PP15-039 Transient Modeling of Integrated Nuclear Energy Systems with Thermal Energy Storage and Component Aging and Preliminary Model Validation via Experiment

National Universities Consortium, Nuclear Hybrid Energy Systems Project

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Q. Wu, Oregon State University

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INL NUC Meeting
Columbus, OH
High-level Scope (FY15 start, 3-yr scope)

Focus on integral PWRs as the nuclear heat source for “near-term” applications:

• Model potential electric and thermal energy storage systems integrated with nuclear systems (NCSU)
• Model anticipated transient behavior/response of subsystems (NCSU)
• Perform limited experiments and mine existing data to validate models (OrSU)
• Assess the impact of aging and degradation of key components (e.g. valves) on the implementation of system control (OhSU)

**Note: Additional elements related to advanced reactors were included in year 1, conducted by MIT, UNM, and OrSU. These are not reported in this status.
Generalized Tightly Coupled HES

- Nuclear Energy
- Concentrated Solar
- Wind
- PV Solar
- Natural Gas
- Low Temp Processes
- High Temp Processes
- Intermediate Temp Processes
- Topping Heat
- Thermal Storage
- Power Generation
- Electrical Energy
- Battery
- Low Carbon Products: Fuel, Chemicals, Metals, Water, etc.
- Low Carbon Electrical Power Grid
Current Status: NCSU
Development of Modeling and Simulation Tools (NCSU – J.M. Doster)

- Modification of existing NCSU-developed model that includes a nuclear reactor, power conversion system, local electric grid with sufficient detail for controls engineering

- Hybrid application: Expand integral PWR (IPWR) models to allow diversion of steam and electrical power during off-peak electrical demand
  - Steam diversion in a hybrid system will initiate a reactor transient due to tight coupling of the system – need tools to adequately characterize coupled system response and to optimize operational strategies for transient maneuvers
  - IPWR model will be used to determine electrical and steam energy that can be supplied to the user as a function of time based on weather and electricity demand
  - Control algorithm to apportion energy; user interface to allow selection of energy users and apportionment of energy among them
Model Status

- IPWR model has been extended to allow bypass steam to be diverted to thermal energy storage (TES) applications while maintaining constant reactor power.

- Bypass options include connection points:
  - Upstream of the Turbine Control Valves, allowing approximately constant steam temperature and pressure at steam generator exit conditions.
  - Downstream of the Turbine Control Valves prior to entering the high pressure turbine. 
    *Disadvantage* – Steam conditions are a strong function of the turbine demand.
  - From a tap off the low pressure turbine.
    *Disadvantage* – Steam conditions are a strong function of the turbine demand.

- Coupled simulations have been demonstrated for Sensible Heat TES systems and Chilled Water Storage.
Sensible Heat TES System Design
(Connection at Pressure Equalization Header)
Model Status

- Charging simulation for a typical summer day with approximately 30% variation in turbine load over 24 hour period
- Control strategies implemented to maintain reactor thermal output at essentially constant levels
- Bypass flow directed to TES system (inverse of turbine load)
- Charging mode models complete
- Discharge mode models currently under development
- mPower-sized forced circulation IPWR model demonstrated
- NuScale-sized natural circulation IPWR model in final stages of testing
- Abstract accepted for June ANS Embedded Topical Meeting in San Francisco
Development of Modeling and Simulation Tools – Storage Systems (NCSU – S. Terry)

• Modeling of candidate energy storage systems
  – High pressure steam accumulators for storage of primary reactor steam
  – Low pressure steam accumulators for storage of process steam
  – Hot water storage for process or HVAC applications
  – Chilled water generation and storage for process or HVAC applications
  – Compressed air storage for us in process and in combustion gas turbine generators

• Goal is to optimize the energy use mix while operating the reactor at steady state

• Simulated electrical and thermal demand profiles selected based on typical industrial and military customers

• Various control strategies employed to determine control hierarchy and storage mix to produce the most economically viable system
Model Status

• Chilled Water Storage
  – Electric Chiller and Storage Models – COMPLETE
  – Absorption Chiller Model – COMPLETE
  – Integration with m-Scale Model – COMPLETE

  – Absorption chiller has been modeled using two methods:
    • Low fidelity model for typical operating conditions with slow moving reactor power / flow / pressure
    • High fidelity model that captures all of the physics
      → Very long run time, so this will be used for transient analyses

  – Major issue being explored is how reactor load affects pressure and valve capacity; negatively affects chiller capacity at relatively high partial loads
Chilled Water Storage Model Status

- Model runs are being made to conduct parametric analyses and to model different events, such as reactor ramping and emergency conditions.
- Chilled water system is too small for mPower-sized reactor.
- Model being coupled to smaller NuScale-sized reactor model just finished by Doster.

Reporting:
- 1 paper published in *ASME Journal of Energy Resources & Technology*
- 1 abstract accepted for June ANS Meeting in San Francisco.
- 1 paper in progress for *International Journal of Refrigeration*.
- Corey Mienheimer anticipated to finish the PhD later this summer.
Energy Storage Model Status

- **Compressed Air Storage**
  - Fola Odeniyi has completed her MS thesis on compressed air storage
  - May pick work up with new PhD student in the fall as we integrate storage technologies

- **Steam Accumulators**
  - Tucker Daniels continues his work, hoping to finish MS later this summer
  - Accumulator model is complete
  - Model has not been connected with SMR model yet
  - Anticipate some of the same issues with pressure as seen for the absorption chiller
Key Publications & Theses – NCSU


Current Status: Oregon State
Experimental Validation of Simulation Tools (OrSU – Q. Wu)

- Multi-Application Light Water Reactor (MASLWR) test facility
  - 1/3 height scale NuScale model, capable of simulating steady state and accident transients
  - Steady operation (natural circulation) at various core powers
  - Transition from one steady operation to another at different power levels
  - Loss of feed water accident, including reactor blowdown, containment condensation, and cooling pool heat exchange

Objectives:
- Process and transmit IAEA ICSP data, gathered at MASLWR in 2010, to research team
- Develop RELAP5-3D model of MASLWR for load-following and other studies
- MASLWR Modified Scaling
  - Original MASLWR scaling is only for accident conditions
  - Develop full power steady state scaling parameters to run load-following simulations
MASLWR Modified Scaling

• Purpose
  – Find the relation between power of a prototypic system and the existing model system
  – “Reverse scaling” effort for use of legacy data (ICSP)

• Re-scaling method
  – MASLWR was scaled to reduced power, not full power
  – Full power operations need a separate set of scaling parameters
  – All physical properties of the test facility are fixed
  – Assumptions:
    • Single-phase liquid flow
    • Fluid property similarity
    • Steady state
    • Incompressible flos
    • Friction scaling factor fixed
    • …
  – Activity completed – see MS Thesis, Kyle Hoover, December 2016
RELAP5-3D Model Description

- Benchmarked against SP-3 data
- Based on a MASLWR model that required further adjustments
- Contains all MASLWR subsystems
  - Only primary and secondary utilized
  - Other subsystems included, but not benchmarked
- Updated deck based on revised facility description report and mechanical drawings
OSU-MASLWR Work - Conclusions

• New scaling parameters were generated for full power operation of the OSU-MASLWR system

• A RELAP5-3D model was developed and shown to adequately agree with test data
  – Overall flow loss is modeled adequately, but specific flow losses are not modeled well
  – Secondary flow agrees well at times
  – Temperatures agree well

• Future work:
  – Attempt to obtain more accurate form loss factor distribution
  – Compare distortions to original scaling analysis
  – Utilize RELAP model and scaling analysis within the broader project
**Key Publications & Theses – Oregon State**


Current Status: Ohio State
Distributed Test Facility (OhSU – C. Smidts)

- Distributed Test Facility (DTF) Capabilities
  - A test facility that assembles geo-distributed software and hardware components into a prototype cyber-physical control system
  - Test the reliability and performance of digital systems within their possible operational environments
  - DTF Interface manages components, applications and users
  - Current capabilities include NPP Simulator and Steam Generator (SG) hardware-in-the-loop (HIL) setup
  - Future work will include integrating the Online Monitoring System

- Progress
  - NCSU Small Modulator Reactor simulator
    - Efforts to integrate this simulator with the DTF are ongoing
    - Completed training of simulator design and source code layout at NCSU
    - Identified subsystems in the simulator which can be interfaced with the HIL and the subroutines and variables involved with each subsystem
    - Application interface development is under way, leveraging previous work and lessons learned in interfacing the SG HIL test setup and GSE gPWR Nuclear Power Plant full-scale Simulator within the DTF
Online Monitoring System (OhSU – C. Smidts)

• Goal: Design an Online Monitoring (OLM) System to track the impact of system duty cycles on aging, control and reliability of the steam bypass and steam delivery system

• Progress
  – Developed an Integrated System Failure Analysis (ISFA) based OLM system design method; the method is based on the following steps:
    • Define the OLM design criteria, including fault injection stopping criteria and OLM modification criteria
    • Make a preliminary design of the OLM system, including the layout of measurement and control components and maintenance and alarm strategy
    • Construct the ISFA models
    • Inject faults into the system, which includes defining fault location/type/characteristics and fault injection number/time
      – A new valve degradation model has been developed to define fault characteristics, which incorporates usage (frequency of opening and closing) along with natural aging
    • Simulate
    • Identify fault behaviors, including fault propagation paths and fault features
Online Monitoring System (OhSU – C. Smidts)

- **Progress**
  - Developed an ISFA-based OLM system design method (continued)
    - Determine whether faults can be identified by their fault propagation paths; if not, refine the OLM design
    - Complete the final OLM design configuration
    - Obtain a database of all fault behaviors
  - Applied the OLM design method to a simple case study of a holdup tank system; the method performs well on the case study
  - Designed a software tool to simulate fault propagation
  - Applied the OLM design method to the secondary loop of the nuclear power plant for the Nuclear Hybrid Energy System
    - Proposed a preliminary design of the OLM system for the secondary loop
    - Constructed ISFA models of the secondary loop
    - Simulated some fault propagation paths in the secondary loop
    - Future Work: fault feature identification, fault diagnosis, and final OLM system for the secondary loop
Online Monitoring System – Details

**Define the OLM design criteria** (finished)
- Fault injection stopping criteria
- OLM modification stopping criteria
  - Sensor addition stopping
  - Key component reliability refinement stopping

**Preliminary design of the OLM system for the secondary loop** (finished)
- Early design of the secondary loop
  - Function and output requirement
  - Thermal cycle and component selection
  - Input/Output parameters of components
- Early design of the OLM system
  - Measurement and control components
  - Maintenance and alarm strategy

**Construct ISFA model** (finished)
- Component model
- Function model
- Behavioral rules
- Function failure logic

**Fault Injection** (finished)
- Fault property
  - Location, type, parameter
- Fault Injection
  - Number, time

**Final OLM design configuration** (future)
- Final OLM system design
  - Measurement and control components
  - Maintenance and alarm strategy
- Database of all possible fault behaviors

**Fault diagnosis** (future)
- Whether to classify all possible faults
  - If not, whether to modify the OLM design
    - Evaluate fault and cost ranking
    - Identify which sensor & controller we need to add

**Identify fault behaviors** (future)
- Fault propagation paths:
  - Component A → component B → ... → system failure
- Signal feature:
  - Period, mean value, frequency spectrum, Shannon entropy

**Simulate fault propagation** (finished)
- Simulation software tool
  - Simulation result table
  - Measurement & control components signals change table
  - Unobserved signal change expectation table
Online Monitoring System – Details

- Integrated System Failure Analysis Model: (Component & Function)

<table>
<thead>
<tr>
<th>Hardware Component</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steam generator</td>
<td>transfer heat from the primary system into water in the secondary system</td>
</tr>
<tr>
<td>Steam turbine</td>
<td>use thermal energy to do mechanical work</td>
</tr>
<tr>
<td>Condenser</td>
<td>convert steam from its gaseous to its liquid state</td>
</tr>
<tr>
<td>Pump</td>
<td>moves fluids by mechanical action; increase the pressure of fluids</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Software Component</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Configuration Manager</td>
<td>Initialize the system</td>
</tr>
<tr>
<td>Sensor</td>
<td>Read value; Calculate/store value</td>
</tr>
<tr>
<td>Valve Controller</td>
<td>control valves based on valve control logic</td>
</tr>
</tbody>
</table>
Online Monitoring System – Details

- Fault propagation simulation and preliminary fault diagnosis result:
  - At t=6, inject a pipe leak (F1-P11 Leak)
  - F1 propagation path: pipe 11 leak → temperature sensor 1 broken → condenser failure → system failure
  - Feature: e.g., the open-close cycle of the steam bypass valve, and features can be imported to database
Key Publications & Theses – Ohio State


- Guo, Q., 2015, *A Distributed Test Facility for Cyber-Physical Systems*, Ph.D. Dissertation, Department of Mechanical and Aerospace Engineering, Ohio State University, Columbus, Ohio, August 2015. (submission to STIMS pending patent application)

- Zhu, M., 2016 *Design of an Online Monitoring System for Degrading Hardware Components Using Failure Modes and Effects Analysis*, Undergraduate Honors Thesis, Department of Mechanical and Aerospace Engineering, Ohio State University, Ohio, April 2016.


OVERVIEW OF MULTI-YEAR MILESTONES
Milestone Summary: Year 1

- Complete letter report on basic storage system performance (NCSU)
- Deliver compiled data from the OrSU MASLWR facility (OrSU)
- Complete LMFR NACC model with thermal energy storage (UNM)
- Submit annual project status report (INL)
Milestone Summary: Year 2

- Complete MASLWR RELAP5 models (NCSU/OrSU)
- Complete on-line monitoring system design (OhSU)
- Deliver the distributed test facility application interfaces for the involved systems (OhSU)
- Submit annual project status report (INL)
Milestone Summary: Year 3

- Deliver modules and associated documentation for reactor, balance of plant and storage systems (NCSU)
- Compile RELAP5 analysis results for MASLWR experiments (OrSU)
- Deliver prototype on-line monitoring system and related algorithms for steam bypass and steam delivery systems (OhSU)
- Complete system testing within the distributed test facility (OhSU)
- Submit final project report (INL)
Follow-on Proposals Submitted

  - Partners: INL, Ohio State, North Carolina State
  - Would leverage a joint appointment with C. Smidts at OhSU
- Overall objective
  - The proposed research will provide a novel, automated cyber-security evaluation method for complex energy systems based on three-level hierarchical models...
  - The methodology will integrate data from different entities within the HES that influence cyber-security, leading to a systematic approach for defending against security risks at the early stages of the system development lifecycle.
- Proposal status: Neither funded, nor rejected...
- Key feedback:
  - Almost all feedback from reviewers was positive.
  - Weakness: “A great deal of the funded work happens at the universities. INL could more greatly benefit from this research effort through involving more of our researchers.”
  - Overall committee response: “This proposal is strategically aligned with N&HS’s… This LDRD is of high priority for funding… N&HS recommends this proposal for funding as resources become available and prioritization of proposals are completed.”
Additional Items of Note

- Shannon Bragg-Sitton approved as Adjunct Professor, Department of Nuclear Engineering, North Carolina State University, October 2016 – September 2019
- Shannon Bragg-Sitton approved as School of Nuclear Science and Engineering, Courtesy Faculty, rank of Assistant Professor, Oregon State University, November 2016 – November 2020
- Establishing Joint Appointment for Carol Smidts, Ohio State University