# Simulations of Turbulent Diffusion in Wire-Wrapped Sodium Fast Reactor Fuel Assemblies

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**Argonne National Laboratory**

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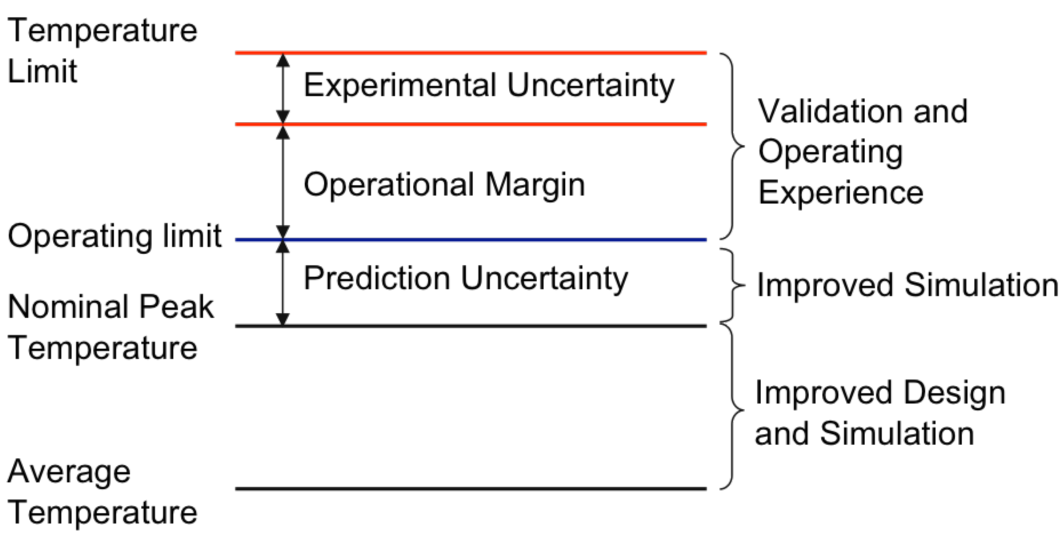
# Overview

- Background and Motivation
- Multi-scale approach to design and safety analysis
- Review of initial results
- Recent Results
- Full-size assembly simulation benchmarking
- Conclusions and Future Work

# Path Forward to Future Commercial ABR's

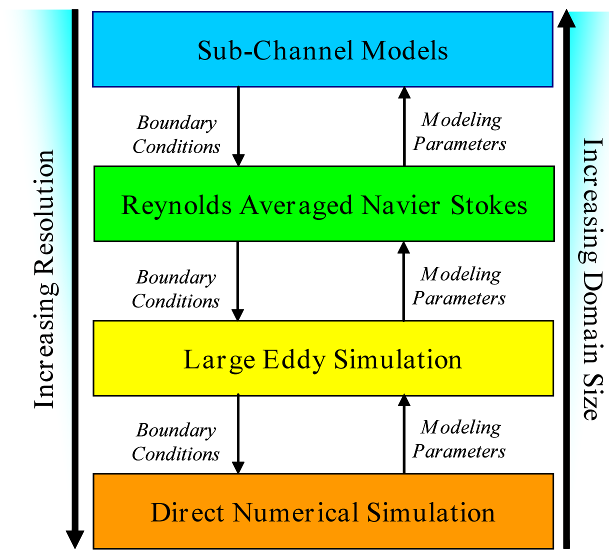
- Path Forward
  - Design simplifications (reduce mass of steel)
    - Compact reactor vessel
    - Compact intermediate components
    - Advanced compact fuel handling systems
  - New technologies that allow for reduced structural materials inventory and compact piping systems
  - Improved management of design and safety margins

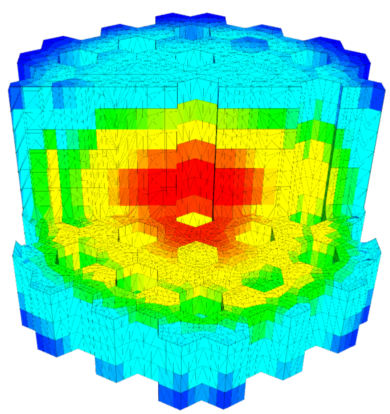


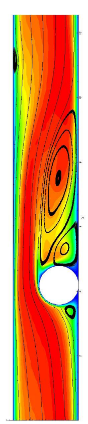
# Role of Advanced Simulations

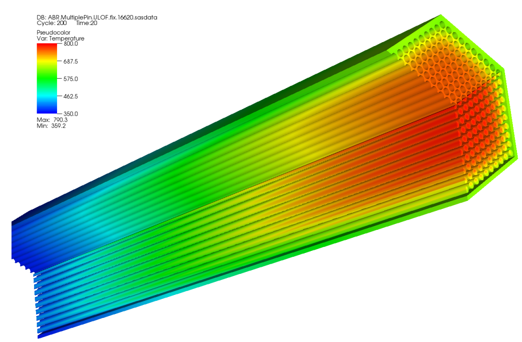
- Need to develop multi-resolution modeling approach capable of quantifying the complex interactions from fuel centerline to the ultimate heat sink.
  - This presents a challenge because of the large domains in time ($10^{-7}$ seconds to years) and space ($10^{-6}$ meters to 10s of meters).
  - In the absence of experiments, higher-fidelity models need to provide accurate, geometry-dependent parameters to lower-fidelity models that can capture much larger domains in both space and time.

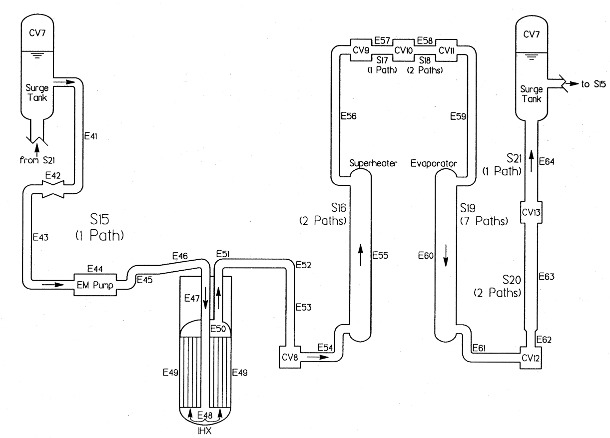
T/H Modeling Domains



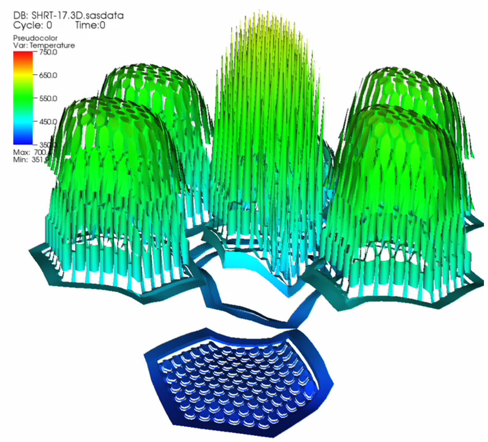





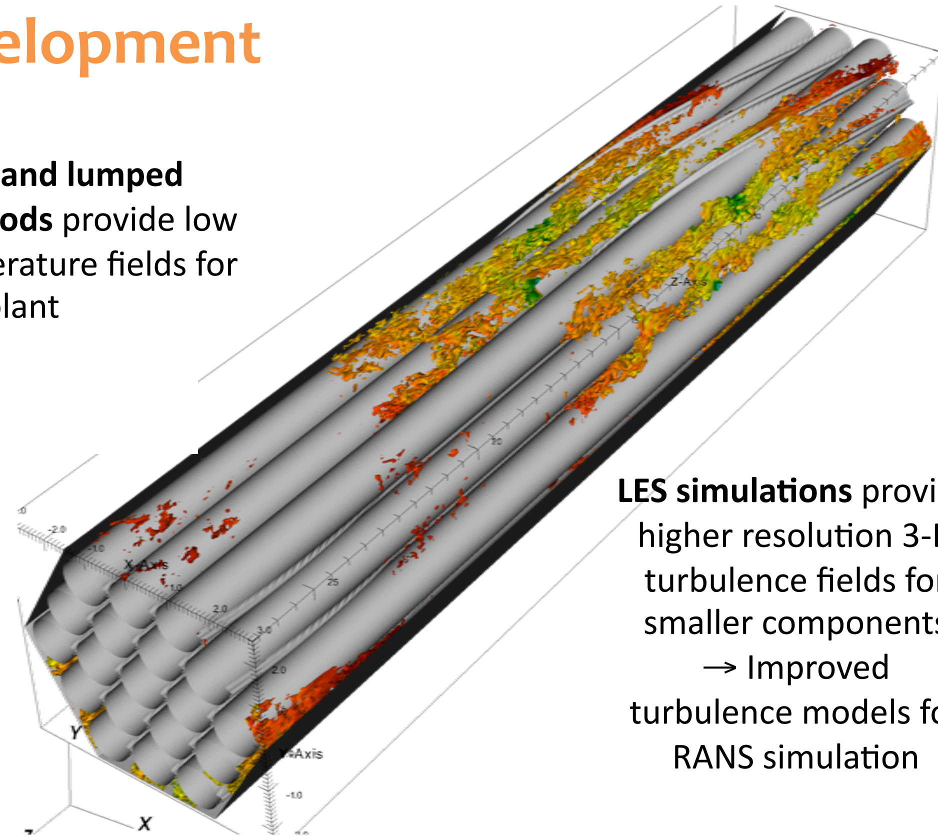




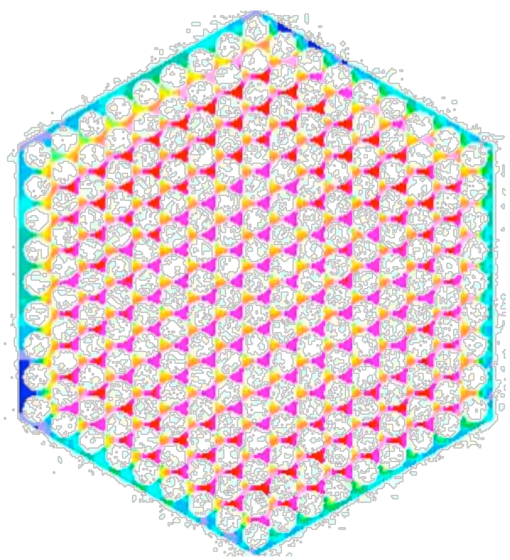
# Thermofluid Code Development




**Sub-channel and lumped parameter methods** provide low resolution temperature fields for full plant

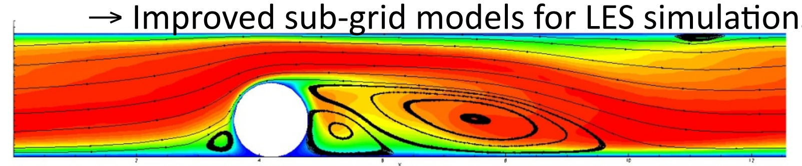



**LES simulations** provide higher resolution 3-D turbulence fields for smaller components
→ Improved turbulence models for RANS simulation



**RANS simulations** provide high resolution 3-D temperature fields for large components
→ Improved models for lower fidelity simulations

**DNS simulations** provide first principles turbulence fields for small characteristic geometries
→ Improved sub-grid models for LES simulations



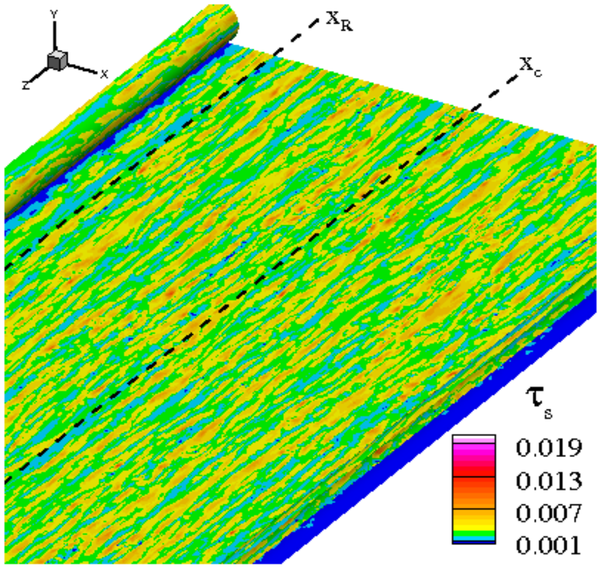
# Key Findings 06-08: Direct Numerical Simulation of Turbulence

## Plane Channel + Wire in Cross Flow

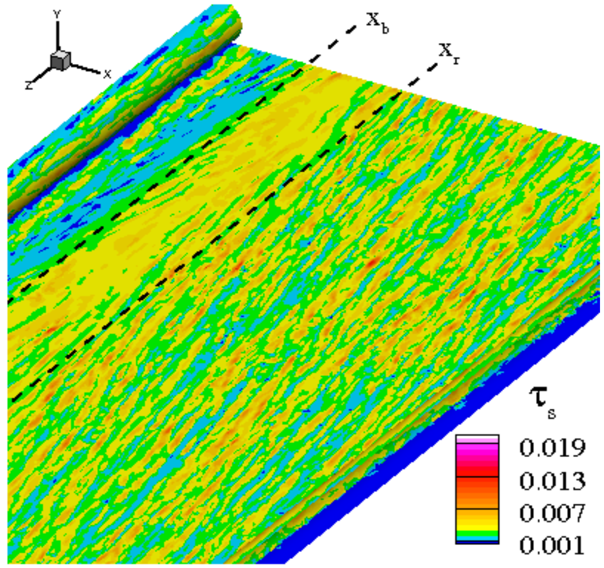
R. Ranjan & C. Pantano, UIUC

- *Single wire in a channel with cross flow simulated at $Re_b$ =6000 using a spectral code:* ***gold standard turbulence benchmark***
- *3 million node hours through INCITE award.*

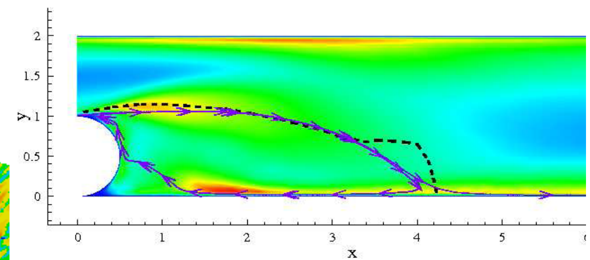
*Wall Shear: No Cross-Flow*




*16% Cross-Flow*




*TKE, 16% CF*




*Separation in wire wake leads to increased variance in wall shear. Anticipate similar effects for heat transfer.*

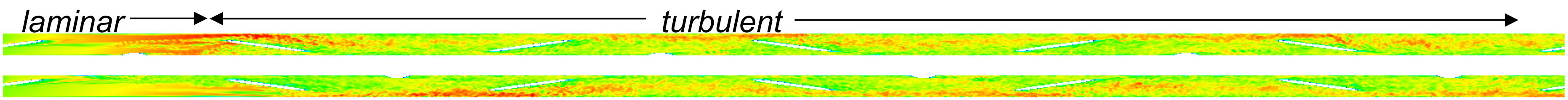
Ranjan, Pantano, & Fischer, *DNS of swept flow over a wire in a channel, J. Fluid Mech., 2009 (in review).*

# Key Findings 06-08: LES of SFR Subassemblies

## 7 pin wire-wrapped assemblies

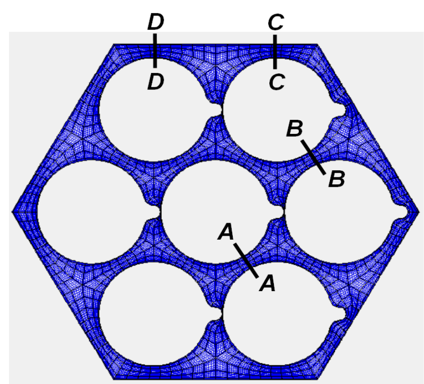
P. Fischer, A. Obabko and J. Lottes, Argonne

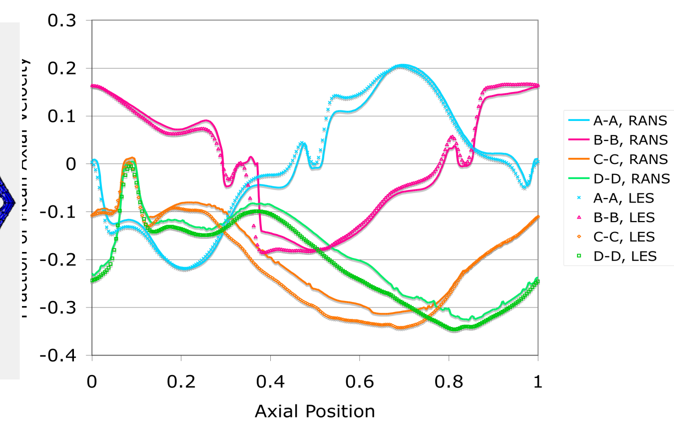
- *Transition to turbulence with inflow/outflow boundary conditions occurs at z~30 $D_h$*
  - *Verified in: single-pin x periodic array* and *7-pin x 3H subassembly*
  - *Therefore: axial periodicity is warranted → significant savings (10 x)*




*Transition in a 7-pin subassembly with laminar inflow conditions*

- *LES and RANS simulations give comparable results for cross-flow distributions in 7-pin case:*
  - *We have a mechanism for validating RANS, which gives considerable savings.*
  - *Data provides direct input to core-scale simulations*



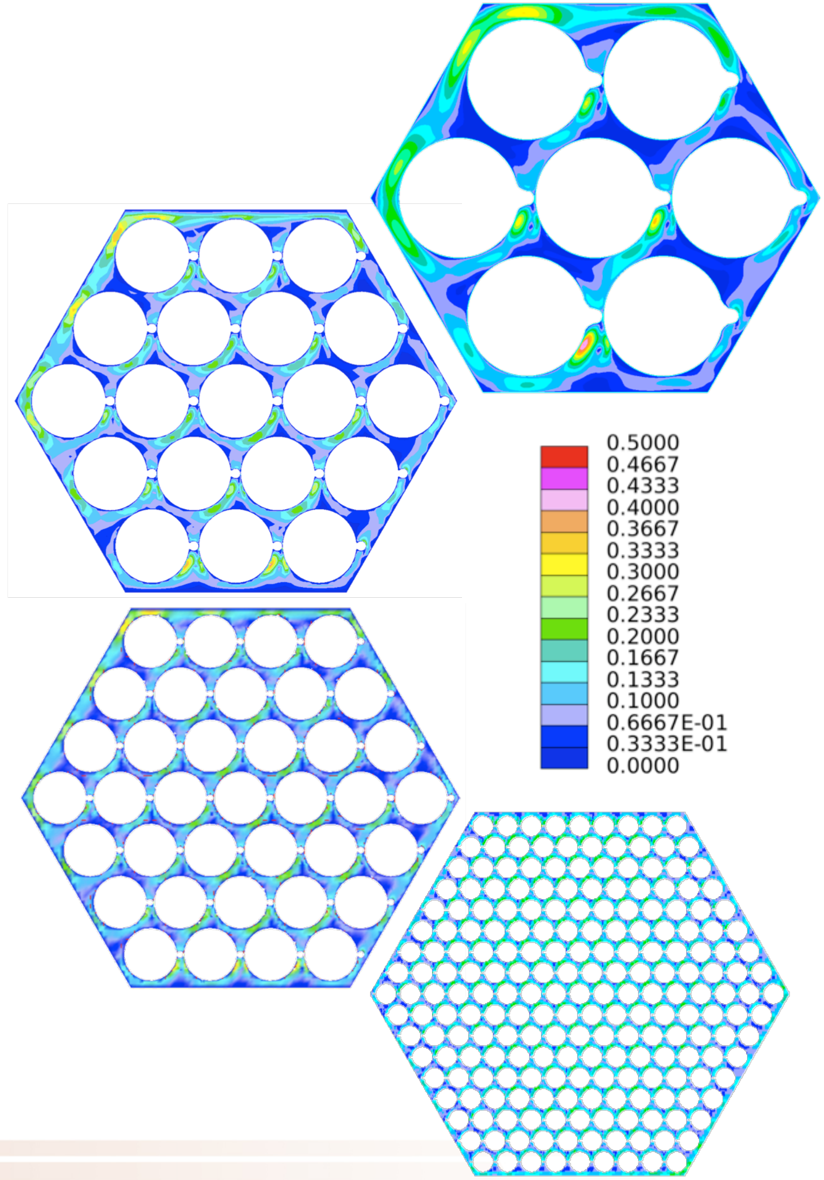

*Velocity for RANS vs LES*

# Key Findings 06-08: RANS Simulations of SFR Assemblies

## 7-37pin wire-wrapped assemblies

D. Pointer, Argonne and J. Smith, UIdaho

- Demonstrated evolution of flow field from 7 to 217 pin assemblies
  - Reduced importance of bulk swirling and increased complexity of flow field with increasing pin count
  - Fundamental change in flow behavior between 19- and 37-pin assemblies
    - Consistent with evidence in pressure drop data sets



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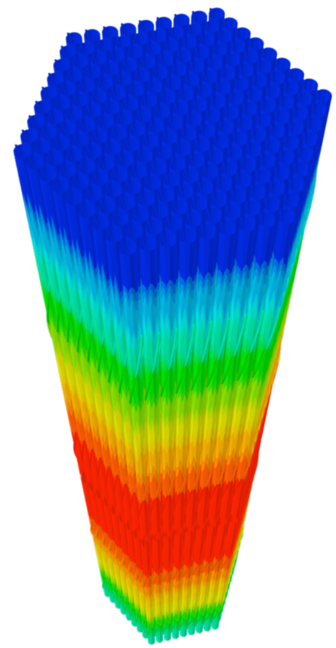
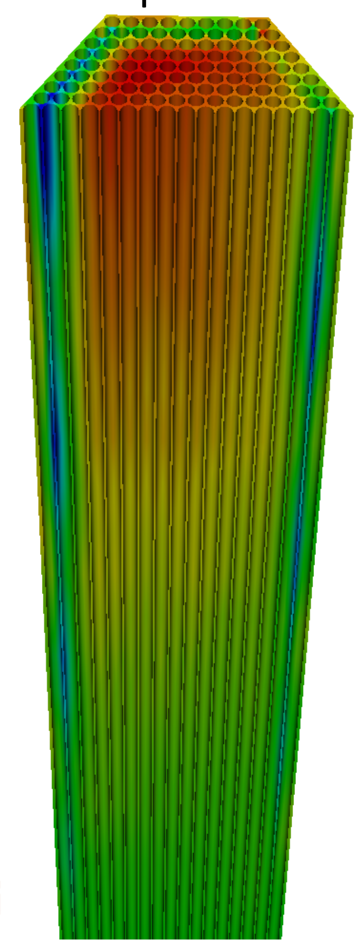


Power Distribution

Difference in predicted temperature



# Predicted Dimensionless Pressure Loss Coefficient from RANS Simulations vs. Correlations

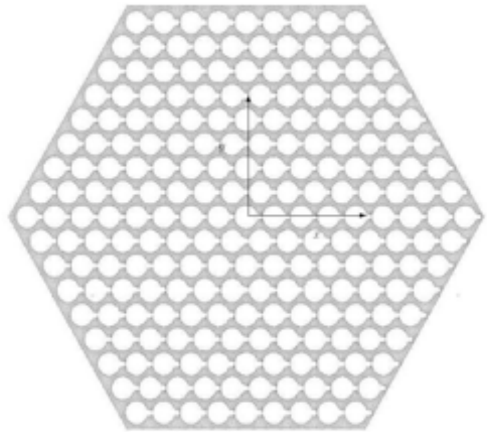
- The dimensionless pressure loss coefficient is the pressure drop normalized by the dynamic head, so that Cp=f (L/D).
- The Cheng & Todreas correlation assumes that there are three fundamental sub-channel types: interior, edge, and corner. Each of the three types of sub-channel frictional losses is calculated separately. The bundle friction factor is then averaged.
- The Rehme correlation is a simpler single equation formulation based on representative geometric parameters.

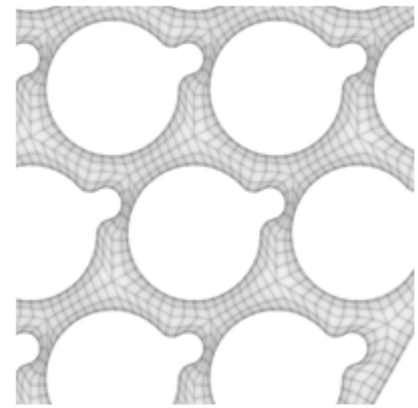
| Number of Pins | Cheng & Todreas Correlation | Rehme Correlation | RANS Simulation Prediction |
|---|---|---|---|
| 7* | 1.116 ± 14% | 1.179 ± 5% | 2.282 |
| 19 | 1.088± 14% | 1.041 ± 5% | 1.199 |
| 37 | 1.075 ± 14% | 0.943 ± 5% | 1.059 |

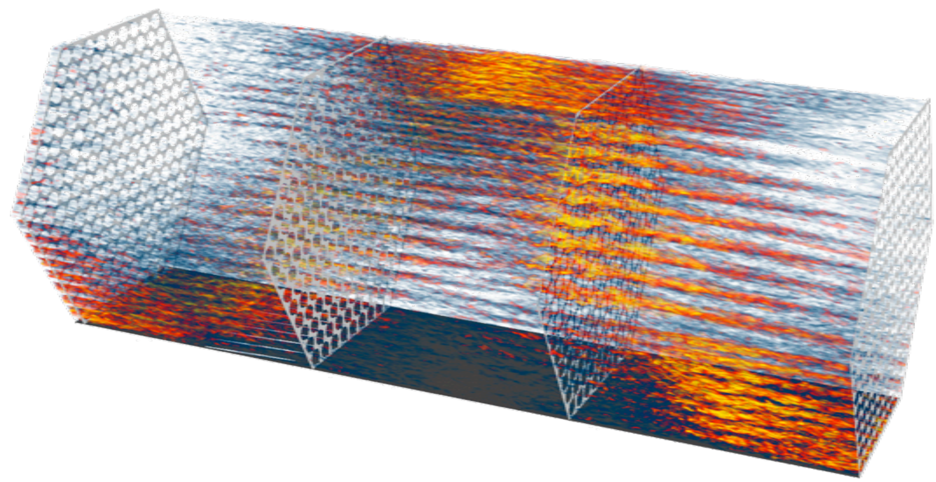
* Small 7-pin assemblies are not within the range of applicability of the correlations

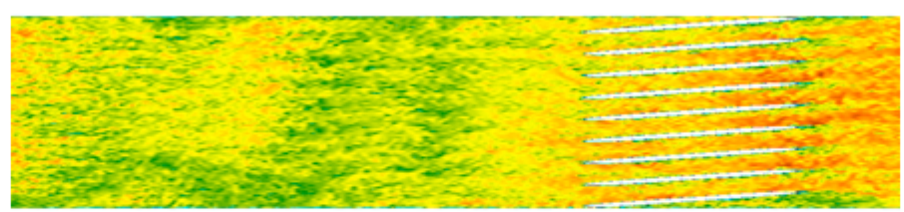
# LES Simulations of 217 pin assemblies

- Using spectral element code Nek5000
  - Single wire pitch H with periodicity in the axial direction
  - Reynolds number reduced to $Re_D$=15000 to reduce computational burden
    - Based on prior experience with smaller assemblies
    - Confirm scaling with RANS simulations
  - 2.95 million spectral elements of order N=7 (n=1.01 billion)
    - Have also run N=9 (n=2.1 billion)
  - Under-resolved – particularly axially
    - 4x larger than any previous Nek5000 run









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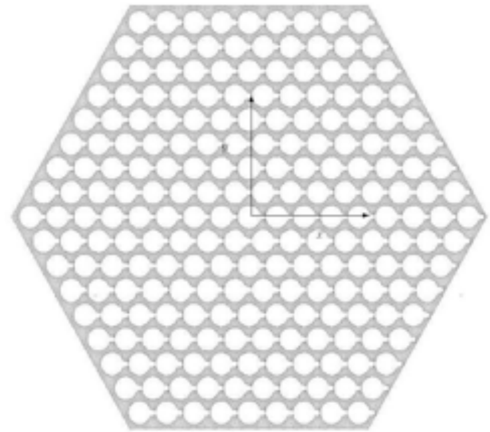
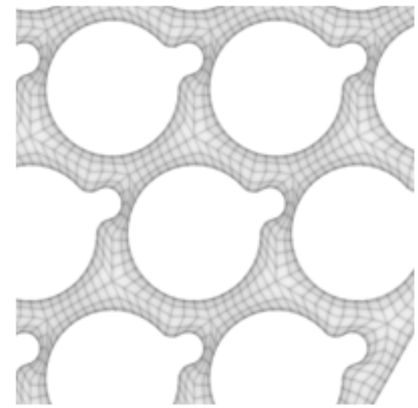
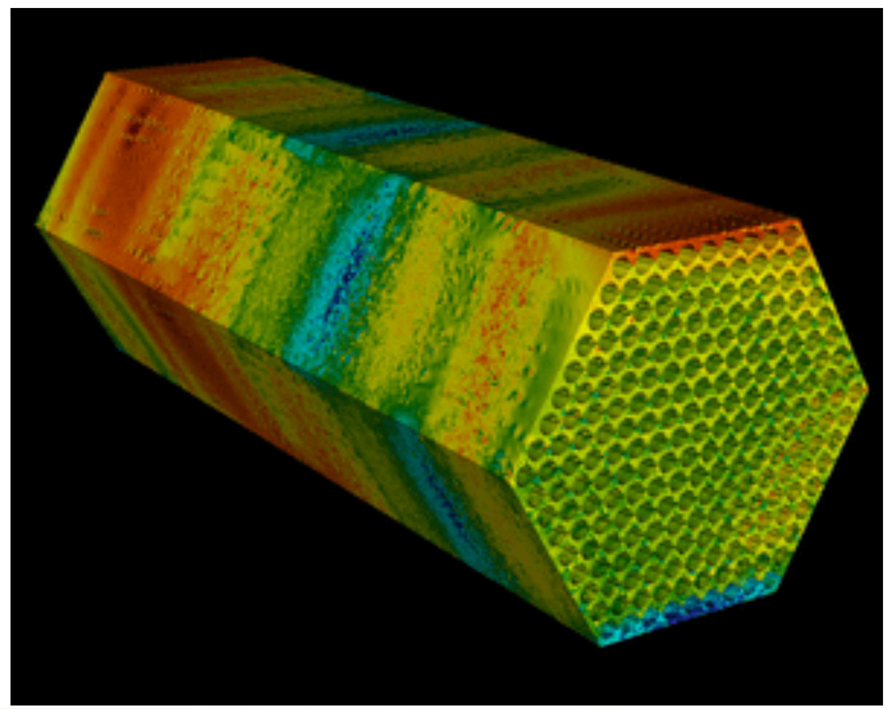
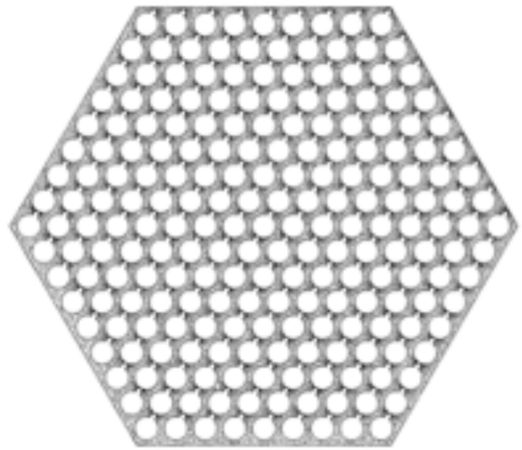


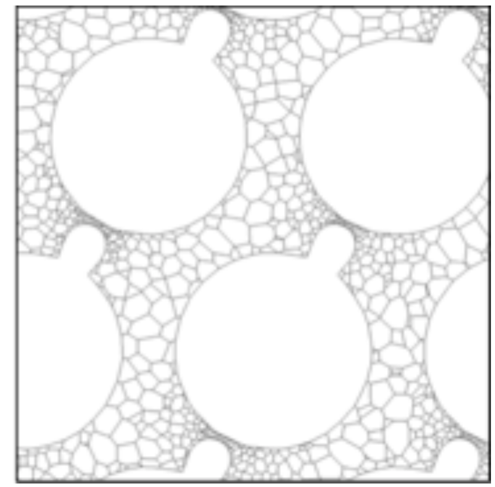


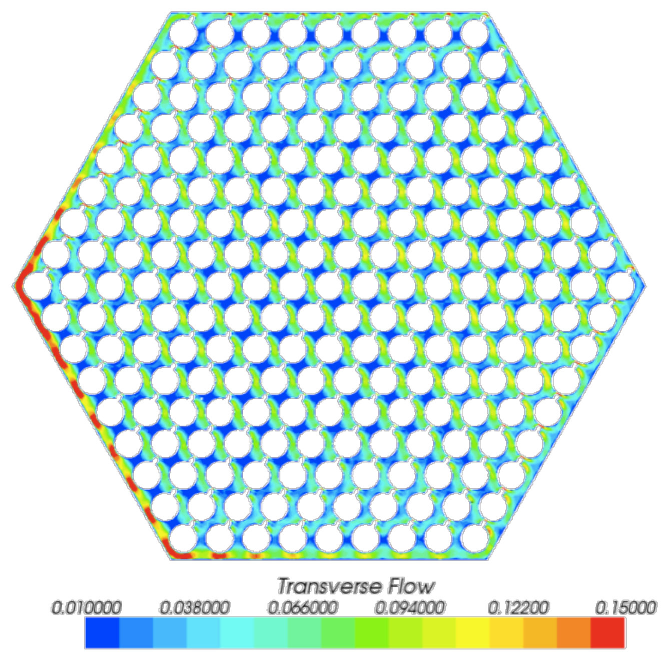


# RANS Simulations of 217 pin assemblies

- Using commercial code STAR-CCM+
  - 5 wire pitches, 5H, with inflow/outflow boundary conditions
  - Reynolds number reduced to $Re_D$=15000 to match LES conditions
  - 22 milion cells
    - Have also run n=44million
  - Under-resolved – particularly axially

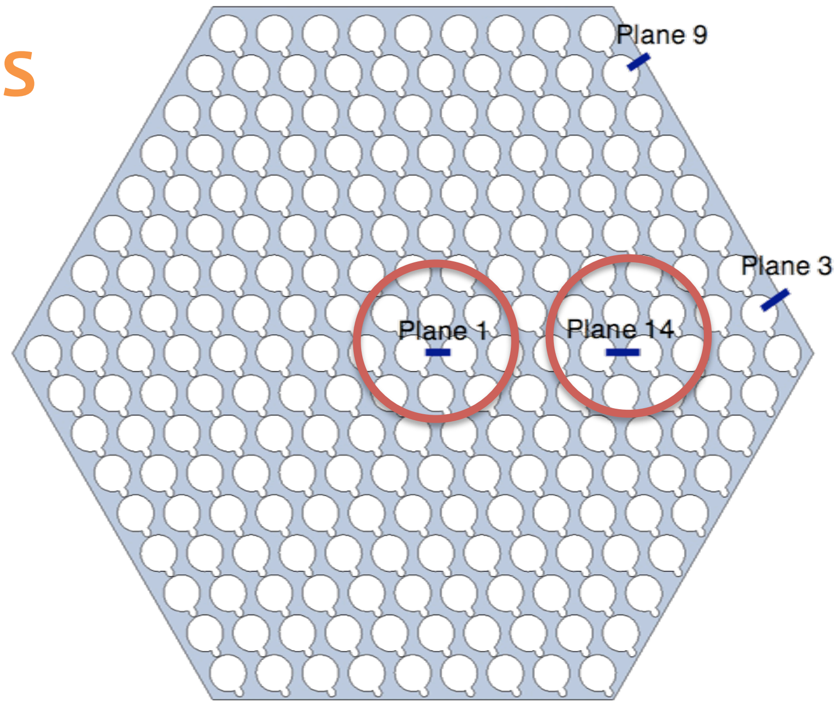


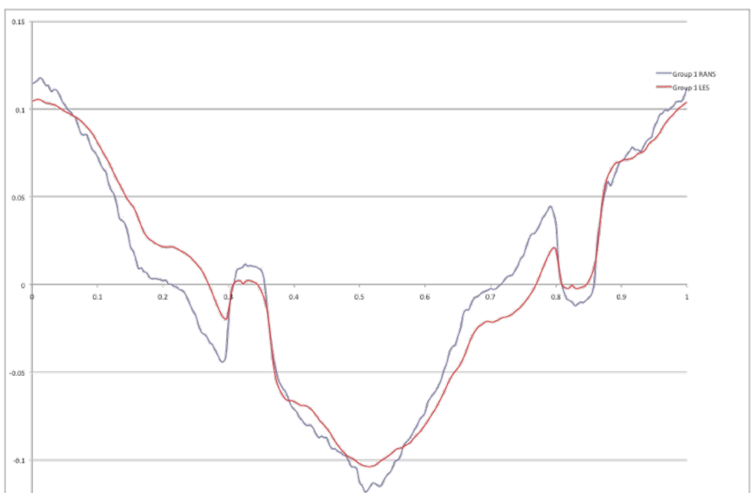




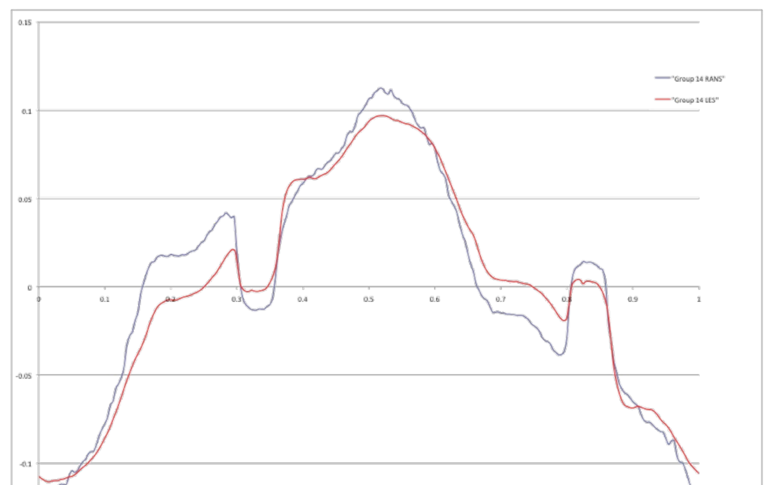
# Benchmarking of LES vs RANS

- Extract field data along selected planes.
- Calculate velocity component normal to plane
- Average data across plane to collapsed data to an axial profile of average normal velocity



Plane 1



Plane 2

# Benchmarking of LES vs RANS

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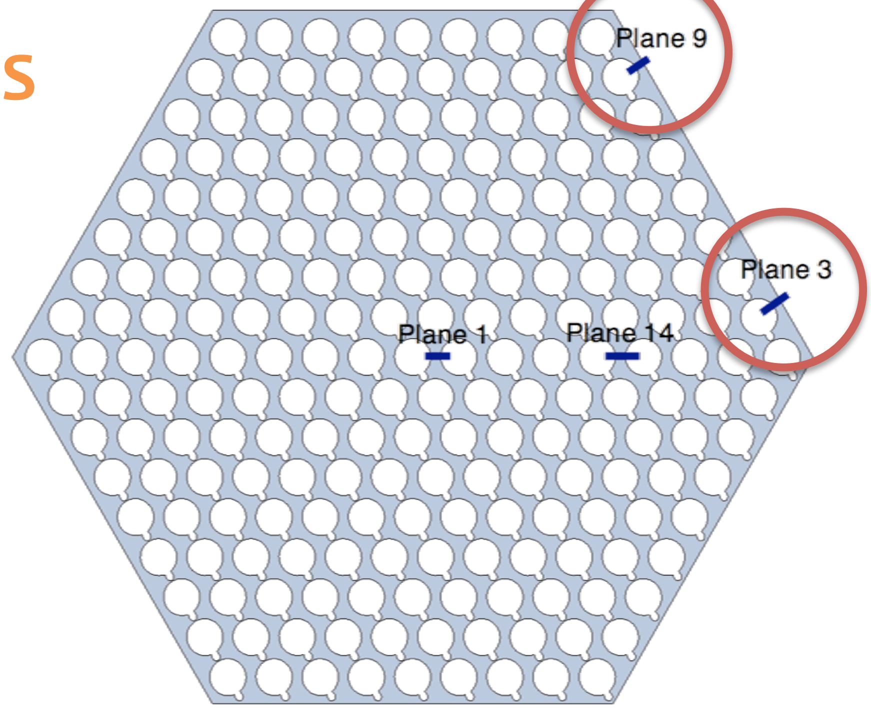
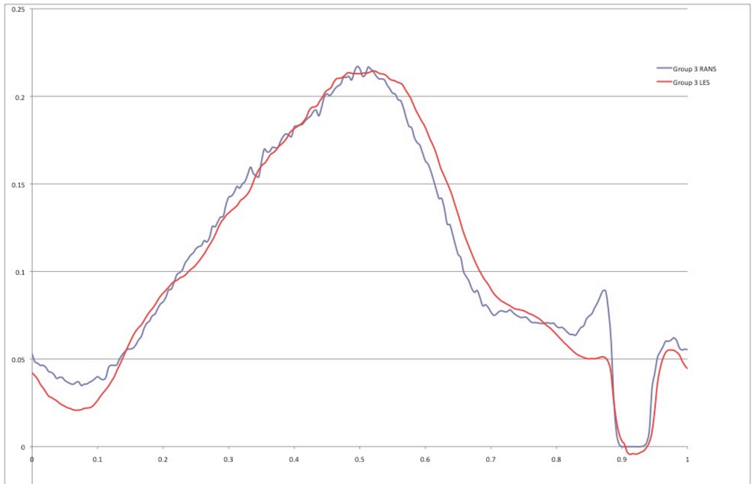
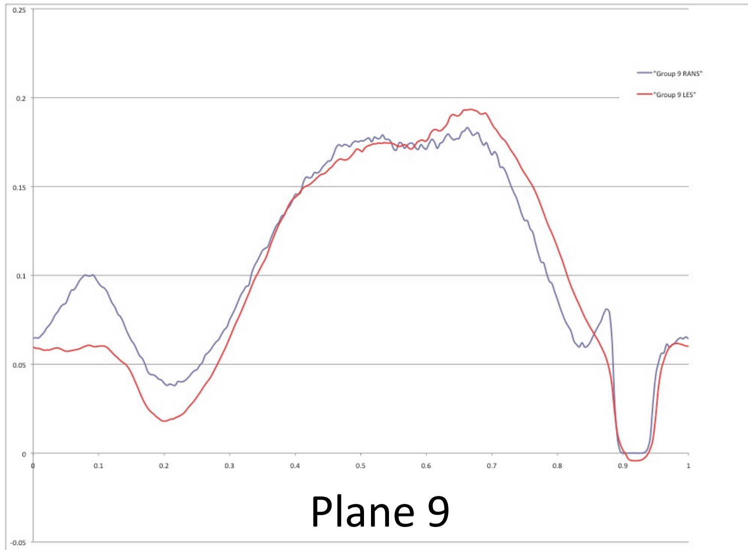


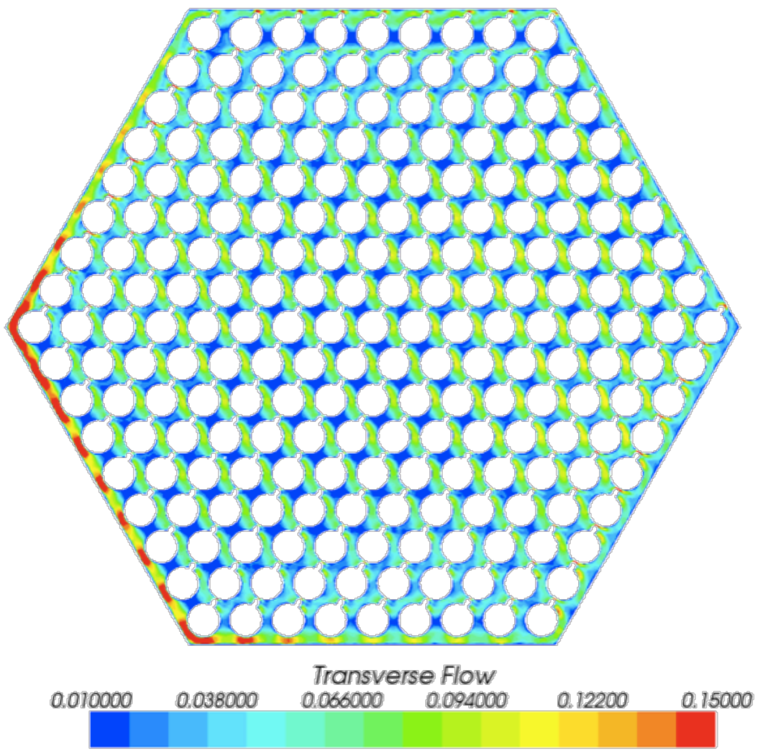




Plane 3

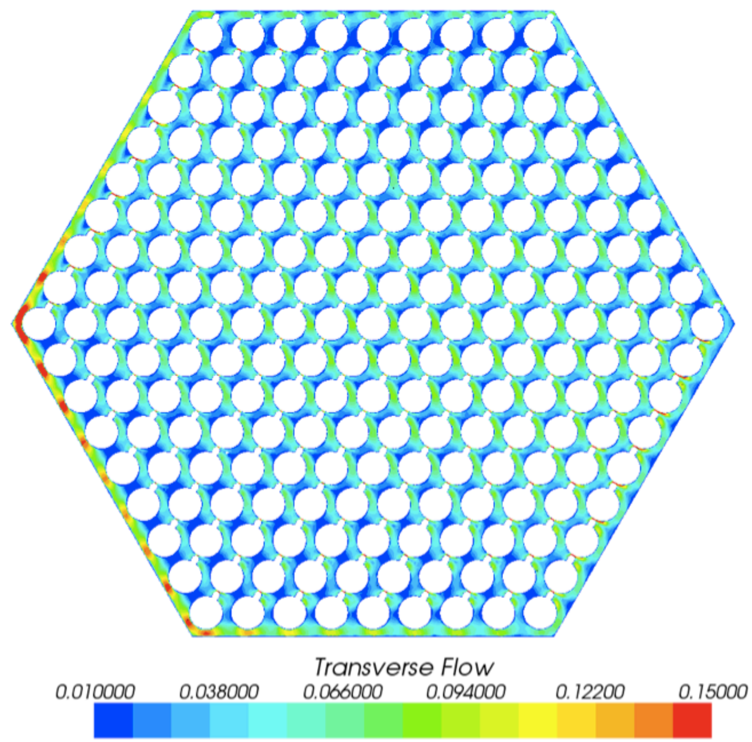



Plane 9

# RANS Simulations
# $Re_h$=15000 vs $Re_h$=108,000




Re = 15,000




Re = 108,000

# RANS Simulations

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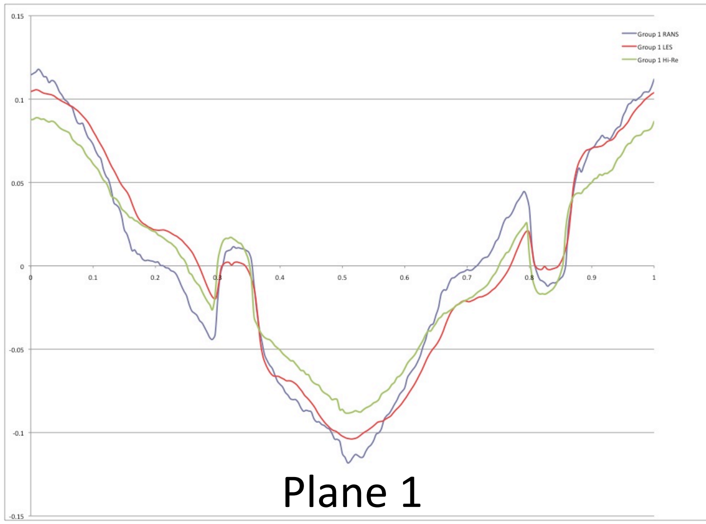
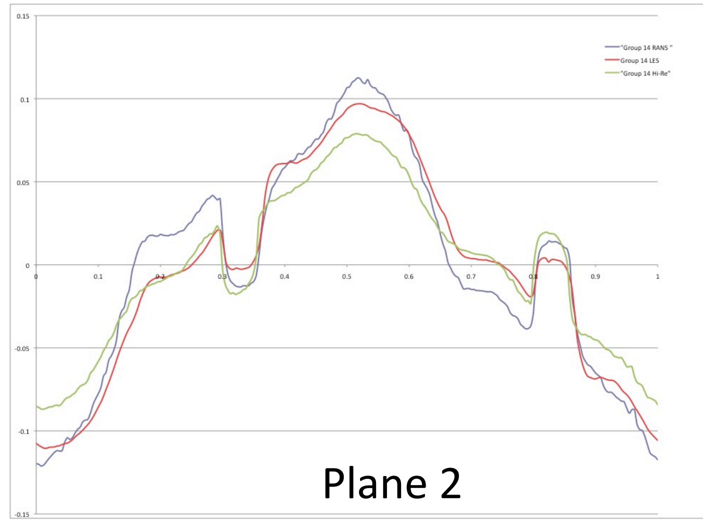
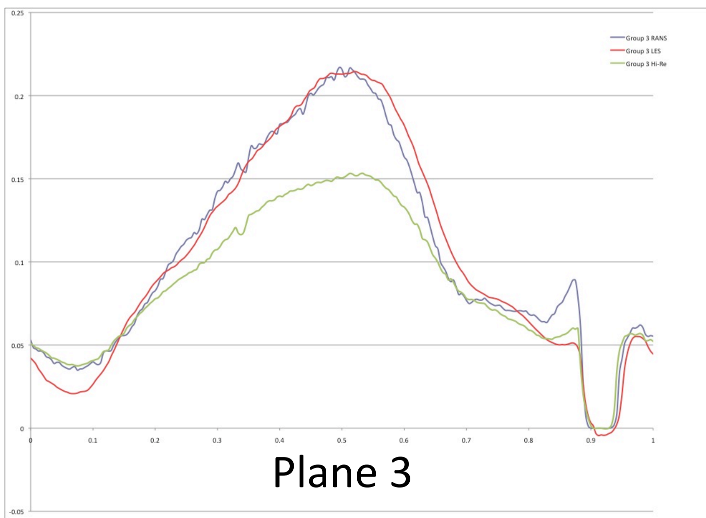


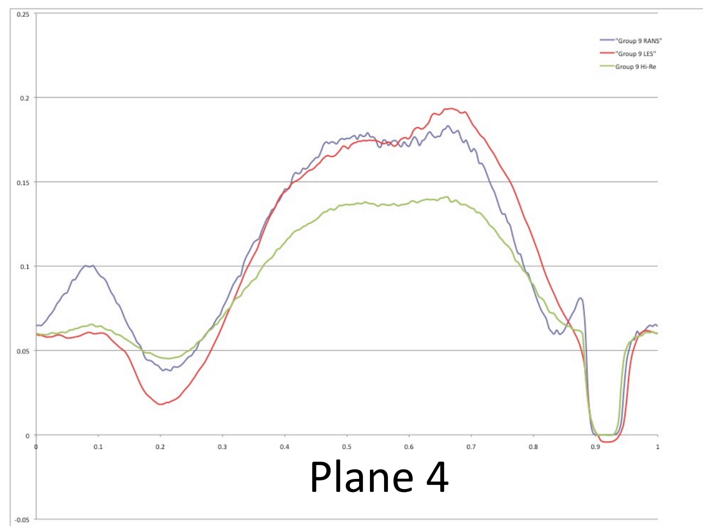
Plane 1



Plane 2



Plane 3



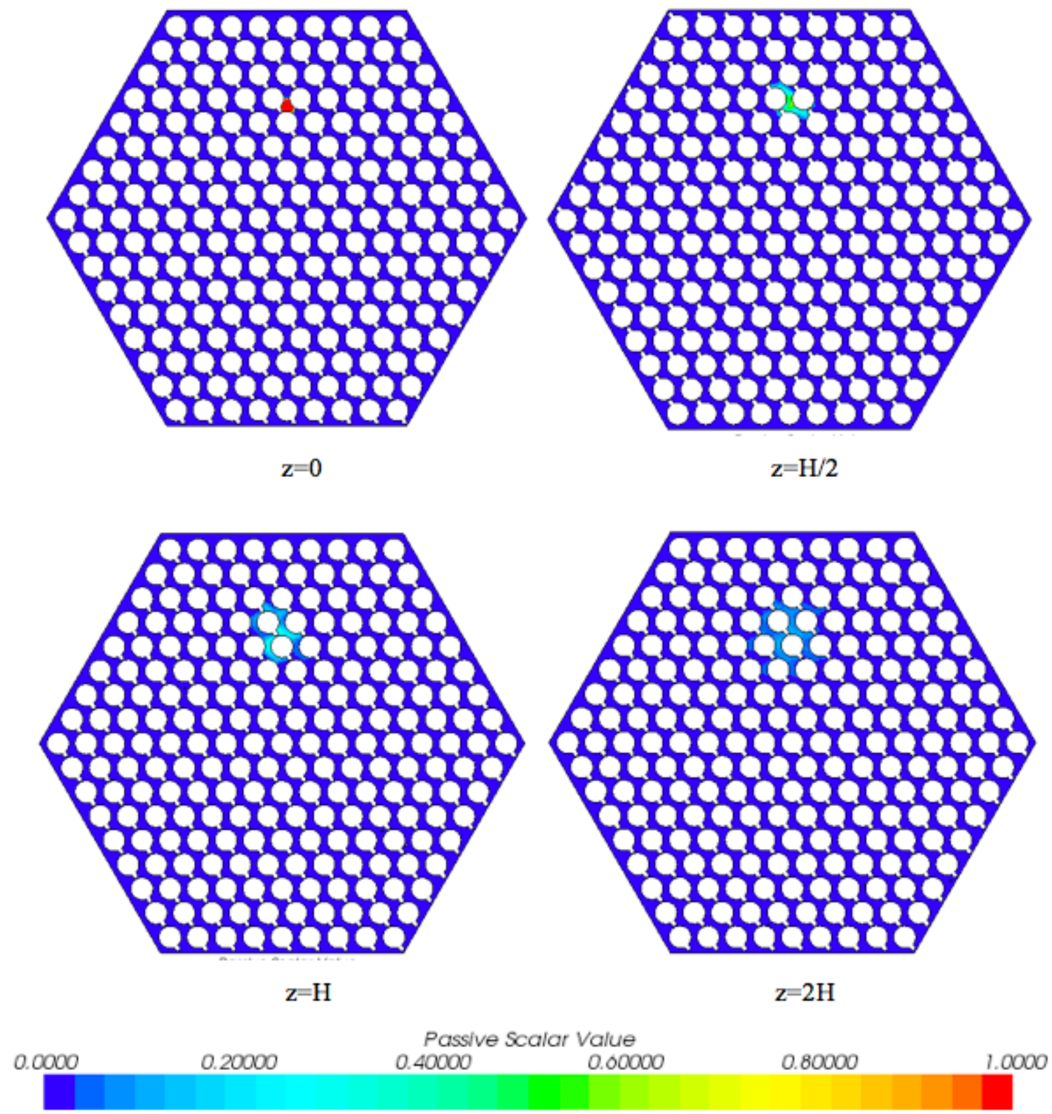
Plane 4

# Conclusions

- A series of LES and RANS based CFD simulations of a 217-pin wire-wrapped sodium-cooled fast reactor fuel assembly have been completed
  - initial benchmark of RANS models against high fidelity LES simulations in large wire wrapped pin bundles.
- Initial comparisons show that RANS and LES predict similar transverse flow fields within the assembly – a well mixed flow through the central channels and a swirling flow through the edge channels along the assembly boundary.
  - Much different than the flow field in 7- and 19-pin assemblies where swirling flow dominates
- Comparisons of RANS to 1-D subchannel simulations reveal bias in temperature distribution as a consequence of azimuthal starting position of the wire relative to can wall.
- Comparisons of detailed inter-channel exchange velocity profiles show that the two methods generally agree.
  - RANS simulations tend to predict more inter-channel mixing
  - Less turbulence generation on the windward side of the wire wrap spacer

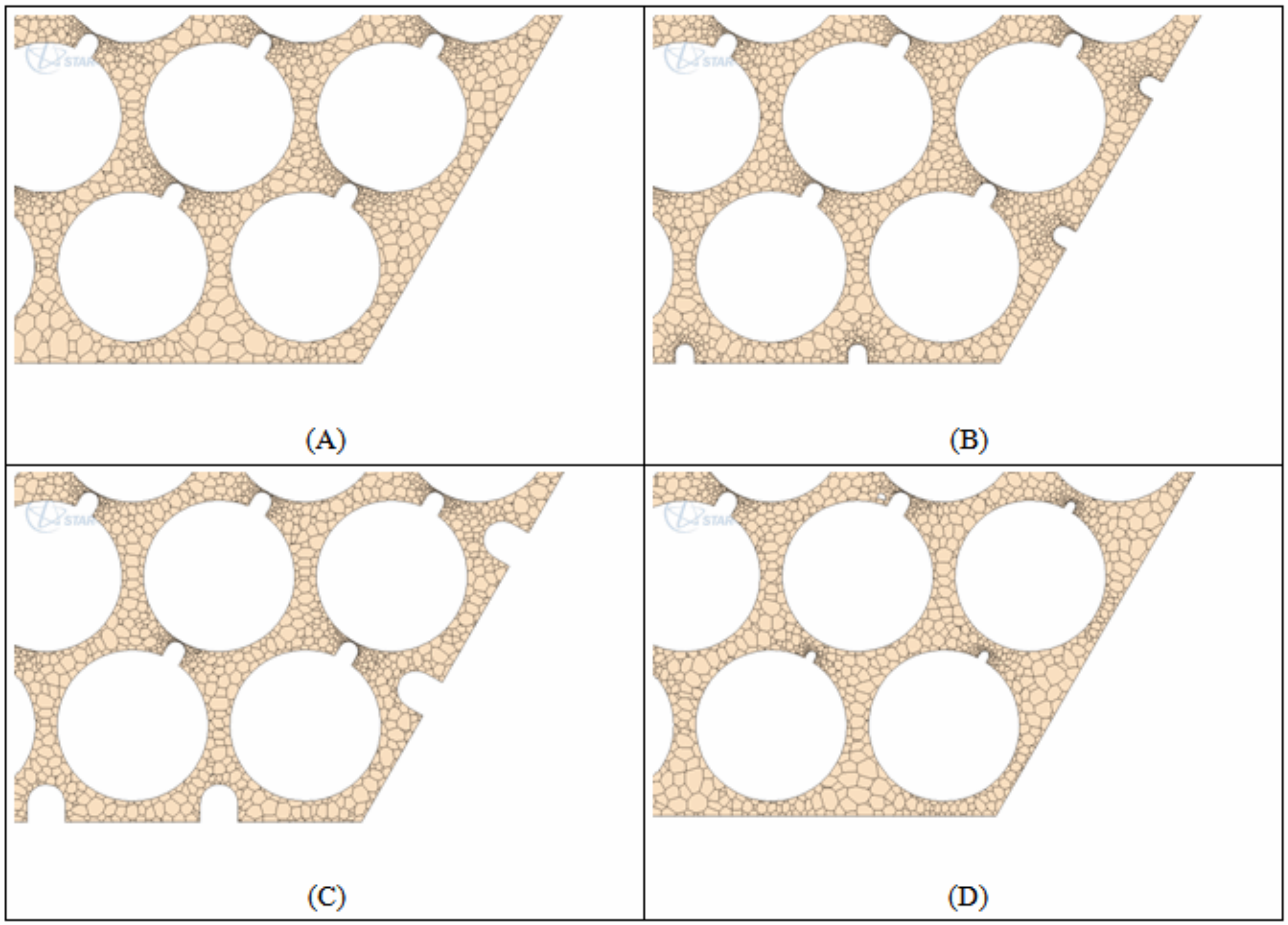
# Current Efforts: Turblent Diffusion

- Benchmarking of turbulent diffusion based on legacy experiments
- Water experiments using conduction probes to track plume diffusion
  - Use single injection port in variety of sub-channel locations
- For the interior channels, one observes that fluid is swept into the channel from which the wire is exiting.
- Discharge into the other subchannels is not evenly split between the neighboring subchannels – there is a significant bias for the flow to follow the wire
- By z=H, the peak concentration has typically moved two or three channels.



# Current Efforts: Design Studies

- Alternative edge channel geometries
- Wire wrap vs. Spacer Grid



# Questions?