Modeling of smoke spread and gas transport in an aircraft

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Background

- Between 2003 and 2004, full-scale fire tests* were conducted at the FAA Tech Center in the cargo compartments of two types of aircraft: Boeing 707, McDonnell Douglas DC10.
- B707 is a narrow-body aircraft with no ventilation in its cargo compartment of ~25 m^3 volume,
- DC10 is a wide-body aircraft with forced ventilation in its cargo compartment of ~100 m^3 volume.
- The test data served to validate the FAA smoke transport code § developed by Sandia National Labs as a result of a multi-agency effort over a five year period.


Boeing 707


McDonnell Douglas DC10

* Blake, D. and Suo-Anttila, J., Aircraft Cargo Compartment Fire Detection and Smoke Transport Modeling, Fire Safety Journal, Vol. 43, No. 8, 2008.

§ Suo-Anttila, J., Gill, W., Luketa-Hanlin, A., and Gallegos, C., Cargo Compartment Smoke Transport Computational Fluid Dynamics Code Validation, DOT/FAA/AR-07/27, Federal Aviation Administration, July 2007.

Motivation

- The motivation was to implement standardized, feasible and efficient certification procedures - for the fire detection devices in cargo compartments - by improving the current practices with the help of analytical capabilities/numerical modeling.
- With the same motivation, the current study evaluates a different solver: **F**ire **D**ynamics **S**imulator (**FDS**)¶, developed at the National Institute of Standards and Technology (NIST).
  - FDS solves Navier-Stokes equations for low Mach number thermally-driven flow, specifically targeting smoke and heat transport from fires,
  - It has been verified/validated for a number of fire scenarios.

Objective is to assess the predictive abilities of FDS when applied for smoke transport in aircraft cargo compartments.

Validation metrics: in the first three minutes of fire initiation compare

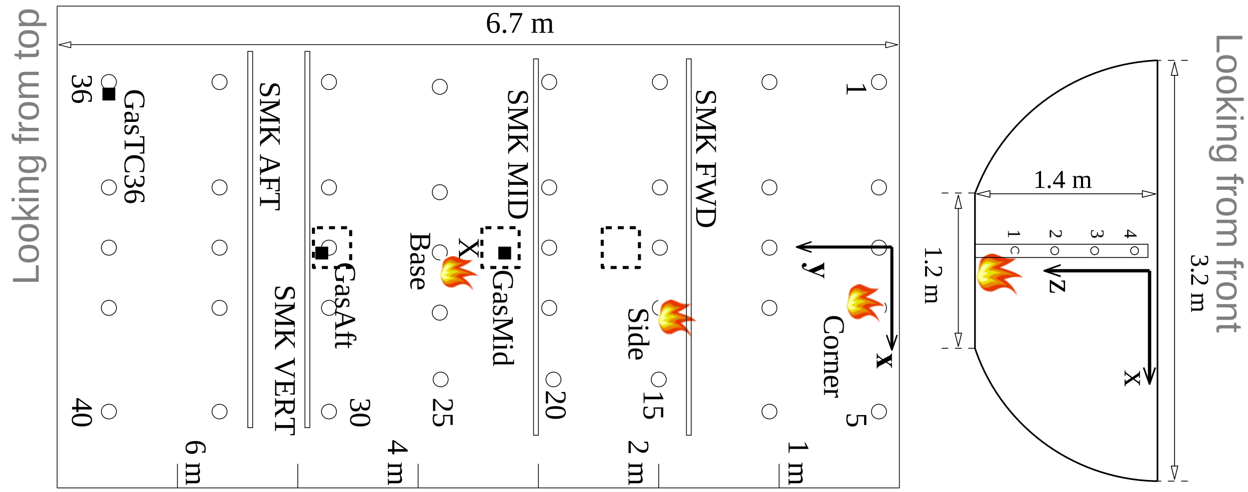
- increase in ceiling temperatures and gas concentrations,
- decrease in light transmissions, $LT = exp(-K_m \sum_{i=1}^{N} \rho_{soot,i} \Delta x_i / L) \times 100\ (\%)$

¶ http://code.google.com/p/fds-smv/

Test set-up

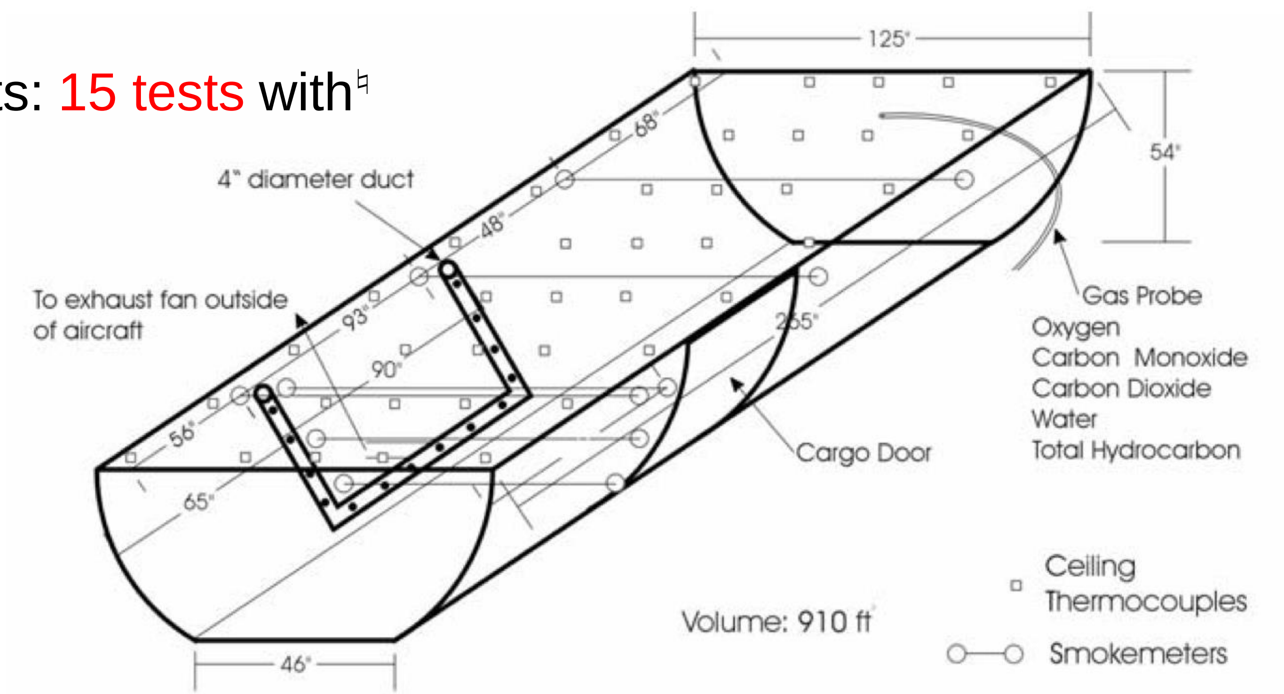
Boeing 707

- Narrow-body
- No ventilation
- Negligible leakage
- 3 fire scenarios



Ground test measurements: 15 tests with[♮]

- 40 thermocouples
- 6 smokemeters
- 3 gas analyzers



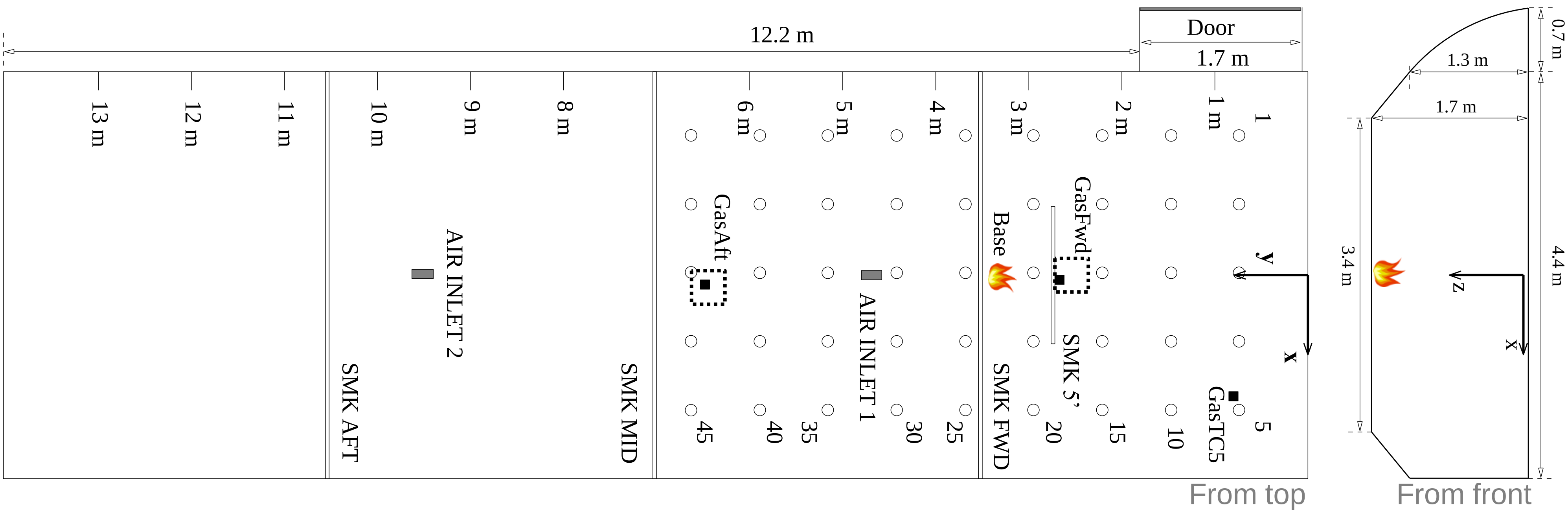
[♮] Blake, D., Development of Standardized Fire Source for Aircraft Cargo Compartment Fire Detection Systems, FAA Technical Note, DOT/FAA/AR-06/21, 2006.

McDonnell Douglas DC10

- Wide-body
- Forced ventilation
  - with a total volume flux of 400CFM
- Leakage through door

Ground test measurements: 15 tests with[♮]

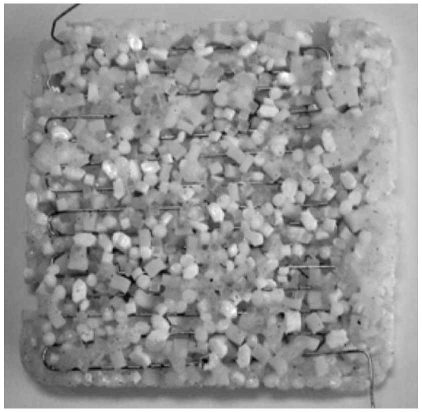
- 45 thermocouples
- 4 smokemeters
- 3 gas analyzers

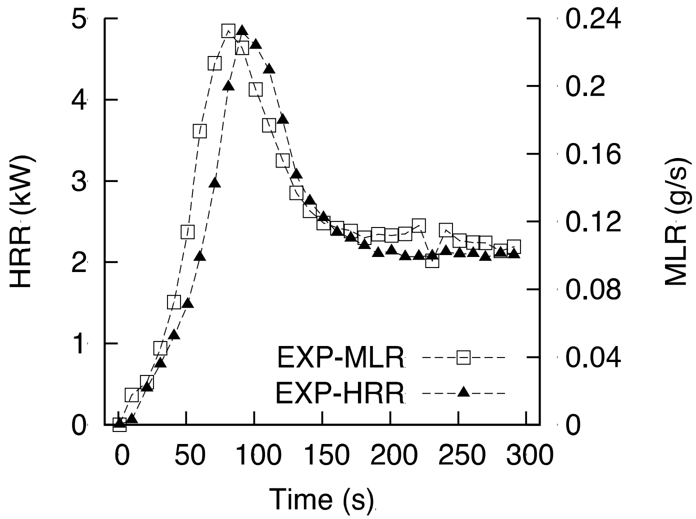


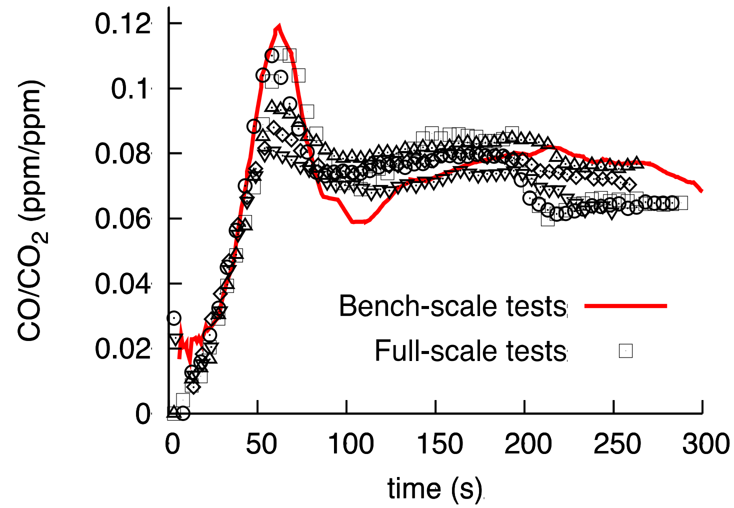
[♮] Blake, D., Development of Standardized Fire Source for Aircraft Cargo Compartment Fire Detection Systems, FAA Technical Note, DOT/FAA/AR-06/21, 2006.

Fire source[#]

- The FAA's standardized fire source** is a compressed resin block made up of pellets of polyethylene, nylon, acrylic, polystyrene, PVC, PBT, etc.,
- When burned it yields combustion products similar to the actual luggage fires,
- It had embedded nichrome-wire to enable remote ignition,
- Its burning was well-characterized with a set of cone calorimetry tests (heat release rate, mass loss rate, production rates of CO, CO_2, and soot were measured).
- Ventilation characteristics of the bench-scale and full-scale tests are similar.



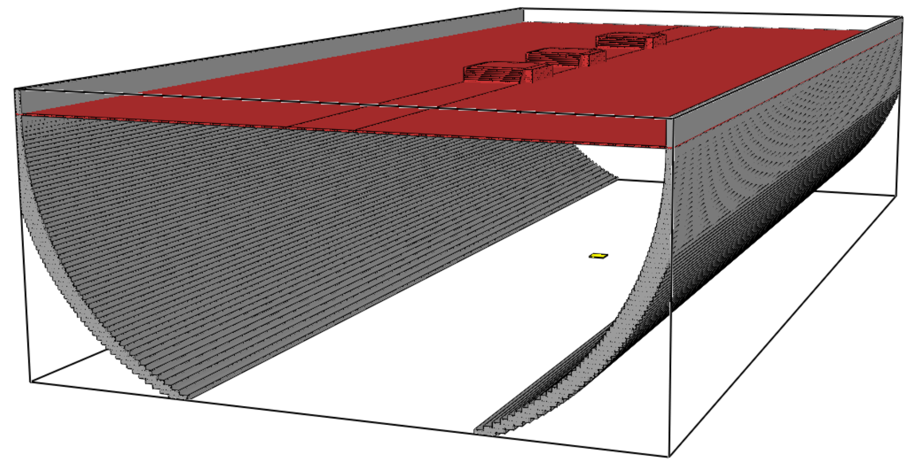




[#] Filipczak, R., Blake, D., Speitel, L., Lyon, R., and Suo-Anttila, J., Development and Testing of a Smoke Generation Source, Proceedings of the Fire and Materials Conference, San Francisco, California, 2001.

** Blake, D., Development of Standardized Fire Source for Aircraft Cargo Compartment Fire Detection Systems, FAA Technical Note, DOT/FAA/AR-06/21, 2006.

Boeing 707 – Test Cases 1, 2 & 3

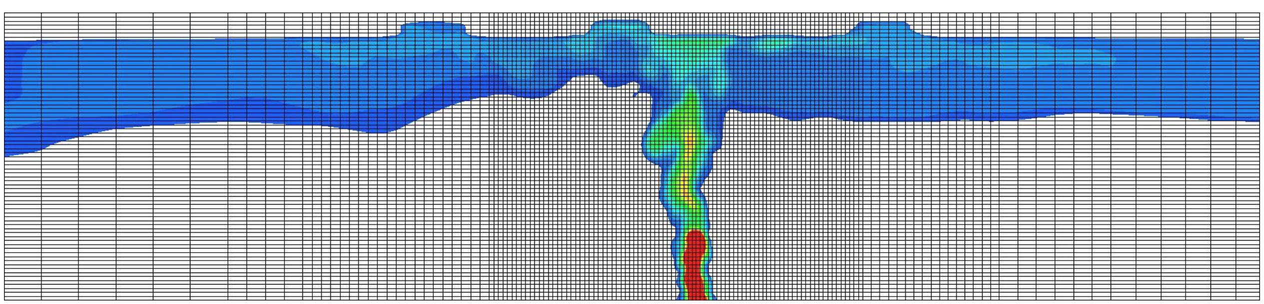


- Non-uniform rectilinear grids chosen according to the characteristic fire diameter:

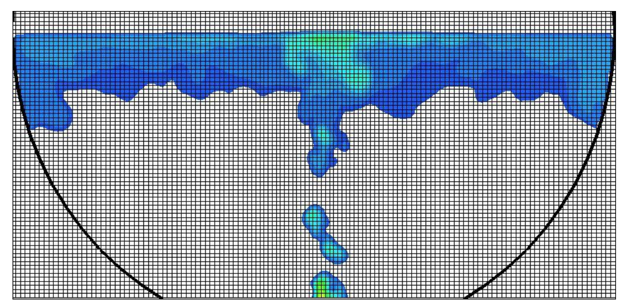
$$D^* = \left(\frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{g}}\right)^{2/5}$$

- 164x180x135 grid points, D*/Δx=10, are used for 3.2x6.7x1.4 m^3 volume, ~10 days runtime,
- Wall material (cargo liner – fiberglass epoxy resin) with the following property set:

$$\rho = 1683 \text{ kg/m}^3,$$
$$c_p = 1200 \text{ J/kgK},$$
$$k = 0.3 \text{ W/mK}$$



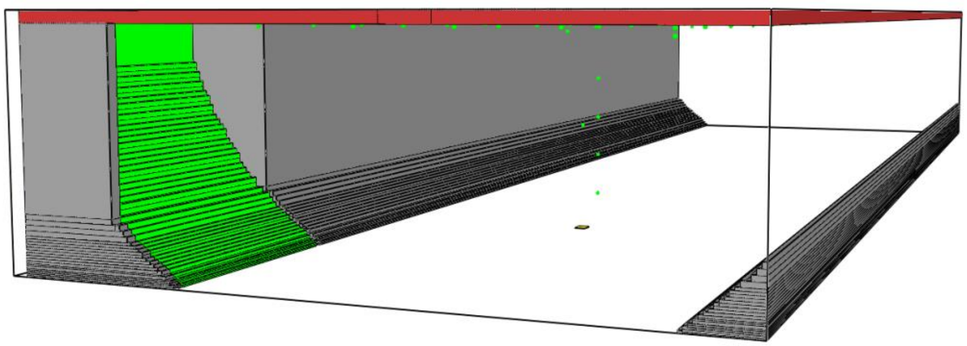
Looking from side

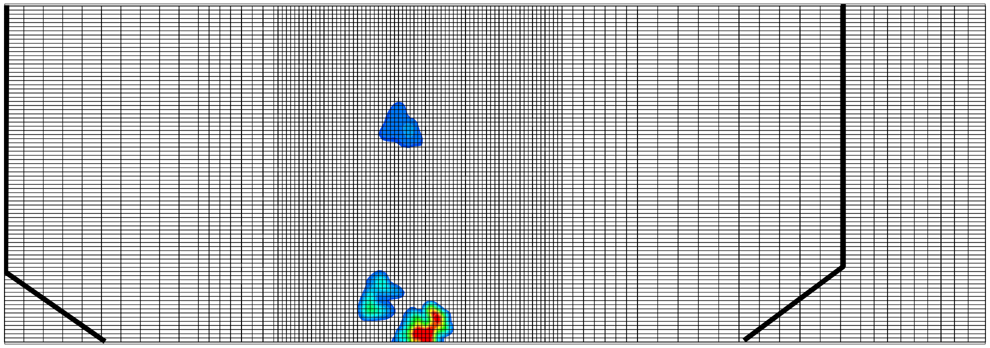


Looking from front

McDonnell Douglas DC10 – Test Case 4

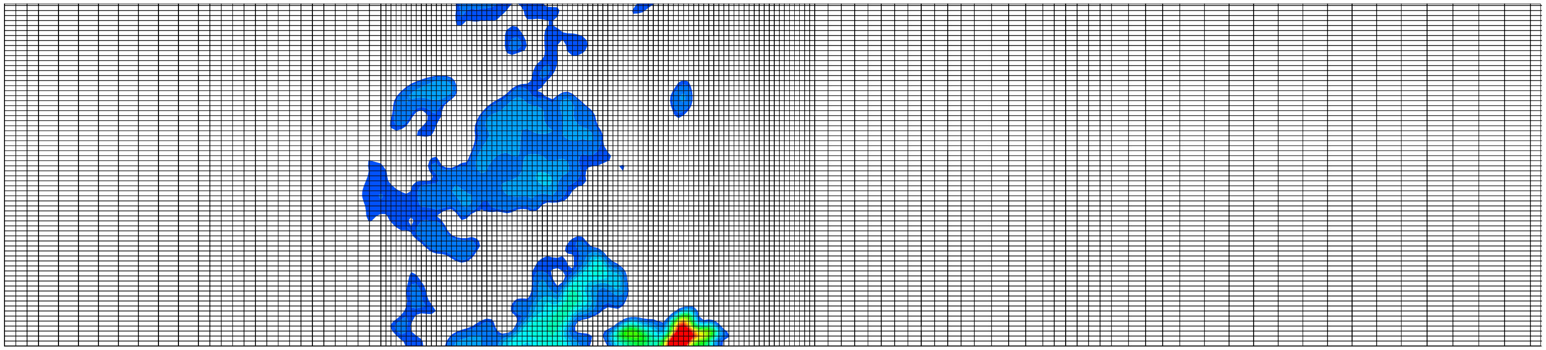
- 135x240x81 grid points are used for 5.2x14.0x1.8m^3 volume, $D^*/\Delta x=5$, ~10 days runtime.
- Wall material is galvanized steel and is assumed to have the following property set: $\rho = 7850$ kg/m^3, $c_p = 460$ J/kgK, $k = 46$ W/mK.



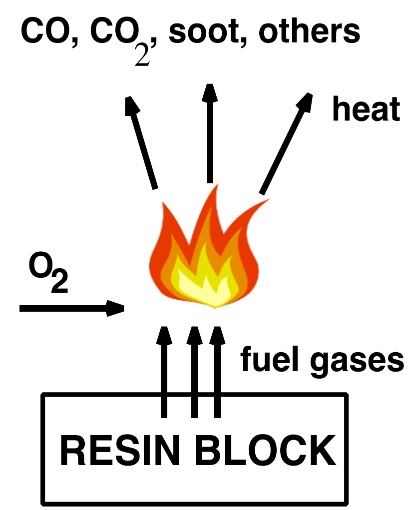


Looking from front

Looking from side



Production rates



Determined through mixture fraction formulation with a simple reaction of fuel and air, using the species-release rates measured in the cone calorimeter ($Y_{soot} = 0.125$, $Y_{CO} = 0.065$)

$$Fuel + Air \rightarrow Products$$

$$C_xH_yO_z + \nu_{O_2}\ O_2 \rightarrow \nu_{CO_2}\ CO_2 + \nu_{H_2O}\ H_2O + \nu_{CO}\ CO + \nu_{soot}\ Soot$$

Radiative fraction

Empirical evidence suggests correlations between radiative heat of combustion and yields of CO and soot[¶].

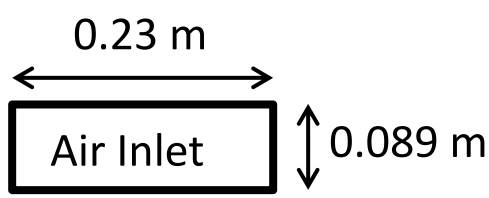
Table: Measured radiative fractions for selected fuels[¶]

Fuel	Ys (g/g)	Y_{CO} (g/g)	Heat flux (kW/m^2)			χ_R
			q''_{rad}	q''_{conv}	q''_{chem}	
Thiophenol	0.122	0.045	13.6	11	24.6	0.55
1-3 Butadiene	0.125	0.048	18.2	15.4	33.6	0.54
Aniline	0.120	0.044	13.5	11.1	24.6	0.55
Polyethylene with Chlorine	0.115	0.042	12.6	10.0	22.6	0.56
FAA standardized fire source	0.125	0.065	-	-	5.0	-

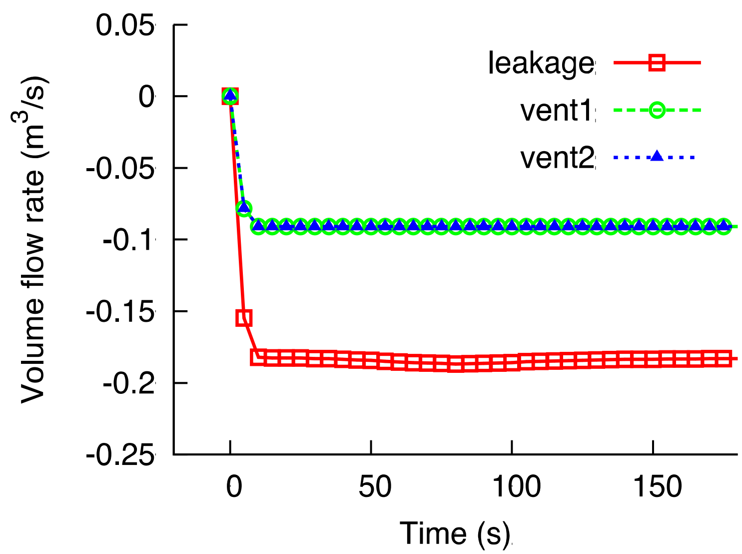
[¶] A. Tewarson, Smoke Point Height and Fire Properties of Materials, NIST-GCR-88-555, NIST, Dec 1988.

Model set-up

- Fire source: flaming resin block:
  - Heat of combustion (HOC) is calculated from the recorded heat release and mass loss rates (HOC = 21 kJ/g),
  - Yields of main combustion products: CO_{yield} = 0.065, $Soot_{yield}$ = 0.125,
  - Radiative fraction, X_R = 0.55.
- Extinction coefficient, K_M = 7600 m^2/kg.
- Werner&Wengle wall model for velocity coupled with standard wall functions for temperature.
- Turbulence modeling: dynamic-coefficient Smagorinsky.
- Scalar transport using Superbee flux limiter.



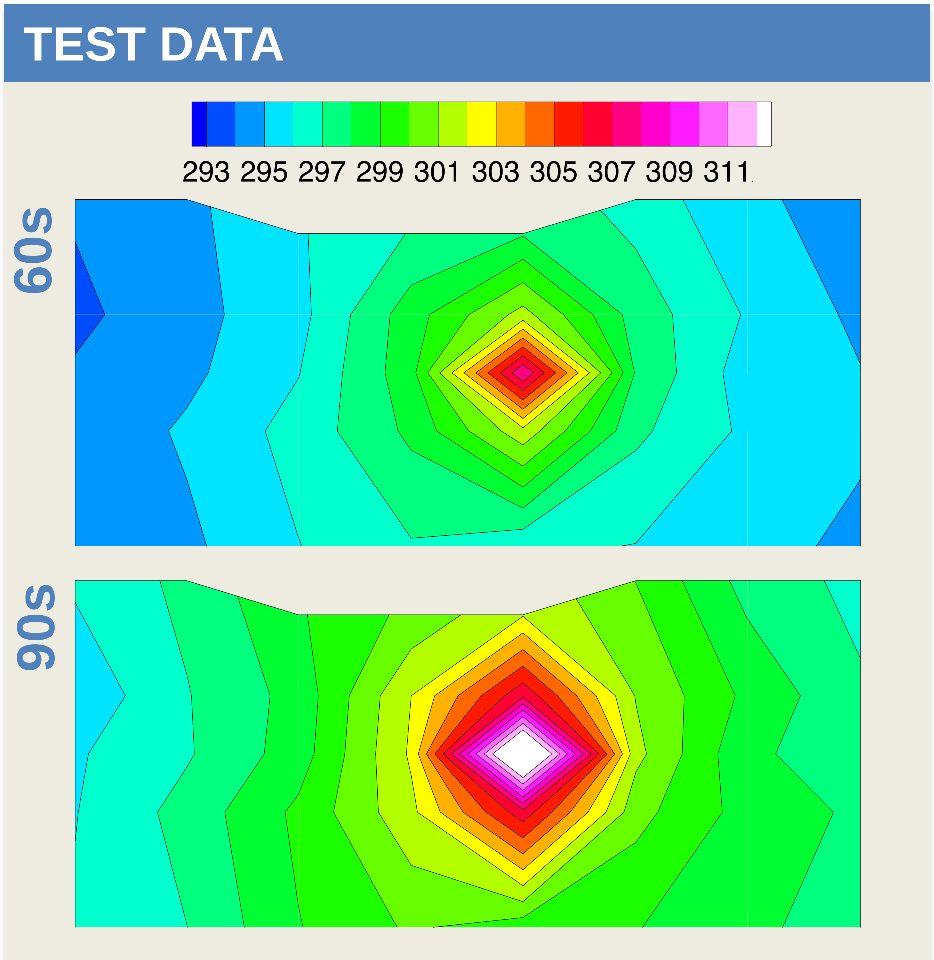
- **For DC10:**
  - Forced ventilation with 400CFM total volumetric flow rate, specified inflow velocity of 4.6 m/s at air inlets.
  - Leakage model to prevent pressure build-up.

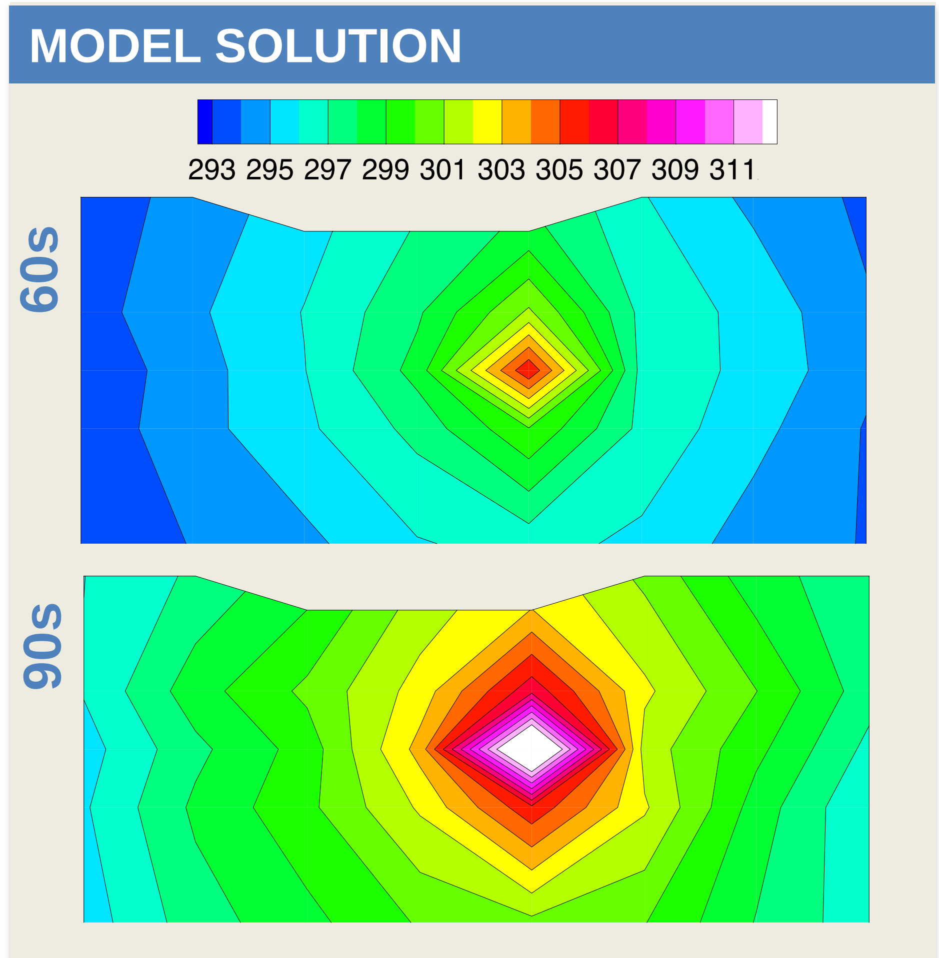


Temperature comparisons

Boeing 707 – Test Case 1

- Contourplots of ceiling temperatures at 60 and 90 seconds show that model predictions agree with the test data and are within experimental uncertainty.



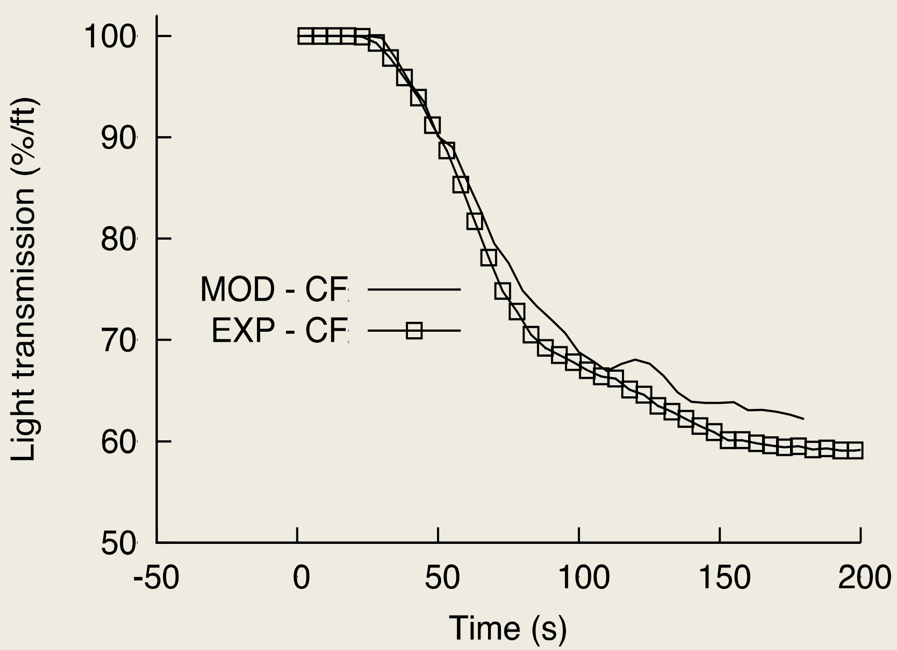


Concentration comparisons

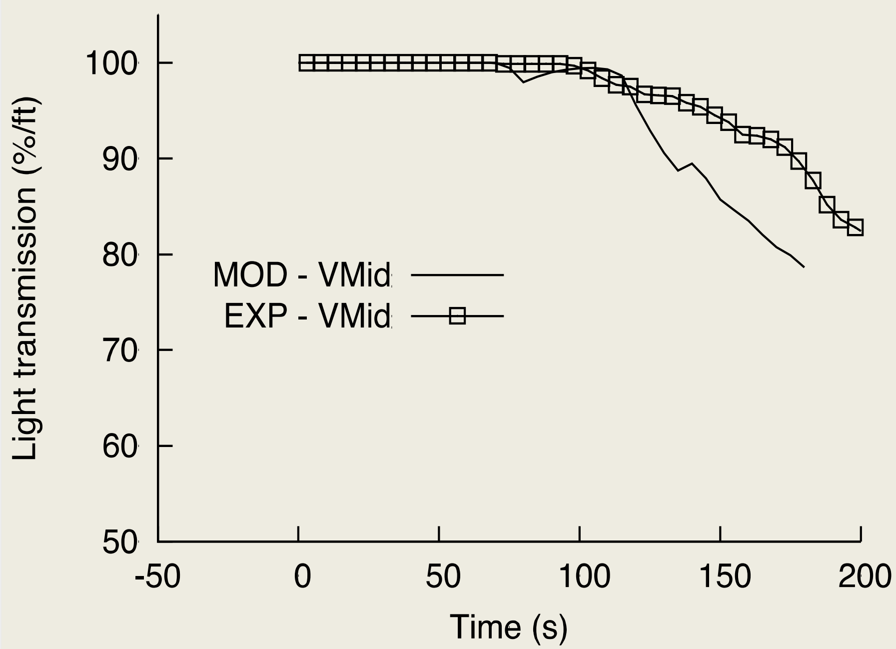
Boeing 707 – Test Case 1

- Predicted light transmissions are generally in good agreement with the measured values. An example is shown below for the ceiling forward beam detector (CF).
- The worst comparison for light transmissions is obtained at the vertical-mid (Vmid) beam detector.

Light transmission at CF



Light Transmission at Vmid

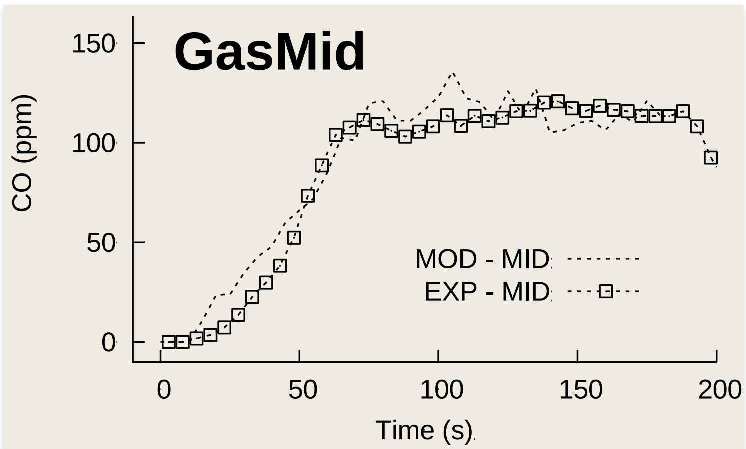


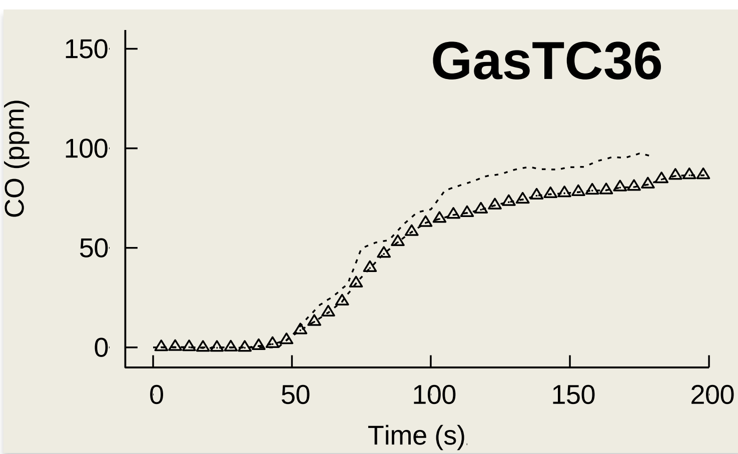
Concentration comparisons

Boeing 707 – Test Case 1

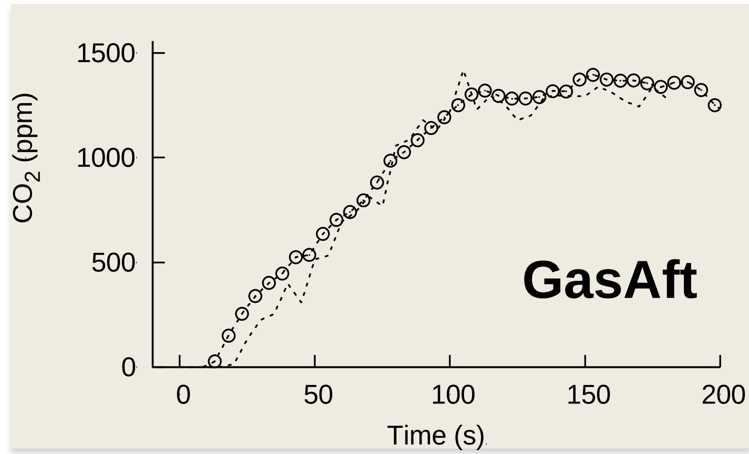
- The CO and CO_2 predictions follow the experimental mean very closely except for those at the gas analyzer TC36, where concentrations of CO and CO_2 are overestimated.

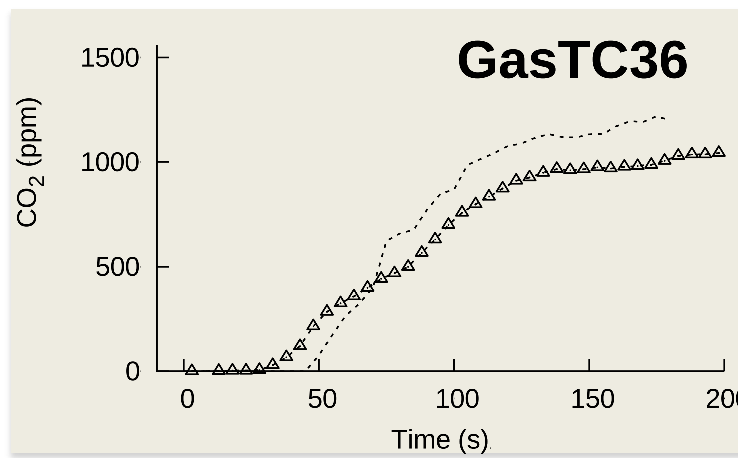
Carbon monoxide





Carbon dioxide

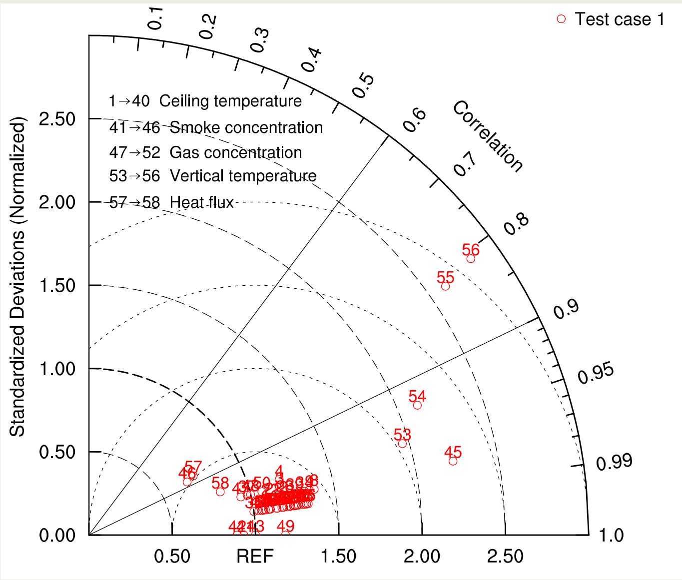




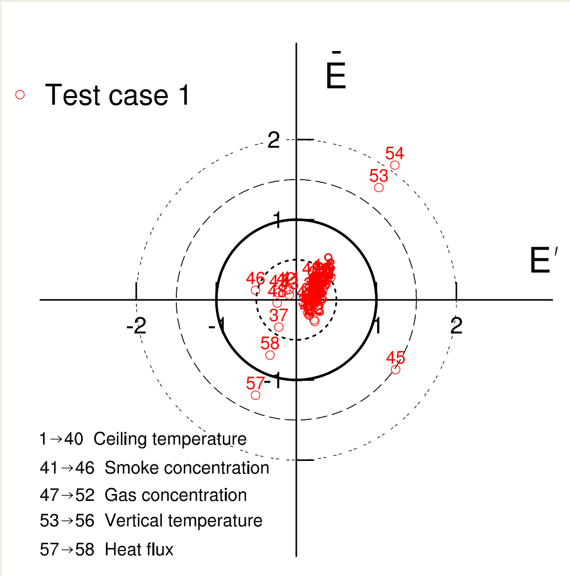
Boeing 707 – Test Case 1

- Various summaryplots can be used for skill assessment: Taylor diagrams, Target diagrams and scatterplots. The scatterplots is the simplest.

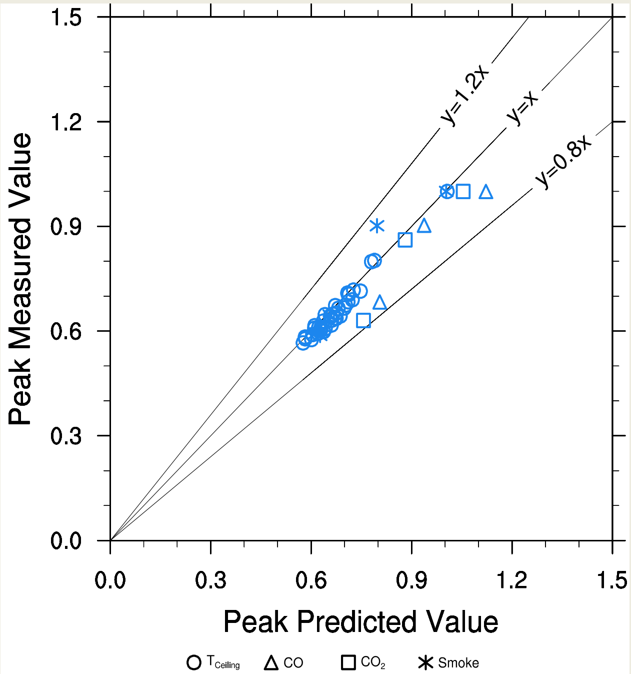
Taylor diagrams



Target diagrams



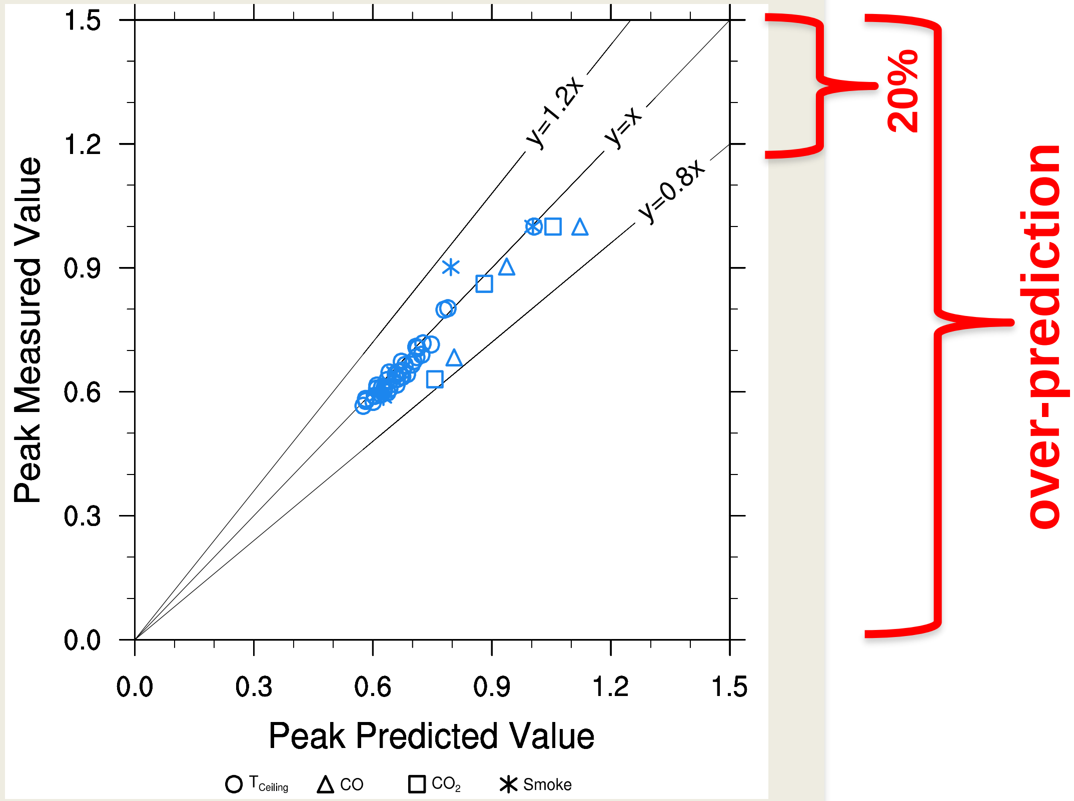
Scatterplots



Boeing 707 – Test Case 1

- In general the agreement between model solutions and experiments is within 20% margin (if not better).
- Vertical temperatures and heat fluxes are out of this error margin (not shown). This is to be expected considering the under resolved walls.
- Scatterplots do not reflect experimental uncertainty.

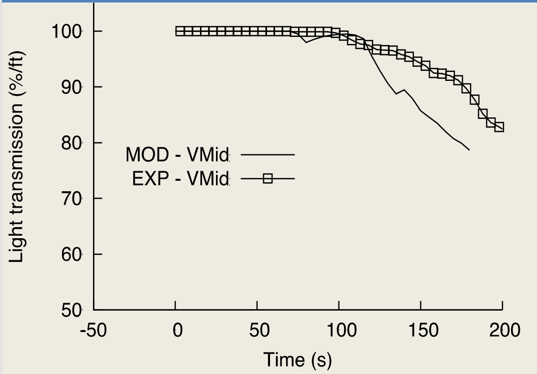
Test case 1 – B707 Baseline fire



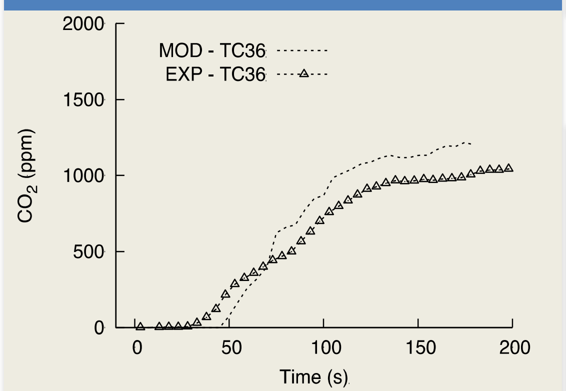
Boeing 707 – Test Case 1

- Worst comparisons are for gas concentrations at TC36, and for light transmission at vertical mid beam detector.

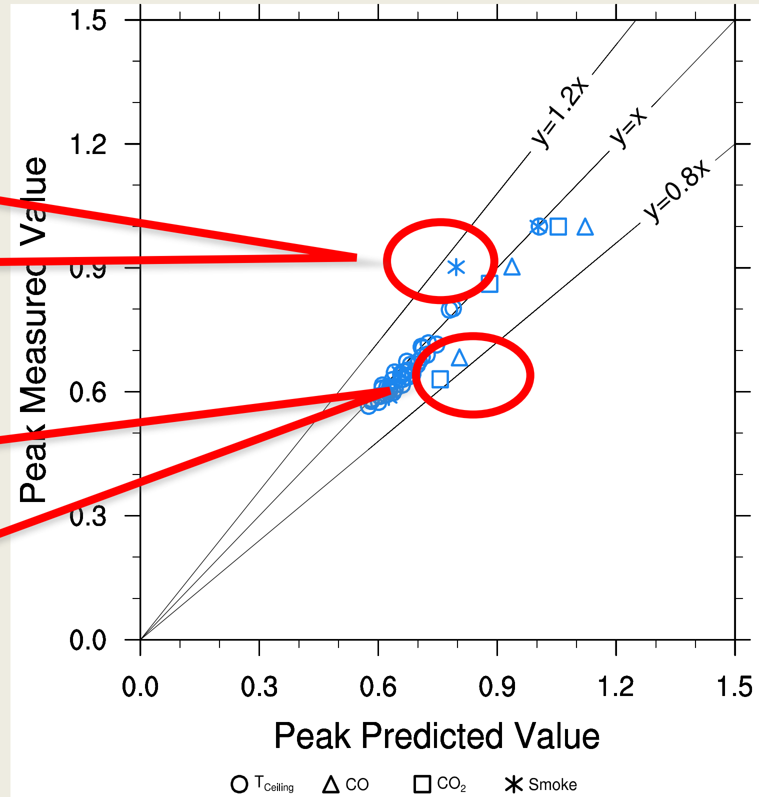
Light Trans. at Vmid



Carbon dioxide at TC36

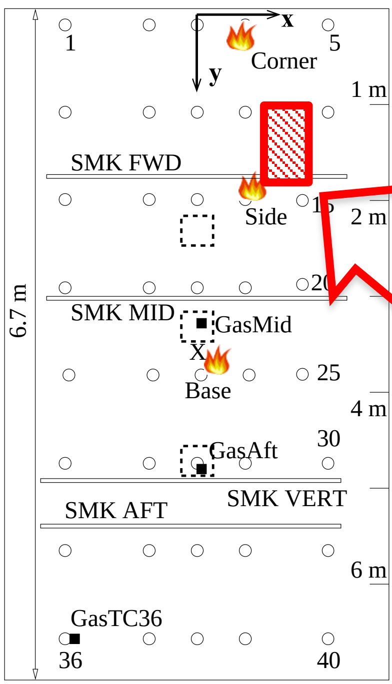


Test case 1 – B707 Baseline fire

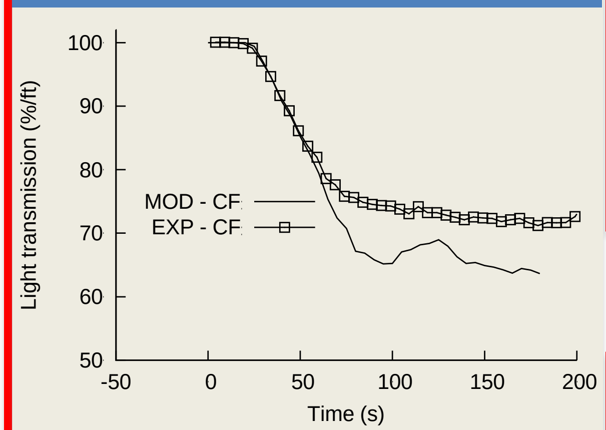


Boeing 707 – Test Case 2

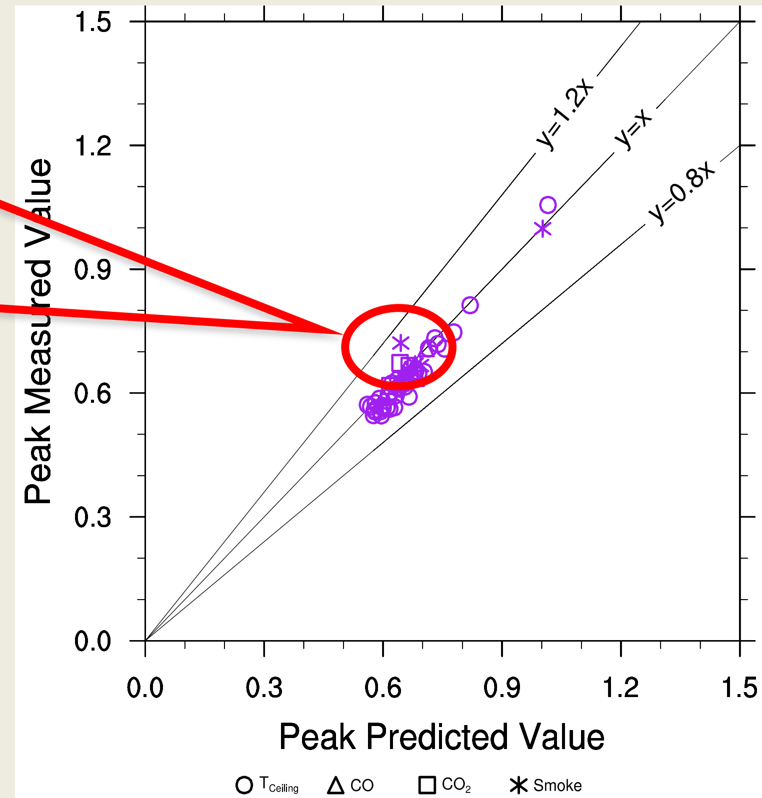
- For test case 2 (corner fire), model overestimates the peak ceiling temperatures and the peak smoke concentration at the ceiling FWD beam detector.



Light Trans. at CF



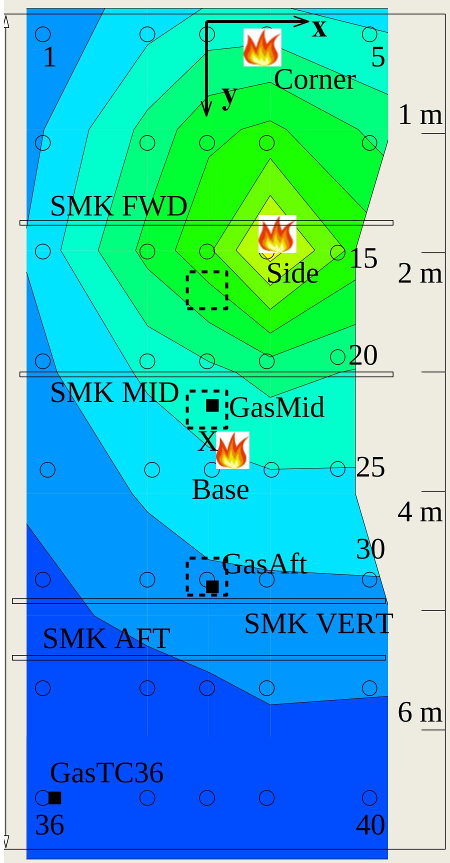
Test case 2 – B707 Corner fire



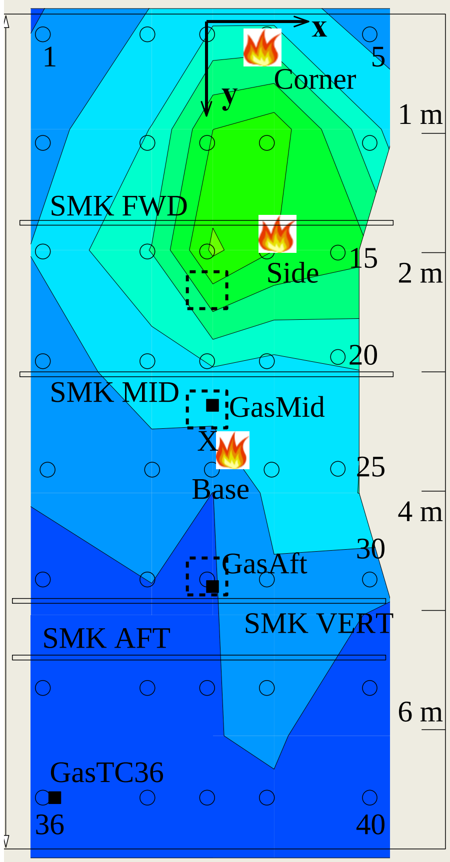
Boeing 707 – Test Case 3

- For test case 3 (side fire), overestimation in ceiling temperatures increases noticeably. It is likely that the fire location in the test was recorded wrong.

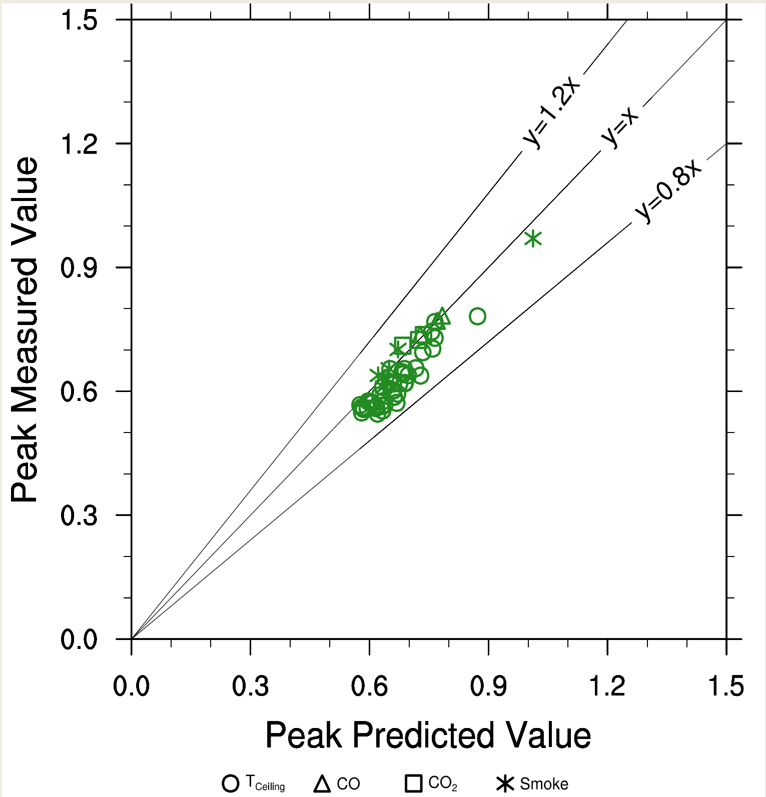
Model data at 60s



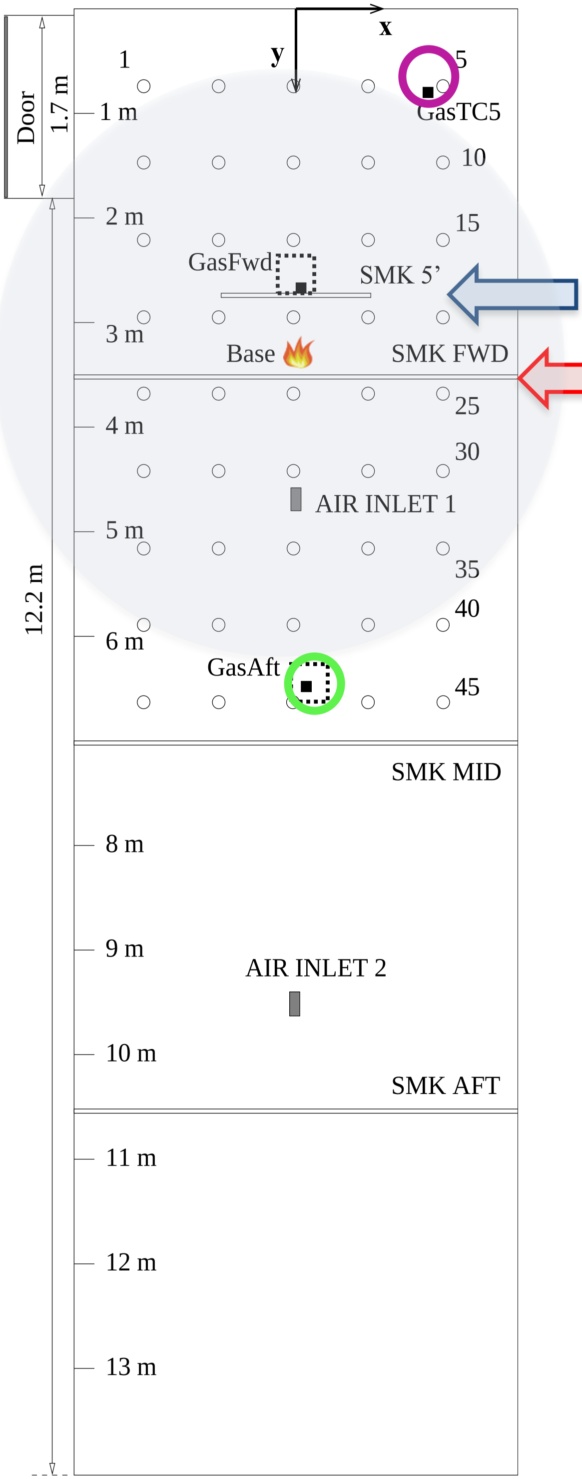
Test data at 60s

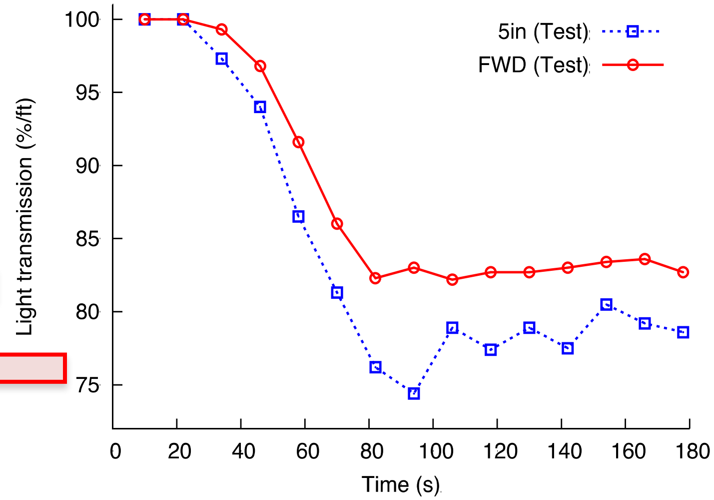


Test case 3 – B707 Side fire



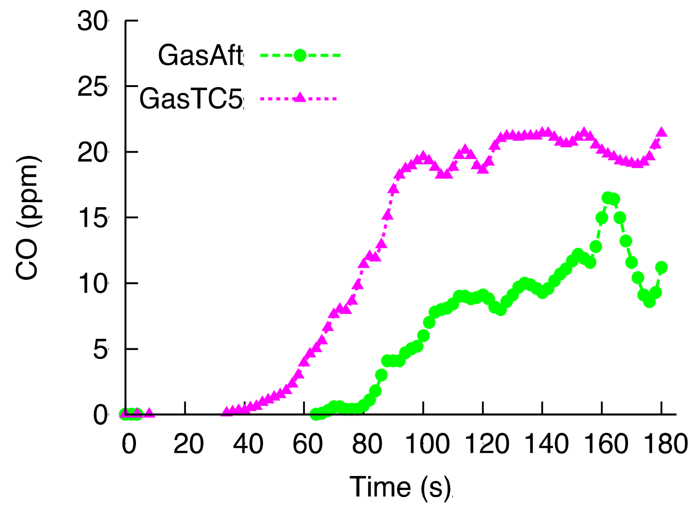
Test data

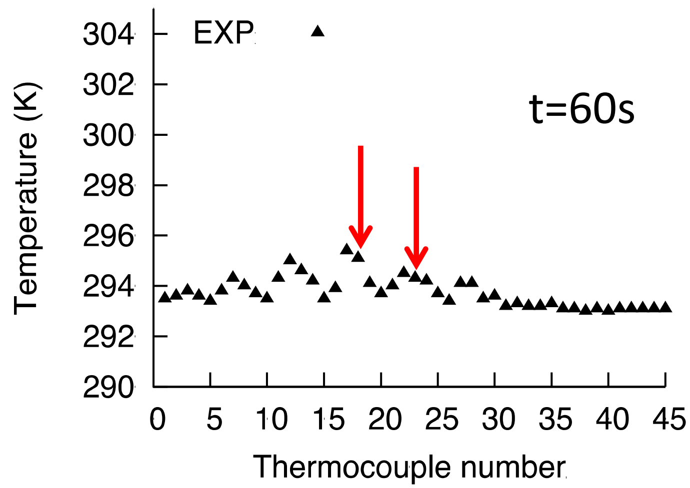




Smoke first felt at the location of smokemeter with a five foot path length (*SMK 5’*) as opposed to the smokemeter closest to the fire source (SMK FWD).

Gas analyzers GasAft and GasTC5 are located approximately at the same distance away from the fire source. However, GasTC5 starts reading concentrations much earlier.

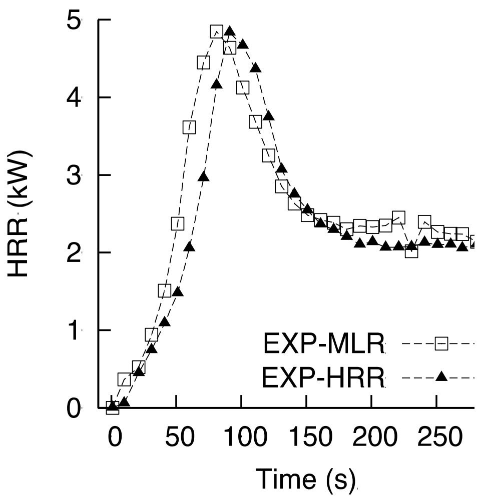


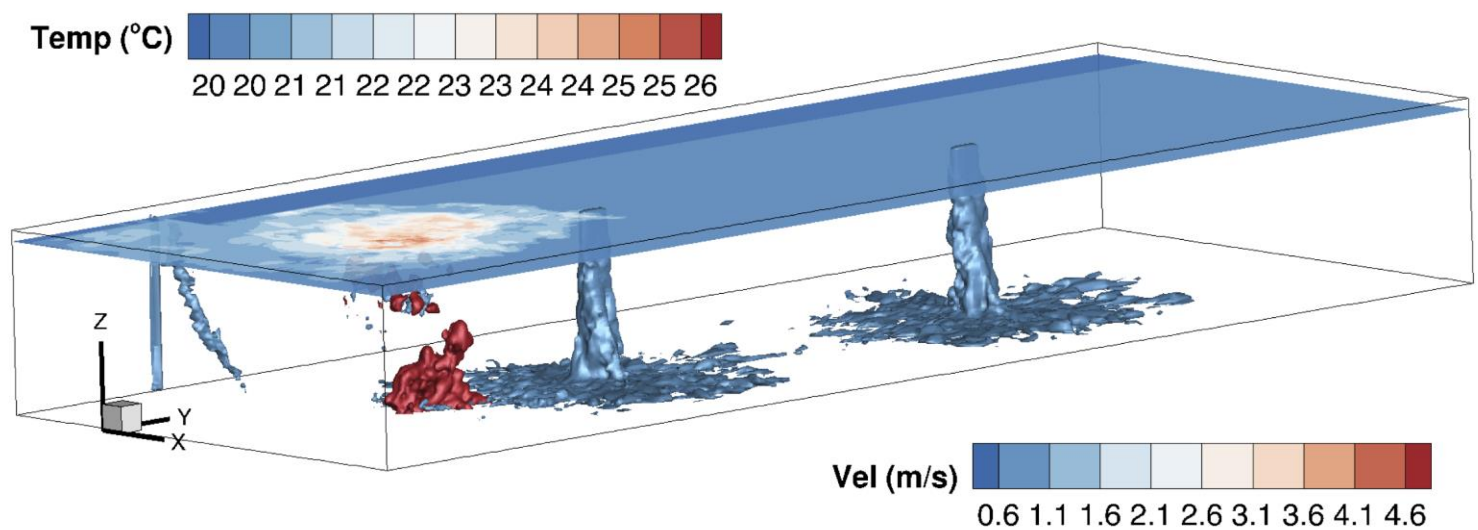


Thermocouples closest to the fire source are TC18 and TC23 on each side of the fire. TC23 does not read the maximum temperature.

McDonnell Douglas DC10 – Test Case 4

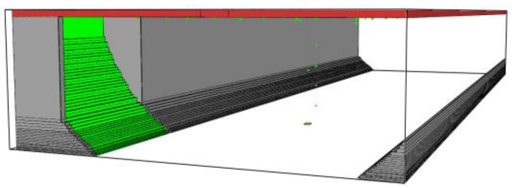
- The interplay between momentum and buoyancy determines the flow field:
  - At the early stages of the fire, momentum overcomes buoyancy, hot gases are pushed away from the air vents,
  - At the later stages with increased heat release rate, buoyancy is strong enough to move hot gases towards the ceiling.

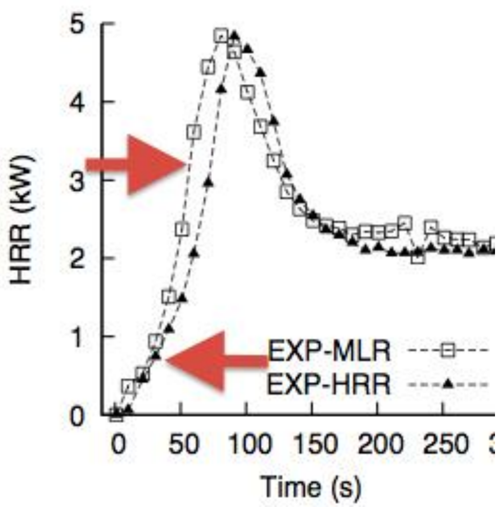


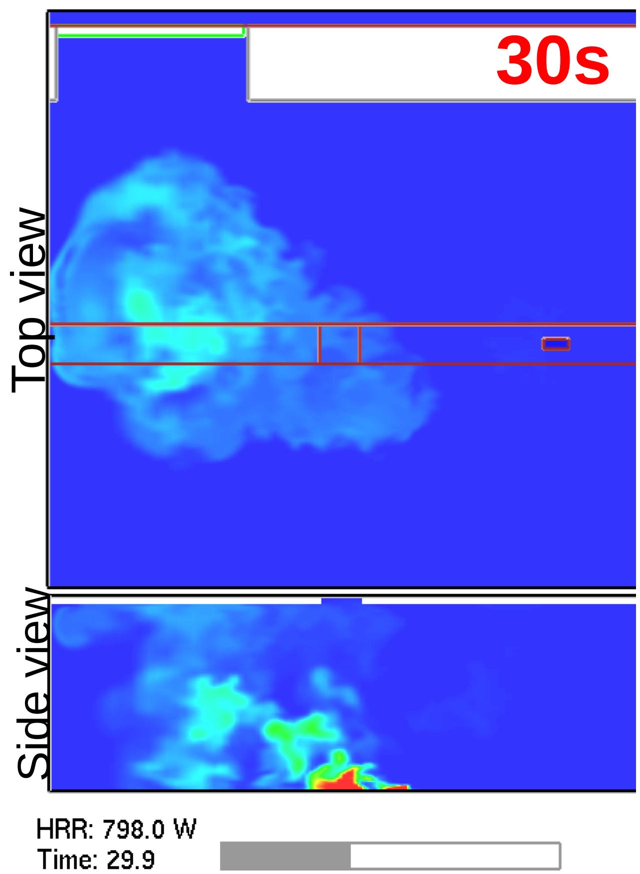


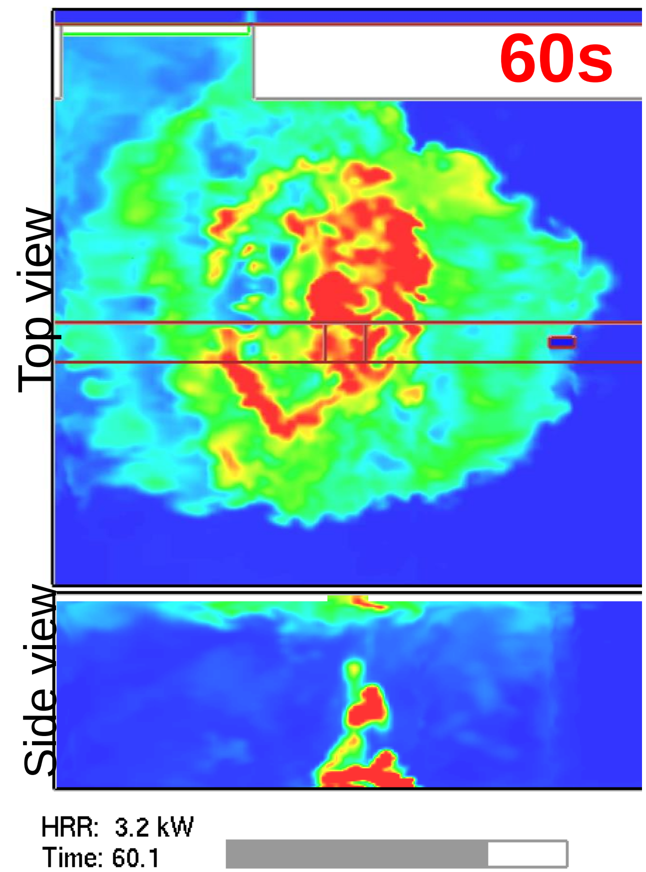
McDonnell Douglas DC10 – Test Case 4

- The transient nature of the fire affects the plume signature at the ceiling.
  - At **30s**, the maximum concentration is close to the forward of the compartment,
  - At **60s**, it moves closer to the fire-source location.
  - At the early stages of the fire, ventilation blows the hot plume away from the fire source. Later as the HRR increases buoyancy strengthens and overcomes the momentum.



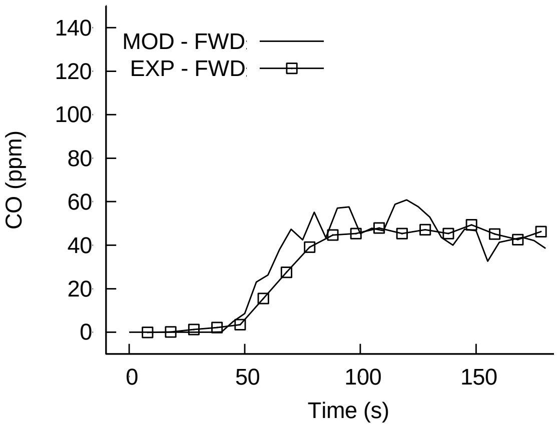


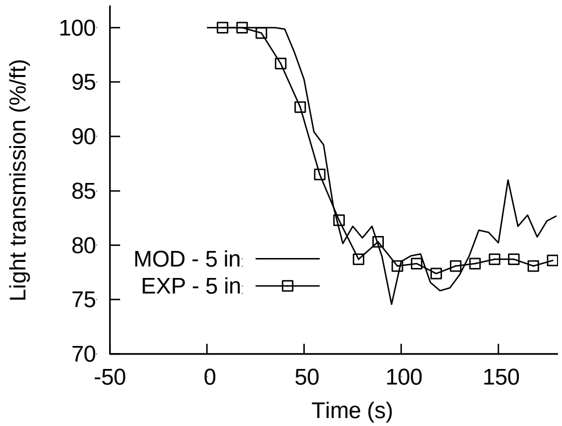


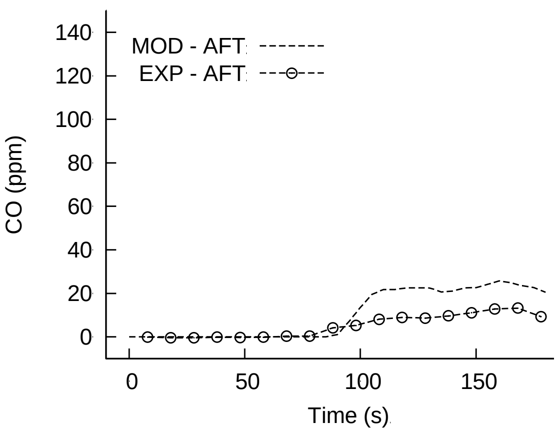


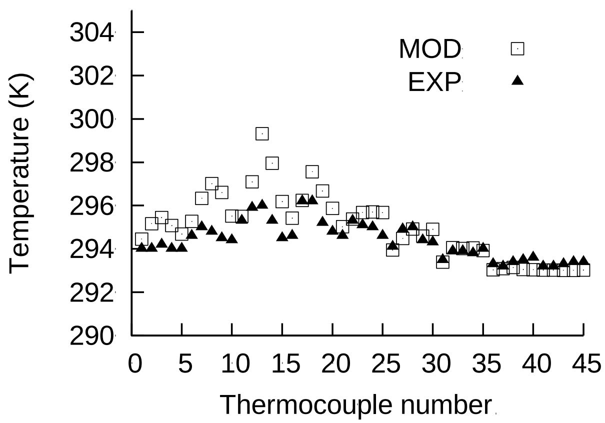
McDonnell Douglas DC10 – Test Case 4

- Comparisons with the test data is not as successful as those for B707 test cases: Gas concentrations and ceiling temperatures are overpredicted.

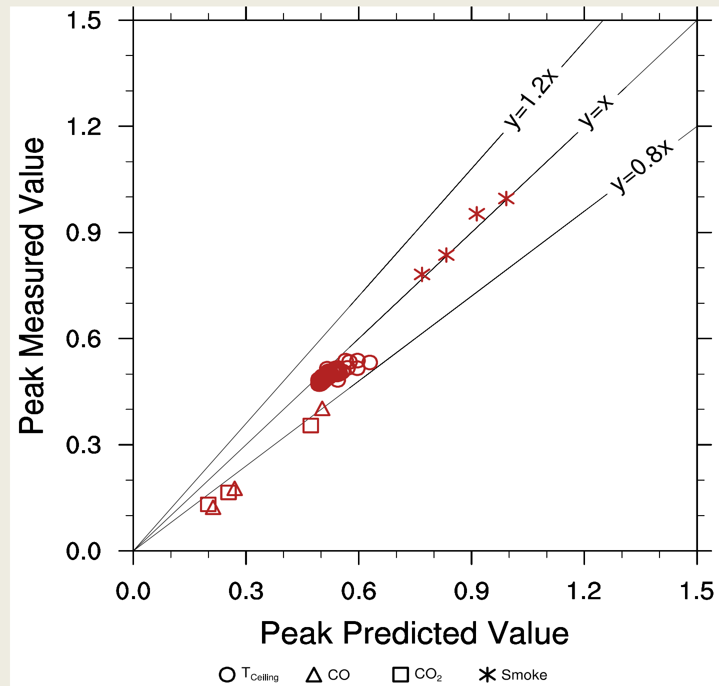








Test case 4 – DC10 fire



Conclusions

Boeing 707

- Mean flow fields are well-predicted except for the wall heat fluxes, hence the slight overestimation of the ceiling temperatures.
- In the evaluation of model performance, it is important to consider possible systematic errors in the test data, as well as the uncertainty in the model-input parameters.

McDonnell Douglas DC10

- Although general flow behavior was successfully reproduced, solutions for this ventilated compartment are not as good as those of the unventilated B707 compartment.

Conclusion

The agreement between the model predictions and experimental data demonstrates the potential of numerical modeling, and encourages its use, as a tool to complement experimental research efforts.

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