A Numerical Study on the Effect of Ceiling Slope on Sprinkler Activations and Spray Transport

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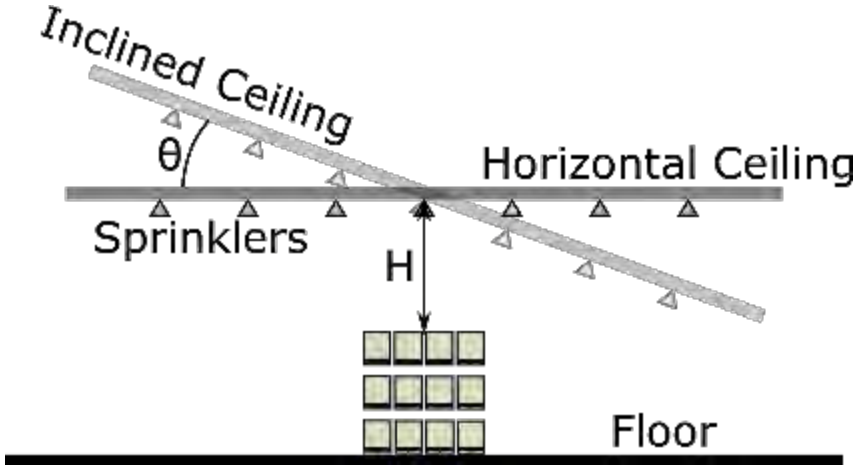
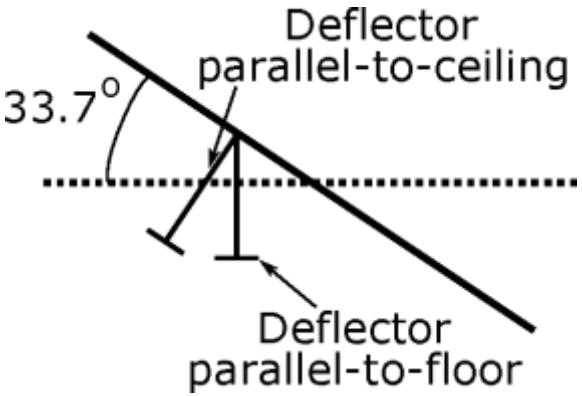
Fire Hazards & Protection Area

Background

- Limited prior research related to protection of storage under ceilings with slopes > 2/12 (9.5°)
- Sprinkler activation pattern relative to fire source location
- Optimal sprinkler installation orientation
- Numerical modeling would provide understanding of protection challenges
  - ceiling slope
  - sprinkler type and orientation





Collaborative Research

FM Global

THE FIRE PROTECTION RESEARCH FOUNDATION
Research in support of the NFPA mission

PIRG

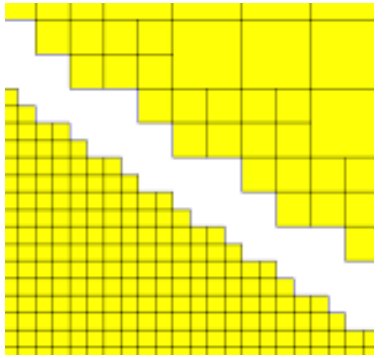
CUSTOM SPRAY SOLUTIONS

Introduction

- FPRF project on “Protection of Storage Under Sloped Ceilings – Phase 1”
  - support NFPA 13 in development of new protection requirements for sprinkler installation
  - phase 1 aim to develop a plan for future research
  - FM Global conducted the numerical modeling
  - CSS reviewed current storage configurations
- Numerical model (FireFOAM) based investigation of
  - effect of ceiling slope on sprinkler activations
  - spray transport to evaluate the effect of sprinkler installation orientations

Past Work

- Majority of experimental studies involved use of residential sprinklers, compartment or tunnel fire scenarios and/or weak plumes
  - Vettori (2003), Kung et al. (1991), Floyd et al. (2010), Bill and Hill (1995)
- Numerical modeling studies
  - attractive tool since large-scale testing can be prohibitively expensive
  - meaningful results provided models used within their limitations
  - HRR range of 100 kW – 1.1 MW
  - use of “saw-tooth” meshes
  - Vettori (2003), Floyd et al. (2010), Davis et al. (1994), Floyd et al. (2008), Carlsson (2013)



Objectives

- Evaluate sprinkler activation times and patterns from ceiling jet simulations
  - under unconfined ceilings having a range of slopes
  - with large-scale growing fires as plume sources (max 15 MW convective HRR)
- Evaluate effect of ceiling inclination on water mass flux distributions over a rack-storage commodity
- Understand the effect of sprinkler orientation
  - two sprinkler orientations: deflector parallel-to-ceiling or parallel-to-floor

Technical Approach

- Sprinkler activation simulations

Fire plume source		3-tier high rack storage of CUP commodity (growing fire HRR)					
Ceiling clearances (H)		3.05 m (10 ft)					6.1 m (20 ft)
Ceiling	inclinations (θ)	0°	9.5°	18.4°	26.6°	33.7°	18.4°
	slopes	0	0.167 2 / 12 in.	0.333 4 / 12 in.	0.5 6 / 12 in.	0.667 8 / 12 in.	0.333 4 / 12 in.

Technical Approach

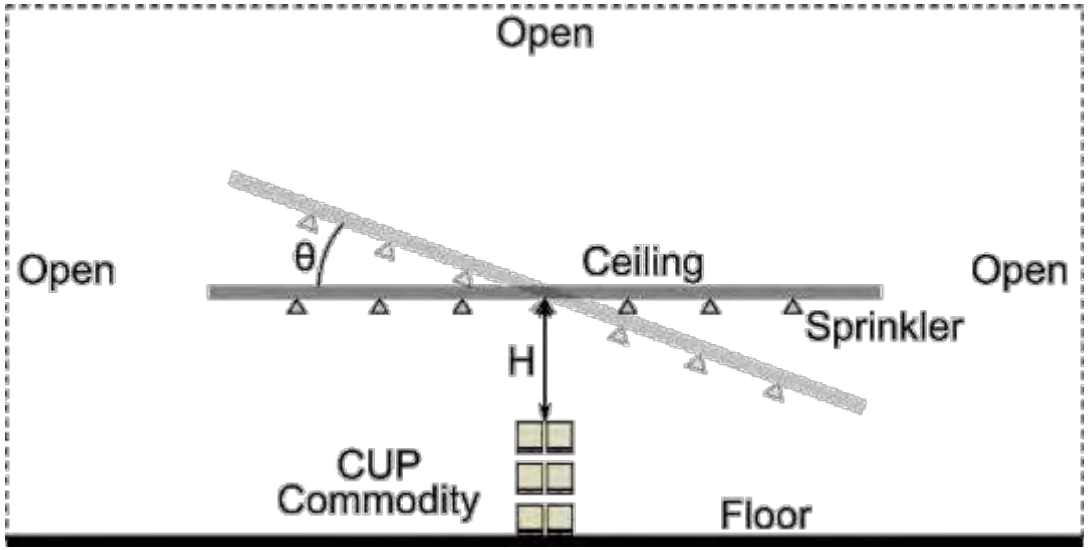
- Sprinkler sprays simulations

Fire plume source	3-tier high rack storage of CUP commodity (fixed HRR)		
Ceiling clearances (H)	3.05 m (10 ft)		
Ceiling **inclinations (θ)**	0°	18.4°	33.7°
Ceiling **slopes**	0	0.333	0.667
Sprinkler type	K200 lpm/bar$^{0.5}$ (K14.0 gpm/psi$^{0.5}$) at 3.4 bar (50 psi)		
Deflector orientations	Parallel to ceiling	Parallel to floor	

Numerical Model

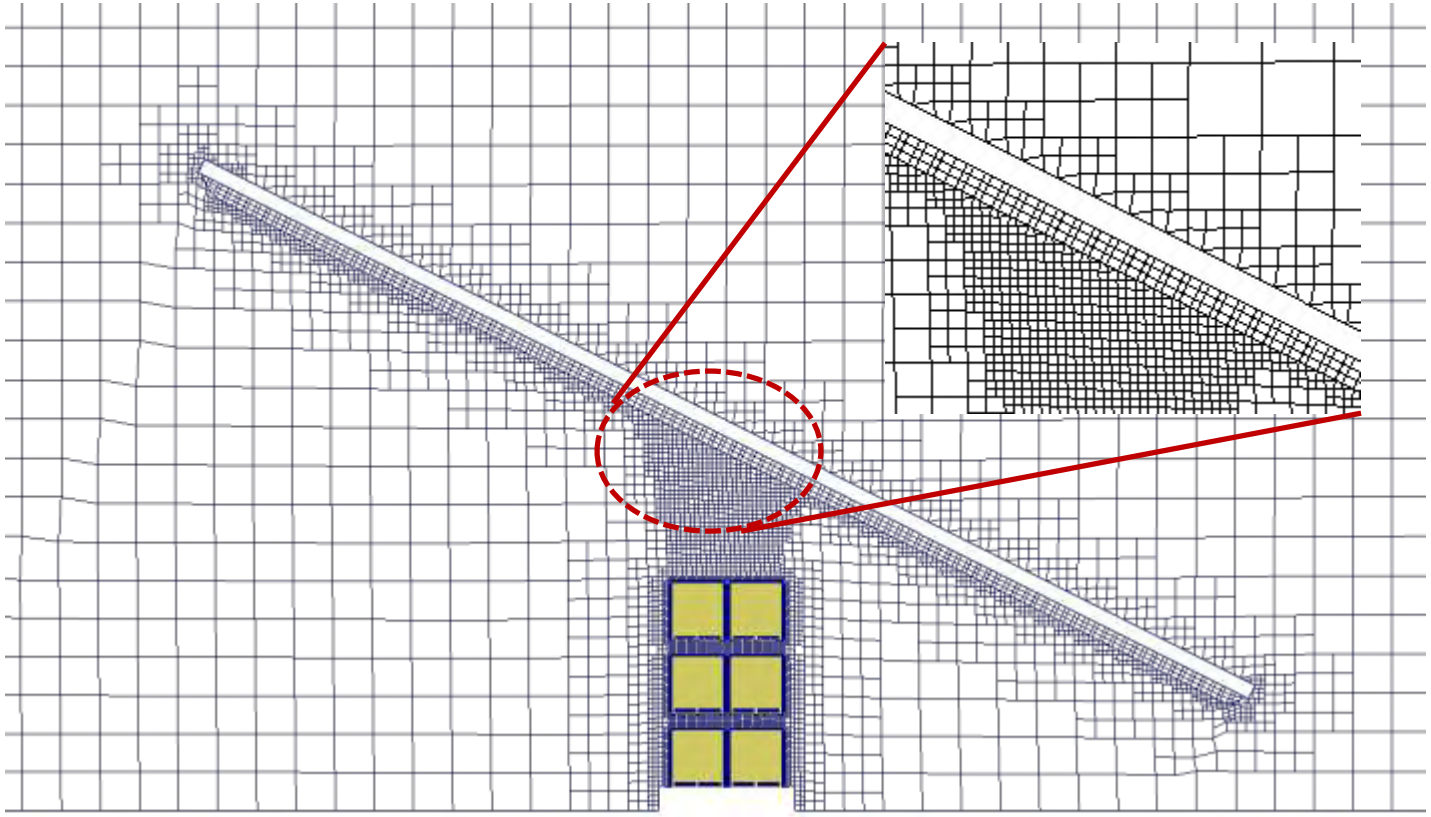
- FireFOAM 2.2.x solver (available from http://www.fmglobal.com/modeling)
- Combustion, turbulent flow and radiation models used for fire plume and ceiling jet
  - model validated against inclined ceiling jet temperature and velocity experimental data
- Lagrangian model for sprinkler spray transport
- No suppression simulations
- Pyrolysis model* used to
  - generate spatiotemporally varying fuel mass loss rates from the CUP commodity
  - time varying mapped BC applied

*developed by Dr. Ankur Gupta

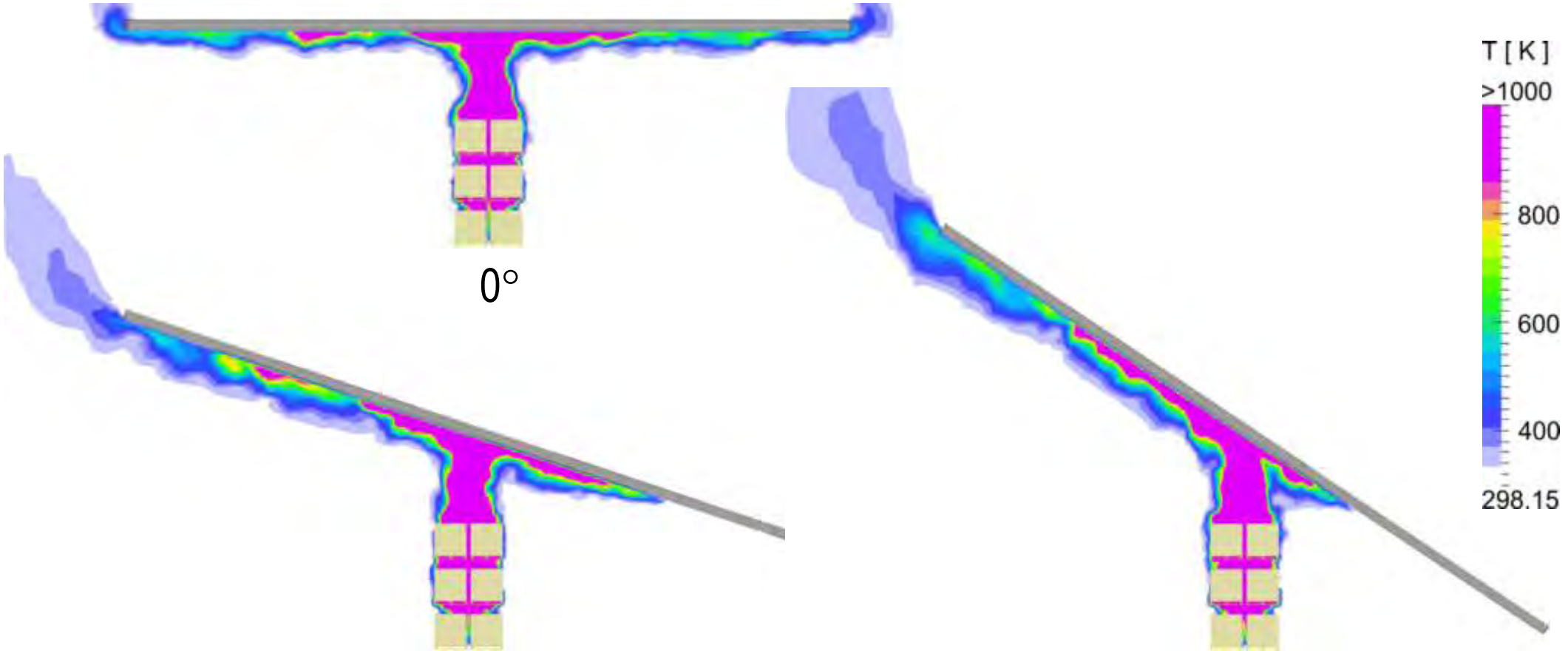


Numerical Model

- STL objects – ceiling, rack-storage array
- No saw-tooth mesh
- Boundary layer mesh below ceiling
  - $(4\ \text{in.})^3$ resolution
- Rack-storage mesh
  - $(1\ \text{in.})^3$ resolution



Instantaneous Temperature Snapshots (100 s after ignition)

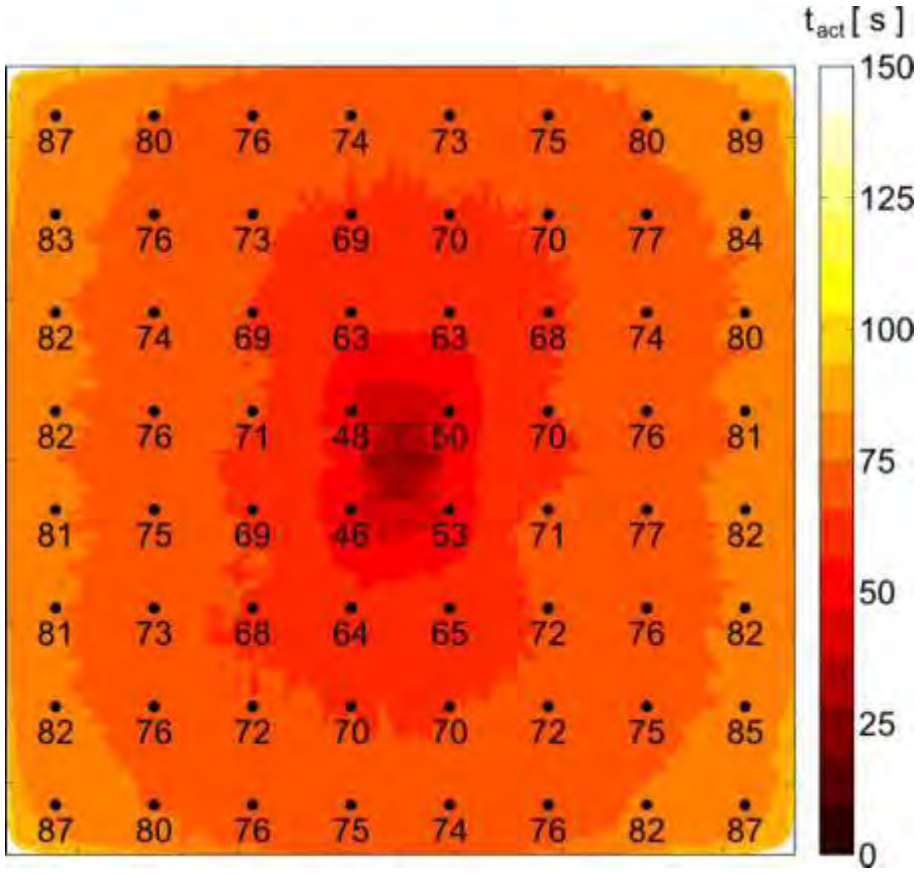


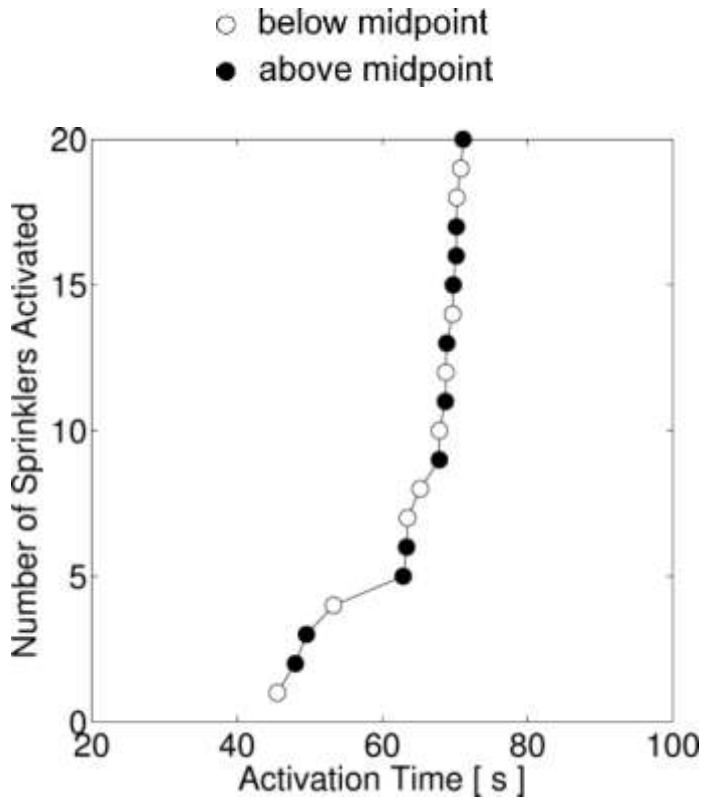
Sprinkler Activation Setup

- Activations 0.33 m (13 in.) perpendicular distance from ceiling
  - using a scalar variable for activation time (t_{act})
  - discrete sprinkler location activations (10 ft x 10 ft) extracted from t_{act} distributions
- Two types of sprinklers: QR/OT and SR/HT
- Assumption
  - no sprays: first-order effect of ceiling inclination on activation times and patterns

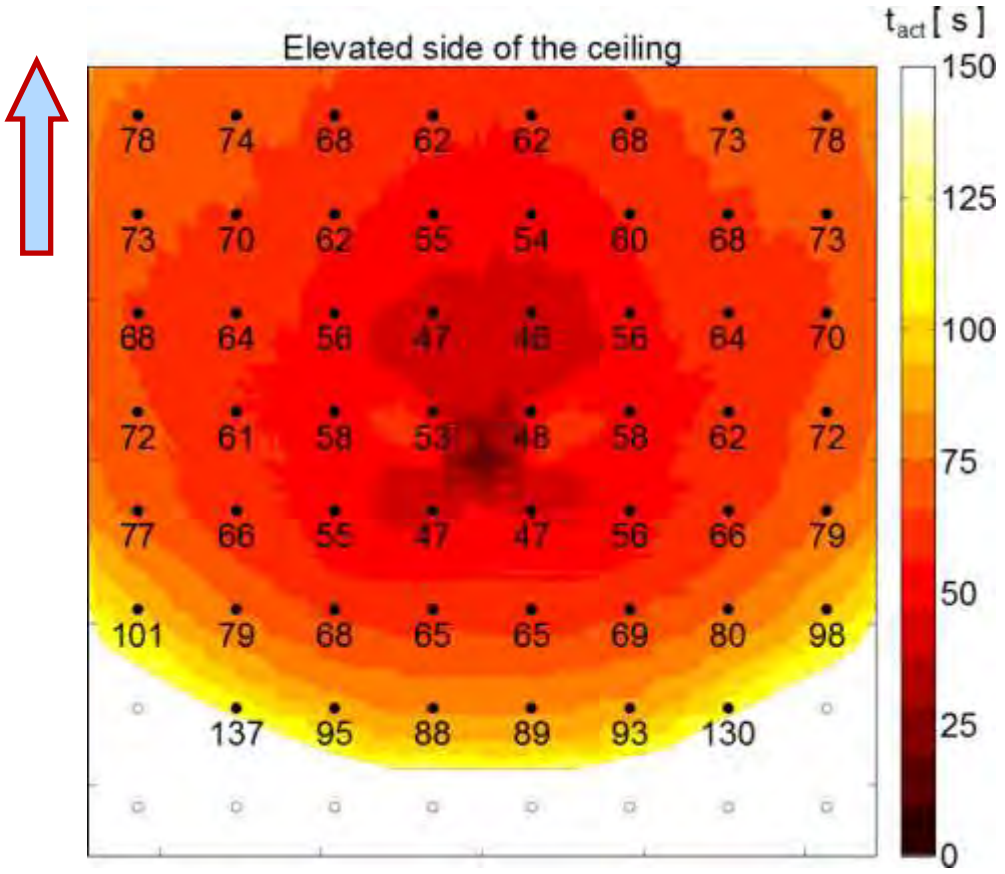
Name	Response	Activation Temperature K (°F)	RTI $(m\text{-}s)^{0.5}$ $((ft\text{-}s)^{0.5})$	C-Factor $(m/s)^{0.5}$ $((ft/s)^{0.5})$
QR/OT	Quick	347 (165)	30 (54)	0.22 (0.40)
SR/HT	Standard	414 (286)	119 (216)	0.95 (1.72)

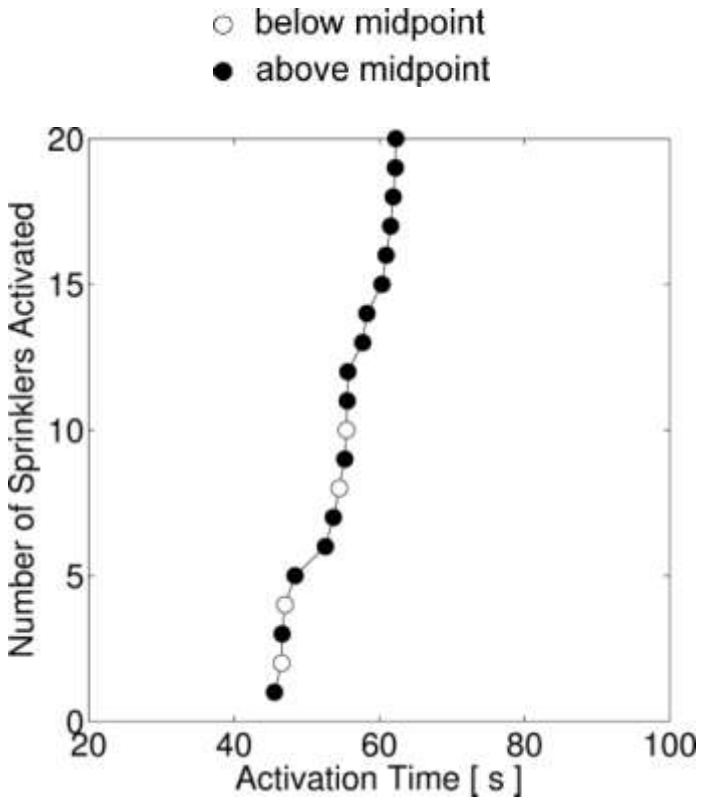
Sprinkler Activation Results (0°, 10 ft cl, QR/OT spk)



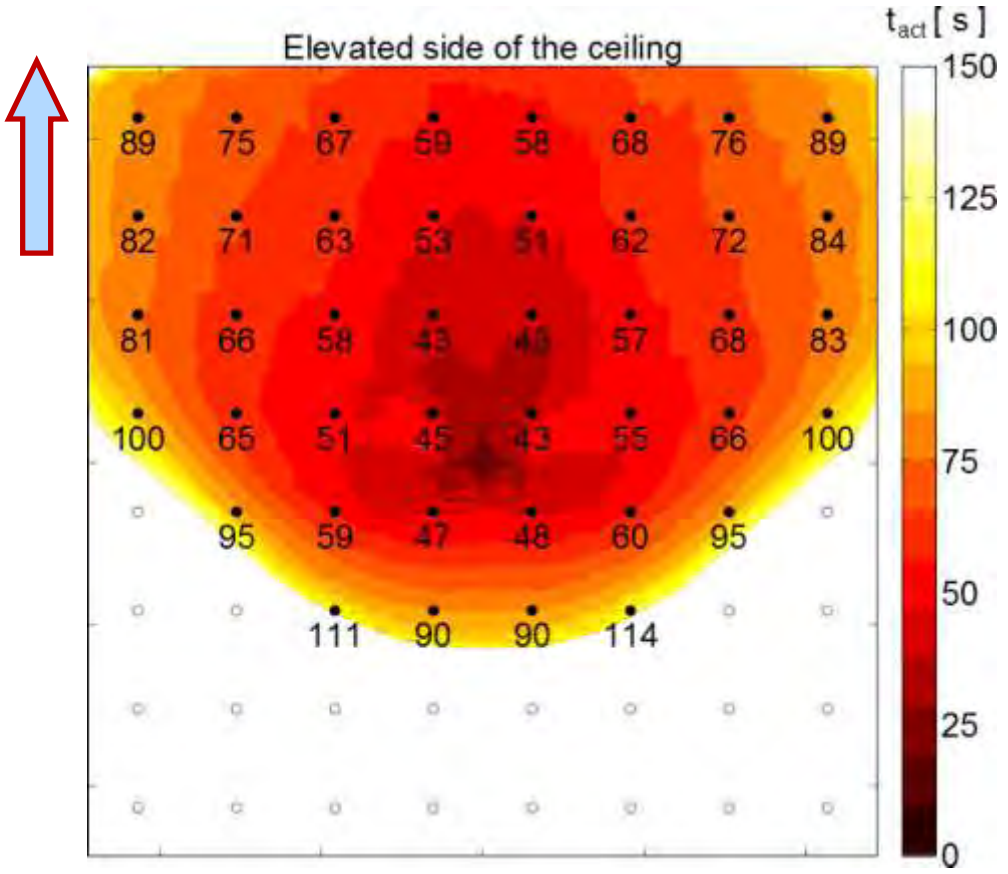


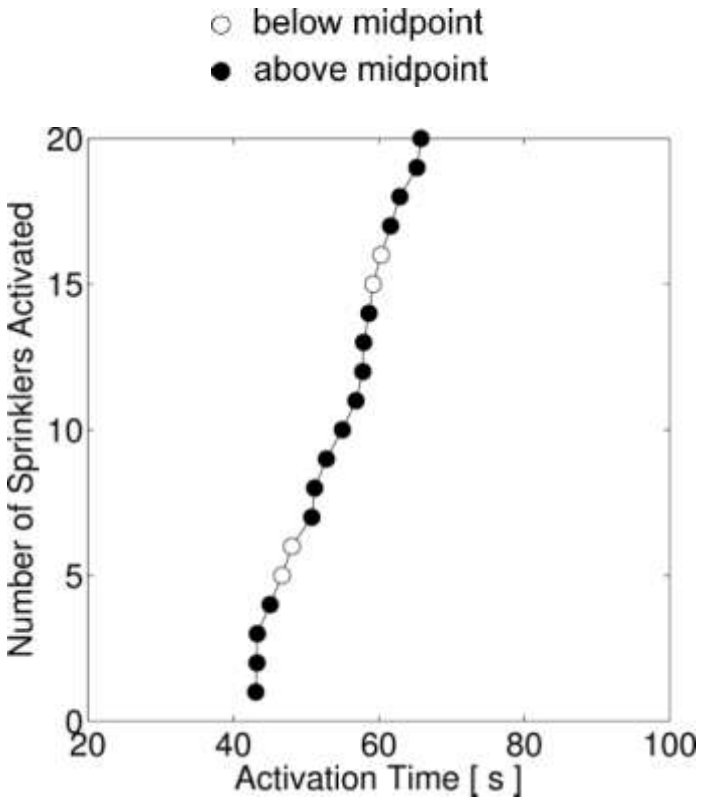
Sprinkler Activation Results (9.5°, 10 ft cl, QR/OT spk)



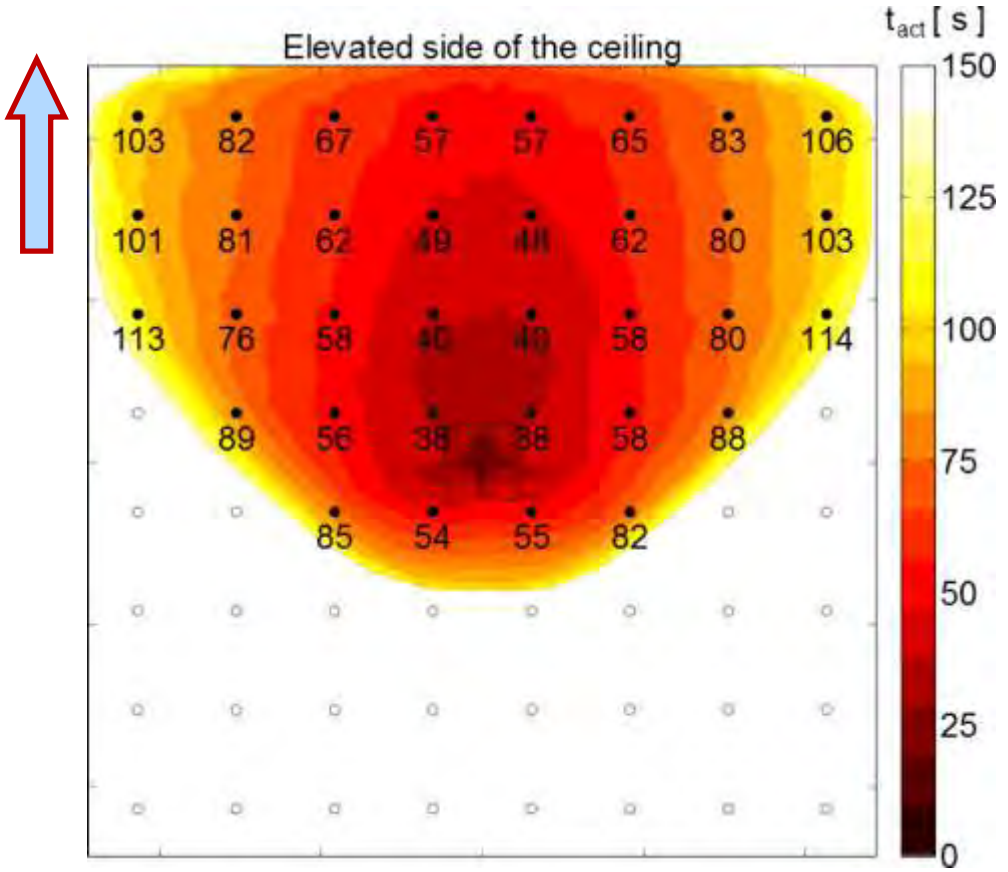


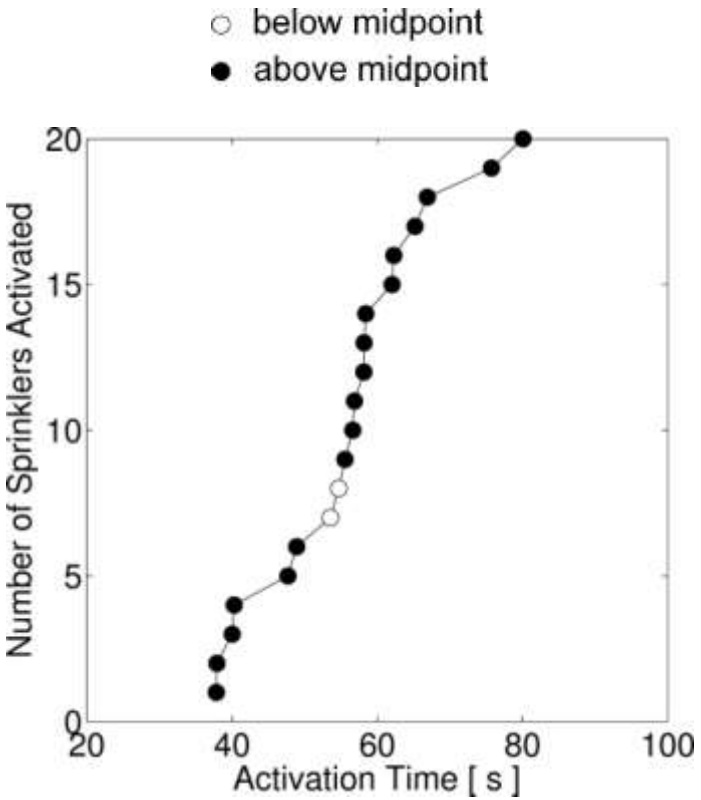
Sprinkler Activation Results (18.4°, 10 ft cl, QR/OT spk)



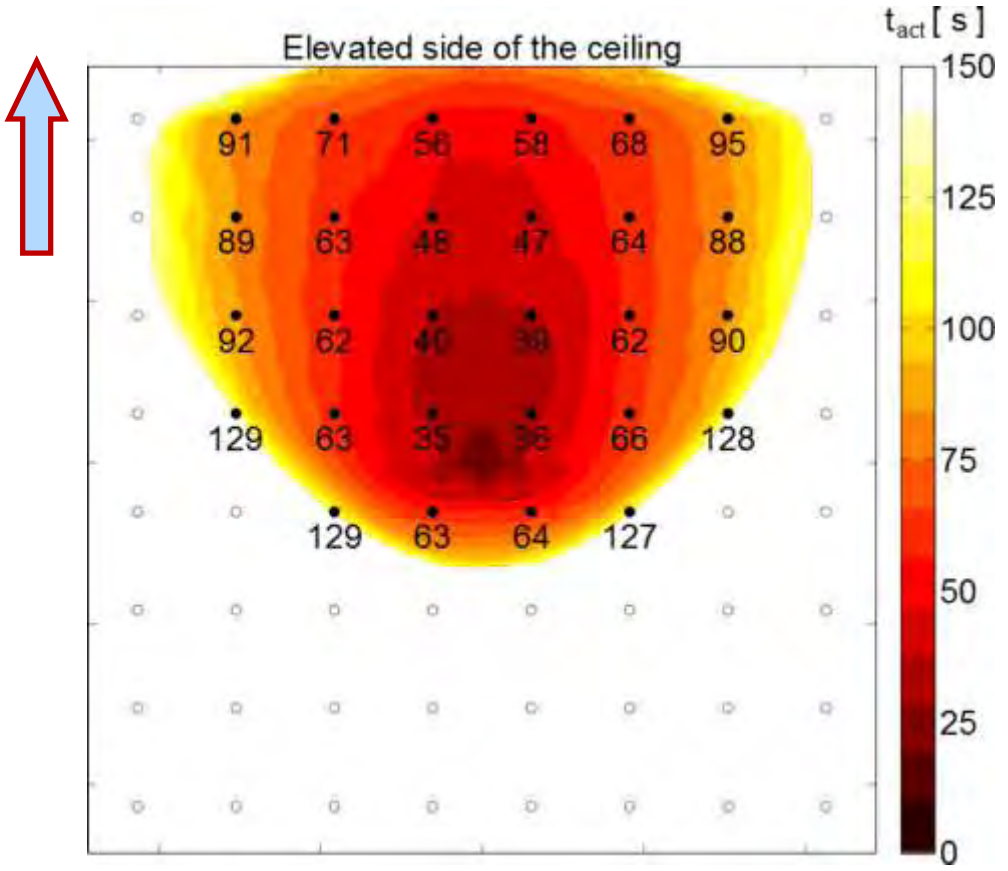


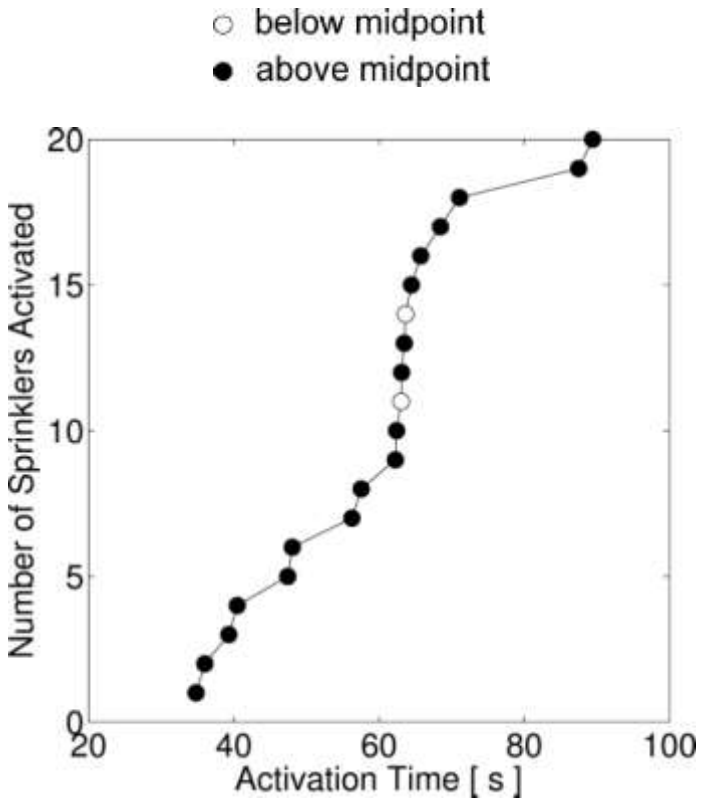
Sprinkler Activation Results (26.6°, 10 ft cl, QR/OT spk)



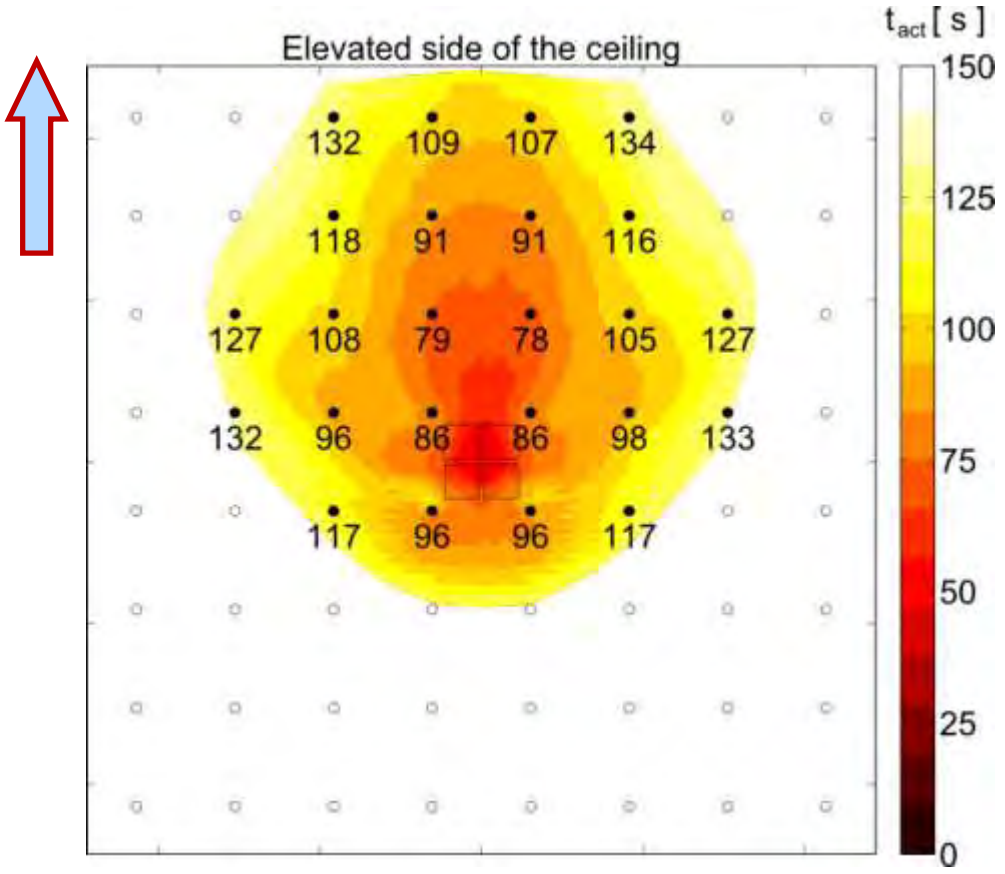


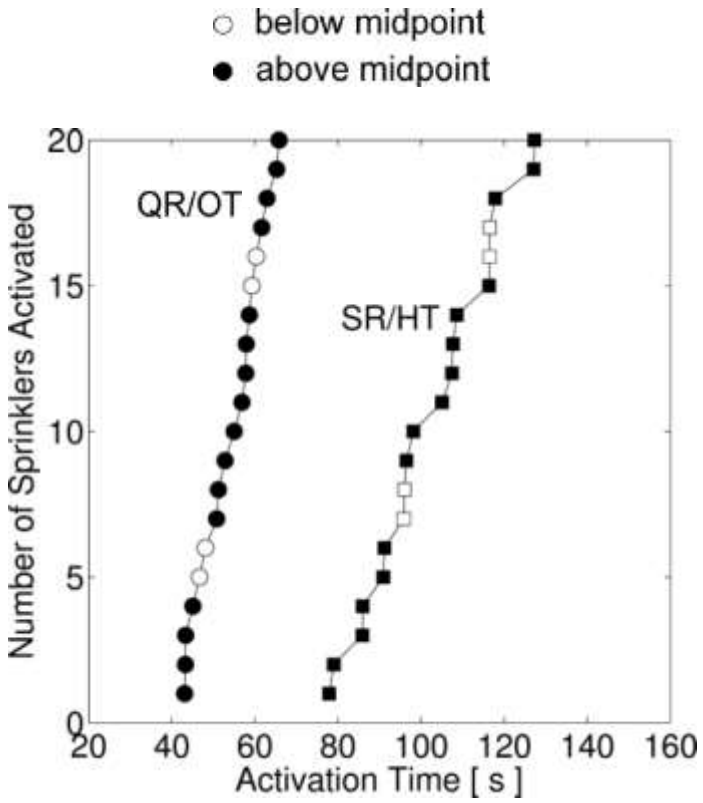
Sprinkler Activation Results (33.7°, 10 ft cl, QR/OT spk)



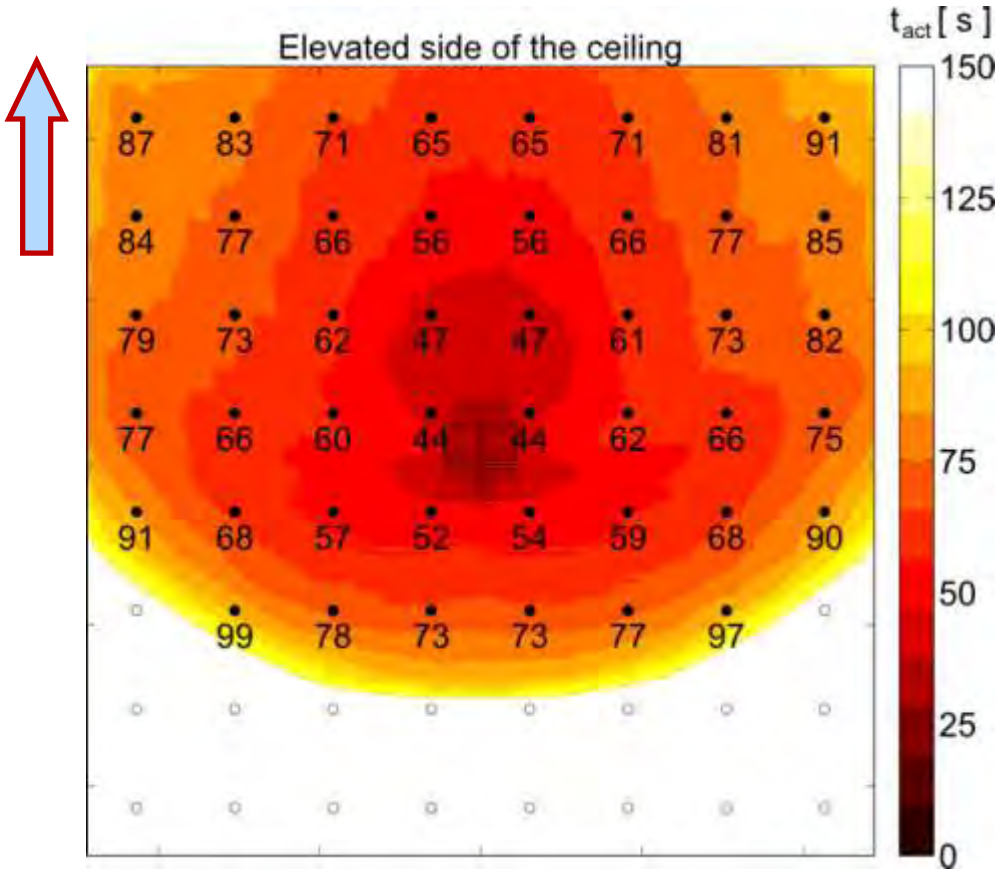


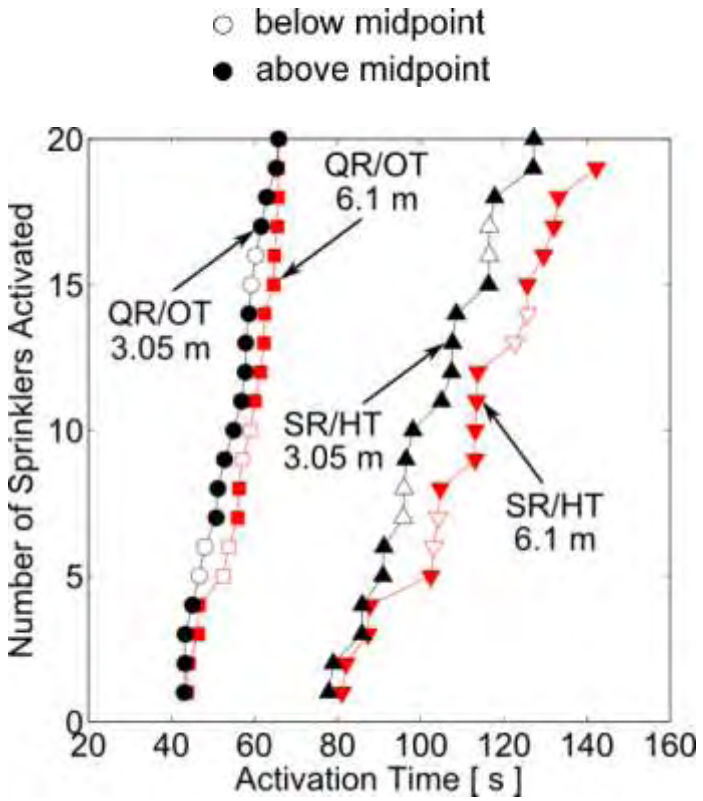
Sprinkler Activation Results (18.4°, 10 ft cl, SR/HT spk)





Sprinkler Activation Results (18.4°, 10 ft and 20 ft cl)





Sprinkler Activation Observations

- For QR/OT sprinklers, ceiling inclination ≤ 18.4°
  - similar activation times and patterns as horizontal ceiling
  - for four sprinklers immediately adjacent to fire source
- For inclinations ≥ 26.6°
  - significant activation delays on lower side of ceiling
  - number of activations on elevated side greatly exceed activations on lower side

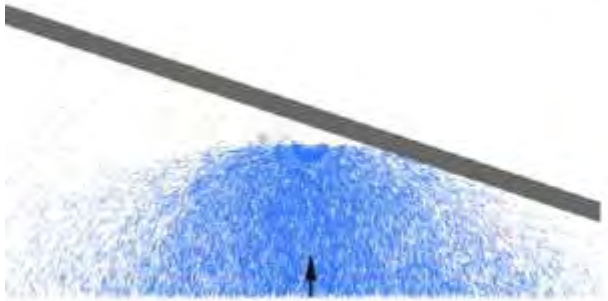
Sprinkler Activation Observations

- For SR/HT sprinklers
  - average activation delay for the four sprinklers increases for 18.4° case
  - four more activations on elevated side occur before sprinklers below lower side activate
  - activation pattern skewness accentuated
- For 18.4° inclination, increasing clearance from 10 ft to 20 ft, for four sprinklers surrounding the ignition location
  - average activation time delays of ~3 s (QR/OT) and ~5 s (SR/HT) occur
  - such delays may have adverse impact on protection design

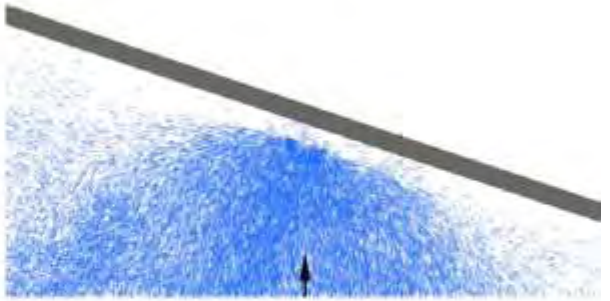
Spray Setup (Single Sprinkler)

- Irrespective of ceiling inclination, activation time for a QR/OT sprinkler located above the ignition location was 25 s
  - spray only simulations
  - with fire: convective HRR of 600 kW

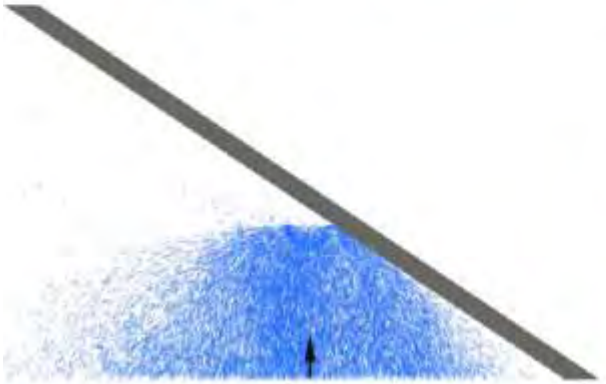
(a) 0°, deflector parallel to floor



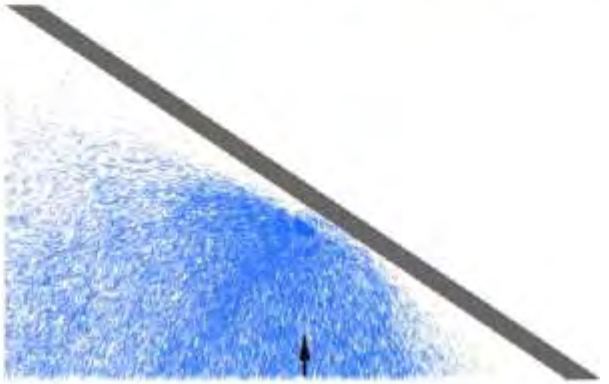
(b) 18.4°, deflector parallel to floor



(c) 18.4°, deflector parallel to ceiling



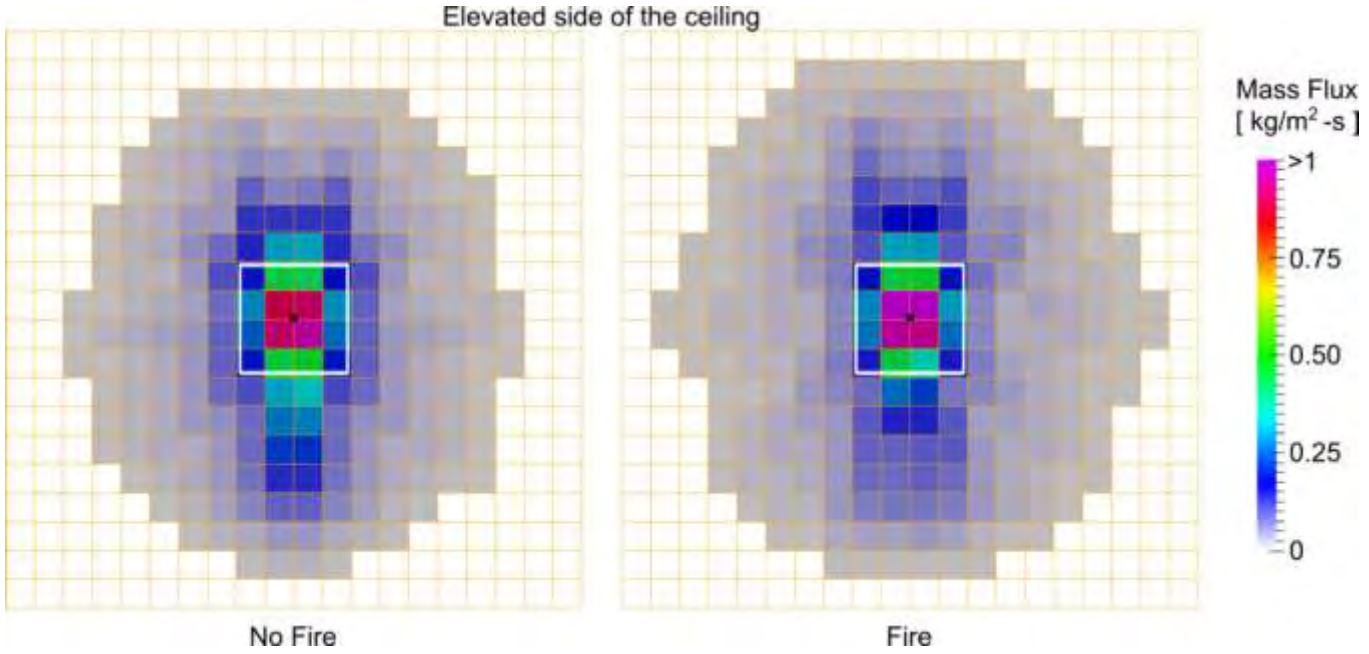
(d) 33.7°, deflector parallel to floor



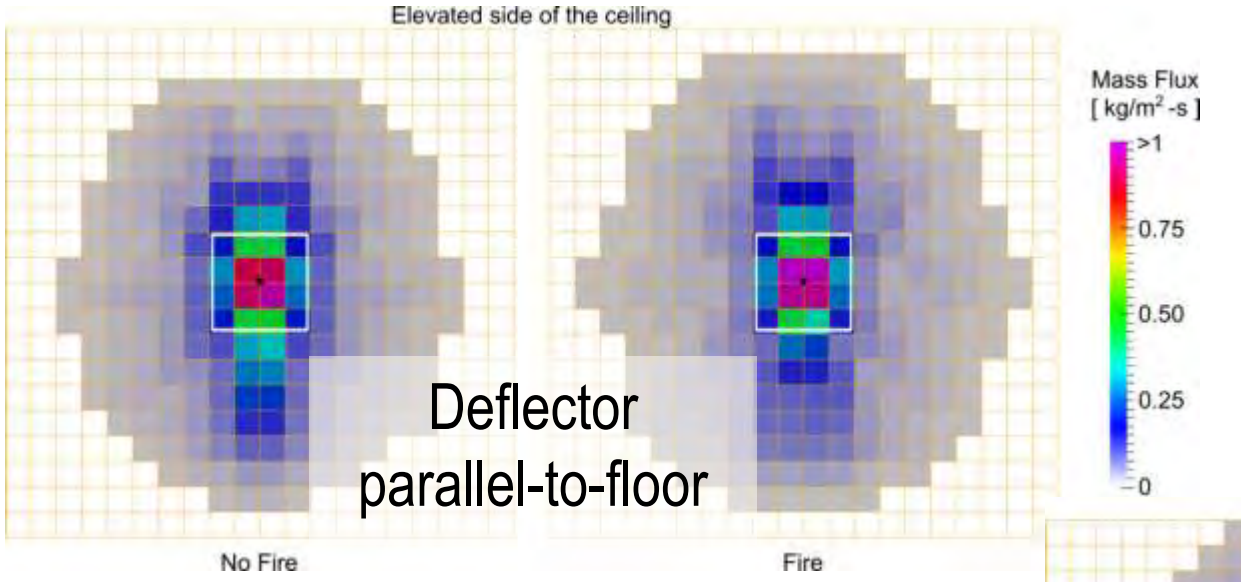
(e) 33.7°, deflector parallel to ceiling

Spray Results (Single Sprinkler, 18.4°, deflector parallel-to-floor)

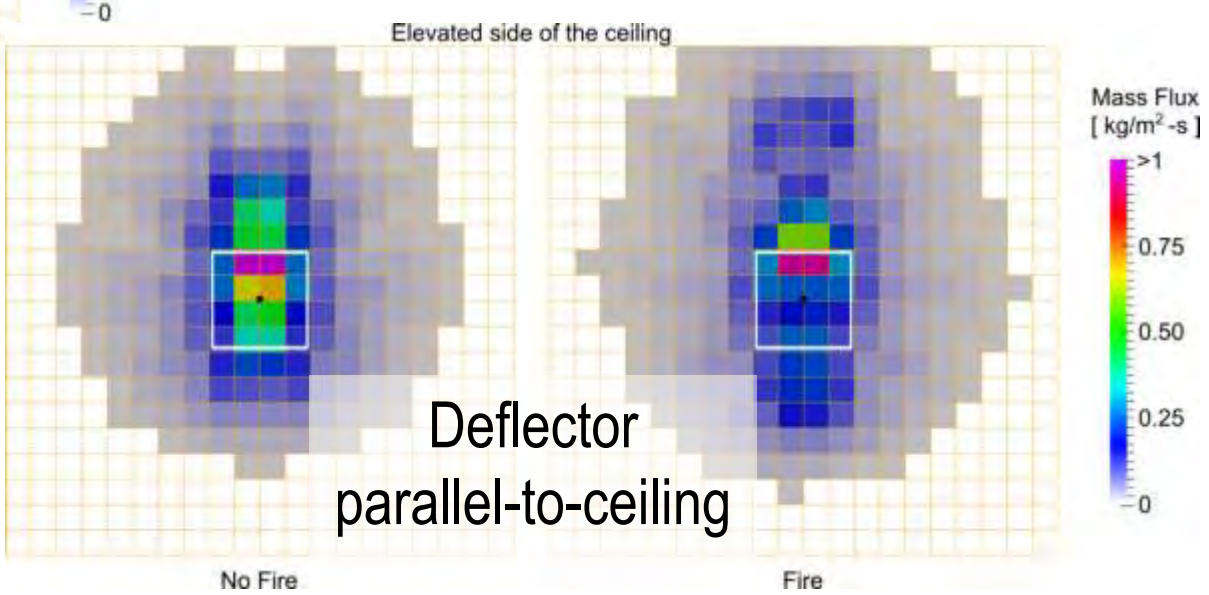
- Comparing water flux distributions above rack-storage array
  - no fire and fire cases
  - 2 ft x 2 ft “buckets”



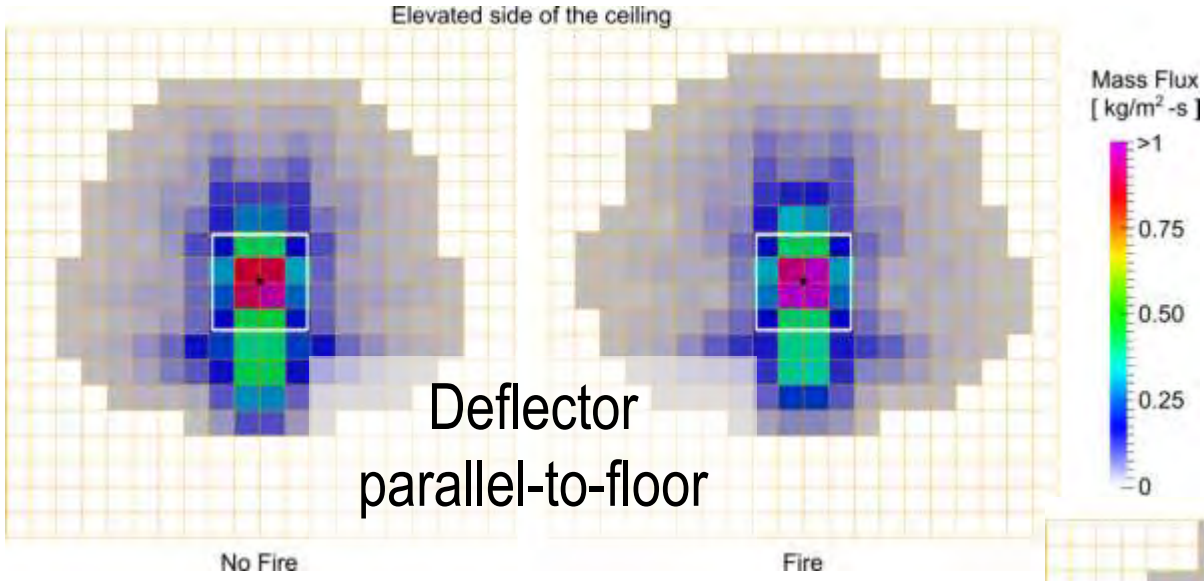
Spray Results (Single Sprinkler, 18.4°)



- Deflector orientation strongly affects water flux reaching the fire source and pre-wetting region
- In presence of a 600 kW plume, reduction was 25% for 18.4° inclination

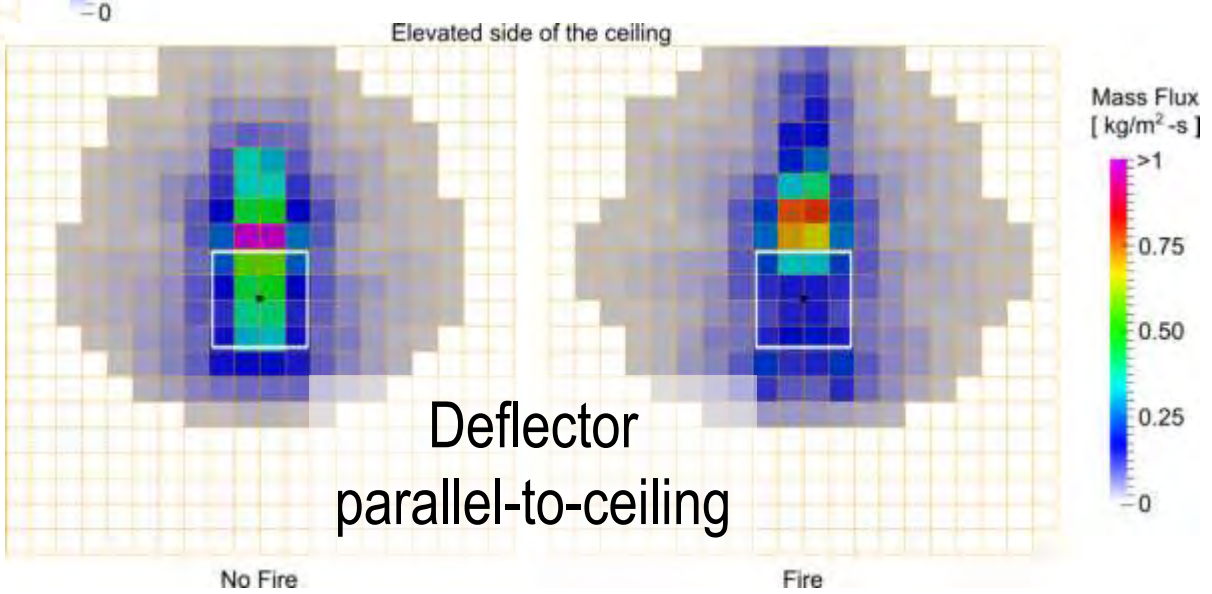


Spray Results (Single Sprinkler, 33.7°)

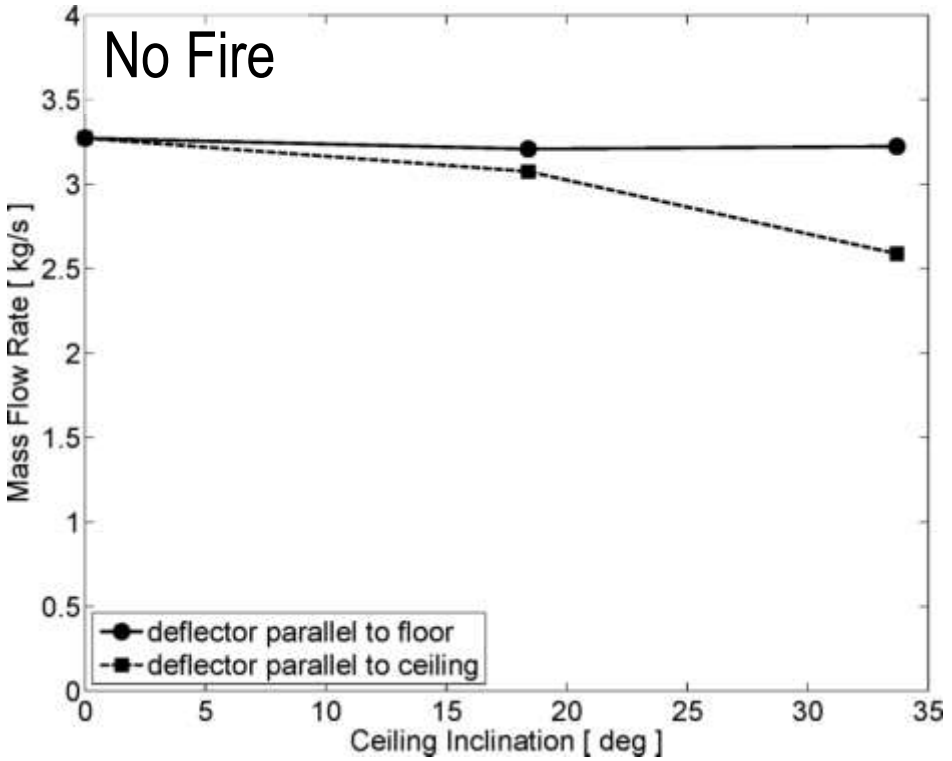


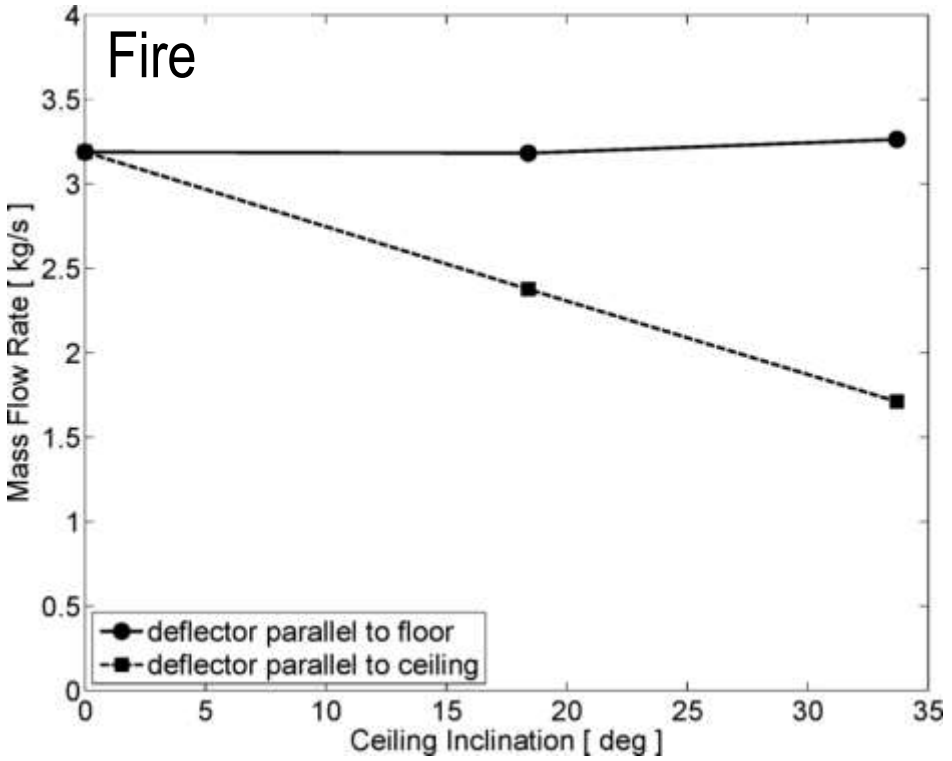
- With increasing ceiling inclination, water flux above commodity reduces when deflector is parallel-to-ceiling
- In presence of a 600 kW plume, reduction was 49% for 33.7° inclination

- With increasing inclination, parallel-to-floor orientation maintained fairly constant water flux to the fire region



Spray Results (Single Sprinkler)

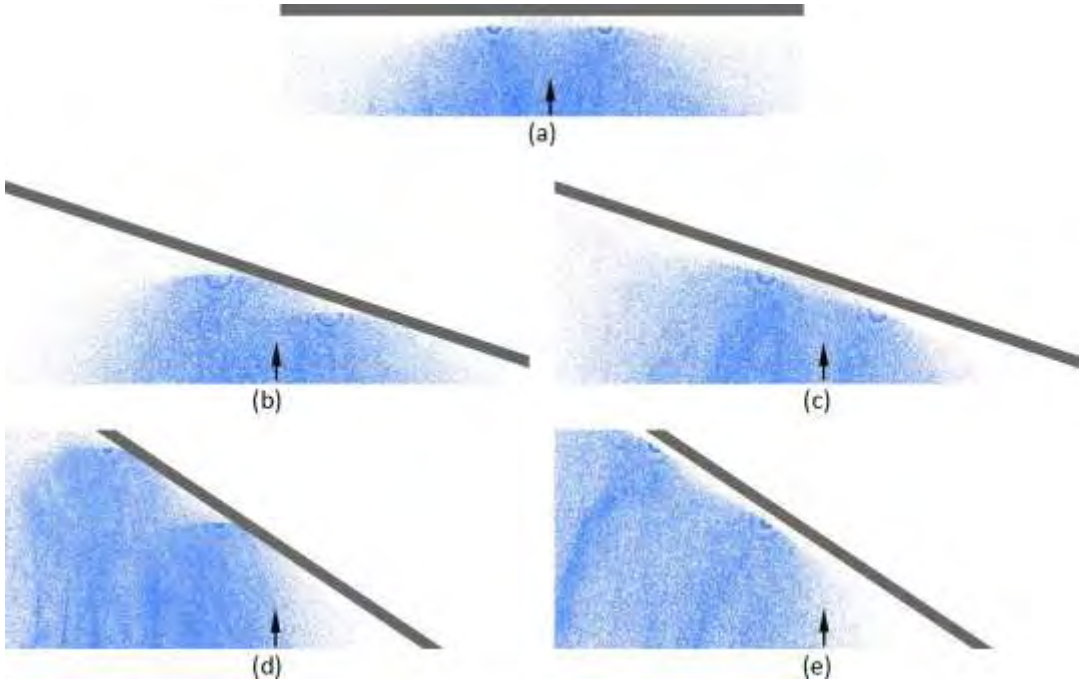




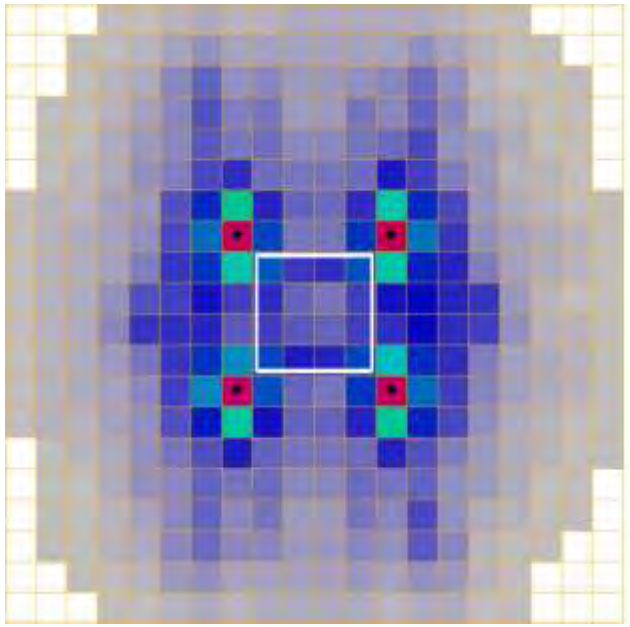
Spray Setup (Four Sprinklers)

- With increasing ceiling inclination, average activation times for four QR/OT sprinklers surrounding the ignition location reduced
  - with fire: average convective HRR of 2.6 MW

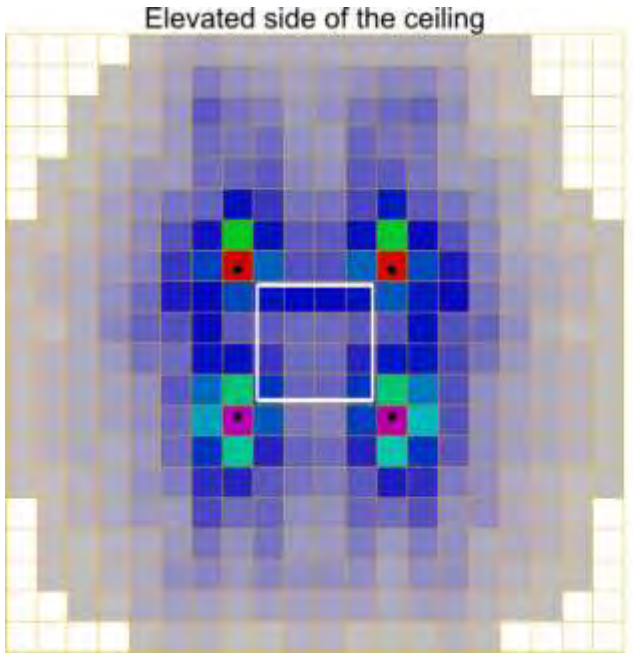
Ceiling Inclination	0°	18.4°	33.7°
		Elevated side	
Sprinkler Activation Times (s)	63 63 / 48 50 / 46 53	43 43 / 45 43 / 47 48	40 39 / 35 36 / 63 64
Average Activation Time, t_{avg} (s)	49	46	38
Convective HRR at t_{avg} (MW)	3.0	2.7	2.1



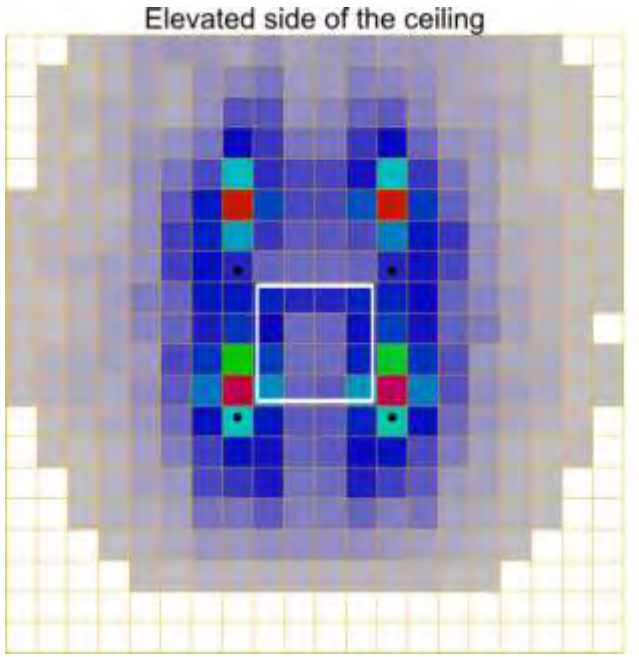
Spray Results (Four Sprinklers, 2.6 MW fire plume)



0°, Deflector
parallel-to-floor

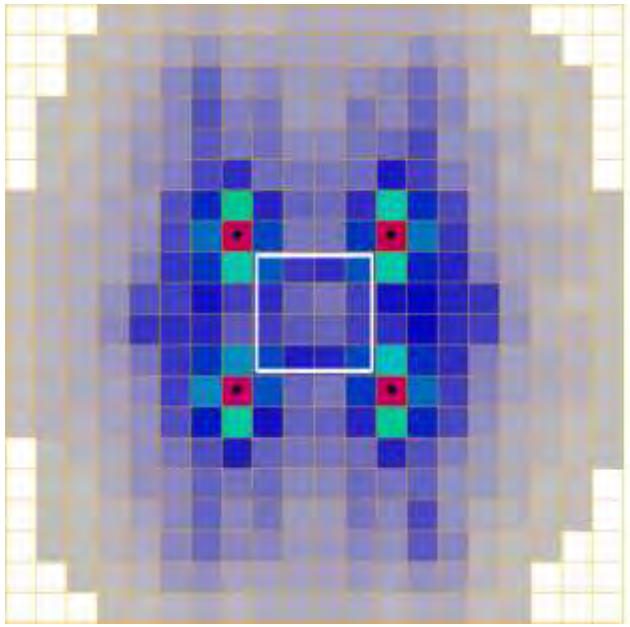


18.4°, Deflector
parallel-to-floor

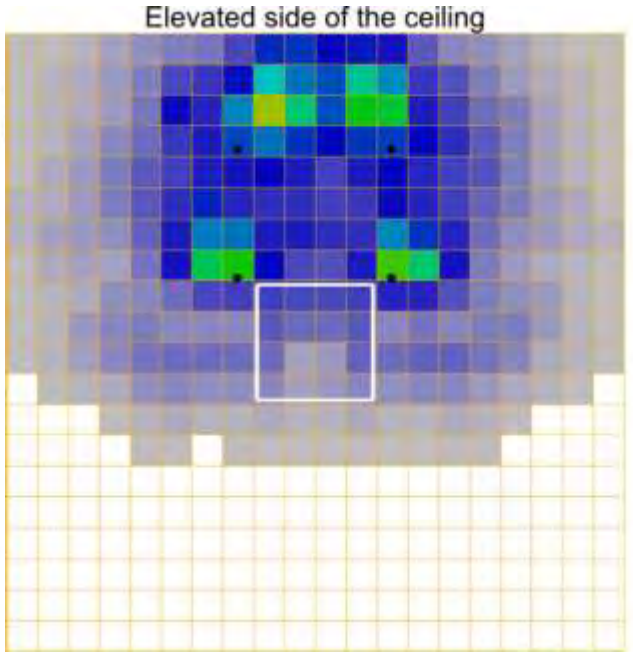


18.4°, Deflector
parallel-to-ceiling

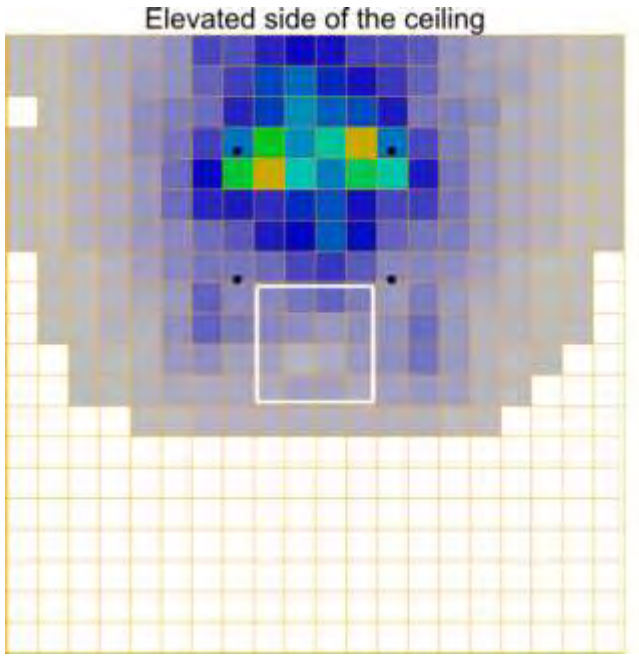
Spray Results (Four Sprinklers, 2.6 MW fire plume)



0°, Deflector
parallel-to-floor

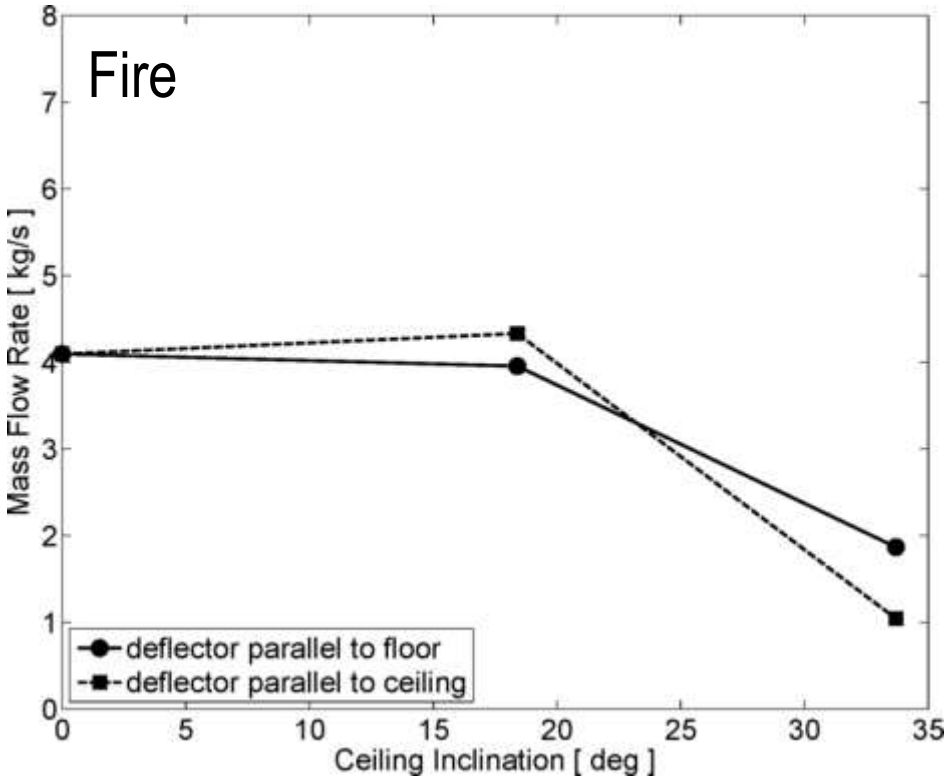


33.7°, Deflector
parallel-to-floor



33.7°, Deflector
parallel-to-ceiling

Spray Results (Four Sprinklers)



- For 33.7° inclination
  - low spray density on the fire region due to highly skewed activation pattern
  - water flux to fire region reduced by 54-76% as compared to horizontal ceiling
- For inclinations ≤ 18.4°, deflector parallel-to-ceiling
  - water from the sprinklers on the lower side is projected towards the fire region

Deflector Orientation

- Significant effect on water flux to the fire region for the single sprinkler cases
- Reduced effect for the four sprinklers cases
- Parallel-to-floor orientation preferable for the scenarios investigated

Future Work

- Phase 2 research involving FireFOAM simulations
  - effect of ceiling obstructions on sprinkler activations and patterns
  - spray simulations with ESFR and non-ESFR sprinklers
  - collaboration with FPRF/PIRG contractor
  - develop large-scale testing recommendations

Acknowledgements

- Lou Gritzo
- Sergey Dorofeev
- Yi Wang
- Chris Wieczorek
- Ankur Gupta
- Ben Ditch
- Wes Baker
- Dave Fuller
- FPRF / PIRG technical committee members
- Amanda Kimball
- Andre Marshall
- CSS team members