DOE-NE Fast Reactor Methods and Safety R&D Program

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In 2012, five topical fast reactor safety gap analyses were completed through expert elicitation with 40+ specialists from the DOE lab complex, academia, industry and international bodies:

- Fuels and Materials
- Accident Initiators and Sequences
- Computer Codes and Models
- Sodium Technology
- Source Term Characterization

In 2014, smaller group of national lab experts developed a consolidated plan to prioritize R&D:

- Coordinated knowledge preservation and management effort
- Maintenance of, and improvements to, legacy fast reactor computer codes

Fast Reactor Methods & Safety R&D Program has since aimed to address these recommendations toward closure of the identified gaps.
EBR-II Metallic Fuel Irradiation Testing Database:
- Detailed pin-by-pin fuel irradiation information: Digitized micrographs, profilometry measurements, gamma scans, porosity and cladding strain measurements, and scans for other microstructural characteristics to support fuel qualification and code validation.

IFR Materials Information System and EBR-II Physics Analysis Database:
- Pin-by-pin fuel fabrication and core load information for each EBR-II cycle.
- Operating parameters, temperature, fluence, and burnup predictions as input to fuels performance codes and for validation of depletion capabilities.

FFTF Metallic Fuel Irradiation Testing Database:
- Test Design Descriptions (fabrication data and QA documentation for IFR-1 and MFF series of metal fuel tests)
- Reports and available operational data for irradiation cycles
- Results for impact of metal fuel tests on reactor operating parameters such as reactivity feedbacks and direct measurement data (in-core assembly growth, assembly pull forces, IEM cell exams).
- **EBR-II Safety Test Database**: ~80 experiments from the comprehensive shutdown heat removal, balance of plant, and inherent control testing program conducted at EBR-II during 1984-97 period.
  - Including the landmark inherent safety demonstration test (unprotected station blackout)

- **FFTF Passive Safety Testing Database**: Natural circulation tests as a reliable means of decay heat removal during unprotected loss-of-flow transient, extending passive safety experience to a large-size SFR
  - Including impact of unique core restraint system design and GEM device

- **TREAT Test Database**: Archive of documents, meta- and numerical data from ~800 one-of-a-kind tests as the basis of present knowledge of transient fuel behavior on key phenomena related to transient fuel performance including fuel failures.

- **SFR Component Reliability Database**: Based on combination of original CREDO data, as well as revisited EBR-II, FFTF, and FERMI run logs, to support Fast Reactor PRA.
Characterization of Historical Information:

- Database development efforts have so far emphasized preserving historical information and its organization in modern electronic format for user friendly access.
  - Data and information are entered and managed in accordance with applicable QA and regulatory requirements in the new electronic format, but its pedigree is not addressed.
- An evaluation of the historical metallic fuel irradiation information is ongoing
  - Determine if it provides a sufficient technical basis and QA pedigree to support a future SFR fuel qualification activity.

Following methods are considered for qualification of legacy data:

- **QA Program Equivalency**: Determine if the acquisition, development, or processing of data have been performed in accordance with sound technical, administrative practices or procedures in compliance with requirements and guidance of NQA 1.
- **Peer Review**: Independently evaluation of data to determine if the employed QA methodology is acceptable and confidence is warranted in the data acquisition.
- **Data Corroboration**: Determine if subject matter data comparisons can be shown to substantiate or confirm parameter values.
- **Confirmatory Testing**: When tests can be designed and performed to establish the quality of existing data.
MONJU Benchmark: Mixing and heat transfer in upper plenum of MONJU during the turbine trip test for validation of thermal stratifications using CFD methods

PHENIX End-of-life Tests
- Natural circulation heat removal test
- Asymmetric control rod withdrawal test

EBR-II Benchmarks: Analysis of a protected loss of flow and the unprotected station blackout tests to demonstrate potential of a pool-type metal-fueled SFR to survive accidents far more severe than Fukushima

FFTFT Benchmark: Analysis of unique FFTF passive safety test (unprotected loss of flow) based on benchmark specification from PNNL
- Including the response of passive gas expansion module (GEM) device and core radial expansion feedback from the unique core restraint system design based on “limited free-bow” concept
EBR-II Benchmarks: Structure

- Four-year program (June 2012-June 2016)
  - Phase 1: Blind simulation of two tests (effectively five separate benchmarks)
  - Phase 2: Model refinements, extended comparisons against plant data, code-to-code comparisons, sensitivity studies, and results qualification

- 19 participants, representing 11 countries – largest IAEA FR CRP
  - Developed benchmark specifications and provided technical support
  - Organized and conducted four research coordination meetings and assembled final IAEA report
  - Involved millennials in analysis of legacy tests (early career+postdocs)

- Primarily supported with nodal neutronics, systems and subchannel analysis codes (DIFF3D/REBUS/PERCENT, SAS4A/SASSYS-1, SAM)
  - Neutronic benchmark for $k_{\text{eff}}$, $\beta$, and reactivity feedback coefficients
  - Two separate benchmarks for SHRT-17 and SHRT-45R tests
  - Additional benchmark for two instrumented subassemblies
EBR-II Benchmarks: Tests studied

- Two EBR-II Shutdown Heat Removal Tests studied:
  - SHRT-17: the most severe protected loss of flow, started from 100% power and flow, natural circulation flow established
  - SHRT-45R: the most severe unprotected station blackout, started from 100% power and flow
  - Instrumented subassemblies XX09 (fueled) and XX10 (steel pins)

- EBR-II core, reactivity feedback coefficients, and primary coolant system modeling (with given IHX-IS inlet flow and temp. as BCs)

- Sensitivity studies performed on:
  - Heat transfer coefficients
  - Fuel porosity
  - Reactivity coefficients
  - Axial heat conduction
  - Neutronics modeling level (spherical harmonics, discrete ordinates)
  - Inclusion of gamma heating
  - Decay heat modeling
  - Pump characteristics
  - Plena and cold pool modeling
EBR-II Benchmarks: Results

SHRT-17

Primary Flow

XX09 Outlet Temp.

SHRT-45R

Primary Flow

XX09 Outlet Temp.
The two primary pumps and associated piping must be modeled individually.

0-D representation of upper plenum and IHX inlet plenum is inadequate.

Thermal stratification in the cold pool is also important to improve pump inlet temperature predictions.

Heat transfer between the Z-pipe and the cold pool and leakage paths between the upper plenum and cold pool are important and evaluated only parametrically.

Heat transfer between the instrumented subassemblies and the surrounding subassemblies requires detailed modeling, particularly for XX10 (non-fueled subassembly surrounded by fueled subassemblies).

Modeling axial heat conduction near the instrumented subassembly flowmeters produce improved temperature predictions.

SAS4A/SASSYS-1 sub-channel results compared to thermocouple data at the beginning of SHRT-17.
Additional EBR-II Tests Analyzed

Additional benchmark specifications developed for other EBR-II tests

**BOP-301 and BOP-302R**
- Loss-of-heat-sink tests – intermediate pump trip at full primary flow
- BOP-301: 50% power, 2/3 intermediate loop flow
- BOP-302R: full power and intermediate loop flow
- Simple flow mixing model in cold pool was added
- Good prediction of inlet plena and Z-Pipe inlet temperatures, improved IHX inlet temperature predictions

**SHRT-43R and SHRT-45**
- Unprotected loss-of-flow
- SHRT-43 initiated at full flow and 2/3 power but at the same window as SHRT-45R
- Same as SHRT-45R, but a different test window (different core load)
- Similar prediction accuracy as for SHRT-45R, giving added confidence to the SHRT-45R results
Mechanistic Source Term Development

- Identified as Possible Licensing Gap
  - No previous mechanistic source term assessments for metal fuel, pool-type SFRs
  - Need to identify and communicate unique phenomena to the regulator

- Radionuclide Release from Failed Metal Fuel Pins
  - Release fraction estimates developed based on fuel pin burnup level and failure conditions
    - Extensive review of past accidents and experimentation as well as chemistry modeling

- Trial Mechanistic Source Term Calculation
  - A best-estimate calculation of radionuclide release
    - From initiating event to offsite consequence
    - Additional goal to identify influential radionuclides & phenomena and possible code/data gaps
  - Analysis includes many computer codes
    - SAS4A/SASSYS-1, HSC Chemistry, Bubble Transport Code, CONTAIN-LMR/MELCOR, etc.
Safety Analysis Code Improvements: MELCOR and CONTAIN-LMR Integration

Motivation:
- Provide CONTAIN-LMR sodium accident analysis capability under MELCOR integrated severe accident code for SFR source term assessments, level 2/3 PRA, and containment DBA analyses.

Status:
- Sodium chemistry models from CONTAIN-LMR are implemented into MELCOR 2.1
- Additional interface data variables are being added for the atmosphere chemistry model.
- A combination of experimental and code-to-code and benchmarking studies are being conducted.

Initial applications:
- Trial mechanistic source term calculations
- JAEA sodium fire modeling collaboration with data from Sandia and JAEA experiments
- Planned MELCOR and ASTEC-Na crosswalk
Probabilistic Risk Analysis for Advanced Reactors

- Passive Safety System Reliability
  - Development of a mechanistic assessment of passive safety system reliability and success criteria
    - Integration of system code modeling results directly into PRA event sequences
    - Allows best-estimate plus uncertainty analysis rather than the use of conservative assumptions

- Component Reliability
  - Developing reliability estimates based on failure data from a variety of past sources and analyses
    - Leveraging U.S. database development efforts

- Simulation-based (Dynamic) PRA
  - Seamless integration of time-dependent processes and mechanistic assessments into PRA
    - Important for passive system performance and external event analysis
    - Coupling system codes with PRA tools such as ADAPT and RAVEN
ARC FOA: PRISM PRA Update

Program Team

Program Deliverables
- PRA Methodologies Report including Initiating events selection, Mechanistic success criteria analysis, & Passive system reliability modeling.
- PRISM PRA summary report for all hazards, all modes

Relevant Prior Work
- ESBWR DCD PRA in which passive design and digital I&C modeling techniques were advanced
- ALMR program - Initial PRA development state-of-the-art in its era
- PRA standard development including Non-LWR standard
- ANL expertise in SASS4A/SASSYS-1 mechanistic tool, passive reliability, and sodium component data

Anticipated Benefits of the Proposed Technology
- New PRA methodologies will be developed that will help other non-LWRs more efficiently analyze risk
- Models in a modern code will greatly simplify future risk studies—in response to regulator inquiries for example
- Risk informed R&D will allow future work to be prioritized by its impact on safety and reliability

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Fast Reactor Codes: Steady-state characterization

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<thead>
<tr>
<th>Phenomenon</th>
<th>Code</th>
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<tbody>
<tr>
<td>Neutron and Gamma Diffusion/Transport</td>
<td>MC(^2)-3</td>
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<tr>
<td></td>
<td>DIF3D/VARIANT</td>
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<td>Fuel Cycle Performance</td>
<td>REBUS</td>
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<td></td>
<td>ORIGEN</td>
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<tr>
<td>Fuel Performance</td>
<td>LIFE-METAL</td>
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<tr>
<td>Core-Wide Thermal Hydraulics</td>
<td>SAS4A/SASSYS-1</td>
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<td></td>
<td>SE2-ANL</td>
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<tr>
<td>Single-Channel Thermal Hydraulics</td>
<td>Nek5000</td>
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<tr>
<td>Fuel-Assembly Bowing &amp; Core Radial Expansion</td>
<td>NUBOW-3D</td>
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## Fast Reactor Codes: Transient characterization

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<tr>
<th>Phenomenon</th>
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<th>Role</th>
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<tbody>
<tr>
<td>Fission Gas Behavior</td>
<td>LIFE-METAL</td>
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<td>SAS4A/SASSYS-1</td>
<td>Secondary</td>
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<tr>
<td>Fuel and Clad Motion</td>
<td>SAS4A/SASSYS-1</td>
<td>Primary</td>
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<td>LIFE-METAL</td>
<td>Secondary</td>
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<td>Primary/Intermediate System Heat Transport</td>
<td>SAS4A/SASSYS-1</td>
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<td>Structural Response</td>
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<td>SAS4A/SASSYS-1</td>
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<td>Inherent Reactivity Feedback</td>
<td>PERSENT</td>
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<tr>
<td>Passive Heat Removal</td>
<td>SAS4A/SASSYS-1</td>
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<tr>
<td>Sodium-Water Interactions</td>
<td>SWAAM-II</td>
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<td>Sodium Fires</td>
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Analyses supporting a license application will require NRC-acceptance of codes and methods
- Development and maintenance of codes in accordance with an acceptable QA framework, demonstration of sufficient model maturity and fidelity

Current RTDP effort dedicated to development of software quality assurance (SQA) framework for SFR safety codes
- Goal: Establish and implement plans to ensure that code development activities are performed in accordance with applicable SQA requirements

Initial focus on development and implementation of a provisional SQA program for SAS4A/SASSYS-1
- Compliance with regulatory guidance and commercial dedication reqs:
  - NUREG/BR-0167, NQA-1-2008/2009, EPRI TR 3002002289, IEEE Standards, etc.
- Sustainable SQA: Necessary to account for increased quality rigor in budgeting and scheduling
Qualification of SFR Codes/Methods: SAS4A/SASSYS-1 SQA Plan

**Staged development process:**

- Identify and develop appropriate supporting documentation
  - Software Quality Assurance Plan, Configuration Management Plan, Coding Standards, various procedures, Software Requirements, Software Design, Verification and Validation...
- Implement provisional program: Training, procedures etc.
- Regular program audits to identify and prioritize gaps
- Resolution of gaps as per audit results
- Continued maintenance and improvement throughout software lifecycle

**Technical activities:**

- Expansion of V&V test suite, implementation of expanded automated testing, improved compiler support, etc.