System Analysis Module (SAM)

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A practical plant-level system analysis tool for advanced reactors (SFR, LFR, MSR/FHR);

Advances in software environments and design, numerical methods, and physical models;

Flexible multi-scale multi-physics integration with other high-fidelity tools.
Development Approach

- Built-on MOOSE framework and other modern software libraries
  - Advanced solution methods
- Modern code development practice
  - Object-oriented C++ code
  - Modular, easy to develop and incorporate new capabilities
  - Designed for easy code reuse and code maintenance;
- Component based development
  - User friendliness
- Flexible for coupling with other M&S tools for multi-scale multi-physics modeling.
Robust and high-order FEM model of single-phase fluid flow and heat transfer has been developed and verified;

Component-based code development and system modeling;

Flexible coupling capability between fluid and solid components enables a wide range of engineering applications;

Closure Model Enhancements.
In-Vessel Spent Fuel Storage design relies on natural convection and conduction to remove the decay heat in the spent fuel assemblies.

SAM is uniquely suitable due to its flexibilities, accuracies and efficiency for modeling the conjugate heat transfer and natural circulation.

Heat transfer to all major solid structures must be modeled, including the assembly duct wall, the core barrel, the IVS shroud, and the core shielding.

Timely analysis assured the safety of the spent fuel storage, also avoided the potential design changes of the IVS.
SAM Core Modeling Options

- **Single-Channel Modeling**
- **Multi-Channel Modeling**
  - Enabled by flexible fluid-solid CHT model in SAM;
- **Flexible Full Core Modeling**
  - HexLatticeCore component developed for SFR core modeling;
  - Automatically generate the core lattice (Multi-Channel or Single-Channel), and inter-assembly structures based on simple inputs.
7-Assembly demonstration problem with high power Assembly 0, and low power Assembly 6

- The six sides of the hexagon duct wall of one assembly are modeled separately;
- Multi-channel assembly model is used;
- Very good agreement with CFD results, while the computational cost is reduced by 5-6 orders of magnitude.

CFD results of duct wall temperature distributions

Average axial and radial wall temperature distributions
Objectives: Model the multi-dimensional flow and thermal stratification phenomena in large enclosures (outlet plena) for reactor safety analysis.

- Multi-dimensional conversation equations on a coarse mesh;
- No turbulence modeling;
- Developing closure models for inter-cell interaction and wall frictions;
- Additional diffusive term in the energy equation to account for the turbulence effects and the use of coarse mesh.

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0
\]

\[
\frac{\partial (\rho \vec{v})}{\partial t} + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla p + \nabla \cdot \vec{t} + \rho \vec{f}
\]

\[
\frac{\partial (\rho h)}{\partial t} + \nabla \cdot (\rho h \vec{v}) = \nabla \left( k_{eff} \nabla T \right) + q'''
\]

\[
\rho = \rho(p, \beta T)
\]
Preliminary Results from Verification Tests

- Test Problem: natural convection in a square cavity
  - Fixed temperatures on left and right walls; adiabatic top and bottom walls;

\[ Ra = 1.0 \times 10^5 \]

Normalized temperature distributions,
\[ Ra = 1.89 \times 10^5, \ Y/L = 0.5 \]
Multi-Physics Multi-Scale Integration

- Flexible multi-scale multi-physics integration through coupling with other M&S tools
- Coupling with CFD codes
  - STAR-CCM+
  - Nek5000 (under development)
- Integration with SAS4A/SASSYS-1
  - Joint collaboration between DOE-NE’s ART and NEAMS programs
- Planned Additional Coupling
  - PROTEUS
  - SHARP/SAM/Bison/Workbench
Enhancements for MSR/FHR modeling

- Engagements with FHR IRPs under DOE-NE’s NEUP program
  - FHR system T/H modeling
  - Code benchmarks
- NEUP project on salt freezing modeling
  - 1D freezing module in SAM
- Argonne LDRD project on MSR modeling
  - Radiation heat transfer
  - Liquid fuel transport in the primary loop
  - Additional closure models for salt fluid

SAM Model of PB-FHR DRACS

(Work performed by K. Ahmed (UWM) under the support of NEUP fellowship)
Following QA and verification approaches used by MOOSE and MOOSE-based applications.
- Continuous development with version control
- Unit testing
- Line coverage

Over 150 test problems have been developed and included in the regression test suite

Software Verification
- Regression, Benchmark Tests, and Bug Reporting
- Documentation
- Verification with Analytical Benchmarks
- Verification with Code-to-Code Comparison

Software Validation
- Unit, Component, Subsystem, System, Integral tests
- Validation Matrix and Gaps
- EBR-II, FFTF, CIET, etc.
SAM User Engagements

- **Usage**
  - Availability/Computational resource
  - Input syntax/GUI

- **Limited distribution only**
  - Non-Disclosure Agreement
  - Special agreement with universities;
  - Users: UWM, OSU/UM, ORNL/PSU, Oklo Inc. etc.

- **Free open-source license planned for STH (pipe-network) simulation capabilities**

- **Training/Tutorial**

- **Internal use at Argonne**
  - KAERI SPP on PGSFR design
  - DOE programs: ART, AFC
Ongoing and Future Work

- Reduced-order model for thermal-stratification
- Enhancements for MSR/FHR modeling
  - NEUP project on salt freezing modeling
  - LDRD project on MSR modeling
- Continued capability enhancements and V&V
  - Additional Component models
  - User experience (usability)
  - Benchmark with FFTF and other IET tests
- Multi-scale multi-physics coupling with other M&S tools
  - SAM/SAS
  - SAM-Nek5000, SAM-PROTEUS
  - SHARP/SAM/Bison/Workbench
References:


Thank you for your attention!

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Questions?
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[Components]

... 

[./core]
  type = HexLatticeCore
  position = '0 0 0'
  orientation = '0 0 1'
  n_side = 2
  assem_pitch = 0.14598
  assem_Dft = 0.13598
  assem_layout = 'F1 F1 F1 F1 F1 F1 F1 F1 F1'
  radial_power_peaking = ' 1 1 1 1.5 1 0.5'
  ref_hs = reference_hs
  ref_duct = duct_wall

[../]

[./F1]
  type = MultiChannelRodBundleParameters
eos = eos
  n_channel = 2
  n_side = 9
  pin_diameter = 8e-3
  wire_diameter = 0
  pin_pitch = 9.04e-3
  length = 0.8128
  n_elems = 20
  dim_hs = 2
  name_of_hs = 'fuel gap clad'
  Ts_init = 638.15
  n_heatstruct = 3
  width_of_hs = '0.003015 0.000465 0.00052'
  elem_number_of_hs = '2 1 1'
  material_hs = 'fuel-mat gap-mat clad-mat'
  power_shape_function = ppf_axial
  beta = 0.01

[../]

...
- Review, select, and implement a set of thermal-hydraulic closure models
  - Focused on heat transfer and friction correlations
  - Sodium, simple fluoride salt and air EOS models
- Interactions with IAEA NAPRO Coordinated Research Project
- Selection criteria and points of consideration:
  - Fluid type (sodium) and flow geometry examined
  - Applicable flow regime and geometric ranges
  - Uncertainty of correlation
  - Model complexity / user-accessibility
  - Popularity amongst system code users
  - State-of-the-art investigation
- Verified with unit test problems
- Initial study on the effects of closure models in SFR safety analysis
- Phenomena Identification
- Software Verification
  - Regression, Benchmark Tests, and Bug Reporting
  - Documentation
  - Verification with Analytical Benchmarks
  - Verification with Code-to-Code Comparison
- Software Validation
  - Unit, Component, Subsystem, System, Integral tests
  - Validation Matrix and Gaps
- Schedule and Priorities
Demonstration of SAS/SAM Coupling

ABTR Model

Power and Flow during ABTR ULOF

Reactivity Feedback Effects