



SCHOOL OF PUBLIC POLICY

CENTER FOR INTERNATIONAL &
SECURITY STUDIES AT MARYLAND

Safeguards-by-design for advanced nuclear systems

By Lance K. Kim, M.P.P., Ph.D.

CISSM Working Paper

July 2017

This paper was made possible with the generous support of the John D. and Catherine T. MacArthur Foundation.

Center for International and Security Studies at Maryland
4113 Van Munching Hall, School of Public Policy
University of Maryland
College Park, MD 20742
(301) 405-7601

Abstract

The emergence of an advanced nuclear industry has renewed the pursuit of small modular and advanced reactor technologies to supply low carbon energy. By the same token, these developments potentially expose gaps in current safeguards practices, particularly for reactor designs utilizing novel coolants and fuel forms—underscoring calls for the early application of Safeguards-by-Design to effectively and efficiently detect diversion and misuse. Other innovations may necessitate additional measures to credibly assure the absence of undeclared activities. This paper discusses three types of advanced nuclear and nuclear-related technologies as illustrations of these challenges: 1) micronuclear reactors, 2) molten salt reactors, and on the balance-of-plant side, 3) thermal energy storage and dry cooling. It then identifies high-level safeguards development needs associated with these on-the-horizon technologies so as to elevate safeguards considerations in the minds of reactor developers and investors.

Acknowledgements and Disclaimer

This working paper was supported under a contract with the Center for International and Security Studies at the University of Maryland in the School of Public Policy. The author also acknowledges the support of Southern Company Services in the preparation of this working paper. The views and opinions expressed in this working paper are those of the author.

Introduction: Perceptions of safeguards

The emergence of an advanced nuclear industry has renewed the pursuit of small modular and advanced reactor technologies to supply low carbon energy. Departing significantly from current technologies in power output and utilizing new coolants and fuels, these concepts promise significant performance advantages over existing technologies.[1] They also potentially expose gaps in existing safeguards practices designed to detect the diversion of fissile material and the misuse of declared nuclear facilities.

To address these gaps, many private-sector advanced reactor developers have expressed commitments to the “three S’s” of safety, security, and safeguards. They also profess to ensure that these priorities are achieved “by design”—that is, carefully planned and built into the reactor design—to avoid costly and protracted back-fitting. The ballooning cost of safeguarding the Japanese reprocessing facility at Rokkasho underlines the necessity for early adoption of Safeguards-by-Design approaches to efficiently achieve safeguards objectives.[2], [3]

Many developers, however, appear to treat the three S’s in the order described, with safeguards a distant third priority. The relative immaturity of many advanced reactor designs may explain the lack of focus on safeguards. Yet at times, safeguards appear explicitly underemphasized and even misunderstood. For example, state-level proliferation threats are often conflated with physical protection threats posed by non-state actors. The distinction between proliferation resistance and safeguards¹ is also sometimes blurred, touting proliferation resistance benefits without detailing a safeguards approach. By comparison, developers appear to readily grasp safety and security considerations involving random equipment failures and malevolent human acts committed by others.

The lack of focus on safeguards may stem from a reluctance by developers to view themselves as the potential enemy. Re-born in the minds of Silicon Valley entrepreneurs, far removed from nuclear technology’s defense establishment origins, some advanced nuclear reactors are thought by their developers to serve a virtuous and moral purpose—saving the world from climate change rather than contributing to its destruction.[6] To many in these entrepreneurs, the anxieties of the nonproliferation community appear to be anachronistic and unrealistic—the result of hyperactive imaginations forged in a bygone era. Moreover, they conclude that nuclear power’s benefits far outweigh the risk of a civilian nuclear program leading to nuclear weapons. The notion that any reactor, even the venerable light water reactor, poses a proliferation risk is often downplayed by nuclear power’s proponents.²[7]

¹ Whereas proliferation resistance is defined as the “characteristic of [a Nuclear Energy System] that impedes the diversion or undeclared production of nuclear material or misuse of technology by the Host State seeking to acquire nuclear weapons or other nuclear explosive devices”,[4] safeguards is an element of proliferation resistance concerned with the “...the timely detection of diversion of significant quantities of nuclear material from peaceful nuclear activities to the manufacture of nuclear weapons or of other nuclear explosive devices or for purposes unknown, and deterrence of such diversion by the risk of early detection.”[5]

² Arguably, advanced reactor developers could embrace this argument i.e. if existing designs are acceptable for international sale, then many advanced reactors could be as well.

While cases of diversion and misuse of civilian nuclear power facilities have been rare, this view glosses over the role of effective safeguards to achieving this outcome. As no nuclear reactor is proliferation-proof, an inadequately safeguarded reactor may be the most prone to proliferation. In the case of a light water reactor, a state may come to view low burn-up fuel in the core as an attractive source of weapons usable plutonium were it not for the likelihood of detection by safeguards.

Recognizing the importance of safeguards to achieving nonproliferation objectives, this working paper offers a high-level examination of selected advanced nuclear technologies with the dual goals of: 1) elevating safeguards considerations in the minds of advanced reactor developers and investors, and 2) raising awareness of emerging technologies amongst the safeguards community. In addition to outlining potential gaps in safeguards practices, the paper also identifies research to draw down these risks.

Of the systems under active exploration by private-sector reactor developers, three classes of nuclear and nuclear-related technologies appear to be generating significant interest: 1) micronuclear or very small modular reactors (vSMRs) for use in remote areas, 2) molten salt reactors with liquid fuel, and on the balance-of-plant side, 3) thermal energy storage and dry cooling to cope with market distortions and water stress. These systems are only a sample of the technologies under exploration by developers. The focus on them, and the potential safeguards challenges they present, should not be construed as a condemnation, merely part of the process of promoting effective and efficient safeguards.

Micronuclear reactors

While lacking a widely accepted definition, micro-nuclear or vSMRs are generally lower in power output than small modular reactors.³ Of the vSMR designs evaluated by a recent study conducted for Canada's Ontario Ministry of Energy, electrical power output ranged from a couple to a few dozen MWe.[8] Such reactors may find markets supplying electrical power and process heat to small communities and industrial operations (e.g., oil and gas production, mining operations, military installations) in remote arctic and island areas currently reliant upon costly and unreliable diesel generation.[8]–[14]

For many micronuclear design concepts, factory prefabrication with minimal in-field construction activities incorporates many of the lessons learned by the U.S. Army when it constructed small reactors at remote sites with short construction seasons and high installation cost rates.[15], [16] From 1957 to 1976, the U.S. Army built and operated several small reactors based on light water and gas reactor technology ranging in size from 3 to 45MWt, including the PM-3A reactor at McMurdo Station in Antarctica (**Error! Reference source not found.**). The military advantages of these reactors included “the reduced logistics load for transportation systems, the resistance of the nuclear power plant to damage because of its inherent heavy construction, and the suitability of the nuclear power plant for underground construction because of its lack of combustion gases.” One disadvantage cited was “the possible contamination of a small area in the case of destruction of a nuclear power plant.”[14]

³ Small modular reactors are defined as producing less than 300MWe in output.[8]



Figure 1 PM-3A reactor components arriving by ship at McMurdo Station, Antarctica

In addition to presenting some of the same advantages of these past systems, new micro-nuclear designs may also improve the safeguardability of the system on the whole. In particular, some micronuclear designs incorporate difficult-to-access, long-life cores, which could present intrinsic physical barriers to diversion and make it possible to maintain continuity of knowledge over nuclear material over decade-long timescales. Yet, developers also must strike a balance between guarding against unauthorized access and facilitating access by international inspectors who will need to conduct periodic inspections. For instance, the designs of sealing systems, reactor internals, and other physical barriers should allow for regular physical inventory taking and design information verification.[17], [18] Special instrumentation (e.g., ultrasonic under sodium viewing and active neutron interrogation fork detectors [19], [20]) will be needed for designs with opaque coolants (e.g., sodium or lead) to verify the identity of serialized fuel assemblies, and perform gross and partial defect tests.

Siting these reactors in remote locations may have mixed effects for safeguards. Their remoteness may raise barriers to diversion and misuse, but they may also disproportionately increase the costs of in-field safeguards activities in comparison to larger, more centrally located facilities.[17] While not an exact analogue, security requirements suffer from similar diseconomies of scale. Estimates of protective guard force requirements to satisfy two-person rules and achieve adequate protection for the 10MWe 4S reactor proposed for Galena, Alaska, represented a major component of staffing and operational costs.[21] Efficiently achieving safeguards objectives in these locations would likely entail extensive use of remote and unattended monitoring systems operating with high assurances of data integrity and authenticity to achieve “operational transparency” and “virtual access” to the reactor.[17] End-of-life considerations may also contribute to long-lasting safeguards burdens. These reactors, some with low burn-up cores at end-of-life, may become long-term liabilities if stranded at far-flung sites by logistical challenges and/or public opposition to spent fuel shipments.

Molten Salt Reactors

Molten salt reactors (MSR, Figure 2) appear to have attained “flavor-of-the-day” status amongst many advanced reactor developers. While wide variations in designs preclude generalization (e.g., thermal vs. fast neutron spectrum, thorium vs. uranium fueled, breeder vs. burner, etc.), the use of fluid fuel rather than solid fuel is the distinguishing feature of all MSR designs.[22]–[24] The intrinsic features and fuel cycles of many molten salt designs promise to increase proliferation resistance by utilizing low-attractiveness, homogenous fuel; by burning plutonium inventories in the case of low conversion ratio systems; and by reducing demand for fuel cycle services, such as enrichment and reprocessing.[24]–[29] Nevertheless, it bears repeating that no design yet conceived, including thorium-fueled MSRs, is completely proliferation proof.[30]

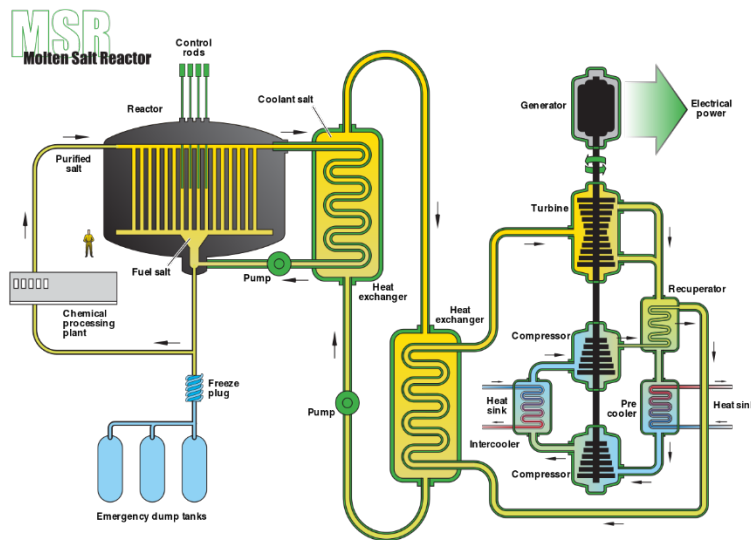


Figure 2. Schematic of a Molten Salt Reactor [31]

Regardless of design features, a model (generic) facility safeguards approach is a key need for this class of reactors utilizing fluid fuel.⁴ Absent this guidance, the acceptability of notional safeguards approaches, such as those where nuclear material “checks in, but doesn’t check out,” is questionable. Indeed, the IAEA anticipates the need for significant research and development efforts to develop a generic safeguards approach:

“... designers should be aware that such reactors cannot be considered item facilities. ... more stringent nuclear material accountancy measures will likely be required to verify the quantities, locations and movements of the nuclear material. These measures can include, but are not limited to, fuel flow monitors, seals, video surveillance, the use of sensors to trigger other sensors, more accurate NDA measurements and sampling plans that select additional items for verification. Most of this instrumentation does not yet exist and a significant R&D effort can be expected.”[3]

⁴ A model (generic) facility safeguards approach is the recommended approach for a particular facility type developed for a postulated reference plant that specifies inspection goals and safeguards activities accounting for diversion assumptions, available safeguards measures, facility design information and practices, etc.

Toward an MSR safeguards approach. A safeguards approach for MSRs could be envisioned as a hybrid of safeguards practices at item reactors (e.g., LWRs), fuel cycle facilities (e.g., fuel fabrication or reprocessing facilities), and on-load reactors where refueling and defueling occurs at power (e.g., CANDU and PBMR reactors).

A conceptual safeguards approach for the Pebble Bed Modular Reactor (PBMR) illustrates a case of an on-load reactor where item accountancy is not entirely applicable because of the use of unserialized, semi-indistinguishable pebble fuel. Like the PBMR, a MSR safeguards approach may comprise three principal material balance areas (MBA): a storage area each for fresh and spent fuel that are treated as item facilities, and a reactor area treated as a non-item facility where an "...engineered solution [prevents] significant accrual of MUF (Materials Unaccounted For)..."[19]

Fuel receiving, storage, and shipping MBAs can be treated as item facilities by sealing and serializing containers of solidified fuel salt. Like other on-load reactors such as CANDU, fuel-item transfer activities from receiving areas to the core, and from the core to storage and shipping areas, could be assayed and monitored by integrated instrument systems backed by dual layers of containment and surveillance measures that minimize common tampering or failure modes.[32] In fuel storage areas treated as item MBAs, the primary advantage is the absence of MUF. Nevertheless, in the event of a loss of item integrity, materials accountancy will play a key role in reestablishing continuity of knowledge. For example, following the 2003 fuel handling incident at the Paks Nuclear Power Plant in Hungary, the rubble from damaged fuel assemblies was containerized and reverified with "gram precision" with gamma- and neutron-based nondestructive assay techniques.[33]

The principal MSR safeguards challenge will likely arise from the rate of MUF accrual in the MBA bounding the core. This will be particularly true for reactors with long intervals between anticipated maintenance outages with infrequent opportunities for inventory verification. For the limited number of non-item facilities that currently exist, the International Atomic Energy Agency (IAEA) has relied upon safeguards approaches that assure continuity of knowledge—an approach that may lead to costly and complicated containment and surveillance (C/S) systems. In these instances, should continuity be lost, the inability to reverify inventories through materials accountancy risks a noncompliance finding for the remainder of the facility's lifetime.[19] This possibility reinforces the fundamental importance of materials accountancy in a safeguards approach to recover from losses of continuity and to guard against unanticipated mechanisms for material losses.[34]

While materials accountancy at MSRs will be more involved than item facilities such as solid-fueled fast breeder reactors, accountancy requirements may be less demanding than a reprocessing facility. The absence of unirradiated direct-use material in many MSR concepts distinguishes them from facilities like aqueous reprocessing facilities. Material throughput in MSRs is also generally orders of magnitude lower than large reprocessing facilities, potentially reducing accounting uncertainties associated with material flows. However, measurement uncertainties associated with in-process inventories may significantly contribute to MUF. Uncertainties in reactor physics calculations of in-core inventory changes also require assessment. For LWR spent fuel, uncertainties in plutonium content range from 3% to 10% and sometimes larger, and depend on correlating measurements of gamma and neutron emissions to reactor physics calculations.[35], [36] For reactors that process fuel salt (e.g., to remove gaseous

and particulate fission products [25]), resultant waste streams should also be assayed to ensure that any residual fissile material is practicably irrecoverable.[37]

Table 1. Comparison of fast breeder reactor, a liquid fueled molten salt reactor, and a large reprocessing facility.

	Fast Breeder Reactor	Liquid Fueled Molten Salt Reactor	Rokkasho Reprocessing Plant
Safeguards Approach	Item facility	Non-item reactor	Bulk-handling facility
Inputs	Unirradiated Direct Use	Indirect Use	Irradiated Direct Use
Outputs	Irradiated Direct Use	Irradiated Direct Use	Unirradiated Direct Use
Holdup	N/A	Low-wettability fuel salt, lower surface-to-volume ratio	Annual cleanout
Throughput	Fraction of core load as items	<<800MTHM/year	800 MTHM/year
In-Process Inventory	Core load as items	>4MT Irradiated Direct Use	4MT
Operation Period	Months to years	Up to years	200 days

As noted by the IAEA, much of the needed instrumentation for implementing MSR safeguards requires development.[3] Accurately measuring the fissile content of the reactor’s core could involve periodic reverification of core mass or volume, which would require accounting for dimensional changes of the reactor vessel, as well as guarding against new diversion strategies, such as a “brick in the toilet tank” that would displace fluid fuel for diversion. Pyroprocessing instrumentation might be adapted for molten salt reactor operations (e.g., voltammetric and potentiometric sensors, laser-induced breakdown spectroscopy, etc.[38]–[41]), as nuclear-based, non-destructive assay instrumentation may be blinded by the intense neutron and gamma background of freshly irradiated molten salt fuel.[42]

Containment and surveillance systems adapted to molten salt reactor environments will be essential, complementary measures to material accounting to cover diversion pathways and enhance safeguards efficiency. Many of these systems may need to operate in high radiation fields nearby systems containing irradiated fuel salt and fission products. While these radiation fields may be considered an intrinsic barrier to diversion, remote maintenance capabilities necessary for operations are a potential route to state-level diversion and misuse. Monitoring of this equipment may thus be necessary to exclude their misuse and to detect the introduction of undeclared equipment into process areas.

Process monitoring. Process monitoring approaches have the potential to provide additional assurances of non-diversion. Unlike solid-fueled heterogeneous cores, the homogeneity of MSR cores potentially simplifies measurements of core composition and supports near-real-time accountancy of material inventories—provided that sampling biases can be excluded. Physics-based signatures might also contribute to assurances of non-diversion. Prompt and protracted

diversions of fuel salt leading to abnormal changes in reactivity could trigger an inventory verification and other efforts to investigate these anomalous signatures.[25] Process monitoring can also serve as a consistency check on declarations, as a means of localizing material losses in time, and by assisting in the resolution of other safeguards anomalies.

State Level Concept. Beyond the reactor, advanced fuel cycles with minimal demands for sensitive fuel cycle services, such as enrichment and reprocessing, might also lead to improvements in safeguards effectiveness and efficiency. One way these gains could be realized is by appealing to the holistic nature of safeguards implementation under the IAEA's State Level Concept. Safeguards implemented on a facility-level basis, which have been the norm to ensure uniform safeguards implementation across states, give little consideration to a state's nuclear capabilities and other state specific factors. For example, requirements for the timely detection of diversion from reactors assume the existence of a clandestine reprocessing capability within the state. This conservatism is thought to lead to overly stringent timeliness requirements in states with limited fuel cycle capabilities. By considering a state's nuclear capabilities as a whole, reactor technologies without demand for enrichment and reprocessing might contribute to a Broader Conclusion that "...no indications had been found..." that "...give rise to a proliferation concern." [43], [44] With such assurances in place, safeguards could be applied with lower frequency and intensity at reactors "upstream" of reprocessing on material acquisition pathways.

Balance-of-plant technologies

Some emerging nuclear power-related technologies, such as thermal energy storage and dry cooling, affect the non-nuclear supporting systems of a nuclear power plant known as the "balance-of-plant." These non-nuclear technologies could affect safeguards implementation as much as the nuclear systems. Designed to help power plant operators cope with market distortions and the impact of water stress on operations, these technologies could affect international inspectors' abilities to detect "... undeclared nuclear material or activities in the State as a whole" under a state's Comprehensive Safeguards Agreement.[45] For instance developments in thermal energy storage and dry cooling technologies that affect a plant's heat signature could help states evade detection and monitoring by commercial satellites.[46] This in turn may necessitate more effective and efficient verification by the IAEA and its member states to provide credible assurances that all nuclear material remains in peaceful purposes.

Thermal energy storage. Thermal energy storage technologies that allow a nuclear plant to store excess output while electricity demand is low could increase the profitability of nuclear units in distorted energy markets where electricity prices are depressed and even negative at times. This exact situation is contributing to the premature closure of nuclear power plants with limited load following capabilities.[47] Thermal energy storage systems enable baseload nuclear plants to deliver "on demand peak power" by shifting power output to more profitable times of the day.[48], [49] (

Figure 3)

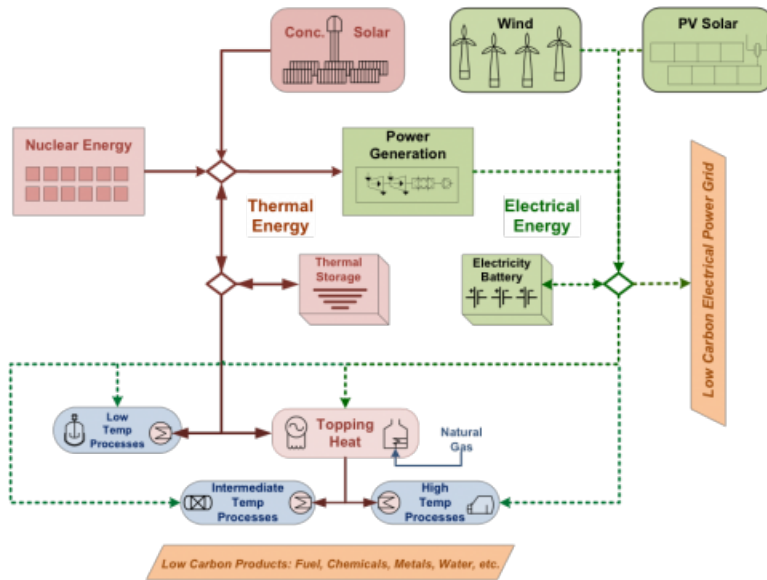


Figure 3 Schematic of a nuclear-renewable hybrid system incorporating thermal energy storage, extracted from [48]

These same capabilities, if refined and adapted, could enable nuclear reactors and other facilities that typically emit thermal signatures to remain hidden and hinder the monitoring of known unsafeguarded facilities (e.g., Yongbyon, North Korea[50]). For instance, steam accumulators, packed-bed thermal storage, sensible heat systems, hot-rock/hot-air systems, and other technologies could hinder detection by delaying thermal energy releases (e.g., steam plumes, warm water outfalls) to periods between observations (e.g., satellite overpasses).[49], [51]–[53] However, heat rejection equipment (e.g., cooling towers) may be more conspicuous if designed for the combined output of the reactor and storage system. For known reactors, thermal signatures may become a less reliable indicator of operational history and fissile material production. These considerations reinforce the need for onsite measures to verify reactor operations and shutdown status.[46]

Dry cooling. Comparable issues arise from heat rejection technologies designed to cope with growing strains on water resources.[54] Nuclear reactors employing cooling technologies with minimal evaporative water losses (e.g., air cooling, sorption-based cooling, multimode [convection/ radiant] cooling) can now be sited in areas where wet cooling—which relies on a source of cooling water—is currently infeasible. (Figure 4)

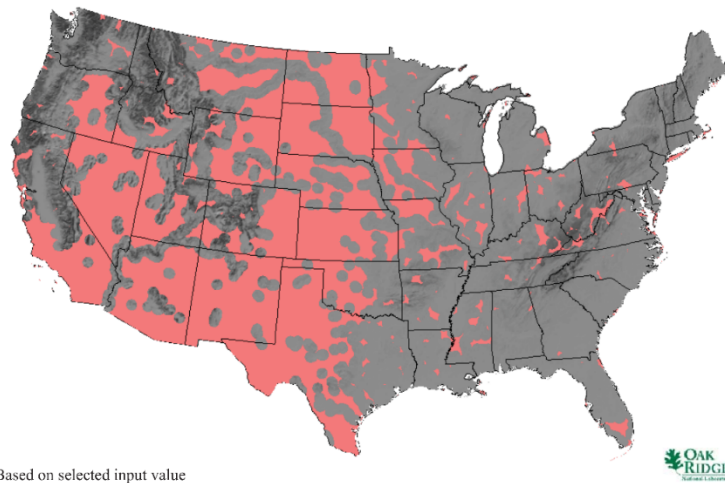


Figure 4 Areas excluded for small reactors due to inadequate stream flow for cooling water (shaded pink) may now accommodate reactors with dry cooling systems, extracted from [55]

If reactors can be sited further from water sources, then this enlarges the space within which to search for clandestine nuclear facilities, potentially requiring new search instruments and techniques.[56] While “large and hot” cooling systems, such as air-cooled condensers and radiative cooling, may be readily detected via remote sensing, “small and cold” systems pose greater challenges. For example, the 20MWt SM-1A reactor at Fort Greely, Alaska, utilized a well doublet to reinject groundwater heated by the reactor. The system drew groundwater from two onsite cooling water wells rated at 1.44 million gallons/day each and injected heated water into a dry well 215 yards north of the facility capable of accepting 2.16 million gallons/day.[15], [57] Though necessity likely drove this development at Fort Greely, its adaptability for concealment purposes illustrates the potential unintentional consequences of these technologies. Thermal signatures of a well doublet may be indiscernible in coarsely pixelated thermal infrared imagery if heat signatures remain buried deep underground or are small in size. Signatures that do emerge could substantially lag behind reactor operations due to the slow movement of groundwater.[53]

Conclusions

This paper presents several of the many safeguards challenges likely to be posed by new designs being pursued by the advanced nuclear reactor industry. As examinations of the design features of some micronuclear and molten salt reactors suggest, identifying these challenges early in the design process improves the odds of cost-effectively implementing safeguards by adapting existing safeguards approaches, modifying facility design, and/or developing innovative safeguards measures and approaches.[58] While resolving some emerging safeguards issues may entail significant research and development (e.g., nuclear instrumentation), other considerations are relatively mundane matters implemented relatively easily in the design process (e.g., electrical power for safeguards equipment).

Additional safeguards challenges may arise as nuclear designs and operations evolve in response to markets and environmental constraints. The emerging balance-of-plant technologies highlighted here point to the need to strengthen safeguards measures to verify reactor operations and the completeness of state declarations. The development of thermal storage and dry cooling technologies may entail a “darkening of the skies,” demanding greater earth observing capabilities and deepening the IAEA’s reliance on member state capabilities.[59]

Complicating matters further, some of these advances will be made by private-sector entities concerned with protecting intellectual property. This could lead nuclear developments to occur less transparently than government-led nuclear power programs. These same commercial sensitivities may stifle early engagement between developers and the international safeguards community. Should these technologies take-off, limited safeguards resources may be quickly strained.

Creative safeguards solutions therefore need to emerge as quickly as the technologies themselves. Doing so requires engagement by all stakeholders. While the safeguards community should strive to anticipate developments and define safeguards approaches, an anticipatory strategy may prove inadequate without efforts to instill a safeguards culture among developers. Doing so requires the nonproliferation community to be seen as solution-oriented rather than engaging in what is often perceived as interminable obstructionism. Similarly, advanced reactor developers must avoid downplaying nonproliferation anxieties. For utilities and investors seeking access to international markets, safeguards-by-design represents a proactive means of drawing-down political and investment risks early in the design process.

About the author

Lance K. Kim is a Senior Nuclear Engineer in the Energy & Environment Division of Southern Research. His research principally supports Southern Company’s advanced reactor projects in the areas of safeguards and technology due diligence. He was previously a Research Fellow in the Nuclear Security Unit of the European Commission Joint Research Centre where he published on open source information analysis and its relation to the International Atomic Energy Agency’s State Level Concept. Prior to the JRC, his work experience includes stints at the Nuclear Regulatory Commission, the IAEA as a U.S. Support Program Fellow in safeguards, the Department of State as an intern in Verification and Compliance, and the RAND Corporation as a Stanton Nuclear Security Fellow. He is a graduate of the University of California, Berkeley with a B.S. in Nuclear and Mechanical Engineering, a M.P.P. in Public Policy, and a Ph.D. in Nuclear Engineering where he was a Public Policy and Nuclear Threats Fellow.

References

- [1] Samuel Brinton, “The Advanced Nuclear Industry,” *Third Way*, 15-Jun-2015. [Online]. Available: <http://www.thirdway.org/report/the-advanced-nuclear-industry>. [Accessed: 17-Jun-2016].
- [2] Michael H. Ehinger and Shirley J. Johnson, “Lessons Learned in International Safeguards - Implementation of Safeguards at the Rokkasho Reprocessing Plant,” Oak Ridge National Laboratory, Oak Ridge, TN, ORNL/TM-2010/23, Dec. 2009.
- [3] “International Safeguards in the Design of Nuclear Reactors,” International Atomic Energy Agency, Vienna, 2014.
- [4] Proliferation Resistance and Physical Protection Evaluation Methodology Working Group, “Evaluation Methodology for Proliferation Resistance and Physical Protection of Generation IV Nuclear Energy Systems,” Generation IV International Forum, GIF/PRPPWG/2011/003, Sep. 2011.
- [5] “The Structure and Content of Agreements Between the Agency and States Required in Connection with the Treaty on the Non-Proliferation of Nuclear Weapons,” International Atomic Energy Agency, INFCIRC/153 (Corrected), Jun. 1972.
- [6] T. Nordhaus, “Time to Stop Confusing Nuclear Weapons with Nuclear Power,” *The Hill*, 14-May-2017. [Online]. Available: <http://thehill.com/blogs/pundits-blog/energy-environment/333329-time-to-stop-confusing-nuclear-weapons-with-nuclear>. [Accessed: 16-May-2017].
- [7] V. Gilinsky, M. Miller, and H. Hubbard, “A Fresh Examination of the Proliferation Dangers of Light Water Reactors,” The Nonproliferation Policy Education Center, Washington, D.C., Oct. 2004.
- [8] Hatch Ltd., “Feasibility of the Potential Deployment of Small Modular Reactors (SMRs) in Ontario,” Ontario Ministry of Energy, Jun. 2016.
- [9] M. Ryan, “A Nuke on the Yukon?,” *American Scientist*, vol. 97, no. 2, p. 112, 2009.
- [10] G. Fay, D. Pride, T. Schworer, R. J. Stevens, F. Williams, and D. Witmer, “Small-Scale Modular Nuclear Power: An Option for Alaska?,” Alaska Center for Energy and Power, University of Alaska, Anchorage, Anchorage, AK, 2011.
- [11] C. Waters and R. Didsbury, “Small Modular Reactors - A Solution for Canada’s North?,” *AECL Nuclear Review*, vol. 1, no. 2, pp. 3–7, Dec. 2012.
- [12] B. Middleton, T. R. Boland, W. E. Schlafli, and B. T. Landrey, “Assessment of Small Modular Reactor Suitability for Use On or Near Air Force Space Command Installations,” Scitor Corporation, Albuquerque, NM, Mar. 2016.
- [13] W. R. Corliss, “Power Reactors in Small Packages,” U.S. Atomic Energy Commission, Oak Ridge, TN, Oct. 1968.
- [14] “Overview of Galena’s Proposed Approach to Licensing a 4S Reactor-Based Power Generation Facility,” City of Galena, Alaska, Mar. 2007.
- [15] L. H. Suid, *The Army’s Nuclear Power Program: The Evolution of a Support Agency*. New York: Greenwood Press, 1990.
- [16] M. V. Ramana, “The Forgotten History of Small Nuclear Reactors,” *IEEE Spectrum: Technology, Engineering, and Science News*, 27-Apr-2015. [Online]. Available: <http://spectrum.ieee.org/energy/nuclear/the-forgotten-history-of-small-nuclear-reactors>. [Accessed: 13-Jun-2016].
- [17] J. Whitlock and J. Sprinkle, “Proliferation Resistance Considerations for Remote Small Modular Reactors,” *AECL Nuclear Review*, vol. 1, no. 2, pp. 9–12, Dec. 2012.

- [18] S. Prasad, A. Abdulla, M. G. Morgan, and I. L. Azevedo, “Nonproliferation Improvements and Challenges Presented by Small Modular Reactors,” *Progress in Nuclear Energy*, pp. 102–109, 2015.
- [19] D. H. Beddingfield and M. Hori, “Nuclear Safeguards Challenges at Reactors Types That Defy Traditional Item Counting,” presented at the JAEA-IAEA Workshop on Advanced Safeguards Technology for the Future Nuclear Fuel Cycle, 2007.
- [20] J. Griffin *et al.*, “Under-Sodium Viewing: A Review of Ultrasonic Imaging Technology for Liquid Metal Fast Reactors,” Pacific Northwest National Laboratory, Mar. 2009.
- [21] “Physical Security for the Galena 4S Nuclear Power Generation Facility,” City of Galena, Alaska, Galena Alaska.
- [22] S. Delpéch, “Molten Salts for Nuclear Applications,” in *Molten Salts Chemistry*, F. Lantelme and H. Groult, Eds. Oxford: Elsevier, 2013, pp. 497–520.
- [23] B. M. Elsheikh, “Safety Assessment of Molten Salt Reactors in Comparison with Light Water Reactors,” *Journal of Radiation Research and Applied Sciences*, vol. 6, no. 2, pp. 63–70, Oct. 2013.
- [24] G. Flanagan, “Safety, Safeguards, and Security Context for MSRs,” presented at the Molten Salt Reactor Technologies - 50th Anniversary of the Startup of MSRE Workshop, 2015.
- [25] D. E. Holcomb, G. F. Flanagan, B. W. Patton, J. C. Gehin, R. L. Howard, and T. J. Harrison, “Fast Spectrum Molten Salt Reactor Options,” Oak Ridge National Laboratory, ORNL/TM-2011/105, Jul. 2011.
- [26] U. Gat and J. R. Engel, “Non-Proliferation Attributes of Molten Salt Reactors,” *Nuclear Engineering and Design*, vol. 201, no. 2–3, pp. 327–334, 2000.
- [27] R. A. Bari, “Safeguards & Security for Advanced Reactors,” presented at the ORNL Workshop on Molten Salt Reactor Technologies, 2015.
- [28] B. Boyer, “Understanding the Possible Molten Salt Reactor Safeguards Issues,” presented at the Technical Meeting on the Status of Molten Salt Reactor Technology, Vienna, Austria, 31-Nov-2016.
- [29] D. Kovacic, “International Nuclear Safeguards and Molten Salt Reactors,” presented at the Molten Salt Reactor Workshop, 04-Oct-2016.
- [30] “Thorium: Proliferation Warnings on Nuclear ‘Wonder-Fuel,’” *Phys.org*, Dec. 2012.
- [31] U.S. Department of Energy Nuclear Energy Research Advisory Committee and Generation IV International Forum, “A Technology Roadmap for Generation IV Nuclear Energy Systems,” GIF-002-00, Dec. 2002.
- [32] B. D. Boyer, D. D. Beddingfield, P. Durst, and R. Bean, “Pebble Bed Modular Reactor Safeguards: Developing New Approaches and Implementing Safeguards by Design,” presented at the Pacific Northwest International Conference on Global Nuclear Security - The Decade Ahead, 2010.
- [33] “Nuclear Non-Proliferation Activities in Hungary 1999-2009,” Hungarian Atomic Energy Authority, Budapest, Hungary, n.d.
- [34] “International Safeguards in Nuclear Facility Design and Construction,” International Atomic Energy Agency, Vienna, Austria, NP-T-2.8, 2013.
- [35] M. Tarvainen, F. Levai, T. E. Valentine, M. Abhold, and B. Moran, “NDA Techniques for Spent Fuel Verification and Radiation Monitoring,” Radiation and Nuclear Safety Authority (STUK), Helsinki, Finland, 1997.
- [36] S. Johnson, “The Safeguards at Reprocessing Plants Under a Fissile Material (Cutoff) Treaty,” International Panel on Fissile Materials, Feb. 2009.

- [37] A. Fattah and N. N. Khlebnikov, “A Proposal for Technical Criteria for Termination of Safeguards for Materials Characterized as Measured Discards,” presented at the American Nuclear Society Annual Meeting, Washington, D.C., 1990.
- [38] M. F. Simpson, D. Rappleye, and M. Stika, “Simulated Response of Electrochemical Sensors for Monitoring Molten-Salt Fueled Reactors,” presented at the Annual Meeting of the INMM, 2014.
- [39] N. J. Gese, J.-F. Jue, B. E. Serrano, and G. L. Fredrickson, “Potentiometric Sensor for Real-Time Remote Surveillance of Actinides in Molten Salts,” presented at the Annual Meeting of the Institute of Nuclear Materials Management, 2012.
- [40] P. A. Zink *et al.*, “Potentiometric Sensor for Real-Time Monitoring of Multivalent Ion Concentrations in Molten Salt,” presented at the Annual Meeting of the Institute of Nuclear Materials Management, 2010.
- [41] N. A. Smith, J. A. Savina, and M. A. Williamson, “Application of Laser Induced Breakdown Spectroscopy to Electrochemical Process Monitoring of Molten Chloride Salts,” presented at the Symposium on International Safeguards: Linking Strategy, Implementation and People, 2014.
- [42] Louise G. Worrall *et al.*, “Safeguards Considerations for Thorium Fuel Cycles,” *Nuclear Technology*, vol. 194, pp. 291–293, May 2016.
- [43] L. K. Kim, G. Renda, and G. G. M. Cojazzi, “Methodological Aspects of the IAEA State Level Concept and Acquisition Path Analysis: A State’s Nuclear Fuel Cycle, Related Capabilities, and the Quantification of Acquisition Paths,” *ESARDA Bulletin*, vol. 53, Dec. 2015.
- [44] International Atomic Energy Agency, “The Safeguards Implementation Report for 2014,” GOV/2015/30, May 2015.
- [45] “The Conceptualization and Development of Safeguards Implementation at the State Level,” International Atomic Energy Agency, Available at: <http://www.isisnucleariran.org/assets/pdf/GOV201338.pdf>, GOV/2013/38, Aug. 2013.
- [46] H. Zhang and F. von Hippel, “Using Commercial Imaging Satellites to Detect the Operation of Plutonium Production Reactors and Gaseous-Diffusion Plants,” *Science & Global Security*, vol. 8, pp. 219–271, 2000.
- [47] M. Goggin, “The Facts About Wind Energy’s Impacts on Electricity Markets: Cutting Through Exelon’s Claims About ‘Negative Prices’ and ‘Market Distortion,’” American Wind Energy Association, Mar. 2014.
- [48] “Changing the Game by Linking Nuclear and Renewable Energy Systems,” *Energy.gov*, 08-Dec-2016. [Online]. Available: <https://www.energy.gov/ne/articles/changing-game-linking-nuclear-and-renewable-energy-systems>. [Accessed: 12-Apr-2017].
- [49] ARPA-E, “HEATS Program Overview.”
- [50] David Albright and Serena Kelleher-Vergantini, “Plutonium, Tritium, and Highly Enriched Uranium Production at the Yongbyon Nuclear Site North Korea’s Nuclear Arsenal May be Growing Significantly,” Institute for Science and International Security, Jun. 2016.
- [51] Daniel Curtis and Charles Forsberg, “LWRs with Heat Storage for Peak Electricity and Industry,” presented at the MIT-Japan Meeting, Cambridge, MA, 16-Sep-2016.
- [52] Charles Forsberg and Per F. Peterson, “Basis for Fluoride Salt–Cooled High-Temperature Reactors with Nuclear Air-Brayton Combined Cycles and Firebrick Resistance-Heated Energy Storage,” *Nuclear Technology*, vol. 196, no. 1, pp. 13–33, Oct. 2016.

- [53] L. K. Kim, R. Jungwirth, G. Renda, E. Wolfart, and G. G. M. Cojazzi, “Potential Signatures and the Means of Detecting a Hypothetical Ground Source Cooled Nuclear Reactor,” *Science & Global Security*, vol. 24, no. 2, pp. 92–113, May 2016.
- [54] “ARID Program Overview,” May 2015.
- [55] G. T. Mays *et al.*, “Application of Spatial Data Modeling and Geographical Information Systems (GIS) for Identification of Potential Siting Options for Various Electrical Generation Sources,” Oak Ridge National Laboratory, ORNL/TM-2011/157/R1, May 2012.
- [56] L. K. Kim, G. Renda, and G. G. M. Cojazzi, “How Much is Enough?: Preliminary Insights from Search Theory as Applied to Detecting Undeclared Activities,” presented at the Institute of Nuclear Materials Management 57th Annual Meeting, Atlanta, GA, 2016.
- [57] “Environmental Radiation Monitoring Plan for SM-1A Nuclear Power Plant Fort Greely, Alaska,” Engineering Division, U.S. Army Engineer Reactors Group, Fort Belvoir, VA, May 1971.
- [58] R. Bari, J. Hockert, E. Wonder, S. Johnson, R. Wigeland, and M. Zentner, “Overview of the Facility Safeguardability Analysis (FSA) Process,” Pacific Northwest National Laboratory, Richland, WA, PNNL-21698, Aug. 2012.
- [59] F. Pabian, G. Renda, R. Jungwirth, L. Kim, E. Wolfart, and G. Cojazzi, “Commercial Satellite Imagery: an Evolving Tool in the Nonproliferation Verification and Monitoring Toolkit,” in *Risk and Information Driven Verification*, Forthcoming.