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White Paper—Current Capabilities at SNL for the Integration of Small Modular Reactors onto Smart Microgrids Using Sandia's Smart Microgrid Technology, High Performance Computing, and Advanced Manufacturing

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EXECUTIVE SUMMARY

Smart grids are a crucial component for enabling the nation's future energy needs, as part of a modernization effort led by the Department of Energy. Smart grids and smart microgrids are being considered in niche applications, and as part of a comprehensive energy strategy to help manage the nation's growing energy demands, for critical infrastructures, military installations, small rural communities, and large populations with limited water supplies.

As part of a far-reaching strategic initiative, Sandia National Laboratories (SNL) presents herein a unique, three-pronged approach to integrate small modular reactors (SMRs) into microgrids, with the goal of providing economically-competitive, reliable, and secure energy to meet the nation's needs. SNL's triad methodology involves an innovative blend of smart microgrid technology, high performance computing (HPC), and advanced manufacturing (AM). In this report, Sandia's current capabilities in those areas are summarized, as well as paths forward that will enable DOE to achieve its energy goals.

In the area of smart grid/microgrid technology, Sandia's current computational capabilities can model the entire grid, including temporal aspects and cyber security issues. Our tools include system development, integration, testing and evaluation, monitoring, and sustainment.

Based on the development guidance for smart grids set by the Energy Independence and Security Act *(EISA), the inclusion of SMRs clearly fulfills many of its energy goals. It is demonstrated that SMRs possess many exclusive features found in no other energy source, and that these features are highly suitable for integration onto smart grids.*

SMR inclusion into smart grids/microgrids supplies highly reliable, scalable, right-sized power sources as part of well-balanced grids. This results in smart microgrids that reliably and economically supply critical infrastructures, military installations, small rural communities, and large populations with limited water supplies.

The general trend is that for SMRs under 100 MWe, very small SMR levelized unit electricity cost *(LUEC) exceeds that of a comparable large reactor by a factor of two. However, if the cost-reduction factors considered for total Cost are factored into an SMR, its LUEC would only be 10 to*

40% higher than a comparable large reactor. Further, if the research trends towards more efficient SMRs and additional cost reduction trends continue (e.g., advanced manufacturing, design simplification, more usage of passive features, etc.), ***<u>SMR LUECs can be made lower than conventional large reactors by employing Sandia's leading-edge triad capabilities</u>.***

In the area of HPC, Sandia has the capacity of 179,858 parallel processors for an astonishing computational power equal to 3,706 teraflops. To better understand this computational power, an air-cooled nuclear fuel bundle experiment using 128 processors only requires a total of 10 hours to simulate. In other words, the calculation only used 0.071% of Sandia's total HPC capacity. This reflects the tremendous potential for Sandia's HPC to solve the nation's energy needs.

It is also noteworthy that HPC provides system designers and analysts a tool that is not only less costly than experiments, but also provides more data, including data that is not currently measurable with current instrumentation. HPC also allows analysts and designers to probe more profoundly into system behavior than experimentation ever could, thereby allowing for the development of more efficient energy systems that are cost-competitive and more benign towards the environment. For example, an entire nuclear reactor can be simulated for safety analysis, and be completely destroyed in the virtual world, without releasing a single radiation particle, without causing any damage to the environment, and at a fraction of an experiment's cost.

In the area of AM, Sandia's goal is manufacturing of fast and cost-effective system components. Our current AM areas of interest and research include many technologies that are either exclusive to Sandia, or that are currently being advanced by Sandia. This includes FastCast, laser engineered net shaping, RoboCast, direct write, thermal spray, and micro-nano scale manufacturing. The three major AM areas of research and development at Sandia are analysis-driven design tools, materials assurance, and multi-material components. The ultimate goal of the Sandia AM program is to have a fully-integrated, model-based, design/production approach that is agile, affordable, and assured.

Despite many recent advances, AM is not as mature as conventional manufacturing methods, and still poses several unique challenges (e.g., inhomogeneities that lead to significant material property variation). However, these are currently being addressed and have short-term solutions. For example, rigorous process controls and best practices are being formulated. In addition, post material treatment of AM components shows significant improvement in material properties.

On the other hand, AM has various remarkable advantages over conventional manufacturing that should be exploited for SMR applications, including simplification of the assembly (integration) process, streamlined path from design to prototyping, the generation of complex geometries and material composites, and on-site manufacturing, which reduces shipping cost, as well as assembly time.

Current areas of process sensitivity research at Sandia include studies in particle packing, heat transfer, melt flow, molten pool dynamics, solidification, microstructure, property performance, and topology design. Conceptually, process sensitivity control will be achieved with point qualification of AM parts, better understanding of the dynamics for machine and process variability, and process qualification. These will be synthesized with the goal of deriving AM best practices.

To be clear, neither Sandia nor anyone else is currently capable of AM of complex, large-scale nuclear-grade components. However, in the future, the above-named advances will provide substantial savings in manufacturing cost and shipping, and the production of AM components that have significant financial savings over conventional manufacturing.

In the longer term, Sandia will continue to seek agile, affordable, and assured fully-integrated, model-based design/production. This will provide additional financial benefits as material variability is better controlled for the production of nuclear-grade materials, thereby allowing Sandia to more economically manufacture complex metallic composites and geometries, as well as streamline subsystem integration. Consequently, this will allow AM of larger nuclear components or nuclear-grade subsystems (e.g., vessel heads, nuclear-qualified material components, and complex structures). The goal is to attain ever-higher complexity, such as the initial manufacturing of fuel rods first, followed by AM of entire fuel assemblies, and culminating in more complex systems, including entire nuclear cores.

INTRODUCTION TO SMR-POWERED SMART MICROGRIDS AT SNL

In this section, governmental and industrial directives for smart grids/microgrids are defined and summarized. Then, compelling reasons why SMRs are highly suitable for smart grids/microgrids are presented, followed by a summary of Sandia's most salient capabilities for integrating SMRs into smart grids/microgrids. Key players within SNL are identified, and their latest capabilities are summarized, with the goal of identifying Sandia's unique capabilities for the integration of SMRs onto smart grids, as part of a comprehensive energy strategy.

SMART GRIDS AND SMART MICROGRIDS DEFINED

An early formal definition with specific directives for a "smart grid" was approved by Congress under Title XIII of the Energy Independence and Security Act (EISA) in 2007, and signed into law by President George W. Bush [Kathan et al., 2008]. According to EISA, the smart grid concept was established because…

> "It is the policy of the United States to support the **modernization** of the Nation's electricity transmission and distribution system to maintain a **reliable and secure** electricity infrastructure that can **meet future demand growth** and **to achieve each of the following, *which together characterize a Smart Grid***."

A summary of the 10 EISA guidelines for smart grid development are identified below, with those in bold italics reflecting direct and compelling SMR/smart grid development opportunities for Sandia (Items 1 through 4):

> ***(1) Increased use of digital information and controls technology to improve reliability, security, and efficiency of the electric grid (including load switching).***
>
> ***(2) Dynamic optimization of grid operations and resources, with full cyber-security.***
>
> ***(3) Deployment and integration of distributed resources and <u>generation</u>, including renewable resources.***
>
> ***(4) Development and incorporation of demand response, demand-side resources, and <u>energy-efficiency</u> resources.***
>
> (5) Deployment of \`smart' technologies (real-time, automated, interactive technologies that optimize the physical operation of appliances and consumer devices) for metering, communications concerning grid operations and status, and distribution automation.
>
> (6) Integration of \`smart' appliances and consumer devices.
>
> (7) Deployment and integration of advanced electricity storage and peak-shaving technologies, including plug-in electric and hybrid electric vehicles, and thermal storage air conditioning.
>
> (8) Provision to consumers of timely information and control options.

(9) Development of standards for communication and interoperability of appliances and equipment connected to the electric grid, including the infrastructure serving the grid.

(10) Identification and lowering of unreasonable or unnecessary barriers to adoption of smart grid technologies, practices, and services."

Further, EISA discusses key merit factors for utilities, with emphasis on cost, reliability, security, and system performance. The merit factors are intended to provide increased energy efficiency, energy diversity, reliability, and societal benefits, such as lower energy cost, innovation, and consumer empowerment [DOE, 2017].

Though smart grid definitions vary in the literature, smart grids typically consist of a variety of energy resources, operational equipment, and measures that include smart meters and appliances, renewable energy resources, and the efficient use of energy. [DOE, 2017; Schenkman, 2015; Wikipedia, 2017]. A smart grid is therefore an integration of smart devices, software, and control devices working in conjunction with diverse energy resources, with the goal of delivering reliable, cost-effective, balanced, and secure energy [DOE, 2017; Schenkman, 2015; Wikipedia, 2017].

Furthermore, a microgrid is considered a “community-scale” grid that is either fully isolated from the primary grid, or one that is linked to the primary grid, but that can automatically separate itself and become autonomous if the primary grid fails [NAED, 2017]. A smart microgrid is therefore a smart grid designed for a “community-scale” (localized, autonomous, island) application [Schenkman, 2015; Ellis 2017].

CURRENT CAPABILITIES AT SANDIA FOR ENABLING THE INTEGRATION OF SMRS ONTO SMART GRIDS/MICROGRIDS

SNL’s microgrid efforts are spread primarily across Organizations 06112, 06113, and 06114 in Group 06110, with collaboration with 1300 (e.g., Org. 1353). Table 1 identifies key players, and their latest capabilities are summarized. As part of the strategic plan, Group 06110 seeks collaboration and working relationships with key utilities, regulatory agencies, international organizations, universities, and the private sector. Group 06110’s strategic approach emphasizes technologies where Sandia leads smart grid modernization efforts.

Sandia’s Center 6100 maintains vast capabilities and numerous funded projects in the area of renewable and distributed systems integration, energy storage, power systems analysis, and microgrids. Our capabilities that are relevant to the microgrid efforts include [Ellis, 2017]:

- Secure and Sustainable Microgrid (SSM) testbed,
- The Distributed Energy Technologies Laboratory (DETL), Communications and Networking (CONET) lab,
- The Energy Storage Test Pad (ESTP),
- Miscellaneous cyber security R&D capabilities,
- Development of defense energy portfolios for the DSA and EC PMUs,

- Microgrid designs for the DOE Grid Modernization Laboratory Consortium Program,
- Energy security assessments and microgrid conceptual designs for military installations and expeditionary operations,
- Implementation of microgrid designs, demonstrations, and lessons learned for military installations,
- Development of training materials for conducting energy security assessments and development of microgrids [e.g., Microgrid Design Toolkit (MDT) for optimizing microgrid designs for civilian and military applications].

Due to its crucial importance to DOE and national security, it is not surprising that several national laboratories are involved in smart grid/microgrid research. However, as grid-modernization continues to broaden and adapt smart strategies, Sandia continues to lead in many areas by identifying and developing innovative technologies and paths-forward. Figure 1 shows Sandia's microgrid experience across the country for a wide range of security assessments, designs, and applications [Nanco, 2016]. Areas where Sandia excels in smart grid/microgrid modernization include:

- Grid cybersecurity and resilience,
- Planning and implementation assessments,
- Integration of distributed resources, renewables, and SMRs,
- Probabilistic methods,
- Grid enhancement and improved efficiency,
- Energy storage, and
- System dampening, load balancing.

Sandia recognizes that advanced grids will require extensive communication, thereby requiring specialized cybersecurity. These capabilities are now interconnected through a high-speed communications link that allows Sandia to control a large variety of distributed resources in various configurations, including microgrids and virtual power plants [Ellis, 2017].

Sandia's computational capabilities can now model the entire grid, including temporal aspects and cyber security issues [Ellis, 2017]. Our tools include system integration, testing and evaluation, and sustainment. For example, as part of the Smart Power Infrastructure Demonstration for Energy Reliability and Security (SPIDERS), Sandia developed a suite of methodologies and tools such as the Energy Surety Design Methodology (ESDM), MDT; see Figure 2), and cybersecurity Reference Architecture (RA) that have been validated and applied to civilian and military critical infrastructures [Ellis, 2017]. SPIDERS resulted in the deployment of resilient and cyber secure microgrids for several military bases. Total investment was in the tens of millions of dollars, and involved a wide range of distributed energy technologies such as energy storage, renewable energy (PV) generation, electric vehicles, and diesel/natural gas.

Sandia also incorporated advanced grid controls to operate interconnected grids connected and independent island systems (e.g., isolated, independent systems). The deployments also emphasized cyber and physical security [Ellis, 2017]. Sandia is also developing cyber-secure and resilient microgrid laboratories, as well as various advanced microgrid tools, with the ultimate goals of building cyber-secure, resilient microgrids and provide efficient energy harvesting and management [Nanco, 2016].

In FY15-16, Sandia led microgrid design and optimization studies in New Jersey, in partnership with DOE and municipal and state agencies. Specifically, we worked on microgrid designs for the City of Hoboken and for NJ Transit. The latter effort resulted in a $600M transportation microgrid project that is currently being deployed. A centerpiece of the project, called NJ TransitGrid, is a 104 MW centralized gas-fired generation facility capable of black-starting and serving critical load even if the commercial grid is unavailable. Based on generation capacity, this plant is similar to a modular nuclear reactor [Ellis, 2017].

Funded by DOE under the Grid Modernization Lab Consortium, Sandia is leading research, design and demonstration projects related to resilient energy infrastructure, including regional demonstrations in New Orleans and New England, among others. Both of these projects involve interactions with utilities and regulatory agencies, and involve application of Sandia technologies to evaluate threats, consequences, and optimal microgrid solutions [Ellis, 2017].

Sandia is also developing a comprehensive resilience metrics framework that has been included in the Quadrennial Energy Review, and is being applied to large-scale systems such as the AEP and MISO service territories. For those projects, we are looking at grid and grid component vulnerabilities to geo-magnetic disturbances (GMD) and other extreme weather-related threats [Ellis, 2017].

Note that the SNL microgrid tools (ESDM, MDT, and RA) were developed on a philosophy that the tools provide rapid grid analysis, without the need for high performance computing. As they are currently coded, the tools can support multi-threading, thereby allowing multiple processors to run simultaneously, for more complex analysis. In the future, we highly recommend that the SNL grid tools be parallelized and coupled with Power Flow or other computational dynamics codes, to further augment SMR/grid system's cost-effectiveness, reliability, security, and applicability [Eddy, 2017; Miner, 2017].

Energy Security Assessments & Microgrid Conceptual Designs	<1 MW Microgrid Operations	Large Scale Microgrid Operations	Community Microgrid Designs

• Creech AFB – FY12 DoD
• Soto Cano – FY12 DoD
• West Point FY12, DoD/DOE OE
• Osan AFB, FY 12, DoD
• Philadelphia Navy Yard – FY11, DOE OE/PIDC
• Camp Smith – FY10, DOE FEMP
• Indian Head NWC – FY09, DOE OE/DoD
• Ft. Sill – FY08, Sandia LDRD
• Ft. Bliss – FY10, DOE FEMP
• Ft. Carson – FY10, DOE FEMP
• Ft. Devens (99th ANG) – FY09, DOE OE/DoD
• Ft. Belvoir – FY09 DOE OE/FEMP
• Cannon AFB – FY11, DOE OE/DoD
• Vandenberg AFB – FY11, DOE FEMP
• Kirtland AFB – FY10, DOE OE/DoD
• Maxwell AFB – FY09, DoD/DOE
• Bagram, Afghanistan – FY13, DoD
• Kuwait – FY15, DoD
• 29 Palms – FY14, DoD/ESTCP
	• Maxwell AFB – FY11 - 14, DoD
	• Ft. Sill – FY10, DoD
	• Ft. Bliss – FY12-13, DoD/ESTCP
		• SPIDERS JCTD – FY11-15, DOE/DoD/CERL
		  • Camp Smith
		  • Ft. Carson
		  • Hickam AFB
		• Ft. Belvoir FY15 DoD
			• Northampton, MA
			• NJ Transit
			• Hoboken, NJ
			• Lihue, Kauai
			• New Orleans, LA
			• Alaskan Villages

Figure 1. Summary of Sandia's experience with advanced microgrids [Nanco, 2016].

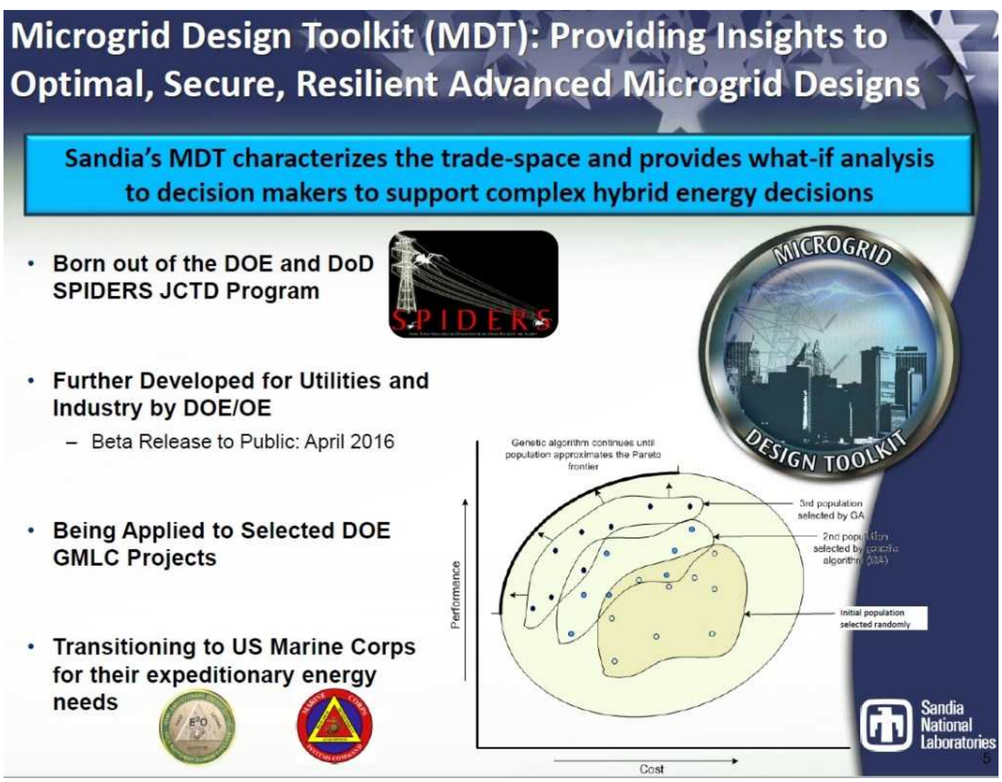


Figure 2. The Sandia MDT.

Table 1. Summary of Key Smart Grid/Microgrid Contacts at SNL.

Organization	POC	Expertise Areas
06110, Grid Modernization and Military Energy Systems	Charles Hanley, Senior Manager	• Create the energy infrastructure of the future, for both the civilian and military sectors. • Electric power grid for civilian and military, including microgrids, energy storage, transmission and distribution. • Execution of the DOE/DoD energy security MOU by performing complex systems analyses. • Prototype systems designs, testing, evaluations and hardware/systems implementations. • *Strong integration and leadership skills in key microgrid capabilities offered by Groups 06112, 06113, and 06114.*
06112, Photovoltaic and Distributed Systems Integration	Abraham "Abe" Ellis, Manager	• Characterization and optimization of components and systems. • Systems reliability. • Advanced models for risk-based analyses. • Tools for high penetration assessments. • Technology Development - energy management systems, new integrated PV systems. • Can help identify SMR microgrid research of interest to DOE/OE. • *Staff can help identify pathways and microgrid tool expansion to address SMR integration onto smart microgrids.*
06113, Electric Power Systems Research	Ross Guttromson, Manager	• R&D and advanced analytics for grid modernization. • Development of improved planning and operations methodologies. • Development and application of advanced algorithmic and computational methods, grid operations, economics, and policy. • System dynamics, operational reliability, advanced renewables integration, electricity market development, smart grid technologies and related information analysis, optimal resource expansion, and computationally based decision support.

		• *Can help with grid resilience and SMR integration onto smart grid.*
06114, Military and Energy System Analysis	Alan Stewart Nanco, Manager	• Systems performance modeling and analysis. • Energy efficiency analysis. • Operational effectiveness. • System of systems assessments and trade studies. • Reliability analysis. • Can help with DOD connections. • *Staff can help identify pathways and microgrid tool expansion to address SMR integration onto smart microgrids.*
01352, Electrical Science and Experiments	Steven Glover, Manager	• Experimental electromagnetic. • Design and manufacturing of advanced power electronic and repetitive pulsed power systems. • Compact high current drivers. • Development and analysis of advanced materials and components, and plasma physics.

An overview of recent Sandia literature related to smart grids/microgrids shows many important innovations in the competitive field of smart grid development and modernization, with emphasis on smart grid attributes that are highly desired by EISA, especially the first four development opportunities noted previously. As evidenced by a host of recent publications describing important contributions to grid modernization, Sandia's grid modernization leadership is strong, well-known, and increasing. Key publications include:

- Summary of current microgrid capabilities at Sandia National Laboratories [Nanco, 2016],
- Workshop/course book, "Fundamentals of Advanced Microgrid Evaluation, Analysis, and Conceptual Design" [Fundamentals, 2017],
- Electricity market development [O'Neill et al., 2016],
- Operational reliability (Figure 3) [Castillo, 2016],
- Wide area controls analysis for the Western Electricity Coordinating Council (WECC) to improve damping of inter-area oscillations using damping controllers [Pierre et al., 2016A; Pierre et al., 2016B] (Figures 4 and 5). Figure 4 discusses a power oscillation transient for the western part of the US, while Figure 5 shows the effect of transient damping at the John Day Dam and Vincent facilities in British Columbia and Alberta.
- Energy storage to dampen inter-area oscillations at WECC [Neely et al., 2013] (Figure 6),
- Communication enabled synthetic inertia (CE-SI) for smart integration of solar onto grids [Concepcion, Wilches-Bernal, and Byrne, 2017] (Figure 7),
- Plus many others.

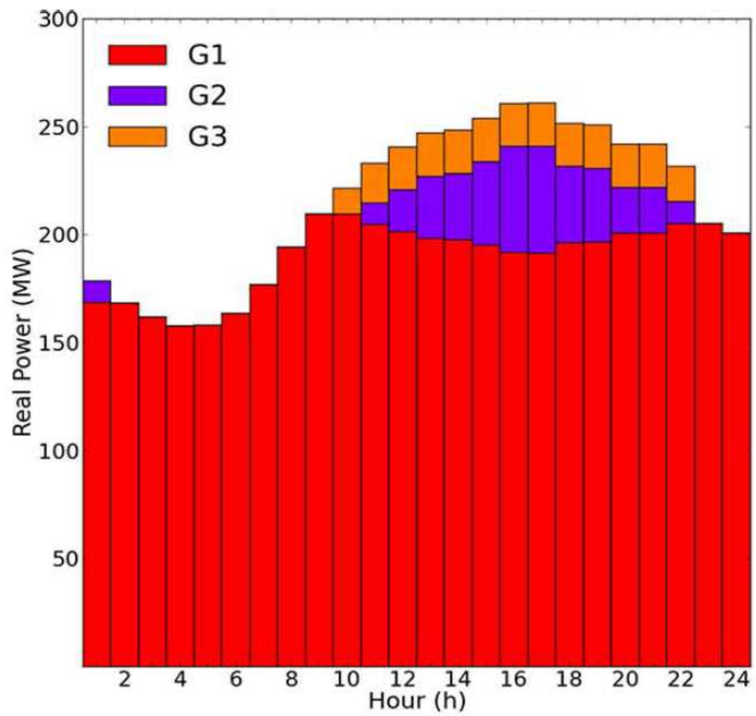


Figure 3. Generator power using a direct current optimal power flow transmission model [Castillo, 2016].

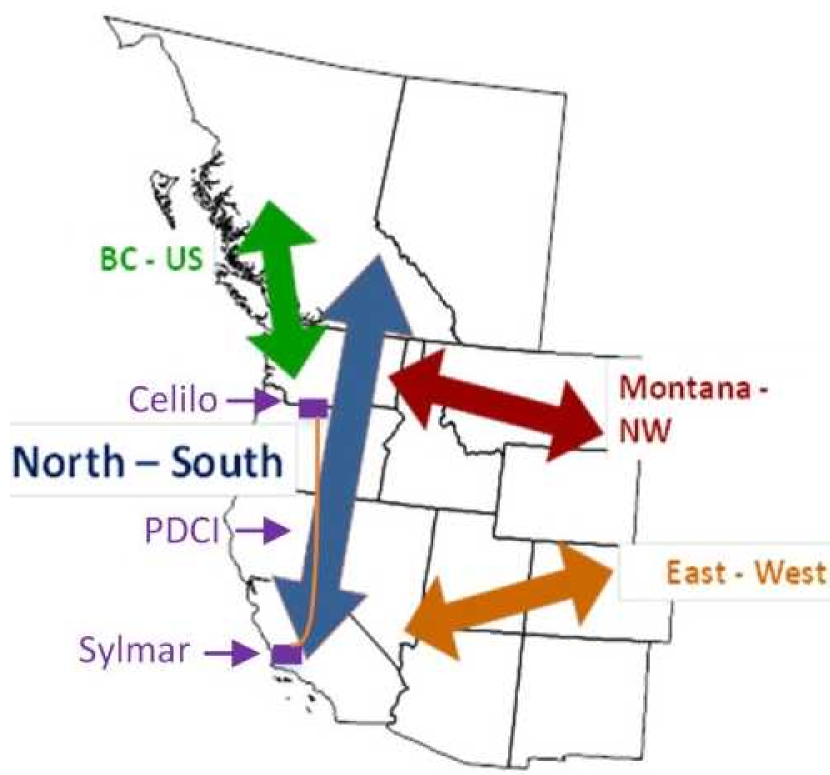


Figure 4. Primary oscillation mode shapes for the WECC [Pierre et al., 2016A]

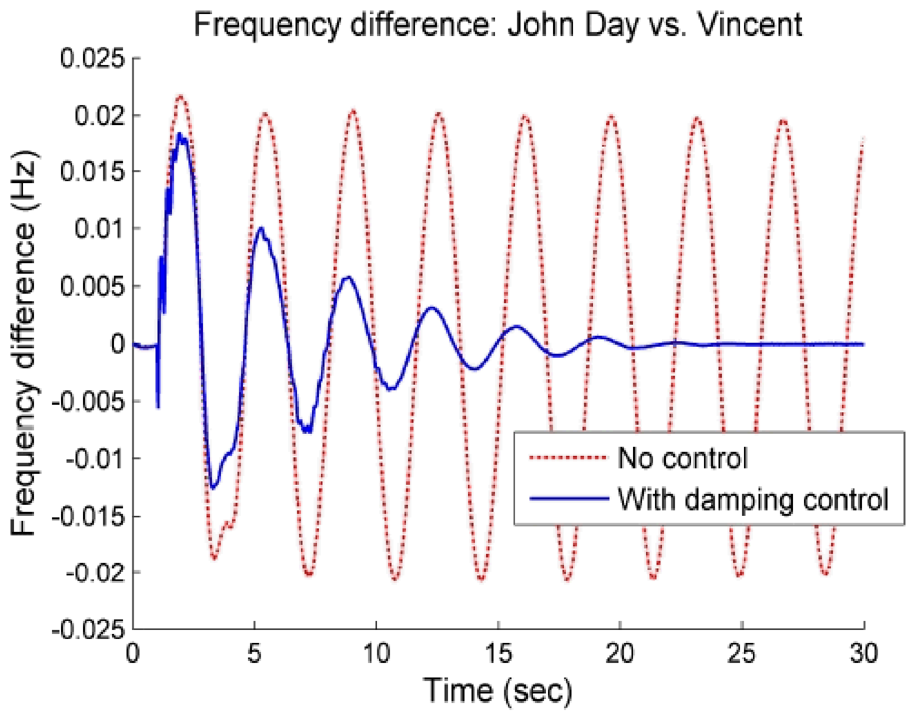


Figure 5. Simulation of wide area damping vs. no damping frequency control [Pierre et al., 2016B].

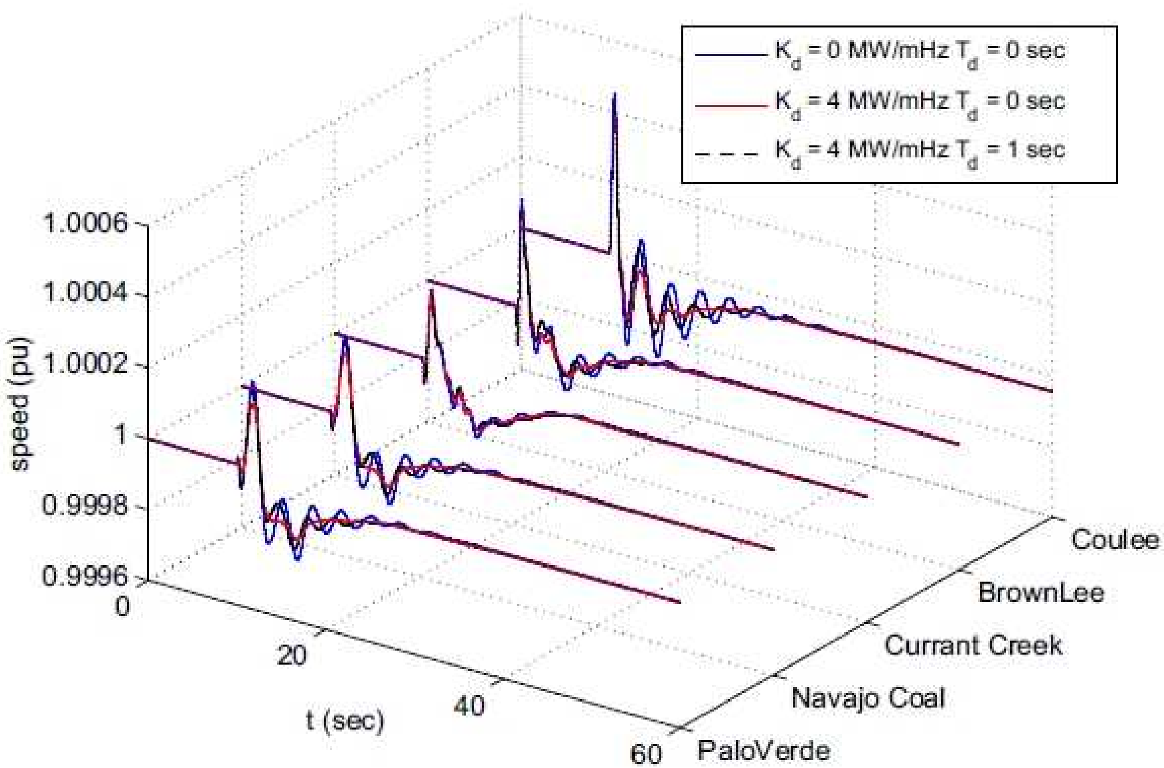


Figure 6. Damping response showing generator speed for five buses in the WECC [Neely et al., 2013].

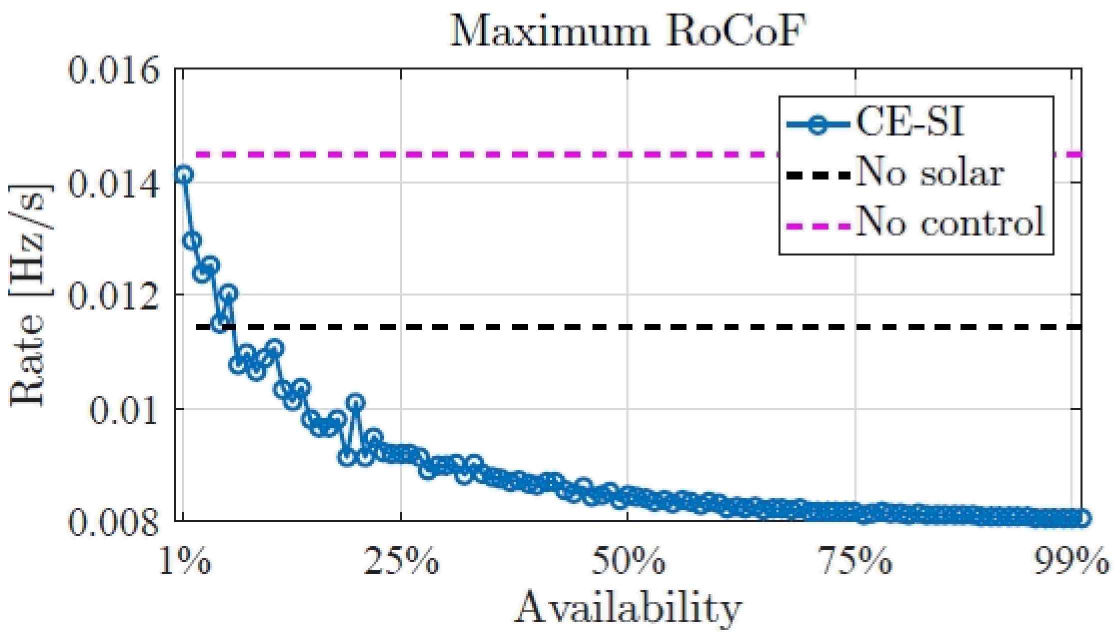


Figure 7. Impact of CE-SI in grids with and without solar power (RoCoF = rate of change of Frequency) [Concepcion, Wilches-Bernal, and Byrne, 2017].

WHY SMRS LINKED TO SMART GRIDS/MICROGRIDS MAKES ECONOMIC SENSE

Based on the development guidance for smart grids set by EISA, the inclusion of SMRs clearly fulfills many of its goals. As will be shown below, SMRs possess many exclusive features found in no other energy source, and these features are highly suitable for integration onto smart grids. This is particularly true because SMRs fulfill many of the smart grid objectives, including:

- <u>Diversified Energy Source.</u> In particular, SMRs diversify the energy portfolio, while supplying a steady, critical power component at times when other energy sources may not. Thus, the baseload capability of nuclear power allows for more efficient power leveling from the high variability of renewables. For example, SMR energy production does not rely on solar flux variations. Further, wind conditions are highly variable, and seasonal water levels and regulations can impact hydroelectric power production. Therefore, a diversified energy portfolio helps ensure a steady grid output, as shown in Figure 8 [NuScale Why SMR, 2017A]. An additional advantage of nuclear is its relatively stable cost, whereas renewable energy fluctuations can be significant.
- <u>Total Cost.</u> Total cost estimates vary, but recent economic analyses indicate that a 125 MWe SMR would cost approximately $1.15B [Kuznetsov and Lokhov, 2011]. This is attributed to a significantly shorter construction time (three to four years [Kuznetsov and Lokhov, 2011; NuScale Economical, 2017]), reduced plant size and supporting infrastructure, potential for incremental deployment if additional power is needed, advanced manufacturing of factory-assembled reactors and components, and the use of passive mechanisms. All these factors reduce capital risk, thereby providing a strong case for utilities and investors who desire a lowered capital risk.

- Cost Effectiveness. A key figure of merit for SMR cost effectiveness is the levelized unit electricity cost (LUEC), which is measured in monetary cost per unit energy. LUEC is synonymous with the levelized cost of energy, LCOE. *The general trend is that for SMRs under 100 MWe, very small SMR LUEC exceeds that of a comparable large reactor by a factor of two; a large, conventional reactor was inherently designed based on economy-of-scale; see Figure 9. However, if the cost-reduction factors considered above under "Total Cost" are factored into an SMR, its LUEC would only be 10 to 40% higher than a comparable large reactor [Kuznetsov and Lokhov, 2011;* Locatelli, Mancini, and Todeschini, 2013*]. Further, if the research trend towards more efficient SMRs, and additional cost reduction trends continue (e.g., advanced manufacturing, design simplification, more usage of passive features, etc.), SMR LUECs will be lower than conventional, large reactors; see Figures 10 and 11.*
- Improved Reliability. In a post Three Mile Island, Chernobyl, and Fukushima nuclear world, the general trends and demands for SMRs are higher levels of reliability and safety. For example, consider the NuScale SMR; because of its inherent passive features and simplified designs, NuScale estimates that their SMR's full power output availability will be greater than 95%. In addition, NuScale estimates that their SMRs will have 73% fewer SCRAMS because their simplified design has fewer system components [NuScale Reliability, 2017]. *Note that simplified designs are a typical SMR trait. In addition, nuclear offers high energy reliability and availability, which are crucial for critical infrastructures* (e.g., military base mission loads [Hightower, Baca, and Schenkman, 2016], ORNL's Spallation Neutron Source, etc.).
- System Performance. Consider load adjustment/load balancing for smart grids. As a rule of thumb, it is recommended that no single power plant unit provide more than 10% of the total grid capacity [Kuznetsov and Lokhov, 2011]. Because of their smaller size than conventional nuclear reactors, an SMR's total energy output is more readily load-leveled with alternative energy resources, thereby allowing the grid to more readily balance energy loads. For the same reason, NuScale is currently working on a smart grid concept using the NuFollow concept, whereby SMRs are integrated with renewable power sources [NuScale Why SMRs, 2017B].
- Societal Benefit. Whereas conventional nuclear reactors require large water resources, SMRs are more amenable to microgrids in arid areas. That is, SMRs are more suitable for waterless power production technology because SMRs are about a tenth to a quarter scale of conventional reactors. Therefore, their cooling requirements from waste heat are considerably smaller. This makes SMRs coolable with advanced dimpled surfaces that reject heat to the environment without the need for massive water evaporation losses from cooling towers [Rodriguez, 2016A]; see Figure 12. An additional societal benefit is the significantly smaller greenhouse footprint of nuclear power vs. conventional energy sources, as shown in Figure 13 [NuScale Why SMR, 2017C].

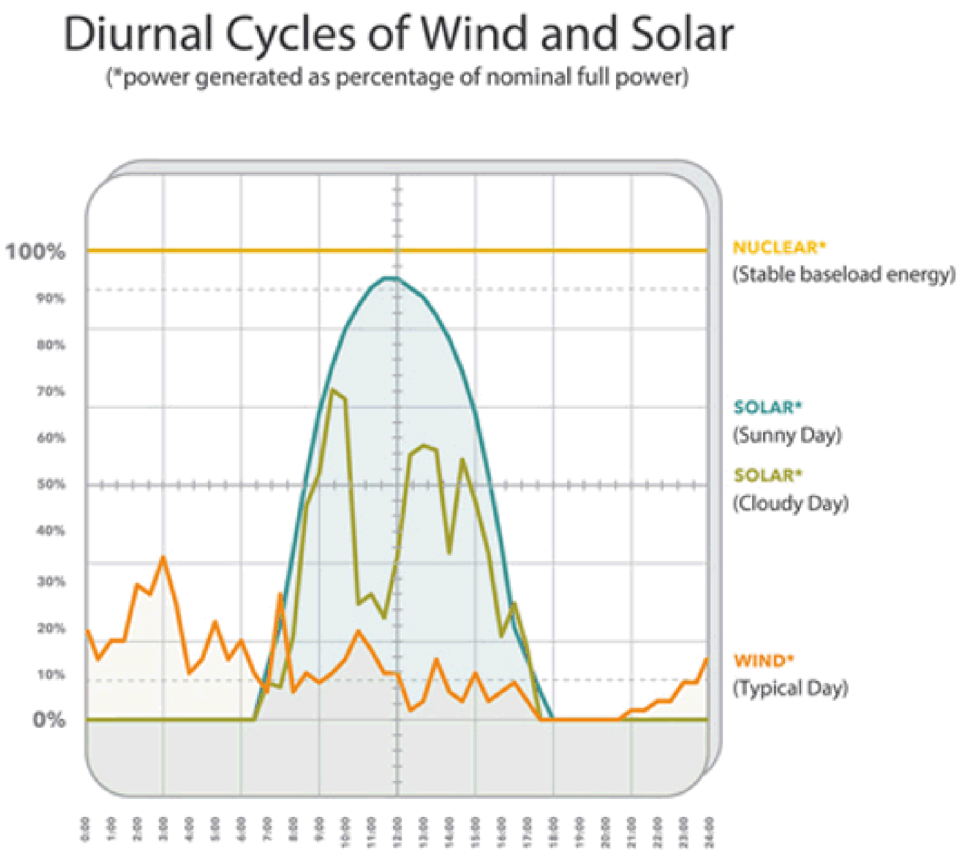


Figure 8. Nuclear, solar, and wind energy output cycles [NuScale Why SMR, 2017A].

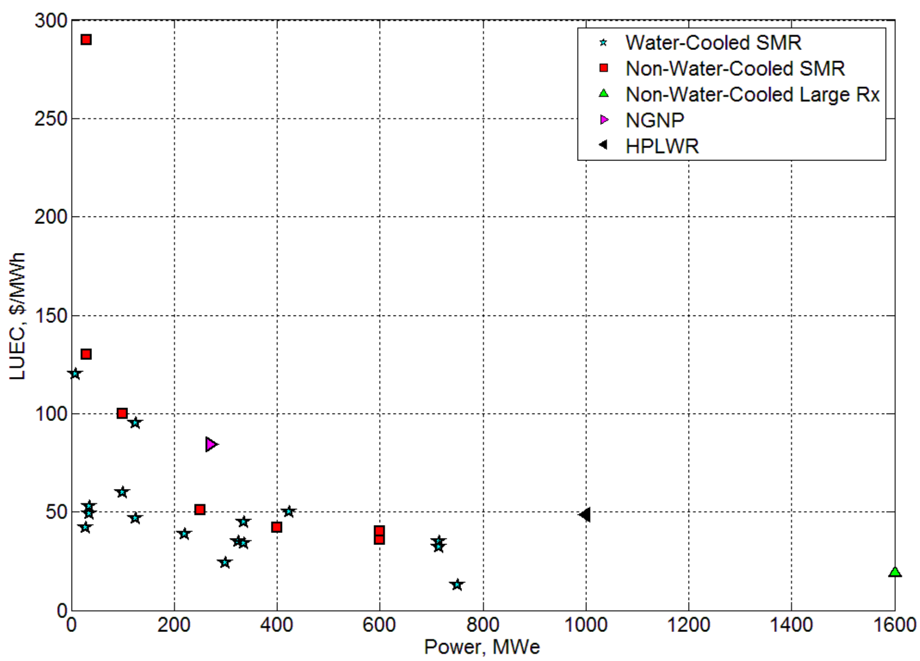


Figure 9. SMR LUEC vs. thermal power.

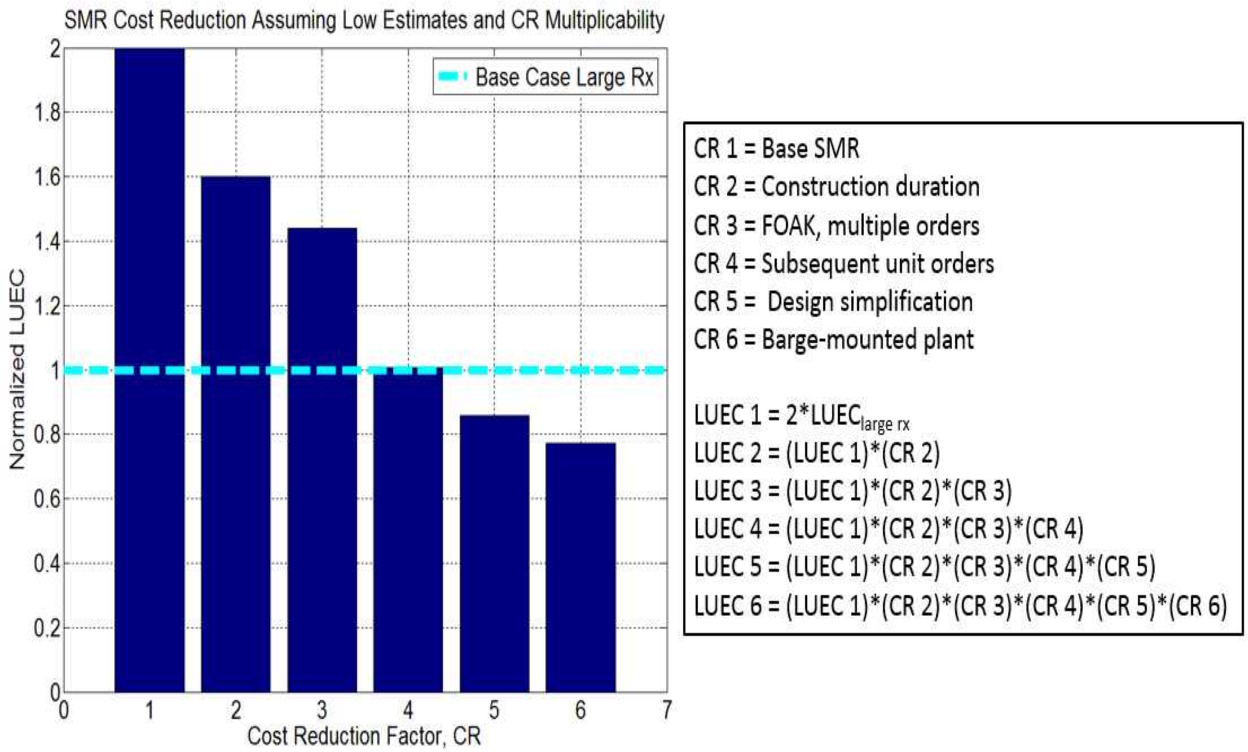


Figure 10. SMR cost comparison: low cost reduction factors.

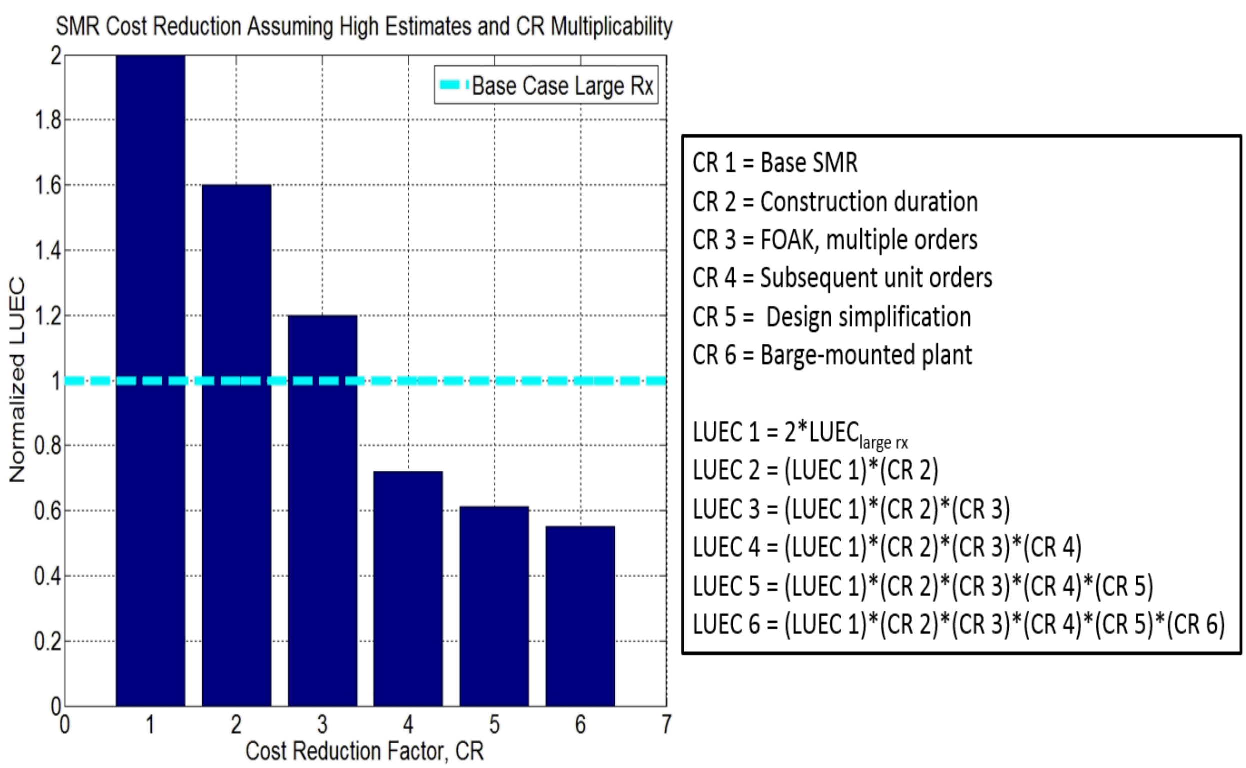


Figure 11. SMR cost comparison: high cost reduction factors.

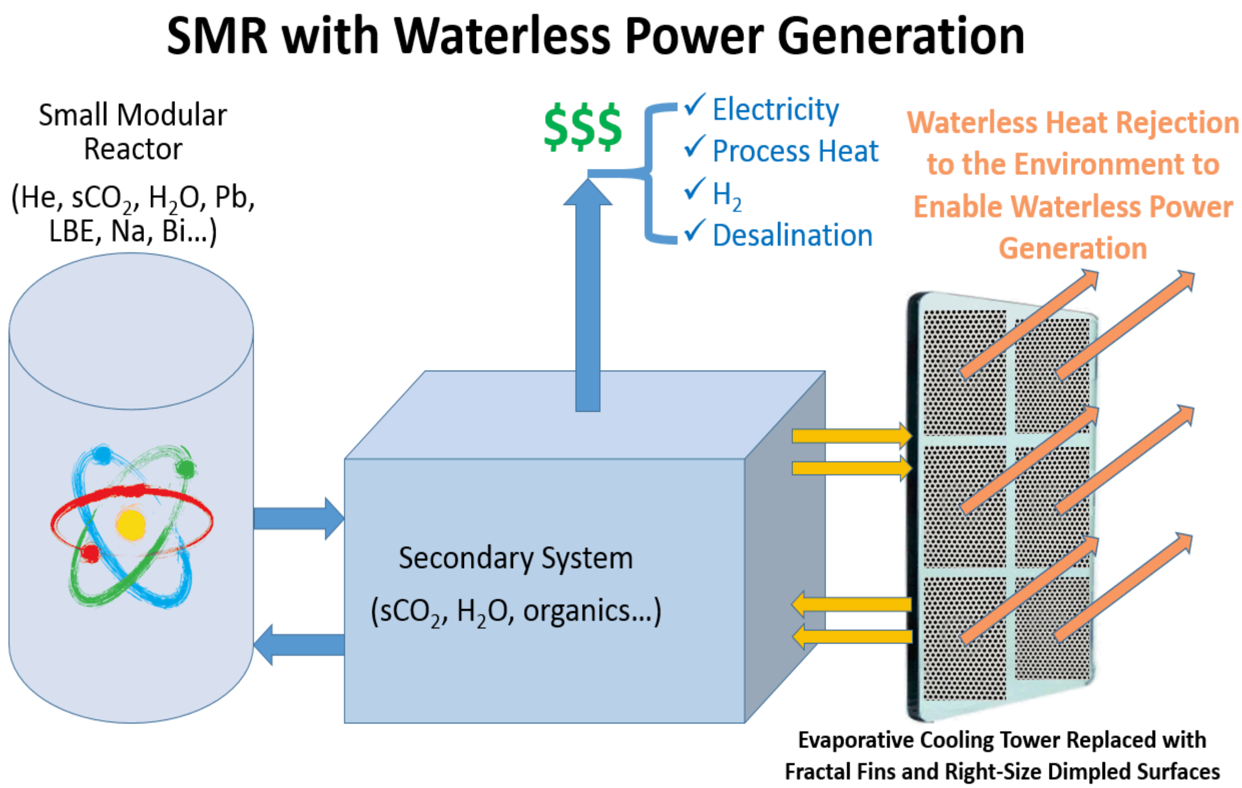


Figure 12. SMR with waterless power generation [Rodriguez, 2017A].

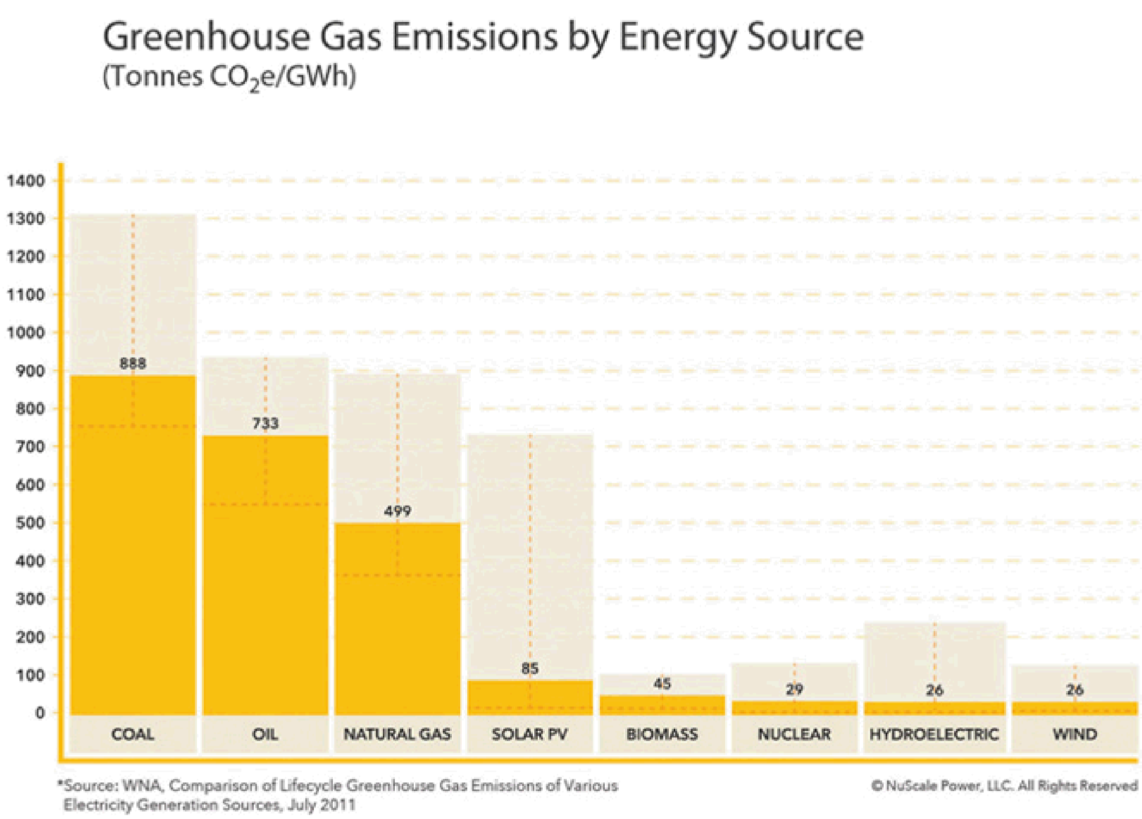


Figure 13. CO_2 Gas Emission from Various Energy Sources [NuScale Why SMR, 2017C].

For the same reasons that make SMRs ideal for smart grids, SMR inclusion into smart power grids takes it a step further by supplying highly reliable, scalable, right-sized power sources onto localized, smart microgrids. This results in smart microgrids that reliably and economically supply critical infrastructures, military installations, small rural communities, and large populations with limited water supplies. Table 2 summarizes key applications where SMRs can be integrated with smart grids/microgrids.

Table 2. SMR Applications for Smart Grids and Smart Microgrids

Application	Smart Grid	Smart Microgrid	Key SMR Advantages
Critical infrastructure	N	Y	• Reliable • Autonomous
Military installation	N	Y	• Reliable • Autonomous
Small rural communities	N	Y	• Scalable • Economical
Large communities with limited water supplies	Y	Y	• Reliable • Economical • Load balancing • Waterless power production • Reduced greenhouse emission
Areas with extreme solar/wind/water changes	Y	Y	• Load balancing • Reliable

INTRODUCTION TO HIGH PERFORMANCE COMPUTING AT SNL

Ever since the advent of massively-parallel computing, SNL continues to lead as a computational powerhouse for solving the nation's toughest multi-physics problems. High performance computing (HPC) provides system designers and analysts a tool that is not only cheaper than experiments, but also provides more data, including data that is not currently measurable with current instrumentation. HPC also allows analysts and designers to probe more profoundly into system behavior than experimentation ever could, thereby allowing for the development of more efficient energy systems that are cost-competitive and benign towards the environment. For example, an entire nuclear reactor can be simulated for safety analysis, and be completely destroyed in the virtual world, without releasing a single radiation particle, without causing any damage to the environment, and at a fraction of the experiment's cost. With faster computation and the resolution of crucial physical parameters, it is not surprising that HPC forms part of SNL's comprehensive triad to incorporate SMRs onto grids for the generation of secure, environmentally-benign energy at competitive cost.

SNL's most advanced and recent HPC capabilities are summarized here, and are synthesized into paths forward for future project development. The DOE is currently focusing on water-cooled SMRs, e.g., NuScale. However, they have also expressed recent interest in non-water cooled reactors. Consequently, both types of SMRs are explored in this document.

HIGH PERFORMANCE COMPUTING AT SANDIA

In the area of HPC, key directions include the reduction of SMR risk, increased thermal efficiency to make SMRs cost-competitive with other energy sources, and modeling of the entire SMR micro-grid. In order to perform integral analysis of SMRs, or very detailed analysis requiring millions to billions of computational nodes, massively parallel computing systems are required. Sandia has approximately 10 such systems, which are divided into three networks: restricted, classified, and external collaboration, as shown in Table 3. The total number of processors (i.e., cores) is 179,848, for a total computational power of 3,706 teraflops. To gain a better notion of what this computing power means, consider an air-cooled nuclear fuel bundle experiment at low heat flux that was simulated using Sandia's Fuego computational fluid dynamics (CFD) code. For the 6 million elements calculation, 128 processors were used for a total of 10 hours to reach 15 s of transient time. In other words, the calculation only used 0.071% of Sandia's total HPC capacity. Figure 14 shows the results of a CFD simulation, which used the state-of-the art large eddy simulation (LES) dynamic Smagorinsky turbulence model [Rodriguez, 2016B]. The figure shows the velocity arrows as natural circulation generates a flow field around the fuel (left hand side), thereby allowing the analyst to determine whether swirl structures designed for enhanced cooling of the fuel, are functioning properly. The fuel rod temperature is shown on the right hand side of Figure 14. Among other crucial fuel design issues, the analysis helps the designers determine areas where cooling is insufficient when hot spots are generated.

Table 3. High Performance Computing Capacity at SNL.

Platform Type	Number of Cores	Computing Power, teraflops
Sandia Restricted Network (SRN)	115,600	2,550
Sandia Classified Network (SCN)	37,176	516
External Collaborative Network (ECN)	27,072	640
TOTAL	**179,848**	**3,706**

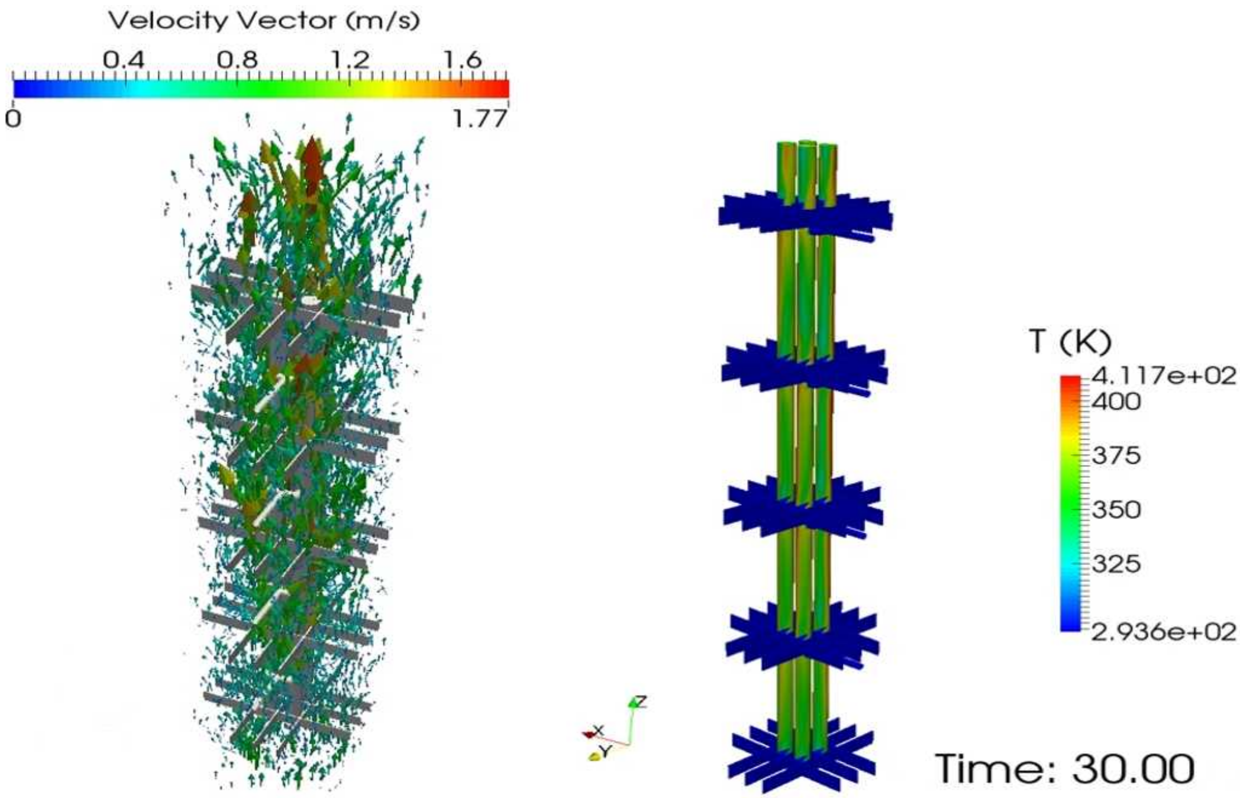


Figure 14. CFD simulation of natural circulation fuel bundle experiment—velocity and temperature distribution [Rodriguez, 2016B].

Figure 15 shows a fully-coupled HPC simulation using CFD, heat transfer, and structural analysis for a Westinghouse water-cooled fuel rod [Rodriguez and Turner, 2012]. The figure shows the fluid temperature distribution as it flows past the fuel rods, spacers, and swirl mixing vanes, once again allowing the analyst a highly-detailed view of the internal workings of a given design, and its ability to work properly. Figure 16 shows that coupling heat transfer onto the CFD and structural dynamics results in more fuel vibration, which is consistent with experimental data.

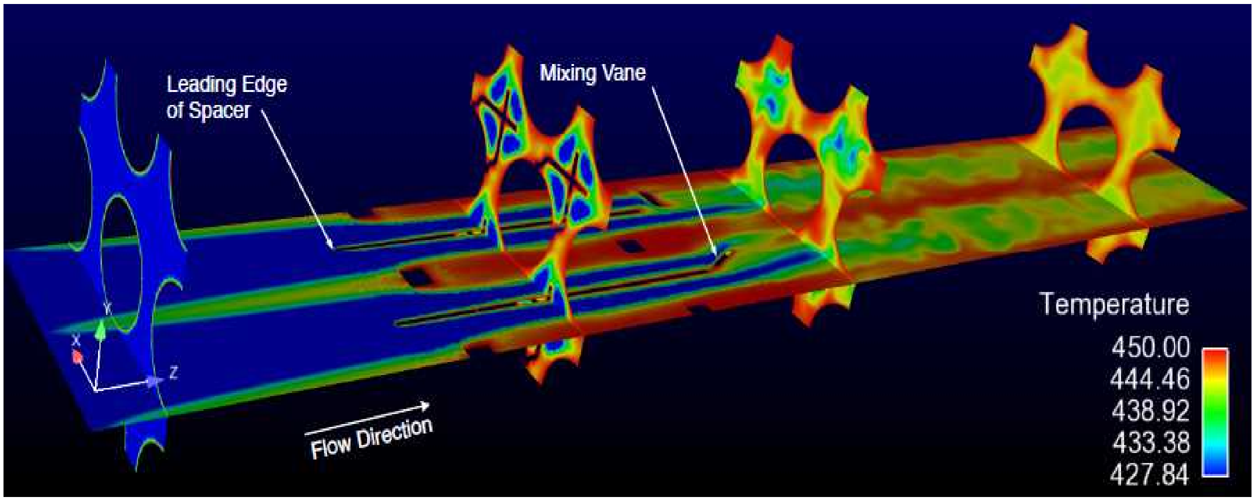


Figure 15. Coupled CFD, heat transfer, and structural analysis of Westinghouse fuel rod [Rodriguez and Turner, 2012].

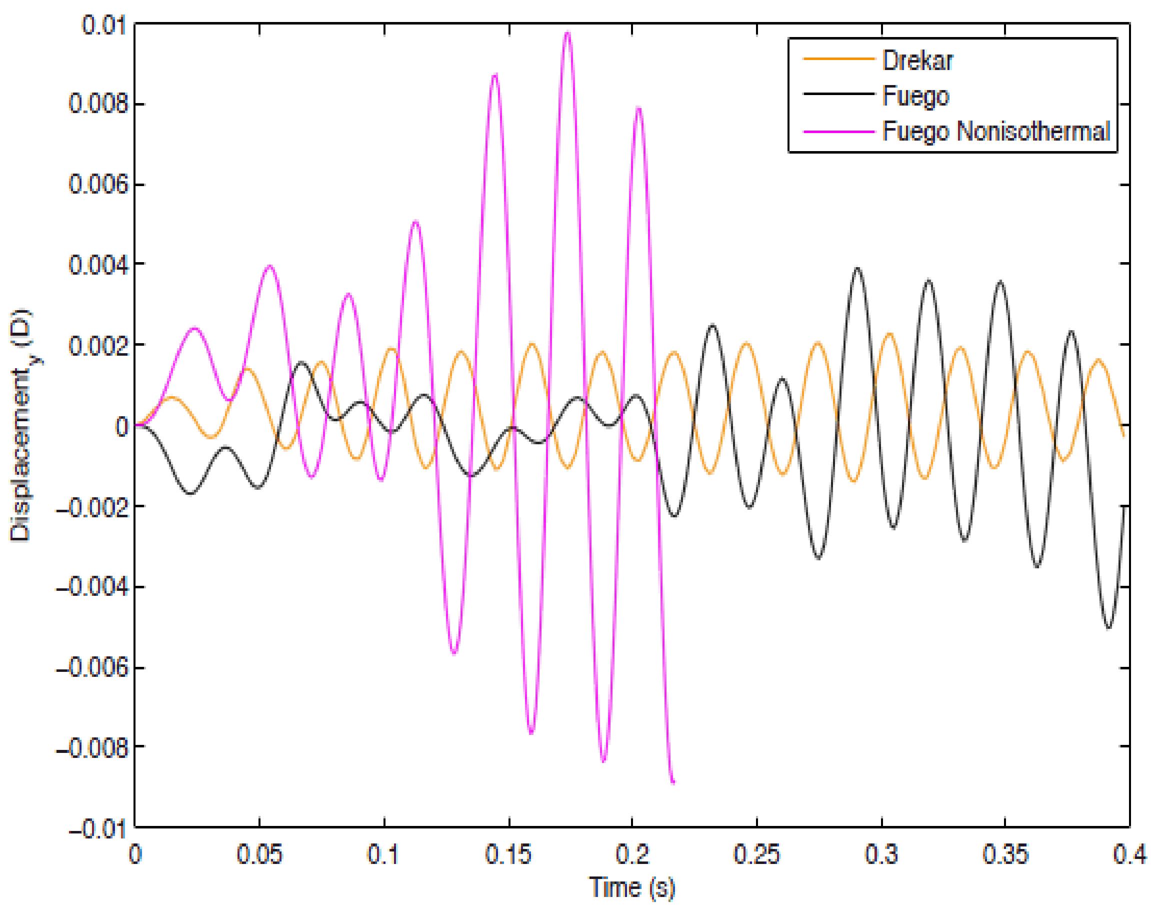


Figure 16. Shows the important effect of heat transfer on structural dynamics [Rodriguez and Turner, 2012].

Figure 17 shows a very high temperature reactor (VHTR) lower plenum using coupled CFD, heat transfer, and gas radiation dynamics [Rodriguez, 2011]. For this helium-cooled reactor, the analysis helps minimize hot spots, thermal stresses, areas where flow is stagnant, and so forth.

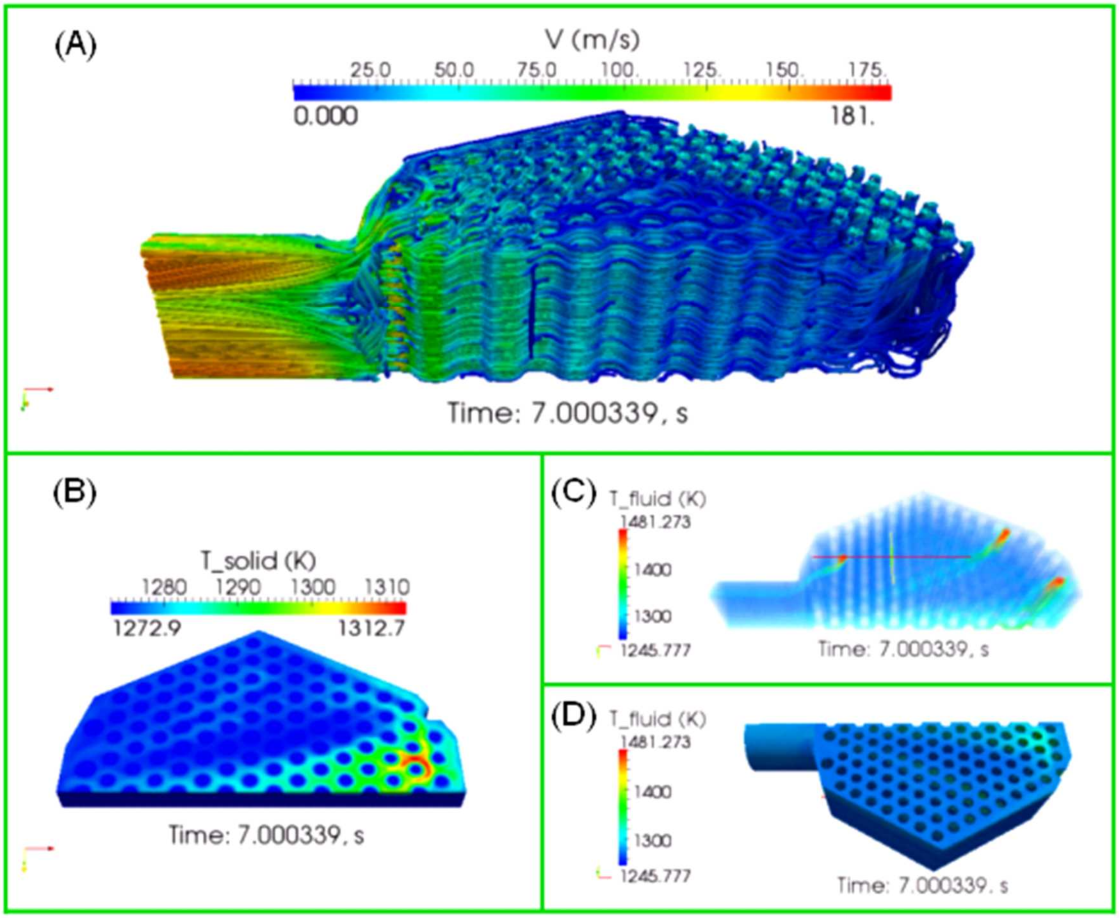


Figure 17. HPC output showing VHTR lower plenum simulation: (A) Velocity streamlines. (B) Plate temperature distribution, (C) Volume rendering of fluid temperature, and (D) Fluid temperature at the bottom side [Rodriguez, 2011].

Table 4 summarizes key thermalhydraulic capabilities of Sandia's codes suitable for HPC (e.g., Fuego, Calore, Presto, as well as full-plant integral analysis (MELCOR). The table confirms that the more detailed the calculation, the more engineering output will be obtained, but at a higher computational time requirement.

MELCOR is ideal for very fast, integral analysis of SMRs, if detailed output is not required. For example, MELCOR was used in 2016 to simulate various severe accidents for a prototypical NuScale SMR core, as shown in Figure 18 [Ingersoll et al., 2014]. Sandia recently added models into MELCOR to address unique SMR issues, including [Beeny, Young, and Humphries, 2015;

Lindgren, 2015A; Lindgren, 2015B; Louie, 2015; Rodriguez, 2015; Rodriguez et al., 2015; Young and Gelbard, 2015]:

- Geometry (Allow the simultaneous modeling of reactor pressure and containment vessels),
- Heat transfer (Add new shroud model for heat transfer from reflectors and condenser model),
- Aerosol behavior (resuspension model), and
- Spent fuel pool (SFP) heat transfer, modeling, and analysis.

Figure 19 shows the MELCOR temperature distribution of an SMR fuel during a hypothetical, severe accident. A comparison with analytical solutions showed excellent agreement.

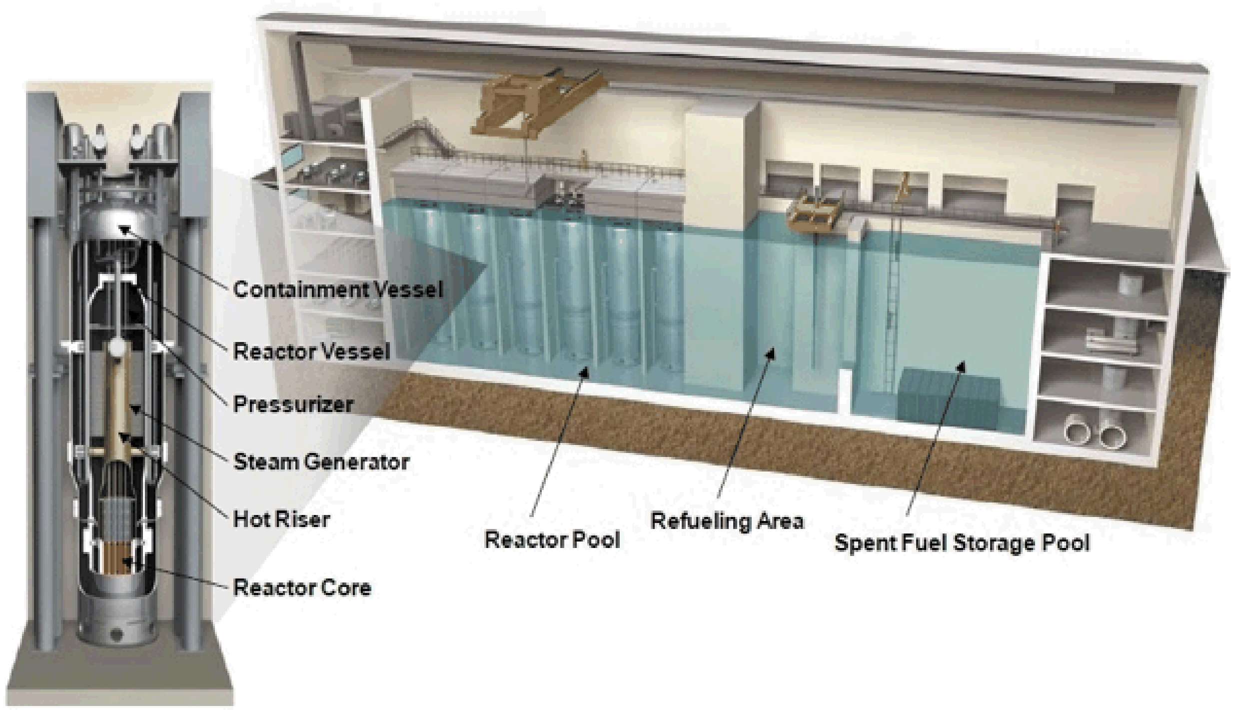


Figure 18. NuScale SMR configuration [Ingersoll, D. T. et al., 2014].

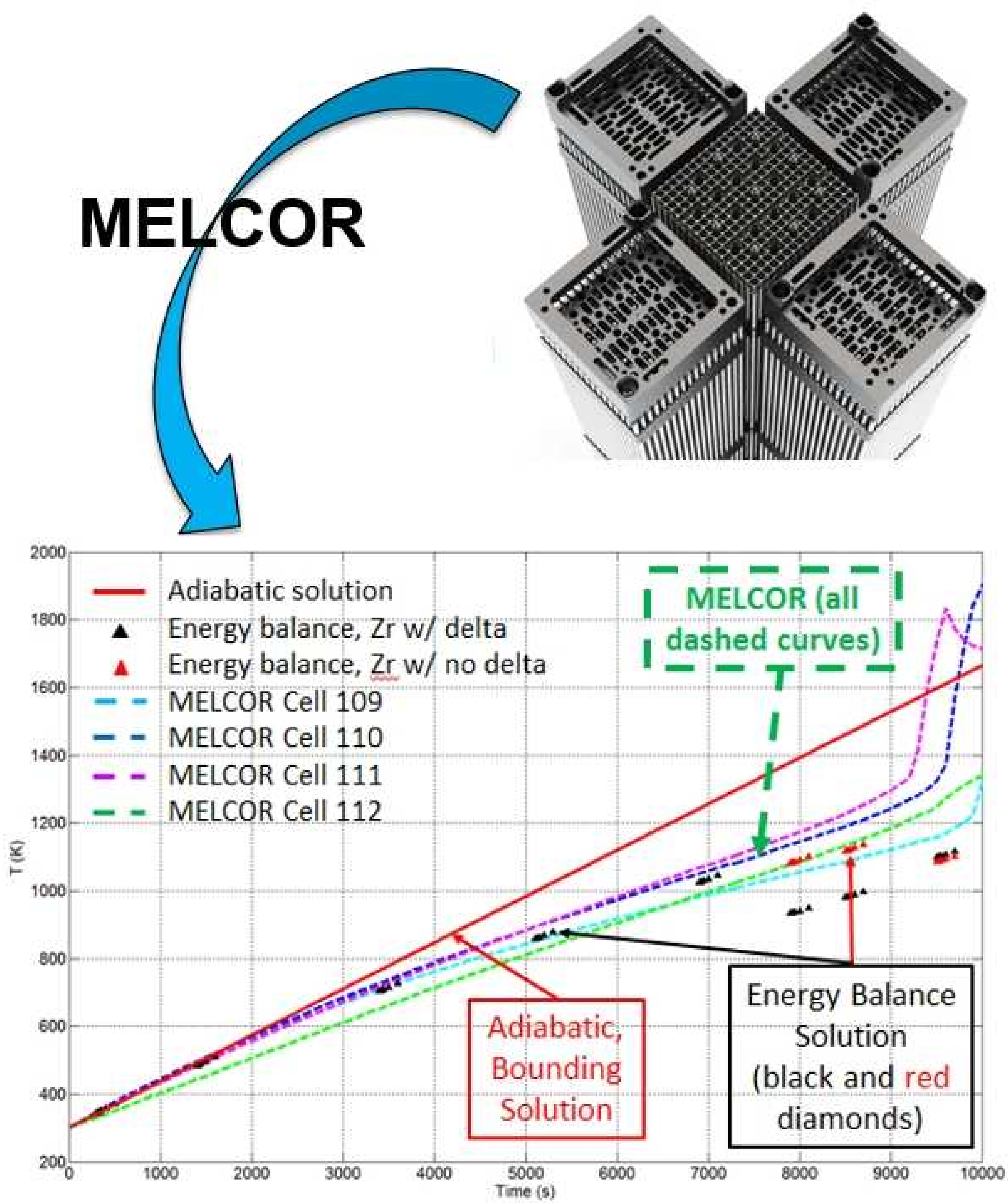


Figure 19. MELCOR simulation of SMR fuel during a hypothetical, severe accident [Rodriguez, 2015].

Table 4. Thermalhydraulic Nuclear Reactor Analysis Tools at SNL.

Key Parameter	Control Volume	Finite Element	
	MELCOR	Fuego-Calore	
		RANS	LES
Applicability	Ideal for integral system calculations. Suitable where fast, lumped (low-level engineering results) are suitable.	Ideal for detailed system components under turbulent flow.	Ideal where detailed, dynamic results are important.
Approximate Computational Time Requirements	SMR core using 1 processor and run to 36 transient hours: 3.6 hours.	Fuel bundle using 128 processors and run for 30 transient s: 1 hour.	Fuel bundle using 128 processors and run for 30 transient s: 10 hours.
Fluid Temperature	Lumped	Entire Scalar Field	Entire Field
Fuel Temperature	Lumped	Entire Scalar Field	Entire Field
Pressure	Lumped	Entire Scalar Field	Entire Field
Mass flow rate	Lumped	Entire Scalar Field	Entire Field
Velocity	Lumped	Entire Vector Field	Entire Field
Dynamic Turbulence Fluctuation Effects on Key Parameters	No	No	Entire Field up to Taylor eddies

Table 5 shows which Sandia codes are suitable for water-cooled reactors, while Table 6 shows a set of auxiliary codes suitable for more comprehensive SMR analysis, including dynamic optimization and sampling for design and safety analysis (DAKOTA), economic analysis (H2-Sim), risk and consequence analysis (MACCS), and neutronics (MCNP).

Table 5. Codes Suitable for Water-Cooled SMR Analysis.

Code	Purpose	Notes
Fuego	CFD	*Fuego, Presto, CALORE, and DAKOTA are coupled.
Presto	Structural	
CALORE	Conduction and radiation heat transfer	
MELCOR	Safety, integral analysis for entire system; two phase flow.	

***These are part of the Sierra suite of high performance codes available at Sandia. Because they share the same framework, they are readily coupled by user-input request.

Table 6. Auxiliary Codes for Comprehensive SMR Analysis.

Code	Purpose	Notes
Microgrid Design Toolkit (MDT)	Optimize microgrid designs for civilian and military applications.	Has been validated and applied to civilian and military critical infrastructures [Ellis, 2017].
Energy Surety Design Methodology (ESDM)	A quantitative, risk-based tool to enable communities to identify and solve critical, high-priority energy needs.	Has been validated and applied to civilian and military critical infrastructures [Ellis, 2017].
Microgrid Cybersecurity Reference Architecture (MCRA)	Tool to perform cybersecurity analysis, including design and implementation of secure microgrid control networks, network segmentation, and monitoring.	Has been validated and applied to civilian and military critical infrastructures [Ellis, 2017].
DAKOTA	Dynamic optimization/sampling of computations.	Straightforward coupling with Sierra tools.
H2-Sim	Economic analysis of systems.	
MACCS	Risk analysis (quantification of risk and consequences from accidents: dose, cost, and public health).	MELCOR and MACCS are readily coupled; the MELCOR output serves as MACCS input.
MCNP	Neutronics	

Sandia has various codes that are suitable for non-water-cooled SMR analysis. This is summarized in Table 7. For example, the Fuego code requires that the user input the desired material properties for the coolant. This is achieved via user functions, tables, or calls to material properties packages such as CANTERA. The same situation occurs with MELCOR. However, MELCOR already has a suite of internal material properties for coolants, including helium, carbon dioxide, argon, oxygen, air, as well as water and water vapor. A recent version of MELCOR was upgraded to include sodium as part of the default version (MELCOR-Na). Finally, Eta-Fprime is a Sandia-proprietary fast-running program that calculates within a second key design criteria such as peak velocity and temperature for laminar and turbulent molten metals, including sodium (Na), bismuth (Bi), lead (Pb), and lead-bismuth eutectic (LBE) [Rodriguez and Ames, 2015]. Because it is the fastest tool available at Sandia, its utility is the fast-scoping of new non-water SMR designs. For example, Table 8 shows the peak velocities, Prandtl number (Pr), Grashof number (Gr), and Nusselt number (Nu) attainable by various metal coolants. (Note that Pr, Gr, and Nu are great metrics for measuring heat transfer capacity.) Finally, Table 9 shows the expected reactor size and life based on power levels ranging from 0.5 to 100 MW_{th}, assuming U-235 enriched to 19.9% (with the "lightly-enriched" category).

Table 7. Non-Water-Cooled SMR Capabilities.

Code	Notes
Fuego	User-input material properties. Full 3D analysis.
MELCOR	User-input material properties. Relatively-fast integral tool.
MELCOR-Na	MELCOR based on sodium. Relatively-fast integral tool.
Eta-Fprime	Sodium, lead, bismuth, lead-bismuth eutectic. Laminar and turbulent flows. Fastest scoping of nuclear reactor concepts.

Table 8. Coolant Merit Comparison for SMRs with Various Molten Metal Coolants Based on Eta-Fprime Calculations.

	Pr	Gr_L	Ra_L	Nu_L	u_{max} (m/s)
Na	0.0054	1.03×10^{12}	5.56×10^{9}	38.0	0.471
Bi	0.018	2.23×10^{12}	3.97×10^{10}	83.4	0.264
LBE	0.021	2.16×10^{12}	4.49×10^{10}	89.4	0.261
Pb	0.026	9.16×10^{11}	2.39×10^{10}	80.6	0.246

Table 9. SMR Fast-Reactor Design Parameters.

Power (MW_{th})	Total Fuel Mass @19.9% U-235 (kg)	Neutron Flux (n/cm^2-s)	Core Life (years)
0.5	105	1.5×10^{14}	10
1.0	135	2.3×10^{14}	7
25	2,000	4×10^{14}	4

100	**6,000**	**5 x10^{14}**	**3.5**

INTRODUCTION TO ADVANCED MANUFACTURING AT SNL

Sandia continues to be involved in additive manufacturing (AM) ever since this innovative manufacturing concept began well over 30 years ago [Smith, 2016]. The Sandia AM budget in 2016 totaled $20 million in over 80 distinct projects, with approximately 50% of the funding spent on R&D, and the remainder primarily in applications related to the stockpile [Smith, 2016]. Key issues related to the AM of US stockpile components are manufacturing processes, material variability, and the cost to qualify components; these issues will also be of significant impact when applied to AM for the nuclear industry [Frazier, 2016; Vernon, 2016].

AM AT SANDIA

Sandia uses AM technologies with the goal of manufacturing fast and cost-effective specialized and complex system components. Our current AM areas of interest and research include [Smith, 2016: Mark F. Smith, Deputy Director for Additive Manufacturing at Sandia; Jared, 2016B]:

- FastCast (licensed/commercialized Sandia AM technology),
- Laser engineered net shaping (licensed/commercialized Sandia AM technology) [Griffith and Gill, 2002; Jared, Kammler, and Keicher; Mudge and Wald, 2007],
- RoboCast (licensed/commercialized Sandia AM technology),
- Direct write (current capability, activity) [Cook and Keicher, 2016],
- Thermal spray (current capability, activity), and
- Micro-nano scale (current capability, activity).

The three major AM areas of research and development at Sandia are

- analysis-driven design tools,
- materials assurance, and
- multi-material components [Smith, 2016].

The ultimate goal of the Sandia AM program is to have a fully-integrated, model-based, design/production approach that is agile, affordable, and assured [Smith, 2016].

Despite many advances, AM is not as mature as conventional manufacturing methods, and still poses several unique challenges, including inhomogeneities. Figure 20 shows inhomogeneities in the form of lack-of-fusion voids and partially-melted or loosely-attached powder particles [Salzbrener et al., 2017]. As a result of inhomogeneities such as these, material property variations invariably arise. For example, Figure 21 shows material property variations for a set of 1,000 printed samples of 17-4 PH stainless steel [Salzbrener et al, 2017]. For this set, there was a 33% variation in yield strength, 25% in ultimate tensile strength, and 80% difference in percent strain at failure. Similar material properties variations and other material issues (e.g., porosity) are noted in other studies for 17-4 PH stainless steel and other stockpile components [Jared, 2016A; Smith, 2016].

While such variations may be acceptable in some industries, they are likely not be acceptable for critical, nuclear-grade component materials. To mitigate this issue, additional material processing can be rendered to the AM components. This has been shown recently to significantly improve its material properties and variability. Such processes include hot isostatic pressing (HIP), whereby improvements of 13% were observed in the Weibull characteristic strength [Salzbrener et al., 2017]. Further variability minimization can be obtained using controlled flow rate and temperature specification (e.g., AM process sensitivities) [Gu et al., 2012; Smith, 2016; Frazier, 2016; Deibler, 2017]. Current areas of process sensitivity research at Sandia include studies in particle packing, heat transfer, melt flow, molten pool dynamics, solidification, microstructure, property performance, and topology design [Smith, 2016]. In addition, AM materials can be more prone to corrosion when compared with conventional methods, as shown in Figure 22 [Jared, 2016A].

Conceptually, process sensitivity control will be achieved with point qualification of AM parts (individual part qualification), better understanding of the dynamics for machine and process variability, and process qualification [Deibler, 2017]. These will be synthesized with the goal of deriving best practices for AM.

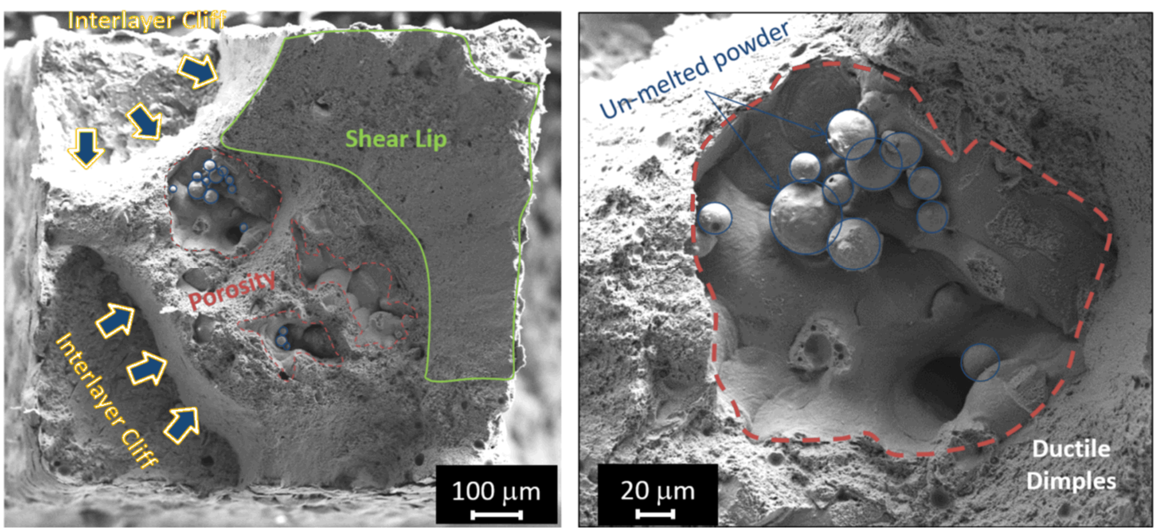


Figure 20. Inhomogeneities in the form of lack-of-fusion voids and partially-melted particles [Salzbrener et al., 2017].

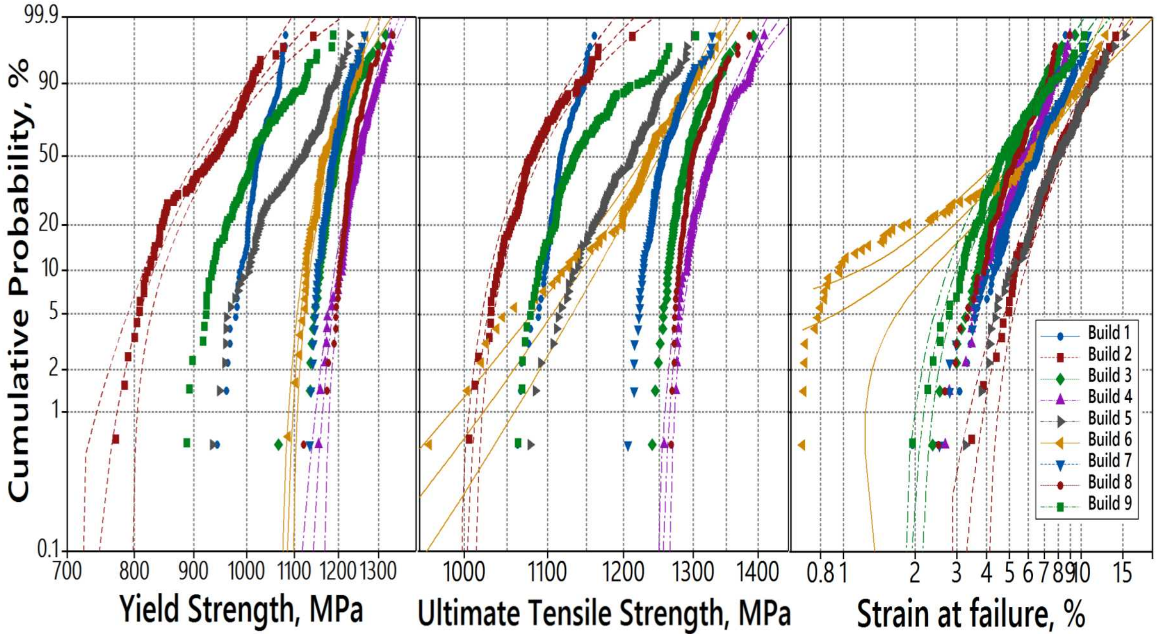


Figure 21. Variation in key structural material properties from 1,000 AM samples [Salzbrener et al., 2017].

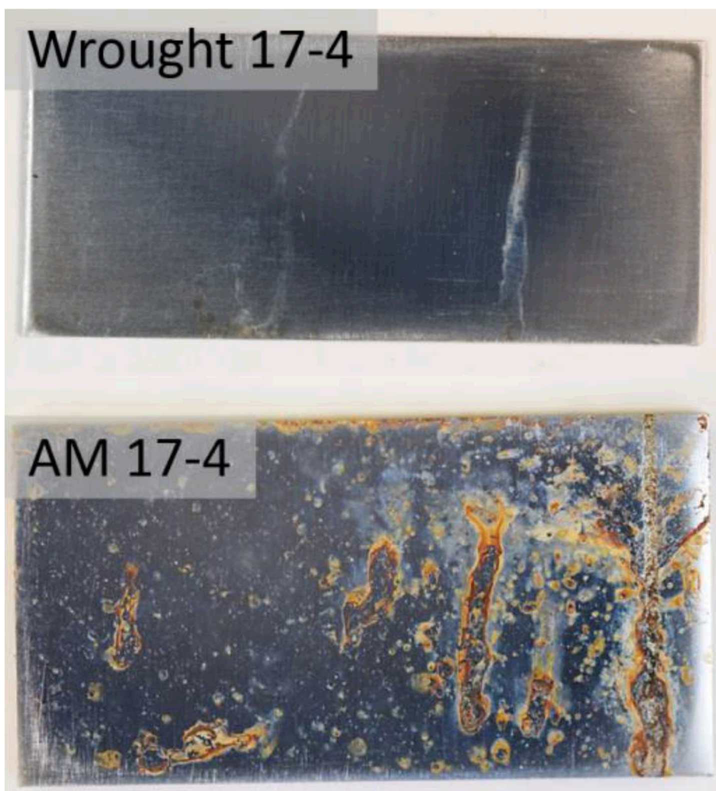


Figure 22. Stainless steel 17-4: wrought vs. AM exposed to the same corrosive environment [Jared, 2016A].

On the other hand, AM has remarkable advantages over conventional. These include

- Simplification of the assembly (integration) process (Figure 23) [Smith, 2016].
- Streamlined path from design to prototyping (reduces errors, is much faster and cheaper) (Figure 24) [Rodriguez, 2017B].
- The generation of complex geometries and material composites (Figures 25-28) [AT Kearney, 2015]. Note that the item in Figure 27 was not manufactured at Sandia, but is shown to reflect how sophisticated AM currently is; Sandia can readily produce such item as well. As noted in the figures, the degree of complexity in terms of geometry, functionality, and material matrix has increased substantially in recent years. *Figure 28 shows the point where AM is more cost-effective than conventional manufacturing.*
- On-site manufacturing, which reduces shipping cost, as well as assembly time.

When used in a judicious manner, these advantages over conventional manufacturing will result in high-quality components that are manufactured at significant cost reduction [Jared, 2016A]. These cost reductions will significantly reduce the cost of SMRs, enabling them to compete with other forms of energy production.

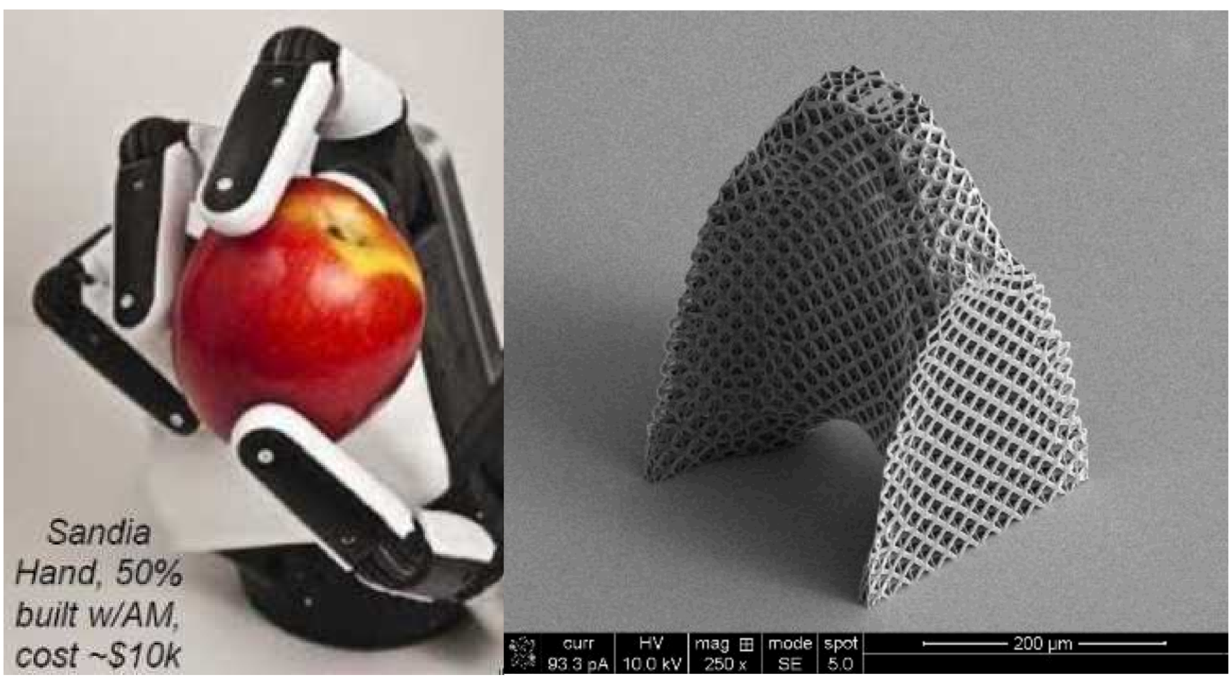


Figure 23. AM advantages over conventional manufacturing—simplified assembly process, rapid prototyping, and the generation of complex geometries at Sandia [Smith, 2016].

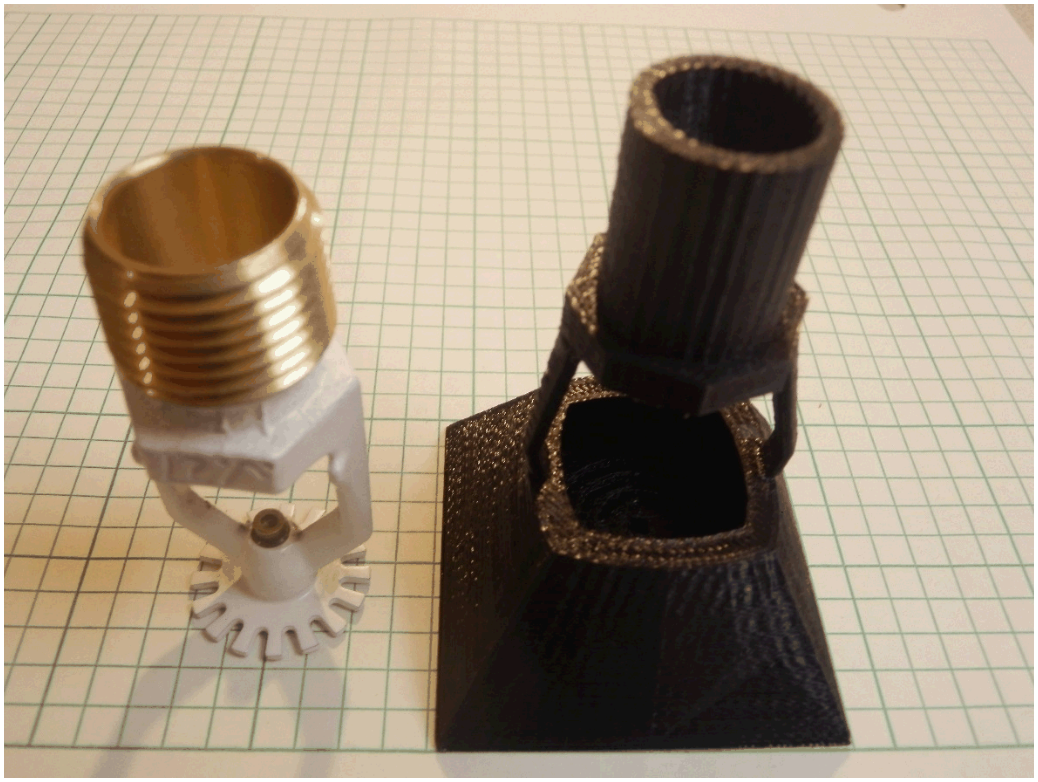


Figure 24. Rapid design and prototyping of an advanced fire sprinkler design at Sandia (LHS: conventional design; RHS: AM) [Rodriguez, 2017B]

Figure 25. An example of FastCast at Sandia [Smith, 2016].

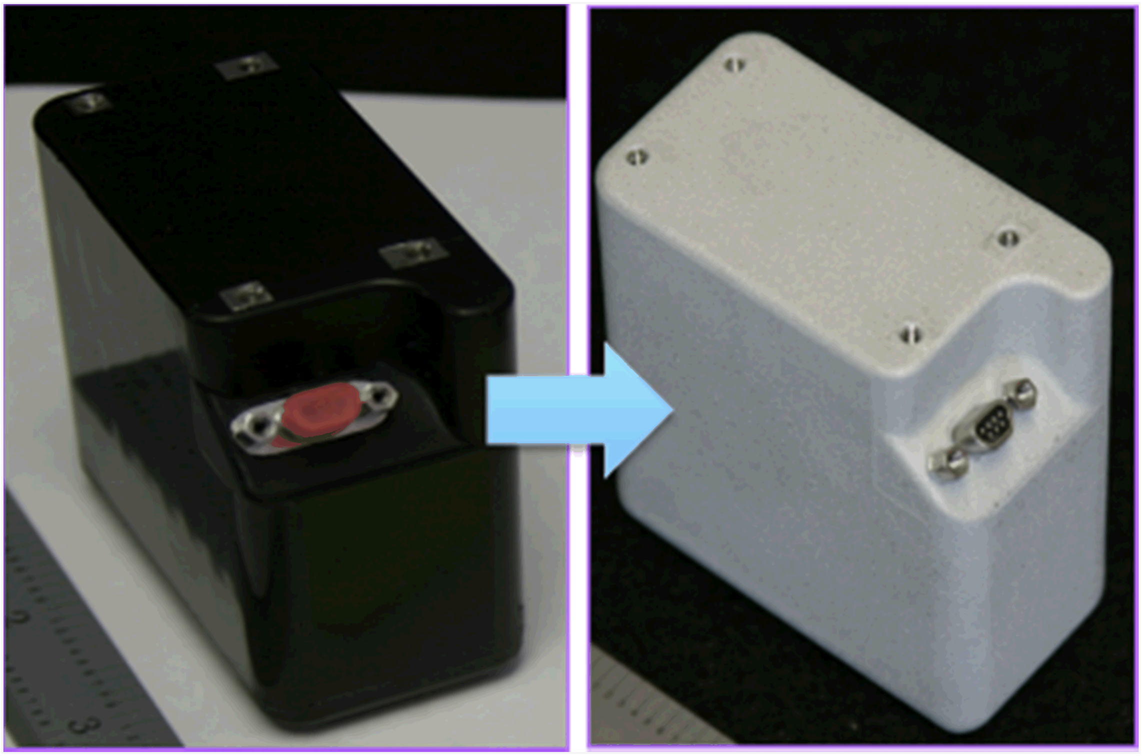
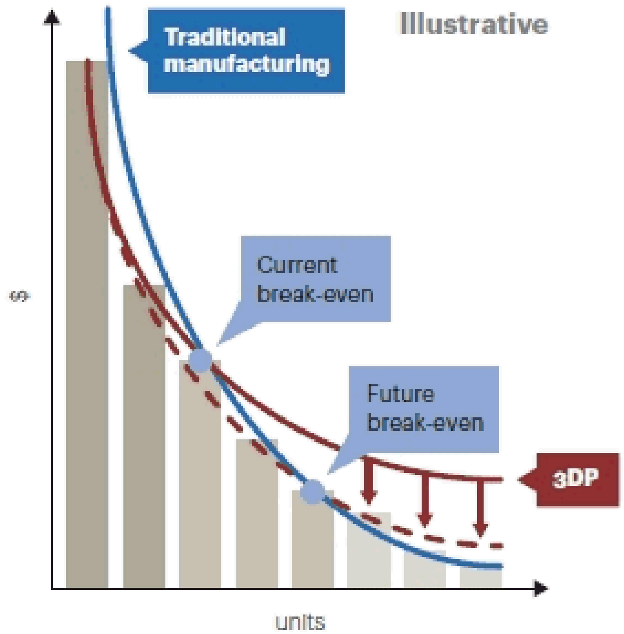


Figure 26. An example of thermal spray using metal on plastic at Sandia [Smith, 2016].

Figure 27. An example of a working system using AM manufacturing: US Army grenade launcher [Hodgkins, 2017].

Break-even comparison: traditional manufacturing vs. 3DP

Should-cost analysis by materials, functional performance, and structural characteristics



Sensitivity[1]	Change	Impact on break-even quantity[2]
Buy to fly ratio[3]	+10%	14 → 35% ↓
	–10%	50 → 125% ↑
Raw material $/lb	+10%	14 → 35% ↓
	–10%	50 → 125% ↑
Setup/run hours ratio	+10%	21 → 5% ↓
	–10%	23 → 5% ↑
Shop rates	+10%	11 → 50% ↓
	–10%	100 → 350% ↑
Material application (lb/hour)	+10%	4 → 82% ↓
	–10%	100 → 350% ↑

Figure 28. Cost comparison between AM and conventional manufacturing [AT Kearney, 2015].

How Can Current Sandia AM Contribute Towards Making SMRs Cost-Competitive?

Sandia can compete and lead in various areas towards achieving cost-competitive SMRs, both now and in the future.

In the near-term, niche applications where Sandia's AM technology can make SMRs more cost-competitive than if conventional manufacturing methods were used, include:

- Any system components where assembly simplifications result in the reduced integration work required to integrate subcomponents, thereby reducing labor costs.
- New SMR subsystems that require research and development. In such cases, rapid prototyping of the components will result in significantly-reduced costs because of the close coupling between design, computational analysis, and experimental validation [Rodriguez, 2017B; AT Kearney, 2015].
- Production of any subcomponents with complex geometries, especially components that are only needed in small quantities [AT Kearney, 2015].

In the future, the number of components that are cost-competitive via AM will only increase exponentially as process and materials controls are implemented, systems are integrated, and larger components are manufactured. To be clear, neither Sandia nor anyone else is currently capable of AM of complex, large-scale nuclear-grade components. However, in the future, the above-named advances will provide substantial savings in manufacturing cost and shipping, and significant extension of AM components that will result in financial savings.

Once Sandia has a fully-integrated, model-based, design/production approach that is agile, affordable, and assured, major financial benefits will be reaped as material variability is better controlled for the production of nuclear grade materials. In addition, this will lead to the economical manufacturing of complex metallic composites, complex geometries, and subsystem integration. In summary, this will allow AM for vessel heads, nuclear-qualified material components, and complex structures that reach higher complexities, such as the initial manufacturing of fuel rods first, followed by AM of entire fuel assemblies, and culminating in entire nuclear cores and other large structures.

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