EXPERIMENTAL ACTIVITIES FOR GSI-191

Department of Nuclear Engineering, Texas A&M University

INTRODUCTION

Generic Safety Issue 191 (GSI-191), "Assessment of Debris Accumulation on PWR Sump Performance", can be categorized into the head loss through a debris bed on the strainer (the upstream effect) and the debris penetration through the strainer (the downstream effect). Texas A&M University (TAMU) has constructed test facilities and been performing experimental activities to understand and resolve the both effects. Also, TAMU has developed techniques to characterize the debris size distribution, from nanometers to macro size (millimeters). TAMU is modifying the facilities to conduct chemical experiments to analyze the effect of chemicals on head loss and debris penetration.

RESEARCH OBJECTIVES

- **Head loss** and **Debris Bypass** through the fibrous bed generated on strainers
- **Effects** of fluid **temperature** and approach **velocity** on head loss and debris bypass
- **Effects** of additional **chemicals** and **particles** on head loss and debris bypass
- **Water chemistry** effects on debris Bypass
- **Characterization of debris size distribution**
- **Thermal-hydraulic calculation** to provide the containment and primary system condition using RELAP5-3D and MELCOR.

EXPERIMENTAL FACILITIES

- High Temperature Vertical Loop - 185 ˚F (85 ˚C), 6" ID Test Section
- High Temperature Horizontal Loop - 185 ˚F (85 ˚C), 4" ID Test Section
- Low Temperature Horizontal Loop - 113 ˚F (45 ˚C), 4" ID Test Section
- Debris Size Characterization Systems - nanometers to millimeters
- Chemical Analysis Systems - XRD, XRD, ICP-MS, XPS, and NMR

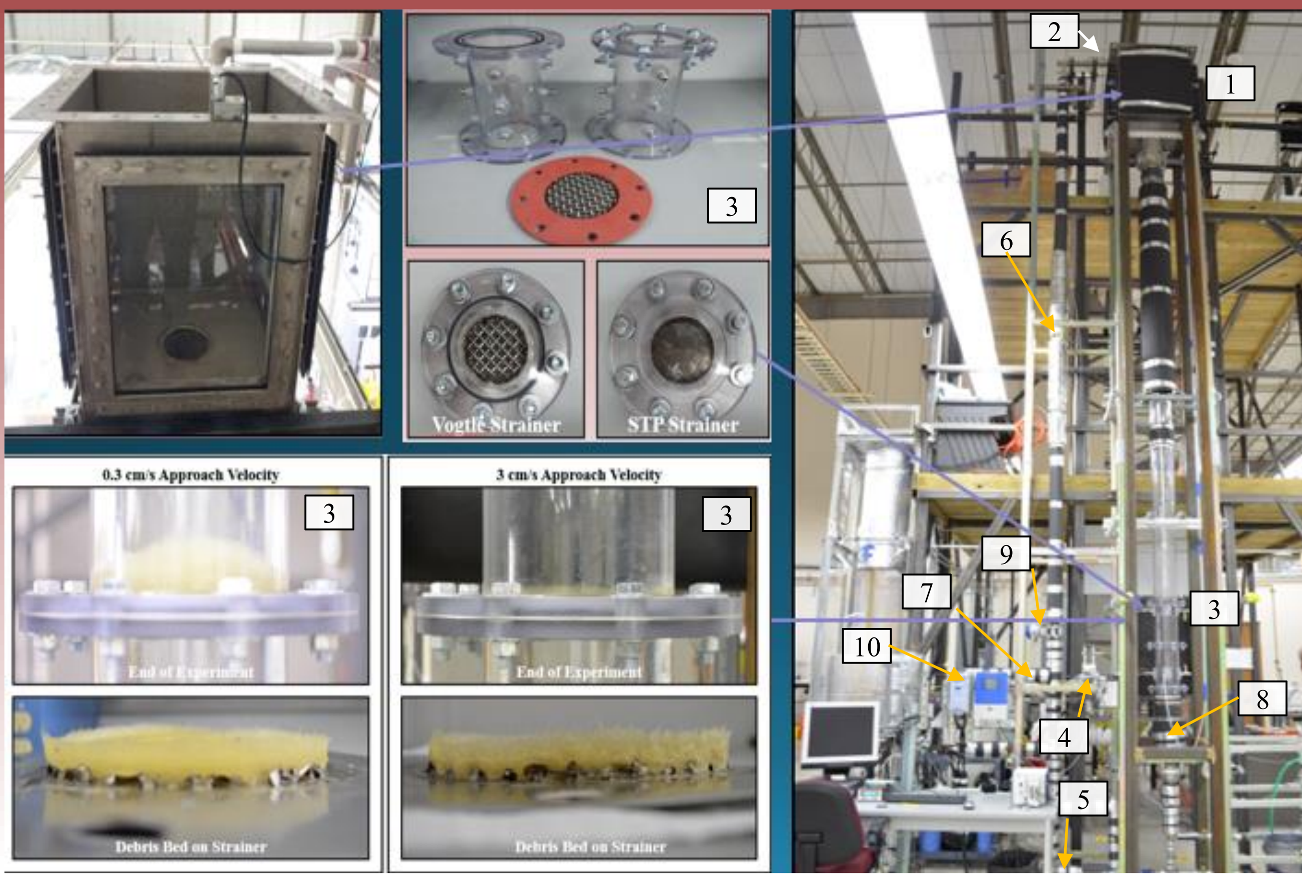
PUBLICATIONS

- Lee, S., Hassan, Y. A., Abdulsattar, S. S., & Vaghetto, R. (2014). Experimental study of head loss through an LOCA-generated fibrous debris bed deposited on a sump strainer for Generic Safety Issue 191. *Progress in Nuclear Energy*, *74*, 166-175.
- Saya Lee, Yassin A. Hassan, Rodolfo Vaghetto, Suhaeb Abdulsattar, Matthew Kappes, "WATER CHEMISTRY SENSITIVITY ON FIBROUS DEBRIS BYPASS THROUGH A CONTAINMENT SUMP STRAINER," Proceedings of the 2014 22nd International Conference on Nuclear Engineering,ICONE22,July 7-11, 2014, Prague, Czech Republic
- Saya Lee, Suhaeb Abdulsattar, Yassin A. Hassan, " HEAD LOSS THROUGH FIBROUS BEDS GENERATED ON DIFFERENT TYPES OF CONTAINMENT SUMP STRAINERS," Proceedings of the 2014 22nd International Conference on Nuclear Engineering,ICONE22,July 7-11, 2014, Prague, Czech Republic
- Serdar Ozturk, Xinrui Ma, Yassin A. Hassan, "Rheological Characterization of Buffered Boric Acid Aqueous Solutions," ANS Winter Meeting, Nov. 10-14, 2013, Washington D.C., U.S.A

EXPERIMENTAL ACTIVITIES FOR GSI-191

Department of Nuclear Engineering, Texas A&M University

High Temperature Vertical Loop for Measurement of Head Loss and Debris Bypass



#	COMPONENT	#	COMPONENT	#	COMPONENT
1	Water Tank	5	High Temperature Pump	9	Magnetic Flow Meter
2	Mixing Propeller	6	External Heaters	10	Control Panel
3	Test Section (6” ID)	7	Heating Loop		
4	Pressure Transducer	8	1µm Filter		

CAPABILITIES

- Approach Velocity: 0.005 ~ 0.5 ft/s
- Temperature: 185 °F (85 °C)
- Different Strainer Types Applicable
- Dynamic and Integral Debris Sampling
- Facility Components Chemical-resistant

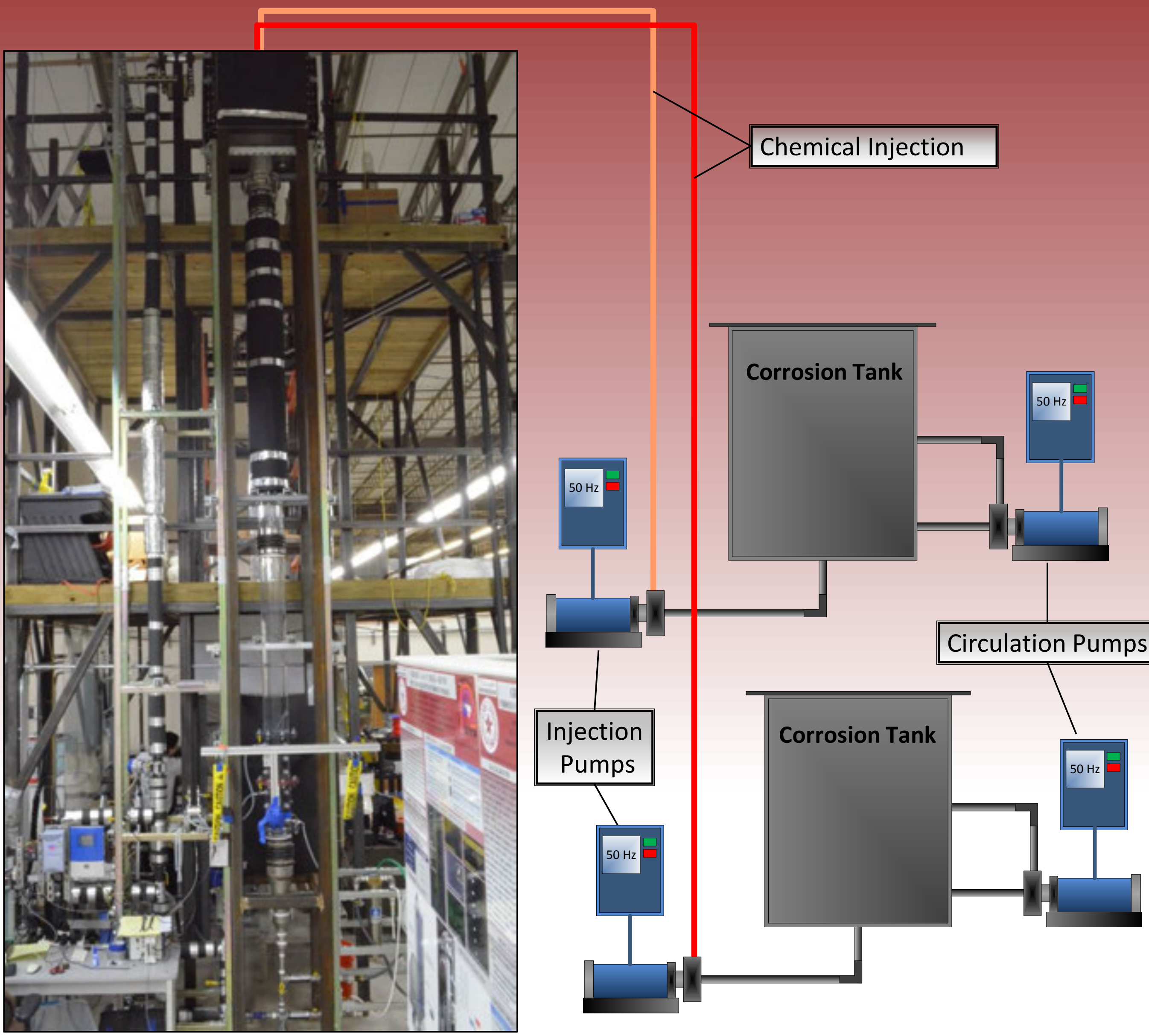
PUBLICATIONS

- Lee, Saya, Yassin A. Hassan, Suhaeb S. Abdulsattar, and Rodolfo Vaghetto. "Experimental study of head loss through an LOCA-generated fibrous debris bed deposited on a sump strainer for Generic Safety Issue 191." *Progress in Nuclear Energy* 74 (2014): 166-175.
- Saya Lee, Suhaeb Abdulsattar, Rodolfo Vaghetto, Yassin A. Hassan, “Experimental Study Of Fibrous Debris Head Loss Through Sump Strainer,” Advances in Thermal Hydraulics (ATH '12), November 11-15 2012, San Diego, CA.

EXPERIMENTAL ACTIVITIES FOR GSI-191

Department of Nuclear Engineering, Texas A&M University

Head Loss & Chemical Effects Experiment Facility



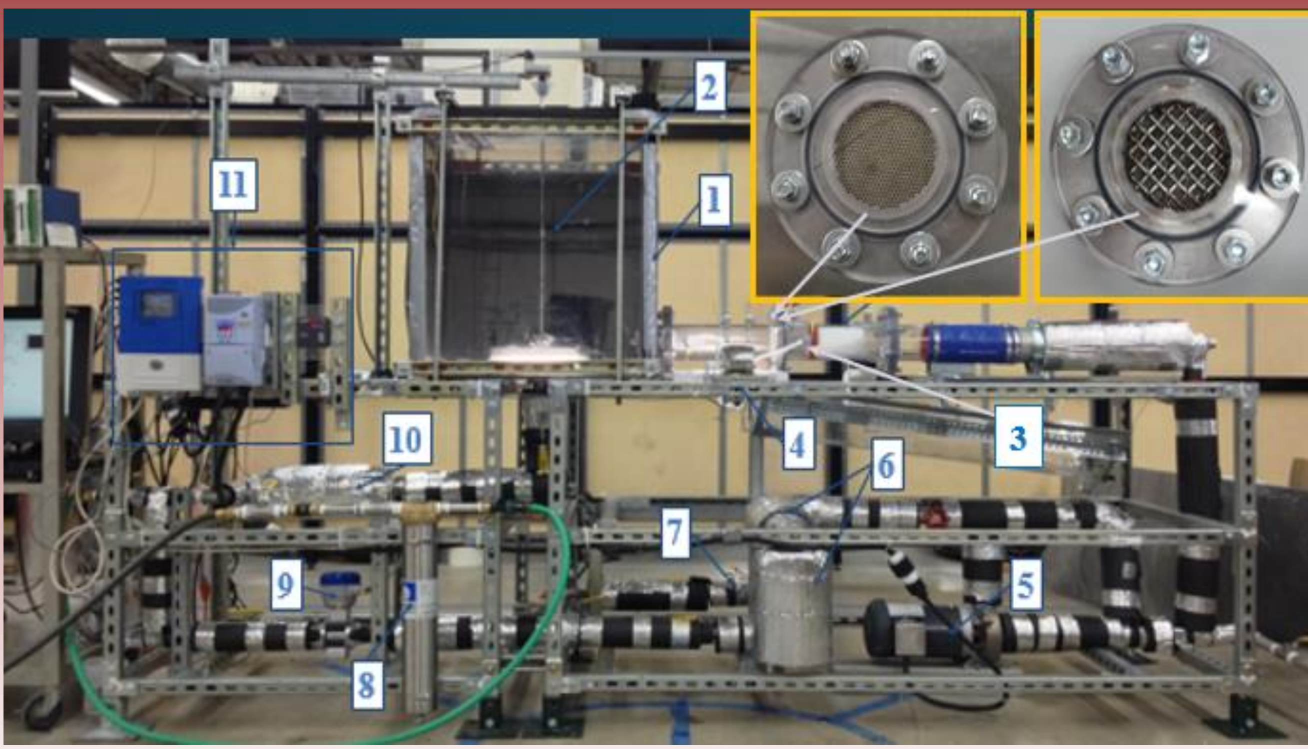
CAPABILITIES

- Includes all the capabilities of the high temperature vertical loop
- Measurements of head loss through fibrous and particulate debris beds
- Chemically-induced head loss evaluation
- High accuracy pressure drop instrumentations for different pressure ranges
- Corrosion tanks can be connected to the horizontal loop (see next slide)

EXPERIMENTAL ACTIVITIES FOR GSI-191

Department of Nuclear Engineering, Texas A&M University

High Temperature Horizontal Loop for Measurement of Head Loss and Debris Bypass



#	COMPONENT	#	COMPONENT	#	COMPONENT
1	Water Tank	5	High Temperature Pump	9	Magnetic Flow Meter
2	Mixing Propeller	6	External Heaters	10	Temperature Control Heater
3	Test Section (4” ID)	7	Heating Loop	11	Control Panel
4	Pressure Transducer	8	1μm Filter		

CAPABILITIES

- Approach Velocity: 0.005 ~ 0.5 ft/s
- Temperature: 185 °F (85 °C)
- Different Strainer Types Applicable
- Dynamic and Integral Debris Sampling
- Facility Components Chemical-resistant

PUBLICATIONS

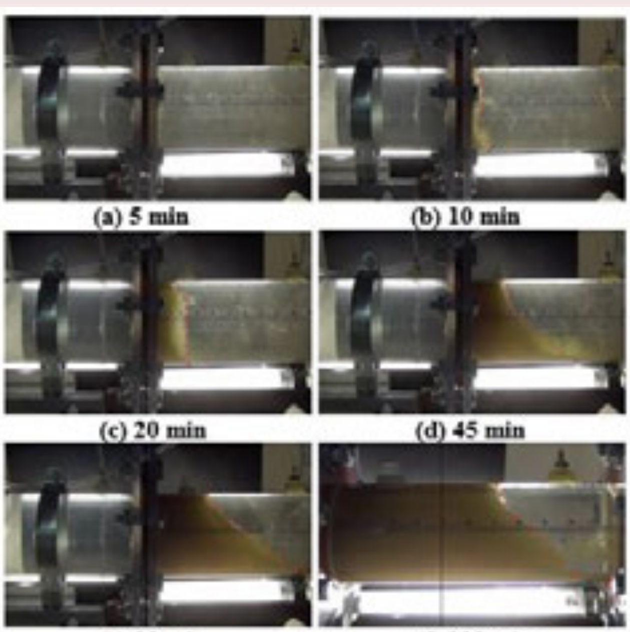
- Saya Lee, Yassin A. Hassan, Rodolfo Vaghetto, Suhaeb Abdulsattar, Matthew Kappes, "WATER CHEMISTRY SENSITIVITY ON FIBROUS DEBRIS BYPASS THROUGH A CONTAINMENT SUMP STRAINER," Proceedings of the 2014 22nd International Conference on Nuclear Engineering,ICONE22,July 7-11, 2014, Prague, Czech Republic
- Saya Lee, Rodolfo Vaghetto, Yassin A. Hassan, “Measurement of Water Chemistry Sensitivity on NUKON Fibrous Debris Penetration through a Sump Strainer,” Risk Management for Complex Socio-Technical Systems (RM4CSS), November 11-15, 2013, Washington, D.C.

EXPERIMENTAL ACTIVITIES FOR GSI-191

Department of Nuclear Engineering, Texas A&M University

Low Temperature Horizontal Loop for Measurement of Head Loss and Debris Bypass

#	COMPONENT	#	COMPONENT	#	COMPONENT
1	Water Tank (~ 200 liters)	4	Centrifugal Pump	7	Mixing Propeller
2	Test Section (4” ID)	5	Flowmeters (3%, 5% F.S)	8	Data Logger
3	Pressure Transducer (+/- 6 Pa)	6	Cameras	9	Strainers



(a) 5 min (b) 10 min (c) 20 min (d) 45 min (e) 90 min (f) 900 min

Build-up of fibrous debris bed on the strainer, at U = 0.52 cm/s

CAPABILITIES

- Approach Velocity: 0.005 ~ 0.1 ft/s
- Temperature: 113 °F (45 °C)
- Strainer Exchangeable
- Dynamic Debris Sampling
- Chemical Resistance

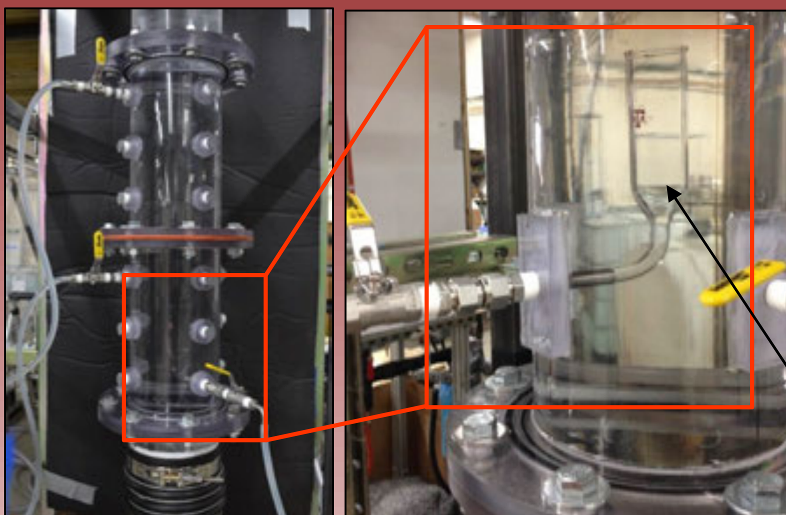
PUBLICATIONS

- Lee, Saya, Yassin A. Hassan, Suhaeb S. Abdulsattar, and Rodolfo Vaghetto. "Experimental study of head loss through an LOCA-generated fibrous debris bed deposited on a sump strainer for Generic Safety Issue 191." *Progress in Nuclear Energy* 74 (2014): 166-175.
- Saya Lee, Suhaeb Abdulsattar, Rodolfo Vaghetto, Yassin A. Hassan, “Experimental Study Of Fibrous Debris Head Loss Through Sump Strainer,” Advances in Thermal Hydraulics (ATH '12), November 11-15 2012, San Diego, CA.

EXPERIMENTAL ACTIVITIES FOR GSI-191

Department of Nuclear Engineering, Texas A&M University

Debris Sampling and Size Characterization

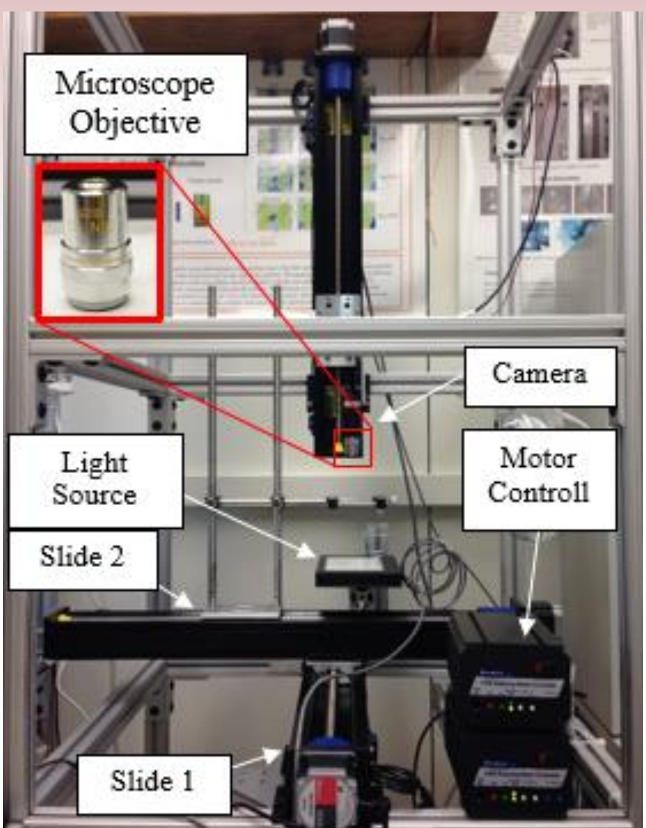


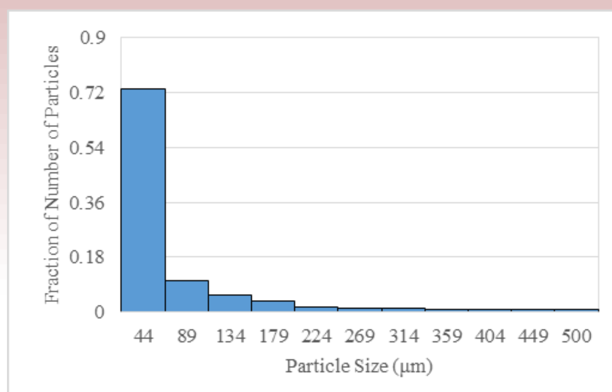
DYNAMIC SAMPLING

The sampling port installed downstream of the strainer allows dynamic sampling at the same flow speed without disturbing the flow, which is known as isokinetic sampling.

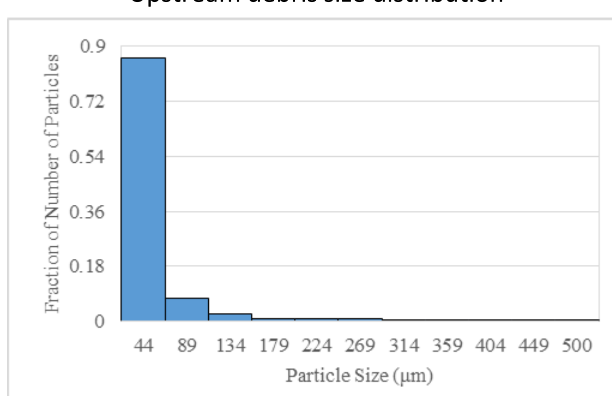
Isokinetic Sampling Probe

SIZE CHARACTERIZATION





Upstream debris size distribution



Downstream debris size distribution

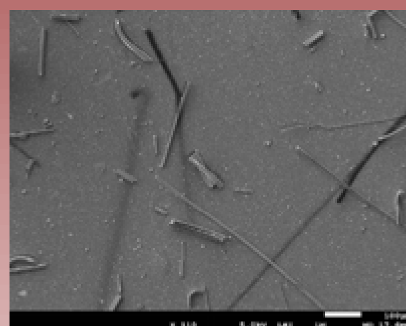
EXPERIMENTAL ACTIVITIES FOR GSI-191

Department of Nuclear Engineering, Texas A&M University

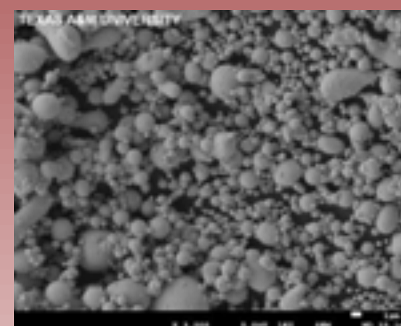
Submicron Size Characterization Capabilities

SEM

- Magnifications up to 1,000,000x
- Guaranteed resolution: 1 nm.



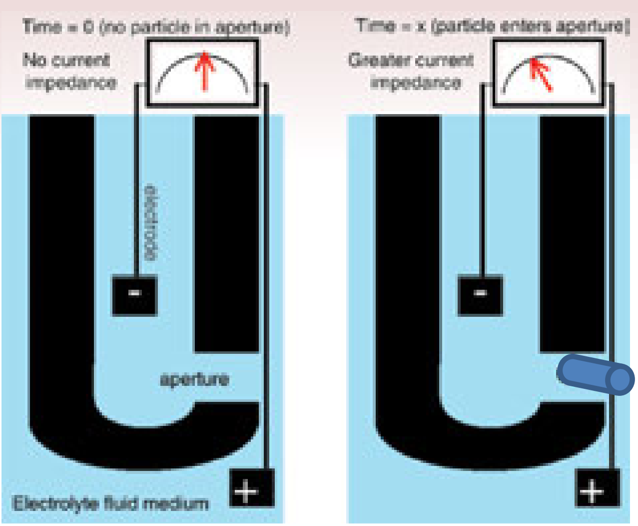
NUKON debris

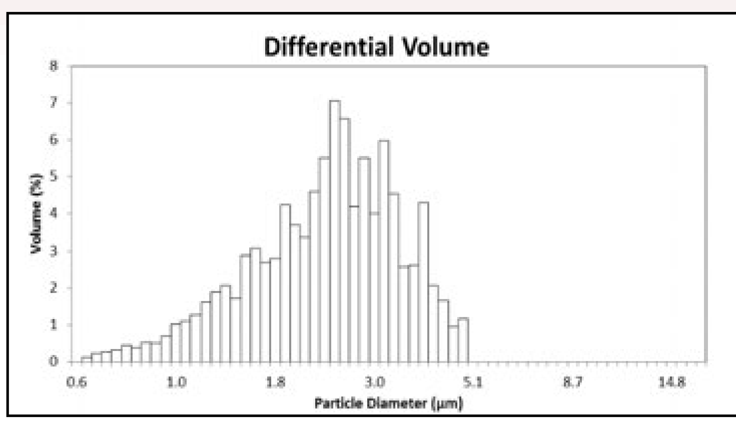


Tin particles

Using ESZ

Electronic Sensing Zone (ESZ) technique





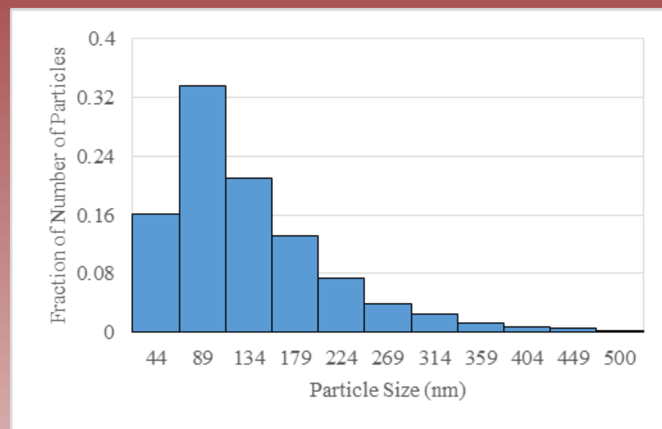
EXPERIMENTAL ACTIVITIES FOR GSI-191

Department of Nuclear Engineering, Texas A&M University

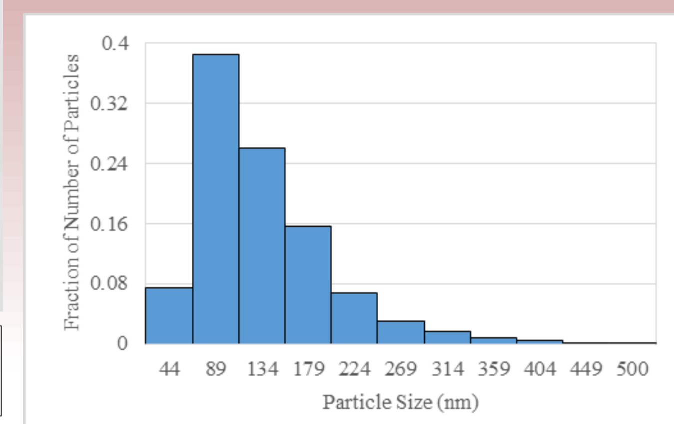
Nano-Size Characterization Capabilities

NANOSIGHT

- Size resolution: 2nm
- Range: 2 – 1000 nm

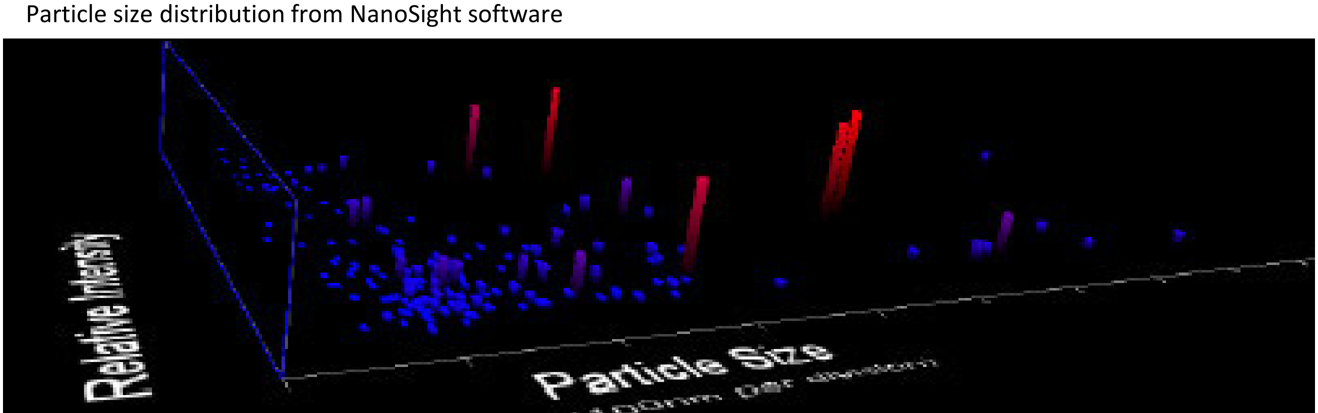


Upstream debris size distribution



Downstream debris size distribution

Particle size distribution from NanoSight software

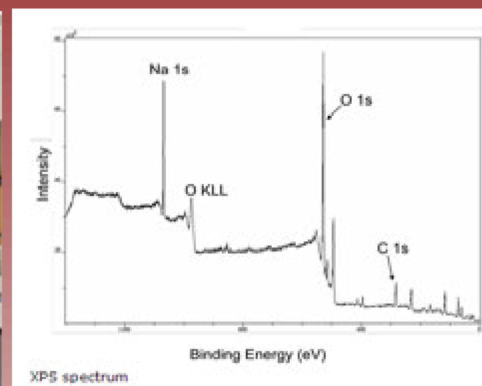


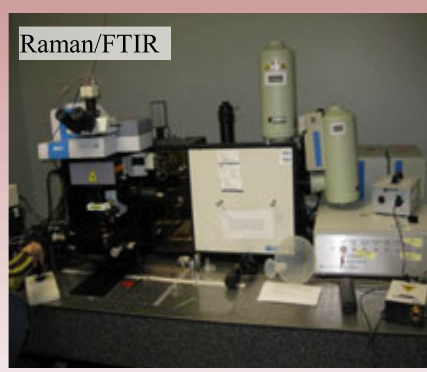
EXPERIMENTAL ACTIVITIES FOR GSI-191

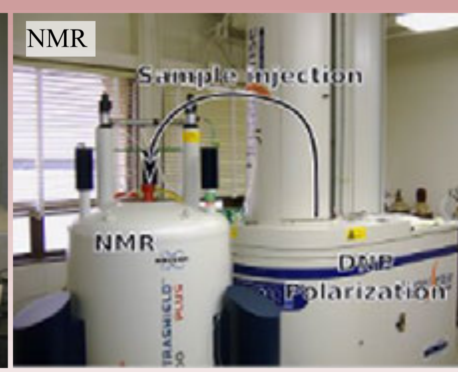
Department of Nuclear Engineering, Texas A&M University

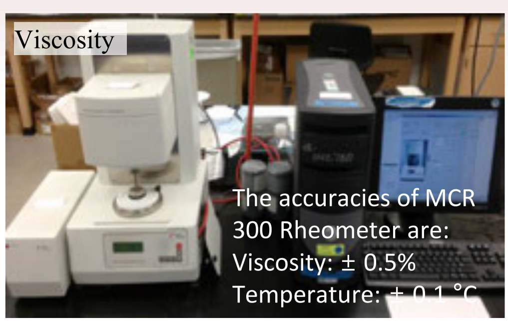
Chemical Precipitate Characterization

Analysis
ICP-OES or ICP-MS (filtered and total)
Particle size distribution
XRD
NMR (B, Al, Si)
TEM
XPS
Viscosity and Turbidity

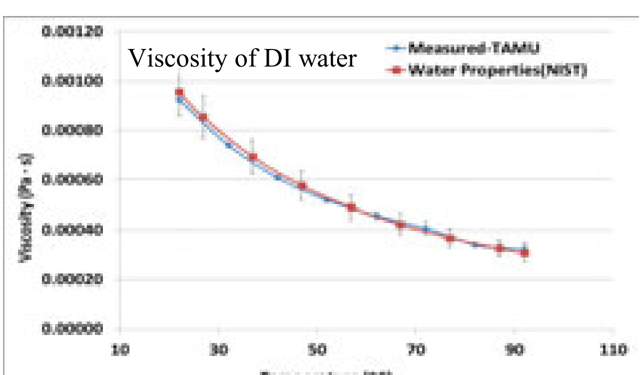


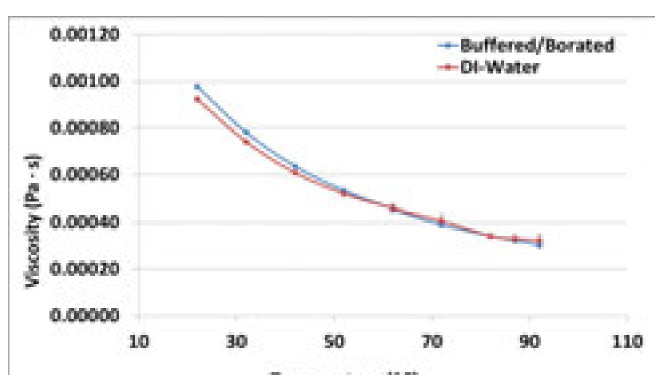






TAMU performed viscosity measurement of buffered borated water with trisodium phosphate or NaOH. The Method was validated by comparing the measured viscosity of deionized (DI) water to the data given by NIST





COMPUTATIONAL ACTIVITY FOR GSI-191

Department of Nuclear Engineering, Texas A&M University

CAPABILITIES

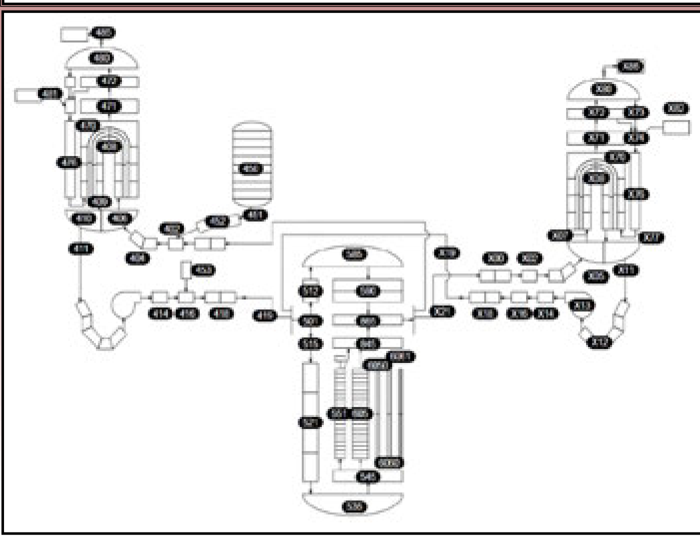
TAMU has developed standardized models of the primary system and reactor containment with system codes largely used in analysis of LWR transients.

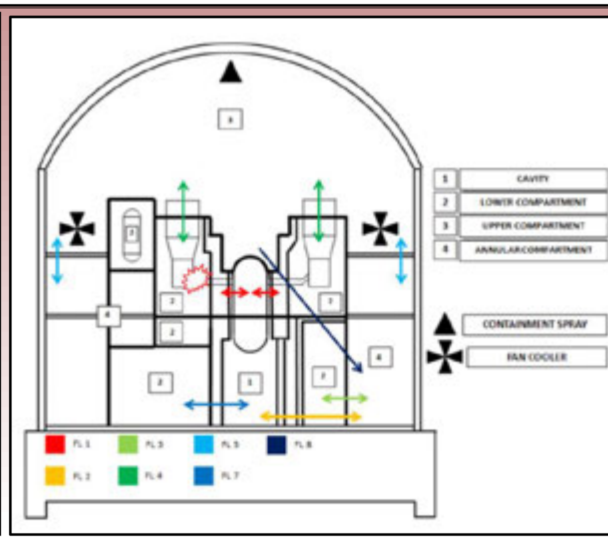
RELAP5-3D models of different US PWRs have been prepared and currently used to perform thermal-hydraulic simulations to support the GSI-191

MELCOR models of reactor containments are being used to perform the simulations of the containment response during LOCA

RELAP5-3D and MELCOR have been linked to perform simultaneous simulations of the primary system and containment response during LOCA scenarios under different plant conditions

Other computational capabilities include Computational fluid Dynamics CFD (Star-CCM+, Neptune, CFX, Fluent), sub-channel codes (COBRA-TF) and other system codes (GOTHIC).





The models developed have been used for:

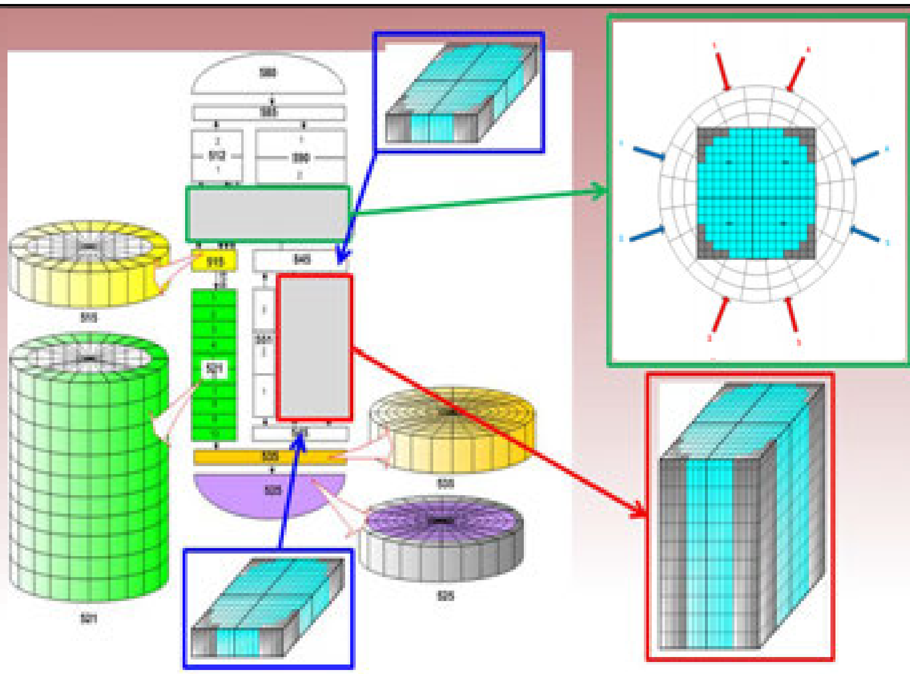
- Predict the system response during LOCA scenarios under hypothetical full or partial core blockage at the bottom of the core;
- Perform sensitivity analysis of the containment response under different plant configurations including:
  - ECCS pumps availability
  - Containment engineered features availability
  - RWST and CCW temperatures
- Estimate the sump pool temperature profiles used for experimental analysis
- Estimate specific thermal-hydraulic parameters (sump switchover time, sump pool temperature, ECCS flow rates, etc.) as a function of:
  - Break size
  - Break location
  - Other plant conditions
- Support the PRA with specific accident scenarios

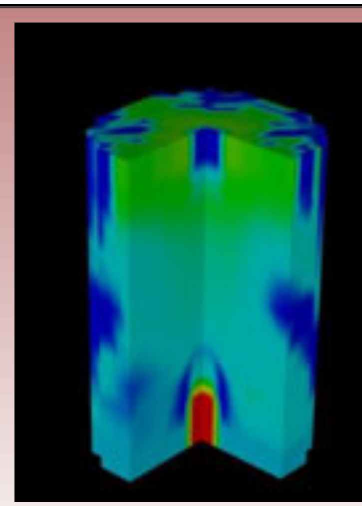
COMPUTATIONAL ACTIVITY FOR GSI-191

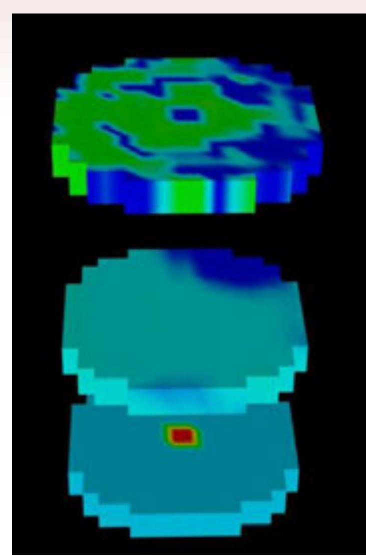
Department of Nuclear Engineering, Texas A&M University

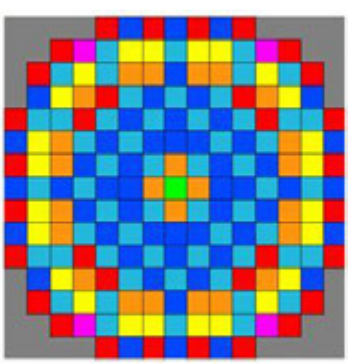
RELAP5-3D MULTI-DIMENSIONAL MODEL

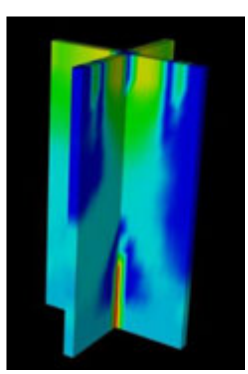
A realistic representation of the vessel internals and reactor core has been achieved using the multi-dimensional capabilities of RELAP5-3D. The model simulated the core with 193 fuel assemblies with cross-flow using Cartesian components, including the capability of defining a realistic radial power profile.
A 3D model of the reactor vessel and core has been developed and used to perform simulations of LOCA transients under different hypothetical core blockages scenarios.
3D Visualization tools were developed to perform 3D animations of thermal-hydraulic parameters of interest, and visualize the flow patters inside the core.

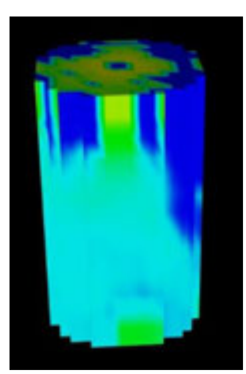












PUBLICATIONS

R. Vaghetto, Y.A.Hassan, “Study of debris-generated core blockage scenarios during loss of coolant accidents using RELAP5-3D,” Nuclear Engineering and Design, 261 (2013) 144– 155

Applications of Computational Fluid Dynamics (CFD)

Department of Nuclear Engineering, Texas A&M University

INTRODUCTION

In the last decade, the Texas A&M University has actively performed the CFD calculations about the nuclear engineering problems.

The nuclear engineering problems considered were

- Two-phase flow (subcooled flow boiling, pool boiling, isothermal two-phase)
- Air-ingress accident in VHTR, Inlet-plenum mixing in VHTR
- Reactor Cavity Cooling System (RCCS)
- Flow in a pebble bed, Flow in a rod bundle
- Debris sedimentation (GSI-191), etc.

CFD CAPABILITIES

Solvers Available

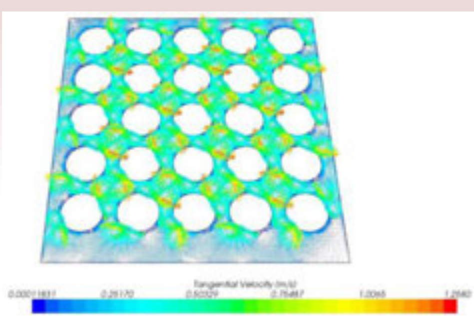
- Commercial CFD codes: ANSYS FLUENT, ANSYS CFX, STAR-CCM+
- Open source CFD codes: OpenFOAM, Code_Saturne, Hydra
- In-house code: Lattice Boltzmann method (LBM) code

CPU Resources

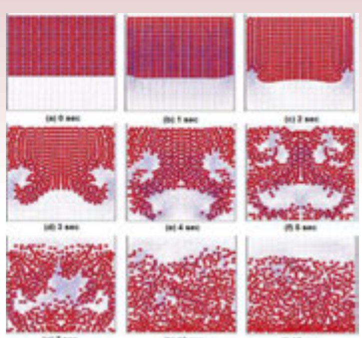
- HPC system- Number of Processing Cores: 3168 (at 2.8 GHz)

APPLICATIONS

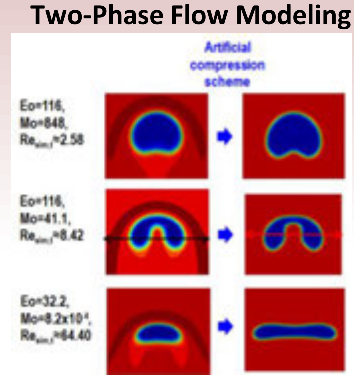
PWR Rod Bundle



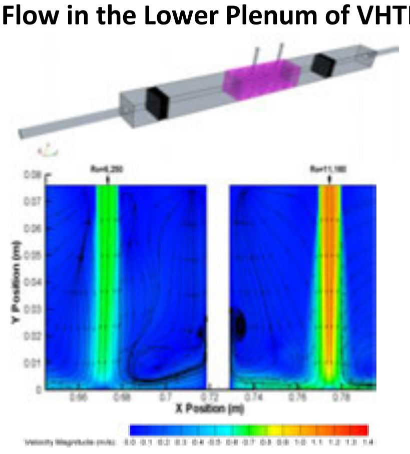
Particle Sedimentation



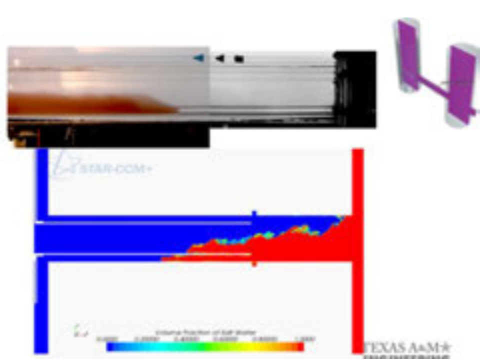
Two-Phase Flow Modeling



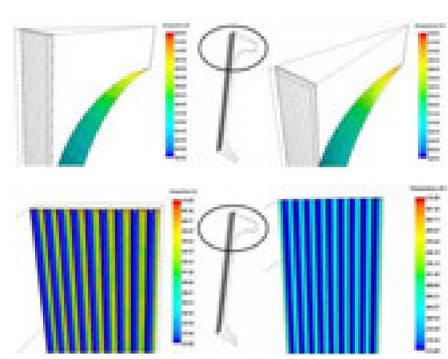
Flow in the Lower Plenum of VHTR



Air-Ingress Accident



Reactor Cavity Cooling System (RCCS)



EPRI CFD Round Robin Benchmark for PWR Fuel Rod Assembly

Department of Nuclear Engineering, Texas A&M University

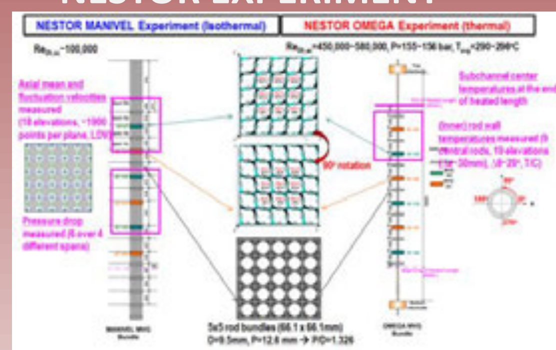
INTRODUCTION

- **In-core crudding risk assessment** requires **local heat transfer** information predicted by **the computational fluid dynamics (CFD)** in a rod bundle.
- The thorough **CFD validation** should precede **the CFD prediction** of the local heat transfer.
- Various CFD methodologies can be effectively compared through **the round-robin benchmark**.
- TAMU has organized and participated in the round robin benchmark against the **NESTOR experiment** since 2011.
- **Ten organizations** participated in the Round Robin.

OBJECTIVES

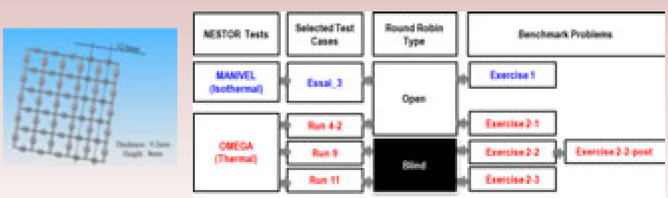
- Benchmark CFD codes to high fidelity experimental data for a rod bundle flow
- Develop the **Best Practices Document** for CFD users that can be applied to in-core crudding risk (CILC, CIPS, etc.) assessments and future assembly and core designs

NESTOR EXPERIMENT

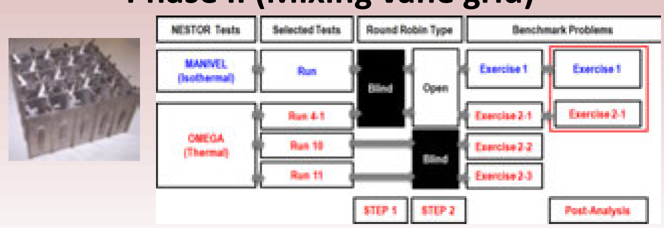


STRUCTURE OF ROUND ROBIN

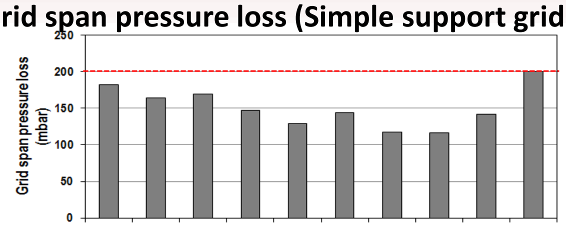
Phase I (Simple Support Grid)



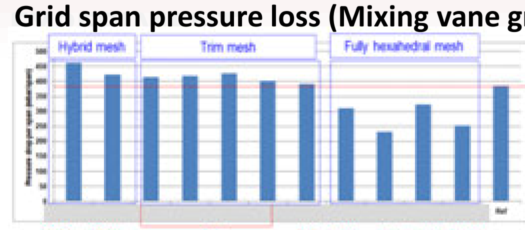
Phase II (Mixing vane grid)



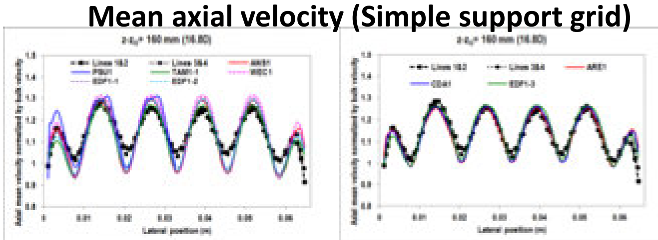
Grid span pressure loss (Simple support grid)



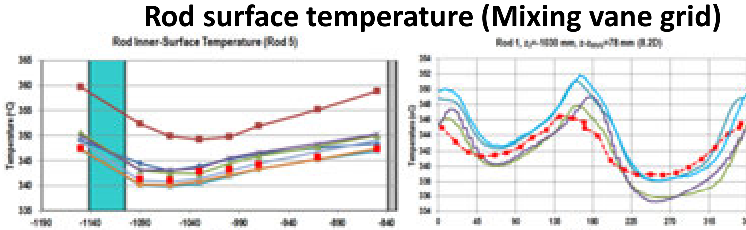
Grid span pressure loss (Mixing vane grid)



Mean axial velocity (Simple support grid)



Rod surface temperature (Mixing vane grid)



PUBLICATION

- S.K. Kang, Y.A. Hassan, “Computational Fluid Dynamics Benchmark of High Fidelity Rod Bundle Experiments: Industry Round Robin Phase 1 – Rod Bundle with Simple Support Grids,” EPRI, Palo Alto, CA:2014.3002000504.

Application of Lattice Boltzmann Method

Department of Nuclear Engineering, Texas A&M University

INTRODUCTION

- **The Lattice Boltzmann Method (LBM)** is a kinetic approach to solving the fluid field as an alternative to Navier-Stokes equation.
- The LBM has some noted features like simplicity, computational efficiency, parallelism, algebraic operation and particle base scheme that distinguishes it from the other conventional CFD methods.
- The in-house LBM code was developed and has been applied to several engineering problems.

CAPABILITIES

Governing Equations

<u>Flow Equation</u>
- **Lattice models:** D2Q9, D3Q19, and D3Q27
- **Collision models:** SRT, TRT, and MRT

<u>Energy Equation</u>
- **D2Q5, D2Q9, D3Q7, D3Q15 thermal LBEs**
- **Hybrid models (Finite-difference Eq.)**

<u>Two-phase flow Equation</u>
- **Cahn-Hillard Eq. (D2Q9, D3Q19)**

Turbulence Models

<u>LES SGS models</u>
- **Smagorinsky model**
- **WALE model**
- **Vreman model (w/ dynamic model)**

Boundary Methods

<u>Mesoscopic boundary method</u>
- Bounce-back scheme (original/modified)
- Bouzidi et al.' scheme
- Yu et al.'s scheme
- Multi-reflection scheme

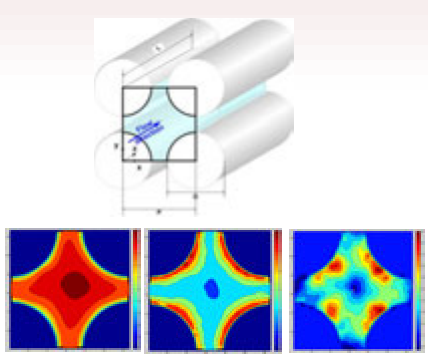
<u>Immersed Boundary Method (IBM)</u>
- **Sharp interface scheme**
  - Linear inter-/extrapolation
  - Bi-/trilinear interpolation
- **Diffuse interface scheme**
  - Implicit / explicit methods
  - 2, 3, 4, 5, and 6-point discrete delta functions

Applications

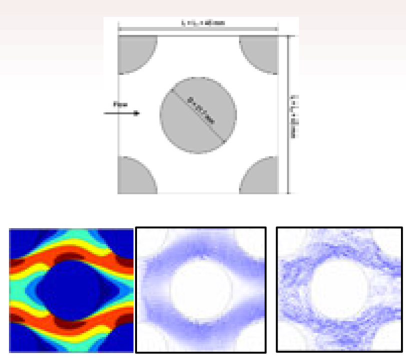
- **Fluid-structure interaction**
  - Inline oscillation
  - Crossflow oscillation
  - Flow induced vibration
    - 1 DOF
    - 2 DOF
- **Particle-fluid flow**
  - 2D cylinder particle sedimentation
    - 1, 2, and 504 particles
  - 3D spherical particle sedimentation
    - 1, 2, 768, and 2048 particles
  - Oblate spheroidal particle sedimentation
  - 3D particle in a circular pipe flow
  - Particle sedimentation with heat transfer
- **(Liquid-vapor) two-phase flow**
  - Static bubble (2D/3D)
  - Single bubble rising in a channel
- **Internal flows**
  - 2D Poiseuille flow
  - 3D circular pipe flow
- **External flows**
  - Flow past a cylinder
  - Flow past a sphere
- **Natural convection (NC)**
  - NC in a 2D square cavity
  - NC in a 3D square cavity
  - NC in a 2D square cavity with an eccentric cylinder
- **Porous approach**
  - Pore-scale simulation (porous channel)
  - REV-scale simulation
- **Non-Newtonian fluid flow**
  - 2D and 3D Poiseuille flow
  - Flow-driven by a rotating disk
- **Turbulent flows**
  - Flow in a circular pipe
  - Flow in a square channel
  - Flow in a pebble bed
  - Flow in a rod bundle

APPLICATIONS – Large Eddy Simulation (LES)

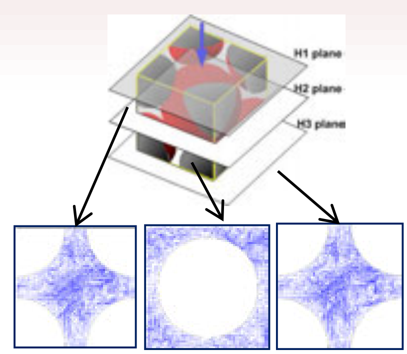
Flow in a Rod Bundle



Cross-flow over a Rod Bundle



Flow in a Pebble Bed



PUBLICATIONS (selected)

- S.K. Kang, Y.A. Hassan, "The effect of lattice models within the lattice Boltzmann method in the simulation of wall-bounded turbulent flows," Journal of Computational Physics, 232, 100-117, 2013.
- S.K. Kang, Y.A. Hassan, "A direct-forcing immersed boundary method for the thermal lattice Boltzmann method," Computers & Fluids, 49, 36-45, 2011.
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Application of Lattice Boltzmann Method: Fluid-Solid Interaction

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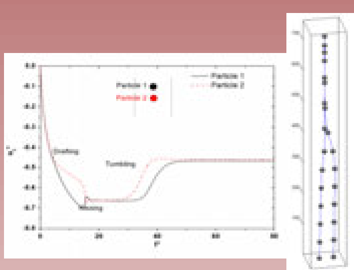
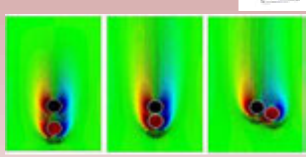
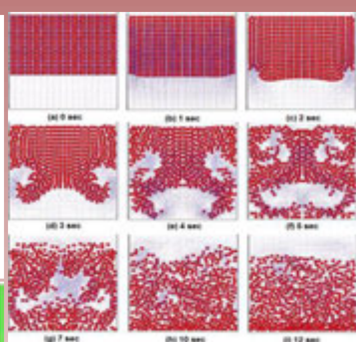
INTRODUCTION

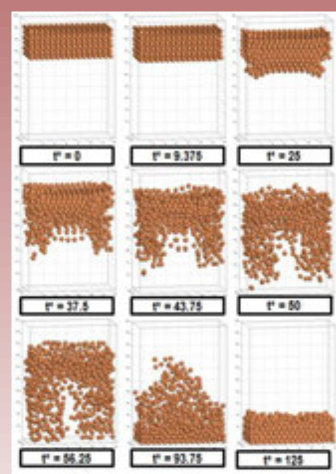
- Coupled with the **immersed boundary method (IBM)**, the **lattice Boltzmann method (LBM)** has been applied to fluid-solid interaction problems, such as particle sedimentation, particulate flows, and fluid-structure interaction.
- **The direct numerical simulation** based on the two-way coupling between solid and fluid was performed.

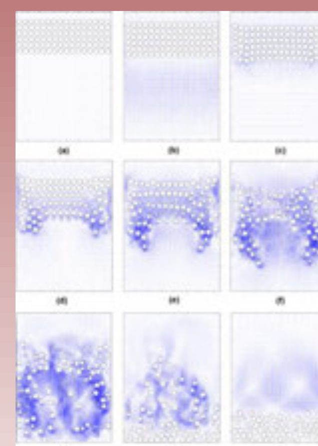
PARTICLE SEDIMENTATION





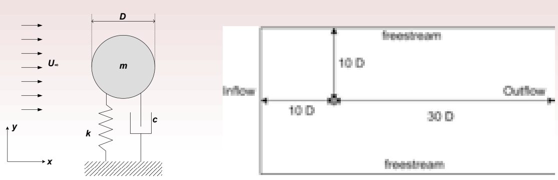


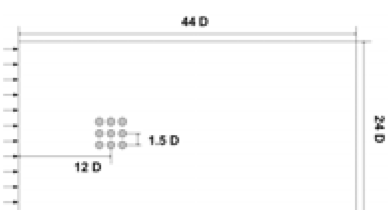


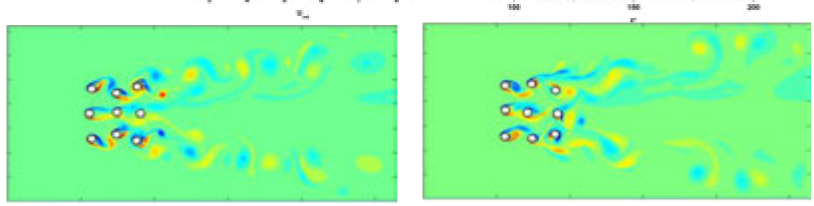


FLUID-STRUCTURE INTERACTION

FLUID-STRUCTURE INTERACTION







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- S.K. Kang, Y.A. Hassan, "Simulation of particle behaviors in the pipe flow," Transactions of the American Nuclear Society, Washington, D.C., Nov. 2013.
- S.K. Kang, Y.A. Hassan, "Direct numerical simulation of debris sedimentation using the immersed boundary lattice Boltzmann method," Proceedings of Advances in Thermal Hydraulics (ATH 12), San Diego, Nov. 2012.
- S.K. Kang, Y.A. Hassan, "An immersed boundary-lattice Boltzmann method for large particle sedimentation," Proceedings of 7th International Topical Meeting on Nuclear Reactor Thermal Hydraulics, Operations and Safety (Nuthos7), Seoul, Korea, Oct. 2008.