Nuclear Energy University Programs

ARC-2
Advanced Energy Conversion

Technical POC - Jim Sienicki
presented by Bob Hill

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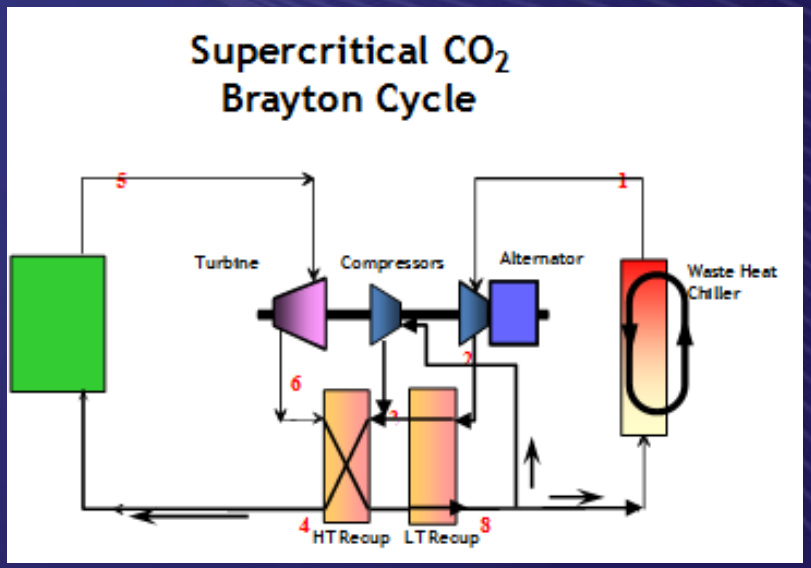


Advanced Reactor Concepts

The mission is to develop and refine future reactor concepts that could dramatically improve nuclear energy performance (e.g., sustainability, economics, safety, proliferation resistance)

The strategic approach is to:

- Tackle key R&D needs for promising concepts
  - *Fast reactors for fuel cycle missions*
  - *Fluoride salt cooled thermal reactor for high-temperature missions*
- Develop innovative technology features with potential benefits to many concepts (e.g., energy conversion)
- Utilize international collaborations to leverage and expand R&D investments
  - *Continuation of multi-lateral Generation-IV R&D Projects*
  - *Investment in strategic bilateral or trilateral partnerships*
- Stimulate ideas for transformational reactor concepts

ARC Organizational Structure

Advanced Reactor Concepts (ARC) is part of Reactor Concepts RD&D, with the NE-74 designation

ARC is organized into several technical areas:

- Management and Integration (*Hill-ANL)*
- Fast Reactor Concepts *(Grandy-ANL)*
- Thermal Reactor Concepts *(Holcomb-ORNL)*
- Energy Conversion Technology *(Rochau-SNL)*
- Nuclear Data *(Hill-INL)*
- Generation-IV International Support *(McFarlane-INL)*
- Transformational Concepts

Other DOE-NE R&D initiatives include advanced reactor applications

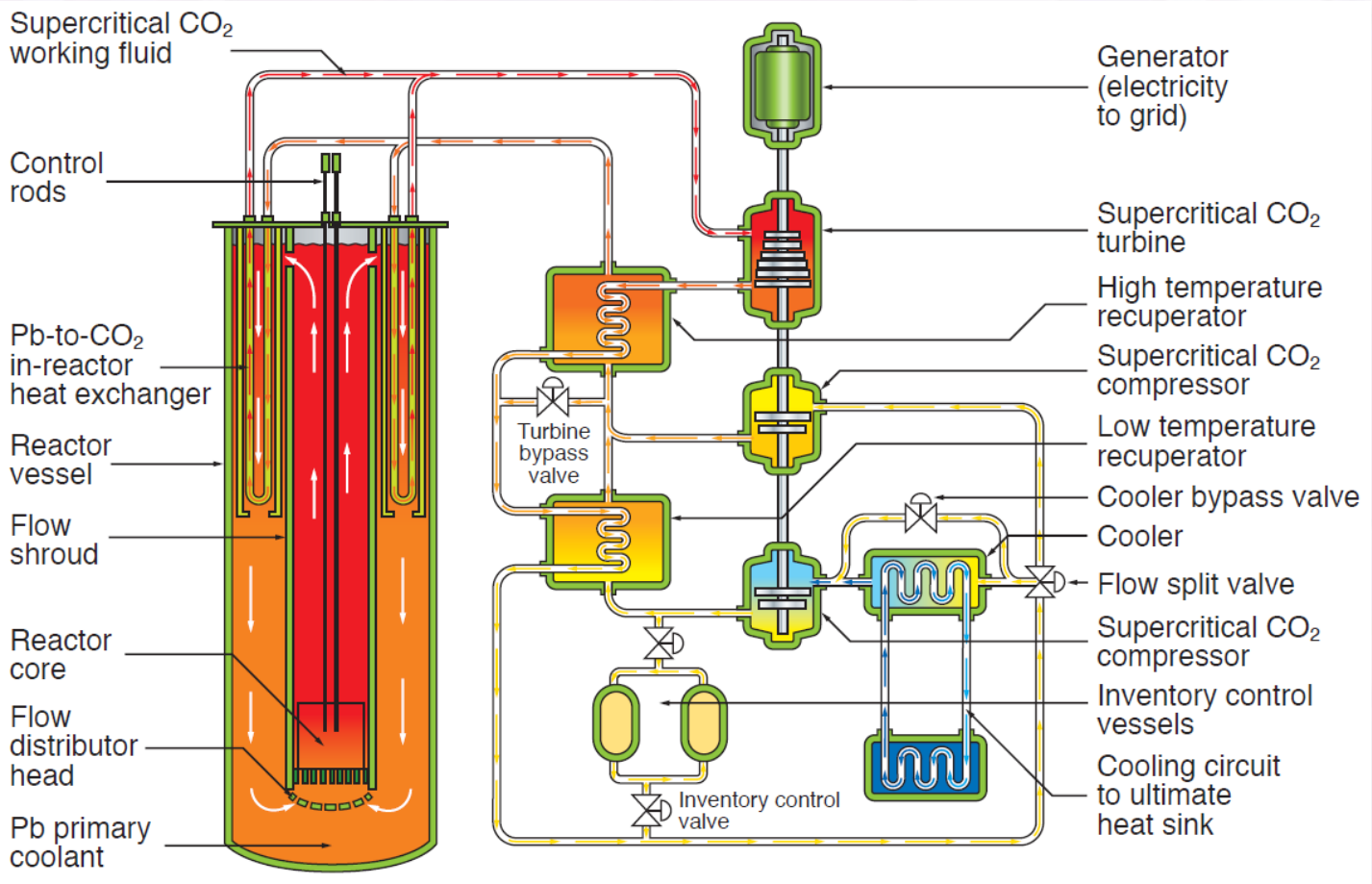
- Modeling and Simulation *(NE-71)*
- Transmutation Fuels *(NE-FCT)*
- High Temperature Fuels *(NE-73)*

Advanced Energy Conversion

- The Rankine steam cycle has traditionally been utilized for converting the thermal energy released in the reactor core into electricity delivered to the electrical power grid
- Advanced energy conversion involves R&D into energy conversion approaches that offer capital cost, safety, and efficiency benefits beyond the current Rankine steam cycle
- Current focus is upon the supercritical carbon dioxide (S-CO_2) Brayton cycle
- The development of refined heat exchangers is also required to couple advanced reactors (SFR, FHR, LFR, VHTR, etc.) to new energy conversion technology

Innovative Energy Conversion Example

- S-CO_2 Brayton cycle coupled to SSTAR small Lead-Cooled Fast Reactor concept - 44 % efficiency for core outlet temperature of 567 °C

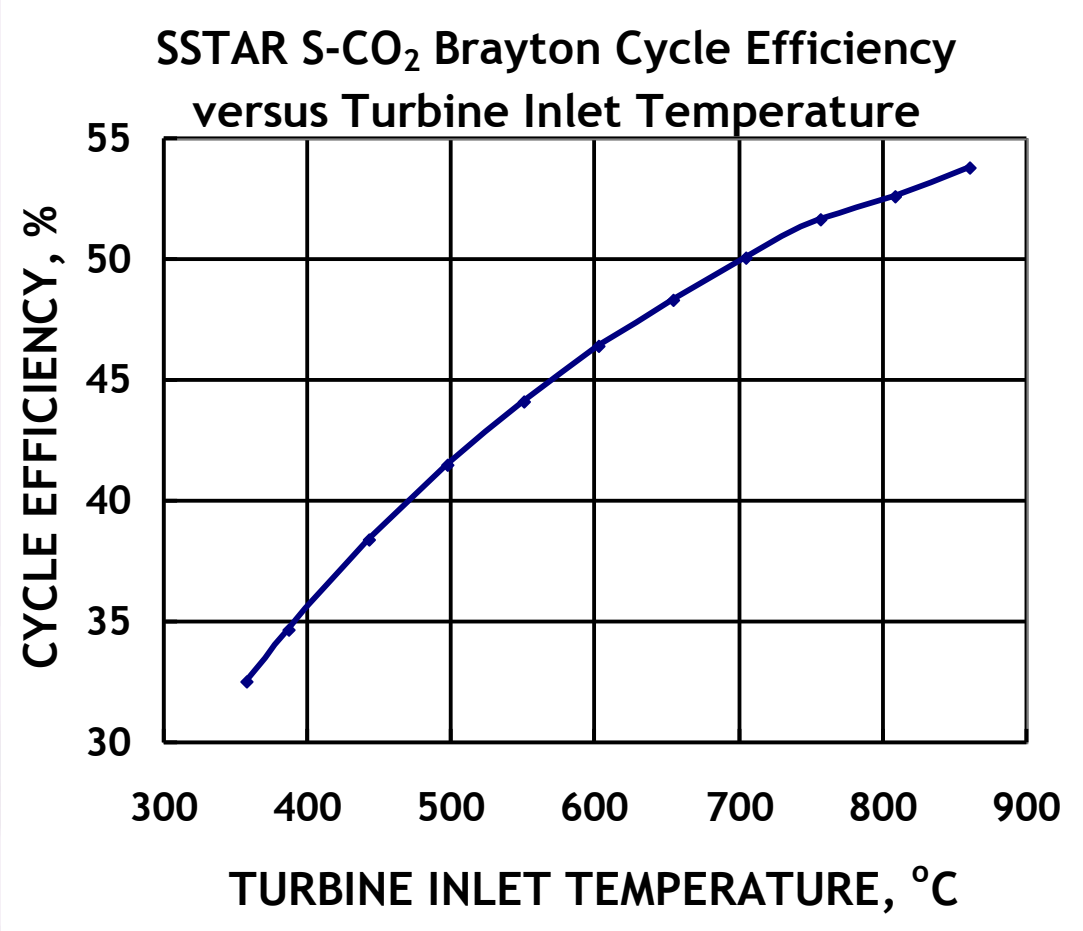


Benefits of S-CO_2 Brayton Cycle

- Potential for lower capital cost than steam cycle
  - Turbomachinery (turbine and two compressors) is remarkably small with potential for significantly reduced component costs
  - Eliminates condenser, deaerator, feedwater pumps, and feedwater heaters of steam plant
  - Higher cycle efficiency than steam cycle for higher SFR core outlet temperatures (e.g., 45 % at 550 °C) further reducing plant cost per unit electrical power and increasing plant net present value
- Improved safety and potential reduction of capital costs by eliminating problematic coolant-working fluid reactions
  - Sodium reacts energetically with water releasing heat and generating combustible hydrogen gas, steam generator design and operation must accommodate potential sodium-water reactions
  - Improved safety for Lead-Cooled Fast Reactors (LFRs) because molten Pb and CO_2 are calculated not to react chemically

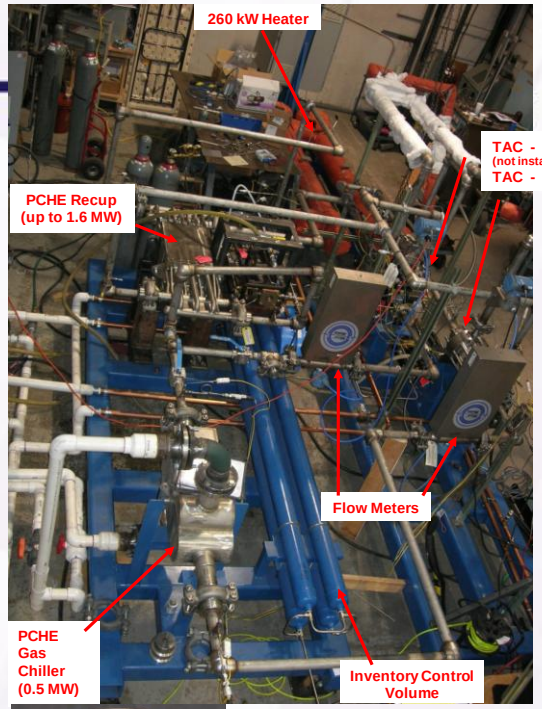
Thermal Efficiency Improvements

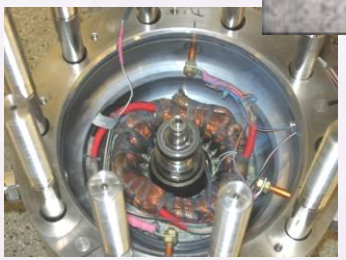
- Efficiency versus turbine inlet temperature for small LFR



S-CO_2 Cycle R&D Status

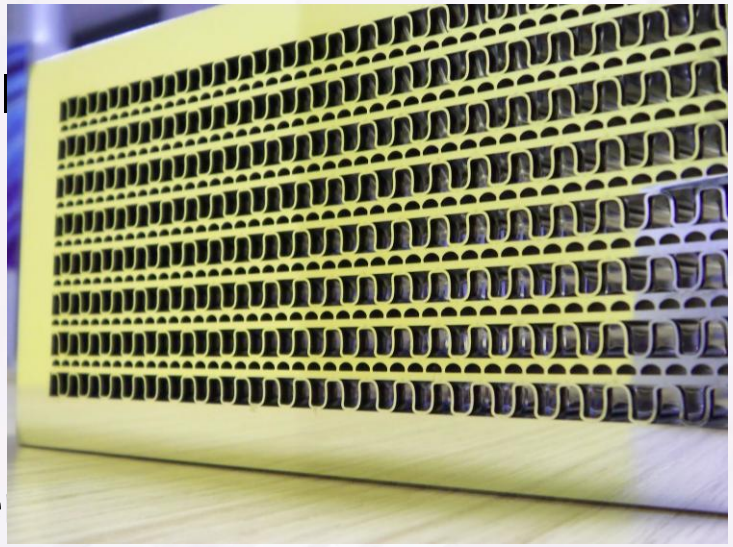
- Sandia National Laboratories (SNL) is carrying out a phased assembly of small-scale (~ 0.78 MWt heat input) S-CO_2 recompression Brayton cycle to demonstrate viability and controllability of the S-CO_2 cycle
- Data with completed S-CO_2 cycle at SNL expected in FY 2013
  - Current small-scale recompression loop has demonstrated <u>net power production</u> from heat input with S-CO_2
  - Supported by separate small-scale compressor loop operational since at SNL to address control and stability and develop small-scale turbomachinery technology
  - Demonstrated that small-scale main compressor can be operated stably around the critical point covering full range of conditions of interest at critical point, on liquid and vapor side





S-CO_2 Cycle R&D Status

- At Argonne, a Plant Dynamics Code model system level transient analysis including strong CO_2 property variations near the critical point
  - Validated by small-scale compressor tests
- Development of Na-to-CO_2 heat exchanger
  - Test plugging of small sodium flow channels by precipitation of sodium oxide
  - Tests on fundamental Na-CO_2 interactions under prototypical conditions
  - Tests of sodium freezing or thawing inside of heat exchanger and ability to efficiently drain
  - Thermal shock testing of a small-scale PCHE

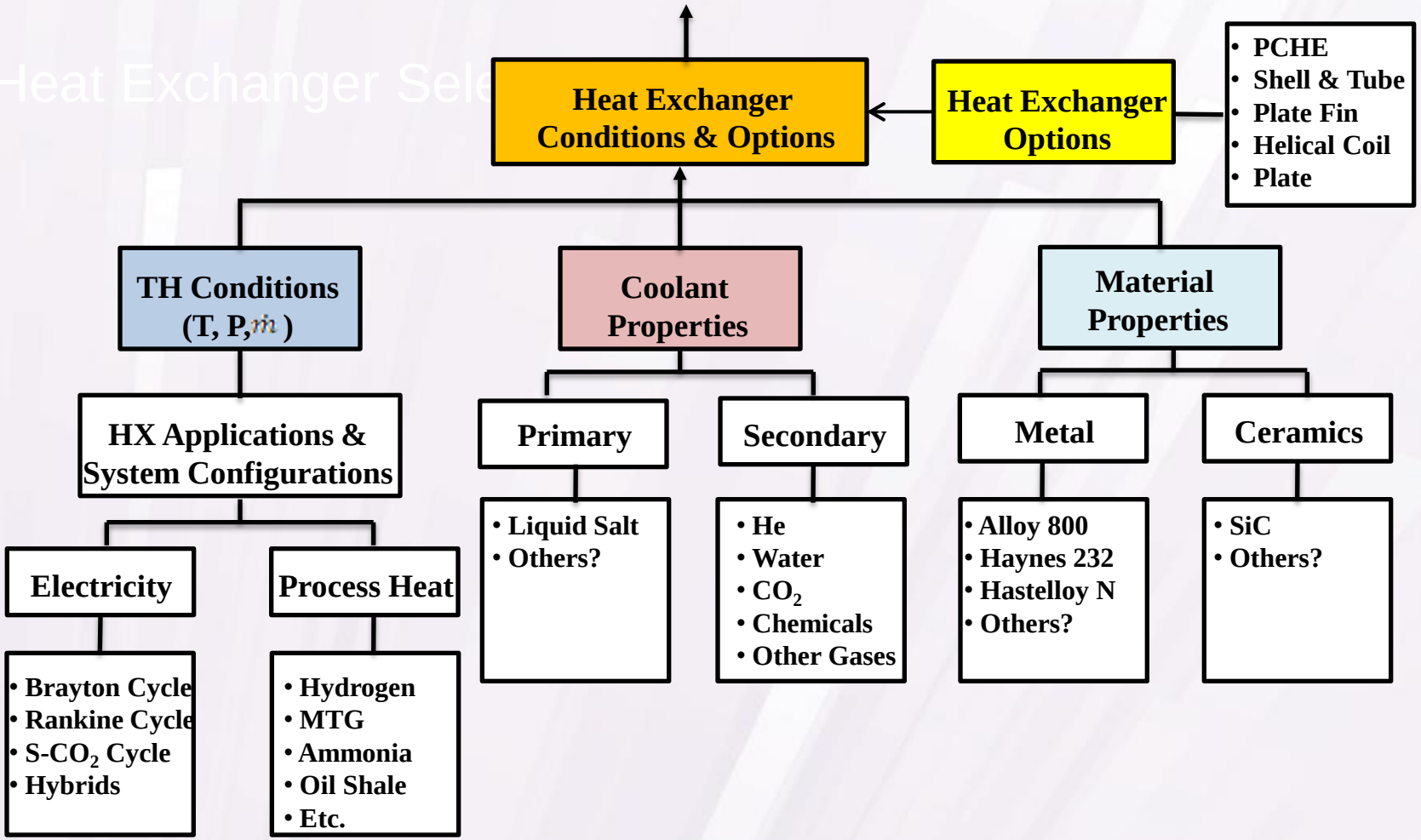


Sodium-CO2

Test/vessel

Molten Salt Heat Exchanger R&D

Heat Exchanger Selection/Design



Relevant Existing NEUP Awards

- On May 20, 2010, DOE announced $ 38 M in awards for 42 university-led projects under DOE's Nuclear Energy University Program (NEUP)
- $ 475,005 awarded to Rensselaer Polytechnic Institute (RPI) for "Development and Validation of Multidimensional Models of Supercritical CO_2 Energy Conversion Systems for Nuclear Power Reactors" supporting Gen IV
- $ 651,447 awarded to University of Wisconsin, Madison (UW) for "Corrosion in Supercritical Carbon Dioxide: Materials, Environmental Purity, Surface Treatments, and Flow Issues" supporting Gen IV
- FY 2011 awards have not yet been announced

Challenges for Advanced Energy Conversion Systems

- Performance should exceed that of the current state of the art (i.e., mature Rankine superheated steam cycle)
- Main figure of merit is nuclear power plant cost per unit electrical power
  - Reduction could be realized through lower capital cost of power converter equipment
  - Improvement in efficiency is important mainly because it can reduce the NPP cost per unit electrical power
  - Must consider both the alternative energy conversion cycle and the technology to couple diverse reactor types
- Compatibility of working fluid with reactor coolant and temperature range
- Component materials is another major considerations

ARC-2 FY 2012 Workscope

Development of new energy conversion systems that use advanced technologies or innovative engineering is sought. Supercritical CO_2 shows promise as a working fluid suitable for fast and thermal reactors because of its compatibility with materials and thermodynamic properties. Basic R&D is needed in turbomachinery performance and loss mechanisms. System optimization requires a detailed modeling of the system components and their response to steady-state and off-normal conditions. The university participants could contribute detailed CFD modeling of keycomponents, such as the main compressor, for comparison to one-dimensional system level models and experimental data from ongoing small-scale testing. Alternately, contributions could be made to the development of plant dynamics models and control strategies, including the investigation of alternative cycle layouts (e.g., having turbomachinery on multiple shafts). The efficiency of different power conversion cycles is degraded by leaks at component interfaces. R&D is needed to develop models and/or test beds to predict the performance of seals (labyrinth, dry liftoff seal, brush, etc.) and bearings. Another topic could be projects that explore coupling of the reactor heat source with diverse process heat applications (cogeneration, coal-to-liquids, chemical feedstocks) and/or other energy products with an emphasis on novel approaches that can greatly improve the ease of coupling, the operability of the combined system, and the ultimate economics. The scope of the proposed project should include a thorough viability assessment of the advanced energy conversion system, a detailed technology gap analysis, and a comprehensive technology development roadmap.

Summary of ARC-2 Research Needs

- Innovative energy conversion concepts
  - Evaluate performance and gaps
- Turbomachinery performance
  - Off-normal behavior
  - Performance of seals
  - Loss mechanisms
- Modeling for system optimzation
  - Heat transfer behavior and performance
  - Plant dynamics and control
- Coupling of new energy conversion technology to diverse process heat applications or energy products

ARC-2 NEUP Contacts

The ARC-2 Advanced Energy Conversions POCs are:

- Federal – Brian Robinson (DOE)
- Technical – Jim Sienicki (ANL)

Some key researchers in the different areas are:

- Supercritical CO_2 Turbomachinery
  - *Rochau (SNL), Wright (SNL)*
- Fast Reactor Heat Exchanger
  - *Sienicki (ANL), Reed (ANL)*
- Molten Salt Heat Exchanger
  - *Patterson (INL), Holcomb (ORNL)*