CFD Modeling of Industrial Fire and Suppression Using HPC

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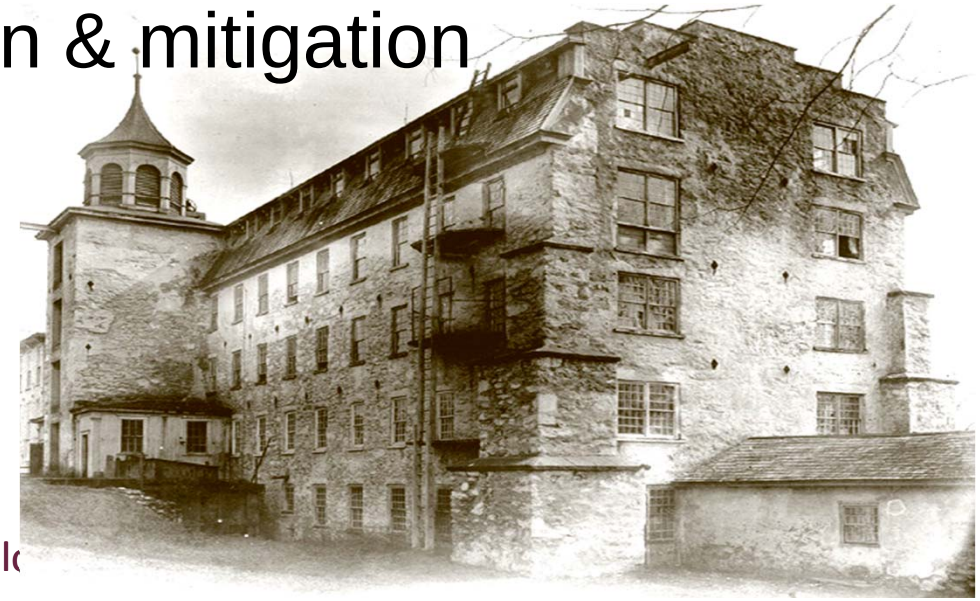
FM Global – A Unique Company

- Largest commercial and industrial property insurer
- “The majority of loss is preventable”
- Engineering and Research
- 180 years of loss prevention & mitigation

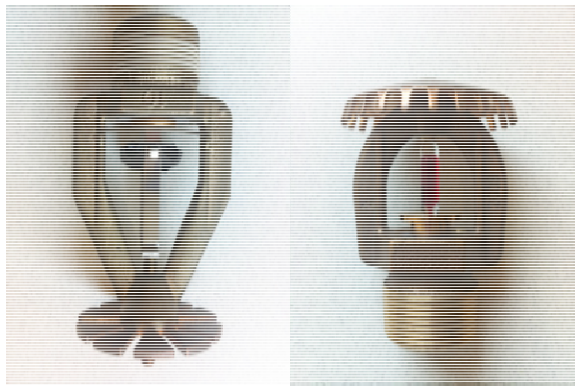


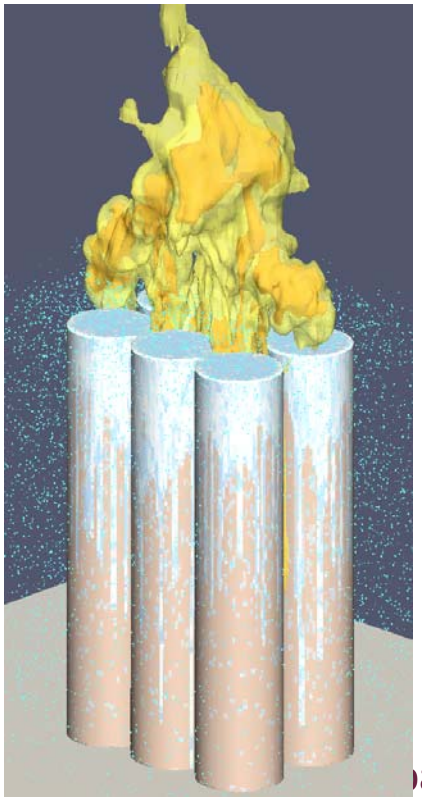
Industrial & Commercial Fire

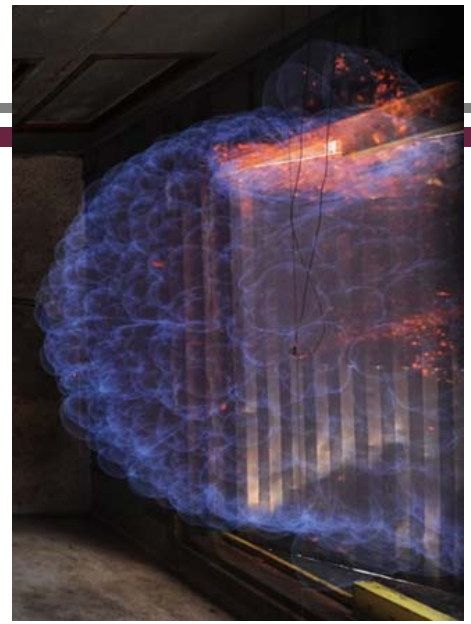
- Annual loss in US: $3 billion
- Across all industries: manufacturing and storage
  - Chemical
  - Semi-conductor, data center
  - Pharmaceutical
  - Forrest product
  - Mining
  - etc.

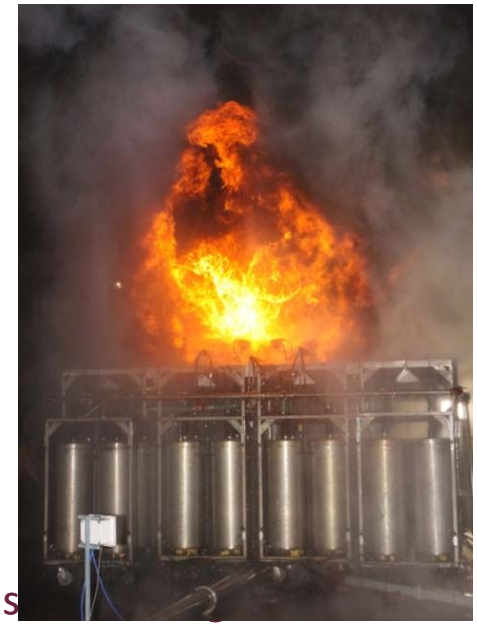
Fire Research

- Large scale tests
- Explosion
- Suppression
- Flammability
- Fire Modeling







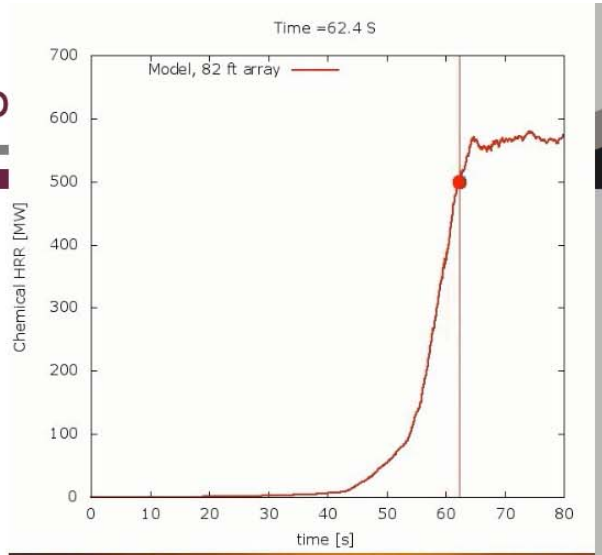


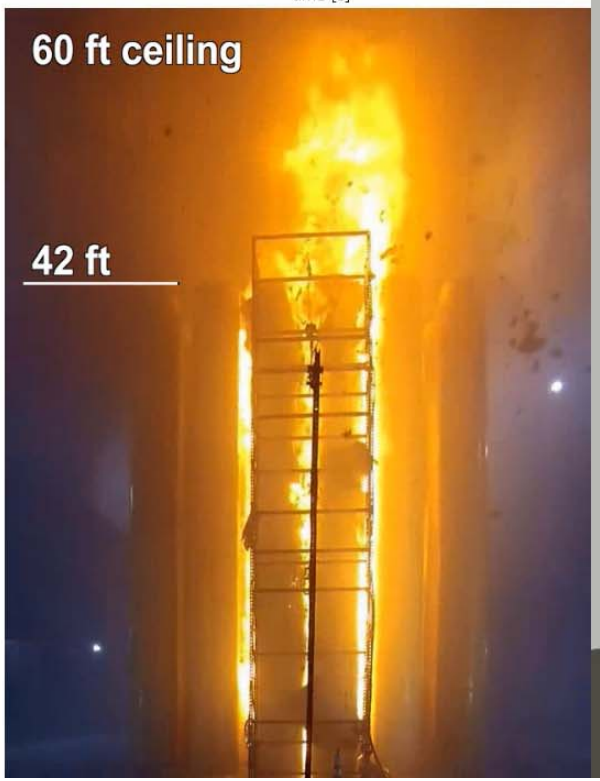
Fire Research

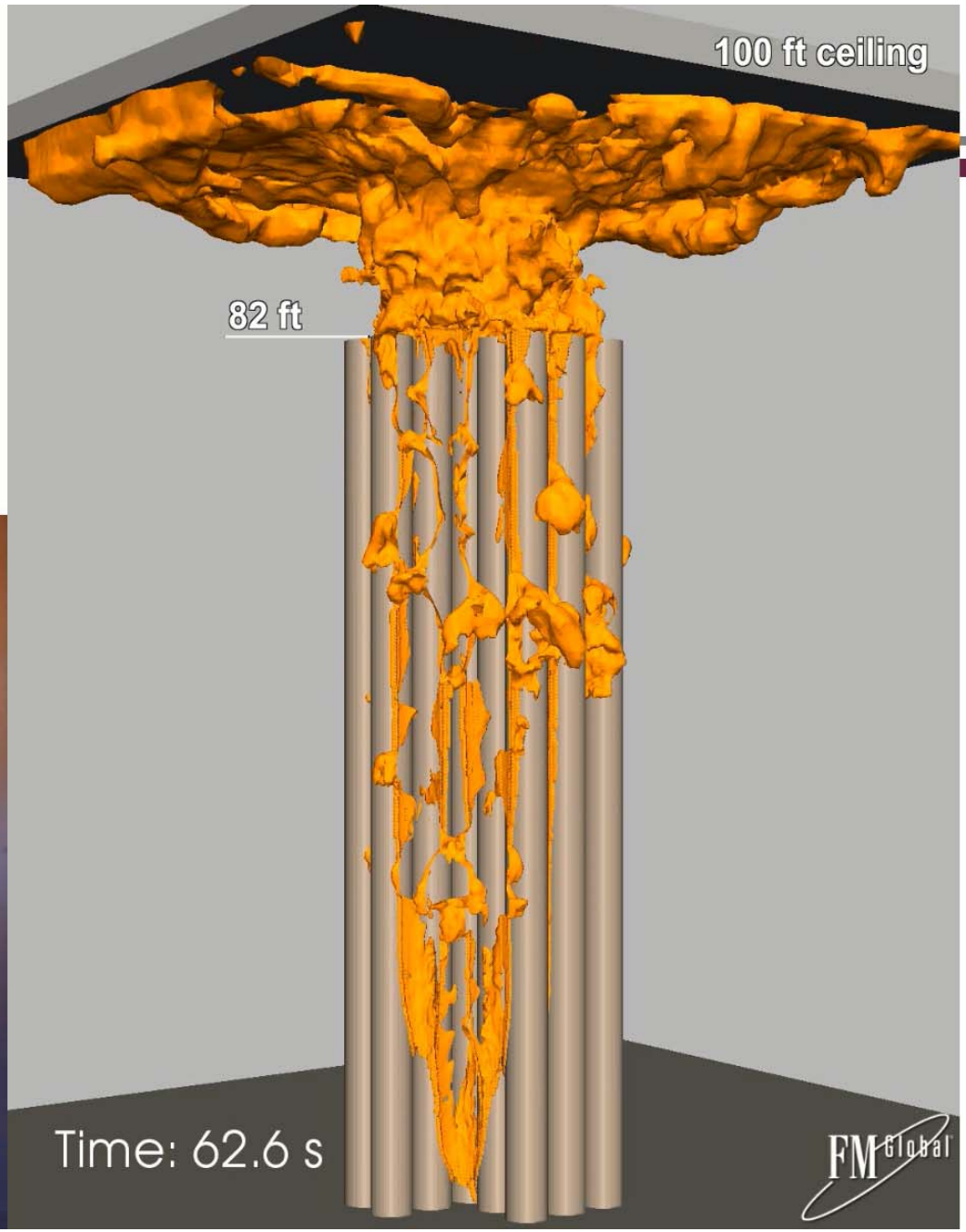
- Testing and experimental
  - Largest fire testing lab
- Modeling
  - 2000 core cluster

ed.

FM Glo


Time =62.4 S
Model, 82 ft array
Chemical HRR [MW]
time [s]
0
100
200
300
400
500
600
700
0
10
20
30
40
50
60
70
80


60 ft ceiling
42 ft


100 ft ceiling
82 ft
Time: 62.6 s
FM Global

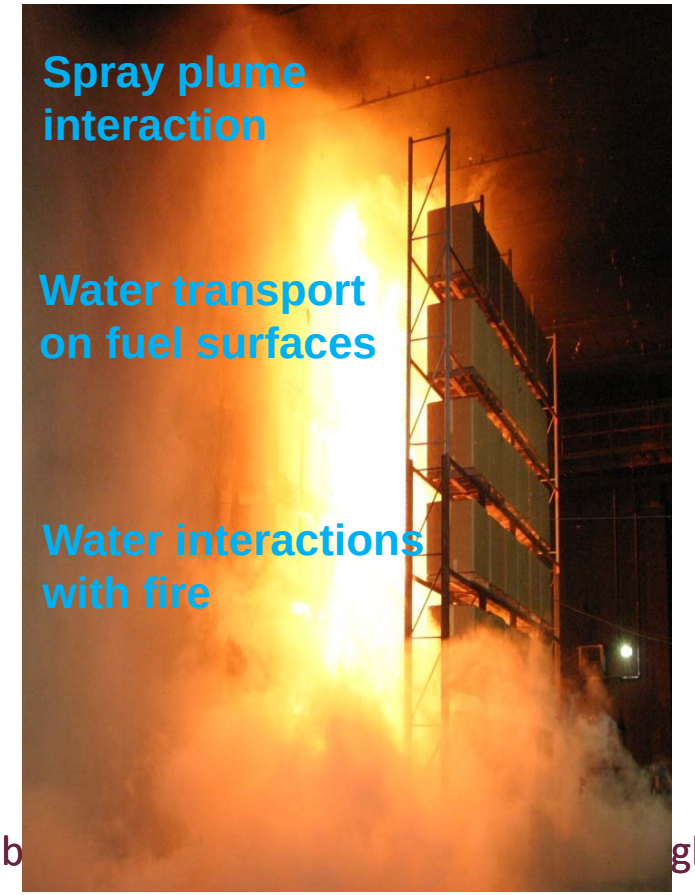
Why CFD Modeling

- Large scale fire tests are:
  - Expensive
  - Hard to quantify & generalize results
  - Limited by test facility & safety
- Physical based fire model
  - Gain insight of fire test
  - Help design and interpret tests
  - Reduce number of large-scale fire tests

Multi-Scales & Physics -- HPC

Fire Growth

Suppression

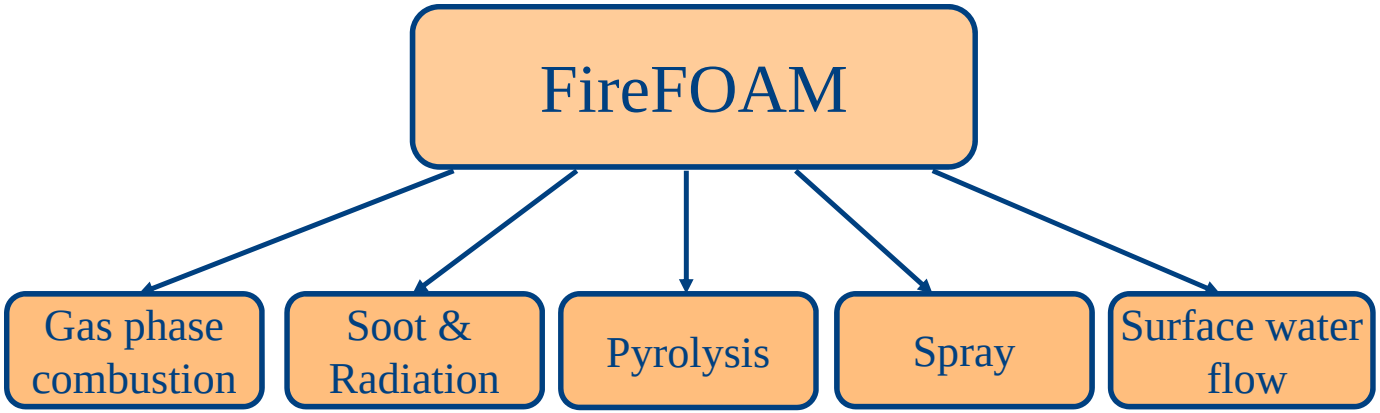


OpenFOAM and FireFOAM

- Open source CFD toolboxes written in C++
  - Unstructured mesh
  - Segregated solution
  - Pressure-based solver
  - 2nd order fully implicit scheme
  - Parallel computing: MPI
  - Object oriented programming

FireFOAM

- A buoyancy-driven diffusion flame LES solver
- With fire specific sub-models
- Open source (fmglobal.com/modeling)



Gas Phase Eqns: LES

Mass

$$\frac{\partial \bar{\rho}}{\partial t} + \frac{\partial \bar{\rho}\tilde{u}_j}{\partial x_j} = 0$$

Eddy-viscosity model

Momentum

$$\frac{\partial \bar{\rho}\tilde{u}_i}{\partial t} + \frac{\partial \bar{\rho}\tilde{u}_i\tilde{u}_j}{\partial x_j} = \frac{\partial}{x_j}\left(\bar{\rho}(\nu + \nu_t)\left(\frac{\partial \tilde{u}_i}{\partial x_j} + \frac{\partial \tilde{u}_j}{\partial x_i} - \frac{2}{3}\frac{\partial \tilde{u}_k}{\partial x_k}\delta_{ij}\right)\right) - \frac{\partial \bar{p}}{\partial x_i} + \bar{\rho}g_i$$

Sensible Enthalpy

$$\frac{\partial \bar{\rho}\tilde{h}_s}{\partial t} + \frac{\partial \bar{\rho}\tilde{u}_j\tilde{h}_s}{\partial x_j} = \frac{D\bar{p}}{Dt} + \frac{\partial}{x_j}\left(\bar{\rho}\left(D_{th} + \frac{\nu_t}{\mathrm{Pr}_t}\right)\frac{\partial \tilde{h}_s}{\partial x_j}\right) - \frac{\partial \bar{\dot{q}}''}{\partial x} + \overline{\dot{\omega}'''_{h_s}}$$

Specie Mass Frac

$$\frac{\partial \bar{\rho}\tilde{Y}_k}{\partial t} + \frac{\partial \bar{\rho}\tilde{u}_j\tilde{Y}_k}{\partial x_j} = \frac{\partial}{x_j}\left(\bar{\rho}\left(D_k + \frac{\nu_t}{\mathrm{Pr}_t}\right)\frac{\partial \tilde{Y}_k}{\partial x_j}\right) + \overline{\dot{\omega}'''_{Y_k}}$$

EDC combustion models

Liquid Phase: Thin Film Flow

Thickness

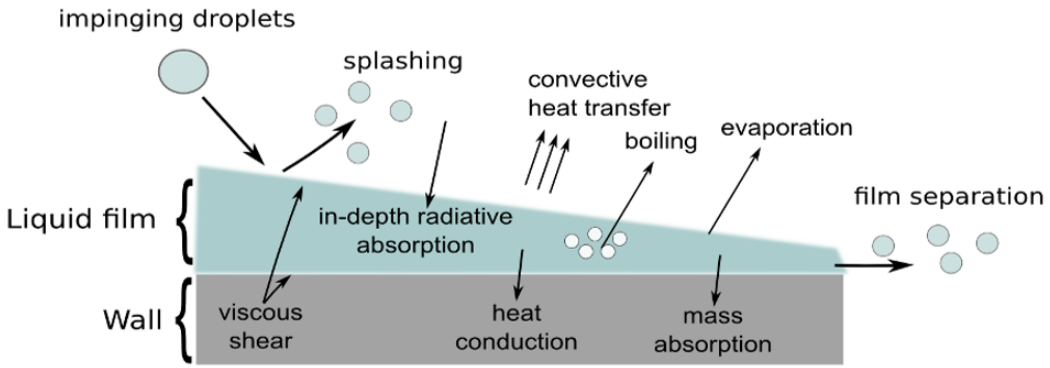
$$\frac{\partial \rho\delta}{\partial t} + \nabla_s \cdot [\rho\delta\mathbf{U}] = S_{\rho\delta}$$

Momentum

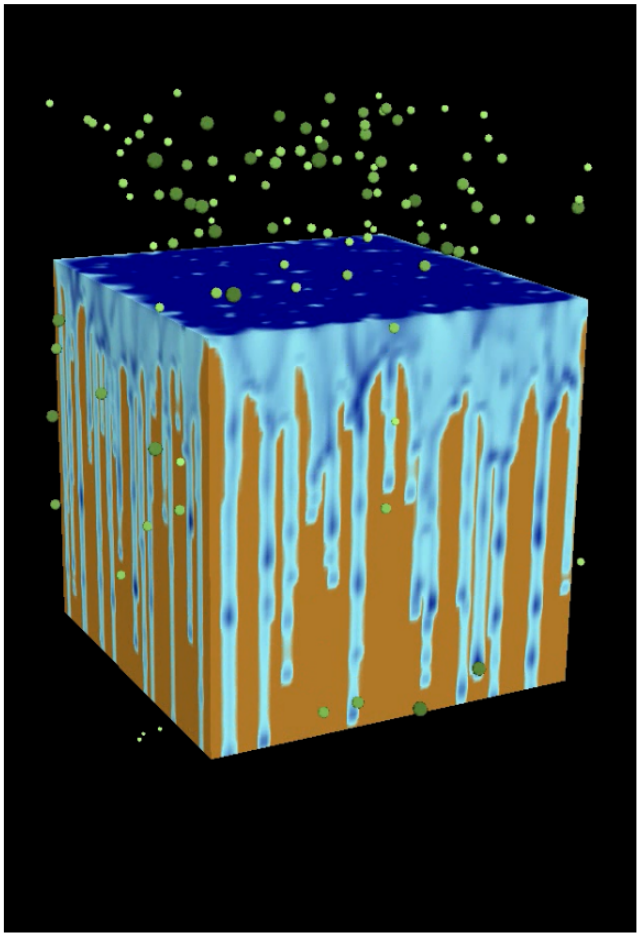
$$\frac{\partial \rho\delta\mathbf{U}}{\partial t} + \nabla_s \cdot [\rho\delta\mathbf{U}\mathbf{U}] = -\delta\nabla_s p + \mathbf{S}_{\rho\delta\mathbf{U}}$$

Enthalpy

$$\frac{\partial \rho\delta h}{\partial t} + \nabla_s \cdot [\rho\delta\mathbf{U}h] = S_{\rho\delta h}$$



Meredith, et. al, 2011, *Fire Safety Science* **10**



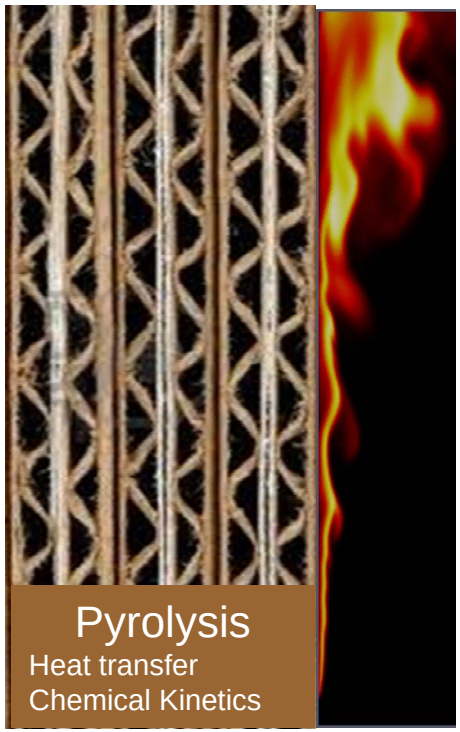
Solid Phase: Pyrolysis

- Heat transfer and chemical process

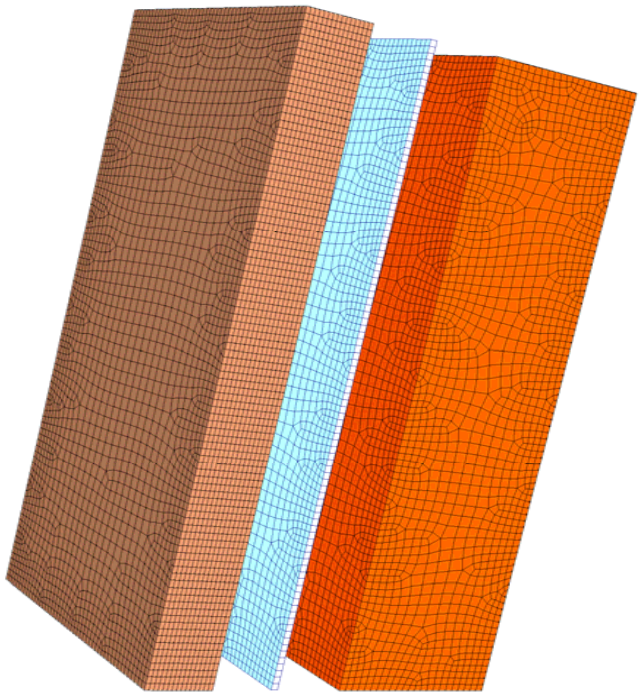
$$Virgin \rightarrow \nu_c Char + \nu_g Gas$$

$$\dot{m}''' = -\rho A \exp\left(\frac{-E_a}{RT}\right)$$

$$\frac{\partial}{\partial t}\left(\rho_s Cp_s T\right) = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial \dot{q}_r''}{\partial x} + \dot{m}''' H_p$$



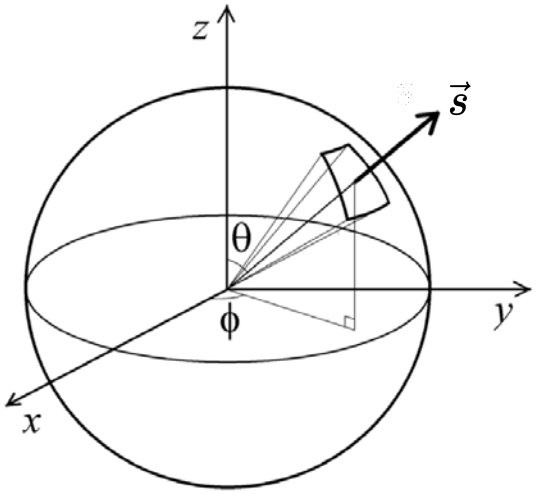
Coupling

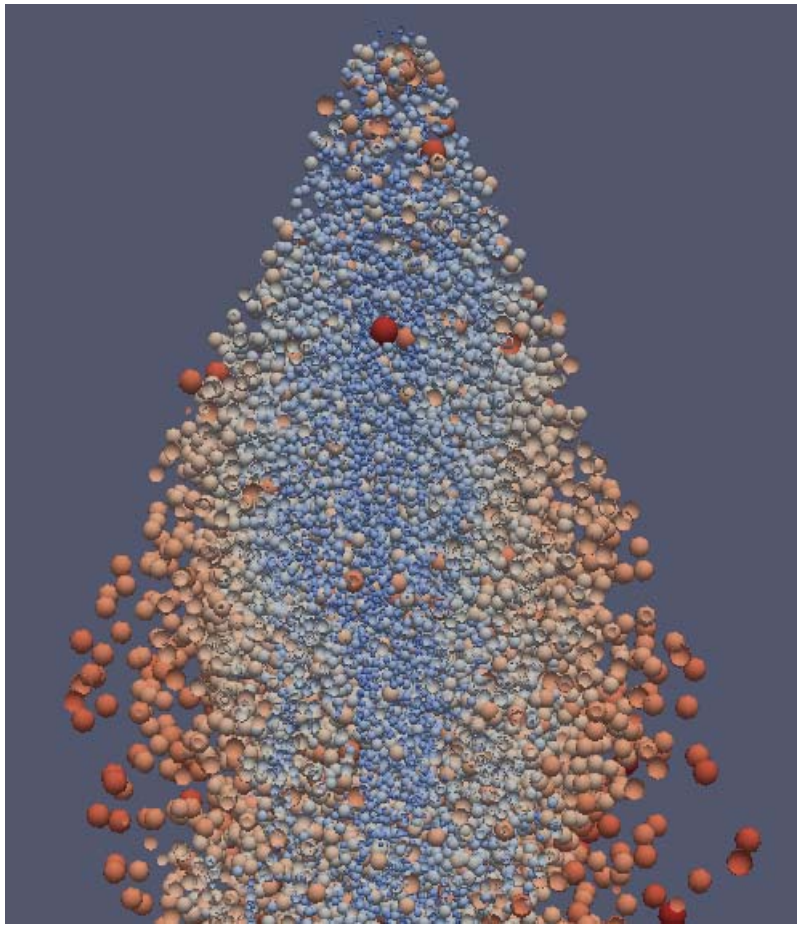


Solid Liquid Gas

Discrete Phase

- Droplet transport:
  - Lagrangian Particle Tracking
- Radiation:
  - Directional & spectral dependence

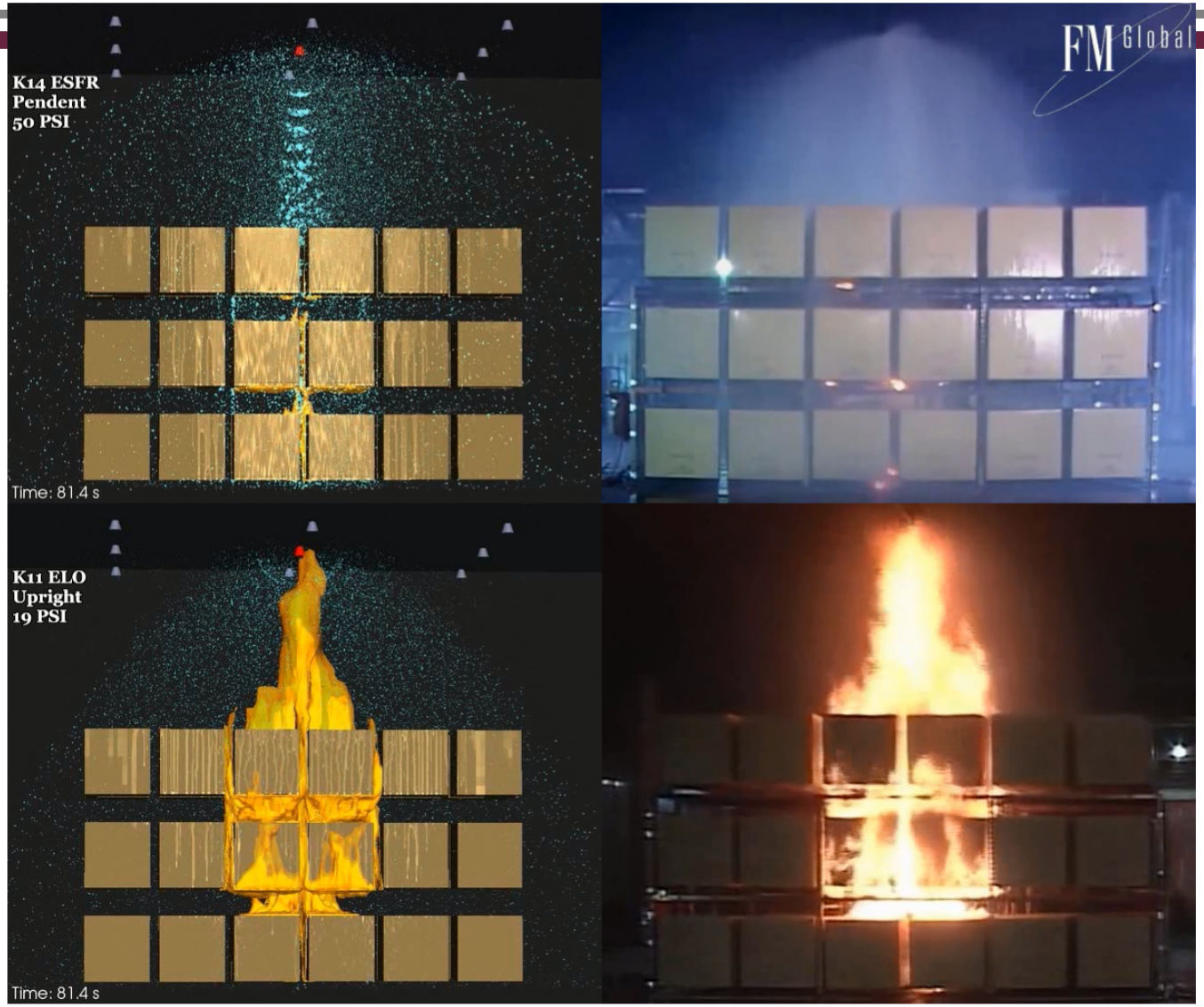




Scale Up

Quick Resp.
High flow rate

Regular Resp.
Low flow rate

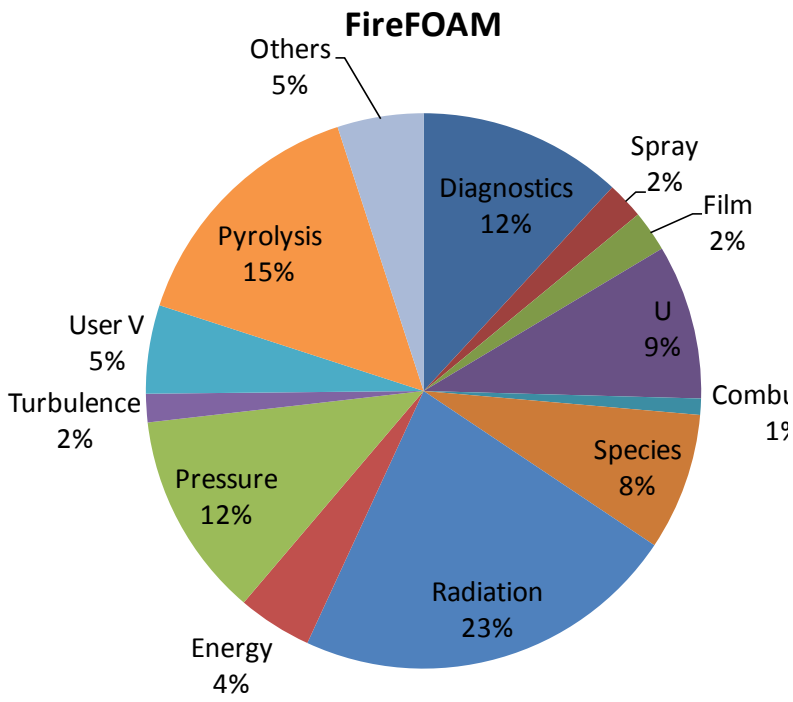


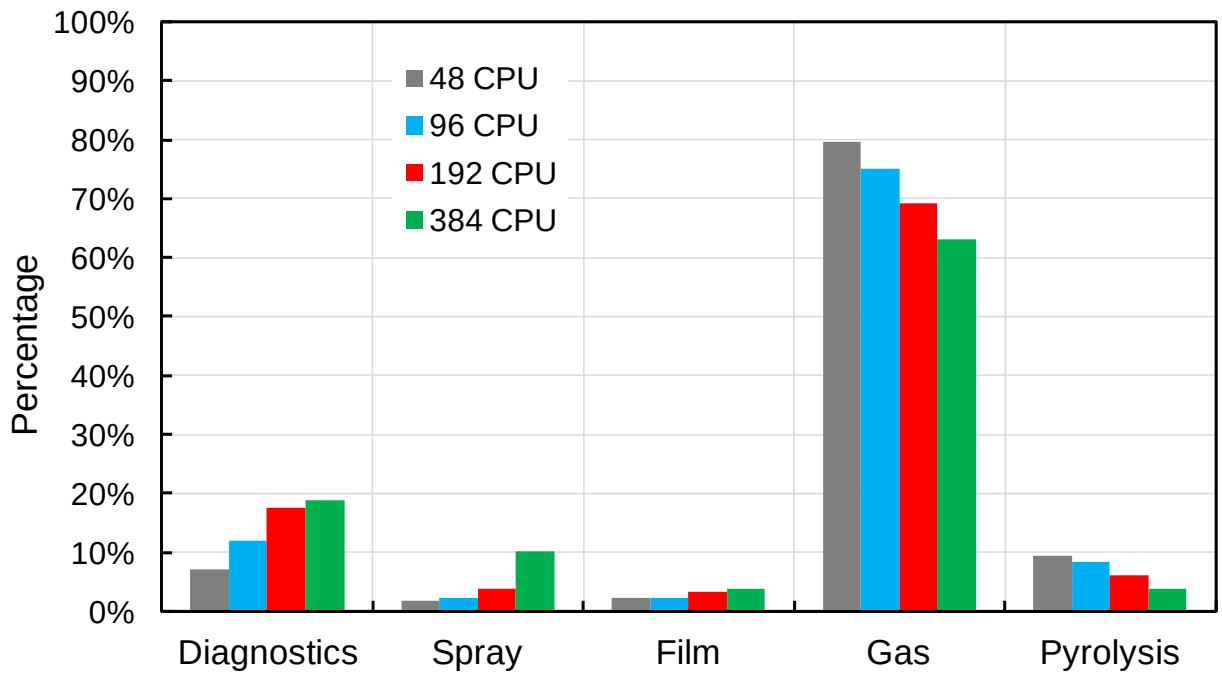
- Wang, Meredith, Zhou, et. al, 2014, *Fire Safety Science* **11**

Projects in OLCF

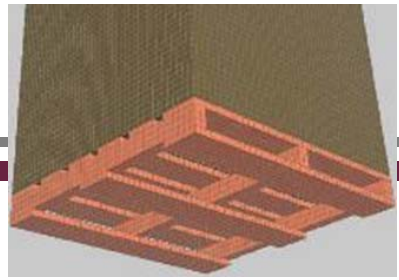
- Profiling
- Rack storage
- Roll paper
- Sprinkler atomization -- VOF
- IO improvement

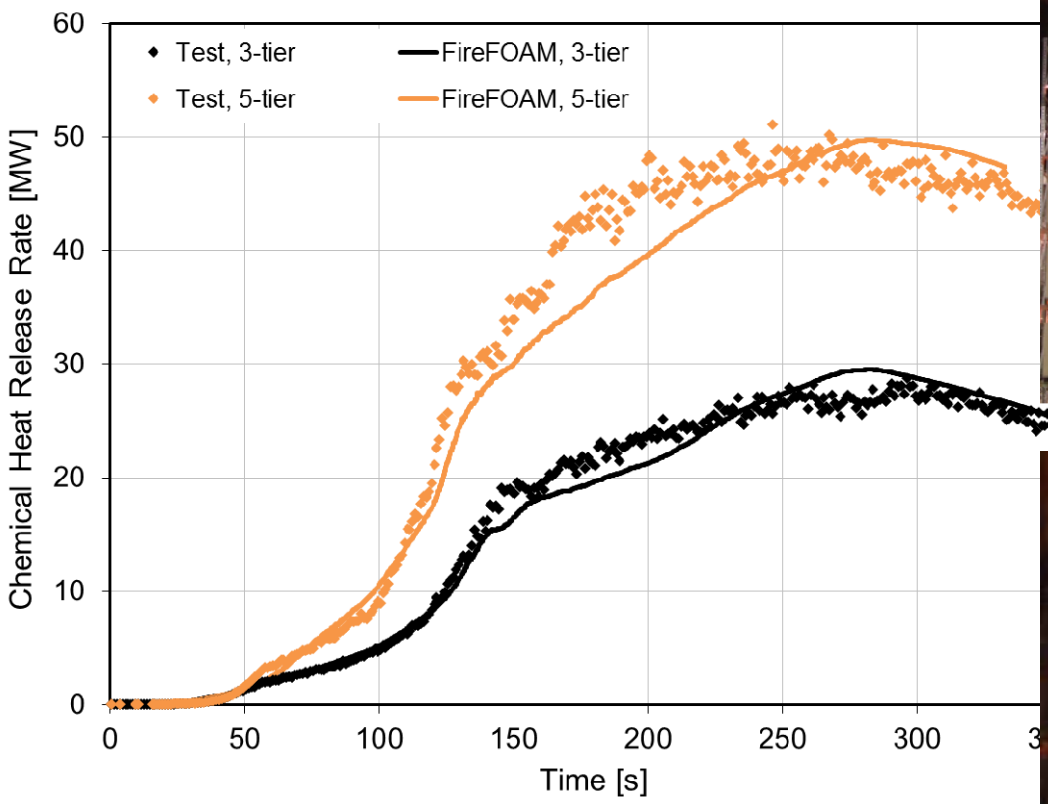
Profiling

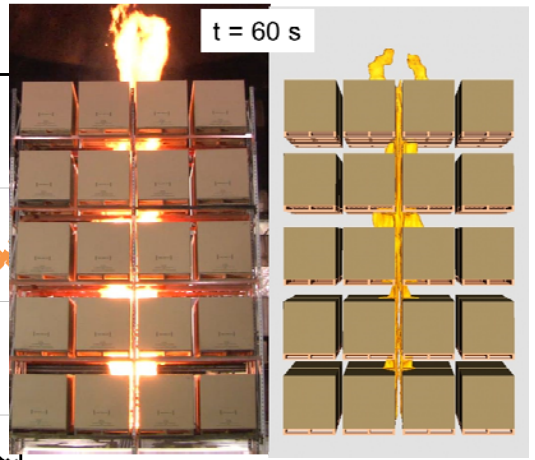


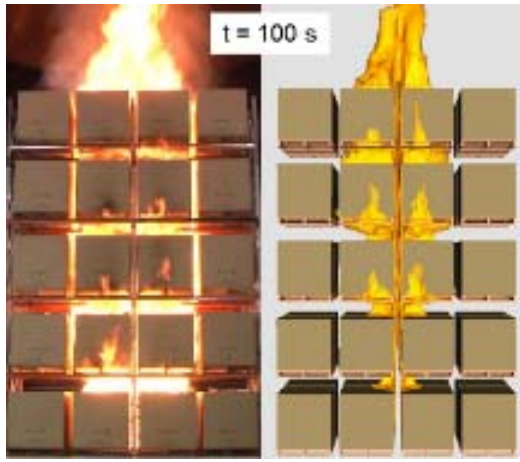


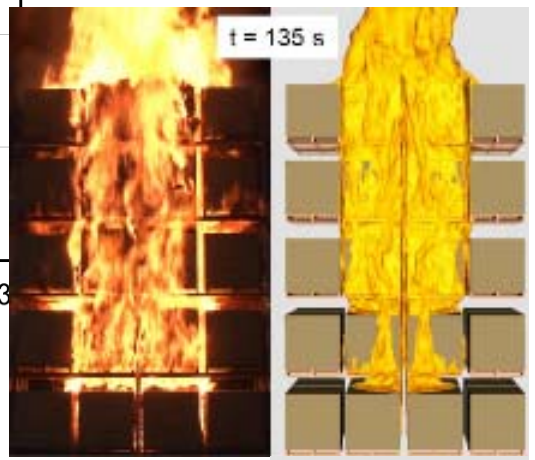
Rack Storage

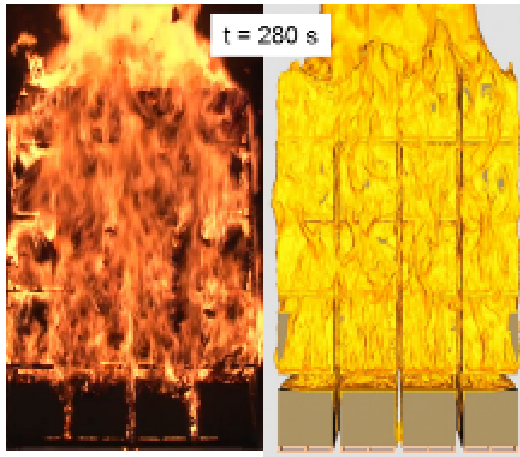




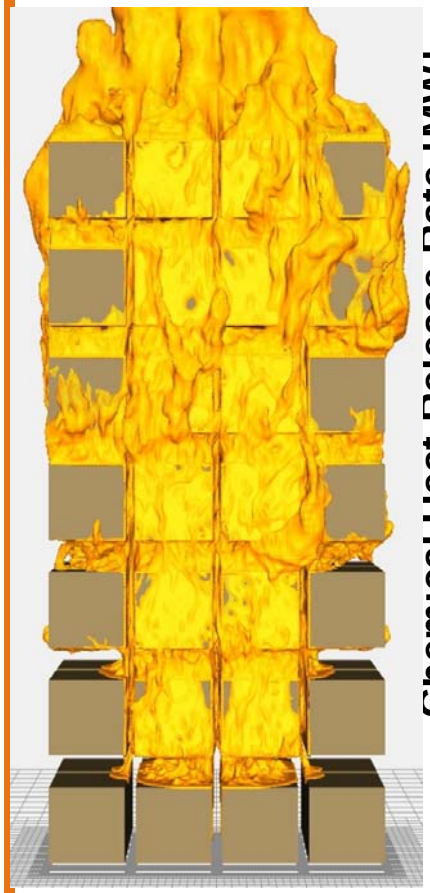


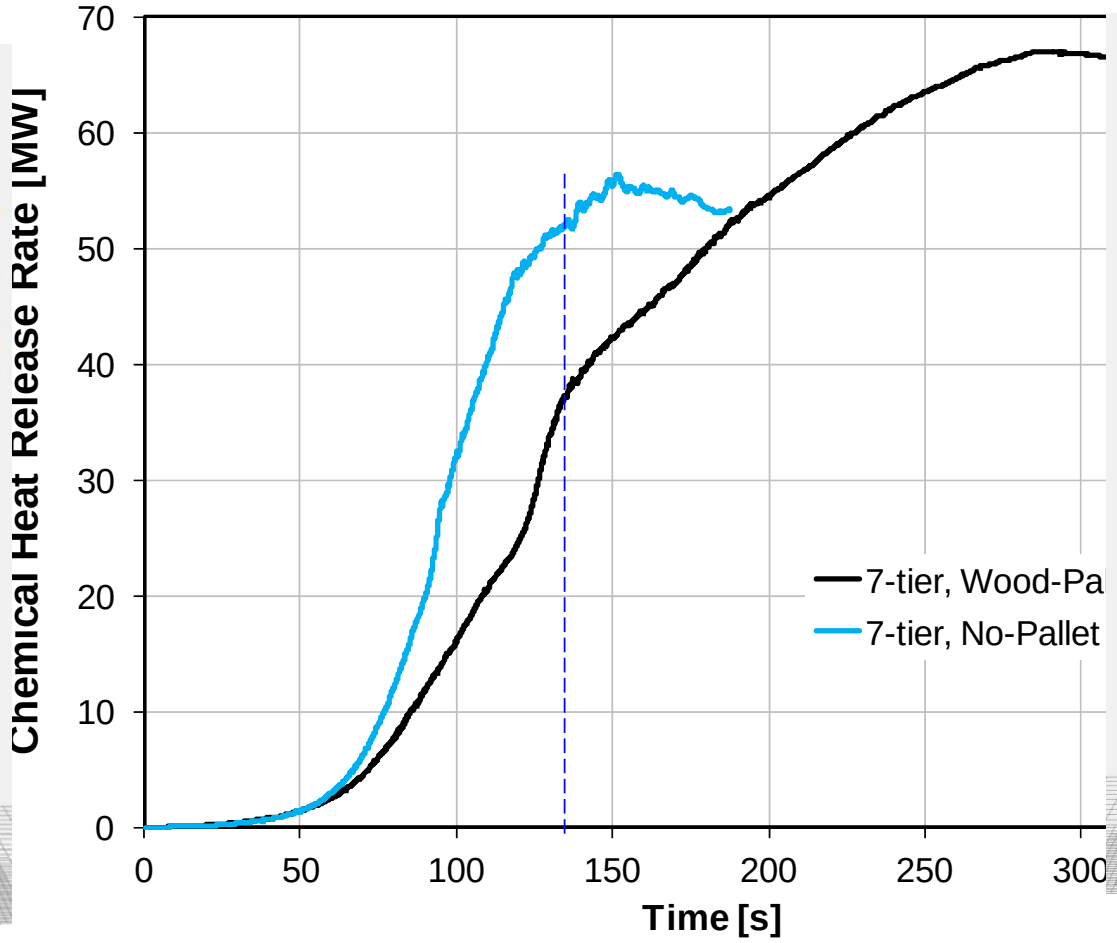


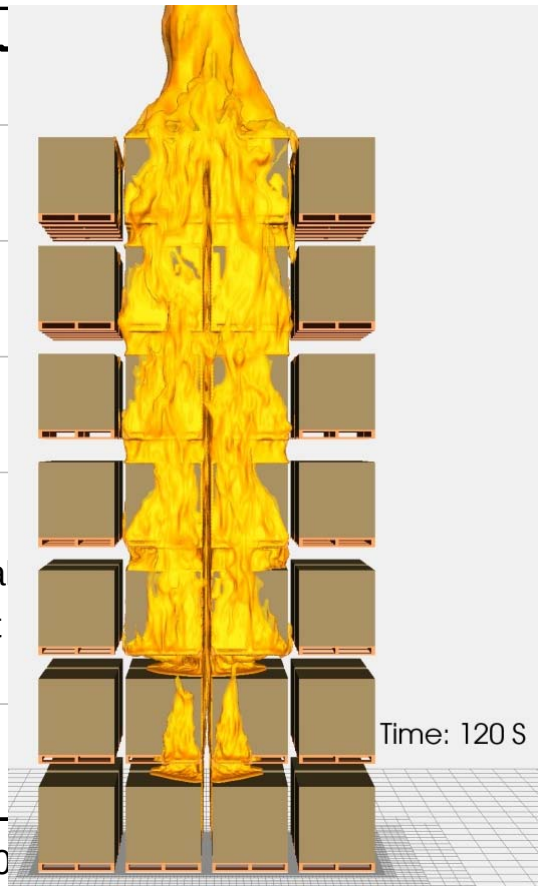




Scale Up

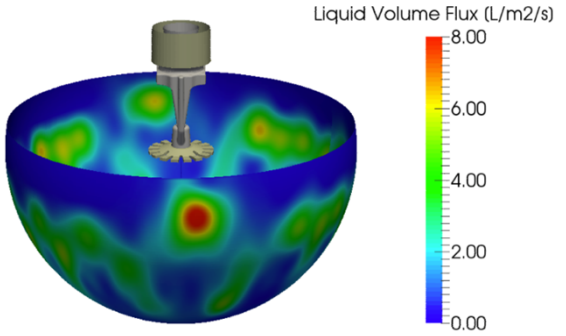


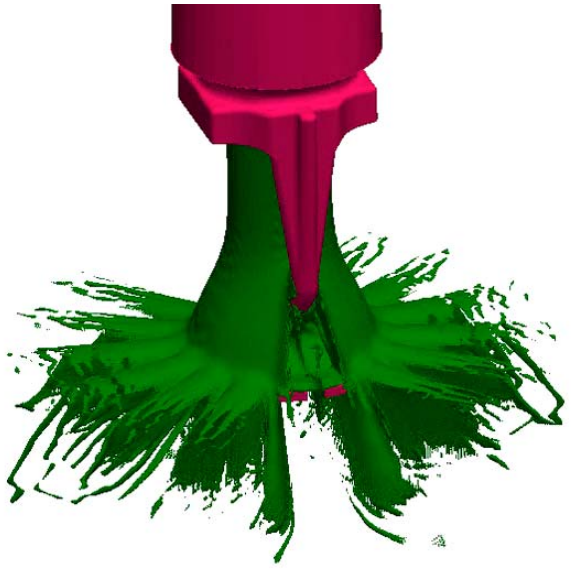




Sprinkler Atomization -- VOF

- Injection pattern
  - Velocity, droplet size, number, etc.
  - Laser diagnostics
  - Fire modeling inputs
- Volume of Fluid (VOF) approach
  - First principle
  - Computational intensive





IO Improvement

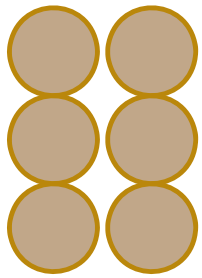
- OpenFOAM I/O
  - Many small files
  - Not scalable
- ADIOS
  - Adaptive I/O system
  - Minimizes input/output bottleneck

Norbert Podhorszki, Karl Meredith, Mark Olesen

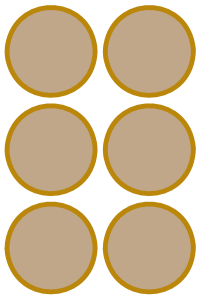
Paper Burns Well!

Fire Hazard – Test Experience

- >20MW, 1-5MW/s
  - Paper type: weight based
  - Storage Height
  - Storage configuration



Standard array



Open array

Protection Challenges

- Storage height increase
  - 15-20 meters or more
- Open array

Roll-paper Pyrolysis: Thick & Thin

- Thermally thick to thin transition
  - 1D -- Delamination
  - 2D – Peeling
- Fast burning of single paper sheet
  - Transition back to thick material
  - No char layer buildup, and heat transfer blockage

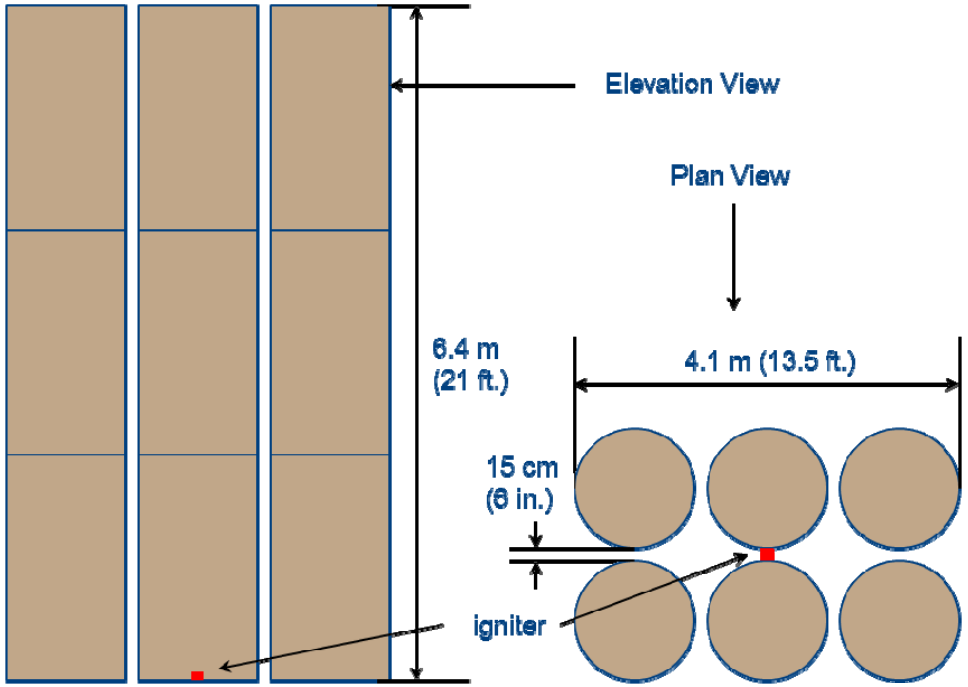
26lb paper, FPA, Bench scale

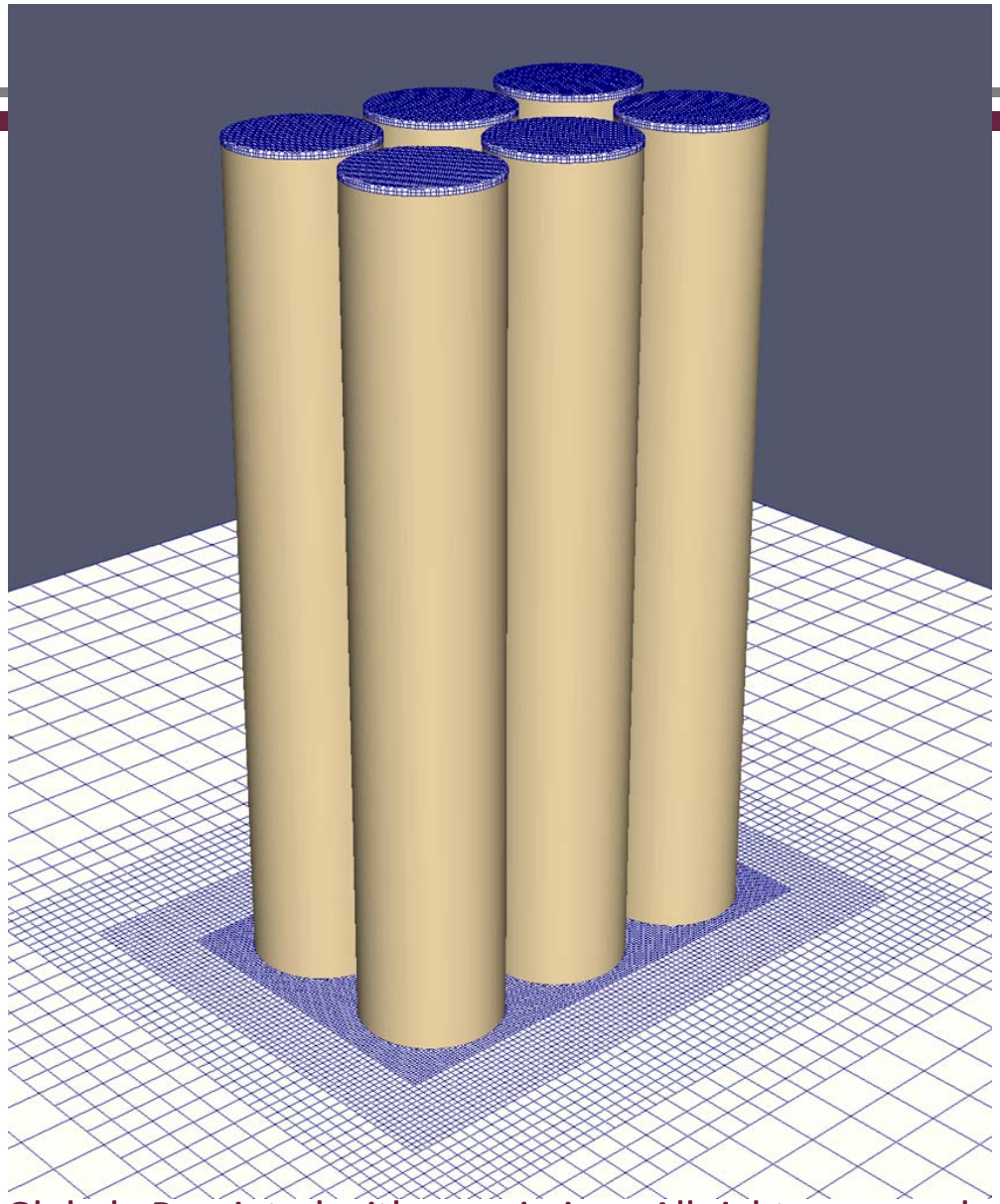
Zeng D., Chaos, M., Wang, Y., and Dorofeev S.B., "Experimental and Pyrolysis Modeling Study of Delaminating Materials" Proceedings of the 14th International Conference on Fire and Materials, San Francisco, (2015) 285-299.

Calibration → Validation → Prediction

- 26-lb paper test matrix
  - Intermediate-scale parallel roll
    - 2.13m (1-roll high)
  - Open Array
    - 4.26 m (2-roll high)
    - 6.39 m (3-roll high)
    - 8.52 m (4-roll high)
  - Standard Array
    - 6.39 m (3-roll high)

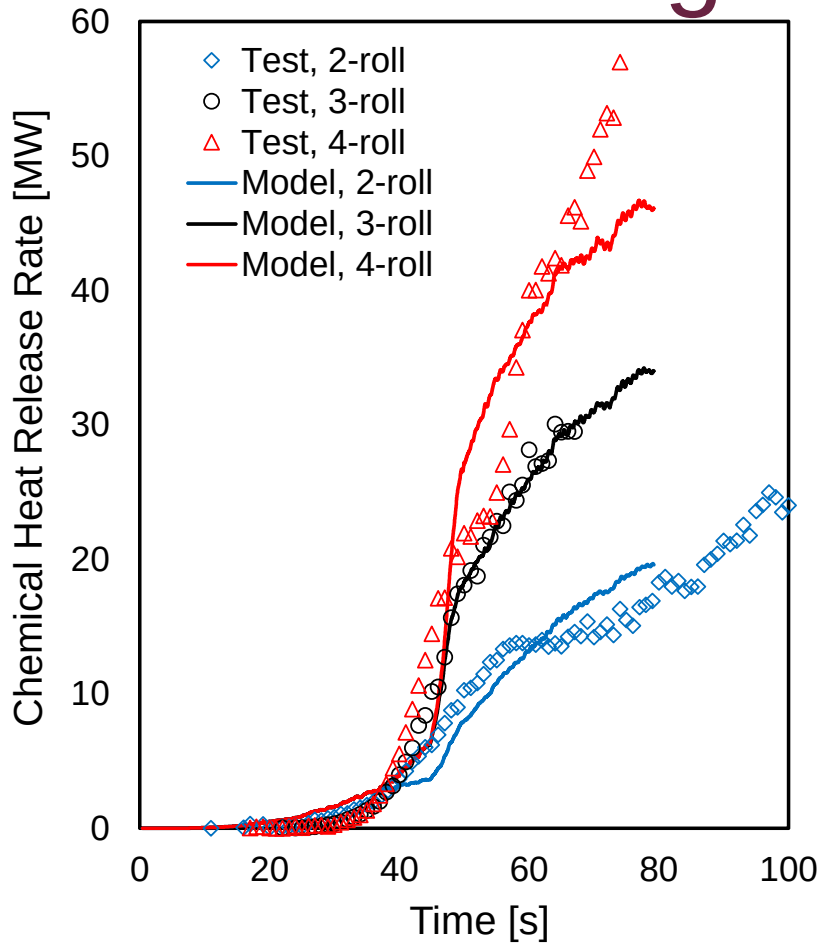
Mesh

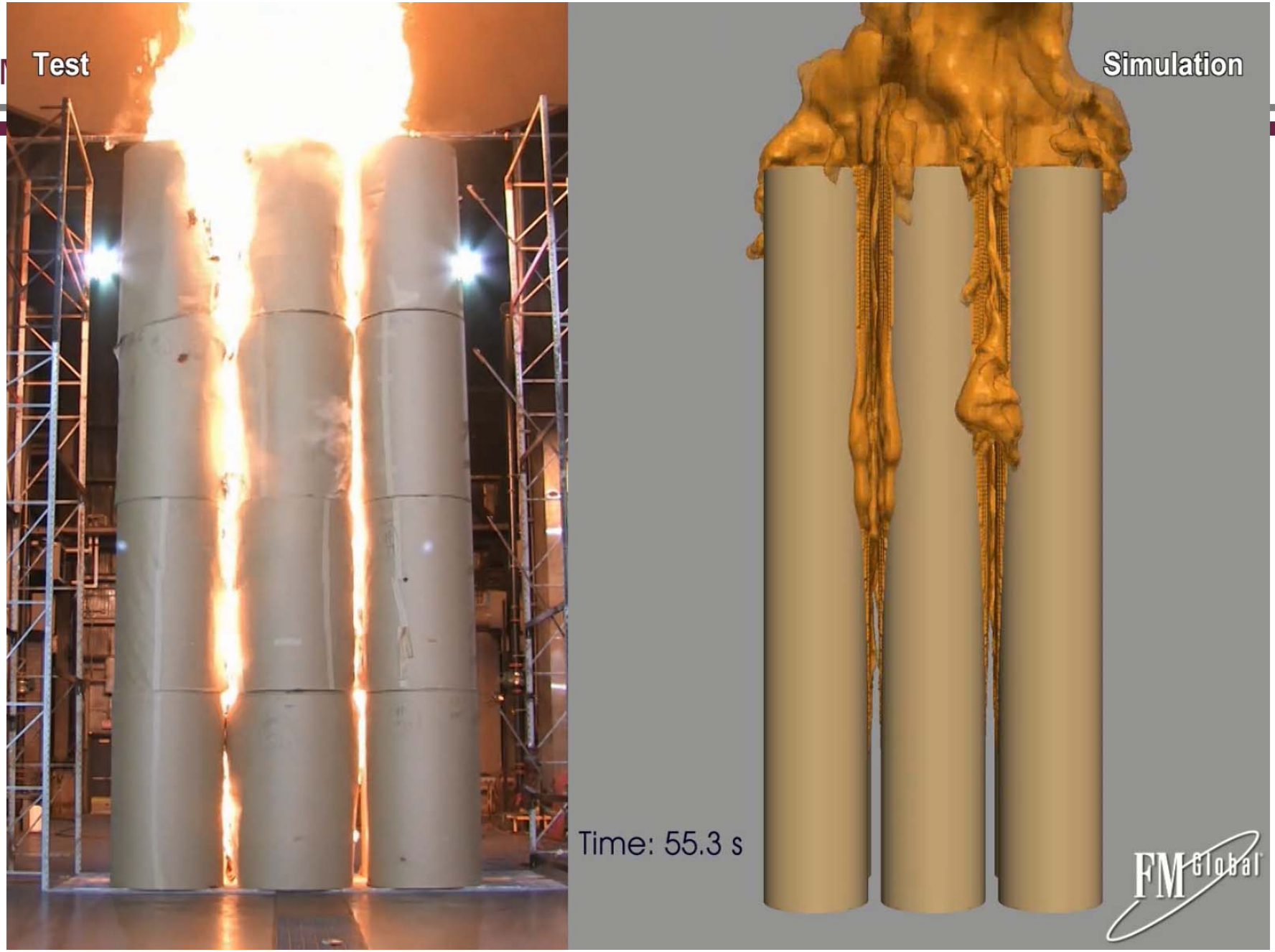




HRR Prediction for Different Heights

Peak Fire Growth Rate (MW/s) 5 seconds average		
H	**Model**	**Test**
4.26 m	**0.81**	**0.67**
6.39 m	**2.1**	**1.7**
8.52 m	**3.5**	**2.78**




Test
Simulation
Time: 55.3 s
FM Global


Time: 50.6 s

HPC for Industrial CFD

- I/O and in situ diagnostics
- GPU
  - Pressure Poisson Solver
  - Lagrangian droplet
  - Thermal radiation
- Broader industrial user base of OpenFOAM

Acknowledgement

- OLCF Staff
  - Suzy Tichenor
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  - Ramanan Sankaran
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  - Many others ……
- Team at FM Global
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  - Ning Ren
  - Prateep Chatterjee
  - Ankur Gupta
  - Sergey Dorofeev
  - Many others ……

Thanks!

Questions?