CHANGING WHAT'S POSSIBLE

Introduction to Breakout #1:
Concept Discussion

Ji-Cheng (JC) Zhao
Program Director

teaming with:
Ron Faibish, **Ryan Umstattd**, **Colleen Nehl**,
Adam Fischer, and **Adrienne Little**

ARPA-E Safe and Secure Megawatt-Size Nuclear Power Workshop
March 16-17, 2016, Washington, DC

Micro Modular Reactors (MMRs)

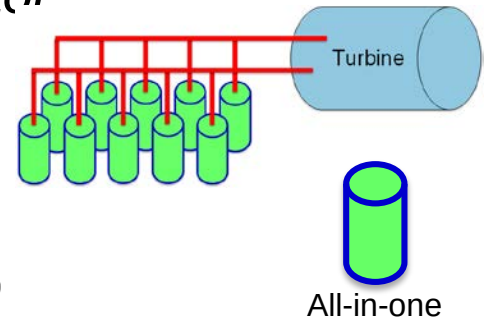
In-factory certification

Make in factories

- *Inherently safe & secure designs such as solid core*
- *Deployment of advanced materials, sensors & controls*
- *Assembly-line efficiency & strict quality controls*
- *Made to order - minimal delay & much reduced capital*

Certify in factories

- *Licensing/certification once only for each type of reactor*
- *Safety tests (earthquake shake tables…faulty tests)*
- *Much reduced certification/licensing cost*



Transport to sites

- *Minimal site requirements (emergency planning zone)*
- *No need for on-site spent fuel storage*
- *Much expanded use with size flexibility/modularity*
- *Tow-away decommission*

- Make & certify MMRs like jet engines
- Make MMRs safer than jet engines

Key questions: design concepts

- **Are there inherently safe (passively safe) & secure designs at the MMR size?**
  - What mechanisms can lead to passive safety? → solid core & water-free? neutron economy & control of criticality
  - Fuel options, core options, heat transfer media
  - Fuel ↔ material/core ↔ heat transfer medium compatibility
  - Power extraction mechanism: supercritical CO_2 turbines, heat pipes & Stirling engines, "batteries" … closed or open loops?
  - Passive heat sinks in case of an event
  - Independence from external power blackout
  - Projectile resistance – from the reactor or from an enclosure

Take advantage of the diverse expertise in breakout groups

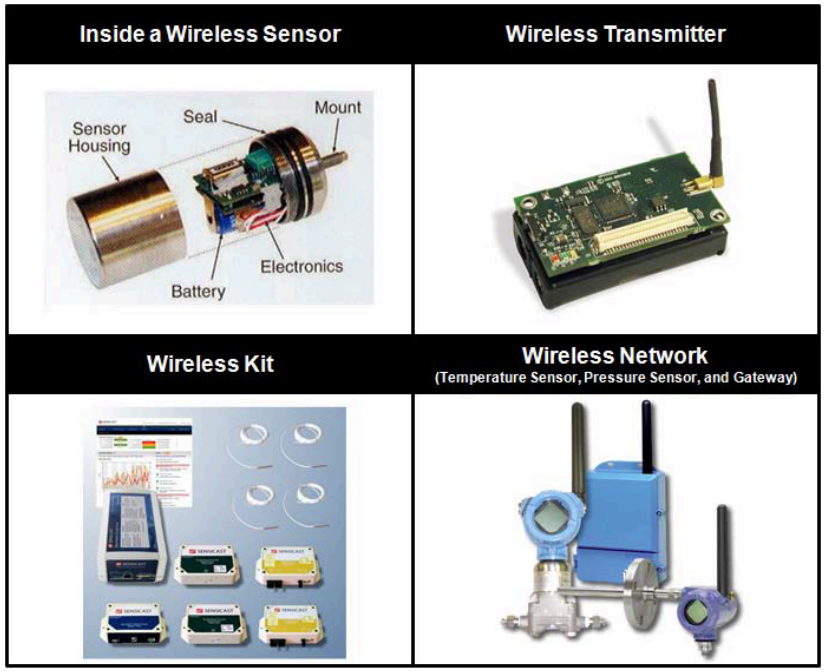
Key questions: design concepts (cont.)

- How to achieve load-following capability?
- Black-start capability
- All-in-one vs separate non-critical/non-nuclear components (on-site attachment should not require to re-certification)
- How to achieve zero EPZ?
- Dependency on autonomous controls?
- How to achieve complete prevention of radiation leak?
- Proliferation resistance

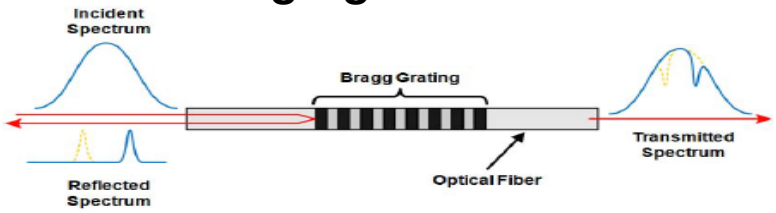
Key questions: Sensors & Controls

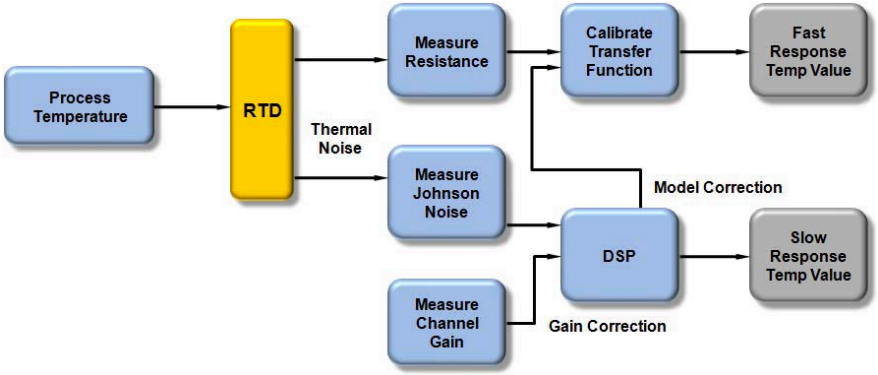
- **What key sensors and controls technologies need to be developed to enable safe, secure, autonomous operation?**

Wireless sensors



Emerging sensors





- Wireless issues: cybersecurity, battery life, and interference
- Fiber-optic issues: radiation darkening of fiber-optic and lack of nuclear-qualified sensors

Source: NRC, EPRI

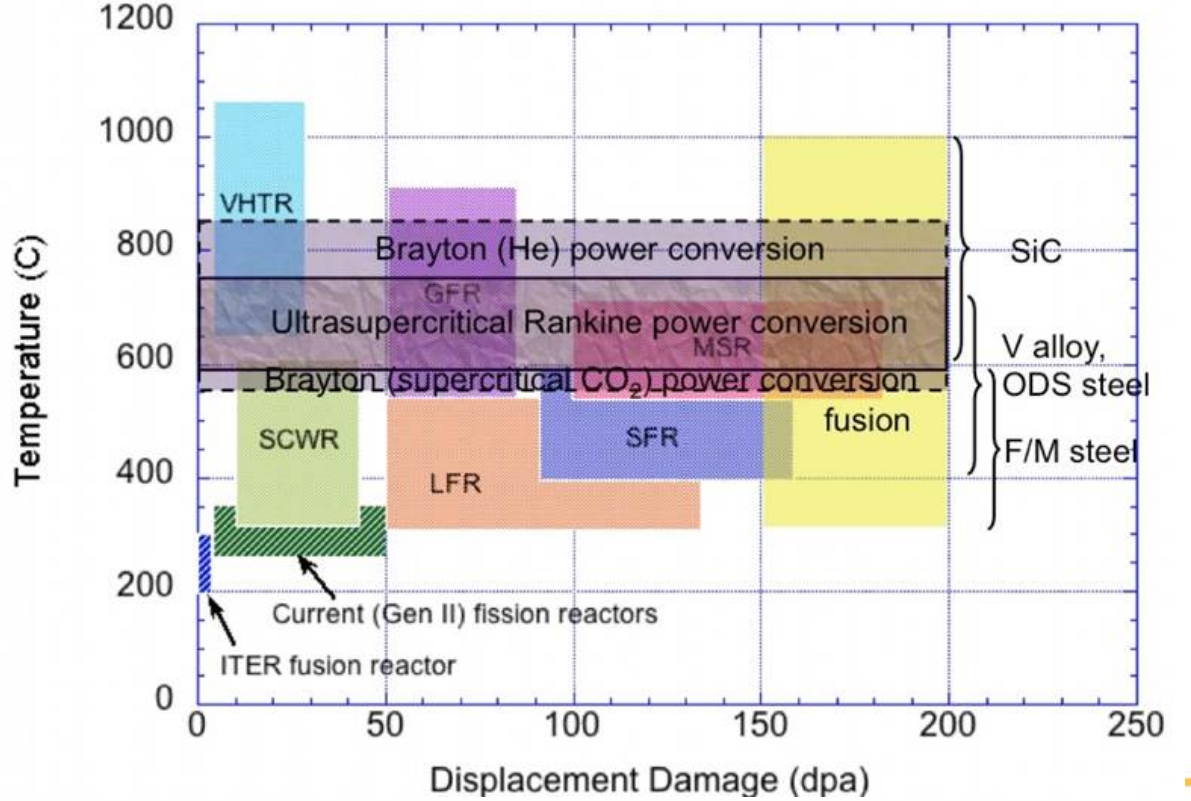
Key questions: Sensors & Controls

- Introduction of new materials in Gen IV-type nuclear reactors will necessitate a greater need for core structural health monitoring.
- Next generation of reactors is expected to have autonomous diagnostic capabilities for increased safety and efficiency. This goal is readily achievable using online monitoring (ONL).
- Such monitoring will become challenging for high temperatures. New sensing platforms will be to provide data input to monitoring and control systems.
- The highest temperature that the current generation of industrial resistance temperature detectors (RTDs) can measure with good accuracy is about 400ºC. Thermocouples can measure higher temperatures but with compromised accuracy.

Source: EPRI

Key questions: Materials

- **What advanced materials can be deployed in the advanced design and what new materials need to be developed?**



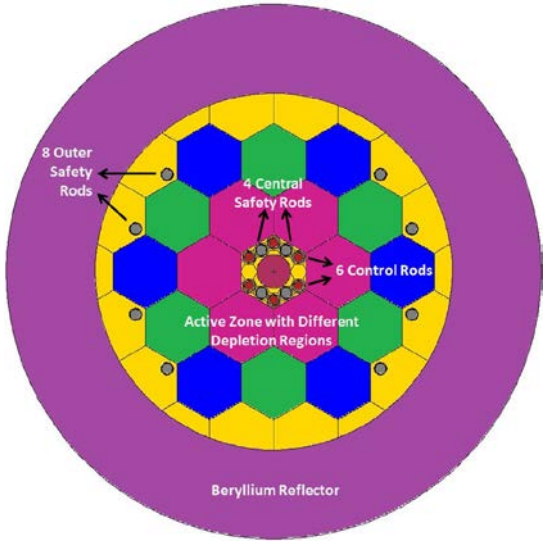
Zinkle

Key metrics

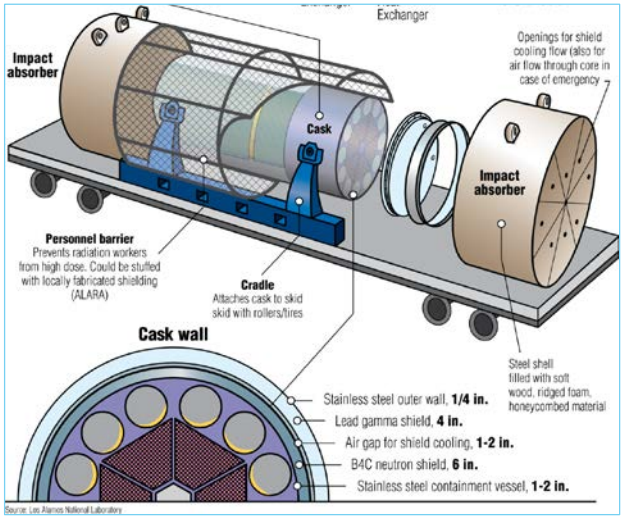
- Physical size: each component fits in an **ISO container**
- Weight: **<59,000 lbs** (per component)
- Lifetime without refueling: **10-20 years**
- Fuels (e.g., enrichment: **<20%**; preferred 4-5%)
- **Load following** capability
- **No external cooling** towers
- **No water** usage
- Resistance to 9.0 magnitude **earthquakes, tsunami water submersion**
- **Inherent (passive) safety, security, and non-proliferation** with sensors and controls

Submitted Concepts for Discussion

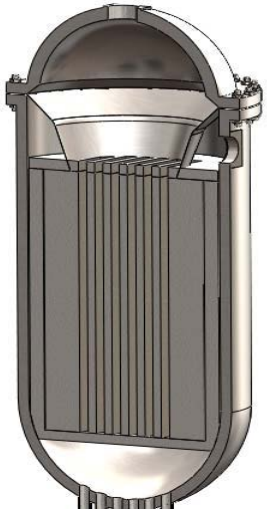
Submitted Concepts: examples



Hu (MIT)



McClure (LANL)



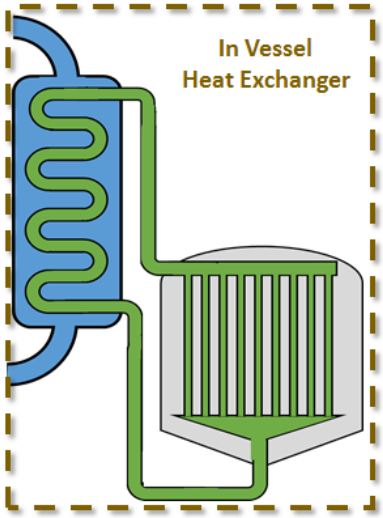
Rochau (Sandia)

DEPARTMENT OF
Engineering Physics
UNIVERSITY OF WISCONSIN–MADISON

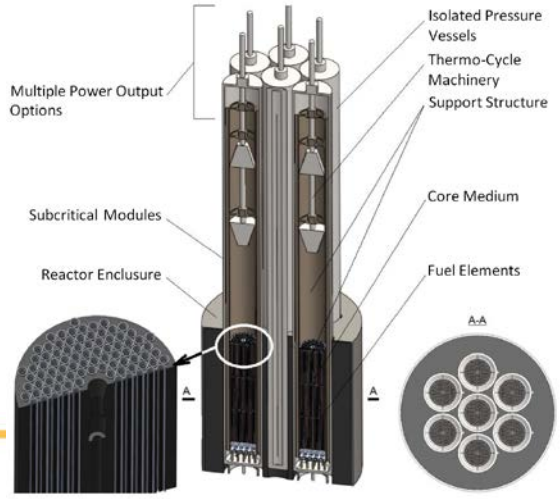
Molten Salt Reactor Technology

Coupled with CO_2 Power Conversion

Scarlat (Wisconsin)



Schmidt (OSU)



Tsvetkov (TAMU)

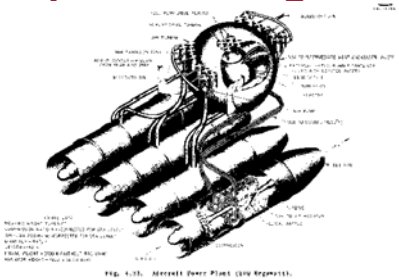
MIT

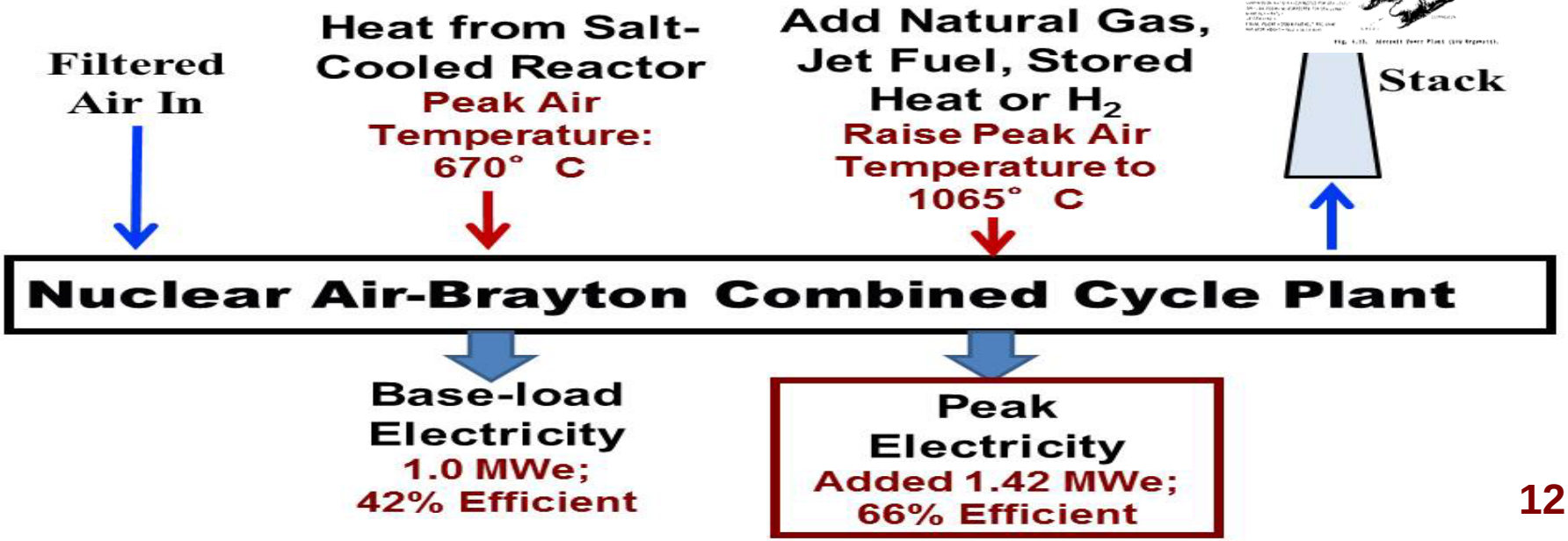
HU

Fluoride-salt-cooled High-temperature Reactor Coupled to Air-Brayton Power Cycle

- Salt coolants developed to couple reactors to Brayton (Jet) Power Cycles
- Gas turbine advances make that practical
- Nuclear Air-Brayton Power Cycle
  - Base-load reactor (42% efficient) with variable power using topping cycle: natural gas, jet fuel, stored heat or hydrogen (remote site generated)
  - Peaking cycle 66% to 70% efficient

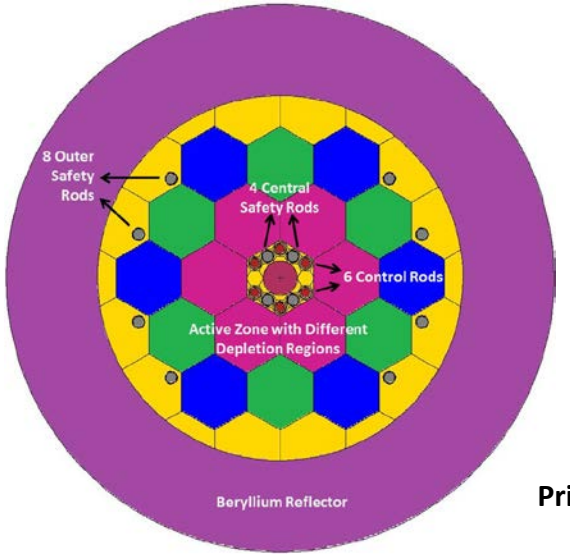
1950s Aircraft Nuclear Propulsion Program

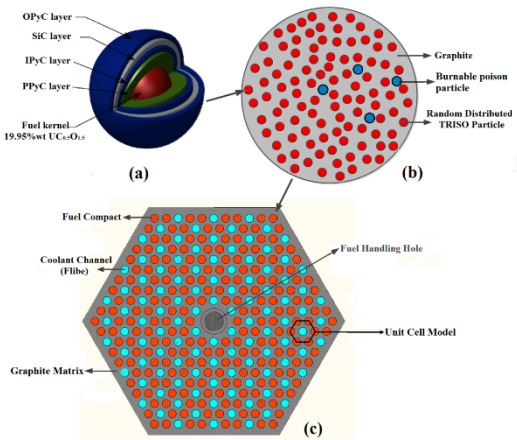




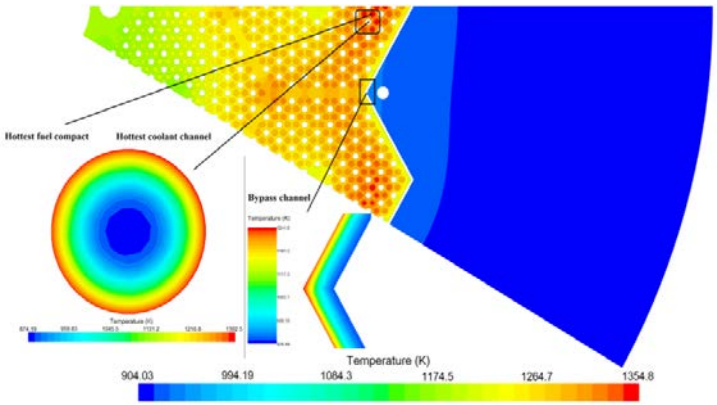
10 MWth Transportable FHR (TFHR)

Match Requirements of Brayton Cycle

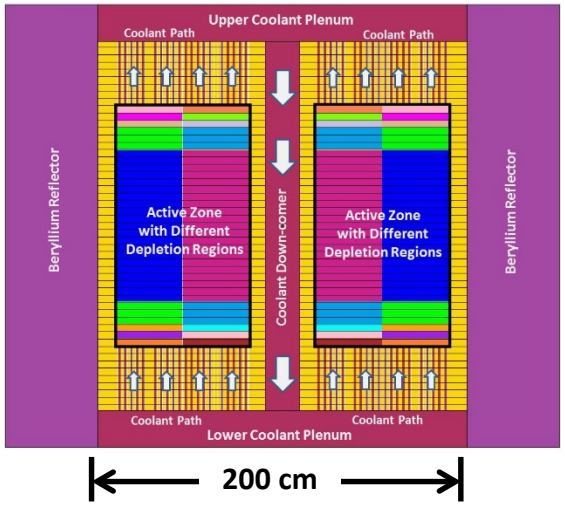




Prismatic assembly with TRISO fuel particles



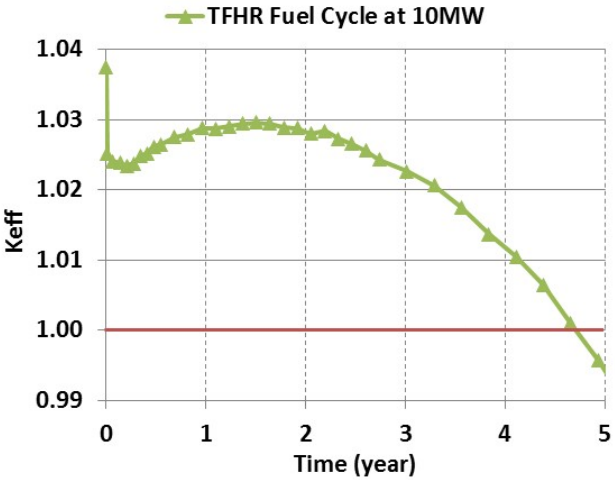
Full 3-dimensional CFD modeling



Design Features

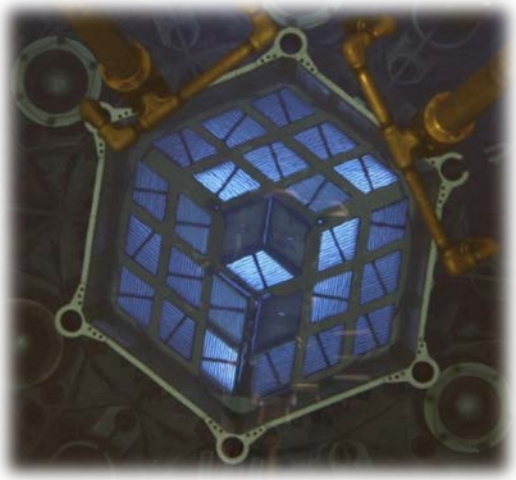
- 10 MWth with ~ 5-yr fuel cycle
- Compact core ~ 2-m diameter
- Tranportable by air, rail or truck
- Flibe salt coolant 600-700 ° C
- High efficiency air Brayton cycle
- 18 prismatic fuel assemblies
- 6 control rods and 12 safety rods
- Center coolant down-comer

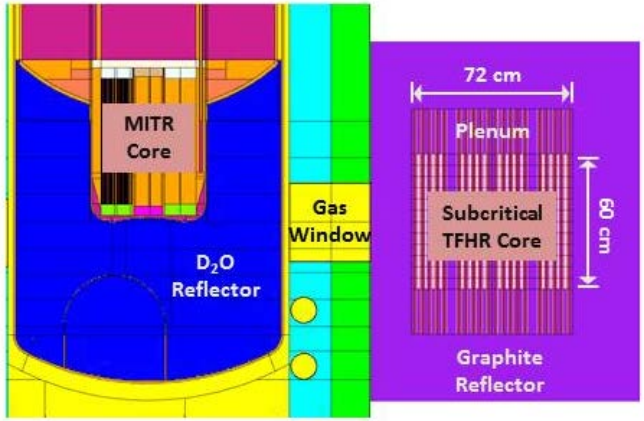
> 10-year fuel cycle optimization in progress



Component Technologies Exist and Work to Develop Large Power Systems

- Systems being developed for large-scale FHR with air Brayton Cycle
- Enabled by
  - Proven HTGR fuel technology
  - Salt-coolant technology
  - Advancing gas turbine technology
- MIT
  - Leading 4 university team investigating option (Berkeley, Wisconsin, New Mexico)
  - Testing materials in 700° C salt in the MIT reactor
  - Developed 10 MWth transportable FHR concept
  - Testing strategy using reactor-driven subcritical facility



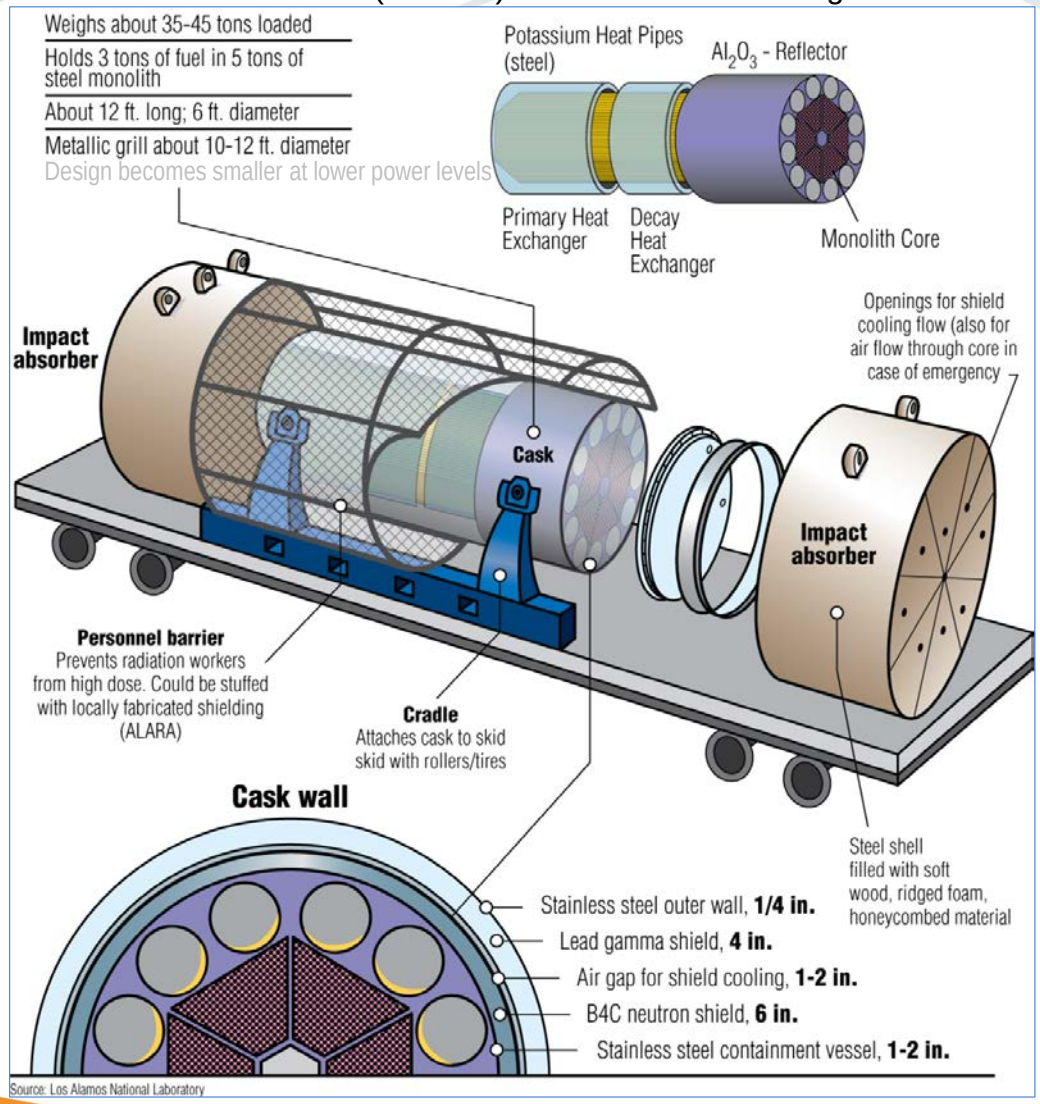


Los Alamos National Laboratory

McCLURE

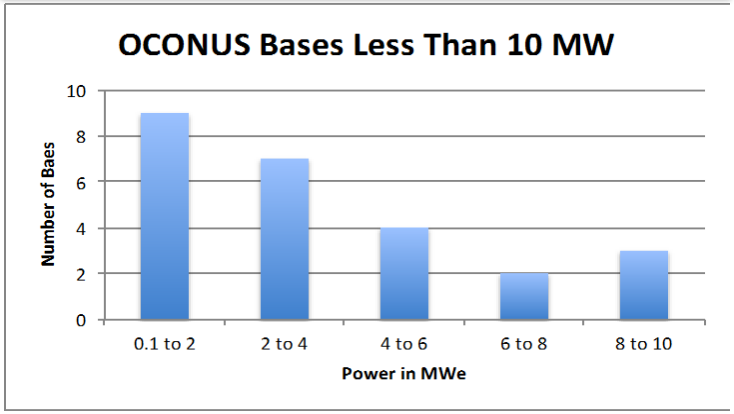
MegaPower Reactor System

Nominal 2 MWe (5 MWth) Mobile Reactor Package



Source: Los Alamos National Laboratory

- Proven UO_2 fuel (19% enriched)
- Solid steel monolith core
- Passive heat pipe coupling with no moving parts in the core
- Housed in armored and shielded cask during operation & transport

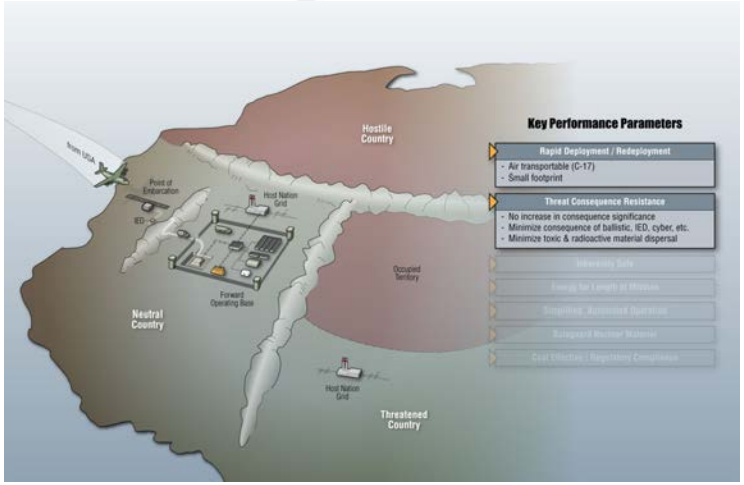


- This unit is designed to be "wheeled in" and "wheeled out" and operational in 72 hours
- Load following design with minimal oversight. Remotely monitored
- Open air Brayton power conversion

Concept

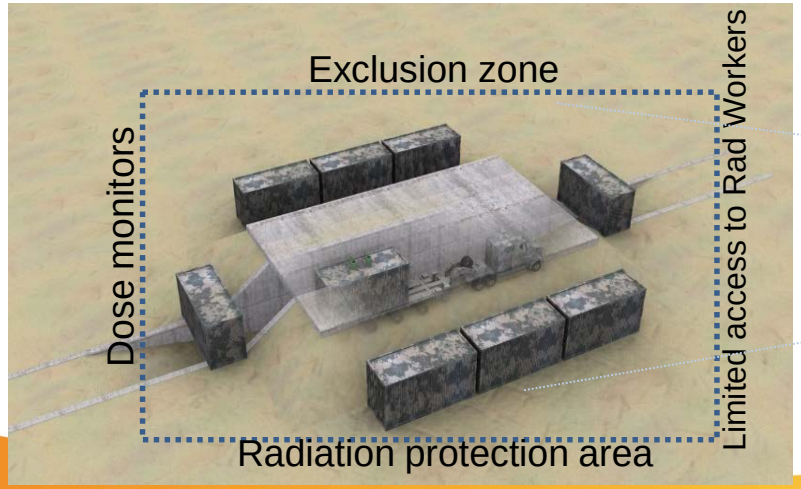
Concept of Operations: Transport to Theater & FOB

Fly reactor to theater

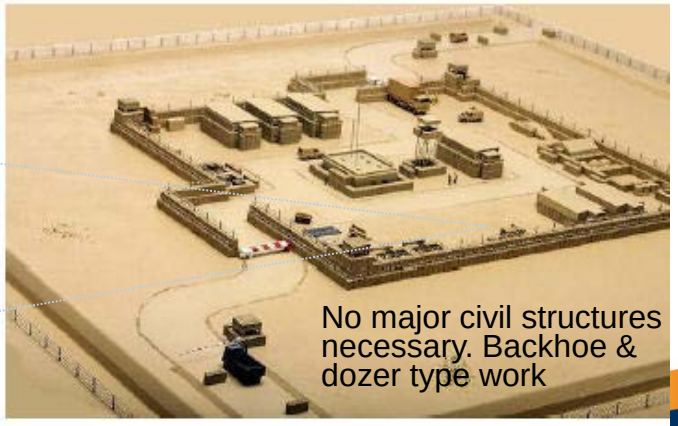


Transport by truck to the base

Protect by earth, barriers, & water jackets



Integrate into the base



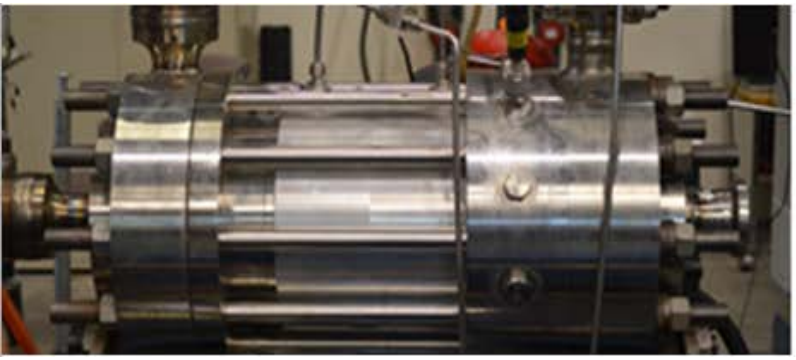
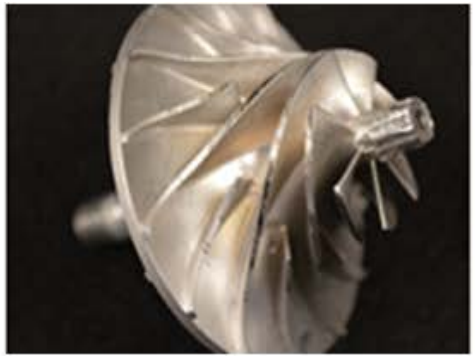
Sandia National Laboratories

ROCHAU

Exceptional service in the national interest

Sandia National Laboratories

energy.sandia.gov


Megawatt Class Fission Reactors

ARPAe Workshop on

SAFE & SECURE MEGAWATT-SIZE NUCLEAR POWER

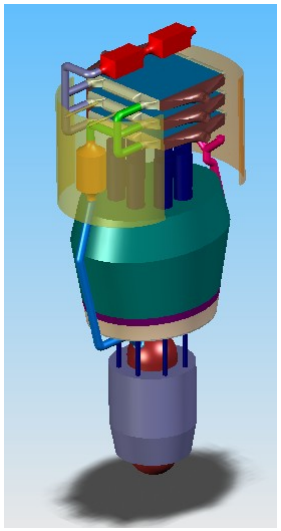
Gary E. Rochau, Manager Advanced Nuclear Concepts, gerocha@sandia.gov

U.S. DEPARTMENT OF ENERGY

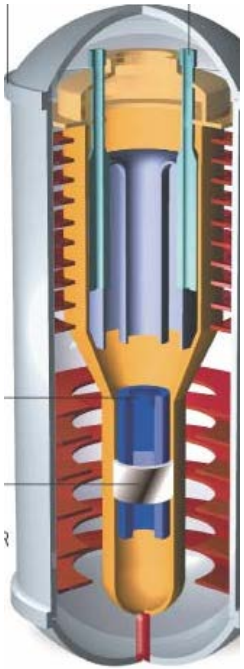
NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000

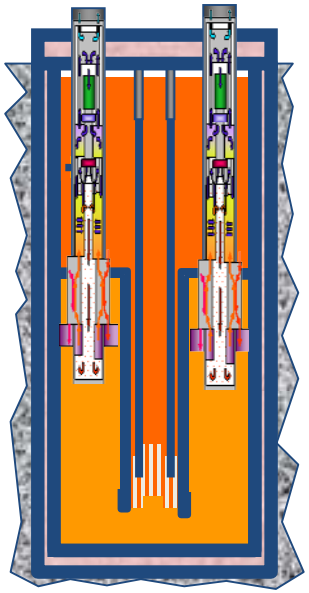
Sandia Concepts Explored



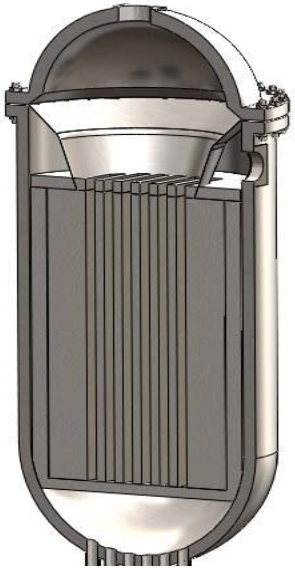
Promethius SR



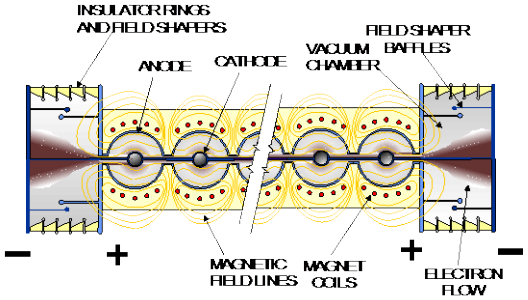
RSR (Cartridge)



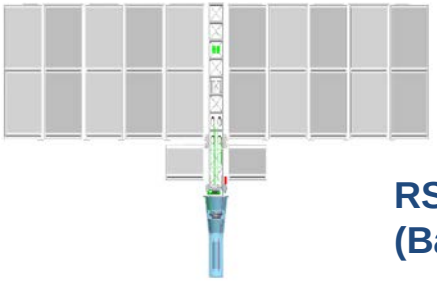
RSR (Battery)



sCO2 GFR

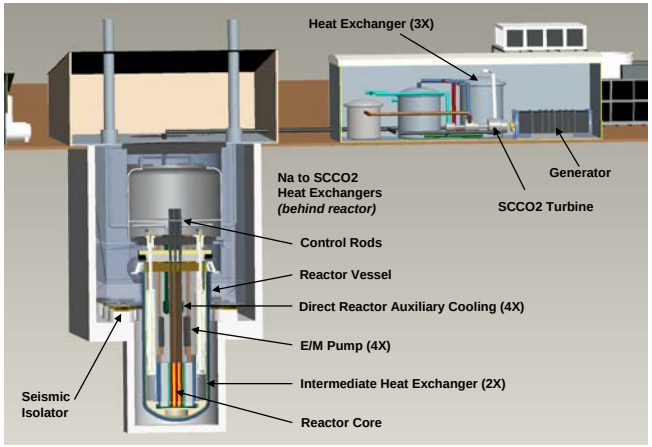


Direct Energy Conversion



FSP (moon base)

RSR System (Baseline)



Critical Component Status

Component	Design	Model	Demon-stration	Fielded	Cost
Reactor (Na GFR)	Concept	Concept	Bench	No	Target ~ 2K$/kWe
Fuel (UO_2 > 10 yr)	TRL 7 (SiC-SiC)	TRL 7	No	No	No
Conversion (sCO_2 Brayton)	Concept	TRL 7	Lab-scale (TRL 3)	No	~1K$/kWe
Safety (CDF<10^{-8})	Final Design	TRL 7	EBR2	EBR2	Established by design
Security (Non-Prolif & Invulnerable)	Concept	TRL 7	TRL 3	TRL 3	Established by design
Operations (Remote with Command Disable)	Final Design	Final Design	Concept	No	unknown
Materials – Power Materials – Facility Materials - System Mass	COTS Concept On Target	COTS Concept On Target	EBR2/STEP No No	EBR2/STEP No No	COTS No No

University of Wisconsin

SCARLAT

DEPARTMENT OF
Engineering Physics
UNIVERSITY OF WISCONSIN–MADISON

Molten Salt Reactor Technology

Coupled with CO2 Power Conversion

Semi truck #1
Molten Salt Reactors

- Are compact
- Have inherent safety features
- And passive safety
- Systems
- Can provide high temperature heat, for high efficiency power conversion systems.

CO2 Test Facilities at UW

1. Valve, seal, high speed flow test facility

2. HX test facility
3. 600C, 3600PSI, 160GPM sCO2 Loop

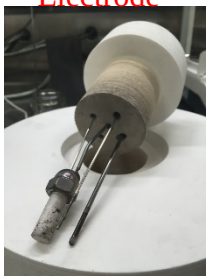
Semi-truck #2
10 MW CO2 Power
Conversion Cycle

Semi-truck #3
10 MW Generator
8'W x 14' L x 10'H
39,700 lb

Corrosion Studies: Metals & Ceramics

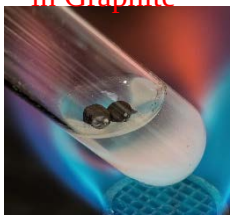
50 kg FLiBe Purification Room

Electrochem. Reference Electrode



Solidification Studies

Tritium Absorption in Graphite



3-Story Heat transfer Salt Loop

UW Current group of molten salt researchers

Molten Salt Research

DEPARTMENT OF
Engineering Physics
UNIVERSITY OF WISCONSIN–MADISON

Capabilities at UW

History at UW, since 2005

1. Molten Salt Heat Transfer Loop: Materials Corrosion and Heat Transfer Phenomena (DoE) [FLiNaK]
2. Liquid Salts as Media for Process Heat Transfer from VHTRs: Forced Convective Channel Flow Thermal Hydraulics, Materials, and Coating (DoE) [FLiNaK, $MgCl_2$-KCl]
3. Thermal Properties of Molten Salts (DoE) [LiCl-KCl]
4. Liquid Salt Heat Exchanger Technology for VHTR-based Applications (DoE) [FLiNaK]
5. Corrosion Testing, Heat Exchanger Diffusion Welded Materials (INL) [KF-ZrF_4]
6. IRP 1: High Temperature Salt-Cooled Reactor (DoE, present with MIT and UC-Berkeley) [mainly FLiBe, but some FLiNaK, KF-ZrF_4]
7. IRP 2 (present): High Temperature Salt-Cooled Reactor (DoE, present with MIT , UC-Berkeley, University of N. Mexico) [FLiBe]
8. CO2 power conversion cycles
9. Tritium transport studies using electrochemical techniques (DOE) [FLiBe and other fluoride salts]
10. Several Private Company Grants [lower temperature salts, e.g., nitrates etc.]

UW Graduate Students

1. Luke Olson (PhD): Corrosion in molten FLiNaK (Savannah River National Lab)
2. James Ambrosek (PhD): Heat transfer loop and corrosion in molten FLiNaK and chloride salts (Woodword Governor)
3. Dan Ludwig (MS): Electrochemistry in molten FLiNaK (Exel Corporation)
4. Steve Sellers (MS): Corrosion in molten FLiNaK (AREVA)
5. Mehran Mohammadian (MS): Electrochemistry in chloride salts (Sargent and Lundy Consulting)
6. Sean Martin (MS): Electrochemistry in chloride salts (Exel Corporation)
7. Jacob Sager (MS): Electrochemistry of chloride salts (KAPL)
8. Brian Kelleher (PhD): FLiBe salt chemistry and purification (TerraPower)
9. Kieran Dolan (MS): Electrochemistry of FLiBe salts (Exel Corp.)
10. Guiqiu Zheng (PhD): Corrosion in Molten FLiBe (post-doc MIT)

Ohio State University

SMIDTS

Minow

Mobile Integrated Nuclear Operational Workhorse

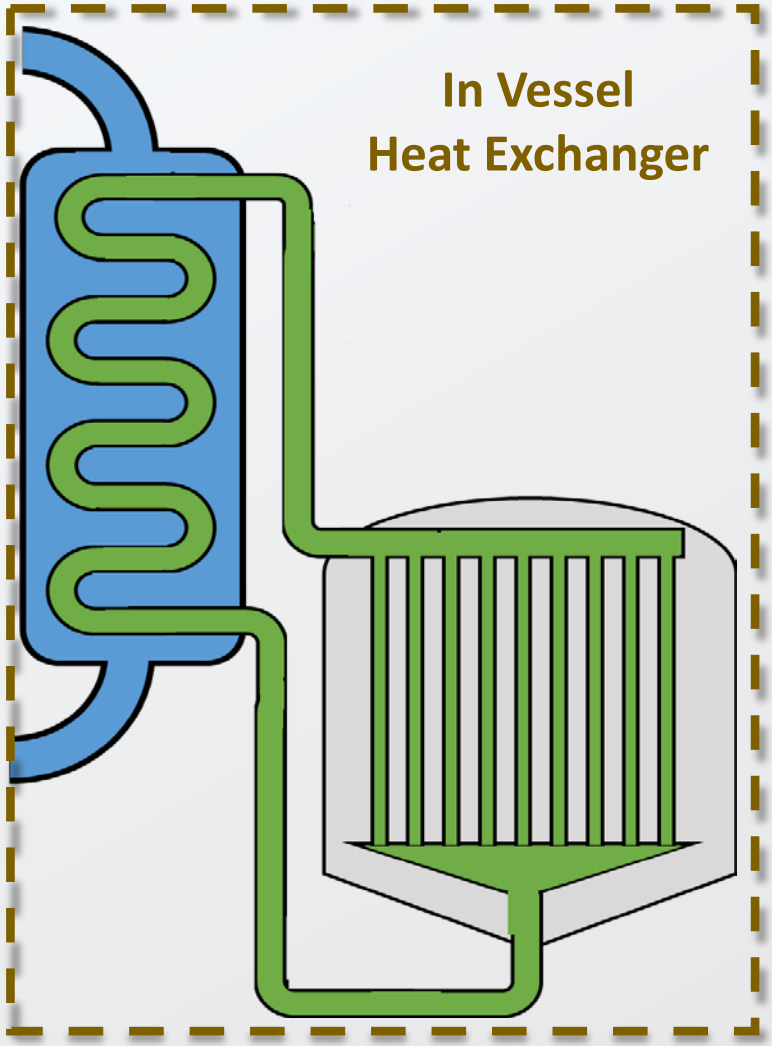
Thomas Blue
614-292-0629
blue.1@osu.edu

Carol Smidts
614-292-6727
smidts.1@osu.edu

Nuclear Engineering

Central Innovations:

- *Molten Salt Cooled*
  - Exceptional heat transport
- *Natural Circulation Driven*
  - No pumps
- *Existing High-Temperature Fuel Form*
  - TRISO in SiC Matrix
  - Proliferation resistant
- *Truck Transportable*
  - Power to desired cites/sites
- *No Water Usage/Cooling Tower*



Key Design Goals

Power Output	10 MWe
Power Conversion	Supercritical CO_2
^{235}U Enrichment	≤ 19.75%
Safety Mechanisms	Inherent / Passive
Physical Size (per component)	ISO Shipping Container Compatible
Operation	Autonomous and Load Following

The Ohio State University

Minow

Mobile Integrated Nuclear Operational Workhorse

Thomas Blue
614-292-0629
blue.1@osu.edu

Carol Smidts
614-292-6727
smidts.1@osu.edu

Nuclear Engineering

Minow Leverages Existing and Emerging Technologies

TRISO in SiC Matrix fuel

- Part of the Accident Tolerant Fuel Program and irradiated at INL
- Needs to be investigated and optimized for molten salt environment

Molten Salt Coolant

- Considerable expertise being built at ORNL and elsewhere
- Natural convection needs to be studied for Minow

Super Critical CO_2

- Loops constructed and tested at SNL
- Yet to be demonstrated in a nuclear system

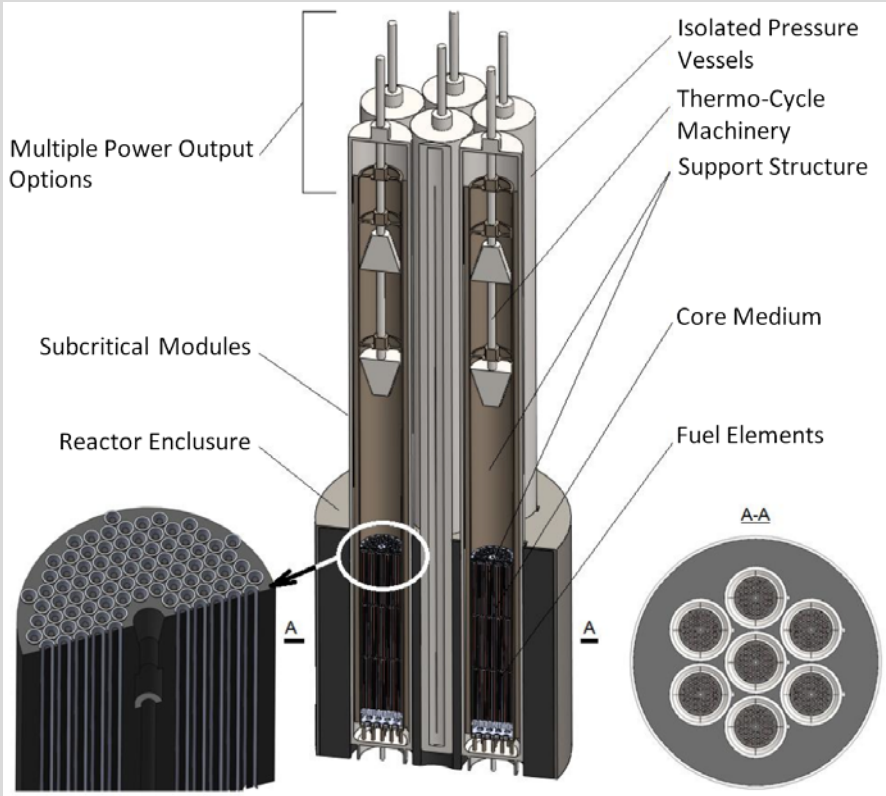
The Ohio State University

Texas A&M University

TSVETKOV

Pavel V. Tsvetkov
Department of Nuclear Engineering, Texas A&M University

Integral Multi-Module Unit (IMMU)



Concept: Multi-Functional Configurable Power Units for Variable Multi-Product Output to Meet Grid and Energy Needs

Functionality: Process Heat, Water, Electricity

Licensing: Subcritical Module

Design: 3S = Safety, Security, Safeguards by Design

Technology: Off-The-Self Reactor Component Solutions - Materials, Fuel, Energy Conversion Sub-Systems

Response to operating conditions unique to the novel modular design

- Battery type refueling
- Module reshuffling

Differences between one large module and a multi-module configuration

- Low capitol costs
- Economically competitive with larger plants
- Small in size
  - Take advantage of natural convection
  - Inherently safe, passive safety systems
  - Decreased staffing requirements
  - Several units at same site to increase power
  - Faster construction times
- Ideal candidate for emerging energy grids

Design Features

- Subcritical, self-consistent modules
  - Each module contains an assembly that includes fuel elements surrounded by coolant pressure channels in a graphite matrix along with direct Brayton cycle turbo-machinery
  - Eliminates criticality accidents during construction, transportation, and after decommissioning
  - Critical configuration created when several modules brought within proximity of one another

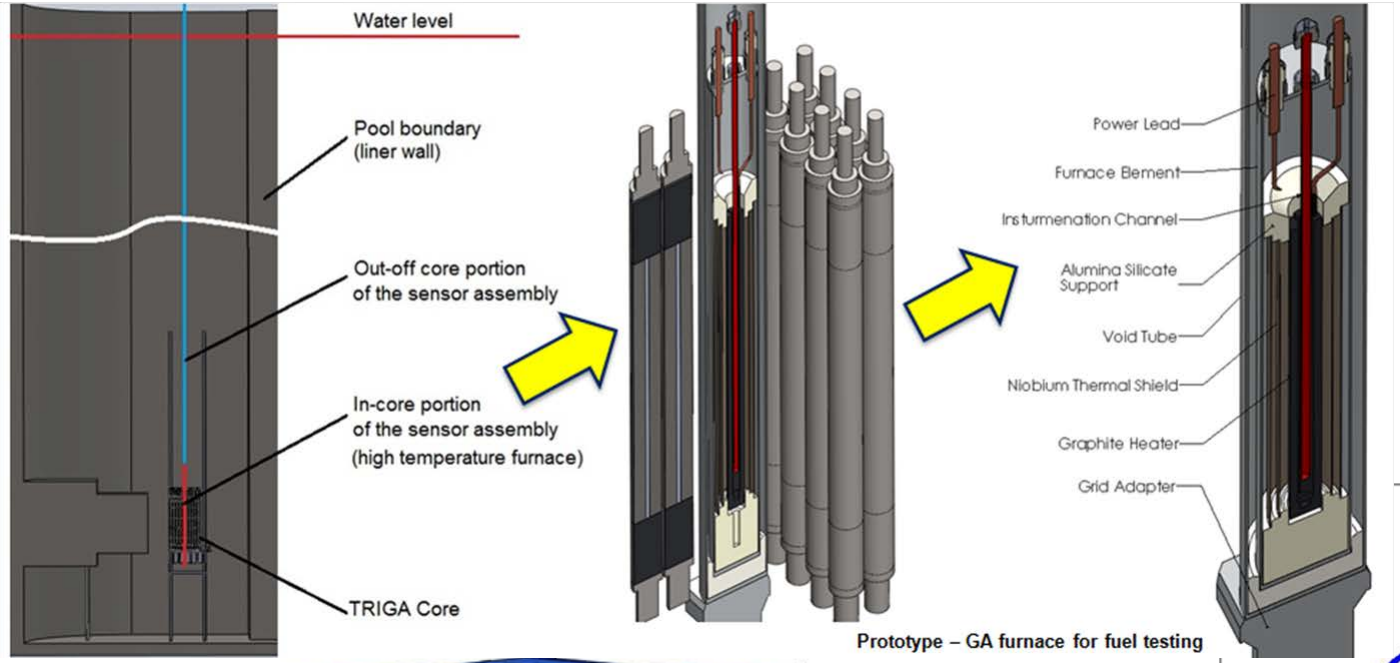
Design Applications

- Battery type construction and operation
  - Factory construction
  - Shipped to site by rail or barge
  - Operated until end of life
  - Shipped to post-processing facility
- Grid size appropriate design
  - Small, emerging energy grids
  - Replace older plants
- Concurrent electricity and industrial process heat generation

Pavel V. Tsvetkov
Department of Nuclear Engineering, Texas A&M University

Integral Multi-Module Unit (IMMU)

Emulation of Conditions in TRIGA



Prototype – GA furnace for fuel testing

Testing

Integration of Applications

"Sizing"