Modeling Smoke Transport in Aircraft Cargo Compartments

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International Aircraft Systems Fire Protection Working Group Meeting

October 30, 2002

Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed-Martin Company,
for the United States Department of Energy under Contract DE-AC04-94AL85000.

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Sandia National Laboratories Team Members

- Experimental
  - Walt Gill and Jill Suo-Anttila
- Model Development
  - Jim Nelsen and Stefan Domino
- Graphical User Interface and Code Development
  - Carlos Gallegos
- Code Verification
  - Tom Voth
- Technical Support
  - Louis Gritzo, manager of the Fire Science and Technology Department

Outline

- Project overview
- Smoke transport code features
  - Pre-processor
  - Analysis
  - Post-Processor
- Model Verification
- Baseline Validation Data and Selected Validation Metrics
- Baseline Simulation Results
- Preliminary Comparisons
- Future Activities

Project Collaborators

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- Define standard fire sources for detection.
- Conduct cone calorimeter experiments to characterize fire source and full scale experiments for model validation.

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- Develop computational fluid dynamics simulation tool to predict the transport of heat, smoke and gases throughout an aircraft cargo compartment.

- Develop miniature gas sensors for use in fire detectors.
- Provide funding for CFD model development and validation.

NIST National Institute of Standards and Technology

- Evaluate the response of existing aircraft smoke detectors to actual fires and to nuisance alarm sources.
- Recommend sensor combinations and alarm algorithms to discriminate between the two.

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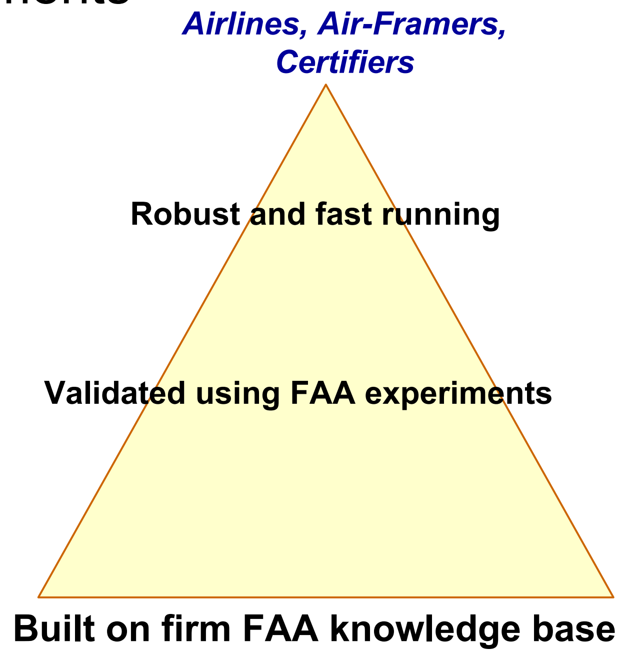
Modeling Smoke Transport in Aircraft Cargo Compartments

Goal: Develop a CFD-based simulation tool to predict smoke transport in cargo compartments



- Improve the certification process
  - Identify optimum smoke detector locations
  - Specify sensor alarm levels
  - Identify worst case fire locations
  - Reduce the number of flight tests
- Fast running
- Suitable for non-expert users
- Experimental data for source term characterization from FAA experiments
- Validated using FAA full-scale experiments

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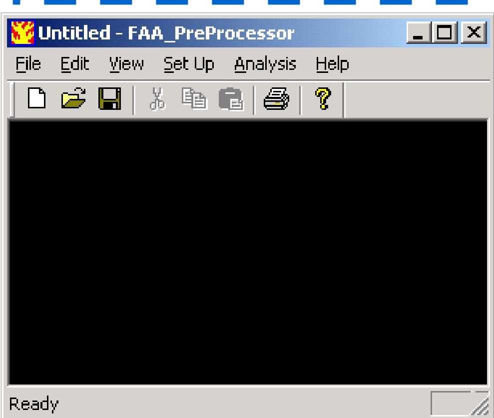
Software Design

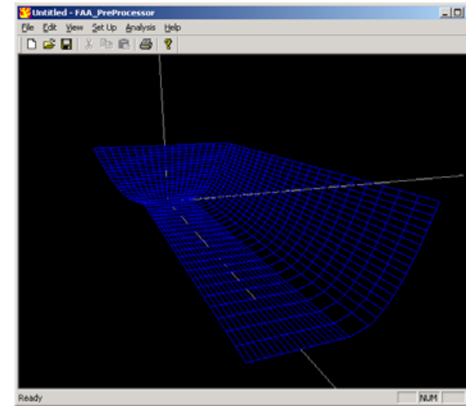
Graphical User Interface

Pre-Processor

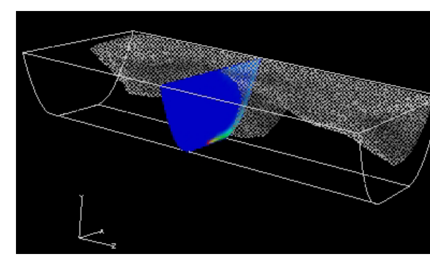
Analysis Module

Post-Processor





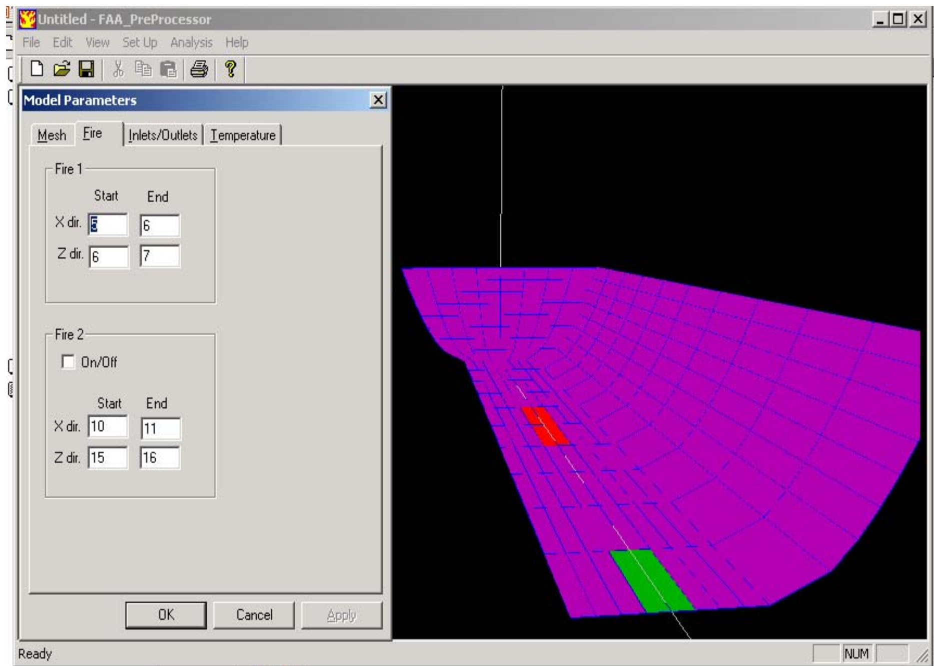
$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_j) = S_m^p$$



Pre-Processor

Provide models for different aircraft

- Boeing 707, 727, 747, etc.
- User defined



User Can:

- Refine mesh
- Enter fire(s) location and type
- Enter ventilation velocities and locations
- Enter initial compartment temperature

Instantaneous visual feedback

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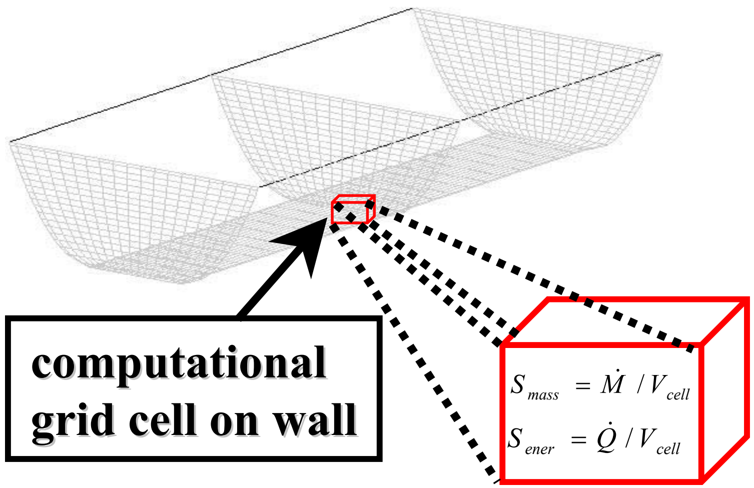
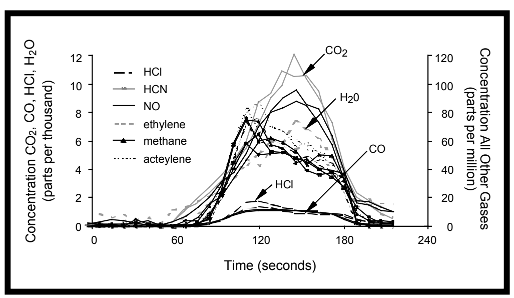
Smoke Transport Analysis Code





- Curvature of compartment is resolved on grid
- Arbitrary ventilation inlets and outlets can be specified
- Location and type of fire can be selected
- HRR, MLR are time varying inputs (as measured in FAA experiments)
- Species tracking: presently soot, CO, and CO_2 but addition of more or different species possible
- Simulation time on the order of hours
- Validated using FAA full-scale experiments

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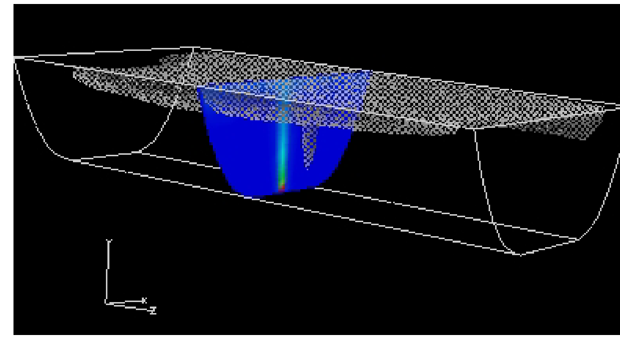
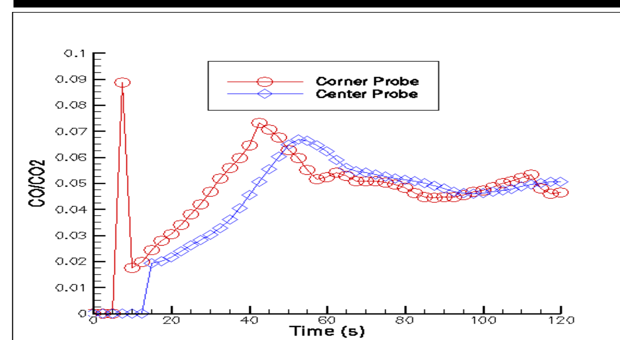
Post-Processor

Allow users to manipulate data in a variety of ways

- contour plots
- time history of field variables
- 3D smoke visualization in time





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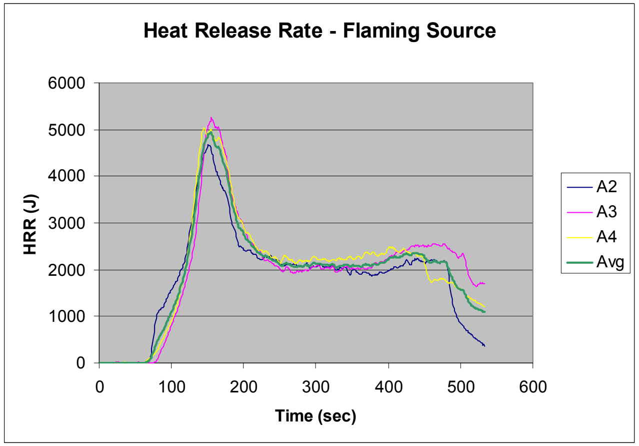
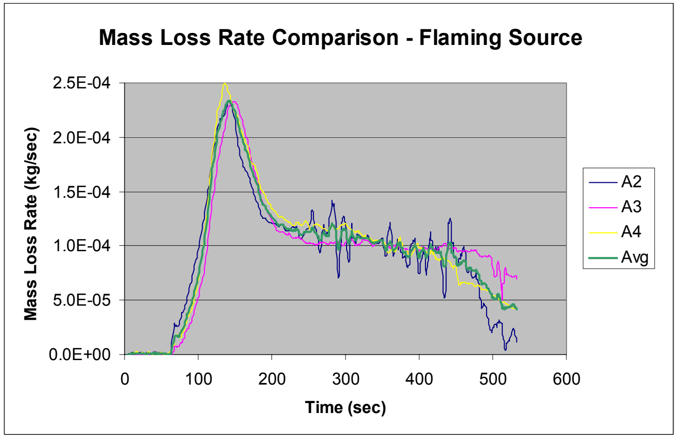
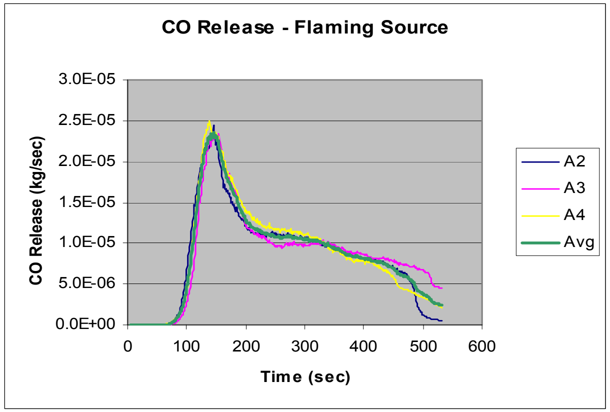
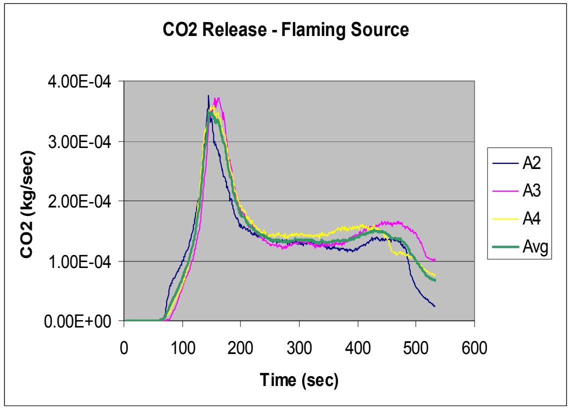
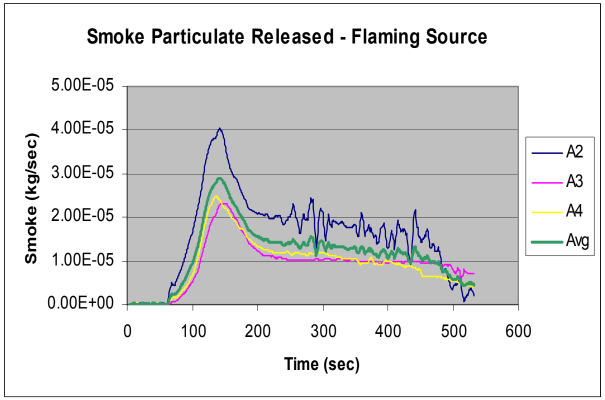
Flaming Source Characterization











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Verification via the Method of Manufactured Solutions

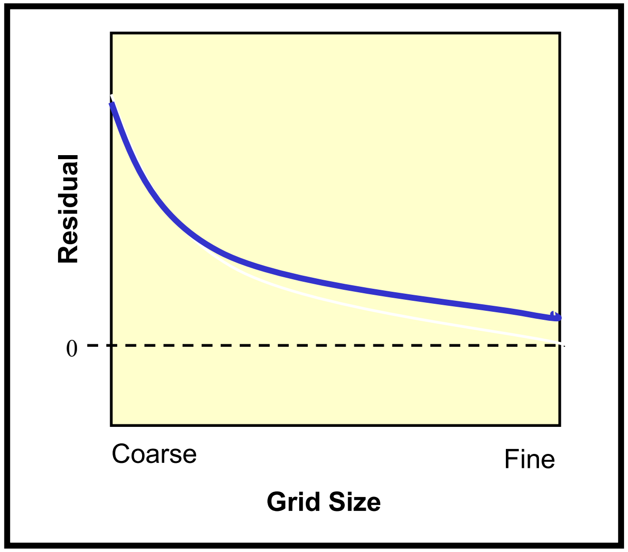
Navier Stokes Equations

This section introduces the momentum and continuity equations as they are implemented in the FAA code. The momentum equations are assumed to have the form,

$$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left\{\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right\} + S_{mom,i}\ .$$

The continuity equation has the form,

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u_i)}{\partial x_i} = S_{cont}\ .$$



Calculations

A solution to the equations is assumed (u, v, w, P) and the source term required so that the solution satisfies the equations is derived. The Navier-Stokes Equations are solved with the source term added and the solutions should converge to the assumed solution if the numerics are correct.

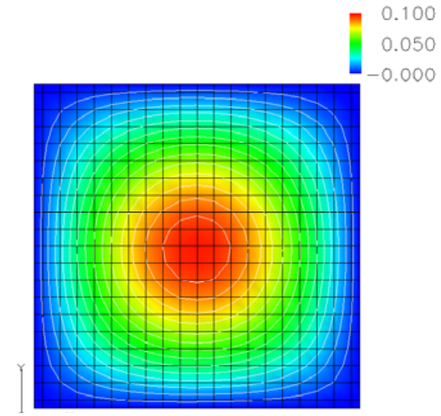
Verification of the Smoke Transport Model

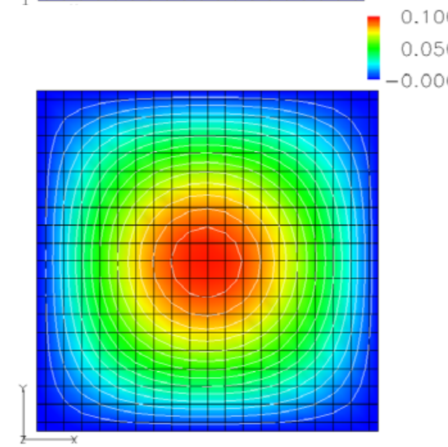
Source Terms

This section introduces the momentum and continuity source terms that are required so that the manufactured solution,

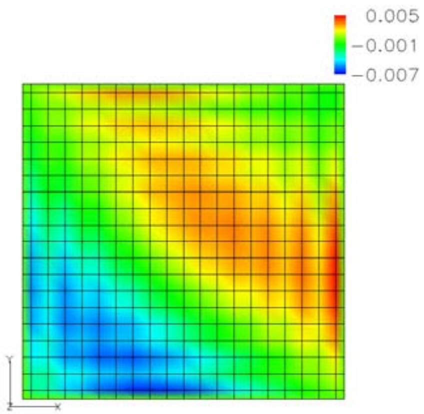
$$u(\mathbf{x},t) = U_0 t^2 \cos(\kappa x)\sin(\kappa y)\sin(\kappa z)$$
$$v(\mathbf{x},t) = U_0 t^2 \cos(\kappa x)\sin(\kappa y)\sin(\kappa z)$$
$$w(\mathbf{x},t) = 0$$
$$P(\mathbf{x},t) = 0$$

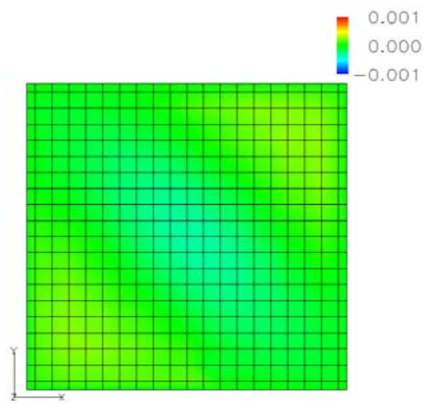
satisfies the laminar Navier Stokes equations as programmed in the FAA code. (simulations performed by Tom Voth)





Predicted x and y-velocity components





Predicted pressure and z-velocity component at time = 1, Uo=0.1

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FAA Full-Scale Validation Experiments

- Validation experimental matrix – full factorial with five replicates

Factor	Number of Levels	Specification
Fire location	4	Center(1), Flat Wall(2), Curved Wall(3), Corner(4)
Ventilation	2	None(1), Natural(2)
Geometry	2	707(1), DC9 lower(2)

- Baseline (center, 707, no ventilation)
- Instrumentation
  - 40 ceiling thermocouples
  - 3 gas analyzer locations
  - 6 smokemeters

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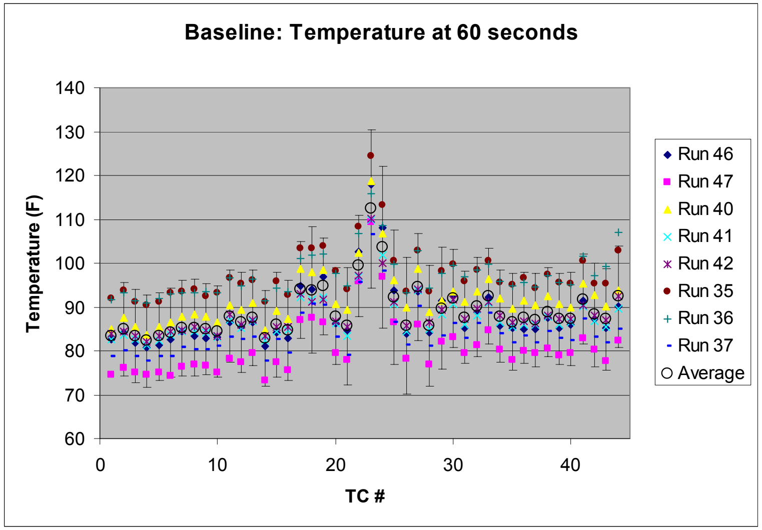
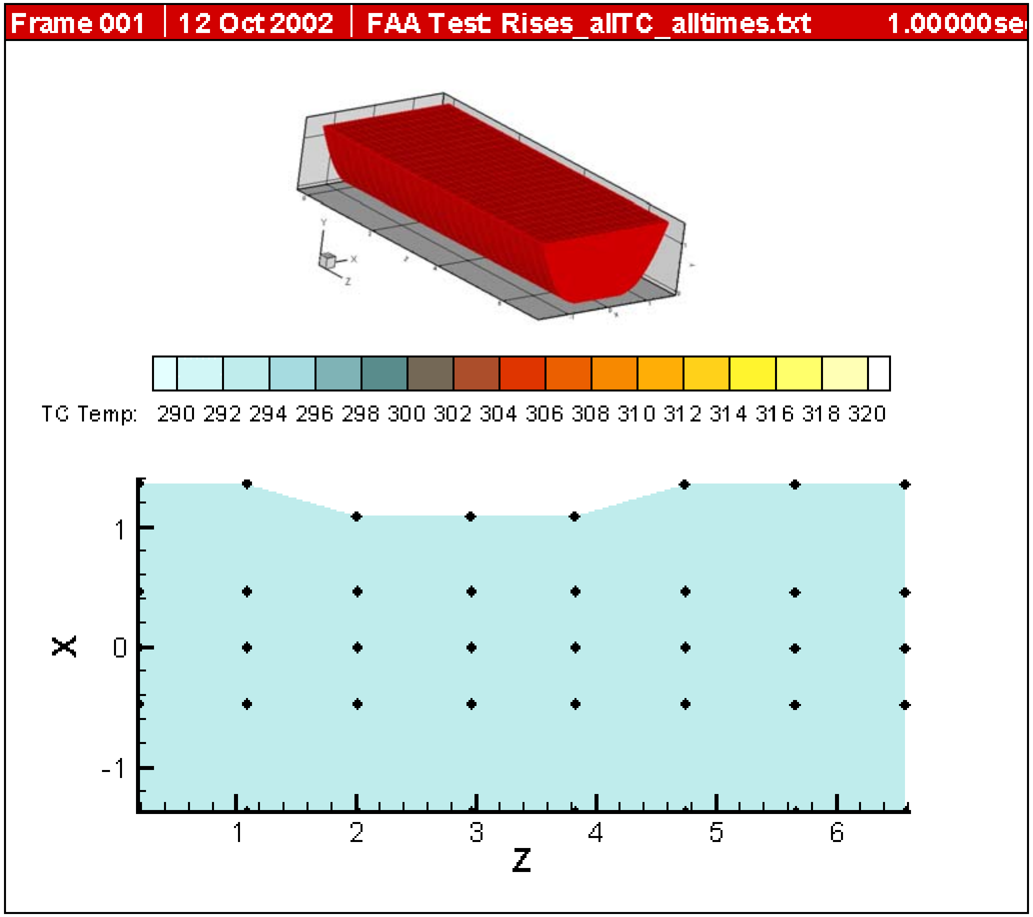
Baseline Ceiling Temperature Data

- Temperature Validation Metric
  - Rise at 60 sec, 120 sec, 180 sec
  - Absolute not possible due to different starting temperatures



Absolute temperatures at 60 sec



Animation of Baseline ceiling thermocouple temperatures

Baseline Smokemeter Data

- Smokemeter Validation Metric
  - Average at 60 sec, 120 sec, 180 sec
- Data is highly repeatable
- Experimental uncertainty being evaluated

%LT	60s_EXP	2 *SD (60s)
fwd	80.3	4.9
mid	78.6	4.6
aft	79.1	5.9
High	97.7	3.0
Mid	99.9	0.2
Low	99.9	0.3

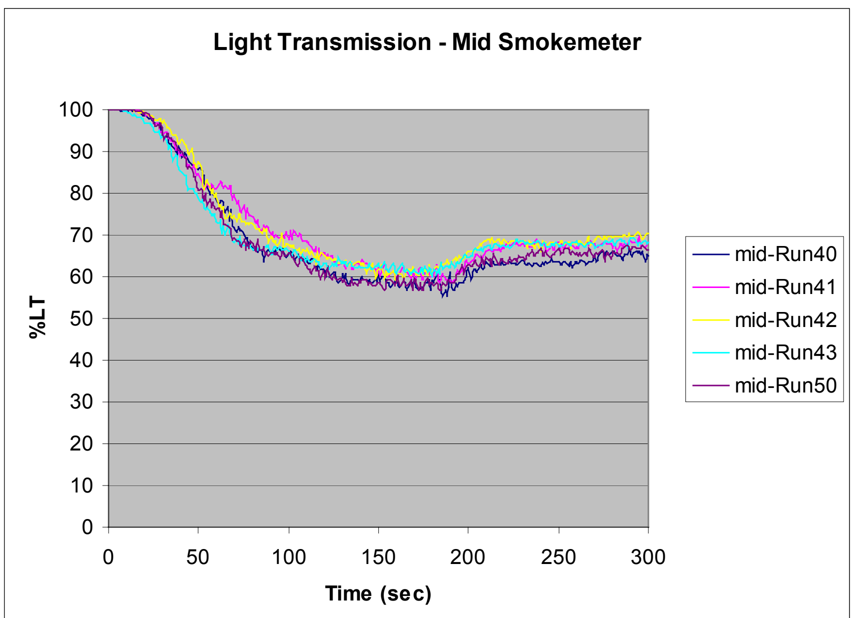
Experimental %LT at 60 sec

%LT	120s_EXP	2 *SD(120s)
fwd	65.1	3.8
mid	63.4	5.1
aft	63.9	4.2
High	73.8	6.2
Mid	95.5	3.9
Low	99.8	0.4

Experimental %LT at 120 sec

%LT	180s_EXP	2 *SD (180s)
fwd	60.8	3.9
mid	59.8	3.1
aft	60.7	4.2
High	64.4	5.2
Mid	87.6	10.1
Low	97.5	2.1

Experimental %LT at 180 sec



Transient data sets showing variability

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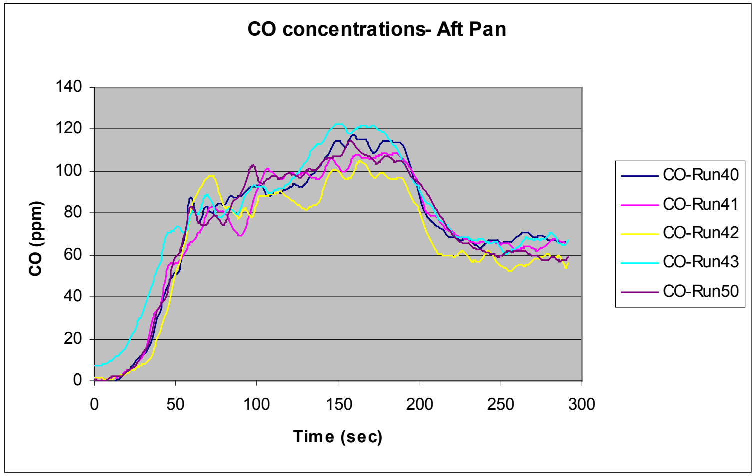
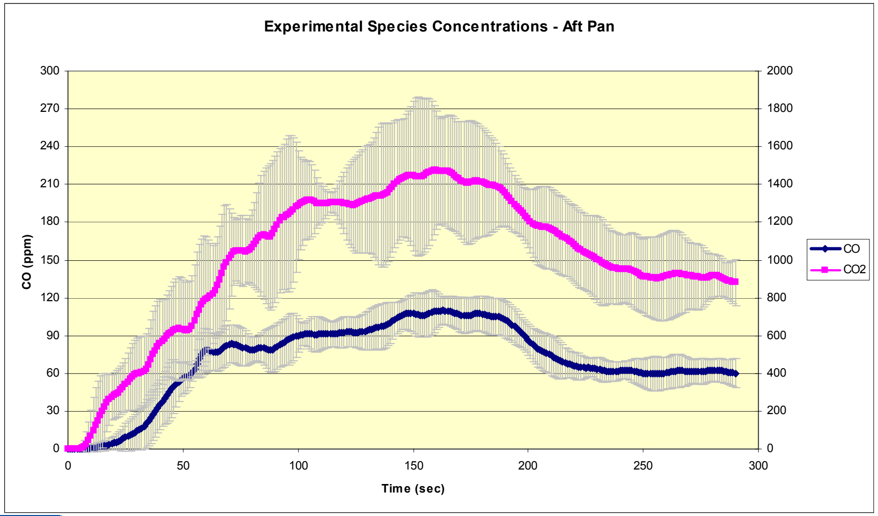
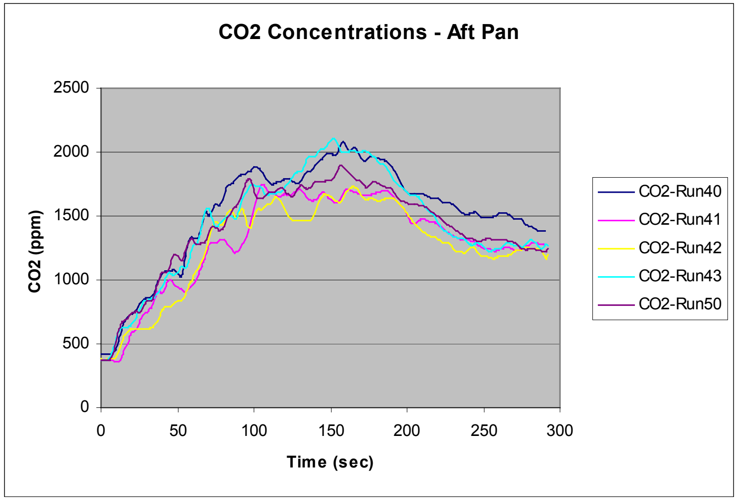
Baseline Gas Analyzer Data

- Smokemeter Validation Metric
  - Average rise at 60 sec, 120 sec, 180 sec
- Variability of data quantified
- Uncertainty of analyzers alone
  - CO: 1% of 500 ppm = ± 5 ppm
  - CO2: 1% of 2500 ppm = ± 25 ppm





Average rise at all times with total uncertainty



CO and CO2 transient experimental data

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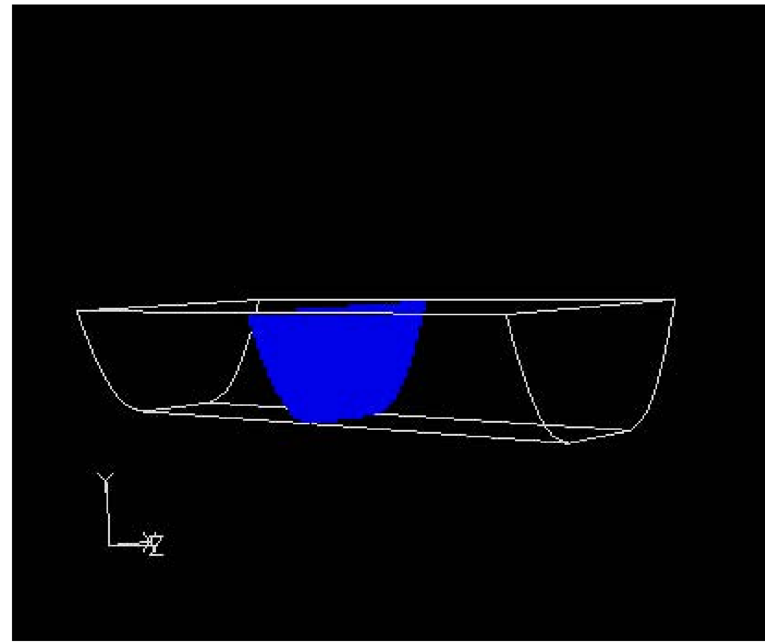
Smoke Transport Code Simulations

- **Baseline simulation**
  - **Flaming resin block**
  - **Source in center of 707 compartment**
  - **No ventilation**
- **1 hour of run time per minute of actual time**



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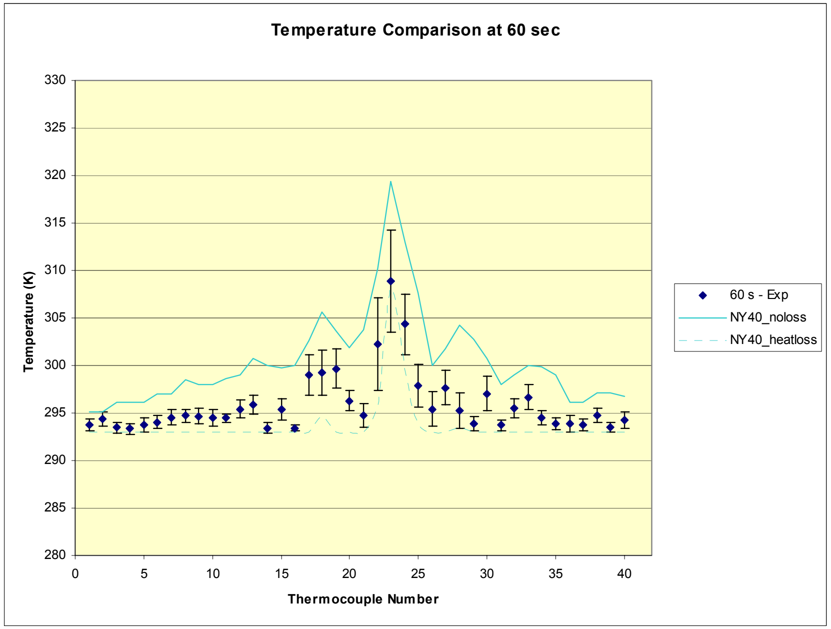
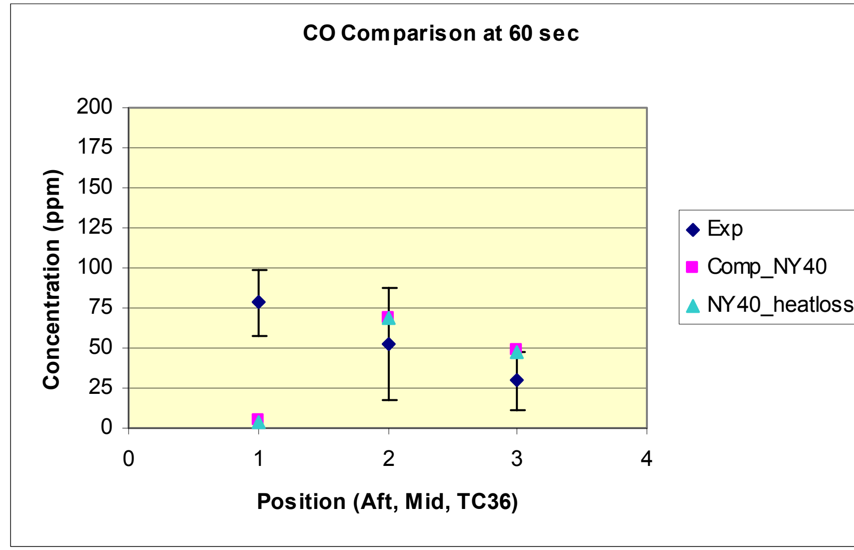
Preliminary Temperature Comparisons at 60 seconds

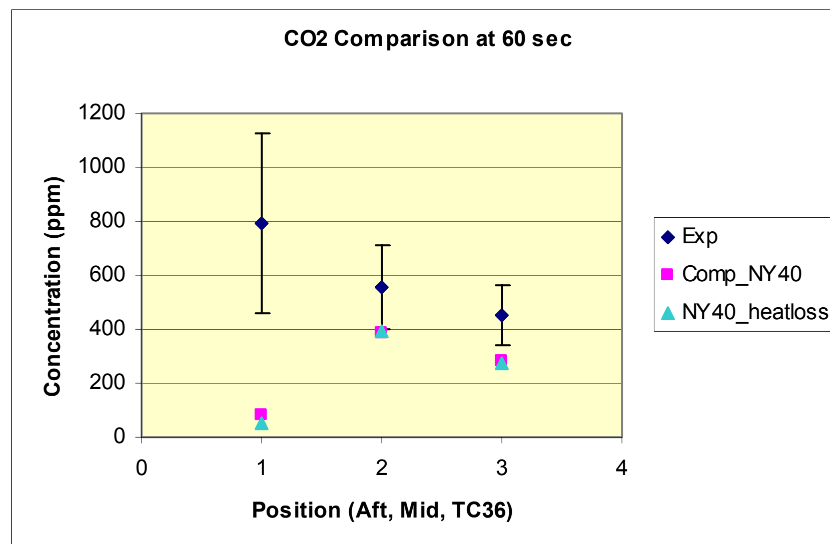
- Experimental data trends are captured
  - Radiation loss from the fire
  - Heat loss to the walls
    - Experimental data is bracketed by adiabatic and heat loss with isothermal wall simulations
    - Additional information on wall temperatures and/or heat fluxes are required
- Micro-foil heat flux sensor is recommended for use in experiments for further assessment and submodel development



Preliminary Concentration Comparisons at 60 seconds

- Agreement is good except for Aft pan
- Magnitudes of CO2 comparisons are less favorable at later times, but trends are captured
- Correction for analyzer response was not included
- Recessed area modeling is in progress





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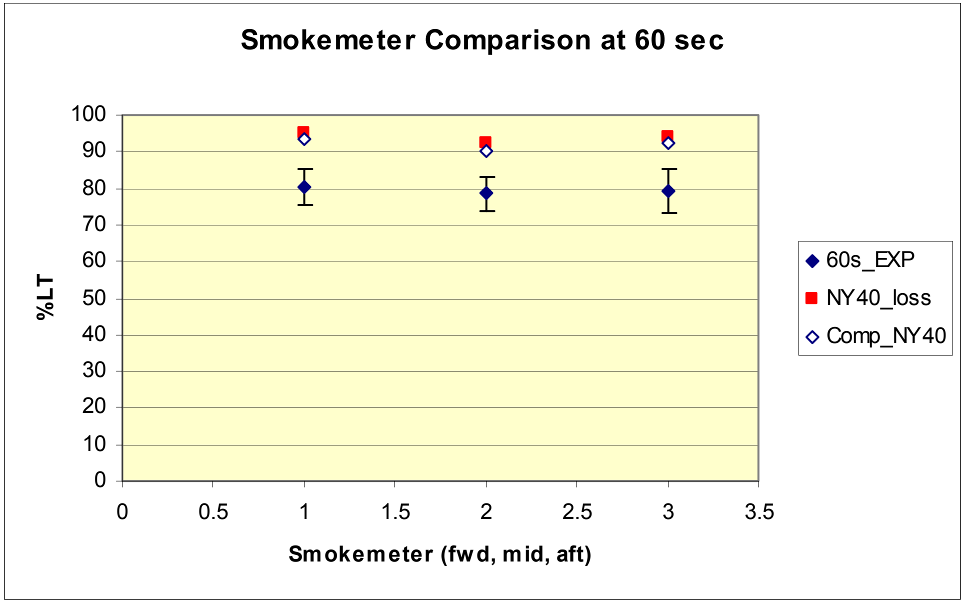
Preliminary Smoke Meter Comparisons at 60 seconds

- Trends are predicted
- Model is consistently higher; less soot present
- Error bars represent experimental variation
  - Uncertainty of system has not been assessed
- Uncertainty in soot extinction coefficient for input to the model
  - Measured values vary within a factor of 2
  - Can result in ~10% variation in light transmission for calculation



Conclusions and Path Forward

- Trends for validation metrics are predicted
- Fair agreement in magnitudes were obtained for some of the validation metrics
- Additional experiments are required to fully assess the model capabilities
- Model additions are required
  - Recessed areas
  - As determined from above experiments

Problem	Hypothesis	Reason	Test
Temperatures only bracketed	Need heat loss to walls	Data are between extremes	Measure wall temp and flux
	Need radiation loss from source	High temperatures	Hot plate experiment
Light transmission is too high	Value for extinction coefficient is low	Experimental data known to vary by 2x	Accept, include as model uncertainty
	Experimental uncertainty	Beam steering, calibration	Hot plate experiment and calibration
	Soot not being transported correctly	Too little soot in predictions	Assess species transport model
Concentrations of species	Recessed area not included	Recessions are known to impact flow	Add to computational model
	3 species do not make up entire MLR	Impacts flow field and transport	Add fourth species (remainder of MLR)

Future Activities

- Continue Validation of the smoke transport code
  - Series of full-scale experiments
  - Code modifications and additions

- Develop and implement user interface (Dec '03)
- Documentation and release of code to small user community (Feb '04)
- Revisions and final release of code (Feb '05)