OPERATIONS STAFFING ISSUES RELATING TO SMRs

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1.0 INTRODUCTION

One of the assumed characteristics of Small and Medium Sized Reactors (SMRs) is the potential to require a much smaller staff per reactor than existing large reactors. (This paper focuses on operator staffing for SMRs and does not address other aspects of staffing such as for plant administration, maintenance, or security. Security issues are addressed in a separate ANS white paper: "Physical Security for Small Modular Reactors.") In sum, staffing levels may be reduced for a typical SMR Nuclear Plant Facility (NPF) without compromising safety. The small size of the SMR NPF and its inherently safe, passive design eliminate the need for a plant operation staff of the magnitude employed at current commercial Nuclear Power Plants (NPPs). The operations of an SMR are more typically automatic, and less human intervention is required. Given the simpler and more automated operation of advanced SMR designs, operator action to place the plant in a safe condition for either design-basis or beyond-design-basis ("severe") accidents generally requires passive observation and confirmation, not active intervention. Extending this argument, the number of Licensed Operators (LOs) in a multi-modular SMR facility of equivalent cumulative output may also be less than would be required for equivalent large plants of the Generation (GEN) III/III+ designs.

In either of these cases, the reduced staffing requirements could be accomplished with submittal of and approval of exemption requests to current regulations until such time as the regulations would be updated to accommodate the new SMR designs. Because SMR designs provide for simpler operation and increased automation, the number of on-shift LOs can be reduced, and their collateral (nonlicensed) duties can be increased without compromising safety. Therefore, the total operating staff for the facility can be dramatically reduced.

The purpose of this white paper is to promote discussion that results in the U.S. Nuclear Regulatory Commission (NRC) approving reduced operator staffing for SMRs based on clearly identifiable criteria and to obtain tailored guidance on the number and duties of LOs within the framework of existing regulations. Early discussions between representatives of SMR applicants and the NRC staff concerning staffing should be held to determine, among other things, whether seeking such an exemption in one or more areas will be necessary.

2.0 BACKGROUND

The NRC regulates facility staffing through its regulations and a collection of guidance documents issued by the NRC staff. Operator staffing is an important subset of the overall staffing requirements to be considered for SMR designs, and when considering the overall reductions in plant staffing based on the size and simplicity of SMRs, operating staff could be much larger in proportion of the total staffing than for existing plants. NRC rules in 10 CFR 50.54(m)(2)(i) (Ref. 1) regulate reactor plant control room staffing. See Appendix A. The NRC also issued a "Policy Statement on Engineering Expertise on Shift," available at 50 FR 43621 (Ref. 2), which forms guiding principles relating to the qualification of the operating staff. Taken together, the regulations and Policy Statement determine the number of personnel required in the control room. The number of personnel in the control room on-shift must be multiplied by some factor to reflect total operating staffing. (For current operating plants this factor is between 10 and 20. It is anticipated that for smaller, simpler SMRs, this factor may be reduced.) Five shifts of personnel are typically provided to provide 24-hour coverage while accommodating needed time off and training time. In addition, each LO typically has at least one nonlicensed individual in a support role due to the generally practiced limitations on the collateral duties that LOs may be assigned.

In addition, NUREG-0800, Chapter 13 (Ref. 3), provides guidance on the section of an applicant's Safety Analysis Report (SAR) that describes the structure, functions, and responsibilities of the on-site organization established to operate and maintain the plant. NUREG-0800, therefore, also guides the operational staffing requirements of SMRs.

The NRC does, however, allow licensees to seek exemptions from regulatory requirements when warranted. See 10 CFR 50.12 (Ref. 4). Applicants or licensees may request exemptions from the staffing regulations in 10 CFR 50.54(m) and NRC guidance. NRC guidance document NUREG-1791 (Ref. 5) offers the staff guidance on exemption requests from power plant LO staffing requirements. (See also "Technical Basis for Regulatory Guidance for Assessing Exemptions Requests from the Nuclear Power Plant Licensed Operator Staffing Requirements Specified in 10 CFR 50.54(m)," NUREG/CR-6838 (Feb. 2004) (Ref. 6).)

3.0 PROBLEM/ISSUE STATEMENT

NRC regulations and policies stipulate operator staffing requirements for licensed nuclear reactor facilities. These requirements are based on experience with the operation of the large, base-loaded reactors currently in use in the United States. These staffing requirements may not be appropriate or necessary for the new SMR designs, especially considering the simpler and more automated operation of these advanced designs. Additionally, excessive manning requirements need to be addressed early in the design review to avoid placing an undue economic burden on the operation of these SMRs, impacting the perceived viability of SMR vendors' business plans.

For example, using the staffing requirements in 10 CFR 50.54(m)(2)(i), a single-unit 10-MW(electric) Toshiba 4S reactor plant would be required to maintain four LOs per shift on-site. Four on-shift LOs translate into a combined operating staff of 40 to 80 personnel under current requirements. Considering the size and simplicity of the plant, and the minimal operator intervention necessary for either normal operation or accident response, this level of staffing is excessive.

Using 10 CFR 50.54(m)(2)(i) to determine the staffing requirements for a NuScale design plant with twelve modules, for example, is even more problematic, as the table (see Appendix A) does not consider a plant arrangement with greater than three units (reactors) or all the modules being operated from a single control room. Regardless, extrapolating the requirements of 10 CFR 50.54(m)(2)(i) to a twelve-module SMR facility would result in staffing numbers far in excess of those believed necessary to safely operate the reactor facility.

It should be noted that the SMR Special Committee is not suggesting that the level of qualification be reduced for the operators of SMRs. Ensuring the safe operation of smaller reactors will still require extensive training and testing for the operating staff, in line with existing NRC and Institute of Nuclear Power Operations (INPO) requirements. Experience from other industries shows that staffing can be reduced as automation and simplicity are increased. For example, airlines routinely operate with two-man flight deck crews when three-man crews for long-haul flights used to be the norm, reflecting the increased automation and reliability of flight controls. The U.S. Navy has significantly reduced the manning of the new Littoral Combat Ships (LCS) compared to previous frigate-sized warships. The LCS manning strategy includes reliance on “cross-rate” training—in other words, increasing the training of each operator to allow him or her to perform additional collateral duties. Experience in other industries shows that less manning usually is associated with increased training and experience of the operating staff.

Appendix B contains a discussion of selected SMR design features that reflect the simplicity and automation that can allow implementing the strategies to reduce operating staff manning described above.

4.0 DISCUSSION AND ACTUAL WORK

1. RISK PERSPECTIVE ON STAFFING

1.1. Justification for a Risk-Based Approach to Determine Staffing Size

A risk-based approach can be used to inform staffing requirements for SMRs. The risk-based approach could be used to establish that staffing requirements for a simple, Low Power Reactor (LPR) may be smaller than those for existing reactors.

It is expected that the SMR designs in development will have a much lower calculated probability of core damage and radioactive release than current-generation plants. This degree of risk reduction is consistent with the significantly improved risk profile due to the smaller core inventory, the vastly simpler design (fewer systems), and the inclusion of advanced design features such as passive safety systems.

The key differences between staffing for current power reactors and that proposed for staffing SMRs are in the areas of control room design, LO responsibilities, and control room staff organization. Specific proposals to address each of these areas are required to demonstrate the acceptability of the process in the concept of operation of each SMR design.

If current regulations were complied with, the number of LOs mandated in a multi-modular SMR plant control room would be greater than required for the control room of a current large operating unit of the GEN II/III/III+ design. However, a number of the proposed SMR concepts coming forward address a change in the responsibility for each reactor operator to monitor and provide control over more than one unit or module at a time. Thus, the number of operators per unit or module could be lower than the number of operators per unit listed in current regulations in 10 CFR 50.54(m) and NUREG-0800, Chapters 13.1.2 and 13.1.3.

The discussion that follows addresses some of the key features of SMRs that contribute to a reduced likelihood of core damage and release in comparison to the large, current-generation facilities. These features could be taken into account in supporting reduced staffing requirements for SMRs.

1.2. Accident Initiators

Potential accident initiators are grouped into two categories: “internal” events and “external” events. Internal event initiators include system failures such as loss of site power. External events include natural occurrences such as earthquakes and common mode failures such as fires. The potential remote location of an SMR facility introduces the possibility that some external events initiators may have a higher frequency than typically observed for LPRs. For example, external initiating events associated with extreme weather conditions might be more likely. Thus, the SMR design must compensate for potential increased initiator frequencies if a detailed Probabilistic Risk Assessment (PRA) demonstrates this to be the case.

In general, it is anticipated that the frequency of events that could lead to core damage in an SMR design is less than that for current-generation plants due to the simplicity of the design, the enhanced seismic protection (some designs), the reduced need for operator action, and the physical capability to passively accommodate heat removal functions from both the reactor and containment.

1.2.1. Internal Events

The spectrum of internal events typically considered as accident initiators for the current-generation light water reactor (LWR) includes anticipated transients during normal operation and the less likely postulated accidents such as a loss of reactor coolant. Transients may be associated with the reactor function (e.g., failure to scram) or with the power generation function (e.g., closure of steam stop valves). Some of these events have a reduced frequency or can be eliminated as accident initiators in SMR designs based on the plant’s capability to cope with the event. While a design-specific PRA would identify initiators that are unique to that given design, and the associated frequencies of such initiators, general conclusions can also be made about the operating actions needed to respond to these events and conclusions drawn about the impact on manning. For example, if operator action is required in minutes rather than hours, the need for backup manning in the control room is clear. General guidelines on when the number of, timing of, and complexity of tasks require a second operator provides guidance to the designer and establishes clear goals for Human-System Interface (HSI) engineering.

1.2.2. External Events

The characteristics of potential remote sites introduce the possibility that certain external events may be the dominant accident initiators. In particular, earthquake risk is a dominant contributor in some Japanese reactors; several remote U.S. locations could introduce a similar situation. Additional external events that would be of particular concern for SMRs include the following:

- *Flood*: For some SMR designs the reactor is located underground, and groundwater intrusion or flooding of the buildings would be a design consideration.

- *External fire*: If the site includes wooded areas, an off-site forest fire could challenge plant operation.

- *Extreme cold*: Temperatures of -60°F and below represent unique challenges to equipment. A reactor trip under extreme cold conditions could challenge plant equipment until auxiliary power is available to provide heat (e.g., a long station blackout coping period).

- *Extreme snow and/or ice*: Extreme snow and/or ice conditions could prevent access to the plant.

- *Volcanic ash conditions*: Volcanic ash could affect machinery and limit access to the plant.

Although formal demonstration in a risk assessment would be required, it is expected that the safety design of some SMRs could accommodate these challenges because of the capability to provide core cooling with natural circulation in the absence of off-site power and without operator intervention.

1.3. Probability and Consequences of Containment Failure

Except for SMR designs that do not require containment, maintaining the integrity of the containment function remains an important NRC regulatory requirement, regardless of reactor design. Accordingly, there is a need to demonstrate the containment effectiveness as a radionuclide barrier; a typical means of doing so is to evaluate the Conditional Containment Failure Probability (CCFP). The CCFP illustrates the probability of a release given core damage.

SMR designs may use various methods to mitigate events that challenge the containment and reduce the potential for containment failure. Some examples include the use of double and/or low enthalpy containments [Light Water Reactor (LWR) designs] or coolant systems operating at atmospheric pressure in sodium-cooled fast reactor designs.

Containment bypass conditions are also less likely in an SMR than in current-generation LWRs because there are fewer active systems (thus fewer penetrations).

A reduced potential for containment failure supports the suggested reduction in staffing requirements. The severity of the accident consequences does not justify staffing at the level for existing large reactors.

1.4. Timing of Releases

The time of potential releases should be determined to establish the range of required emergency response actions and their impact on staffing decisions. Current advanced designs for large power reactors demonstrate that releases will not occur for at least 24 hours without operator intervention or active safety systems. For the SMR designs, for comparison purposes, it should be possible to demonstrate a longer release time. Analyses performed for the Power Reactor Innovative Small Module (PRISM) design indicated that for all but the most energetic release categories, the time to guard vessel/containment dome failure exceeds 24 hours.

Given the lower power level associated with the SMR designs, and the other design features discussed above, it is anticipated that credible release scenarios would require an even longer time for releases to occur. Adequate time will be available to supplement the initial on-site staffing if necessary in the case of a potential release.

2. CHANGES IN ROLE OF THE LICENSED OPERATOR AND OPERATIONS STAFF

A number of the SMR concepts moving forward in detailed design and in NRC preapplication licensing includes multi-modular designs where modules may be grouped so that one Reactor Operator (RO) can monitor and control multiple modules from a single control station within the main control room (MCR). This is a key difference between staffing for current power reactors and that proposed for some SMR designs in the area of control room design, LO responsibility, and control room staff organization. In these cases, the number of LOs in both the RO and Senior Reactor Operator (SRO) classification is expected to change based on the submittal and NRC acceptance of an exemption request per design, to the current regulations in 10 CFR 50.54(m) and the guidance in NUREG-0800, Chapters 13.1.2 and 13.1.3.

In the multi-modular SMR designs, the role of the operator does not change. The LO maintains responsibility for plant safety by selecting operating state, monitoring and verifying parameters, and initiating manual trip of a module, if trends indicate that auto trip is imminent. The HSI provides the operator with the information required to monitor and control multiple modules during an event. Automation reduces the burden on the operator by performing routine tasks including some tasks performed manually on current reactors.

This is made possible by modern digital controls and the use of proven modern digital technology to perform automated control functions, within the framework of the simple and passive SMR designs. With this technological capability, and the small, simple, and passive SMR design, the workload for traditional operator tasks is expected to be significantly reduced. This allows time for more in-depth monitoring of systems, structures, and components using automated data collection to support tasks such as trending, system evaluation, and planning for corrective actions. The operator can take on additional collateral duties without impacting the timely and effective performance of his or her safety function.

3. STAFFING REQUIREMENTS FOR EMERGENCY RESPONSE

Emergency response considerations for SMRs are the subject of a separate white paper being provided by ANS. Staffing aspects for emergency response are briefly treated here.

SMRs can be designed to function without operator intervention during normal, accident, and postaccident conditions. The passive safety design of the plant places fewer requirements on the staff when dealing with emergencies. Abnormal and emergency plant procedures are expected to minimize the required immediate actions. The required actions would largely be in the nature of monitoring the plant's condition, which can be accomplished by a small staff. Remote-monitoring capabilities are inherent in digital controls reducing, if not eliminating, many of the reporting responsibilities of the on-site operators in an emergency. Once an input or a measured parameter is converted to a digital signal, no significant information loss or degradation occurs regardless of the distance the digital information is transmitted.

The physical layout and reduced size of an SMR plant also contribute to making management of an emergency simpler. The smallest SMRs will occupy less than one acre with perhaps three acres of land needed to support plant activities. Limited radiological controls are required during normal or accident conditions.

The time interval of greatest activity for the licensed ROs is the period immediately after an accident/transient or other plant event. The responsibility of the LO(s) is to establish that the plant is performing within its specified safety limits and is achieving a known safe state in accordance with the plant emergency procedures. The emergency procedures identify the actions that need to be taken in a given plant condition. For events where there is no security risk, the guard staff can also provide predefined administrative, communications, and planning help such as making initial notification of government agencies, calling up the duty roster, or calling for fire or medical support.

4. OTHER RELEVANT CONSIDERATIONS

Under 10 CFR 50.12, the NRC may grant NPP licensees an exemption from otherwise applicable regulatory requirements upon determining that (1) the requested exemption is "authorized by law, will not present an undue risk to public health and safety, and [is] consistent with the common defense and security" and (2) "special circumstances are present" that warrant the granting of the exemption. The regulation identifies the "special circumstances" or justifications for which an exemption may be granted.

If requesting an exemption for staffing requirements were to become necessary or advisable, the basis for seeking it could be the provisions of 10 CFR 50.12(a)(2)(ii), which authorize an exemption where no undue risk to public health and safety is otherwise presented upon showing that application of the regulation "is not necessary to achieve the underlying purpose of the rule."

Any requests for exemptions from the requirements of 10 CFR 50.54(m) concerning the number of licensed personnel should be justified and reviewed using the NRC's "Guidance for Assessing Exemption Requests from the Nuclear Power Plant Licensed Operator Staffing Requirements Specified in 10 CFR 50.54(m)" (NUREG-1791).

NUREG-1791 provides the guidance necessary for submittal of the exemption request and all required task analysis necessary to justify the exemption. The task analysis steps include simulation capability to verify the capability of the human operators to manage multiple SMRs. The verification process identifies issues that need to be addressed in the design of the control room HSI to reduce the potential for human errors in the context of one RO being responsible for monitoring multiple SMRs, under the oversight of a control room supervisor/SRO and with assistance from other licensed staff present in the Main Control Room (MCR).

While licensees can pursue exemptions after the design is complete, the exemption process provides little up-front guidance to the designers. Tailored guidance for the designers is needed early in the process. As discussed above, the current NRC guidance does not extend to the number of units being co-located for some designs or would require an excessive number of operators for other designs. Designers will need to make assumptions about what will be appropriate deviations from NRC requirements. Regulatory certainty and transparency warrant the NRC engaging definitively early in the design process to ensure designers are not making overly aggressive assumptions that result in costly redesign during licensing.

5.0 CONCLUSIONS

As indicated in Section 4.0, this paper focuses primarily on staffing requirements necessary to support safe operation of the new generation of SMR designs. Evaluation of design and operation features for small and advanced reactors indicates that staffing requirements for the new SMR designs may be reduced in comparison to those applied for larger plants without compromising overall safety. The factors that contributed to this demonstrable potential for a reduced number of operating staff include the following:

- Inherent safety, reduced number of systems, and passive safety design require less operator intervention.
- Small source term compared to existing plants reduces the potential consequences of accidents.
- The small site can be monitored and maintained by fewer people.
- A greater proportion of the radioactive systems is contained within the containment structures, and health physics requirements are greatly reduced.
- Even when multiple modules of an SMR design are combined in one facility so as to have a cumulative capacity comparable to a large plant of the GEN III/III+ designs, the above factors suggest that the number of LOs may be less than would be currently required.
- Simplicity of operation allows for additional collateral duties for LOs without compromising essential safety functions.

While formal PRAs for the new SMR designs have yet to be issued, the calculated probability of a significant release and potential for off-site dose consequences can be expected to be lower than those for both advanced reactor designs and current-generation reactors. The reasons for this are the following:

- The simple, passive features should result in a lower calculated probability of core damage than current-generation plants.

- The capability of the containment structure and its passive nature cooling capability provide a reliable barrier to release for those designs that rely on containments.

- The radionuclide inventory is orders of magnitude less than that used in the current large reactors in use.

6.0 RECOMMENDATIONS

1. Updated regulatory guidance is needed. ANS will collaborate with the NRC to develop alternate staffing requirements for SMRs that result in the reduced operator staffing based on clearly identifiable criteria, and such approval will be obtained within the framework of existing regulations.

2. SMR applicants may pursue exemptions on a case-by-case basis. New regulatory guidance addressing staffing requirements for SMRs may not be available at the time of submittals for Design Certification or conditions of licenses. 10 CFR 50.12 allows seeking exemptions from regulatory requirements when warranted. SMR applicants should be prepared to ask for such exemptions in the staffing area if the need for them is identified after discussions with the NRC staff. Early discussions between representatives of SMR applicants and the NRC staff concerning staffing should be held to determine, among other things, whether seeking such an exemption in one or more areas will be necessary.

7.0 REFERENCES

1. C*ode of Federal Regulations*, Title 10, "Energy," Part 50, "Domestic Licensing of Production and Utilization Facilities," Sec. 50.54, "Conditions of Licenses," U.S. Nuclear Regulatory Commission.

2. *Federal Register*, 50 FR 43621, "Policy Statement on Engineering Expertise on Shift" (Oct. 1985).

3. NUREG-0800, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition," Rev. 6, U.S. Nuclear Regulatory Commission. (Sep. 2007).

4. C*ode of Federal Regulations*, Title 10, "Energy," Part 50, "Domestic Licensing of Production and Utilization Facilities," Sec. 50.12, "Specific Exemptions," U.S. Nuclear Regulatory Commission.

5. NUREG-1791, "Guidance for Assessing Exemption Requests from the Nuclear Power Plant Licensed Operator Staffing Requirements Specified in 10 CFR 50.54(m)" (July 2005).

6. NUREG/CR-6838, "Technical Basis for Regulatory Guidance for Assessing Exemption Requests from the Nuclear Power Plant Licensed Operator Staffing Requirements Specified in 10 CFR 50.54(m)," U.S. Nuclear Regulatory Commission (Feb. 2004).

APPENDIX A

Staffing Requirements Reproduced from 10 CFR 50.54(m)

(m)(1) A senior operator licensed pursuant to part 55 of this chapter shall be present at the facility or readily available on call at all times during its operation, and shall be present at the facility during initial start-up and approach to power, recovery from an unplanned or unscheduled shut-down or significant reduction in power, and refueling, or as otherwise prescribed in the facility license.

(2) Notwithstanding any other provisions of this section, by January 1, 1984, licensees of nuclear power units shall meet the following requirements:

(i) Each licensee shall meet the minimum LO staffing requirements in the following table:

Minimum Requirements[1] Per Shift for On-Site Staffing of Nuclear Power Units by Operators and Senior Operators Licensed Under 10 CFR Part 55

Number of nuclear power units operating[2]	Position	One unit	Two units		Three units	
		One control room	One control room	Two control rooms	Two control rooms	Three control rooms
None	Senior Operator	1	1	1	1	1
	Operator	1	2	2	3	3
One	Senior Operator	2	2	2	2	2
	Operator	2	3	3	4	4
Two	Senior Operator		2	3	[3]3	3
	Operator		3	4	[3]5	5
Three	Senior Operator				3	4
	Operator				5	6

[1]Temporary deviations from the numbers required by this table shall be in accordance with criteria established in the unit's technical specifications.

[2]For the purpose of this table, a nuclear power unit is considered to be operating when it is in a mode other than cold shutdown or refueling as defined by the unit's technical specifications.
[3]The number of required licensed personnel when the operating nuclear power units is controlled from a common control room are two senior operators and four operators.

(ii) Each licensee shall have at its site a person holding a senior operator license for all fueled units at the site who is assigned responsibility for overall plant operation at all times there is fuel in any unit. If a single senior operator does not hold a senior operator license on all fueled units at the site, then the licensee must have at the site two or more senior operators, who in combination are licensed as senior operators on all fueled units.

(iii) When a nuclear power unit is in an operational mode other than cold shutdown or refueling, as defined by the unit's technical specifications, each licensee shall have a person holding a senior operator license for the nuclear power unit in the control room at all times. In addition to this senior operator, for each fueled nuclear power unit, a LO or senior operator shall be present at the controls at all times.

(iv) Each licensee shall have present, during alteration of the core of a nuclear power unit (including fuel loading or transfer), a person holding a senior operator license or a senior operator license limited to fuel handling to directly supervise the activity and, during this time, the licensee shall not assign other duties to this person.

(3) Licensees who cannot meet the January 1, 1984 deadline must submit by October 1, 1983 a request for an extension to the Director of the Office of Nuclear Regulation and demonstrate good cause for the request.

APPENDIX B

Survey of Selected Key Design Features of SMR Designs with Implications for Staffing

The following discussion summarizes those features typical of SMRs that most directly affect the necessary staffing for safe operation. These features may or may not be present in each SMR design.

In general, SMRs are both significantly smaller and simpler than the reactors currently licensed by the NRC. The necessity for active operator participation is reduced for both normal steady-state operations and responding to transients and postulated accidents. The potential radiological consequences of any accidents are also orders of magnitude smaller than those of existing plants, due to the smaller source terms. This suggests that a smaller operating crew would be acceptable for normal monitoring and evolutions and for accident response.

B.1. ACCIDENT PREVENTION

B.1.1. Normal Operation

A desirable feature of a power generation source such as a reactor power plant is the ability to follow the system load, that is, to adapt the power output to meet moment-to-moment demand in the electric load it serves, in order to ensure that the power source is producing neither too little nor too much energy. Load-following is achieved in SMR design in various innovative ways.

One method may be by controlling the water flow to the steam generator, thus manipulating the core inlet temperature. As the generator output matches the load, changes in the coolant temperature introduce a positive or negative reactivity effect in the core, causing the reactor power to follow. The load-following capability simplifies operation of the power plant and reduces the likelihood of reactor trips. The ability to remain operating during significant load changes increases plant safety by avoiding the occurrence of off-normal events. The simplicity of such a design also reduces the need for online testing of safety systems. Online testing is itself a source of plant transient initiators.

SMR designs using liquid sodium as a coolant for the reactor permit operation at nearly atmospheric pressure with a large margin to the boiling point of the coolant (subcooling margin). Maintaining the core coolant subcooled provides assurance that the fuel cladding is not being overheated. The subcooling margin for these reactors is much greater than in an existing pressurized water reactor. Operation at atmospheric pressure eliminates the possibility of pressure transients.

B.1.2. Safety Systems

Safety systems for an SMR will include the systems used to shut down the reactor and those used to remove decay heat.

The safety systems of the SMR designs all include some version of a Reactor Shutdown System (RSS). The RSS in an SMR will be inherently simpler than that of the current generation of nuclear plants, primarily due to the smaller size of the reactors. The RSS may be activated either by loss of power, by the neutron detection instrumentation, or by some other process parameter such as the core outlet temperature of the reactor vessel. When activated, the RSS causes the reactor to shut down. Should the RSS fail to be activated, the reactor power level would nonetheless drop if the design incorporates a negative power coefficient of reactivity, bringing the reactor to a shutdown state.

After the automatic shutdown, passive systems remove energy from the reactor and connected loops, respectively. These passive safety systems do not require power for valve movements to initiate them. These systems may rely on natural circulation of the process fluid and/or air and do not depend on operator action.

The inherent capability of these designs to remove decay heat through passive means avoids the need to resort to active systems to maintain the plant in a safe shutdown condition. Table B.1 illustrates the simplicity of the typical SMR safety systems by comparing them to those in current-generation NPPs. The improvement in plant safety of the SMR designs over conventional designs is illustrated by the fact that many or all of the systems/features upon which a current-generation reactor relies are not required to maintain plant safety in a typical SMR design. The SMR designs eliminate the need for these active systems and thus increase plant safety.

TABLE B.1
Comparison of Current-Generation Plant Safety Systems to Potential SMR Design

Current-Generation Safety-Related Systems	SMR Safety Systems
High-pressure injection system. Low-pressure injection system.	No active safety injection system required. Core cooling is maintained using passive systems.
Emergency sump and associated net positive suction head (NPSH) requirements for safety-related pumps.	No safety-related pumps for accident mitigation; therefore, no need for sumps and protection of their suction supply.
Emergency diesel generators.	Passive design does not require emergency alternating-current (ac) power to maintain core cooling. Core heat removed by heat transfer through vessel.
Active containment heat systems. Containment spray system.	None required because of passive heat rejection out of containment. Spray systems are not required to reduce steam pressure or to remove radioiodine from containment.
Emergency Core Cooling System (ECCS) initiation, Instrumentation and control (I&C) systems. Complex systems require significant amount of online testing that contributes to plant unreliability and challenges of safety systems with inadvertent initiations.	Simpler and/or passive safety systems require less testing and are not as prone to inadvertent initiation.
Emergency feedwater system, condensate storage tanks, and associated emergency cooling water supplies.	Ability to remove core heat without an emergency feedwater system is a significant safety enhancement.

B.1.3. Support Systems

Auxiliary or supporting systems can affect the reliability of safety systems. Use of passive systems in place of active systems improves reliability. In the typical SMR design, elimination of all active cooling systems from the reactor side and elimination of all emergency cooling systems from the reactor building result in greatly improved plant simplicity and reliability.

Radiated heat from the reactor vessel is removed by passive means. The conducted heat into the containment may also be removed by the natural air cooling from the surface of the containment. An integral nuclear steam supply system (NSSS) may use an immersed primary pump, so no motor or pump seal cooling is required. As the result, all active cooling systems may be eliminated. This is illustrated in Table B.2 below.

TABLE B.2
Comparison of Current-Generation Plant Safety Systems to Potential SMR Design

Current LWR Support Systems	SMR Support Systems
Reactor coolant pump seals. Leakage of seals has been a safety concern. Seal maintenance and replacement are costly and time-consuming.	Integral designs eliminate the need for seals.
Ultimate heat sink and associated interfacing systems. River and seawater systems are active systems, subject to loss of function from such causes as extreme weather conditions and bio-fouling.	SMR designs are passive and reject heat by conduction and convection. Heat rejection to an external water heat sink is not required.
Closed cooling water systems are required to support safety-related systems for heat removal of core and equipment heat.	No closed cooling water systems are required for safety-related systems.
Heating, Ventilating, and Air-Conditioning (HVAC). Required to function to support proper operation of safety-related systems.	The plant design minimizes or eliminates the need for safety-related room cooling eliminating both the HVAC system and associated closed water cooling systems.[a]

[a]S. Hattori and A. Minato, “Passive Safety Features In 4S Plant,” *1993 Proceedings of the 2nd ASME/JSME Joint Conference Nuclear Engineering: Volume 1*, ASME.

B.2. THERMAL INERTIA

Many SMR designs have a higher thermal inertia than existing licensed designs. This results in fewer severe transients and reduced necessity for operator intervention.

Liquid sodium is a coolant with excellent heat absorption capacity, very high thermal conductivity, low operating pressure (basically atmospheric), and superb natural convection capability. Decay heat can be removed from the core by natural circulation of the primary coolant and discharged to a heat exchanger. Passive cooling can also be provided by natural air circulation around the exterior of the reactor vessel. The large heat capacity of liquid sodium provides a large heat sink for the core. The time to heat up the fluid is substantially longer than for water-cooled reactors, and the available time for responding to accidents is thus significantly increased.

High Temperature Gas Reactors (HTGRs) also exhibit a large thermal inertia of the reactor core, with a large temperature margin between the operation limit and the safe operation limit, and slow temperature variations during power changes in a maneuvering mode.

Small and medium LWRs can also benefit from higher thermal inertia in comparison to existing plants by including a larger reactor vessel relative to the core size, contributing to longer response times in transients and accidents.

B.3. CONTAINMENT

SMR designs reduce the level of challenge to containment vessels/buildings in relation to existing designs. Most LWR SMR designs make use of a primary-system-in-one-vessel approach. The entire primary system is totally contained within one American Society of Mechanical Engineers (ASME) III, Class 1 vessel. By definition, such a vessel is not assumed to fail catastrophically so Loss-Of-Coolant Accidents (LOCAs) are eliminated. However, it remains necessary to have a separate containment vessel to deal with combustible gas and secondary system failures that could lead to core damage. These containment systems can be smaller and less robust than large LWR containments because the range of possible events results in lower pressures and/or temperatures.

HTGR SMR designs have a very robust fuel design that cannot melt under any circumstances encountered in the core. They also use a compressed gas such as helium in the reactor, not subcooled water. This significantly reduces the potential internal challenges to the containment in the event of a leak. There is no event possible in an HTGR that results in the physical challenges to a conventional reactor containment building. Not only is the pressure in the containment lower after a LOCA, but also the resultant impact on the core does not lead to core damage or the accompanying release of fission products. However, there is a range of accidents that can lead to the generation of hydrogen in significant quantities. In addition, there are always small amounts of tramp fission products and activation products in the coolant. The cumulative effect of all these factors lessens the demands on the containment structure so that its cost and complexity are significantly reduced.

The containment for a Sodium-Cooled Fast Reactor (SFR) is typically composed of a steel vessel and may also include a nearly impenetrable outer concrete vault. The entire assembly can be installed underground. Pressurization of the SFR containment appears much less likely than in existing reactors because the reactor coolant system is operated at ambient pressure. The high boiling point of liquid sodium means that less energy is transferred to the containment vapor space if the reactor pressure boundary fails. Use of liquid sodium eliminates hydrogen generation due to water-cladding interaction. As a result, the containment volume can be small, which allows for effective passive cooling. These features mitigate potential releases of radioactive materials in the event of an accident.