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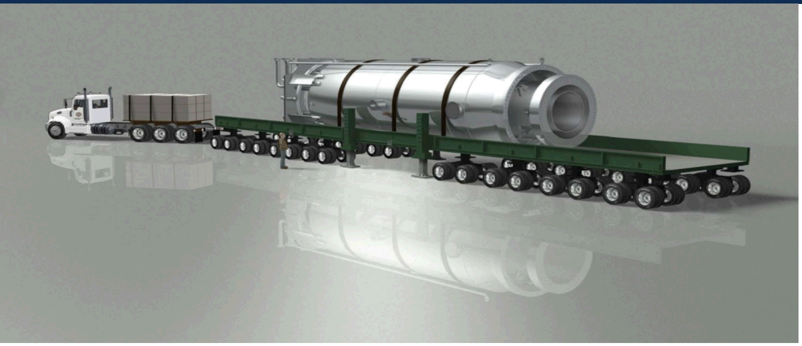

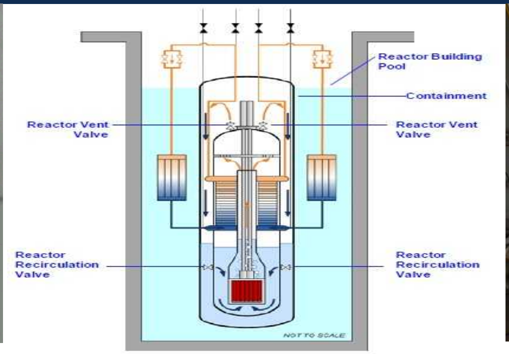

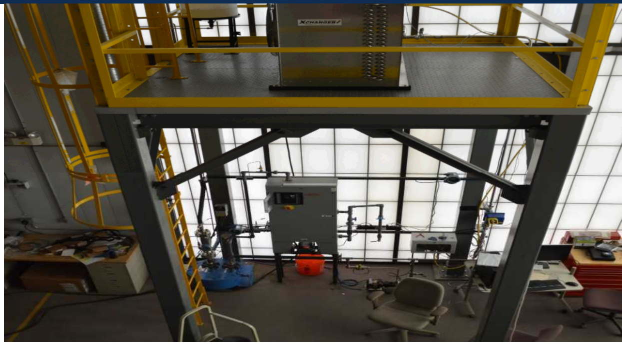

Overview of Small Modular Reactors Projects

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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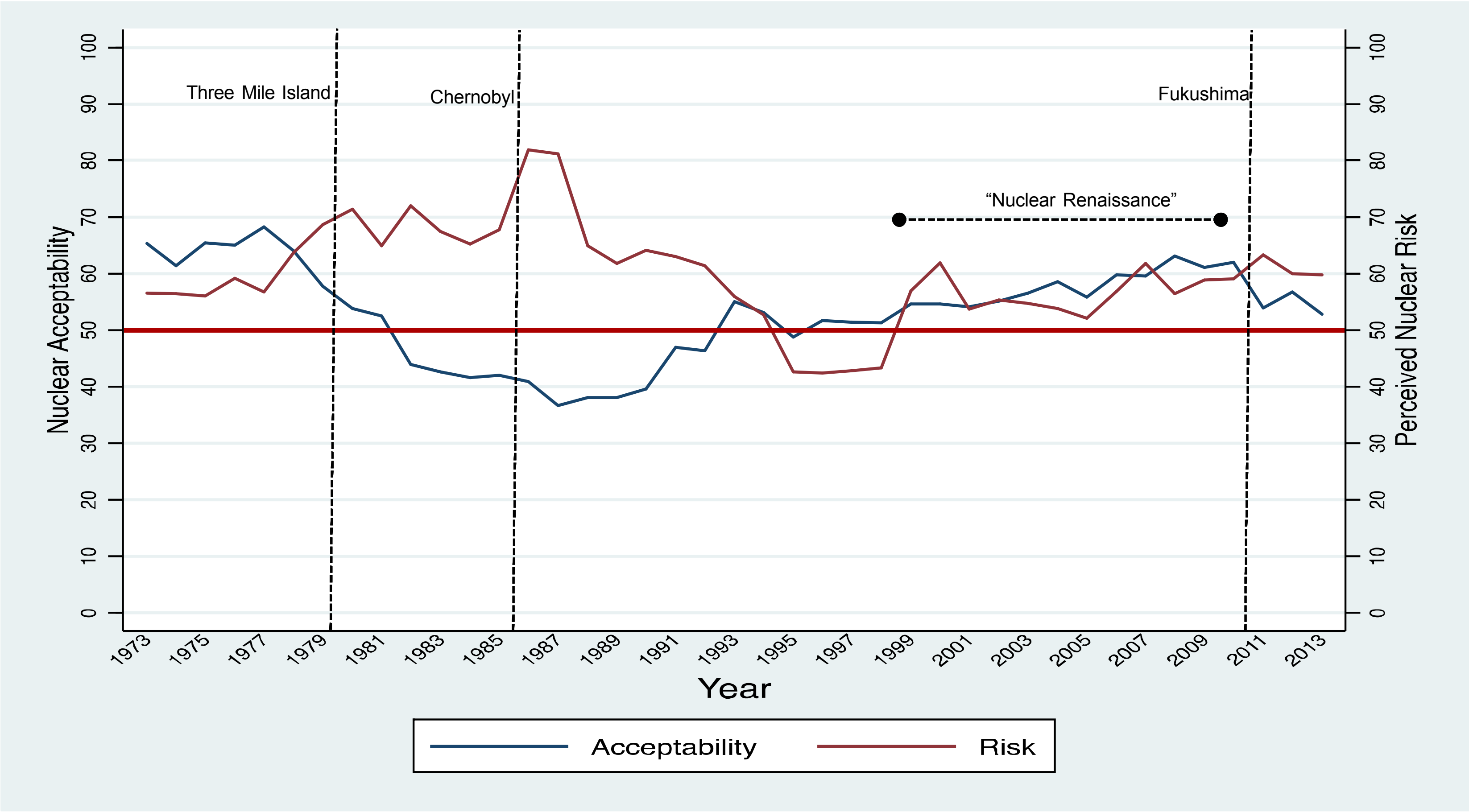
Topics

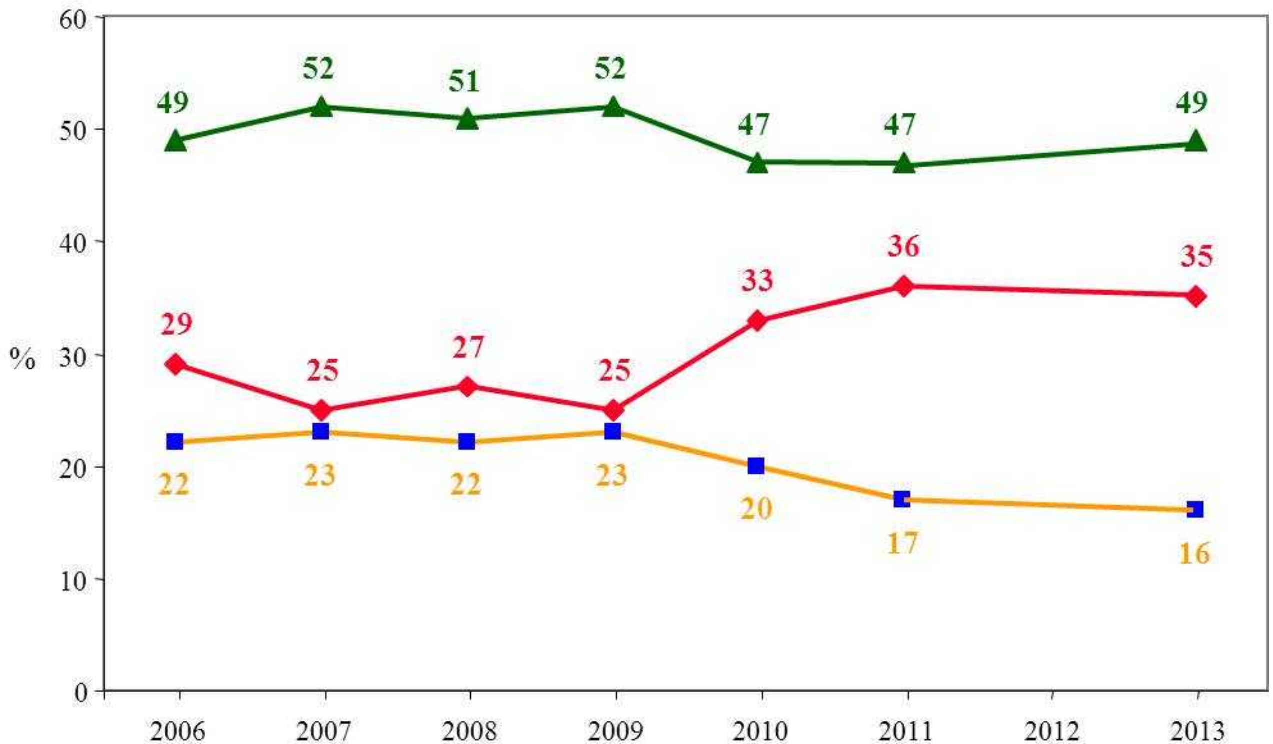
- Role of Nuclear Energy in US Energy Portfolio
- SMR Background Information
- SMR Projects at SNL
  - NuScale Power SMR MELCOR Project
  - SMR Security Analysis for DOE NE
  - SMR Suitability Study for US Air Force Space Command Installations
- S-CO_2 Brayton Cycle for Dry Cooling
- Summary

Trend in attitudes about risk and acceptability of nuclear energy in US between 1973 and 2013



Trend in preferred energy sources in US

- Nuclear energy still seen as important energy source in next 20 years, as measured since 2006



2006–2013

Renewables: 0 .0%

Fossil: + 20.7%

Nuclear: – 27.3%

Small Modular Reactors

- A Small Modular Reactor (SMR) is a nuclear reactor with a nominal power output of 300 MWe of less
- The SMR designation is not dependent on technology
  - Light Water Reactor SMRs
  - Advanced SMRs (e.g., molten salt, liquid metal, high-temperature gas, etc.)
- SMRs being developed in the US, Korea, Argentina, Russia, etc.

“Complexity” Versus “Simplicity”

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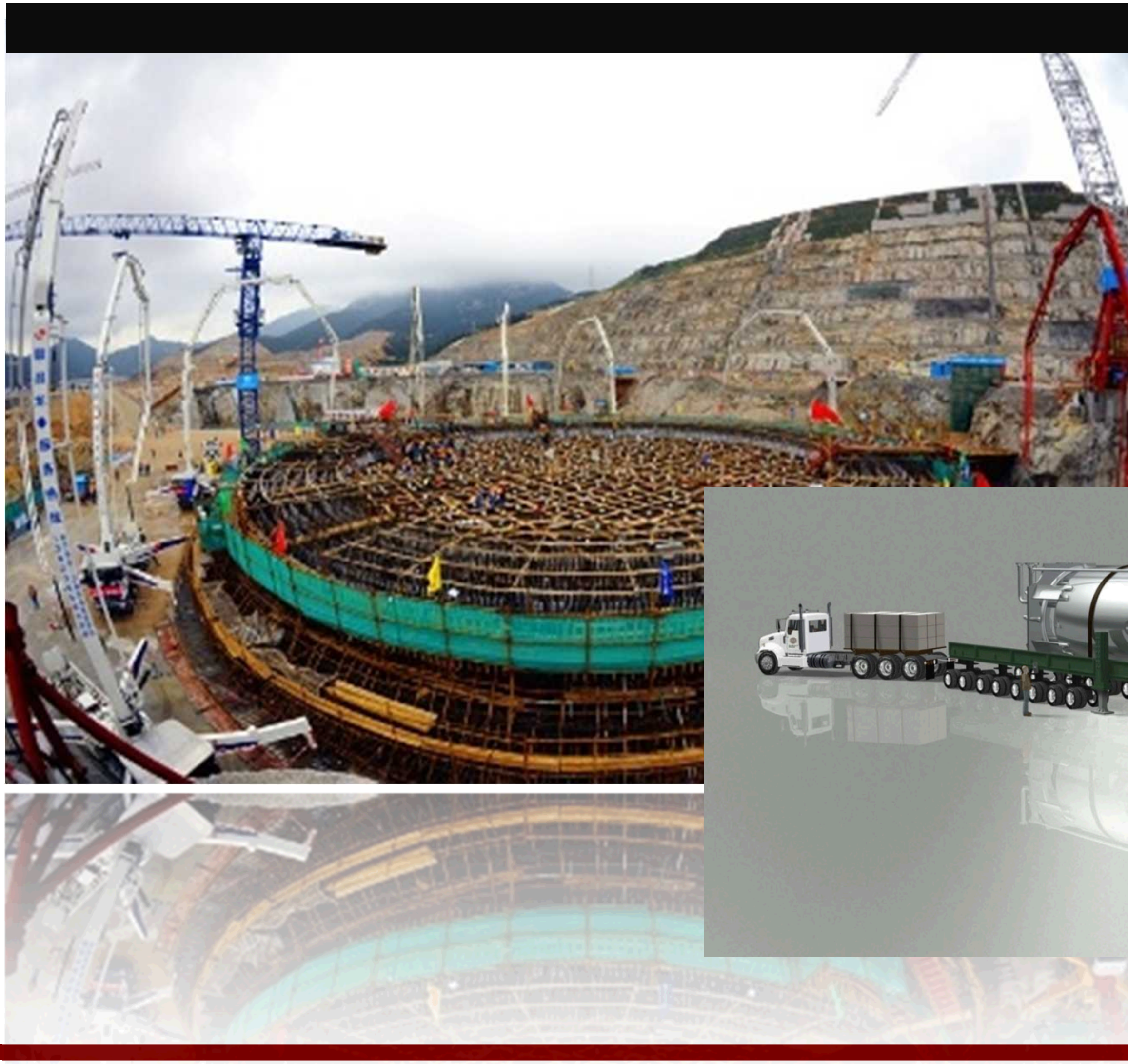
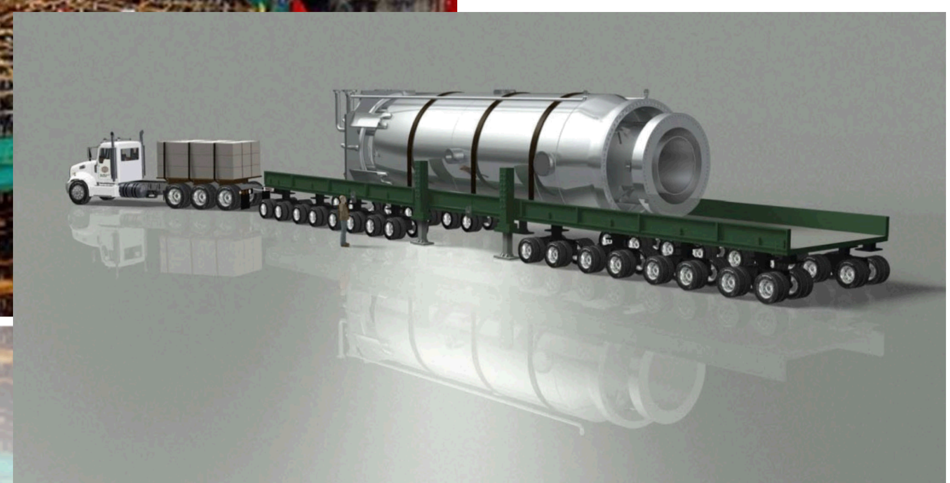


On-site Construction – “Complexity”

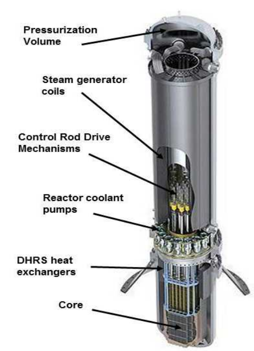
Transport SMR to Site
“Simplicity”



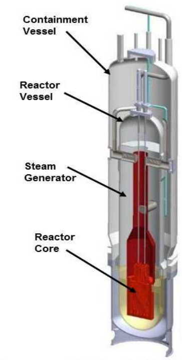
Small Modular Reactors

Near-Term LWR Designs

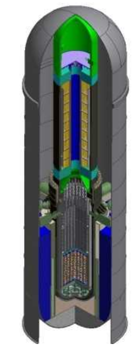
- **Well Understood Technology**
  - LWR based designs
  - Standard <5% UO2 fuel
  - Regulatory & operating experience
    - Planned deployment next decade (2020s)



mPower (Babcock & Wilcox) 125 MWe



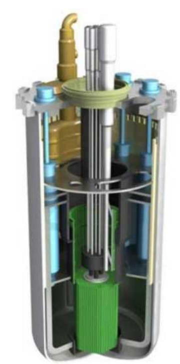
NuScale (NuScale) 45 MWe



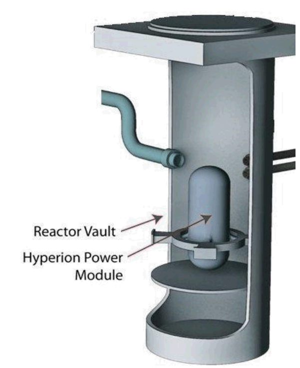
Westinghouse

Longer-Term SMRs

- **New Innovative Technologies**
  - Mostly non-LWR based designs
  - Deployment 20-25 years
- **Broader Applications**
  - Process heat applications
  - Transportable/mobile
  - Long-lived cores



GE PRISM



Hyperion

Design Features that Improve LWR-based SMR Safety

- LWR SMR designs share a common set of design principles to enhance plant safety and robustness
  - Incorporation of primary system components into a single vessel
  - Smaller decay heat
  - More effective decay heat removal
  - Increased water inventory ratio in the primary reactor vessel
  - Increased pressurizer volume ratio
  - Vessel and component layouts that facilitate natural convection cooling of the core and vessel
  - Below-grade construction of the reactor vessel and spent fuel storage pool
  - Enhanced resistance to seismic events

DOE NE's Office of Advanced Reactor Concepts
Small Modular Reactor Program

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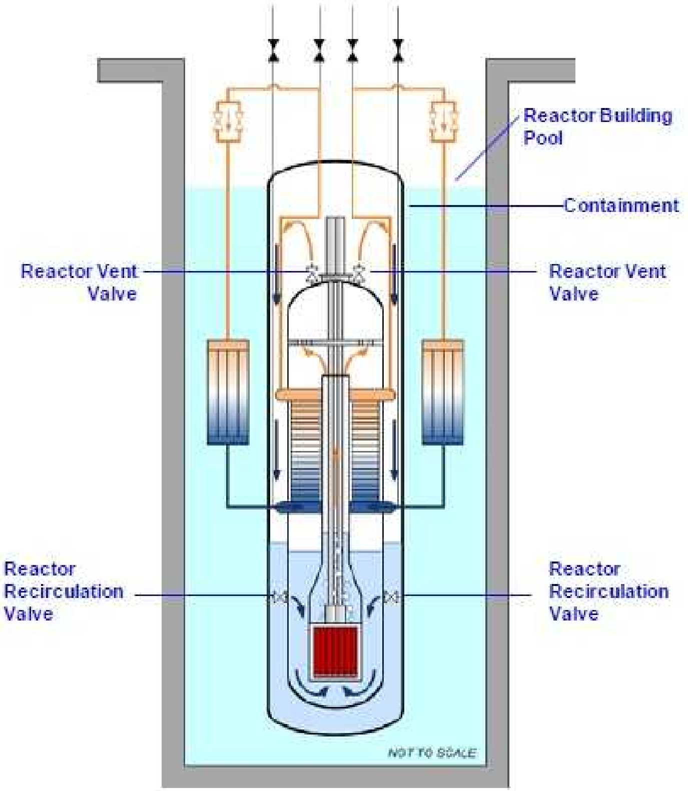
- DOE Small Modular Reactor Program
  - Enable the deployment of a fleet of SMRs in the United States
  - Structured to address the need to accelerate the deployment of mature SMR designs based on LWR technology
  - Conduct needed R&D activities to advance the understanding and demonstration of innovative reactor technologies and concepts
- SMR Program Elements
  - Cost-shared Industry Partnership for SMRs
    - Public-Private Partnerships for design certification & licensing activities
  - SMR Advanced Concepts RD&D
    - Conduct R&D on innovative technologies/systems/components and support generic licensing work
    - Support nuclear codes & standards development activities
    - Collaborate with NRC on SMR licensing framework to support SMR commercialization

NuScale Power SMR MELCOR Project

- Under the DOE NE's Industry Partnership SMR Program, SNL is supporting NuScale Power by performing key analyses as well as safety code development activities that NuScale may used in its design certification application to the US Nuclear Regulatory Commission
- SNL supports NuScale through two primary tasks:
  - MELCOR code development of NuScale-specific models
  - Validation and Verification (V&V) of the new models.
- The two tasks will help NuScale achieve Design Certification for their SMR system

NuScale SMR Melcor Project: Code Development

- Develop Melcor to address the unique aspects of the NuScale SMR:
  - Geometry,
  - Heat transfer, and
  - Aerosol behavior.
- *Geometry:* Allow the simultaneous modeling of the reactor pressure vessel and the containment vessel.
- *Heat transfer:*
  - Implement a shroud model for internal heat transfer from the reflectors.
  - Upgrade the condenser model.
- *Aerosol behavior:* extend the deposition/re-suspension models to treat SMR-specific aerosol behavior.

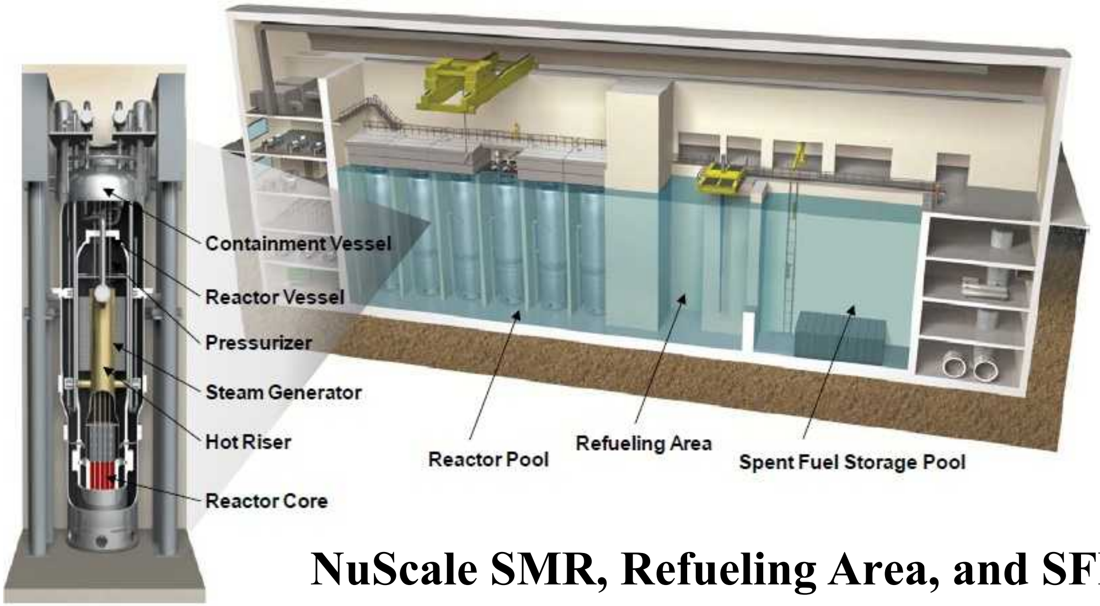


NuScale SMR schematic.

Source: "NuScale Small Modular Reactor for Co-Generation of Electricity and Water", D. T. Ingersoll et al., *Desalination*, Vol. 340, p. 84-93, 2014.

NuScale SMR Melcor Project: V&V

- Perform V&V analysis of the new Melcor models to ensure their adequacy and robustness.
- This will be achieved by developing a spent fuel pool (SFP) input model to run bounding accident scenarios.
- Systematic testing of the new models will be conducted to ensure simulation fidelity.



Source: "NuScale Small Modular Reactor for Co-Generation of Electricity and Water", D. T. Ingersoll et al., *Desalination*, Vol. 340, p. 84-93, 2014.

NuScale SMR, Refueling Area, and SFP schematic.

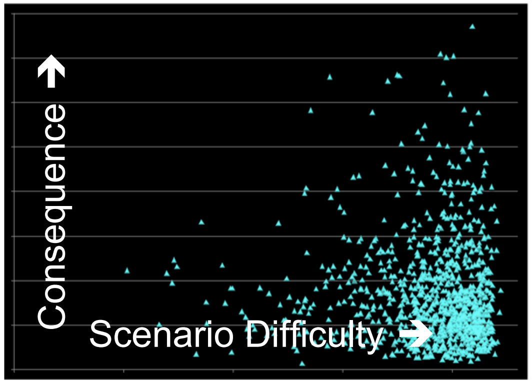
SMR Security Analysis

- SMRs face regulatory and economic challenges in how to apply security to a smaller facility while keeping overall plant costs manageable.
- Increasing security threats lead to high protection costs for nuclear facilities, and commercial facilities need new approaches for optimizing cost.
- The overall goal of this work is to evaluate alternative methodologies for Proliferation and Terrorism Risk Assessment to guide design.
- We are applying the RIMES (Risk-Informed Management of Enterprise Security) methodology for sabotage and terrorism threats to nuclear facilities, using Small Modular Reactors (SMRs) as an example application.

Assessing Security Risk

- Traditional risk is based on a scenario's likelihood and consequence, but to use this for security, one must either
  - Assess the probability of an attack that has never occurred before (highly uncertain, and can change in an instant), or
  - Limit the adversary (e.g., with a design basis threat) and assess the conditional probability that *this* adversary will succeed if they attempt *this* attack scenario (neglects deterrence of the adversary and makes both risk aggregation and defender cost-benefit analysis difficult)
- The RIMES methodology instead focuses on the *degree of difficulty* for an adversary to successfully accomplish an attack:

Attack scenarios that are both easier and higher consequence are of greater risk. Focus security investments on these "high-risk" scenarios.



Analysis of Small Modular Reactors' Suitability for Air Force Space Command Installations – Objectives (Beginning Project)

- Facilitate the Department of Defense's (DoD) understanding of how a Small Modular Reactor (SMR) can benefit the Air Force Space Command (AFSPC) and the DoD,
- Identify any DoD-unique requirements for SMRs that would be placed at installations or integrated into DoD installation microgrids,
- Provide recommendations for the structure of potential partnerships with utilities/operators for notional deployments at candidate DoD installations,
- Identify specific government actions needed to facilitate deployment of SMRs for DoD's energy security needs and the nation's energy security, and
- Inform the discussion of broader market potential among other critical federal installations.

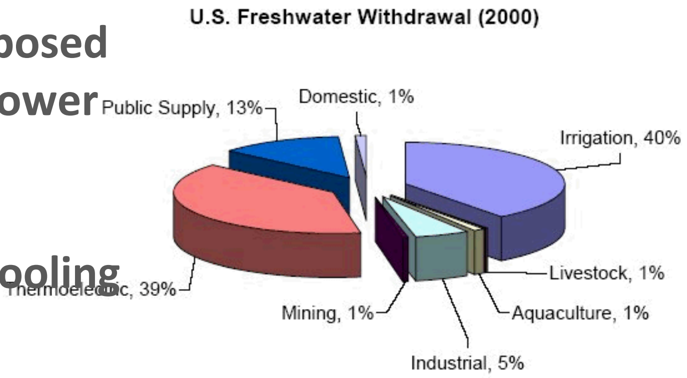
Motivation for dry-cooled s-CO_2 power conversion

- Energy needs are rising, and water usage is becoming more highly regulated.
- Waste heat rejection for electrical power systems already accounts for large fraction of fresh water use.

- Supercritical CO_2 (s-CO_2) power cycles have been proposed as alternative to steam for high efficiency, compact power conversion for nuclear

- s-CO_2 power cycles are well suited for use of dry-air cooling
  - *good efficiency at high heat sink temp*
  - *not limited to a constant heat rejection temp*
  - *closer approach temperatures are feasible*
  - *less capital in building, operating cooling towers.*

– **Benefits of dry-cooled s-CO_2 cycle could allow rise of next-generation nuclear systems, and redraw map for siting of new nuclear**



S-CO_2 Natural Circulation

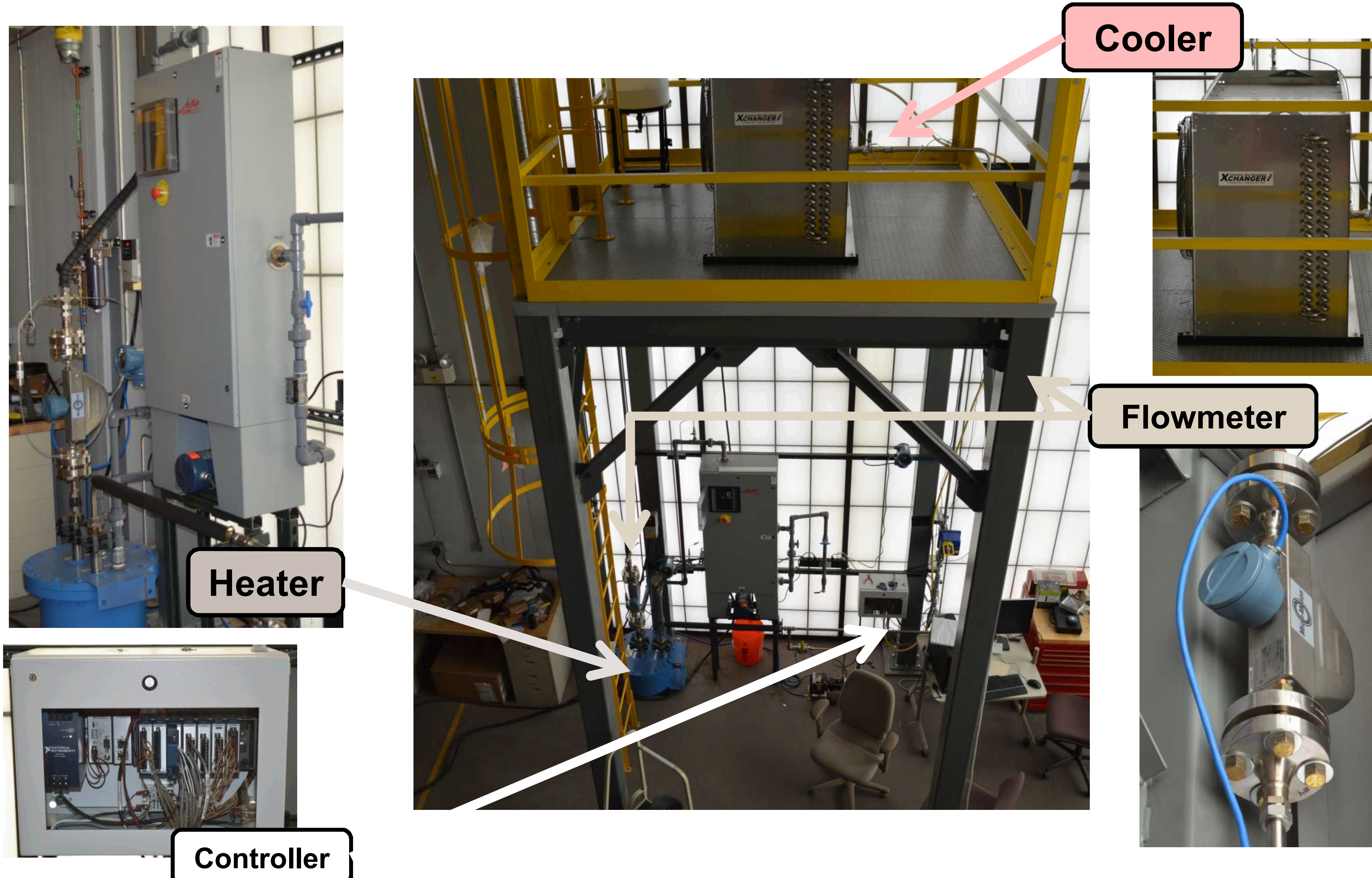
- **Increased reliance on passive emergency cooling using natural circulation is a major goal of next generation SMRs**
- Natural circulation is driven by gravitational head resulting from elevation and density differences in a closed loop.
- Supercritical CO_2 is ideally suited for establishing natural circulation flow
  - Large density variations are achieved for only small elevation in temperature
  - This allows natural circulation to occur earlier in the emergency transient, provide increased flow throughout
  - Buoyancy-to-Viscous forces of a given fluid are a good indicator of natural circulation potential (Grashof number);
  - At conditions of SCO_2 heat rejection system, the Grashof number is 4 orders of magnitude higher than water for a 10C temperature rise

$$Gr = \frac{g\,\beta\,\rho^2\,Lc^3\,\Delta T}{\mu^2}$$

Parameter	Units	CO_2	Water
Bulk Temperature	K	300	300
Pressure	MPa	7.69	7.69
β	1/K	0.039	0.00037
ρ	kg/m^3	275.6	996.7
μ	Pa-s	2.21e-5	6.94e-4
Gr		5.9e14	7.5e10

*Parameters were evaluated at conditions typical of an SCO_2 power heat rejection system.

System Overview



Summary

- SNL is supporting DOE NE, in general, and their SMR Program, in particular:
  - Researching public attitudes about nuclear energy
  - MELCOR is currently being developed to help NuScale achieve Design Certification for their SMR system.
  - Air Force Space Command (AFSPC) sites are being studied to assess the benefits of placing an SMR on or near AFSPC bases.
  - S-CO_2 is being investigated to aid in developing a high efficiency power conversion cycle that can be used in regions with limited water supply AND to provide passively safe decay heat removal from SMRs