Fire Suppression M&S Validation (Status & Challenges)
Systems Fire Protection Information Exchange
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Dr. Vamshi M. Korivi
US Army TARDEC
Vamshi.m.korivi.civ@mail.mil

Contributors: Fire Protection Team (TARDEC), Navy Research Labs, CERDEC & ADAPCO
Outline

• 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
Introduction

• 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
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<th>Physics Being Solved</th>
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<td><strong>Transient Analysis</strong></td>
</tr>
<tr>
<td>• Model fuel spray and fire ball development</td>
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<tr>
<td>• Suppressant Discharge + Acid Mitigation</td>
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<tr>
<td><strong>Turbulence Model</strong></td>
</tr>
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<td>• K-Epsilon with Realizable Wall functions</td>
</tr>
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<td>• Segregated Solver</td>
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<td><strong>Lagrangian Physics</strong></td>
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<tr>
<td>• Two-Way Coupling</td>
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<td>• Evaporation &amp; Devolatization</td>
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<td><strong>Suppressant Discharge</strong></td>
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<td>• Discharge from Pressurized bottle</td>
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<td>• Liquid &amp; Vapor Phase</td>
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<td><strong>Combustion Model</strong></td>
</tr>
<tr>
<td>• Hybrid EBU with finite rate Kinetics</td>
</tr>
<tr>
<td>• 14 Species &amp; 12 reactions</td>
</tr>
<tr>
<td><strong>Radiation Model</strong></td>
</tr>
<tr>
<td>• Participating Media Discrete Ordinate Method</td>
</tr>
<tr>
<td>• WSG model for CO2, H2O and Soot</td>
</tr>
<tr>
<td><strong>Suppression</strong></td>
</tr>
<tr>
<td>• Catalytic &amp; Non-Catalytic effects</td>
</tr>
<tr>
<td>• Acid Levels</td>
</tr>
</tbody>
</table>
Inhibition of JP-8 Combustion

Physical Acting Agents
- Dilute heat
- Dilute reactants
  Ex: water, nitrogen

Chemical Acting Agents
- Reduce flame propagation radicals
- Lower heat release rate

Non-catalytic Agents
  Ex: HFP

Catalytic agents
  Ex: Br in Halon 1301, Na in sodium bicarbonate

Non-catalytic \( \Delta \) in reduced kinetics
 Implicitly accounted for in CFD code

Suppression Mechanism
Non-Catalytic
- Linear Suppression versus agent concentration
- No suppression saturation
- Extinction with sufficient agent

Suppression Mechanism
Catalytic
- Non-Linear Suppression versus agent concentration
- Suppression saturation
- Extinction requires additional mechanism

Inhibited rate of Reaction
\[ R_R = R_R^u - \Delta R_{\text{noncatalytic}} - \Delta R_{\text{catalytic}} \]

Catalytic \( \Delta \) in reduced kinetics

Fuel + Oxygen \( X \) Products
Overview of Reduced Kinetics Scheme for FM200

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

Mechanism: ≈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**: JP-8 + O₂ => CO + CO₂ + H₂O
- **R2**: CO + O₂ <=> CO₂
- **R3**: HFP + JP-8 + O₂ => HF + COF₂ + CO + H₂O
- **R4**: COF₂ + H₂O => CO₂ + HF
- **R5**: NaHCO₃(s) => CO₂ + NaOH(g)
- **R6**: NaOH(g) <=> NaOH(hvy_gas) (hvy_gas = heavy-gas approximation)
- **R7**: NaOH(hvy_gas) + HF => NaF(hvy_gas) + H₂O
- **R8**: NaHCO₃(s) + HF => NaF(hvy_gas) + H₂O + CO₂
- **R9**: JP-8 + O₂ => C (soot) + H₂O
- **R10**: C (soot) + O₂ => +CO₂

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

Halon Kinetics includes HBr acid
## Selected Crew AFES performance criteria:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Requirement</th>
<th>Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fire Suppression</td>
<td>Extinguish Flames without reflash</td>
<td>Y</td>
</tr>
<tr>
<td>Skin Burns</td>
<td>Less than Second degree burns</td>
<td>Y</td>
</tr>
<tr>
<td>Overpressure</td>
<td>Lung damage &lt;11.6 psi; Ear damage ≤ 3.6 psi</td>
<td>Y</td>
</tr>
<tr>
<td>Acid Gases</td>
<td>Acid gas, 5 min dose (HF + HBr + 2\cdot COF₂) &lt; 746 ppm-min</td>
<td>Y</td>
</tr>
<tr>
<td>Agent Concentration</td>
<td>&lt;Lowest Observed Adverse Effects Level</td>
<td>Y</td>
</tr>
<tr>
<td>Oxygen Levels</td>
<td>Not below 16%</td>
<td>Y</td>
</tr>
<tr>
<td>Discharge Impulse Noise</td>
<td>No hearing protection limit &lt; 140 dB</td>
<td>N</td>
</tr>
<tr>
<td>Discharge Forces</td>
<td>Acceleration ≤ 8 g and pressure pulse ≤ 10 psig at crew locations</td>
<td>N</td>
</tr>
<tr>
<td>Fragmentation</td>
<td>Ejected non-agent particles ≤ 300 micrometers</td>
<td>N</td>
</tr>
</tbody>
</table>
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)
Reference: *Fire Extinguishing Agents for Protection of Occupied Spaces in Military Ground Vehicles*
**EXPLORATORY TEST BOX SIMULATIONS**

Solution Time 0.2 (s)

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

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

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Above Design Conc.</th>
<th>Below Design Conc.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Test</td>
<td>Simulation</td>
</tr>
<tr>
<td>Overall</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>Extinguish Flames without reflash</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>K Value</td>
<td>1.56</td>
<td>1.44</td>
</tr>
<tr>
<td>HF Acid (PPM)</td>
<td>&lt;20</td>
<td>47</td>
</tr>
<tr>
<td>COF2 Acid (PPM)</td>
<td>&lt;20</td>
<td>97</td>
</tr>
<tr>
<td>Oxygen Levels</td>
<td>17.4%</td>
<td>18.0%</td>
</tr>
</tbody>
</table>

UNCLASSIFIED: Distribution A. Authorized for Public Release; distribution is unlimited
Comparison of FM200 Concentration (Test & Simulation)

Peak concentration levels measured within the 1st 200 and 340 ms

<table>
<thead>
<tr>
<th>Position</th>
<th>Nose</th>
<th>Knee</th>
<th>11. Two-Nozzle @ 45° HVAC off (test)</th>
<th>11. Two-Nozzle @ 45° HVAC off (simulation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driver</td>
<td>22.74</td>
<td>10.62</td>
<td>200</td>
<td>340</td>
</tr>
<tr>
<td>Commander</td>
<td>0.00</td>
<td>3.34</td>
<td>200</td>
<td>340</td>
</tr>
<tr>
<td>Right Rear</td>
<td>8.35</td>
<td>10.07</td>
<td>200</td>
<td>340</td>
</tr>
<tr>
<td>Gunner</td>
<td>19.02</td>
<td>22.87</td>
<td>200</td>
<td>340</td>
</tr>
<tr>
<td>Left Rear</td>
<td>16.83</td>
<td>36.54</td>
<td>200</td>
<td>340</td>
</tr>
<tr>
<td>FBG</td>
<td>11.33</td>
<td>27.73</td>
<td>200</td>
<td>340</td>
</tr>
</tbody>
</table>

270 ms Criteria

- **Peak > 8.7%**: Good
- **6.7% < Peak < 8.7%**: Acceptable
- **6.7% > Peak**: Inadequate
Crew Compartment Nozzle Configuration Comparison

Configuration I

Configuration II

Config 1 took longer to suppress fire compared to config 2 resulting in higher acids

Nozzle Configuration Comparison
With HVAC Off
### Comparison of Simulation with Test Data

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Configuration I</th>
<th></th>
<th>Configuration II</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Test</td>
<td>Simulation</td>
<td>Test</td>
<td>Simulation</td>
</tr>
<tr>
<td>Overall</td>
<td>Fail</td>
<td>Fail</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>Extinguish Flames without reflash</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>Overall Pressure (psi)</td>
<td>0.59</td>
<td>0.48</td>
<td>0.35</td>
<td>0.31</td>
</tr>
<tr>
<td>Agent Concentration</td>
<td>Below LOAEL</td>
<td>Below LOAEL</td>
<td>Below LOAEL</td>
<td>Below LOAEL</td>
</tr>
<tr>
<td>HF Acid (PPM)</td>
<td>708</td>
<td>656</td>
<td>&lt;20</td>
<td>96</td>
</tr>
<tr>
<td>COF2 Acid (PPM)</td>
<td>161</td>
<td>518</td>
<td>&lt;10</td>
<td>169</td>
</tr>
<tr>
<td>Oxygen Levels</td>
<td>15.9%</td>
<td>15.9%</td>
<td>17.1%</td>
<td>17.2%</td>
</tr>
</tbody>
</table>

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

UNCLASSIFIED: Distribution A. Authorized for Public Release; distribution is unlimited
HFC125 concentration stays above design concentration after 1 sec duration with fan on. Engine Bay fan is set at design point.
Engine Compartment Suppression

Hydraulic Fluid Spray onto Turbo

Hydraulic Reservoir Leak

Solution Time 0.001 (s)

Solution Time 0.001 (s)

FM-200

HFC-125
Summary & Future Work

• 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