U.S. Status of Fast Reactor Research and Technology

Robert Hill
Argonne National Laboratory
Nuclear Engineering Division

May 22, 2013
Evolving Vision for Fast Reactors

From the initial conception of nuclear energy, it was recognized that full realization of uranium energy content would require fast reactors

**Fermi**: The vision to close the fuel cycle

- **50’s**: First electricity generating reactor: EBR-I with a vision to close the fuel cycle for resource extension

- **60-70’s**: Expected Uranium scarcity – significant Fast Reactor programs

- **80’s**: Decline of nuclear – Uranium plentiful
  - USA (& others): once through cycle & repository
  - 2 paths
    - France, Japan (& others): closed cycles to mitigate and delay waste disposal

**Late 90’s** in the U.S.: Rebirth of closed cycle research and development for improved waste management

**Now**: flexible actinide management for fuel cycle missions
Actinide Management in Fast Reactors

- A wide variety of actinide management strategies possible
  - Waste management
  - Resource extension

- Also, important features for small reactor applications
  - Compact (high power density)
  - Extended burnup and cycle length
  - Inherent safety

- With key technology development, also intended for electricity and heat production missions
Capital investment in reactors is the dominant cost of any nuclear fuel cycle; thus,
The primary research focus is capital cost reduction through application of innovative technology solutions
- Concept development studies (improved design approach)
- Advanced structural materials
- Supercritical CO$_2$ Brayton cycle energy conversion
- Advanced modeling and simulation

Other important technology research topics that must be addressed for successful application:
- Safety (and licensing)
- Fuels development (performance and fabrication)
- Undersodium viewing (reliability and maintenance)
Technology Innovations for Capital Cost Reduction
Concept development studies have several important purposes

- **Pursue fundamental understanding of technical utilization of advanced technology options in integrated reactor system**
  - Confirm feasibility of innovative features
  - Estimate the impacts and benefits to prioritize new features
  - Identify and develop favorable system applications

- **Evaluate broad range of technology options**
  - Different configurations and power sizes (e.g., SMR concepts)
  - Different coolant options, fuels, etc.
  - Wide variety of specific design features (e.g., EM pumps, alternate heat transport pathways, fuel handling, etc.)

- **Guide the R&D directions by identifying key (i.e. high impact) technology development needs and challenges**
FY11 and FY12 work focused on SMR (~100 MWe) concepts: unique features include long-lived core and fuel shuffling strategies.

Developed compact fuel handling mechanism:
- Single rotating plug configuration
- Pantograph design
- Offset from center

Detailed analysis and design options for core restraint
- A key feature for inherent safety reactivity feedbacks
- NUBOW bowing analysis code recovered and refined
- Limited free bow design

AFR-100 safety analyses conducted
- Verify inherent safety in double fault transients
AFR-100 Status

- 30 year long lived core
- Metal fuel – inherently safe reactor
- Upper Internal Structure integrated with In-Vessel Fuel Handling System
- In-Vessel Fuel Handling System removed during reactor operations
- Plug is inserted into reactor vessel head in IVTM slot to provide temperature and flow measurements
- Primary and secondary control rod drive system integrated into UIS structure
The facility will test small and intermediate-scale sodium components, examples include:

- Components for advanced fuel handling systems such as grippers, spline shafts, universal joints, bearings, etc.
- Instrumentation including detectors for rapid detection of impurities and improved methods for sodium level measurement
Pumps and Flowmeters were ordered in FY2012

One Flow Meter is completed and will be calibrating within the next few days.

The CA15 pump will be going into the loop for testing in the next few days also.

A lot of the parts are made for the LA125.
Cold Trap has been ordered, fabrication drawings have been received, approved, and cold trap is in fabrication.
Information Recovery Efforts

- Another aspect of the concept development scope involves information recovery efforts
  - Recovery of Information at FFTF (PNNL)
  - Recovery of Information at EBR-II (INL)
  - TREAT information recovery (ANL)
  - Retrieval of fast reactor information from OSTI

- Some key activities that have been pursued include:
  - NUBOW code recovery – supports core restraint design
  - SWAAM (sodium-water interaction) code recovery
    • *Upgraded to include sodium-CO$_2$ interactions*
  - FFTF Transient Testing and Startup Physics Testing Data
  - FFTF Design Standards and Procurement Specifications for major FFTF systems and components
Advanced Steels Provide Greater Safety Margin and Design Flexibility

- Higher strength for constant temperature:
  - Reduced commodities
  - Greater safety margins
  - Longer lifetimes

- Higher temperature for constant stress:
  - Higher plant performance (e.g., thermal efficiency)
  - Reduced commodities
  - Greater safety margins in accident scenarios

- Combinations of above:
  - Greater design flexibility
Advanced Ferritic-Martensitic Steels
Down-Selection: Based on Overall Performance Metrics

Grade 92 Steel With Optimized Chemical Compositions Shows the Best Overall Performance
Further Performance Enhancement Can Be Achieved by Thermo-Mechanical Treatment (TMT)

- Improvement in Brittle Fracture Resistance
- Improvement in High Temperature Toughness
- Improvement in Resistance to Sodium Exposure

Tensile Property Enhancement

Creep Strength Enhancement

Na surface attack on the T5B was ~60% less than the T5A.

~30%

~174X

~515X

~50%
Advanced Austenitic Stainless Steels
Down-Selection: Based on Overall Performance Metrics

NF-709 Austenitic Stainless Steel Shows the Best Overall Performance
Restart of the DeLTA loop proceeding well at LANL

- Two tons of LBE
- Can control Oxygen concentration to levels down to $\sim 1 \times 10^{-8}$ wt%.
- Maximum operating temperature up to 550°C
- Flow velocity up to 2 m/s tested so far.

Progress for FY12
- Updated safety documentation and replaced inoperable sensors on loop (March 2012)
- Completed 7 day run of Flow loop in August 2012
- Collaboration with SCK-CEN- Hosting PhD student, Alessandro Marino (July-October 2012)
- 3000 hour corrosion run underway started in March 2013 (900 hours so far)
**DELTA Corrosion Test Plan**

* Corrosion resistance:
  
  Exposure up to 3000h in flowing LBE at 500°C and Oxygen concentration $10^{-6}$-$10^{-8}$ wt%.

* Flow-rate resistance:
  
  LBE velocities up to 3.5 m/s

* Grand total of 144 specimens tested

Thin test coupons are placed in a cylindrical holder that is lowered into the test section.

Canister loaded with 48 specimens

Gen-4 Module US Technological Impact: Understanding flow velocity and high-temperature effects on LBE steel corrosion properties for exposure times $>2000h$ is critical in the conceptual design of advanced system
Preliminary Visual Inspection Indicates Good Performance of Candidate Cladding Steels

MA956 oxide dispersion strengthened (ODS) steel specimens retrieved after ~900h flowing LBE exposure
Major system upgrades are completed to attain the original testing capabilities of:
- 75,000 RPM on both Turbo-Alternator-Compressor (TAC) units.
- 780 kWth input power.
- Peak operating temperature of 1000°F.
- Peak operating pressure of 18.7 MPa.
- 5.7 kg/sec mass flow rate.
- Net power generation on the order of 250 kWe.

Recent focus:
- Demonstrate theoretical efficiency of the design
- Install diagnostics to measure losses
- Automate control valves for remote operation
- Verified heat exchanger/recuperator performance
- Changed loop piping to power pipe standards
Technology Development Efforts

- Won an award from DOE-EERE/Industry to demonstrate a 10 MWe S-CO2 simple Brayton cycle with dry heat rejection in 2015 and hosted at Sandia
- Demonstrating commercial configurations on 250 KWe loop to gather further industry support for larger scale systems
- Developing cost effective, advanced heat exchangers and testing facilities
- Established a roadmap to demonstrate a S-CO2 Recompression Brayton Cycle scalable to 300 and 1000 MWe by 2020 as a pilot plant.

Sandia National Laboratories
Brayton Laboratory
A variety of R&D issues for coupling new energy conversion to a fast reactor

- **Updated small-scale sodium Plugging Phenomena Loop** has been
  - Modified to assure constant temperature in plugging zone

- **Fundamental Phenomena for IHX**
  - Concern with thermal shock for compact heat exchangers
  - Ability to fill and drain also requires development
  - Small-scale facility being assembled to look at freeze and thaw issues

- **Na-CO$_2$ Interaction**
  - Facility completed and first tests conducted
  - Additional instrumentation is being introduced

- **Dynamic Modeling of Supercritical CO$_2$**
  - Developing control strategies for SFRs covering entire range from nominal power to early decay heat levels
  - Plant Dynamics code being validated by comparison to experiments in the 1 MWt small-scale demonstration loop at SNL
Upgrade of Sodium Plugging Loop

1,800 cubic feet per minute (cfm) air blower with variable frequency drive and chiller

Test section and heaters inside of stainless steel air duct half-wall
Small-scale facility has been assembled to provide fundamental data on interactions between sodium and CO$_2$ in prototypic conditions.

Micro-leak configurations with high pressure supercritical CO$_2$.

Envisioned failure mode for compact diffusion-bonded heat exchangers involves formation of microcracks limiting flow of CO$_2$ into sodium with possibility of self-plugging.

Loop filled with sodium and first testing conducted in September 2012.
Steady-State Results

- The results of the steady-state calculations from the Plant Dynamics Code (PDC) model are surprisingly close to the experiment data
  - Pressures, temperatures, flow rates
  - Despite all the uncertainties of the experimental data
  - Special adjustments for heat loss were needed
Goal: Apply modern, high-performance computing techniques to nuclear reactor modeling
- Use advanced simulation tools to improve accuracy allowing reduced conservative margins, and improved safety assurance
- Provide local data needed to enable predictive fuel performance simulations, allowing exploration of broad range of reactor features
- Understand and reduce uncertainty of computational models
- Develop user and code interfaces to facilitate design integration and promote optimization of advanced reactors

Strategy: Develop flexible, mission-agile toolbox for construction of virtual reactor models
- Adopt multi-scale strategy to enable application to problems relevant to industry using a wide range of computing platforms
- Utilize modular architecture to enable component-wise use by most advanced users or integrated user interface driven application by less advanced users.
- Develop collaborations with customers to define near term applications/demonstrations
Enables application of high-fidelity CFD tools to large reactor problems

- More accurate predictions of temperature and flow effects
- Reduced reliance on engineering correlations with limited applicability
- Capability for benchmarking or calibrating lower-fidelity methods
- Improved understanding of pin bundle flow and heat transfer phenomena
SHARP is the in-vessel reactor performance tool

- Variable fidelity (up to full 3-D) toolset comprising three major physics packages
  - High fidelity neutronics (PROTEUS)
  - High fidelity thermal-hydraulics (NEK5000)
  - High fidelity structural mechanics (DIABLO)

- Physics packages are useful in isolation for problems that don’t warrant coupling
Purpose: Step-by-step demonstration of coupling capabilities.

Completed first integrated SHARP simulations using innovative code coupling capabilities provided by MOAB

- Completed a set of problems of increasing complexity.
- Coupled high-fidelity neutronics (PROTEUS) and thermal hydraulics (Nek5000)
- Send data to structural mechanics (Diablo)
  - Send data back, but not doing the mesh deformation yet
- Confirmed that integration works in serial mode and gets correct answers
- Confirmed that works in parallel for several thousand cores

Progression of simulations leading up to full core EBR-II unprotected passive safety demonstration.
Other Fast Reactor Technology Research
Leverage and expand U.S. investments through international collaborations to support key long-term R&D needs

- Training of next generation by engaging them in advanced reactor concept design, methods development, and international collaborations

IAEA Coordinated Research Projects

- Completion of benchmarks for MONJU plant turbine test and PHENIX natural circulation test
- Initiation of the benchmarks for EBR-II Shutdown Heat Removal Tests on inherent safety demonstration

Major international benchmark exercises

- CEFR core conversion study and shutdown heat removal test planning under U.S.-China bilateral
- ASTRID core design and transient benchmarks (ULOSP and ULOHS) under a U.S.DOE-CEA agreement
- Joint SAS4A development collaboration for oxide fuel response in severe accidents under the US-Japan-France trilateral collaboration on FR safety
EBR-II Shutdown Heat Removal Tests (SHRT)

- Importance of passive decay heat removal capability of advanced reactor designs has been emphasized in the aftermath of Fukushima accident.
- Potential of SFRs to survive even more severe accident initiators with no core damage has been demonstrated during the testing program with EBR-II.
- Two EBR-II SHRT tests are analyzed as the benchmark problems:
  - SHRT-17 (1984): A protected LOF from 100% power and flow
  - SHRT-45R (1986): An unprotected LOF from 100% power and flow
Four year project

- 2013: Blind analyses
- 2014: Preliminary assessments and model revisions
- 2015: Uncertainty evaluations and parametric analyses
- 2016: Documentation of the contributions in an IAEA report

**EBR-II CRP: Participating Organizations**

<table>
<thead>
<tr>
<th>Country</th>
<th>Organizations</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>CIAE, Xian Jiaotong University</td>
</tr>
<tr>
<td>Korea, Republic of</td>
<td>KAERI, KINS</td>
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<tr>
<td>France</td>
<td>IRSN</td>
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<td>The Netherlands</td>
<td>NRG</td>
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<td>Germany</td>
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<td>Russia</td>
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<td>Italy</td>
<td>ENEA, UNIP (GRNSPG)</td>
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<tr>
<td>Switzerland</td>
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<td>India</td>
<td>IGCAR</td>
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<tr>
<td>USA</td>
<td>ANL, TerraPower, MIT</td>
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<tr>
<td>Japan</td>
<td>JAEA, Fukui University, Kyushu University</td>
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</tbody>
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Fast Reactor Safety and Licensing R&D: Safety analysis code improvements

• Development and validation of enhanced safety technologies for accident prevention and mitigation
  – Integrate state-of-the-art engineering technology in FR safety analysis codes

• SAS4A/SASSYS-1 modernization and maintenance
  – AT designation is removed and version 5.0 is copyrighted by ANL
    • Integrates decade-long code development efforts under various programs (INERI, GNEP, AFCI, NEAMS)
  – Ongoing activities include integration of oxide fuel models from CEA/IRSN/JAEA/KIT consortium, revision of code documentation for new features/modules, modernization of data management scheme and other optimizations and enhancements

• MELCOR/CONTAIN-LMR Integration
  – To provide a sodium coolant accident analysis capability under the MELCOR integrated severe accident code
  – Use CONTAIN-LMR models for predicting the physical, chemical, and radiological conditions inside a containment
Fuel Fabrication Development Challenges

- Minimize/eliminate process losses
- Minimize/eliminate waste streams
- Maximize throughput
- Reduce cost
- Use M/S for development
- Scalable and remote operation
- Flexibility and adaptability
- Meet fuel specification
Fuel Characterization: Phase relationships of complex systems

<table>
<thead>
<tr>
<th>Alloy</th>
<th>(\delta-(U,Pu)Zr)</th>
<th>(\zeta-(U,Pu))</th>
<th>(\alpha)</th>
<th>(\gamma)</th>
<th>(R_{wp})</th>
</tr>
</thead>
<tbody>
<tr>
<td>U-25Pu-3Am-2Np-40Zr</td>
<td>82</td>
<td>16</td>
<td>2</td>
<td>0</td>
<td>14.0</td>
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<tr>
<td>U-28Pu-7Am-30Zr</td>
<td>70</td>
<td>27</td>
<td>2</td>
<td>1</td>
<td>9.9</td>
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<tr>
<td>U-29Pu-4Am-2Np-30Zr</td>
<td>89</td>
<td>11</td>
<td>0</td>
<td>0</td>
<td>11.1</td>
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<tr>
<td>U-34Pu-3Am-2Np-20Zr</td>
<td>50</td>
<td>50</td>
<td>0</td>
<td>0</td>
<td>9.3</td>
</tr>
</tbody>
</table>

\[\lambda = -1 \times 10^{-7} T^2 + 2 \times 10^{-4} T + 0.05\] for 100°C to 600°C

\[\lambda = 2 \times 10^{-7} T^2 - 1 \times 10^{-4} T + 0.14\] for 600°C to 1000°C
Fuel Characterization: Fuel-Cladding Compatibility Testing

- (Fe,Cr) (U,Zr)
- (Fe,Cr) (An,Zr) (An,Zr rich)
- (Fe,Cr) (An,Zr)
- (Fe,Cr) (U,Zr)
- (Fe,Cr) (An,Zr) (An,Zr rich)
- (Fe,Cr) (minor An,Zr)

- Establish safety margins
- Diffusion couple testing
- Observe potential melting at 650° C (not observed at 550° C)
- Fuel – clad interface not to exceed 550° C
- Complex non-equilibrium phase and microstructure

- U-30Pu-5Am-3Np-1Ln-20Zr vs HT-9, 650° C, 140hrs
- Results highlights need for fundamental studies on simpler system to aid interpretation
# Fuel Irradiation: Irradiation Testing Program in ATR

## Test Strategy

<table>
<thead>
<tr>
<th>AFC-1</th>
<th>AFC-2</th>
<th>AFC-3</th>
<th>SET-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scoping – Many compositions</td>
<td>Scoping – Focused compositions</td>
<td>Focused compositions</td>
<td>Generic</td>
</tr>
<tr>
<td>Nominal conditions</td>
<td>Nominal conditions</td>
<td>Nominal conditions</td>
<td>Variable conditions</td>
</tr>
<tr>
<td>Drop-in</td>
<td>Drop-in</td>
<td>Drop-in</td>
<td>Instrumented lead</td>
</tr>
</tbody>
</table>

## Capsule Type

- **AFC-1**: Drop-in
- **AFC-2**: Drop-in
- **AFC-3**: Drop-in

## Fuel Types

- **AFC-1**: Metallic Nitrides
- **AFC-2**: Metallic (2 A&B) Oxides (2 C&D)
- **AFC-3**: Advanced Metallic Concepts

## Key Features

- **AFC-1**: Baseline + MA
- **AFC-2**: Baseline + MA + RE
- **AFC-3**: FP control, annular fuel, FCCI barriers, ultra-high burnup

## Time Frame

- **AFC-1**: FY 2003 – FY 2008
- **AFC-2**: FY 2008 – FY 2012
- **AFC-3**: FY 2011 – FY 2017 +

**SET-1**

- FY 2014 – ?

- **Past test series**
- **Test series in progress**
- **Future test series**
PIE of Legacy Fuels from FFTF & EBR-II

- PIE underway on fuel pins from FFTF/EBR-II with relevance to current transmutation mission
  - **ACO-3**: ultra-high burnup (>20%), annular MOX fuels from FFTF
  - **MFF-3,5**: U-10Zr fuels from FFTF with HT9 cladding (PICT > 600° C)
  - **X496**: U-10Zr fuels from EBR-II with low smear density (56%)
New USV Test Facility

- Max Temperature: 650°C
- Max Sodium Flow Rate: 5G/min
- Accept Larger Targets and Components
- Cleaner Sodium
- Safer Design
- Easier Target Setup and Replacement
Transducer Development

Section View of 9-Element Array Assembly

9-Element Array
Array Housing
Characterization of 9-Element Array

Design & Fabrication Cycle

Final Assembly

Radiography
Baseline geometry/material

Under Water
Low-risk quantitative design screening

Under Sodium
Quantitative performance

Analysis/Feedback for FY13 Design

Qualification
Component “Built as Design”

Incoming Materials

Radiography
Assess physical stability of PA

Complete ▶️ In-Progress ▶️ Scheduled
International Fast Reactor Collaborations

United States R&D work is conducted with international partners through

- **Multi-lateral collaborations**
  - Generation-IV SFR – System, Safety, Components, Fuels
  - IAEA and OECD coordinated research projects

- **Bilateral collaborations on diverse topics**
  - China – fast reactor safety analysis
  - Russia – fast test reactor design and user facility model
  - France – reactor and safety analysis for ASTRID prototype
  - Japan – broad range of common R&D interests (e.g., materials)
  - Korea – INERI project on critical experiments
Concept development studies guide R&D tasks by evaluating system impact for broad variety of technology options

- Small-scale facilities for R&D on key technology
- No near-term plan for demonstration reactor

Fast reactor R&D is focused on key technologies innovations for performance improvement (cost reduction)

- Advanced Structural Materials
- Advanced Energy Conversion
- Advanced Modeling and Simulation

Other R&D is conducted to address known technology challenges

- Safety and Licensing
- Fuels Development
- Undersodium Viewing