Smart Grid Design, Development, and Cyber Security for Small Modular Reactors

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Invited Presentation

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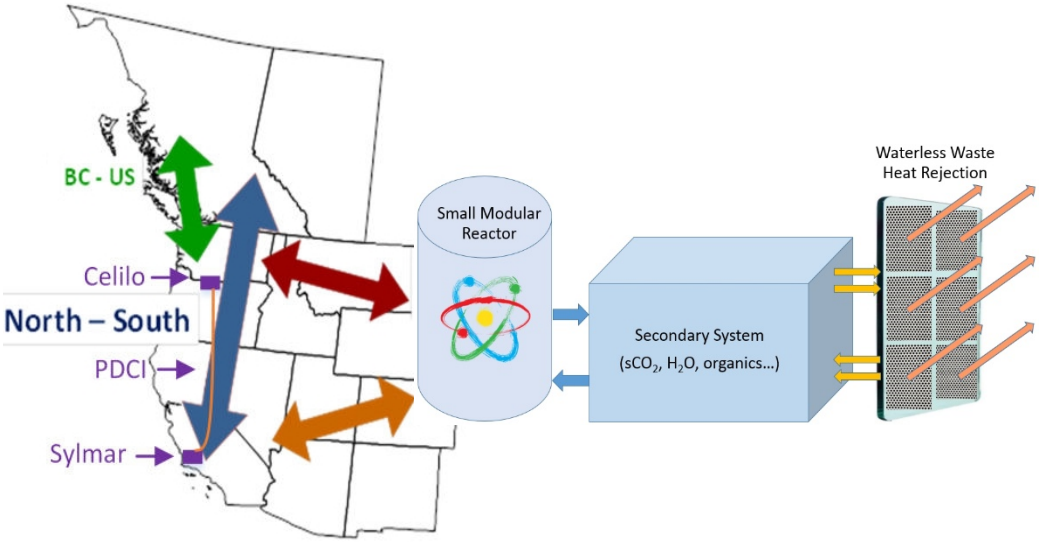

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Introduction

- Motivation—Why Small Modular Reactors (SMRs) in Smart Grids and Microgrids?
- Sandia National Laboratories' (SNL) Integral Approach for Economically-Viable SMRs:
  - ✓ High Performance Computing (HPC) and Computational Dynamics
    - ➢ Coupled Multi-Physics, Computational Fluid Dynamics (CFD)
  - ✓ Smart Grid Tools
  - ✓ Advanced Manufacturing (AM)
  - ✓ State-of-the-Art Experiments
- Path Forward
- Conclusion

Motivation

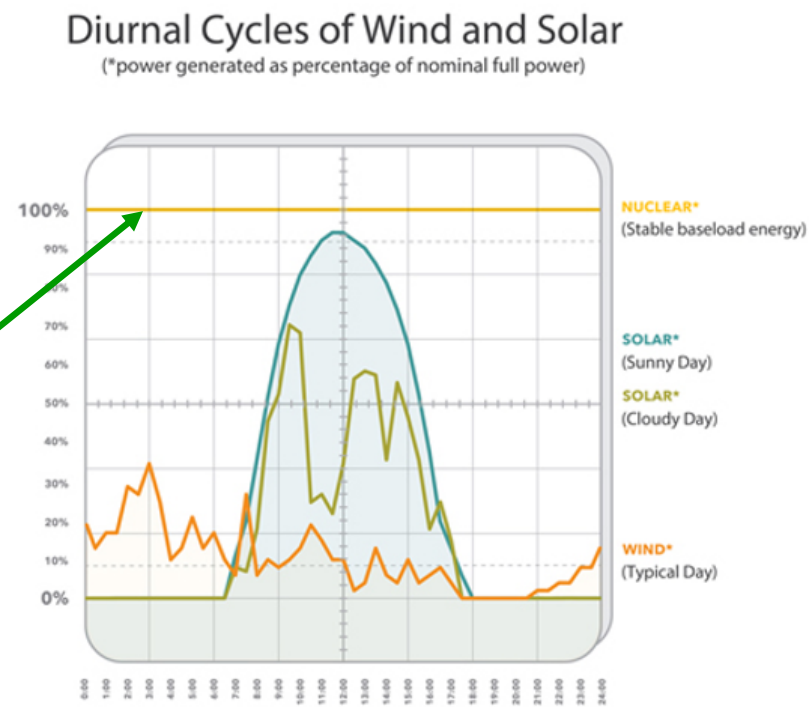
- We are faced with a difficult challenge as a result of diminishing natural resources, a more fragile environment, and increasing population.
  - ✓ Cities with limited water supplies cannot sustain water-based power systems.
  - ✓ Evaporative water loss at power-generating sites is significant.
    - ❖ Current water cycles require 650 to 850 gallons of water per MWh of generated electricity.
    - ❖ 80,000,000 gallons of water *per day* is evaporated at Palo Verde nuclear reactors.
- Clearly, this trend is unsustainable under a growing population with diminishing natural resources.
- It is therefore crucial that more efficient energy and water technologies be developed, while reducing environmental impact.
- ***An ideal solution is the inclusion of SMRs onto smart microgrids.***

Motivation

- The Department of Energy (DOE) is leading grid infrastructure modernization.
- Smart grids and microgrids are a crucial component for enabling the nation's future energy needs.
- Smart grids and microgrids are being considered in niche applications, and as part of a comprehensive energy strategy:
  - Manage the nation's growing energy demands,
  - Critical infrastructures,
  - Military installations,
  - Small rural communities, and
  - Large populations with limited water supplies.

Why SMRs in Smart Grids?

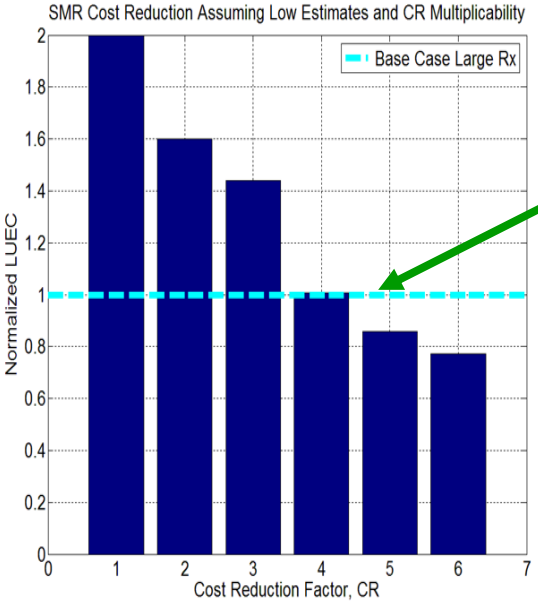
- *SMRs have many exclusive features found in no other energy source.*
- *Unique SMR features that are highly desirable for integration onto smart grids:*
  - ✓ High reliability,
  - ✓ Scalable, right-sized power sources,
  - ✓ Economical,
  - ✓ Load balancing,
  - ✓ Highly-reduced CO_2 footprint,
  - ✓ Diversified energy portfolio, and
  - ✓ Strong potential for lower water usage.



Nuclear, solar, and wind energy output cycles—benefit of nuclear load balancing [NuScale Why SMR, 2017A].

Why SMRs in Smart Grids?

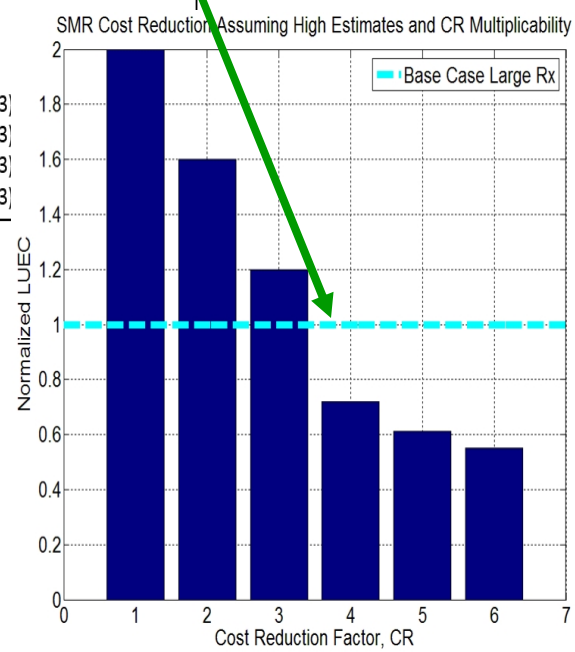
If various cost-reducing measures are implemented, SMRs have a lower levelized unit electricity cost (LUEC) than conventional (large) reactors.



CR 1 = Base SMR
CR 2 = Construction duration
CR 3 = FOAK, multiple orders
CR 4 = Subsequent unit orders
CR 5 = Design simplification
CR 6 = Barge-mounted plant

LUEC 1 = 2*LUEC$_{large\ rx}$
LUEC 2 = (LUEC 1)*(CR 2)
LUEC 3 = (LUEC 1)*(CR 2)*(CR 3)
LUEC 4 = (LUEC 1)*(CR 2)*(CR 3)
LUEC 5 = (LUEC 1)*(CR 2)*(CR 3)
LUEC 6 = (LUEC 1)*(CR 2)*(CR 3)

SMR cost comparison vs. conventional reactor: pessimistic cost reduction factors.



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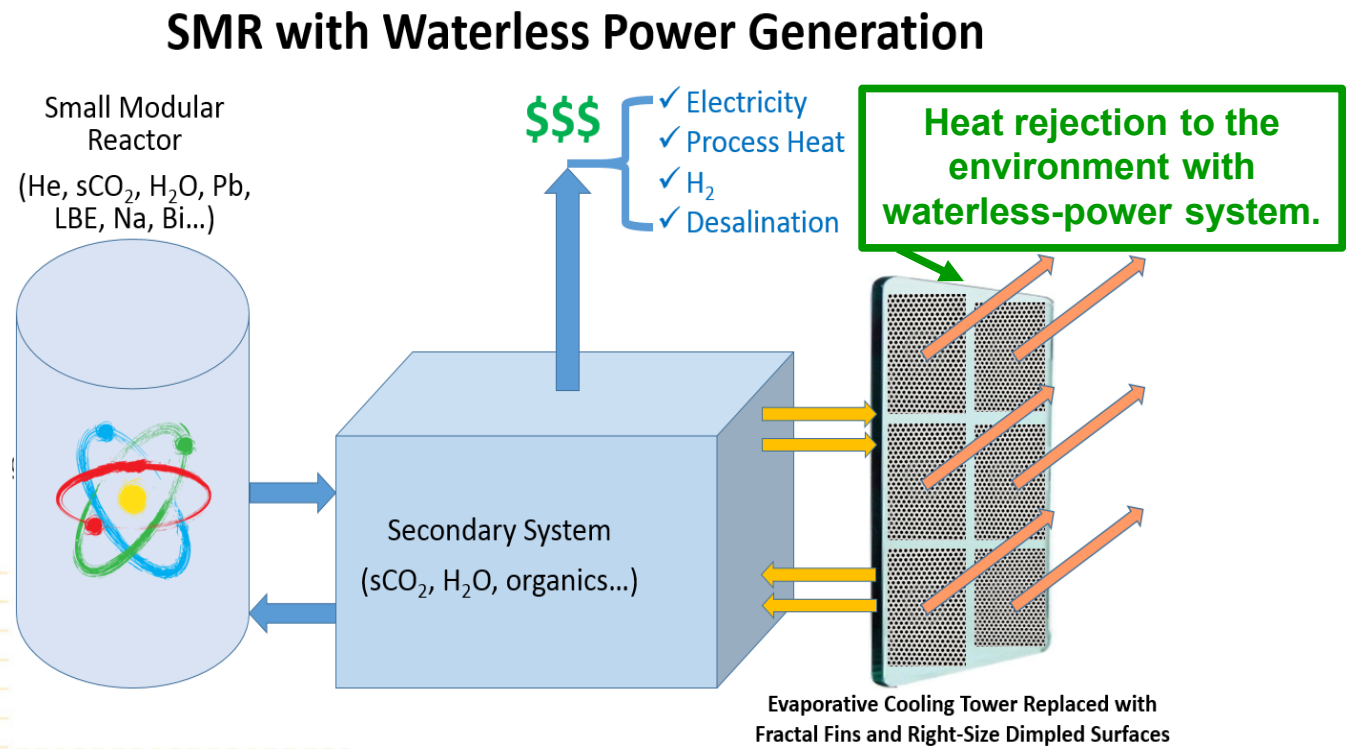
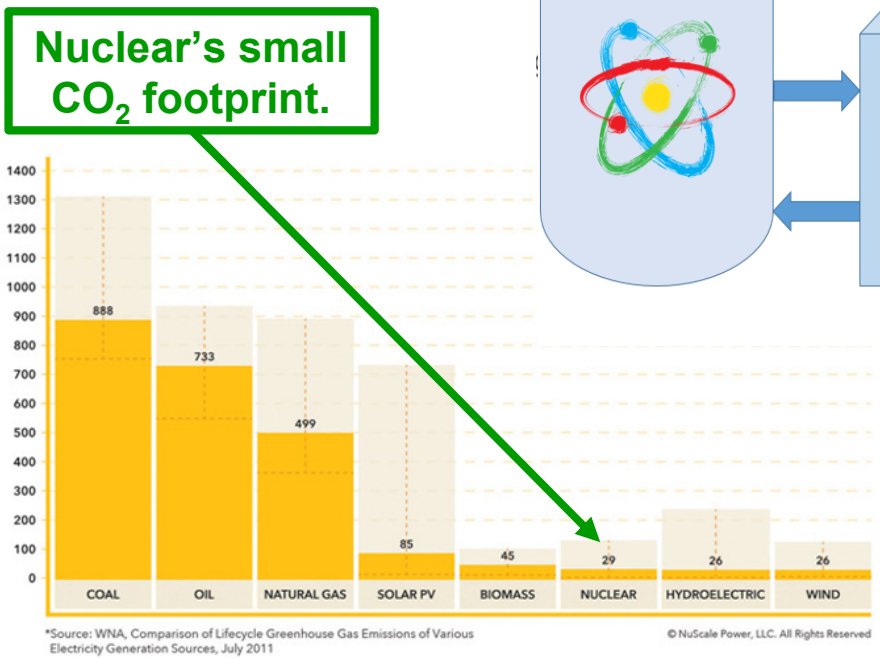
Why SMRs in Smart Grids?



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

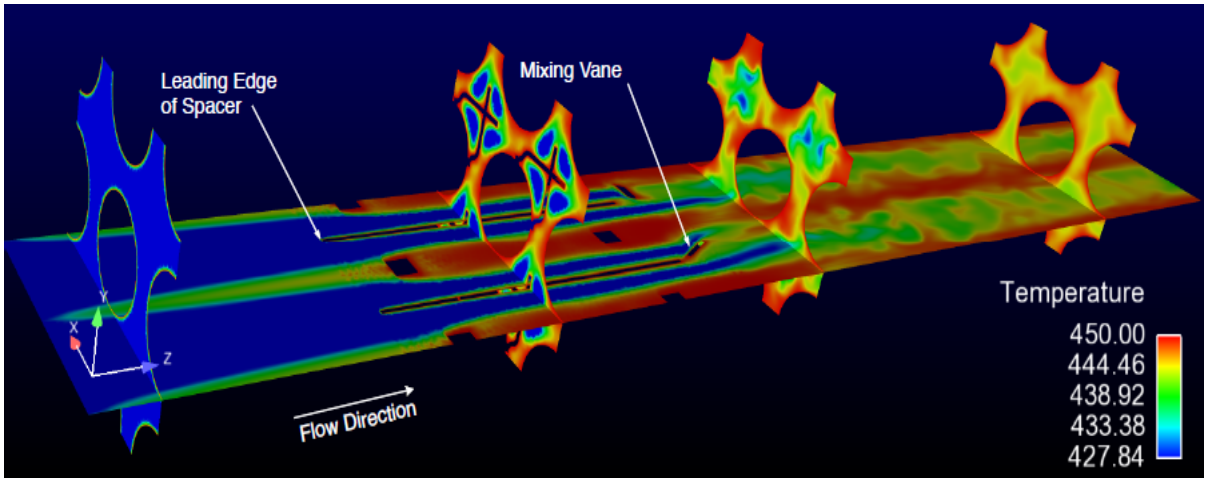


CO_2 Gas Emission from Various Energy Sources [NuScale Why SMR, 2017C].

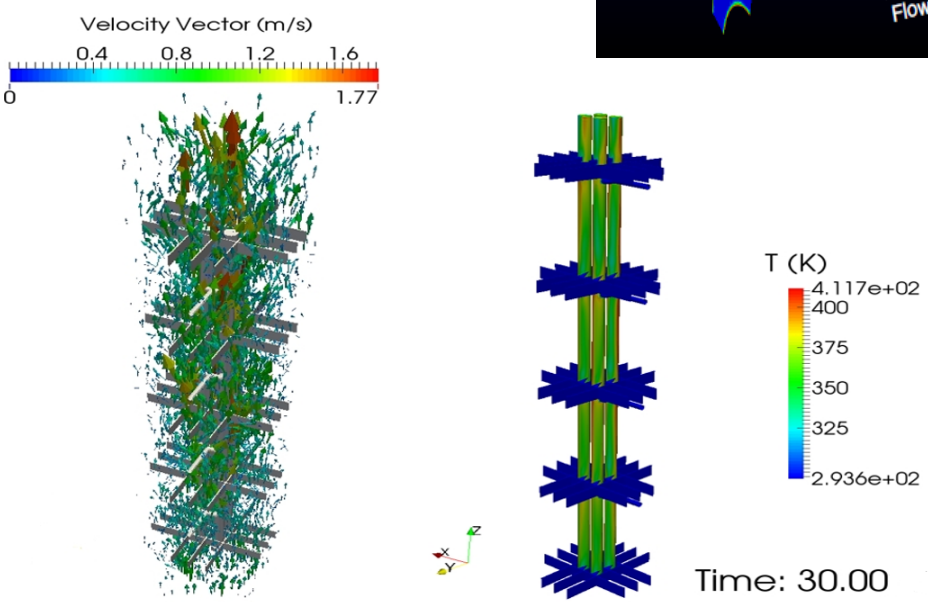
HPC and Computational Dynamics

- SNL has 179,858 parallel processors, for an astonishing computational power equal to 3,706 teraflops.
- As an example, an air-cooled nuclear fuel bundle simulation using 128 processors requires a total of 10 hours to complete.
  - This represents just 0.071% of Sandia's total HPC capacity!
- Our HPC provides system designers and analysts a tool that, compared with experiments, is
  - Less costly,
  - Provides more data (including data that is not currently measurable with current instrumentation), and
  - Probes deeper into system behavior; exploits physics.
- This allows for the development of more efficient energy systems that are more cost-competitive and more benign towards the environment.

HPC and Computational Dynamics



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



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

Smart Grid/Microgrid Technology

- Sandia's current computational capabilities model the entire grid, including temporal aspects and cyber security issues.
  - ✓ Includes a comprehensive set of tools for system development, integration, testing and evaluation, monitoring, and sustainment.
- State-of-the-art smart grid tools at SNL:
  - ✓ Smart Power Infrastructure Demonstration for Energy Reliability and Security (SPIDERS): a suite of smart grid methodologies and tools.
  - ✓ Energy Surety Design Methodology (ESDM): a quantitative, risk-based tool to enable communities to identify and solve critical, high-priority energy needs.
  - ✓ Reference Architecture (RA): has been validated and applied to civilian and military critical infrastructures.
  - ✓ Microgrid Cybersecurity Reference Architecture (MCRA): a tool to perform cybersecurity analysis, including design and implementation of secure microgrid control networks, network segmentation, and monitoring.
  - ✓ Microgrid Design Toolkit (MDT): optimizes microgrid designs for civilian and military applications.

Smart Grid/Microgrid Technology

Summary of Sandia's experience with smart microgrids: design and cyber security [Nanco, 2016].

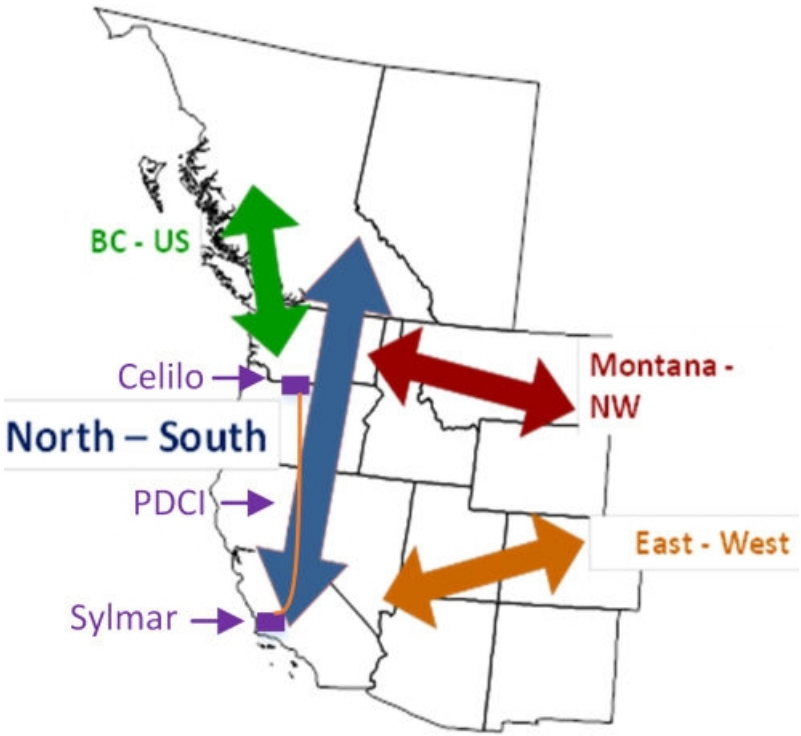
Energy Security Assessments & Microgrid Conceptual Designs	<1 MW Microgrid Operations	Large Scale Microgrid Operations	Community Microgrid Designs

• 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

Smart Grid/Microgrid Technology

Areas where Sandia excels in smart grid/microgrid modernization:

- 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.



Primary oscillation mode shapes for grid security [Pierre et al., 2016A].

Advanced Manufacturing

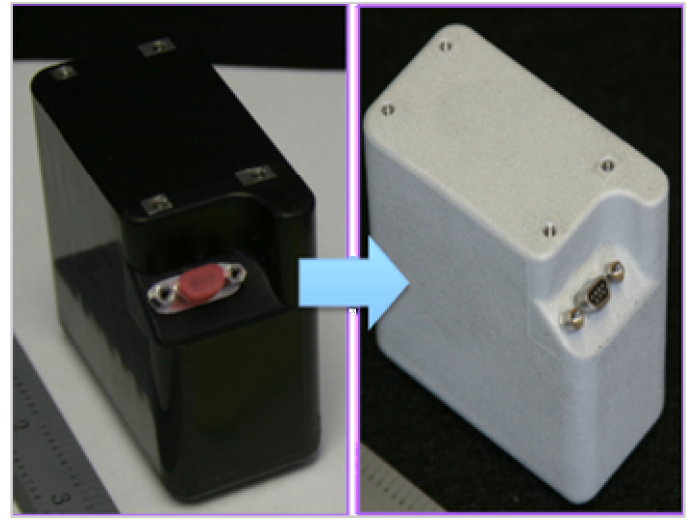
- Sandia's goal is manufacturing of fast and cost-effective system components.
- Our current AM areas of interest and research include technologies that are either exclusive to Sandia, or that are currently being advanced by Sandia:
  - ✓ FastCast,
  - ✓ Laser engineered net shaping,
  - ✓ RoboCast,
  - ✓ Direct write,
  - ✓ Thermal spray, and
  - ✓ Micro-nano scale manufacturing.
- Our three major AM areas of research and development are analysis-driven design tools, materials assurance, and multi-material components.
- The ultimate goal of our AM program is to have a fully-integrated, model-based, design/production approach that is agile, affordable, and assured.

Advanced Manufacturing

- AM has various remarkable advantages over conventional manufacturing that can be exploited for SMR applications:
  - Simplification of the assembly process (integration),
  - Streamlined path from design to prototyping,
  - Generation of complex geometries and material composites, and
  - On-site manufacturing for reduced shipping cost, as well as reduced assembly time.
- Current areas of AM sensitivity research at Sandia include process and material variability.
- 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*.

Advanced Manufacturing

An example of simplified assembly process, rapid prototyping, and the generation of complex geometries at Sandia [Smith, 2016].



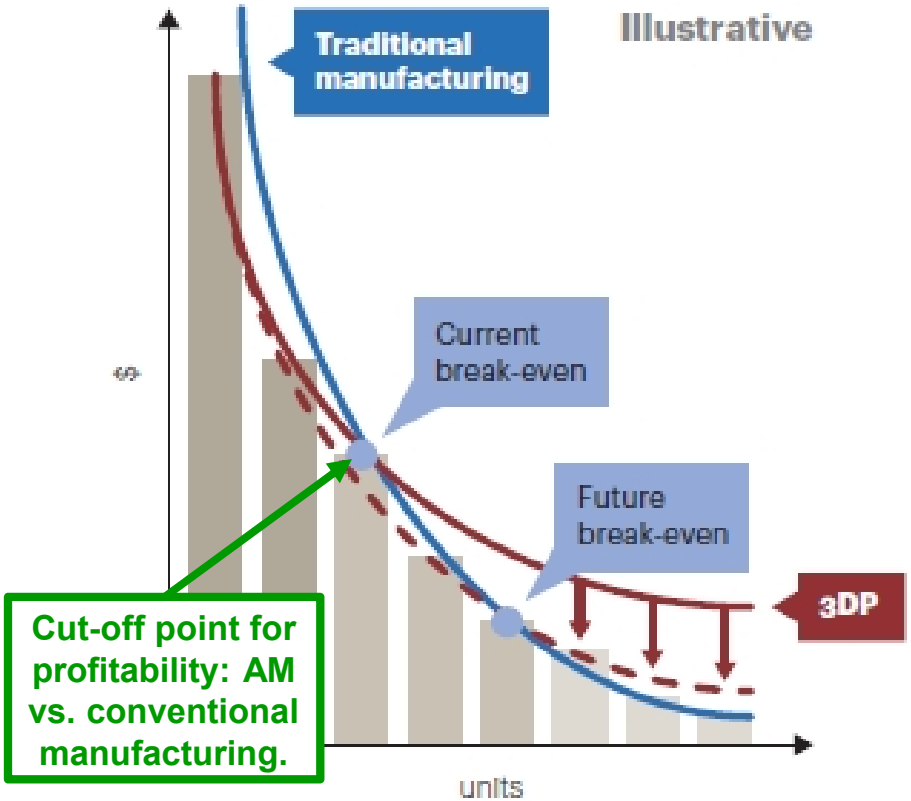
An example of thermal spray using metal on plastic at Sandia [Smith, 2016].

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

Advanced Manufacturing

Break-even comparison: traditional manufacturing vs. 3DP

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

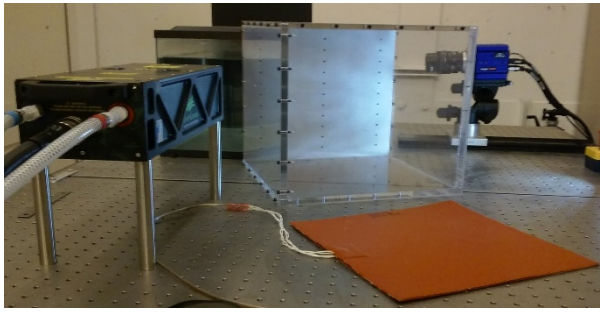


Sensitivity[1]	Change	Impact on break-even quantity[2]
Buy to fly ratio[2]	+10%	14 → 35% ↓
	–10%	50 → 125% ↑
Raw material $/lb	+10%	14 → 35% ↓
	–10%	50 → 125% ↑
Setup/run hours ratio	+10%	21 → 5% ↓
	–10%	23 → 5% ↑
Shop rates	+10%	11 → 50% ↓
	–10%	100 → 350% ↑
Material application (lb/hour)	+10%	4 → 82%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

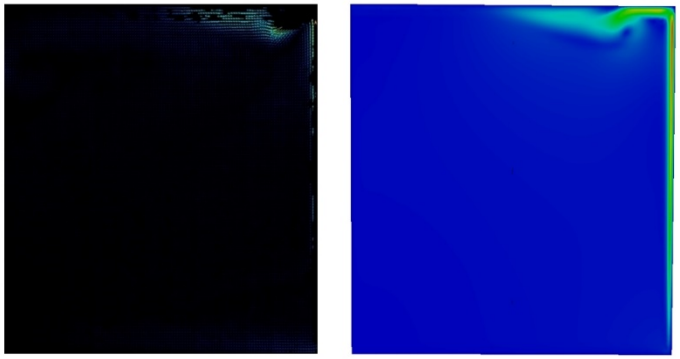
Cost comparison between AM and conventional manufacturing [AT Kearney, 2015].

State-of-the-Art Experiments

- Particle image velocimetry (PIV) allows
  - Economical experimental observation of system fluid velocity.
  - Provides design optimization based on data analysis.
- Example: design an inexpensive, passive, water tank for collection of solar heat (modular solar water tank—MSWT).
- Tools:
  - ✓ HPC, CFD, and PIV.
  - ✓ Recent advances in dimpled surfaces.
- Results:
  - ✓ MSWT harvests $575.10/yr solar heat.
  - ✓ Total cost to build device: $1,514.41.
  - ✓ Break-even point: 2.6 years.



MSWT Experiment 1, q”=840.8 W/m^2

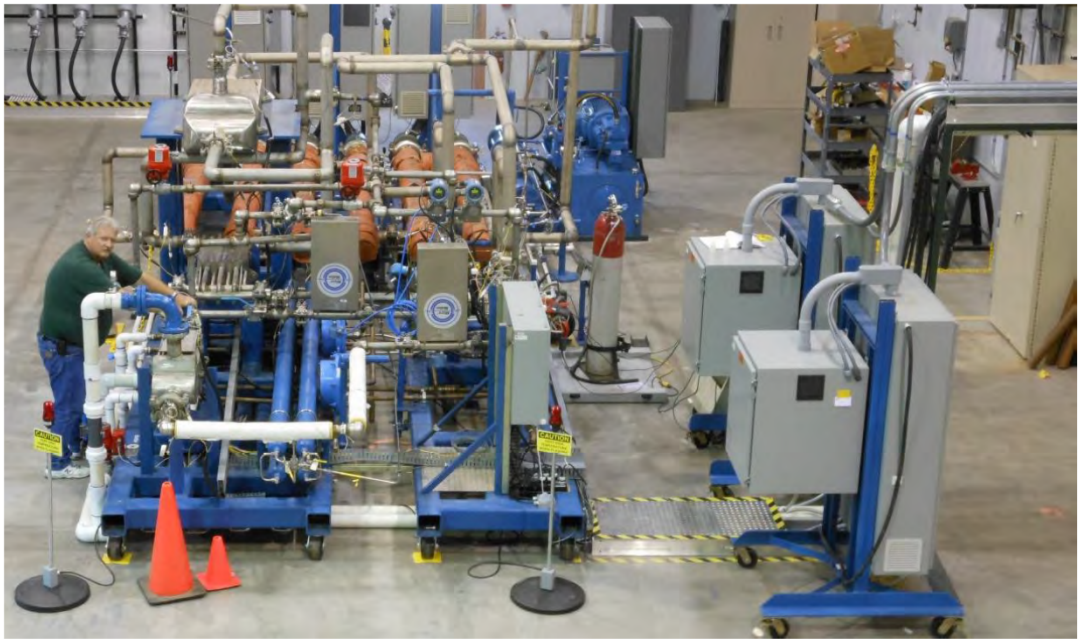


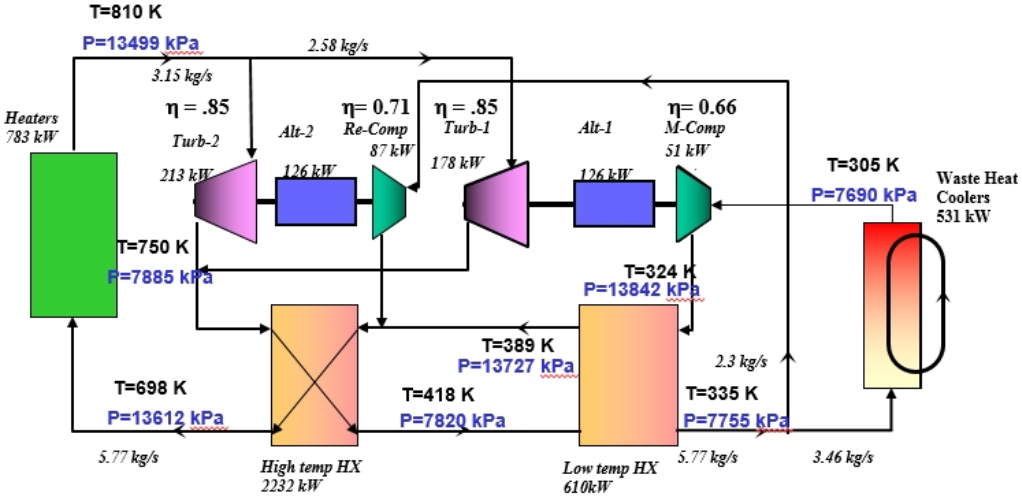
PIV CFD

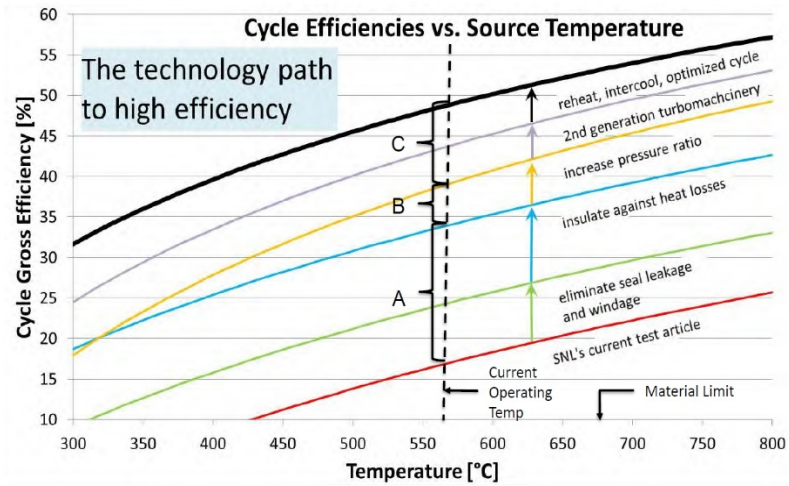
PIV and CFD comparison of experimental vs. computational velocity.

State-of-the-Art Experiments

- 1 MW sCO_2 Brayton Loop.
- 550 °C, 14 MPa.
- Enable waterless power production.
- Commercialize the technology, scale to 1 GW by 2020 [Rochau, 2014].







Path Forward

How Can We Contribute Towards Making SMRs/Smart Grids Cost-Competitive?

Near Term:

- Couple the computational physics with the smart grid tools.
- Apply the HPC towards the streamlined design and modeling of an entire SMR coupled to the grid.
- Apply scaling to validate subsystem behavior using PIV, etc.
- Seek niche applications where AM technology makes SMRs more cost-competitive than conventional manufacturing:
  - Any system components where assembly simplifications result in a reduction in the integration work,

Path Forward

How Can We Contribute Towards Making SMRs/Smart Grids Cost-Competitive?

Near Term (continued):

- Apply tools to new SMR subsystems that still require research and development.
  - Rapid prototyping of the subsystems will result in significantly-reduced costs because of the close coupling between design, computational analysis, and experimental validation.
- Production of any subcomponents with complex geometries, especially components that are only needed in small quantities.
- On-site manufacturing.

Path Forward

How Can We Contribute Towards Making SMRs/Smart Grids Cost-Competitive?

Long Term:

- Parallelize the smart grid tools.
- Increase the fidelity of the SMR-smart grid designs for additional functionality and higher economic return on investment.
- Perform state-of-the-art experiments to further optimize the system performance and to validate the design metrics.
- The number of AM components that are cost-competitive will increase as *best-practice* process and materials controls are implemented, systems are integrated, and larger components are manufactured.
- Continue to seek agile, affordable, and assured fully-integrated, model-based design/production.
- As *material variability is controlled* to approach nuclear-grade quality, more economical manufacturing of complex metallic composites and streamlined subsystem integration will occur.

Path Forward

How Can We Contribute Towards Making SMRs Cost-Competitive?

<u>Long Term (continued):</u>

- 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, starting from relatively simple subsystems, expanding onto highly-complex systems, and culminating in system of systems.
- For example:
  - → start with AM of fuel rods,
  - → followed by AM of entire fuel assemblies, and
  - → culminating in more complex systems (e.g., entire nuclear cores, vessel heads, etc.).

Summary/Conclusion

- SMRs are ideal for enabling environmentally-benign, cost-efficient, load-balanced, diversified, power-production in smart grids.
- High performance computational dynamics is not just “eye candy”, but a powerful predictor of system/design behavior and a resource for advanced systems with excellent profitable margins.
- Smart grid tools are already providing many solutions, as part of DOE’s desire to modernize the grid and provide reliable, economical energy.
- AM already provides cost-competitive SMR components; this trend is expected to increase dramatically as best-practices are implemented.
- State-of-the-art PIV and various modern experimental tools validate system designs and provide data for additional design improvements.
- *The confluence of smart grid tools, HPC, AM, and state-of-the-art experiments are key for profitable SMR/smart grid development*.
- Government/labs/universities: need to seek and partner in emergent technologies that have a strong potential for return on investment.
  - ✓ *Industrial collaboration, scientific advances, and profit will fuel the technical advances and infrastructure of the future.*