Modeling and Analysis of Realistic Fire Scenarios in Spacecraft

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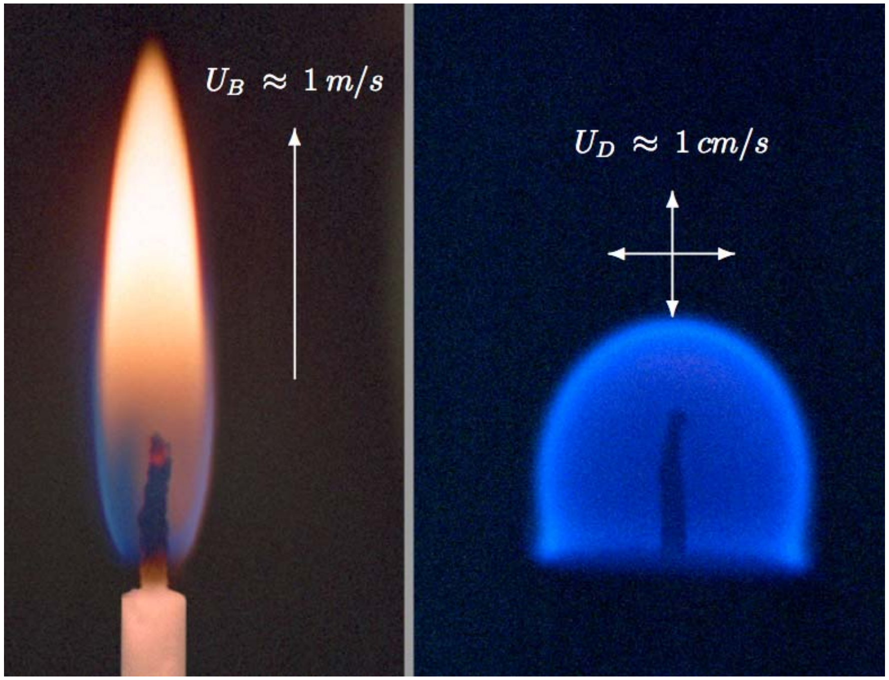
***45th International Conference on Environmental Systems*, 12 – 16 July 2015, Bellevue, Washington**

Introduction

- **Fire is a significant hazard to both crew and vehicle on exploration missions**
- **On long-duration missions abandoning the vehicle and a rapid return to earth are not possible**
- **Fire requires fuel, oxidizer and an ignition source**
  - All three present by necessity on manned spacecraft
- **Large-scale fires are very complex:**
  - Turbulent, chemically reacting flow
  - Complex chemical kinetics involving large hydrocarbon molecules, solid and gas phases and chlorinated or fluorinated species

Uniqueness of Microgravity

- **Flame characteristics and flammability limits change**
  - Low-speed, sub-buoyant flows
  - Normal gravity testing not necessarily worst-case
- **Particulate size and transport changes**
  - Terrestrial standards for detection not necessarily applicable
- **Small, sealed, confined volume with limited egress**

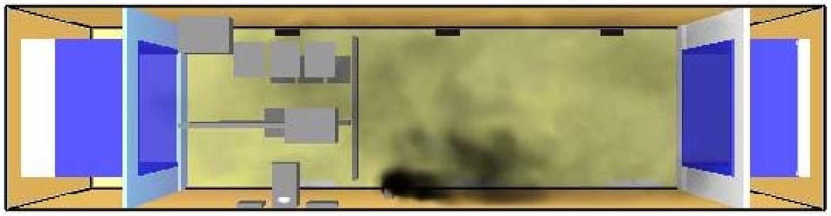


- **Terrestrial large-scale fire models and experiments are of limited utility**
  - Upcoming Saffire experiments are largest to date in microgravity
- **Must rely on numerical models validated and calibrated against the very limited experimental data**

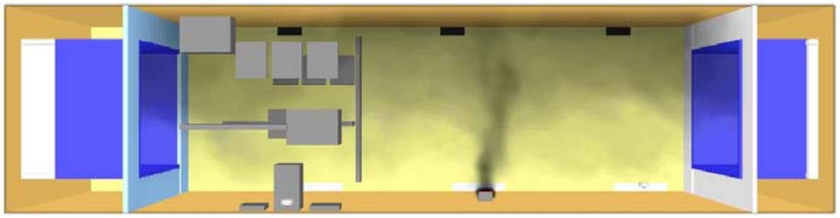
Overall FPDS Approach

Develop a comprehensive modeling capability

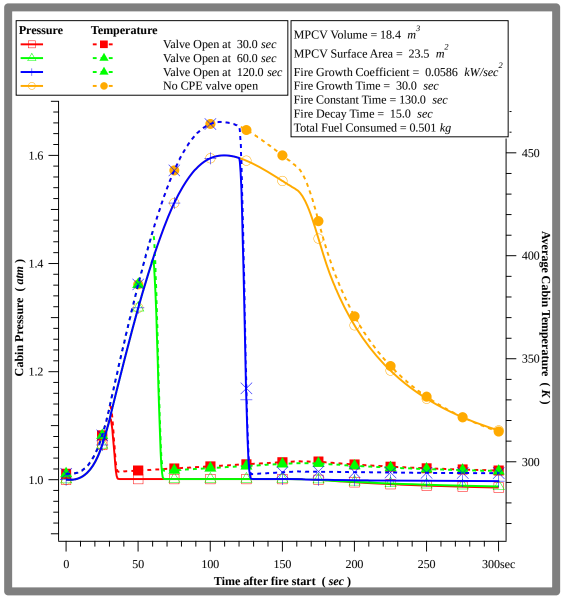
1. **Large Eddy Simulation (LES) CFD models:**
   - Builds off of efforts to model ISS fire detection
   - Detailed treatment of flow inside the vehicle
   - Computationally intensive for realistic spacecraft configurations involving chemically reacting flows
2. **Lumped Capacity Models (LCM):**
   - Builds off of efforts to estimate survivable fires for spacecraft
   - Not as detailed as LES, but more amenable to parametric studies



Microgravity



Normal Gravity



Lumped Capacity Models (LCM)

- **Treat the spacecraft volume as a single 'zone'**
  - Can be extended to multiple zones
- **Assume each zone has a uniform temperature and species concentration**
- **Solve for energy and species conservation in each zone with a prescribed fire**

$$\left(\frac{dQ}{dt}\right)_{loss} + \left(\frac{dQ}{dt}\right)_{fire} + \left[\sum_i \dot{n}_i h_i - \sum_e \dot{n}_e h_e\right] = \frac{dU_{cv}}{dt}$$

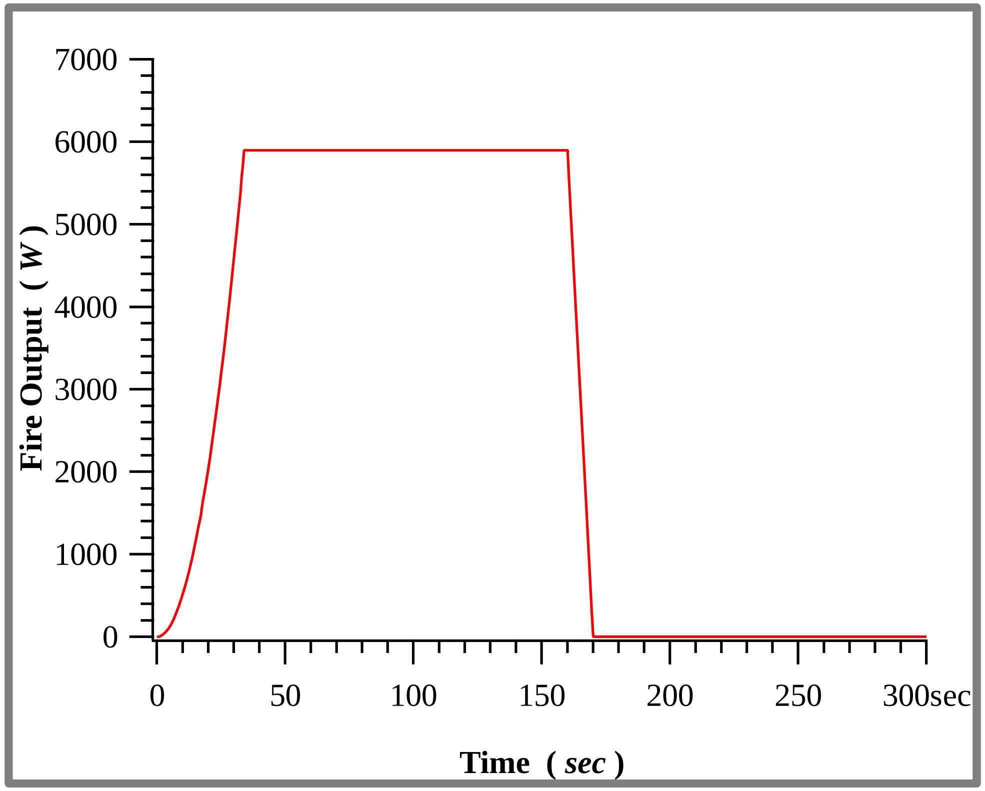
$$\frac{dn_i}{dt} = (\dot{n}_i)_{gen} - (\dot{n}_i)_{con}$$

- **Creates a system of ODEs quickly solved by a range of open-source and commercial solvers**

Base Case Comparison

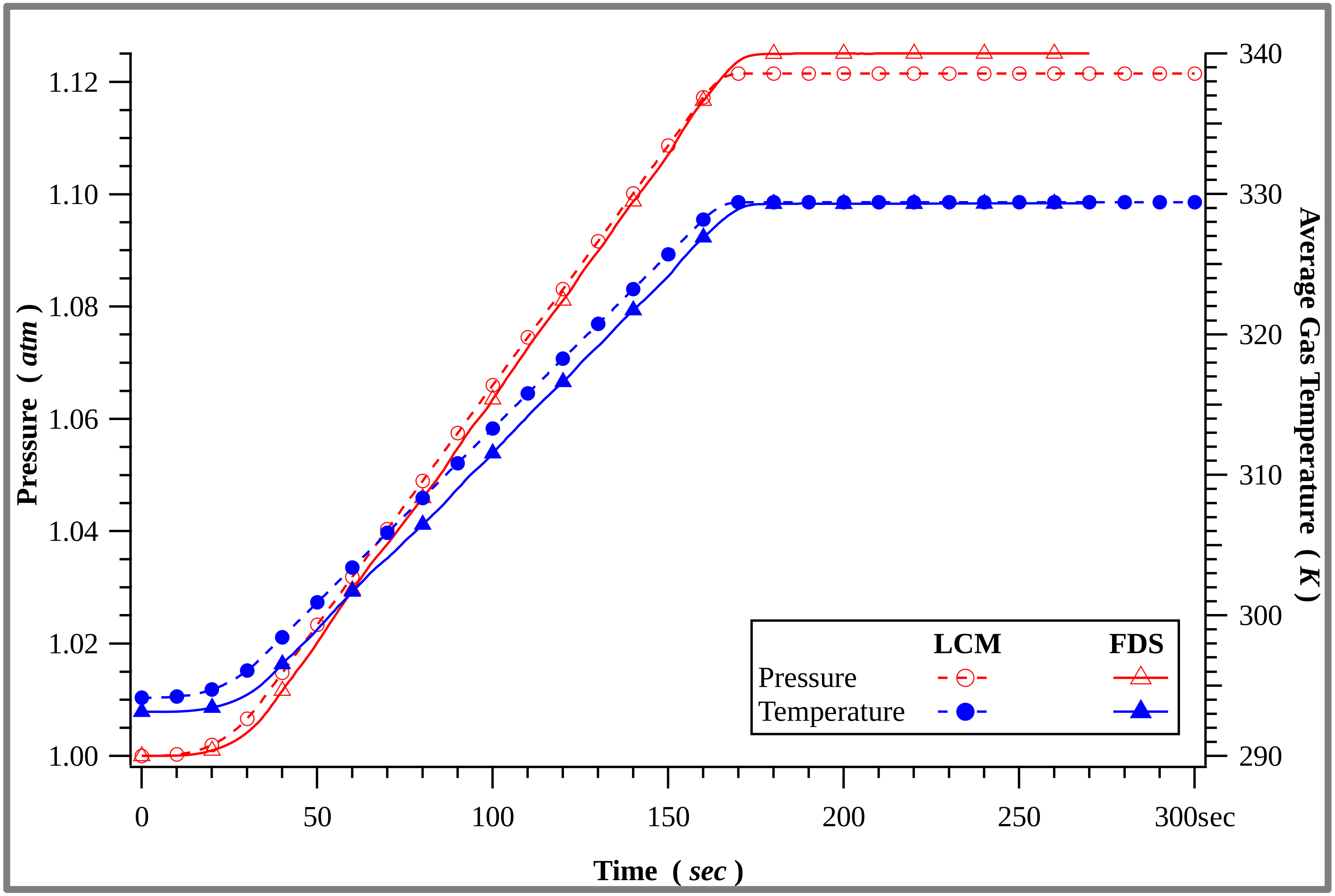
- **Empty, sealed cubic volume 3 *m* on a side**
- **Prescribed heat input**

1. **Adiabatic wall**
   - All energy transferred to gas
2. **Isothermal wall**
   - Heat transfer to the wall

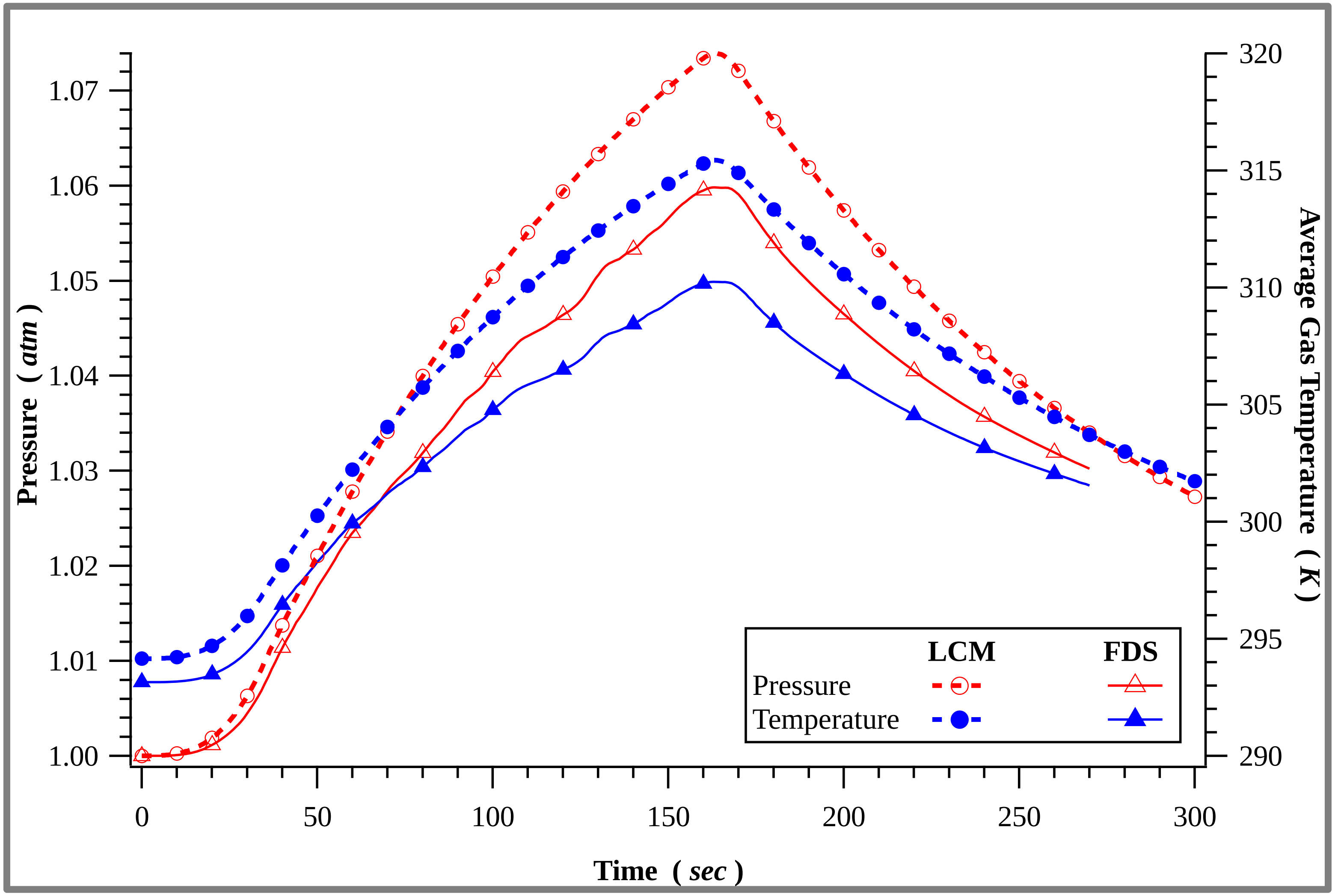


- αt^2 growth first 34 *s* (α = 5.1 *x* 10^{-3} *kW/s*^{2})
- Constant fire for next 126 *s*
- Linear decay to 0 for 10 *s*
- Approximates expected profile from Saffire I

Base Case – Adiabatic Walls



Base Case – Isothermal Wall



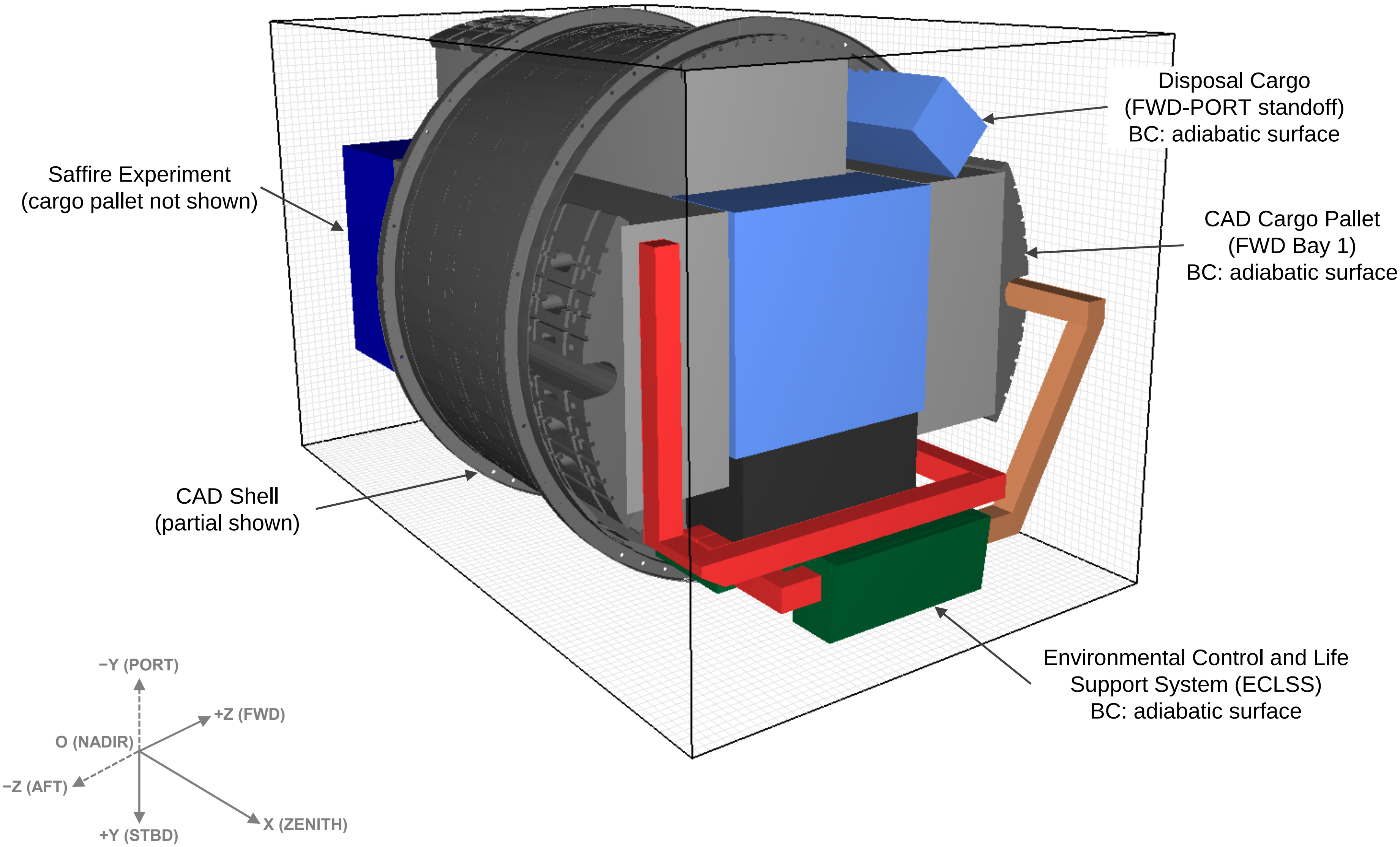
Detailed Computation - Saffire

- **Saffire experiment will be conducted in Orbital Cygnus Pressurized Cargo Module after de-mating from ISS (still in LEO)**
- **Use FDS to simulate the flow and heat transfer in the PCM while the large fuel sample is burned in Saffire**

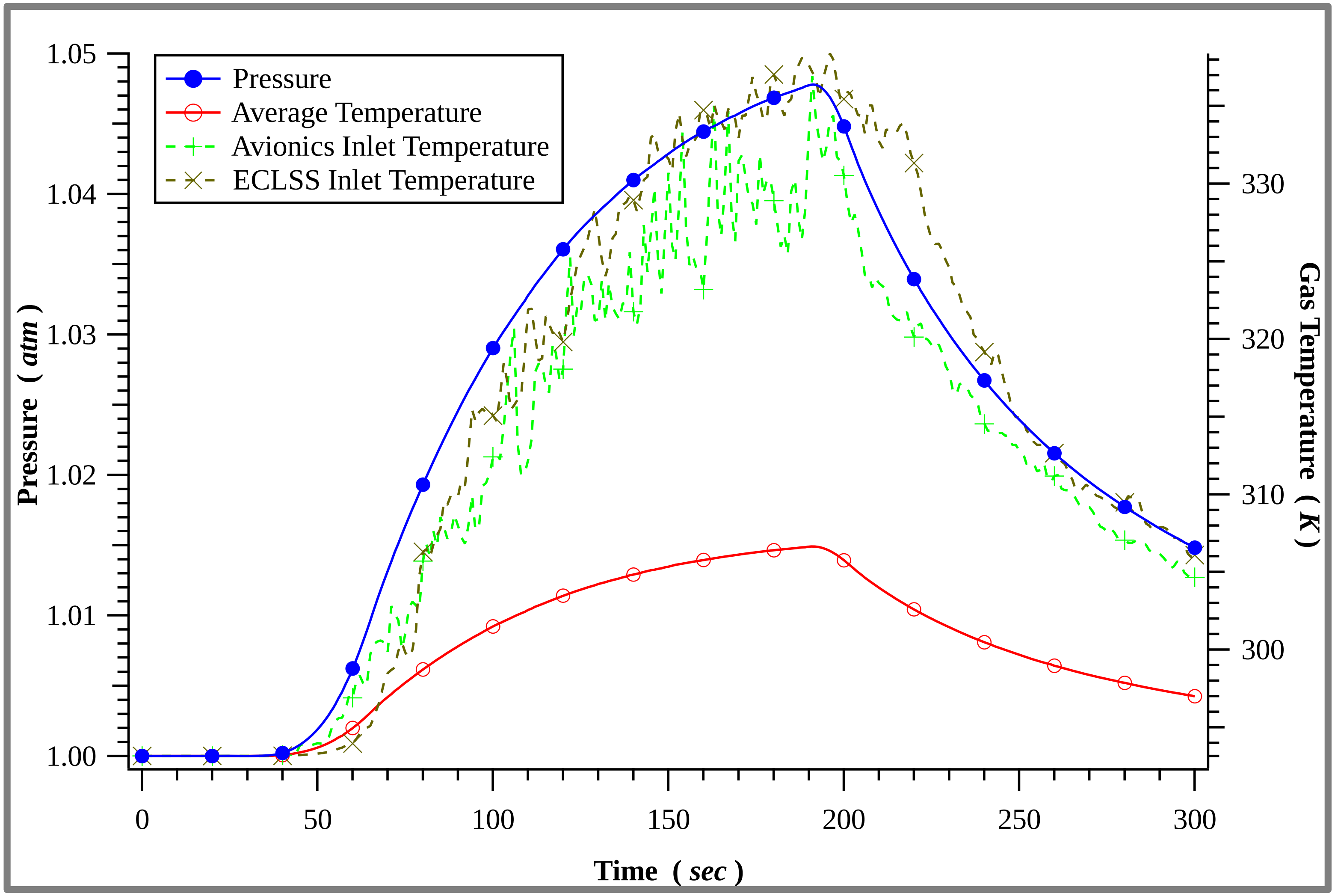
Initial Conditions	Simulation Conditions	FDS Parameters
20 C	Isothermal Shell 20 C	Radiative Frac = 0
1.0 atm	Adiabatic Solid Objects	Suppression OFF
Air (0.21/0.79)	Heat Release at 30 s	Radiation OFF
	Fuel Mass = 0.0541 kg	Stratification OFF
	Saff. Flow = 0.104 m^3/s	Gravity OFF
	ECLSS = 0.0524 m^3/s	
	Gas Vol. = 10.6 m^3	

- **Observe flow and heat transfer in realistic Saffire/PCM configuration**

FDS Configuration - Saffire



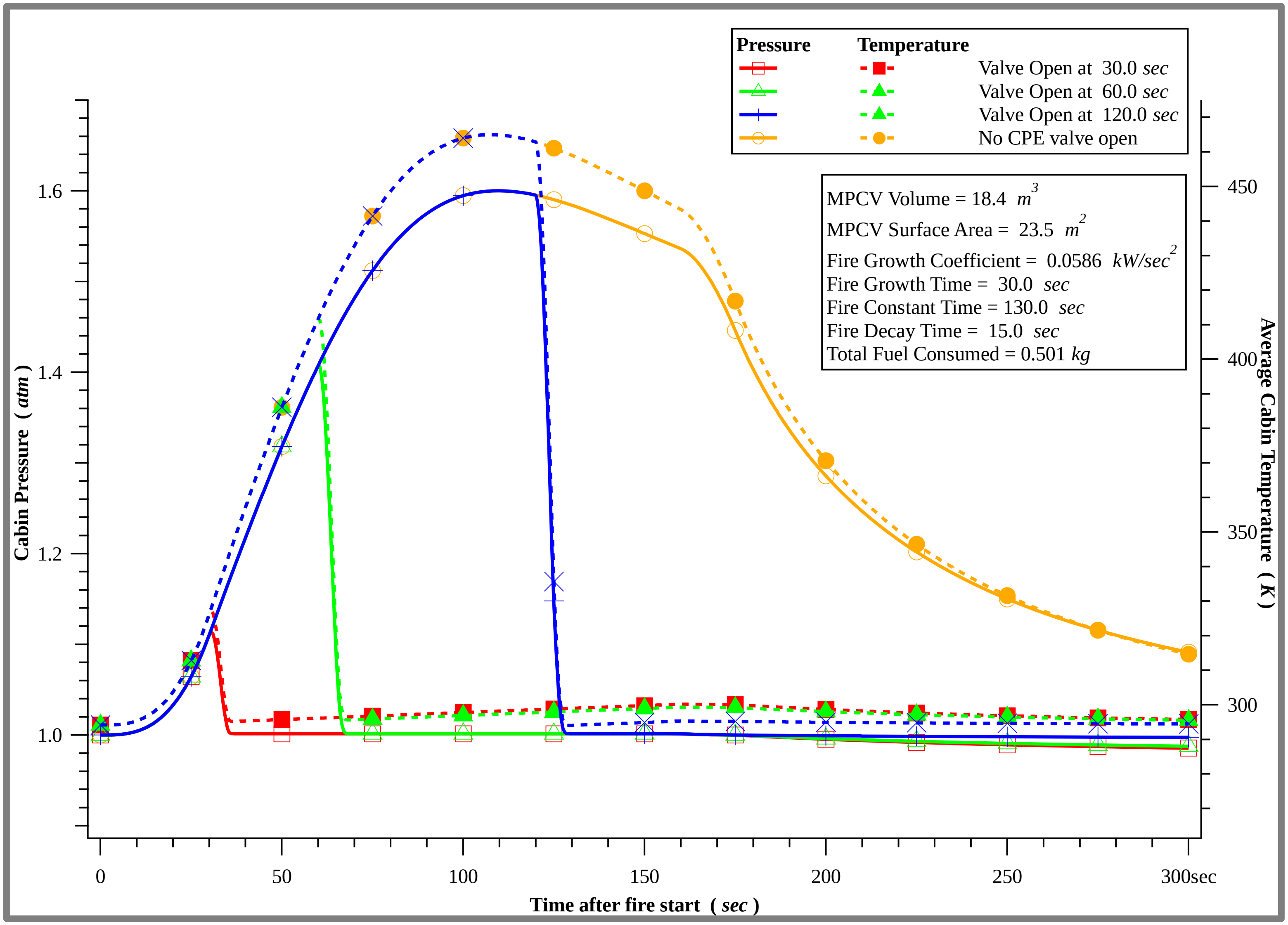
FDS Saffire Computation Results



MPCV Hatch Re-Design Study

- MPCV considered hatch re-design to save weight
- Needed to understand how accidental fire (launchpad) would impact crew/vehicle
- Assess the efficacy of the Cabin Pressure Equalization Valve (CPE)
- Perform parametric studies for different fire scenarios, CPE actuation, vehicle interiors.

MPCV Parametric Study



Discussion

- **FDS can perform high-fidelity simulations of flows inside spacecraft with fires/heat release.**
  - Can show localized results for combustion product accumulation, oxygen depletion, etc.
  - Simulations can take days for long simulation times and/or complex geometries for a single configuration (vehicle interior and flow condition)
- **LCM more amenable to large-scale parametric studies**
  - Can easily run hundreds of simulations over wide-ranging conditions such as vehicle volumes, fire sizes, relief valve sizes, etc.
  - Lack the localized fidelity present in LES
- **Use FDS to calibrate or tune the parameters in the LCM for better fidelity**
- **Currently both models use a prescribed fire. Eventually need models to make *a-priori* predictions of fire based on vehicle interior contents**
- **Models can be extended to include ECLSS scrubbing and flows**

Conclusions

- **FPDS pursuing two model approaches to fire in spacecraft**
  - CFD simulations using FDS build on efforts to model fire detection in ISS.
  - LCM models treat spacecraft as a single volume and build off of efforts to define and predict a survivable fire in a spacecraft
- **The complexity of real fires necessitate this approach**
  - CFD provides detailed predictions in realistic geometries but requires large computational time – not amenable to parametric studies
  - LCM models suited for parametric studies and engineering evaluation of evolving spacecraft designs
- **Demonstrated compatibility of model approaches in simple configuration and capability of both models**
  - Used FDS to simulate flows inside of Orbital Cygnus during Saffire
  - Used LCM to assist in the evaluation of hatch re-design in the MPCV
- **FPDS will continue to develop both model approaches**
  - Incorporate detection into both models
  - Develop the capability to make *a priori* predictions of fire