Sub-scale Analysis of New Large Aircraft (NLA) Pool Fire-Suppression

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Overview

USAF Civil Engineering Center/Fire (AFCEC/CXAE)
Multiscale Experimental Facilities

2-D/3-D Full-Scale Aircraft Fire Testing
Small-Scale Indoor Testing
Interior/Structural Testing

Agent Testing
Vehicle Performance
Materials Testing
Overview

USAF Civil Engineering Center/Fire (AFCEC/CXAE)
Modeling and Simulation

Multi-Component Heat Transfer

Multiphase Flow

Combustion

Molecular Dynamics

Structural Dynamics

Fluid System Design

Contours of Surface Temperature (K)

Wind

Airbus A380

Boeing 777

Boeing 707

Contours of Total Temperature (K)

Particle Traces Colored by Particle Diameter (μm)

Gaseous Contours Colored by Velocity Magnitude (m s⁻¹)
Background

TCA/PCA Method to Determine ARFF Emergency Response Requirements for Transport Aircraft

- Used for nearly 40 years
- Questionable validity when applied to new transport aircraft
- Does not account for physical, 3-D aircraft crash fire dynamics or modern aircraft designs

Source: NFPA 403
Aircraft-Crash-Fuel Spill-Fire-Suppression (ACFFS) Modeling

- Alternative approach to TCA/PCA method using finite element analysis (FEA) and computational fluid dynamics (CFD)
- Enables the consideration of actual ACFFS physical dynamics
  - Post-crash geometry and fuel distribution
  - Wind velocity effects
  - Fire suppression techniques
- Allows end-to-end ACFFS scenarios to be considered beyond the scope of practical experiments
Aircraft-Crash-Fuel Spill-Fire-Suppression (ACFFS) Modeling

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Goal: Develop an Aircraft Fire-Suppression Modeling Strategy Validated by Experiments
Full-Scale NLA Mockup

- Provides realistic, outdoor conditions
- 30.5-m (100-ft) JP-8 fuel pit
- Provides ARFF vehicle performance, egress exercises, and firefighting effectiveness evaluation
1:10 NLA Mockup

- 1:10 geometric similarity* with full-scale NLA mockup
- Centered in 27×24×10-m (88×78×32-ft) indoor fire test facility
- Provides repeatable, cost-effective test environment to support CFD model development

Isometric View  Side View
1:10 NLA Test Overview

- 10 total trials
  - Pool only fire-suppression (5)
  - 1:10 NLA pool fire-suppression (5)
- Windless conditions
- 76 l (20 gal) JP-8 floated over 371 l (98 gal) tap water
- Manual ignition via propane torch
- 60 s pre-burn
- 4 fire suppression nozzles statically positioned to mimic ARFF-style response
- Key measurement parameters: fuel regression, temperature, heat flux
Experiments

1:10 NLA Test Layout

Top View

Front View

- X
- Y
- Z

(Out of the Paper)

Fuel Surface
Vertical Axis
Y
XZ
(Out of the Paper)

Origin

TCs

Total HFG

IR Camera

Conventional Camera

Scale

Nozzle

- ● TCs
- □ Total HFG
- ▲ IR Camera
- □ Conventional Camera
- ▲ Scale
- □ Nozzle

- ○ Hidden TCs
- ■ Radiation HFG

- 1.83 m (6 ft)
- 0.61 m (2 ft)
- 0.36 m (1.20 ft)
- 0.43 m (1.42 ft)
- 0.71 m (23.4 ft)
- 0.84 m (2.76 ft)
- 3.05 m (10 ft)
1:10 NLA Agent Delivery Test Summary

- Modified TRI-MAX 30 delivery system (pressurized cylinder)
- Bete SS 30° fan nozzle (Qty. 4)
  - 90° apart, 30° off principal axes
  - 43 lpm (11.3gpm) total flow rate
  - 10.7 (2.8 gpm) flow rate per nozzle
  - 480 kPa (70 psi) nozzle pressure
- Premixed Mil-spec 3% AFFF
- ≈ 3:1 expansion ratio
- ≈ 78% agent delivery efficiency
  - 5.83 lpm/m² (0.14 gpm/ft²) dispensed
  - 4.53 lpm/m² (0.11 gpm/ft²) “delivered”

*NFPA 403: 5.29 lpm/m² (0.13 gpm/ft²)*
1:10 NLA Fire Suppression Nozzle Details

BETE Estimated Droplet Size Information:
10.7 lpm (2.82 gpm) @ 480 kPa (70 psi)

BETE SS NF2030

30° Spray Pattern

SG = 1
1 cp
Q = 10.7 lpm
V = 27.7 m·s⁻¹
D₃₂ = 340
DV₀.5 = 430
DV₀.1 = 190
DV₀.9 = 780
1:10 NLA Fuel Regression Results

Pool Diameter | Burning Mode
--- | ---
< 0.05 m | convective, laminar
0.05 to 0.2 m | convective, turbulent
0.2 m to 1.0 m | radiative, turbulent, optically thin
> 1.0 m | radiative, turbulent, optically thick

*Source: Babrauskus 1983*

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**Fuel Regression Rate (kg·m⁻²·s⁻¹)**

<table>
<thead>
<tr>
<th>Fuel Regression Rate</th>
<th>Pool Diameter</th>
<th>Burning Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.038</td>
<td>Pool Fire Only</td>
<td>convective, laminar</td>
</tr>
<tr>
<td>0.032</td>
<td>1:10 NLA Mockup</td>
<td>convective, turbulent</td>
</tr>
</tbody>
</table>

*Source: Lam 2009*

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**Fuel Mass (kg) vs. Time (s)**

- **POOL FIRE ONLY**: 2.36 mm·min⁻¹
- **1:10 NLA MOCKUP**: 2.84 mm·min⁻¹

*17% Difference

*Source: Lam 2009*
1:10 NLA Perimeter Heat Flux & Total HRR Results

**Perimeter Heat Flux**

- **TOTAL - POOL FIRE ONLY**
- **RAD - POOL FIRE ONLY**
- **TOTAL - 1:10 NLA MOCKUP**
- **RAD - 1:10 NLA MOCKUP**

**Mean Heat Flux (kW·m⁻²)**

- **POOL FIRE ONLY**
- **1:10 NLA Mockup**

**Mean HRR (MW)**

- **POOL FIRE ONLY**
- **1:10 NLA Mockup**

*Estimated Source: Blanchat et al. 2011*
1:10 NLA Fuel Surface & Perimeter Temperature Results

Fuel Surface Temperature

Example Trial

- Large deviation between sensors due to sensor alignment challenges and asymmetric fuel surface ignition

Perimeter Air Temperature

- Unremarkable difference between pool fire only and 1:10 NLA mockup fuel surface temperatures
- Similar response trend as adjacent heat flux sensors

$T_{BOIL} = 488 \text{ K}$
1:10 NLA Axial Fire Plume Temperature Results

Y = 3.05 m (10 ft)

Y = 4.57 m (15 ft)

Y = 6.10 m (20 ft)

Y = 7.62 m (25 ft)
1:10 NLA Mockup Surface Temperature Results

Mockup Left Hull

Mockup Right Hull

Mockup Bottom Hull

Mockup Wing Bottom
1:10 NLA Fire Suppression Results

Extinguishment based on Mean Total Perimeter Heat Flux

Extinguishment Time (s)

Pool Fire Only 1:10 NLA Mockup

Extinguishment Efficiency

<table>
<thead>
<tr>
<th></th>
<th>Pool Fire Only</th>
<th>1:10 NLA Mockup</th>
</tr>
</thead>
<tbody>
<tr>
<td>99% Inspection</td>
<td>2.30 l/m² (0.056 gal/ft²)</td>
<td>3.04 l/m² (0.056 gal/ft²)</td>
</tr>
<tr>
<td>Inspection (100%)</td>
<td>2.54 l/m² (0.062 gal/ft²)</td>
<td>3.08 l/m² (0.074 gal/ft²)</td>
</tr>
</tbody>
</table>

≈32% DIFF

*USAF P-19 ≈ 2.45 l/m² (0.06 gal/ft²)
Source: McDonald 2004
1:10 Pool Fire Only Test Photos

1 – Pre-Burn

2 – Suppression Start Fire Intensification

3 – Mid-Suppression

4 – Almost Extinguished
Experiments

1:10 NLA Test Photos

1 – Pre-Burn

2 – Suppression Start Fire Intensification

3 – Mid-Suppression

4 – Almost Extinguished
1:10 NLA Simulation Overview

Software

- Geometry created using Solidworks 2016
- Mesh generated using Pointwise v17.x
- CFD model developed using ANSYS Fluent v16.x

Hardware

- Advanced Clustering MicroHPC\(^2\) Workstation
  - CentOS 7 (Linux)
  - 28-core Intel Xeon 2.6Ghz / 128 GB RAM (shared memory)
- Air Force Research Laboratory HPC
  - Red Hat Enterprise (Linux)
  - SGI Ice X 4,590 node (16-core per node) Intel Xeon 2.6 Ghz / 64 GB RAM per node (distributed memory)
1:10 NLA CFD Physical Sub-Model Summary

- Eulerian (Combustion) Model Framework
  - Partially-premixed combustion based on the flamelet generated manifold diffusion flamelet approach
  - 22-species Jet A surrogate skeletal reaction mechanism based on the combustion of $C_{10}H_{22}$, $C_{6}H_{14}$, and $C_{6}H_{6}$ (Strelkova et al. 2008)
  - SST $\kappa-\omega$ (RANS) turbulence
  - Discrete ordinates radiation
  - One-step Khan and Greeves soot

- Lagrangian (Agent Spray) Model Framework
  - Discrete phase model with AFFF solution droplet transport, heating, evaporation, and boiling
  - Two-way turbulence, heat, and mass transfer coupled to gas phase
1:10 NLA Model Domain Summary

Multi-Block Hybrid Mesh Topology

- Structured (hexahedral) high aspect ratio cells used for far-field atmosphere and boundary layer growth
- Unstructured (tetrahedral) cells used to link structured blocks

Pool Fire Only Mesh
\[ \approx 1.46M \text{ Cells} / 1.48M \text{ Nodes} \]

1:10 NLA Mockup Mesh
\[ \approx 3.05M \text{ Cells} / 1.60M \text{ Nodes} \]
1:10 NLA Boundary Condition Summary

- $T_{BOIL} = 488$ K
- Pool Fire Only $V_{INLET} = 0.01$ m/s
- 1:10 NLA Mockup $V_{INLET} = 0.008$ m/s
- Low carbon steel mockup & fire pan wall material properties
- DPM injection properties derived from nozzle and agent delivery specifications and measurements

Fuel Vapor Velocity Inlet

$V_{INLET} = f(m^{"FUEL}, P_{ATM}, M_{FUEL}, T_{BOIL}) @ T_{BOIL}$
1:10 NLA CFD Model Preliminary Findings

Notable Similarities to Experiments

- Mean (pre-burn) perimeter air temperature, fire plume temperature, and total HRR
- Mean (pre-burn) perimeter heat flux
- Post-suppression start fire intensification
- Fire plume puffing frequency
- Mockup surface temperature profile trends compared to infrared camera data
- (Isothermal) agent delivery efficiency

Notable Differences to Experiments

- Increased mockup surface heat-up rate
- Decreased rate of soot production
1:10 NLA CFD Model Sample Results

Pool Fire Only Instant Temperature (K)

Pool Fire Only Mean Temperature (K)

1:10 NLA Mockup Instant Temperature (K)

1:10 NLA Mockup Mean Temperature (K)
Conclusions

- Results suggest major full-scale aircraft pool fire characteristics can be reproduced in an indoor 1:10th scale test environment.
- A fixed ARFF-style agent delivery system provided reliable extinguishment results while removing the uncertainty added by man-in-the-loop firefighting.
- Fire intensification post suppression start was significant, likely due to the rapid increase in air entrainment coupled with agitation of the fuel surface-vapor interface by the agent spray.
- Fire immersed objects can significantly lower the fire HRR while still extending the extinguishment time compared to pool fire only conditions, likely due to blockage effects.
- High quality foam production at laboratory scale to match the full-scale performance of non-aspirated nozzles remains a challenge.
Acknowledgements

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THANK YOU


