Introduction to Breakout #1:
Concept Discussion

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Program Director

teaming with:
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ARPA-E Safe and Secure Megawatt-Size Nuclear Power Workshop
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Micro Modular Reactors (MMRs)

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? \( \rightarrow \) solid core & water-free? neutron economy & control of criticality
  - Fuel options, core options, heat transfer media
  - Fuel \( \leftrightarrow \) material/core \( \leftrightarrow \) 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 issues: cybersecurity, battery life, and interference
  ‣ Fiber-optic issues: radiation darkening of fiber-optic and lack of nuclear-qualified sensors

Source: NRC, EPRI
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.

Key questions: Sensors & Controls

Source: EPRI
Key questions: Materials

- What advanced materials can be deployed in the advanced design and what new materials need to be developed?
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 CO₂ Power Conversion
Scarlat (Wisconsin)

In Vessel Heat Exchanger

Schmidt (OSU)

Tsvetkov (TAMU)
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
10 MWth Transportable FHR (TFHR)

Match Requirements of Brayton Cycle

**Design Features**
- 10 MWth with ~ 5-yr fuel cycle
- Compact core ~ 2-m diameter
- Transportable 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

- Proven UO₂ 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

OCONUS Bases Less Than 10 MW

- Weighs about 35-45 tons loaded
- Holds 3 tons of fuel in 5 tons of steel monolith
- About 12 ft. long; 6 ft. diameter
- Metallic grill about 10-12 ft. diameter

Design becomes smaller at lower power levels

- Primary Heat Exchanger
- Decay Heat Exchanger
- Monolith Core

Openings for shield cooling flow (also for air flow through core in case of emergency)

Steel shell filled with soft wood, ridged foam, honeycombed material

Cask wall
- Stainless steel outer wall, 1/4 in.
- Lead gamma shield, 4 in.
- Air gap for shield cooling, 1-2 in.
- B4C neutron shield, 6 in.
- Stainless steel containment vessel, 1-2 in.

Source: Los Alamos National Laboratory

Unclassified
Concept of Operations: Transport to Theater & FOB

Fly reactor to theater

Transport by truck to the base

Armor and shielding protects the reactor from DBT during transport

Protect by earth, barriers, & water jackets

Integrate into the base

No major civil structures necessary. Backhoe & dozer type work

Dose monitors

Limited access to Rad Workers

Exclusion zone

Radiation protection area

Unclassified
ROCHAU
Megawatt Class Fission Reactors

ARPAe Workshop on
SAFE & SECURE MEGAWATT-SIZE NUCLEAR POWER

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

Promethius SR

RSR (Cartridge)

RSR (Battery)

sCO2 GFR

Direct Energy Conversion

FSP (moon base)

RSR System (Baseline)
## Critical Component Status

<table>
<thead>
<tr>
<th>Component</th>
<th>Design</th>
<th>Model</th>
<th>Demonstration</th>
<th>Fielded</th>
<th>Cost</th>
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<tbody>
<tr>
<td>Reactor (Na GFR)</td>
<td>Concept</td>
<td>Concept</td>
<td>Bench</td>
<td>No</td>
<td>Target ~ 2K$/kWe</td>
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<tr>
<td>Fuel (UO₂ &gt; 10 yr)</td>
<td>TRL 7 (SiC-SiC)</td>
<td>TRL 7</td>
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<td>No</td>
<td>No</td>
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<tr>
<td>Conversion (sCO₂ Brayton)</td>
<td>Concept</td>
<td>TRL 7</td>
<td>Lab-scale (TRL 3)</td>
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<td>~1K$/kWe</td>
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<tr>
<td>Safety (CDF&lt;10⁻⁸)</td>
<td>Final Design</td>
<td>TRL 7</td>
<td>EBR2</td>
<td>EBR2</td>
<td>Established by design</td>
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<tr>
<td>Security (Non-Prolif &amp; Invulnerable)</td>
<td>Concept</td>
<td>TRL 7</td>
<td>TRL 3</td>
<td>TRL 3</td>
<td>Established by design</td>
</tr>
<tr>
<td>Operations (Remote with Command Disable)</td>
<td>Final Design</td>
<td>Final Design</td>
<td>Concept</td>
<td>No</td>
<td>unknown</td>
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<tr>
<td>Materials – Power</td>
<td>COTS COTS Concept On Target</td>
<td>COTS COTS Concept On Target</td>
<td>EBR2/STEP No No</td>
<td>EBR2/STEP No No</td>
<td>COTS No No</td>
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<tr>
<td>Materials – Facility</td>
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<tr>
<td>Materials - System Mass</td>
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University of Wisconsin

SCARLAT
Molten Salt Reactor Technology

Coupled with CO2 Power Conversion

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 #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.

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
**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, MgCl₂-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-ZrF₄]
6. IRP 1: High Temperature Salt-Cooled Reactor (DoE, present with MIT and UC-Berkeley) [mainly FLiBe, but some FLiNaK, KF-ZrF₄]
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)
Minow

Mobile Integrated Nuclear Operational Workhorse

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**

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**Key Design Goals**

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<table>
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<tr>
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<tbody>
<tr>
<td><strong>Power Output</strong></td>
<td>10 MWe</td>
</tr>
<tr>
<td><strong>Power Conversion</strong></td>
<td>Supercritical CO₂</td>
</tr>
<tr>
<td><strong>235U Enrichment</strong></td>
<td>≤ 19.75%</td>
</tr>
<tr>
<td><strong>Safety Mechanisms</strong></td>
<td>Inherent / Passive</td>
</tr>
<tr>
<td><strong>Physical Size (per component)</strong></td>
<td>ISO Shipping Container Compatible</td>
</tr>
<tr>
<td><strong>Operation</strong></td>
<td>Autonomous and Load Following</td>
</tr>
</tbody>
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In Vessel Heat Exchanger
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 CO₂
- Loops constructed and tested at SNL
-Yet to be demonstrated in a nuclear system
**Integral Multi-Module Unit (IMMU)**

- **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 capital 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

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**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
Integral Multi-Module Unit (IMMU)

Emulation of Conditions in TRIGA

Testing

Integration of Applications

“Sizing”