



U.S. ARMY TANK AUTOMOTIVE RESEARCH, DEVELOPMENT AND ENGINEERING CENTER

## Fire Suppression M&S Validation (Status & Challenges)

Systems Fire Protection Information Exchange

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- Introduction
- Physics being solved
- Reduced Chemical Kinetics:
  - Complete description of suppression is complex
  - HFP (+SBC); Halon (+SBC), potassium acetate solution.
- Fire Suppression Evaluation Criteria
- Simulation Results & Comparison with Test Data:
  - Cup Burner
  - Exploratory Test Box
  - Crew Compartment
    - » Concentration
    - » Live Fire Simulation
  - Engine Compartment (In-Progress)
- Summary & Future Work

- **Develop a Computational Fluid Dynamics (CFD) capability for modeling suppression events in ground combat vehicles.**
- **Using known component parameters, M&S allows:**
  - **To conduct trade studies between various layouts.**
  - **Reduces time and cost to compare multiple configurations.**
  - **Provides insight by complementing testing**

## Transient Analysis

- Model fuel spray and fire ball development
- Suppressant Discharge + Acid Mitigation

## Turbulence Model

- K-Epsilon with Realizable Wall functions
- Segregated Solver

## Lagrangian Physics

- Two-Way Coupling
- Evaporation & Devolatization

## Suppressant Discharge

- Discharge from Pressurized bottle
- Liquid & Vapor Phase

## Combustion Model

- Hybrid EBU with finite rate Kinetics
- 14 Species & 12 reactions

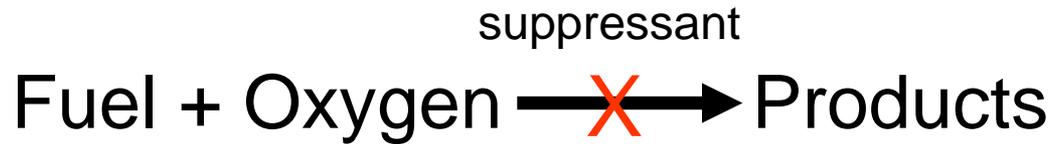
## Radiation Model

- Participating Media Discrete Ordinate Method
- WSG model for CO<sub>2</sub>, H<sub>2</sub>O and Soot

## Suppression

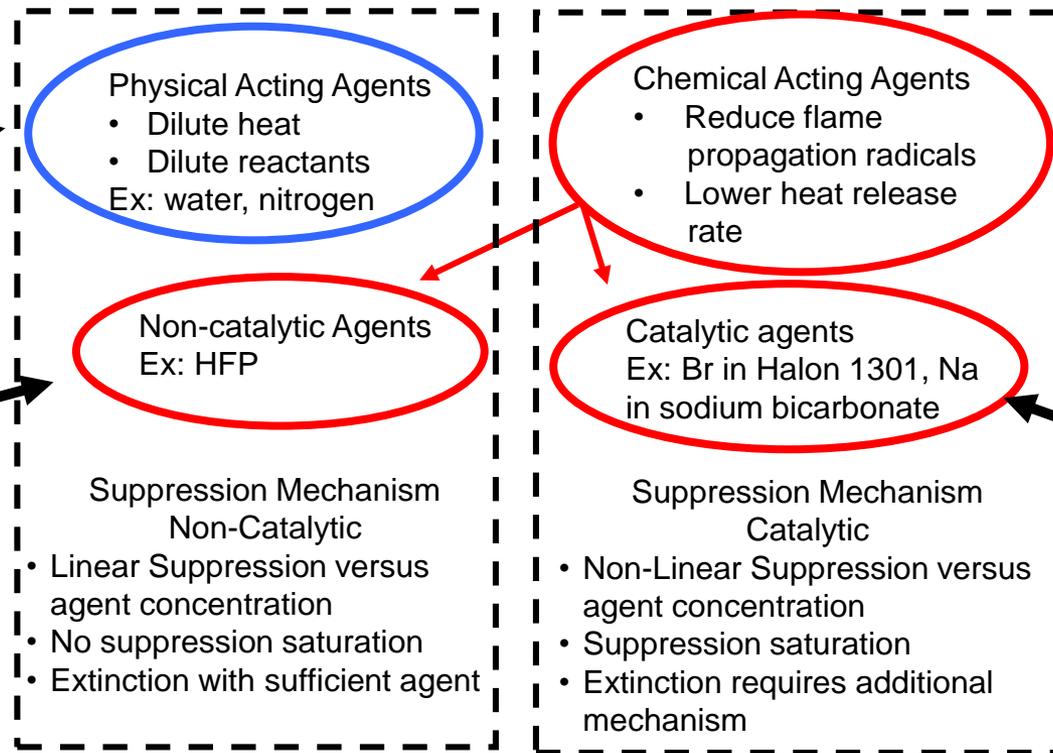
- Catalytic & Non-Catalytic effects
- Acid Levels

# Inhibition of JP-8 Combustion



Implicitly accounted for in CFD code

Non-catalytic  $\Delta$  in reduced kinetics



Catalytic  $\Delta$  in reduced kinetics

Inhibited rate of Reaction

Uninhibited rate of Reaction

$$R_R = R_R^u - \Delta R_{noncatalytic} - \Delta R_{catalytic}$$

# Overview of Reduced Kinetics Scheme for FM200



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## Inhibition of JP-8 combustion by HFP (FM200) and/or sodium bicarbonate powder (SBC)

Mechanism:  $\approx 800$  chemical reactions

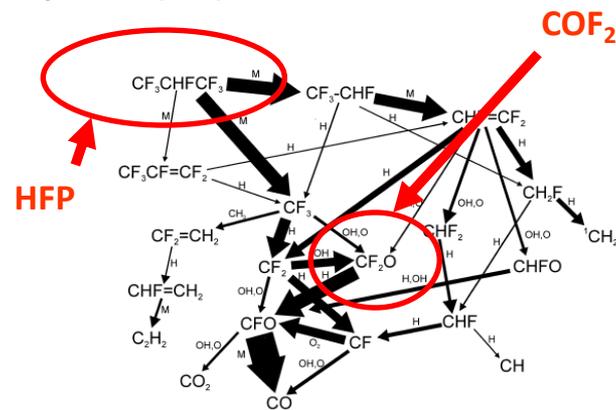
(200 for hydrocarbon fuel—more for JP-8; 600 for fluorine chemistry)

Predicts flame inhibition, acid gas formation

Useful for modeling laboratory experiments

**Not** useful for modeling large-scale fire suppression

- **R1:**  $\text{JP-8} + \text{O}_2 \Rightarrow \text{CO} + \text{CO}_2 + \text{H}_2\text{O}$
- **R2:**  $\text{CO} + \text{O}_2 \rightleftharpoons \text{CO}_2$
- **R3:**  $\text{HFP} + \text{JP-8} + \text{O}_2 \Rightarrow \text{HF} + \text{COF}_2 + \text{CO} + \text{H}_2\text{O}$
- **R4:**  $\text{COF}_2 + \text{H}_2\text{O} \Rightarrow \text{CO}_2 + \text{HF}$
- **R5:**  $\text{NaHCO}_3(\text{s}) \Rightarrow \text{CO}_2 + \text{NaOH}(\text{g})$
- **R6:**  $\text{NaOH}(\text{g}) \rightleftharpoons \text{NaOH}(\text{hvy\_gas})$  (hvy\_gas = heavy-gas approximation)
- **R7:**  $\text{NaOH}(\text{hvy\_gas}) + \text{HF} \Rightarrow \text{NaF}(\text{hvy\_gas}) + \text{H}_2\text{O}$
- **R8:**  $\text{NaHCO}_3(\text{s}) + \text{HF} \Rightarrow \text{NaF}(\text{hvy\_gas}) + \text{H}_2\text{O} + \text{CO}_2$
- **R9:**  $\text{JP-8} + \text{O}_2 \Rightarrow \text{C} (\text{soot}) + \text{H}_2\text{O}$
- **R10:**  $\text{C} (\text{soot}) + \text{O}_2 \Rightarrow +\text{CO}_2$



Kinetic Rate Coefficient for each equation is given in Arrhenius form (three-parameter)

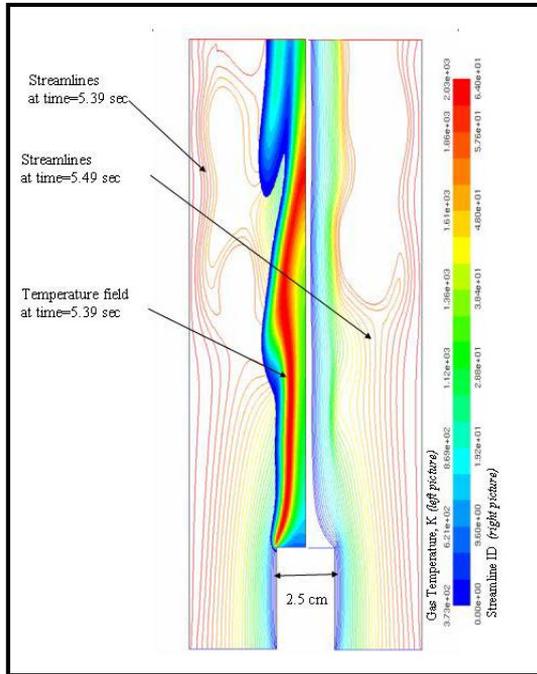
*Halon Kinetics includes HBr acid*

# Selected Crew AFES performance criteria:

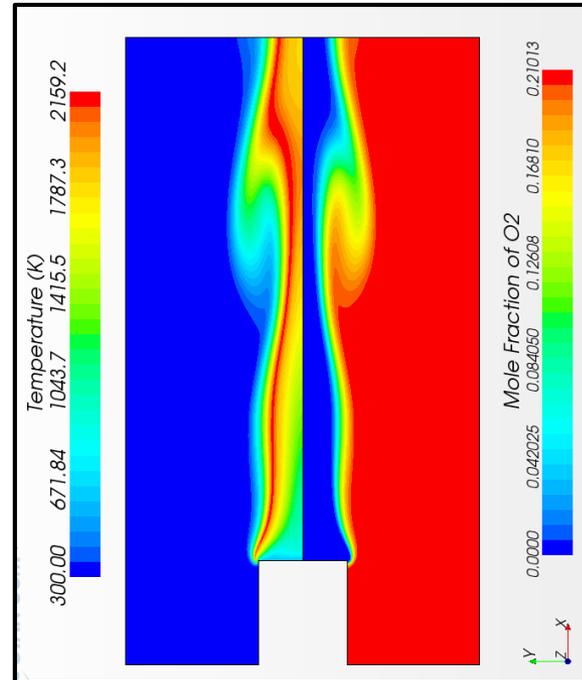


| Parameter               | Requirement   | Simulation |
|-------------------------|---|------------|
| Fire Suppression        | Extinguish Flames without reflash                                   | Y          |
| Skin Burns              | Less than Second degree burns                                       | Y          |
| Overpressure            | Lung damage <11.6 psi; Ear damage ≤ 3.6 psi                         | Y          |
| Acid Gases              | Acid gas, 5 min dose (HF + HBr + 2·COF <sub>2</sub> ) < 746 ppm-min | Y          |
| Agent Concentration     | <Lowest Observed Adverse Effects Level                              | Y          |
| Oxygen Levels           | Not below 16%   | Y          |
| Discharge Impulse Noise | No hearing protection limit < 140 dB                                | N          |
| Discharge Forces        | Acceleration ≤ 8 g and pressure pulse ≤ 10 psig at crew locations   | N          |
| Fragmentation           | Ejected non-agent particles ≤ 300 micrometers                       | N          |

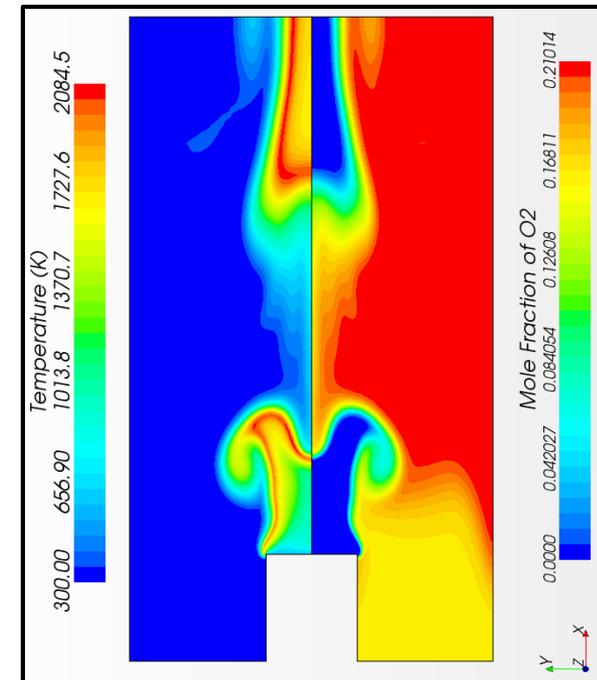
# Cup-Burner Modeling (Determine Flame Extinguishing Concentrations)



**Ref. NRL Paper**  
**(GMRES, 35 species, 217 reactions)**

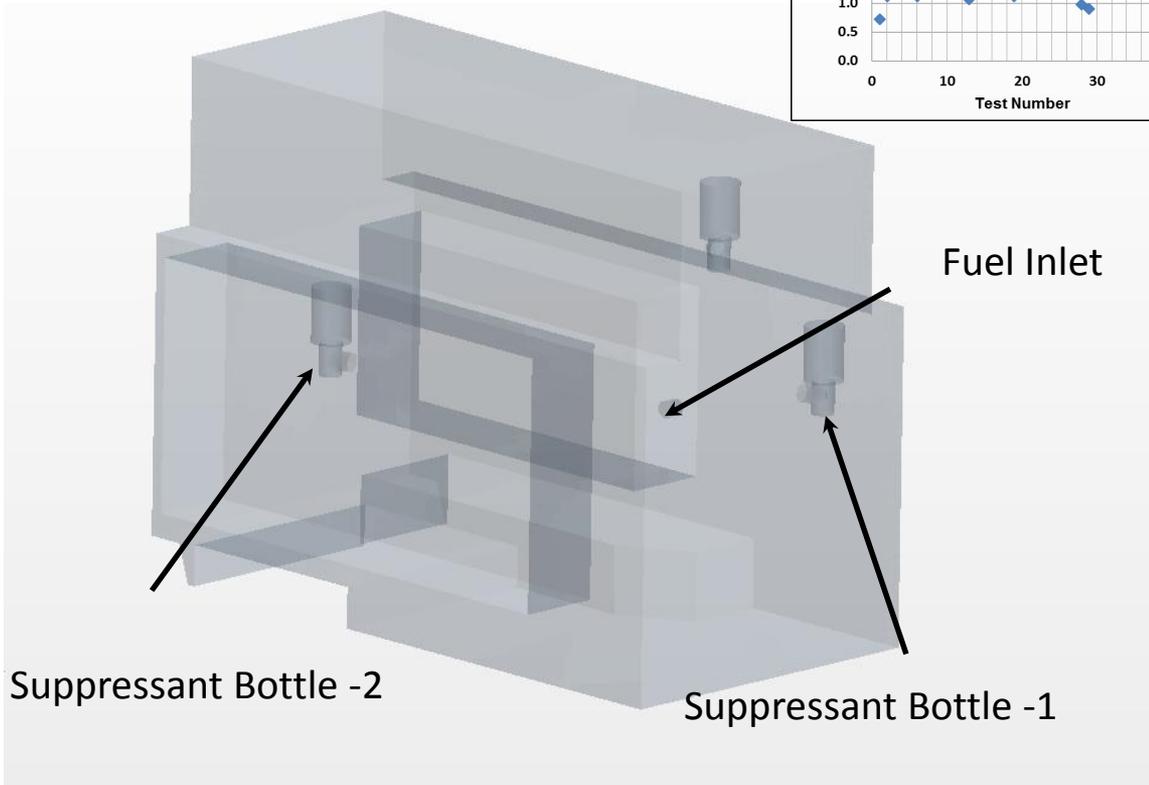
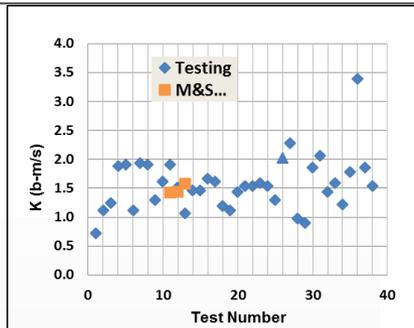


**Uninhibited**  
**(Two-step Global Reactions)**



**Inhibited With Nitrogen**  
**(Two-step Global Reactions)**

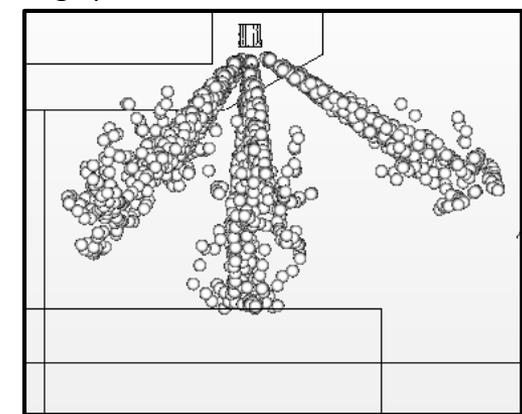
# EXPLORATORY TEST BOX



Fire Ball Generator

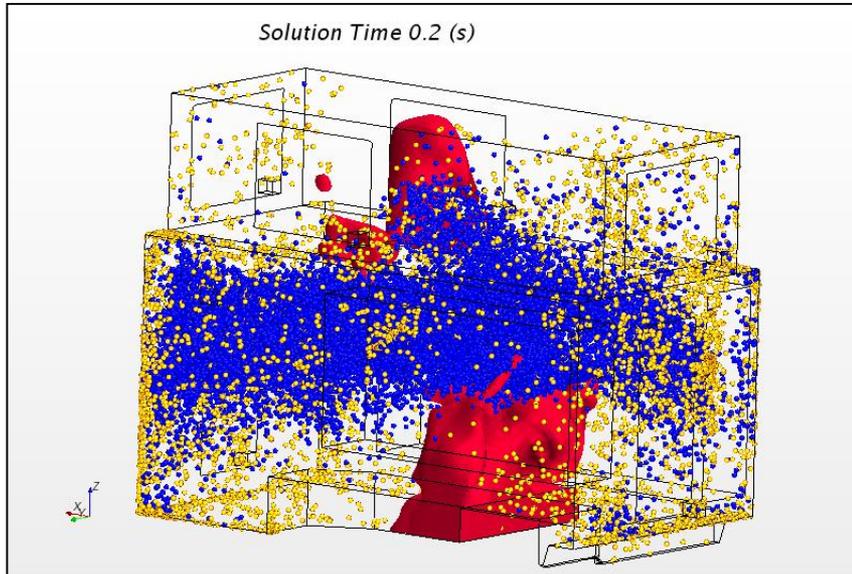


Fireball is based on a medium shaped charge penetration into fuel cell

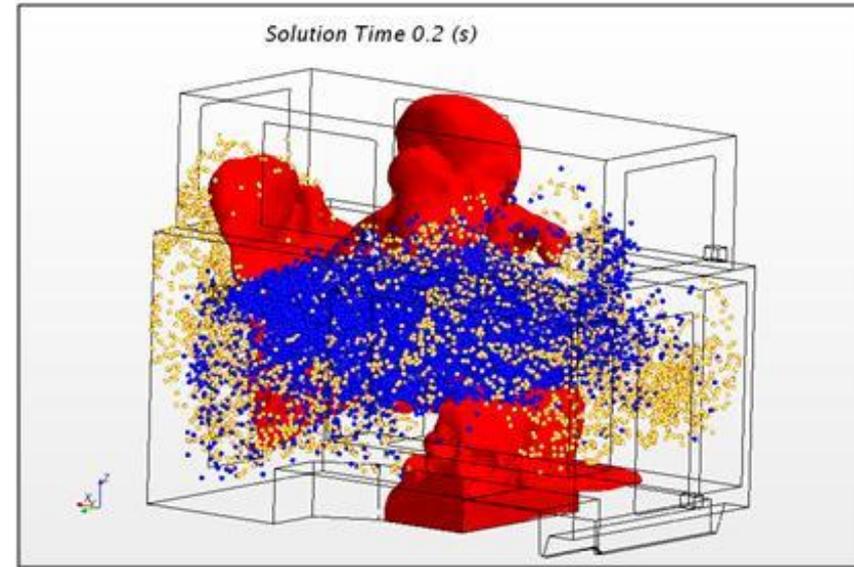


Reference: *Fire Extinguishing Agents for Protection of Occupied Spaces in Military Ground Vehicles*

# EXPLORATORY TEST BOX SIMULATIONS



**Test Box (Successful Suppression)**  
Fire Ball (Red), SBC (Gold), HFC227ea (Blue)



**Test Box (Failed Suppression)**  
Fire Ball (Red), SBC (Gold), HFC227ea (Blue)

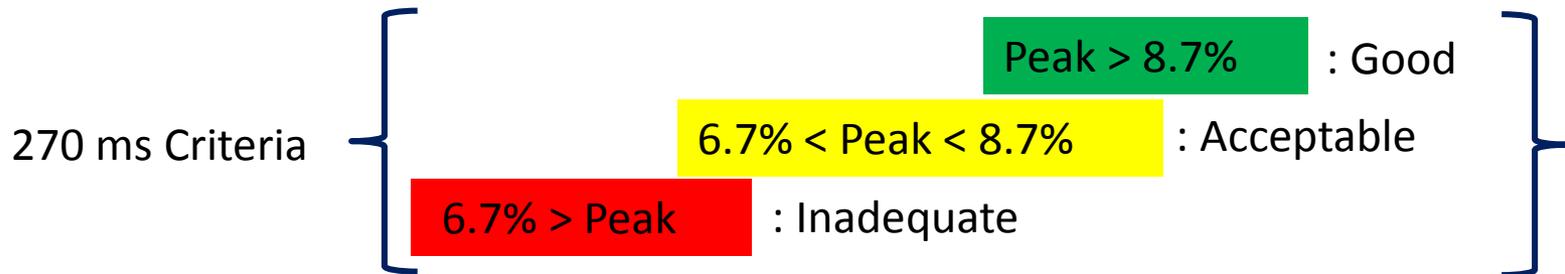
| Criteria                          | Above Design Conc. |            | Below Design Conc. |            |
|-----------------------------------|--------------------|------------|--------------------|------------|
|                                   | Test               | Simulation | Test               | Simulation |
| Overall                           | Pass               | Pass       | Fail               | Fail       |
| Extinguish Flames without reflash | YES                | YES        | YES                | No         |
| K Value                           | 1.56               | 1.44       | 1.14               | 1.44       |
| HF Acid (PPM)                     | <20                | 47         | 3975               | NA         |
| COF2 Acid (PPM)                   | <20                | 97         | 1550               | NA         |
| Oxygen Levels                     | 17.4%              | 18.0%      | 16.5%              | NA         |

# Comparison of FM200 Concentration (Test & Simulation)



Peak concentration levels measured within the 1<sup>st</sup> 200 and 340 ms

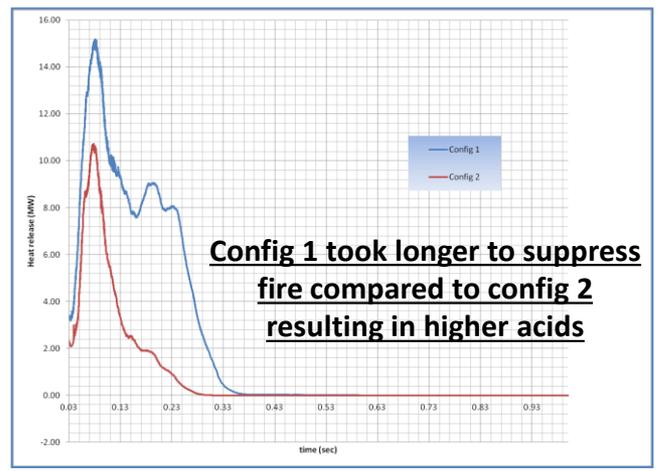
|            |       |  |        | 11. Two-Nozzle @ 45°<br>HVAC off<br><u>(test)</u> |        | 11. Two-Nozzle @ 45°<br>HVAC off<br><u>(simulation)</u> |       |
|------------|-------|--|--------|---|--------|---|-------|
| Position   |       |  |        | 200   | 340    | 200   | 340   |
| Driver     | Nose  |  |        | Green   | Green  | Green   | Green |
|            | Knee  |  | Yellow | Green   | Green  | Green   |       |
| Commander  | Nose  |  | Green  | Green   | Green  | Green   |       |
|            | Knee  |  | Red    | Green   | Green  | Green   |       |
| Right Rear | Nose  |  | Yellow | Yellow  | Red    | Red   |       |
|            | Knee  |  | Yellow | Yellow  | Red    | Green   |       |
| Gunner     | Nose  |  | Green  | Green   | Green  | Green   |       |
|            | Knee  |  | Green  | Green   | Red    | Red   |       |
| Left Rear  | Nose  |  | Green  | Green   | Green  | Green   |       |
|            | Knee  |  | Green  | Green   | Green  | Green   |       |
| FBG        | Front |  | Red    | Green   | Green  | Green   |       |
|            | Rear  |  | Red    | Red   | Yellow | Yellow  |       |



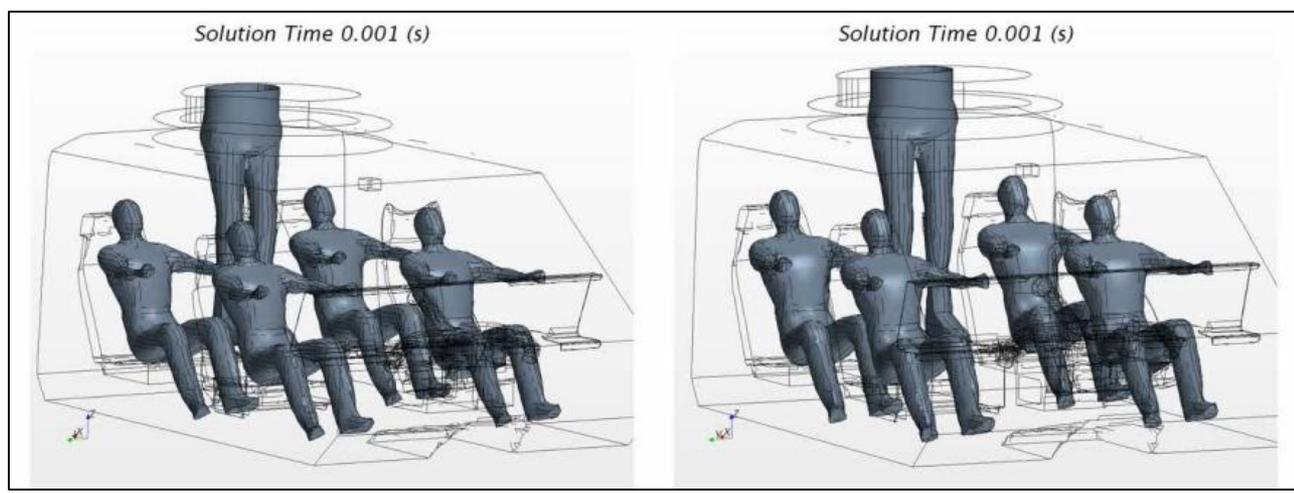
# Crew Compartment Nozzle Configuration Comparison



Configuration I



Configuration II



**Nozzle Configuration Comparison With HVAC Off**

# Comparison of Simulation with Test Data



| Criteria                          | Configuration I  |             | Configuration II  |             |
|-----------------------------------|---|-------------|--|-------------|
|                                   | Test  | Simulation  | Test   | Simulation  |
| Overall                           | <b>Fail</b>   | <b>Fail</b> | <b>Pass</b>  | <b>Pass</b> |
| Extinguish Flames without reflash | YES   | YES         | YES  | YES         |
| Overall Pressure (psi)            | 0.59  | 0.48        | 0.35   | 0.31        |
| Agent Concentration               | Below LOAEL   | Below LOAEL | Below LOAEL  | Below LOAEL |
| HF Acid (PPM)                     | 708   | 656         | <20  | 96          |
| COF2 Acid (PPM)                   | 161   | 518         | <10  | 169         |
| Oxygen Levels                     | 15.9%   | 15.9%       | 17.1%  | 17.2%       |

Typical measurements include high speed video, blast overpressures, temperatures and the chemistry of the atmosphere, in particular the combustion byproducts using Fourier Transform Infrared Spectrometer (FTIR)

# Simulations done To-date for Crew Compartment

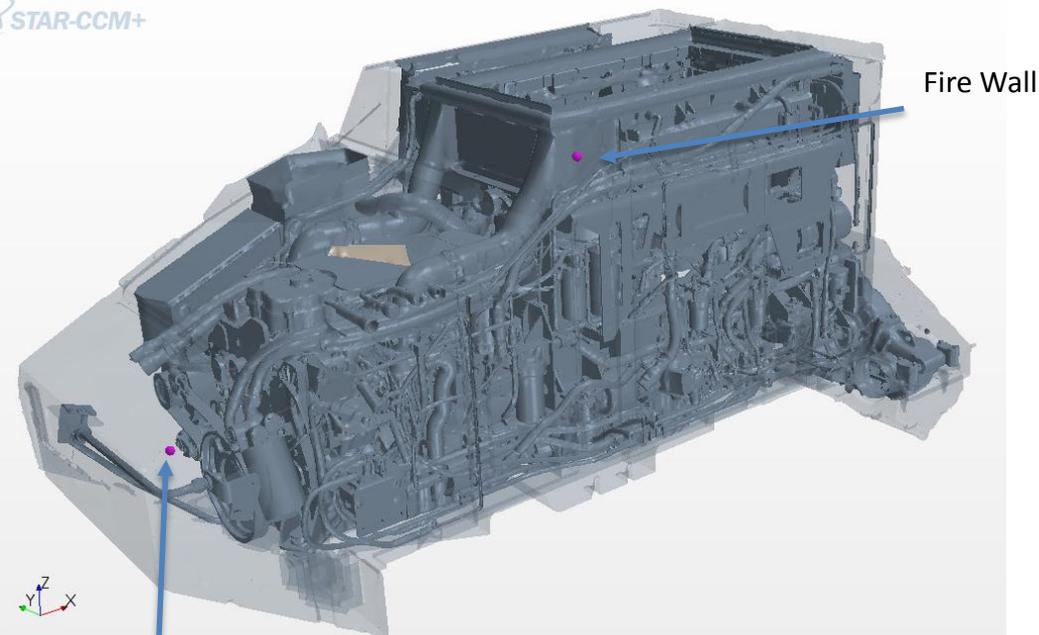


- With & without active air flow
- Fire Ball Generator (FBG) Location change
- Change nozzle parameters
  - number
  - location
  - discharge pattern
- Amount of agent & agent type
- Different clutter characteristics
- Hatch open vs closed scenario
  - RWS vs OGPK

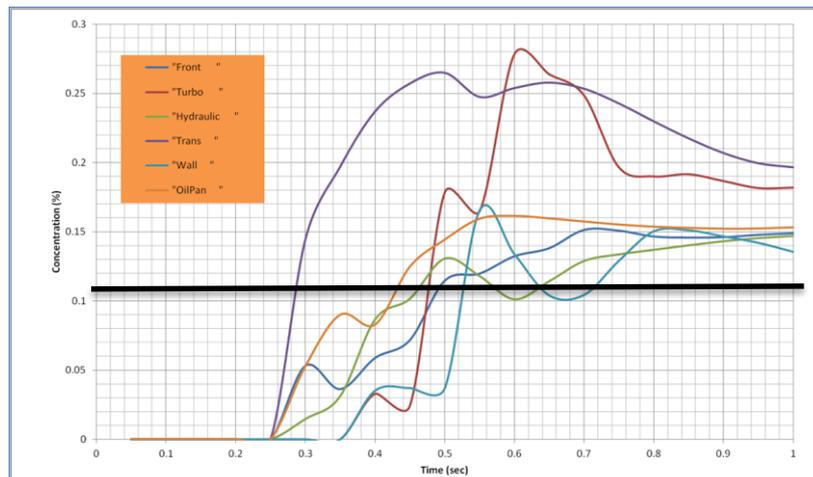
# Engine Compartment Concentration Simulation



STAR-CCM+



Fire Wall



HFC125 concentration stays above design concentration after 1 sec duration with fan on.

Engine Bay fan is set at design point

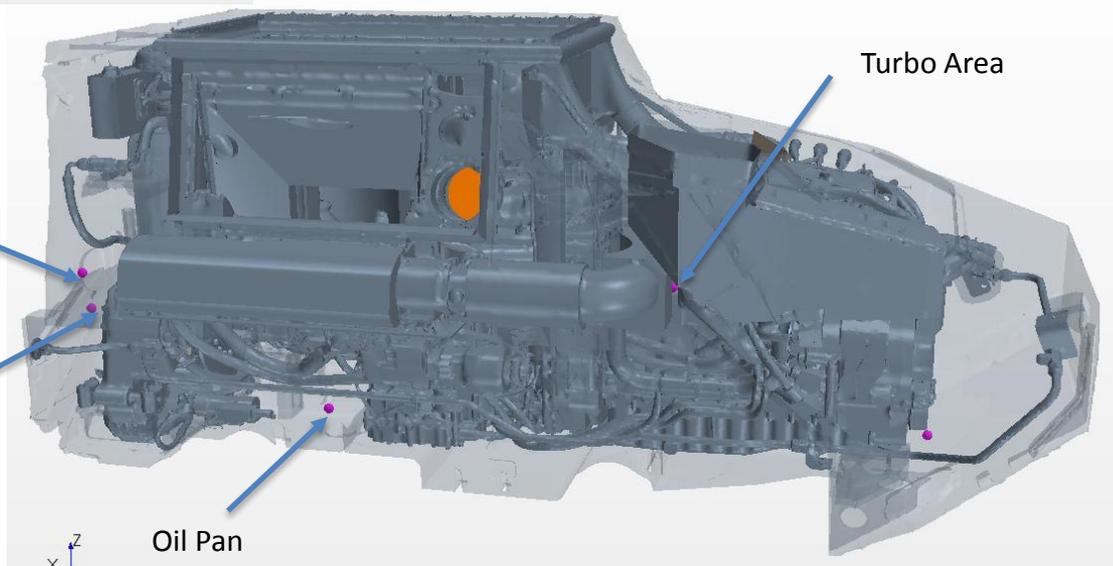
Front Area

Hydraulic Reservoir

Trans

Oil Pan

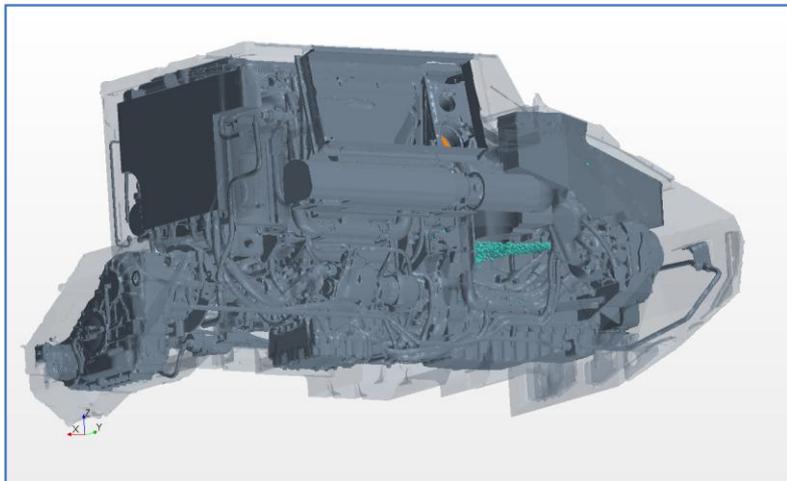
Turbo Area



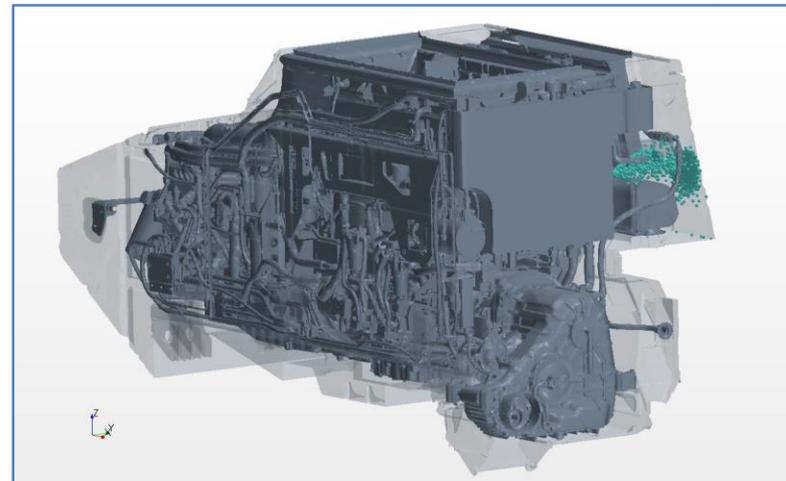
# Engine Compartment Suppression



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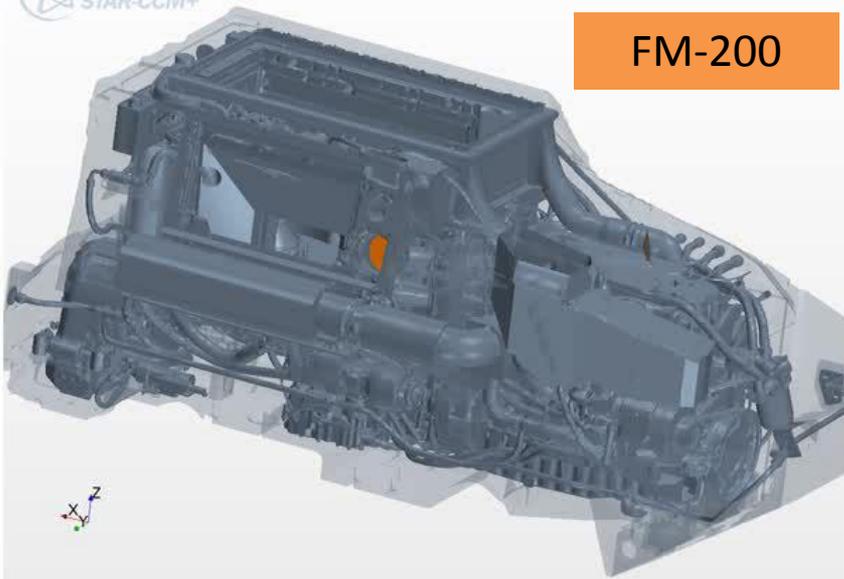


Hydraulic Fluid Spray onto Turbo



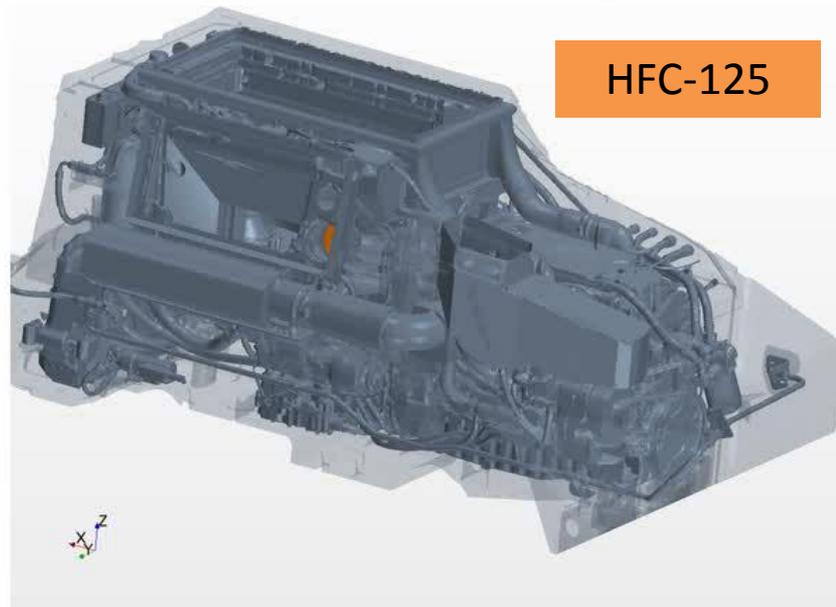
Hydraulic Reservoir Leak

*Solution Time 0.001 (s)*



FM-200

*Solution Time 0.001 (s)*



HFC-125

- Simulation Results Comparison with testing
  - Results are qualitative and to a extent, quantitative
  - Coarse grid implications (adjustment of activation energy, soot)
  - Suppressant Nozzle specification (cone angle)
  - Halon and Water+Potassium acetate validation is limited to-date
- Improve turn-around time
  - Status: 1-2 weeks for geometry preparation, 1 week for computation with DSRC HPC
- Atomization Specification (SWRI & ARL)
  - Scaling with Threat size
  - Phenomenological model
- Discharge of the suppressant (HAI effort)
  - Discharge Lag time, flow split etc.
- Nozzle Characterization effort (ADAPCO)
  - Droplet distribution
  - Velocity distribution
  - Cone Angle

