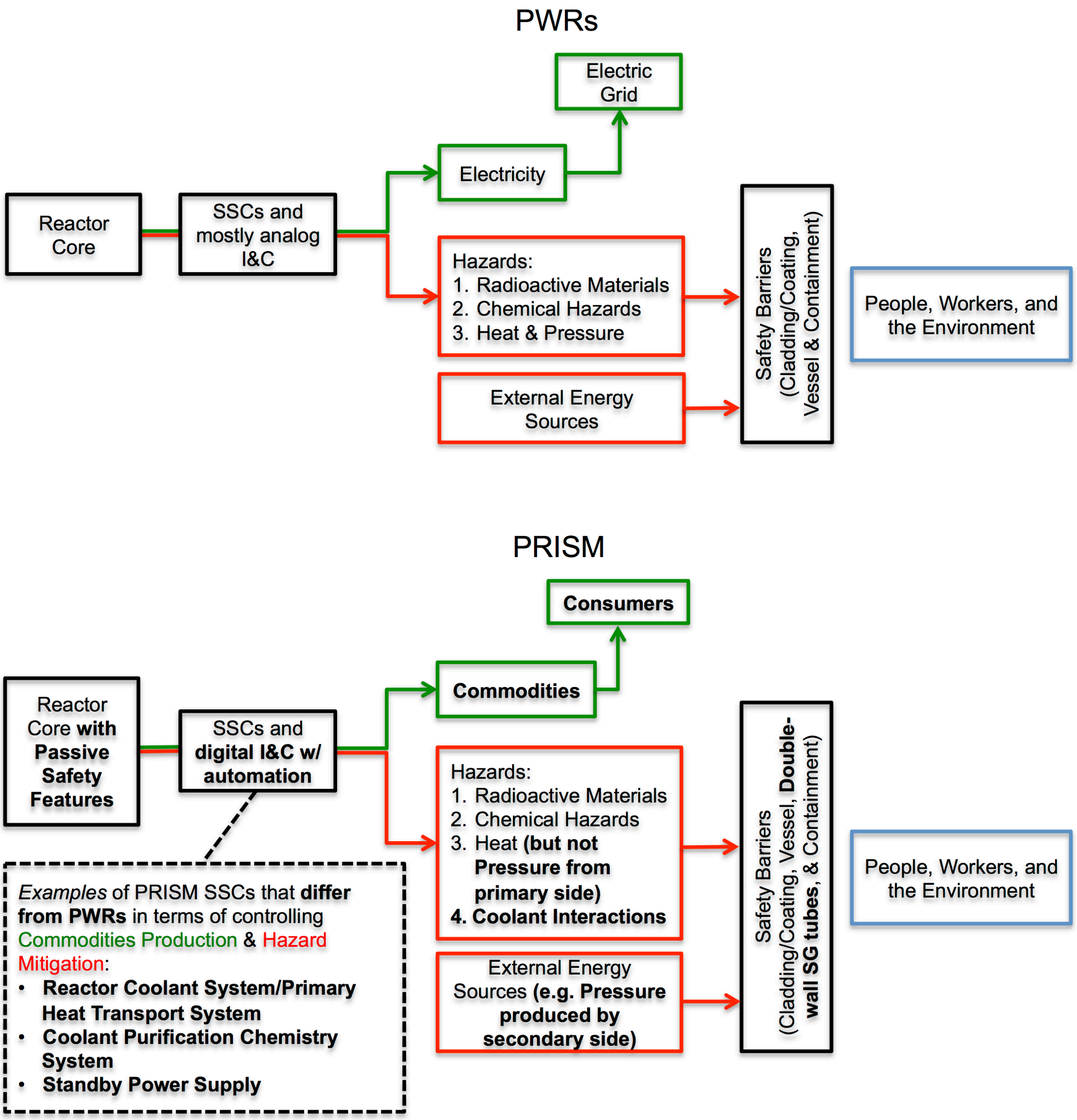
Table 1: Differences in Coolant Characteristics Between PWRs and PRISM

Coolant Characteristic	PWRs	PRISM
Stability *(Single-phase can be easier to control)*	Two-phase fluid *(Coolant can be in liquid or gas state)*	Single-phase fluid *(Coolant will only be in liquid state during normal operations)*
Pressure *(Lower pressure has safety benefits)*	15 MPa	0.1 MPa
Chemical Inertness	Moderately	Not inert *(Reacts with air and water)*

Sodium has the benefits of remaining in a single phase during normal operations, and does not need to be under high pressure to serve its purpose of heat transfer/cooling. Additionally, sodium manages the core's fissile inventory more effectively than water in that there is very little excess reactivity available for power excursions to occur. Sodium also has a high heat capacity that makes high-power-density cores feasible and facilitates a very slow thermal response [8, 9]. However, since the coolant sodium is chemically reactive, one key safety feature that PRISM has that PWRs do not need is double-walled steam generator piping where the secondary sodium-potassium exchanges heat with water. Overall, the coolant characteristics of sodium means that the operator does not have to be concerned with a number of issues that they would with water as the coolant (e.g., steam voiding), but would need to be concerned about sodium's chemical reactivity.

While there are differences in reactor core design, type of fuel used, and coolant characteristics, both PWRs and PRISM are NPPs that at a fundamental level operate on the same underlying thermohydraulic processes. As such, there are a number of similarities with respect to major systems, structures, and components (SSCs), such as reactor vessel, containment structure, reactivity control, reactor cooling system, primary heat transport system, steam generators, and balance of plant systems. All of these SSCs are central to both (1) the generation of electricity or other commodities, and (2) the protection of people, workers and the environment. However, there are a few obvious differences in SSCs between PWRs and PRISM. For example, PWRs have a pressurizer and PRISM does not, due to the fact that the sodium coolant does not need to be under high pressure. PWRs have a chemical volume control system that introduces boron into the reactor coolant system. The chemical volume control system is also the main source of water for the reactor coolant system. Conversely, PRISM has a coolant purification chemistry system that removes impurities from the primary sodium coolant. Additionally, according to Hylko [10], PWRs have an emergency core cooling system that PRISM does not need given that its coolant is in a large pool and is not under pressure. For example, PWRs have emergency diesel generators to help remove decay heat from the reactor core when on-site or off-site power is lost, while PRISM has a standby power supply system used to provide power to help with the orderly and controlled shutdown of systems in order to avoid equipment damage, and not for removal decay heat under abnormal conditions [1, 5]. PRISM has both a primary and secondary sodium system (i.e., intermediate heat transport system) as a means to isolate the radioactive primary sodium from the tertiary water/steam based balance of plant, whereas PWRs have only a primary reactor coolant system, and secondary water-based balance of plant. Overall, though we recognize the specific effects will depend on the details of the final as-built design of PRISM, all of these general differences in SSCs can change the operator's roles, functions, and tasks, and these changes further have potential risk important impacts on the overall plant.

Figure 1 provides high-level conceptualizations of PWRs and PRISM displaying some key similarities and differences between the designs of these two reactor types as a function of (1) the generation of electricity or other commodities, and (2) the mitigation of hazards to people, workers and the environment. Again, though the specific risk impacts on human performance will depend on the as-built design of PRISM, we assert that these are some examples of fundamental design changes that will likely have some risk relevant effects on operator performance, and as a result, overall plant safety.


PWRs

PRISM

Figure 1. High-level Conceptualizations Showing Differences Between PWRs and PRISM.

2.2. Use of Automation

Many have noted, including the International Atomic Energy Agency [11], that the digital I&C system in advanced NPPs will use greater levels of automation to operate these plants as one of many different means to reduce human operator staffing levels. This is driven in large part by the need for advance NPPs to be economically competitive with existing LWRs and other sources of electrical power generation. In the specific case of PRISM using greater levels of automation, [6] states, "Normal reactor operations are conducted using the plant control system (PCS). The PCS contains a high level of automation for plant control, protection of plant investment, and data handling transmission." (pg. 7-1). Furthermore, according to PRISM documentation the primary role of the operator is to:

- Monitor and verify performance of safety systems, though operators will have the capability to initiate reactor shutdown by manual scram or manual activation of the ultimate shutdown system
- Maintain communication with appropriate onsite and offsite personnel

- Initiate recovery actions following an event
- Serve as an important source of knowledge concerning plant status, design, and behavior, especially during the management of off-normal conditions.

The role of the PRISM operator as described is a significant departure from the role the operator plays in existing LWRs. That is, the U.S. nuclear energy industry has historically had humans as a central component of controlling LWR plant operations, so the increased use of automation will likely have a number of significant impacts on the roles, functions, and tasks of the operator. Furthermore, a considerable amount of human factors research has found that increasing the amount of automation in complex human sociotechnical systems (e.g., aviation) and operations (e.g., military) can have detrimental impacts on human performance (for a review, see Sheridan [12] and Lee [13]). Some relatively recent high profile accidents involving human factors issues with automation include the 2009 crash of Air France 447 on its journey from Brazil to France [14], and the 2009 Metrorail (i.e., commuter train) accident in Washington, DC [15]. The common theme underlying both of these accidents is the finding that the design of the automation hindered the human's ability to collaborate with the automation effectively. Examples of some deficiencies in the design of the automation include:

- Not adequately supporting the operator's ability to maintain awareness of the system's state
- Increasing the operator's workload when trying to recover from the automation's failure
- Contributing to a loss of the operator's abilities to skilfully perform manual control tasks that they had to perform when the automation failed.

These impacts on advance NPP operators, explained in more detail in Section 4 below, need to be evaluated for their risk significance.

2.3. Mission

Many advanced NPPs, including PRISM, have been promoted as being able to produce multiple commodities safely and economically, such as electricity, oxide fuels for PWRs from weapons grade nuclear materials [10], process heat for industrial processes, and desalinized water (Ingersoll, [16]). The change from a single mission (e.g., electricity generation) to multiple missions will be a departure from the conduct of operations at LWRs. Coupled with the need to keep operations and management costs economical, this change in mission will have implications for what is expected of operators, including specific HFE issues such as operator training and workload. The risk impact of these changes to the operator's roles, functions, and tasks on overall plant risk need to be evaluated.

3. CHANGES TO THE OPERATOR'S ROLES, FUNCTIONS, AND TASKS

Section 2 showed that the advanced NPP PRISM is designed differently from PWRs, that it is intended to be operated primarily by automation, and is designed to accomplish multiple missions. With these differences from existing LWRs, there are a number of specific changes to the operator's roles, functions, and tasks that are readily apparent, and are summarized here. In reviewing PRISM documentation [1, 5, 6, 10] some examples of additional tasks for PRISM operators, relative to PWR operators, include:

- Supervising the safe production of both electricity and other commodities, such as oxide fuel for PWRs [10]
- Monitoring for sodium coolant interactions with air and water.

According to [6], if a sodium coolant interaction occurs, it will require the operator to monitor for pressure incursions on the intermediate heat transport system from the tertiary side, ensure actuation of isolation valves, and verify the integrity of double-wall piping.

Additionally, according to [1, 5], some examples of tasks PRISM operators will not have to perform that PWR operators do include:

- Monitoring for leaks in the reactor coolant system
- Performing reactor shutdown actions
- Performing decay heat removal actions
- Performing post-accident containment cooling actions
- Managing boron concentration levels in primary reactor coolant system (e.g., primary heat transport system) during normal operations.

Thus, according to the published PRISM documentation, the operator will have virtually no role, functions, or tasks associated with control of normal operations. Their role will be primarily to monitor and verify (i.e., supervise) the performance of safety systems [5]. However, the PRISM operator will have some additional tasks upon failure of the PCS, depending on the severity of the failure of this automated control system. But none of these additional tasks deal directly with maintaining core cooling, or controlling what are considered to be the primary safety functions that exist in LWRs. Post-accident, operators will be responsible for monitoring variables associated with reactivity control, core cooling, and reactor vessel integrity. Clearly, PRISM's engineered design, extensive use of automation, and change in the plant's mission are significant departures from the conduct of operations in PWRs, change the performance parameters of operators, and will likely have risk related implications for HFE issues, including but not limited to, staffing levels and operator workload [6].

4. RISK SIGNIFICANT IMPACTS

Given the differences and complexity of the design of PRISM, the planned use of higher levels of automation, and the proposed changes in the plant's mission, there are a myriad of ways in which these factors can have risk significant impacts on the operator and the plant. However, since we presented only a high level analysis of these factors, we do not provide a comprehensive or exhaustive analysis of the risk significant ways in which these factors affect operator performance. Instead, this paper highlights what we considered to be the most obvious impacts (both positive and negative) to risk.

With respect to the design differences between PRISM and PWRs, the most significant change for human operators in our view is the passive safety design of the reactor core and use of metallic fuel. There are numerous accident scenarios for PWRs that require the operator to actively intervene to mitigate the consequences of those accidents. However, for a number of important accident scenarios, the PRISM operators do not have to perform any actions related to reactor shutdown, decay heat removal, or post-accident containment cooling. As [17] states, "In the event of a worst-case-scenario accident, the metallic core expands as the temperature rises, and its density decreases slowing the fission reaction. The reactor simply shuts itself down. PRISM's very conductive metal fuel and metal coolant then readily dissipates excess heat without damaging any of its components." In short, this design uses the laws of physics to achieve passive safety, and this drastically changes the roles, functions, and tasks of the human operator and their risk significance.

The fact that PRISM is a pool type cooled design (vs. loop cooled) means that the PRISM operator will not have roles, functions, or tasks associated with monitoring for leaks in the reactor coolant system (e.g., primary heat transport system). Many loss-of-coolant accidents scenarios that can occur in loop type PWRs are no longer feasible given the pool type design. The fact that PRISM uses sodium as a coolant means that the operator and/or automation will not have roles, functions, or tasks associated with monitoring the pressure of the reactor coolant system, or be concerned about accidents initiated by the primary system being under high pressure. The fact that PRISM has a standby power supply system that is not needed to remove decay heat is another example of an SSC that has risk implications for the operator. In this case, the operator's roles, functions, and tasks associated with a loss of onsite power event will likely be related to the orderly shutdown of powered systems and the protection of plant assets, and not the removal of decay heat. The operator will also have roles, functions, and tasks associated with monitoring for sodium interactions with air and water. If not automated, the operator may also have some responsibilities related to the coolant purification chemistry system that somewhat overlap with the PWR operator's responsibilities related to the chemical volume control system.

We hope that it is also obvious that PRISM's highly automated digital I&C system prompts a number of additional questions related to the human factors aspect of human-automation collaboration. As previously mentioned, other researchers have asked many of these questions before [7], and there are numerous examples in other high-risk and complex industries outside of the nuclear domain where poorly designed automation has had a risk significant impact on operations [12, 13, 14, 15]. Nevertheless, highly automated advanced NPPs such as PRISM will need to be designed to address the potential risk significance of issues including, but not limited to:

- Operators having difficulty understanding what the automated control system is doing
- Operators losing important skills that they will need when required to intervene (i.e., loss of proficiency or 'deskilling')
- The extent to which a reduced number of operators, potentially monitoring and controlling more than one reactor, will be able to ensure safe operations
- The extent to which there may be additional workload placed on operators when they must control both the NPP thermohydraulic processes and interact with the automated control system

And finally, given that PRISM is designed to produce more than one commodity may mean that there are some risk significant impacts on operator performance and overall plant safety, such as an increase in workload leading to difficulties in controlling plant processes.

In summary, advanced NPP designs differ from existing LWRs in the U.S. with respect to core design (i.e., passive versus active safety features), the type of coolant used (i.e., gas or liquid metal versus water) and/or type of fuel it uses (i.e., metal or triso/prismatic/pebble versus oxide fuel). It is also anticipated that many advanced NPPs will be highly automated, and have multiple missions. While we have identified many of the risk impacts of these changes on human performance in this paper, the specific risk impacts of all changes in advanced NPPs on the roles, functions and tasks of operators needs to be identified, preferably early in the design life cycle of the advanced NPP. Doing so will help the designers include the human performance and operational requirements in their design, including documentation such as technical specifications and procedures.

Furthermore, HFE approaches such as FRA and CWA, as well as HRA, can and should be used to help determine the potential risk impacts. FRA, function analysis, and function allocation help identify, define, and distribute as appropriate the functions the NPP must have to accomplish its goals of safe and reliable production of commodities. FRA not only helps the advanced NPP designer figure out the operational and human performance requirements of their NPP, FRA is also a part of the NRC's HFE program review model [18]. CWA [19] is a complimentary approach to FRA in that it is a framework that models a complex sociotechnical system based on the various constraints the system's design imposes on how functions are defined and work is accomplished. CWA is very appropriate for the problem defined here in that PWRs and advanced NPPs are complex sociotechnical systems that fundamentally accomplish the same work or mission (e.g., generate commodities, protect people and the environment), but both their systems and functions, and the constraints those systems and function place on human operators, vary significantly. CWA is central to identifying how the constraints of the as designed advanced NPP and the cognitive abilities of the human interact such that the risk-significant impacts of the system design on the human operator can be mitigated. Finally, using HRA to further analyze the importance of human action and inaction, including diagnosis and problem solving activities, after risk significant initiating events and/or hardware failures (e.g., secondary sodium water interaction, failure of the PCS, and toxic gas release from an additional tertiary chemical process using process heat from the reactor) is another important aspect to understanding how changes to the design and mission of advanced NPPs can affect human operator performance, and how successful operator performance and operator errors can contribute to overall plant risk.

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References

[1] B. Triplett, E. Loewen, and B. Dooies, *"PRISM: A Competitive Small Modular Sodium-Cooled Reactor,"* Nuclear technology, 178(2), 186-200, (2012).

[2] Y. Tsuboi, K. Arie, N. Ueda, T. Grenci, and A. Yacout, *"Design of the 4S Reactor,"* Nuclear Technology, 178(2), 201-217, (2012).

[3] A. Shenoy, J. Saurwein, M. Labar, H. Choi, and J. Cosmopoulos, *"Steam Cycle Modular Helium Reactor,"* Nuclear Technology, 178(2), 170-185, (2012).

[4] J. Halfinger and M. Haggerty, *"The B&W mPower™ Scalable, Practical Nuclear Reactor Design,"* Nuclear Technology, 178(2), 164-169, (2012).

[5] General Electric, *"PRISM™: Preliminary Safety Information Document,"* (GEFR-00793, UC-87Ta), 1986, San Jose, CA.

[6] J. Donoghue, J. Donohew, G. Golub, R. Kenneally, P. Moore, S. Sands, E. Throm, and B. Wetzel, *"Preapplication Safety Evaluation Report for the Power Reactor Innovative Small Module (PRISM) Liquid-Metal Reactor: Final Report,"* (NUREG-1368). U.S. Nuclear Regulatory Commission, 1994, Washington, DC.

[7] J. O'Hara, J. Higgins, and M. Pena, *"Human-Performance Issues Related to the Design and Operation of Small Modular Reactors,"* (NUREG/CR-7126), U.S. Nuclear Regulatory Commission, 2012, Washington, DC.

[8] S. Bays, S. Piet, N. Soelberg, M. Lineberry, and B. Dixon, *"Technology Insights and Perspectives for Nuclear Fuel Cycle Concepts,"* (INL/EXT-10-19977), Idaho National Laboratory, 2010, Idaho Falls, ID.

[9] J. Tester, E. Drake, M. Golay, M. Driscoll, and W. Peters, *"Sustainable Energy: Choosing Amongst Options,"* MIT Press, 2005, Cambridge, MA.

[10] J. Hylko, *"PRISM: A Promising Near-Term Reactor Option,"* Power, 155(8), 68-74, (2011).

[11] International Atomic Energy Agency, *“Staffing Requirements for Future Small and Medium Reactors Based on Operating Experience and Projections,”* (IAEA-TECDOC-1193), 2001, Vienna, Austria.

[12] T. Sheridan, *“Humans and Automation: System Design and Research Issues,”* John Wiley & Sons, Inc., 2002, New York, NY.

[13] J. Lee, *“Human Factors and Ergonomics in Automation Design,”* In G. Salvendy (Ed.), *Handbook of Human Factors and Ergonomics* (3rd Ed.). John Wiley & Sons, Inc., 2006, New York, NY.

[14] Bureau d’Enquêtes et d’Analyses, *“Final Report on the Accident on 1st June 2009 to the Airbus A330-203 Registered F-GZCP Operated by Air France Flight AF 447 Rio de Janeiro – Paris,”* 2012, Paris, France.

[15] S. Vedantam, *“Metrorail Crash May Exemplify Automation Paradox,”* The Washington Post, Section A, page 9, 29 June 2009.

[16] D. Ingersoll, *“Deliberately Small Reactors and the Second Nuclear Era,”* Progress in Nuclear Energy, 51(4), 589-603, (2009).

[17] http://gehitachiprism.com/what-is-prism/how-prism-works/. Retrieved on 24 March 2014.

[18] J. O’Hara, J. Higgins, S. Fleger, and P. Pieringer, *“Human Factors Engineering Program Review Model,”* (NUREG-0711, Rev. 3), U.S. Nuclear Regulatory Commission, 2012, Washington, DC.

[19] K. Vicente, *“Cognitive Work Analysis: Towards Safe, Productive, and Healthy Computer-Based Work,”* Lawrence Earlbaum & Associates, 1999, Mahwah, NJ.