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Sub-Scale Analysis of New Large Aircraft Pool Fire-Suppression

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14. ABSTRACT
There is concern over the applicability of current aircraft rescue firefighting (ARFF) protection standards for New Large Aircraft (NLA) such as the Airbus A380 and Boeing 777. Current protocol is based on traditional aircraft; in comparison NLA are characterized by unusually large dimensions, composite material integration, as well as enhanced passenger and wing loading, and stored fuel in non-conventional locations. A study is underway to develop an aircraft-crash-fuel spill-fire-suppression (ACFFS) simulation framework to quantify fuel dispersal and to estimate firefighting agent application requirements for accidental scenarios of high interest. The current work presents the design, development, and results to date of sub-scale NLA pool fire-suppression simulations and supporting experiments conducted at the Indoor Fire Testing Facility at Tyndall AFB, FL. Suppression experiments were conducted on a 1:10-scale partial NLA steel mockup designed to resemble major mid-body features of the Airbus A380 engulfed in a 3-m diameter JP-8 pool fire. Computational fluid dynamic (CFD) model development is currently in progress.

15. SUBJECT TERMS
Fire Testing, Fire Suppression, Agent Application, Hydrocarbon Pool Fires, Large-Frame Aircraft, Computational Fluid Dynamics, Combustion, Spray Modeling, Scale Modeling

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Overview

There is speculation about the applicability of current aircraft rescue firefighting (ARFF) protection standards for New Large Aircraft (NLA) such as the Airbus A380 and Boeing 777. Current protocol is based on traditional aircraft; in comparison NLA are characterized by unusually large dimensions, composite material integration, as well as enhanced passenger and wing loading, and stored fuel in non-conventional locations. A study is underway to develop an aircraft-crash-fuel spill-fire-suppression (ACFFS) simulation framework to quantify fuel dispersal and to estimate firefighting agent application requirements for accidental scenarios of high interest. This approach is favorable because it is less expensive and more practical than conducting full-scale experiments. The current work discusses the results of partial NLA fire-suppression experiments conducted in moderately controlled, indoor environmental conditions at 1:10-scale. The purpose of this work was to generate an in-house experimental validation data set to support development of the aircraft pool fire-suppression component of the ACFFS simulation framework. Preliminary design, set-up, and performance of the aircraft pool fire-suppression model is also discussed.

Introduction

NFPA 403 reports the minimum extinguishing agent discharge requirements and response capability for ARFF services at airports based on the theoretical critical area-practical critical area (TCA/PCA) method. The TCA/PCA method is based on ARFF response estimates from over 40 years ago, has questionable validity with respect to NLA, and does not account for non-linear, three-dimensional aircraft crash dynamics or modern aircraft designs. The ACFFS simulation framework is an alternative approach to the TCA/PCA method that uses high-fidelity finite element analysis (FEA) and computational fluid dynamics (CFD). It enables the consideration of physical dynamics that occur during an actual ACFFS event, including post-crash aircraft geometry, fuel spill distribution, wind velocity effects, and fire suppression techniques. The program objective is to predict the severity of ACFFS scenarios so that an alternative or potential modification to the TCA/PCA method may be considered.

The technical approach is as follows: (1) perform dynamic FEA of survivable aircraft crashes, (2) perform high-fidelity CFD analysis of resultant pool fire and suppression, (3) evaluate the severity of ACFFS scenarios, and (4) validate the simulation methodology using aircraft crash, fire, and suppression experiments to determine its degree of reliability. The current work discusses progress on Part 4 and preliminary findings on Part 2 of the ACFFS approach.

Experimental Set-up

Fire-suppression experiments were conducted on a 1:10-scale partial NLA steel mockup designed to resemble the major mid-body features of the Airbus A380 engulfed in a 3.05-m (10-ft) diameter JP-8 pool fire. The current experiments were carried out in a quonset-style indoor fire test facility in a calm atmosphere. A fuel pan scale recorded the change in fuel mass to determine the fuel regression rate. Thirty-one K-type thermocouples recorded a combination of fire perimeter (4), fuel surface (5), mockup surface (15), and axial centerline fire plume temperatures (7). Four water-cooled, Gardon-style dual heat flux gages positioned 90-degrees apart and around the fire perimeter recorded total and radiation heat flux. A single infrared and two standard cameras were positioned ±45-degrees off-axis with respect to the mockup hull to record each fire test.

Ten pool fire-suppression trials were conducted, five with the fire pool only and five that included the 1:10 NLA mockup. A trial began by floating 76 liters (20 gal) of JP-8 overtop 371 liters (98 gal) of tap water and then manually igniting the JP-8 with a propane torch. A 60-s pre-burn period then occurred so that fire conditions could fully-develop. Four fire suppression nozzles positioned 90-degrees apart near the base and perpendicular to the fuel pan then discharged agent. The nozzles delivered a combined 43 $l \cdot min^{-1}$ (11.3 $gal \cdot min^{-1}$) of agent at 480 kPa (70 $lb \cdot in^{-2}$) until the fire was extinguished. The nozzles were 30-degree stainless steel fan nozzles manufactured by BETE. The agent was premixed Mil-spec 3% AFFF discharged via a modified (no air injection) Tri-Max 30 acting as a pressurized cylinder. The agent had an approximate 3:1 expansion ratio, and the fixed nozzle system delivered approximately 78 percent of the agent to the fuel pan.

Experimental Results

Key experimental results are summarized in Table 1. In general, it was found in pool fire only suppression trials that JP-8 burned at an increased rate, thus generating a greater heat release rate compared to trials that included the mockup. The increased heat release rate caused the relative total and radiation heat flux measurements along the fire perimeter to similarly increase. The mockup presence also caused the extinguishment time to increase significantly thereby decreasing extinguishment efficiency. Fire intensification was observed immediately after suppression started. This phenomena resulted in a peak total heat flux rise of 126 and 170 percent over the mean heat flux recorded during the pre-burn period for the pool fire only and mockup cases, respectively. Fire perimeter thermocouple measurements recorded a minor lag in temperature rise while the mockup was present. Fire plume thermocouple measurements did not record a significant disparity with and without the mockup during the pre-burn period. However, mockup trials consistently recorded fire plume temperature peaks during fire intensification on the order of 100 K higher compared to pool fire only measurements. Mockup surface thermocouple measurements consistently recorded increased temperature magnitudes toward the interior of the mockup hull and lesser values closer to its extremities.

Table 1: Test Results Summary

Case	Mean Fuel Regression Rate ($g \cdot m^2 \cdot s^{-1}$)	Mean Total Heat Release Rate (MW)	Mean Total Perimeter Heat Flux ($kW \cdot m^{-2}$)	Mean Radiation Perimeter Heat Flux ($kW \cdot m^{-2}$)	99% Extinguishment Time (s)	Extinguishment Efficiency ($l \cdot m^{-2}$)
Pool Fire Only	38.2±1.4	12.8±0.45	26.7±0.93	21.2±1.4	30.4±4.5	2.30±0.34
1:10 NLA Mockup	31.8±1.3	10.6±0.43	24.8±0.65	17.1±1.0	40.2±6.9	3.04±0.52
% Difference	16.8	16.8	6.94	19.3	32.2	32.2

Note: The values reported are in terms of mean ± standard deviation

Computational Model Set-up

The fire-suppression model used was based on an Euler-Lagrange CFD framework available in ANSYS Fluent v16.x to govern the combustion and agent application processes, respectively. A partially-premixed combustion model using the flamelet generated manifold approach was used to govern chemical reaction kinetics. A 22-species Jet A surrogate skeletal reaction mechanism based on the composite combustion of 72.7-percent decane, 18.2-percent hexane, and 9.1-percent benzene by mass was used to generate the flamelet. The SST κ-ω Reynolds-Averaged Navier-Strokes (RANS) turbulence model was chosen for its accuracy in resolving turbulent flow around bluff bodies such as the mockup. The discrete ordinates radiation and single step Khan and Greeves soot model provided radiation and soot interaction. Agent spray dynamics were accounted for using the discrete phase model (DPM) to simulate AFFF solution droplet transport, as well as its heating, evaporation, and boiling. Two-way turbulence, heat, and mass transfer coupled the gaseous combustion and agent droplet phases.

The indoor fire test facility was approximated using a three-dimensional, cylindrical-shaped domain. The domain floor and ceiling boundaries were modeled as an adiabatic no-slip wall and the surrounding far-field as a pressure outlet. A fuel vapor velocity inlet defined the fire inlet boundary with its conditions extrapolated from the fuel regression rate and the thermodynamic properties of JP-8 fuel vapor at its boiling point. The mockup surface was modeled as a thin wall with shell heat conduction thermally coupled to the surrounding gaseous flow field. Agent spray conditions were defined as DPM flat-fan-atomizer injection types with delivery conditions consistent with the experiment.

Computational Model Preliminary Findings

Preliminary CFD model findings of note show that the mean fire perimeter temperature, fire plume temperature, and mean heat release rate values are similar to experimental results given the range of uncertainty associated with each experimentally measured value in a fire test environment (i.e., 10 to 20 percent for temperature comparisons and 20 to 40 percent for heat flux comparisons). Mean perimeter heat flux, fire intensification, fire plume puffing frequency, mockup surface profile trends compared to infrared camera data, and agent delivery efficiency are among other parameters that compared well with preliminary CFD model results. Notable differences observed showed a modeled increase in the mockup surface heat-up rate as well as a modeled decreased rate of soot production compared to experiments. Quantification of CFD model uncertainty and other factors to quantify its ability to accurately predict flame extinction is currently in progress.

Conclusions

Experimental results suggest major full-scale aircraft pool fire suppression characteristics were reproducible in an indoor 1:10-scale test environment with extinguishment efficiencies reported similar to that of an analogous full-scale aircraft pool fire 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 was shown to be significant, likely due to the rapid increase in air entrainment coupled with the agitation of the fuel surface-vapor interface by the agent spray. The presence of the mockup significantly lowered the fire heat release rate while still extending the extinguishment time compared to pool fire only conditions. This phenomena was likely due to the blockage effect imposed by the mockup to not only limit the effective range of the agent spray, but also in hindering the turbulent fuel-air mixing in the flow regime adjacent to the fuel pan. Preliminary CFD model findings suggested that aircraft pool fire-suppression behavior can be modelled to estimate most of the significant parameters that govern fire suppression for a particular aircraft-pool fire environment. Analysis of the CFD model's overall uncertainty as well as its ability to accurately predict flame extinction is currently in progress.

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

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San Antonio, TX

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

2-D/3-D Full-Scale Aircraft Fire Testing

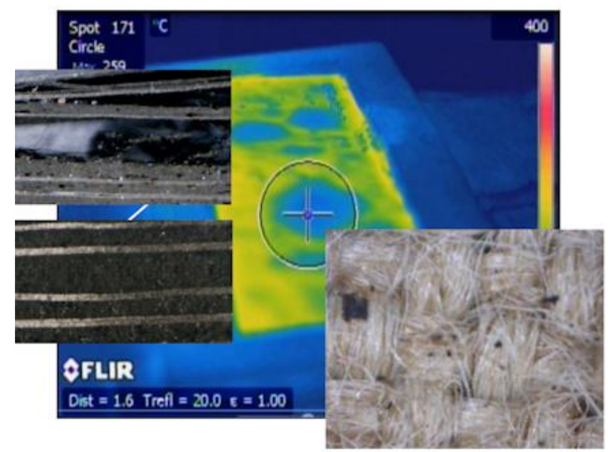
Small-Scale Indoor Testing

Interior/Structural Testing

Agent Testing

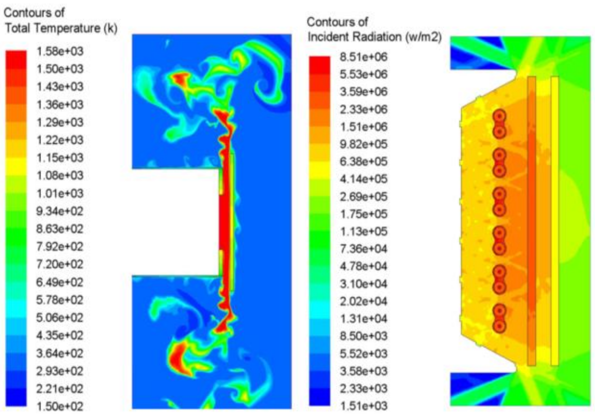
Vehicle Performance

Materials Testing

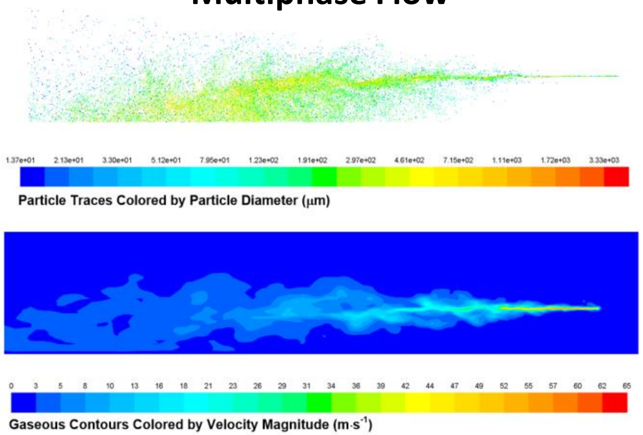


USAF Civil Engineering Center/Fire (AFCEC/CXAE) Modeling and Simulation

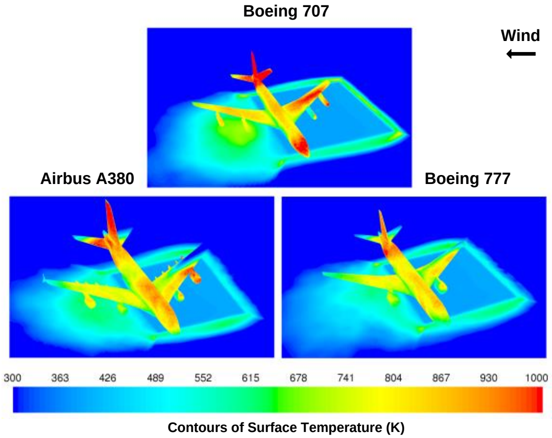
Multi-Component Heat Transfer



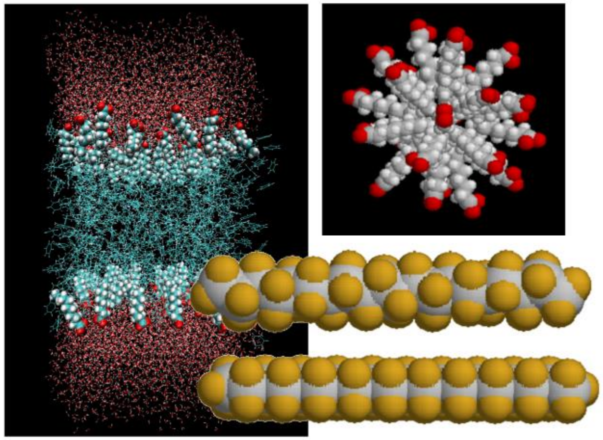
Multiphase Flow



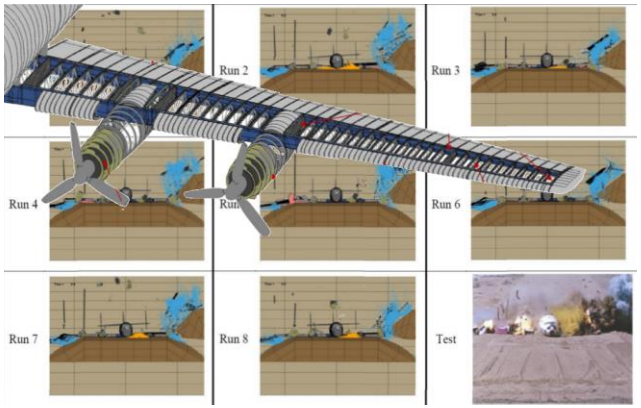
Combustion



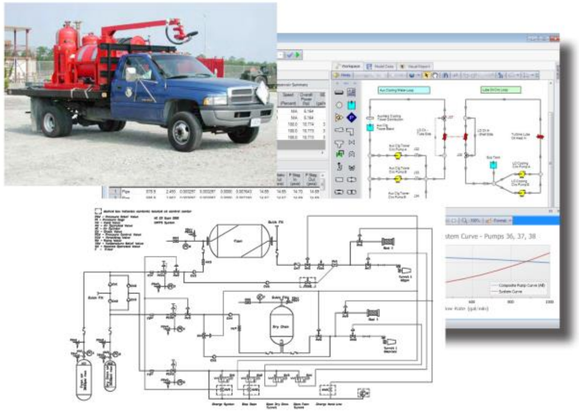
Molecular Dynamics



Structural Dynamics

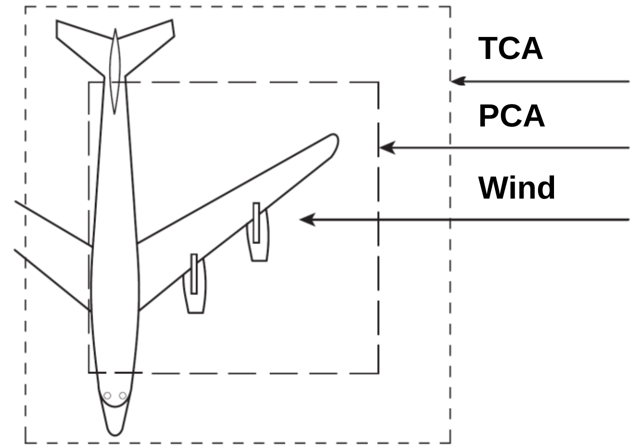


Fluid System Design

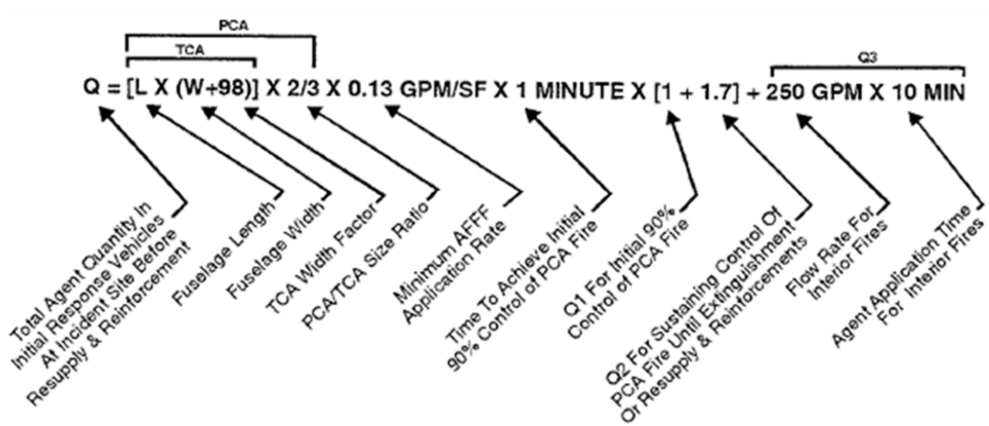


TCA/PCA Method to Determine ARFF Emergency Response Requirements for Transport Aircraft

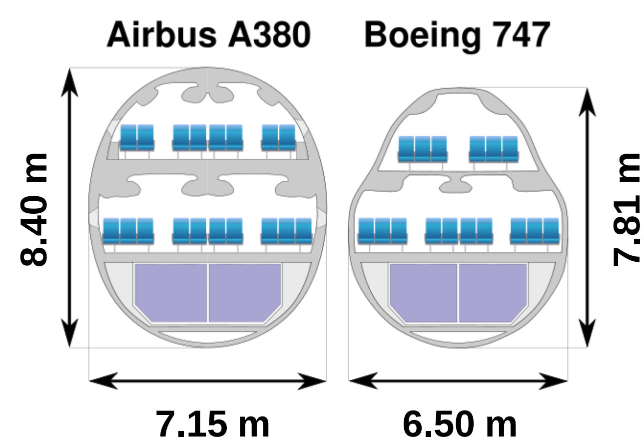
- Used for nearly 40 years
- Questionable validity when applied to new transport aircraft
- Does not account for physical, 3-D aircraft crash fire dynamics or modern aircraft designs



Fixed-Wing Aircraft

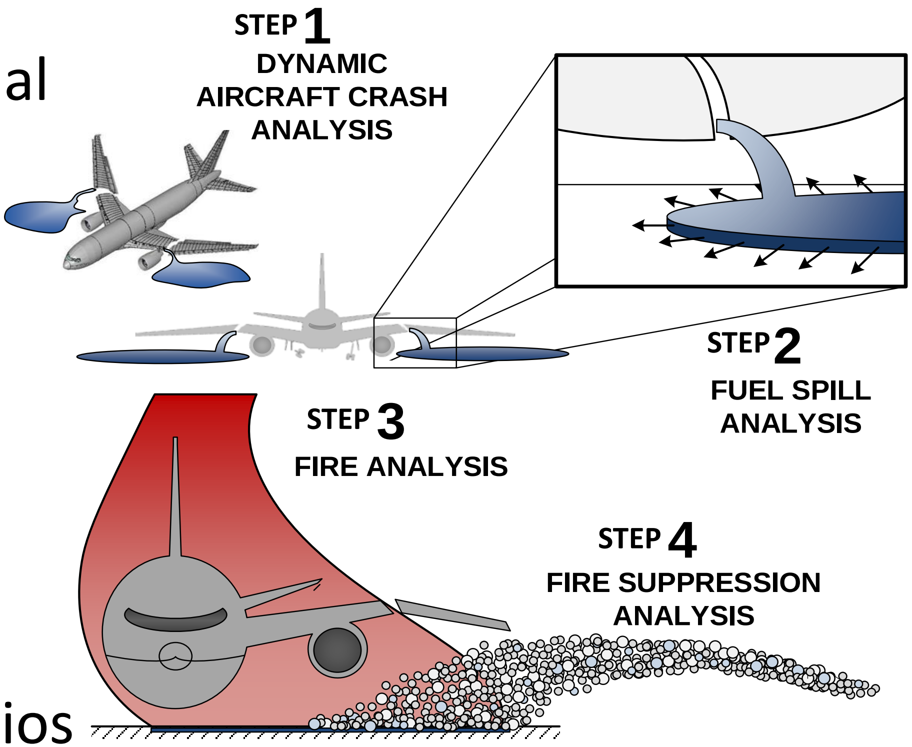


Source: NFPA 403



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



Motivation

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
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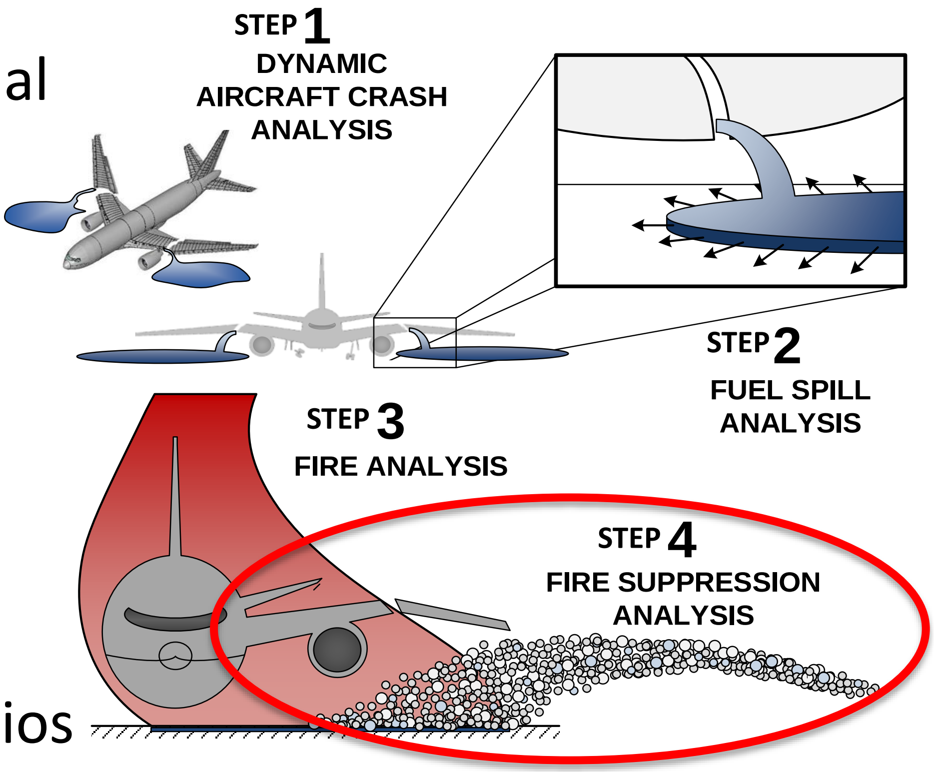
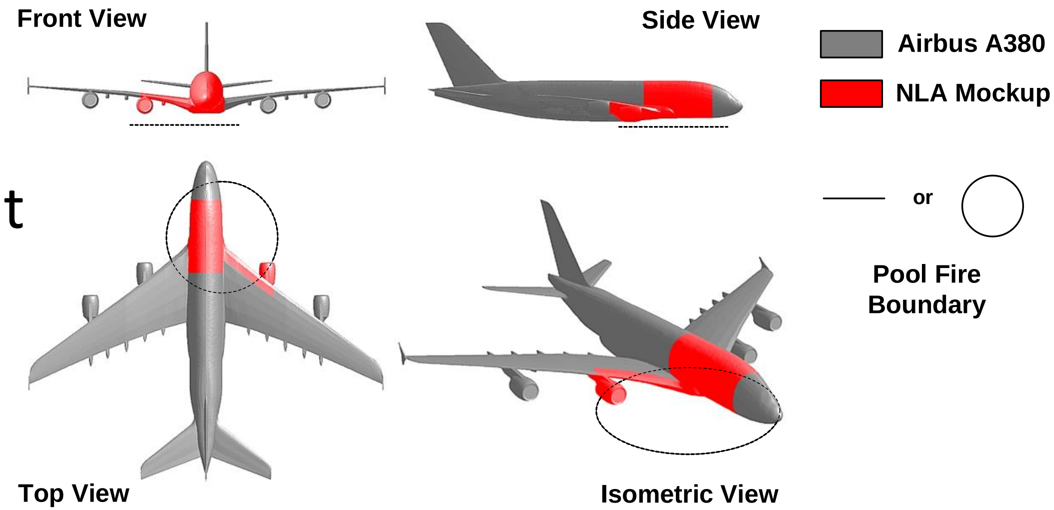
- Allows end-to-end ACFFS scenarios to be considered beyond the scope of practical experiments



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



Side View

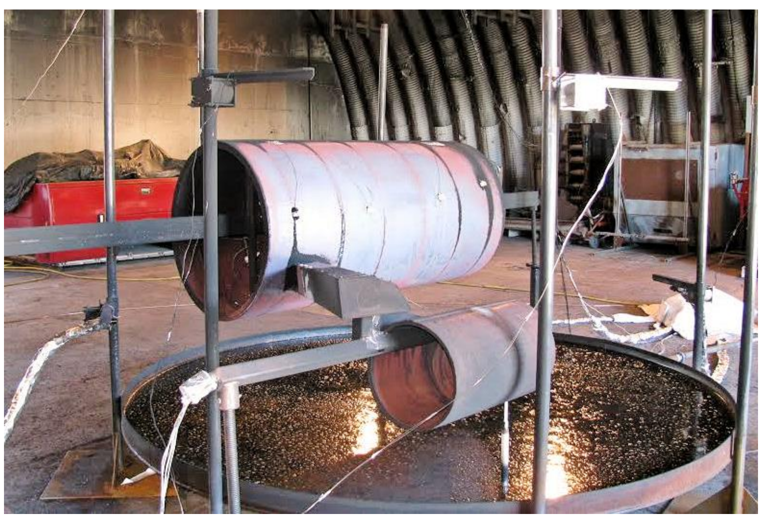
Isometric View

Thermal Characterization

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

Indoor Fire Test Facility

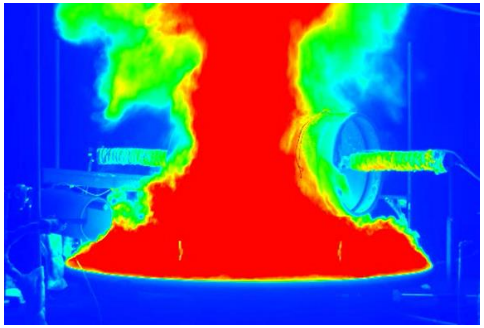


Isometric View

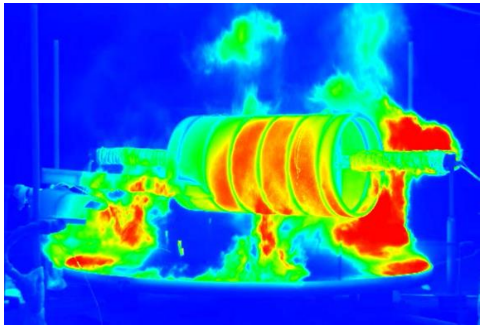
Side View

1:10 NLA Test Overview

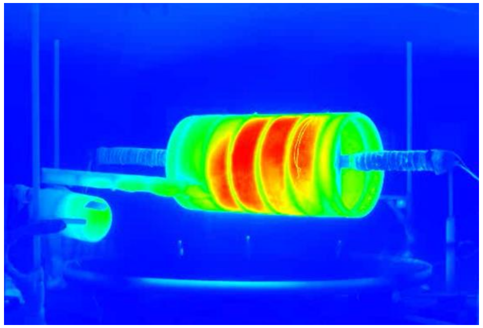
- 10 total trials
  - Pool only fire-suppression (5)
  - 1:10 NLA pool fire-suppression (5)
- Windless conditions
- 76 L (20 gal) JP-8 floated over 371 L (98 gal) tap water
- Manual ignition via propane torch
- 60-s pre-burn
- 4 fire suppression nozzles statically positioned to mimic ARFF-style response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



Pre-burn

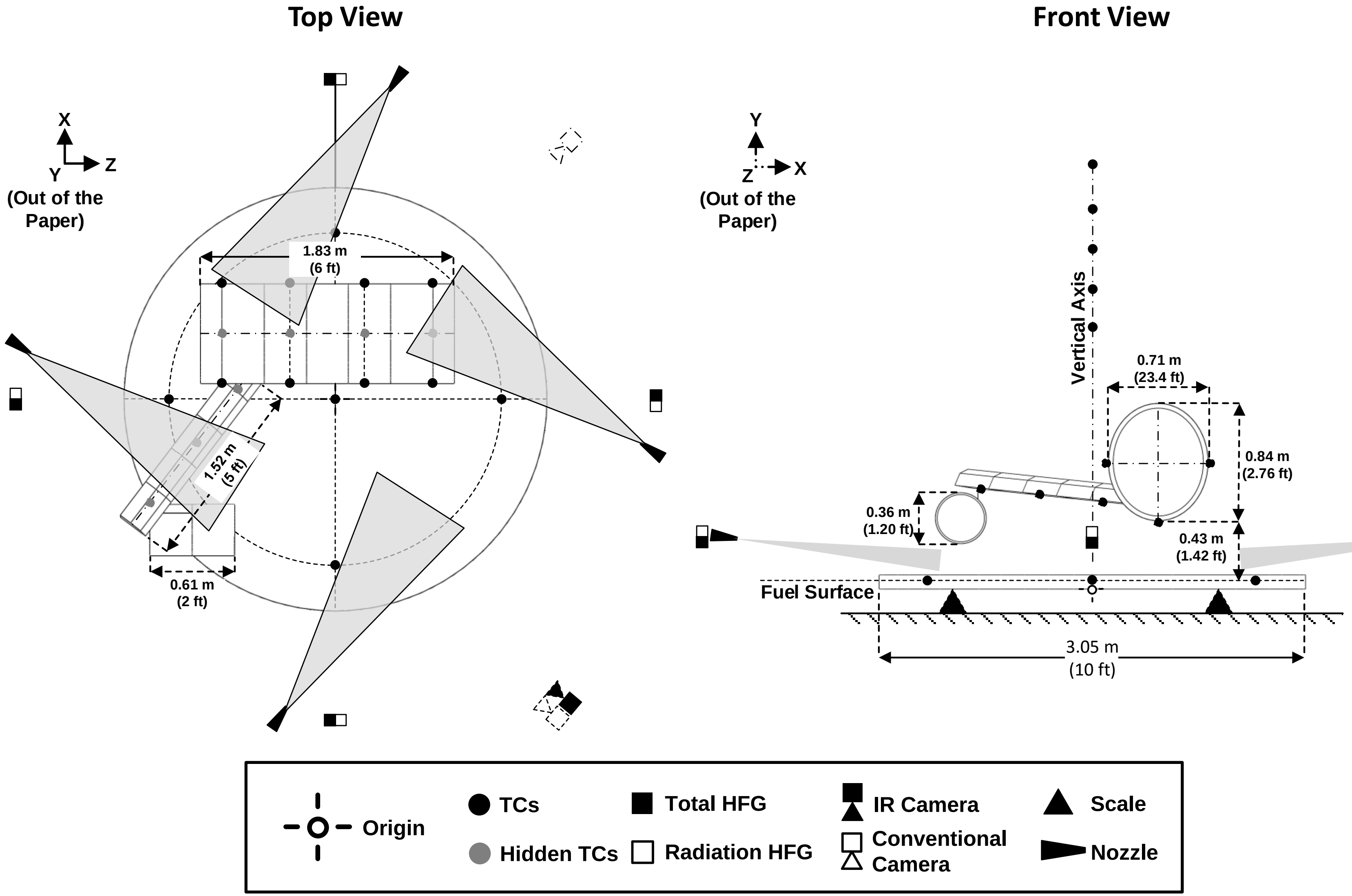


Suppression



Extinguished

1:10 NLA Test Layout

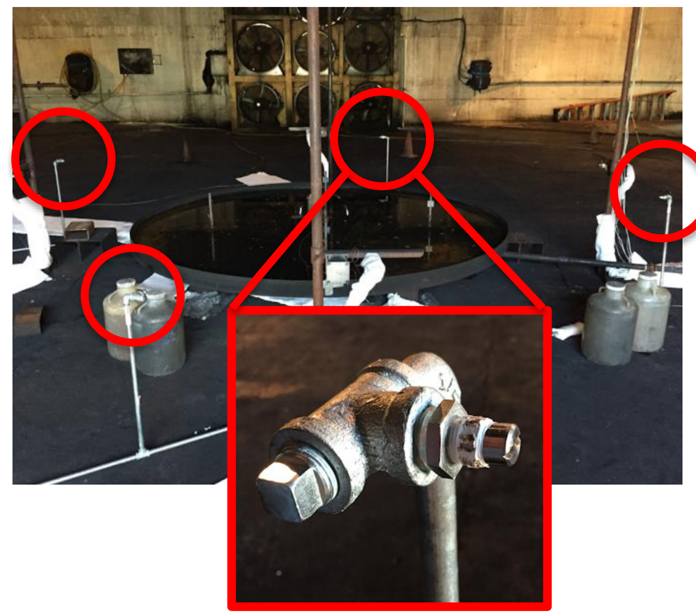


1:10 NLA Agent Delivery Test Summary

- Modified TRI-MAX 30 delivery system (pressurized cylinder)
- Bete SS 30° fan nozzle (Qty. 4)
  - 90° apart, 30° off principal axes
  - 43 lpm (11.3 gpm) total flow rate
  - 10.7 lpm (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”

TRI-MAX 30

Fuel Pan Post-Spray Test

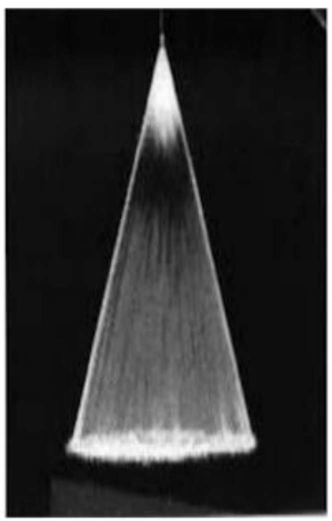


Agent Delivery Piping System

NFPA 403: 5.29 lpm/m² (0.13 gpm/ft²)

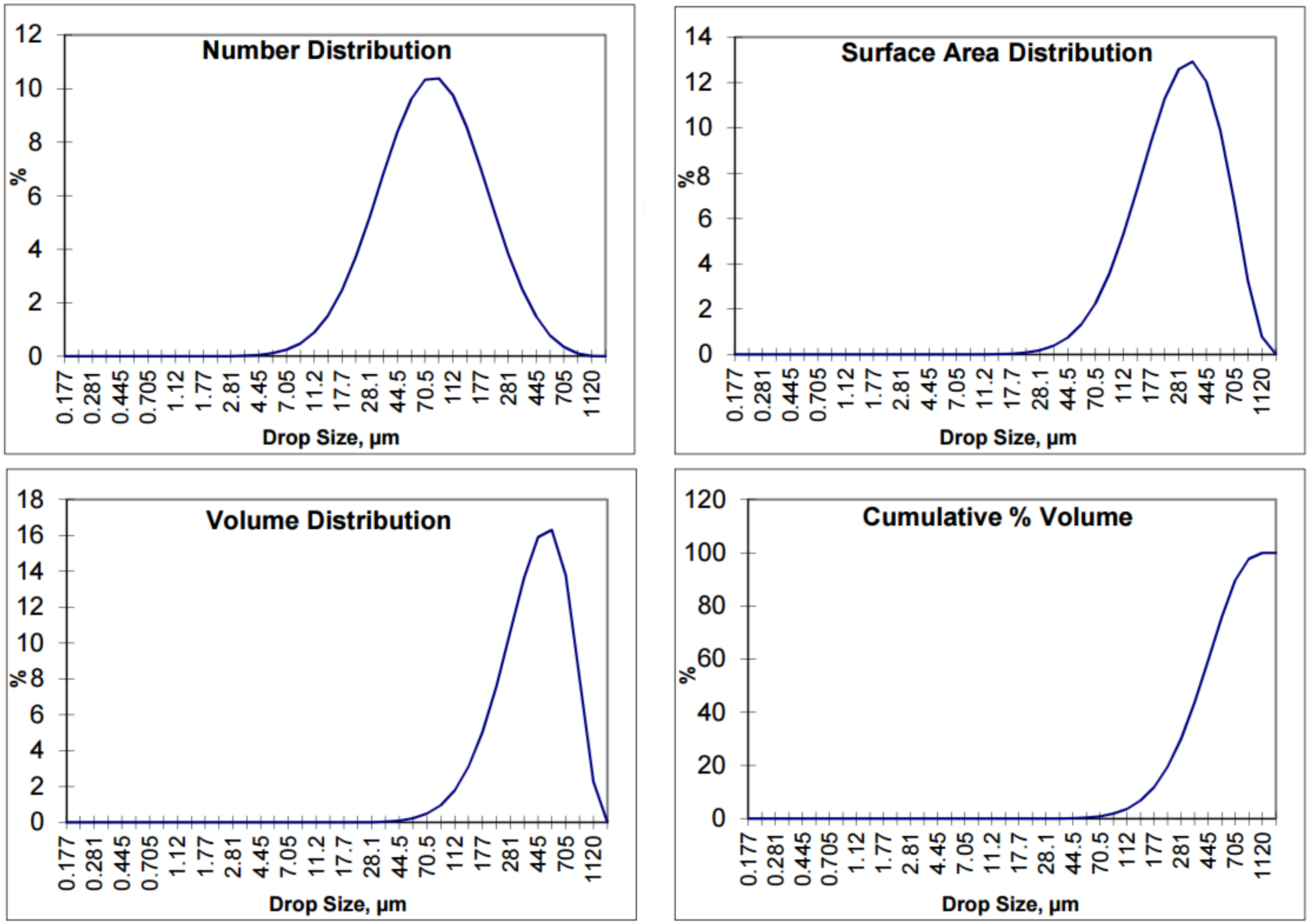
1:10 NLA Fire Suppression Nozzle Details

BETE SS NF2030



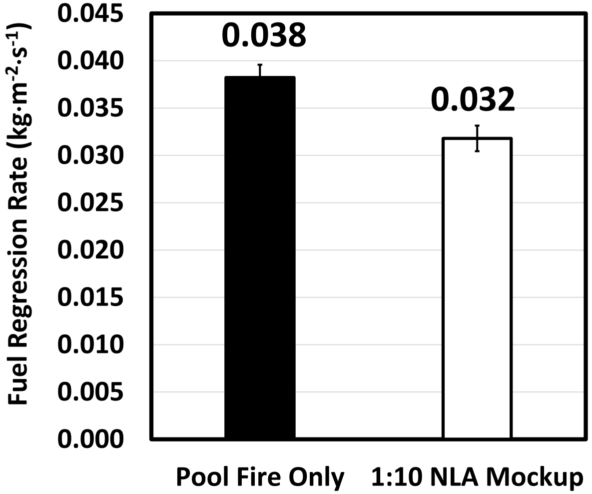
30° Spray Pattern

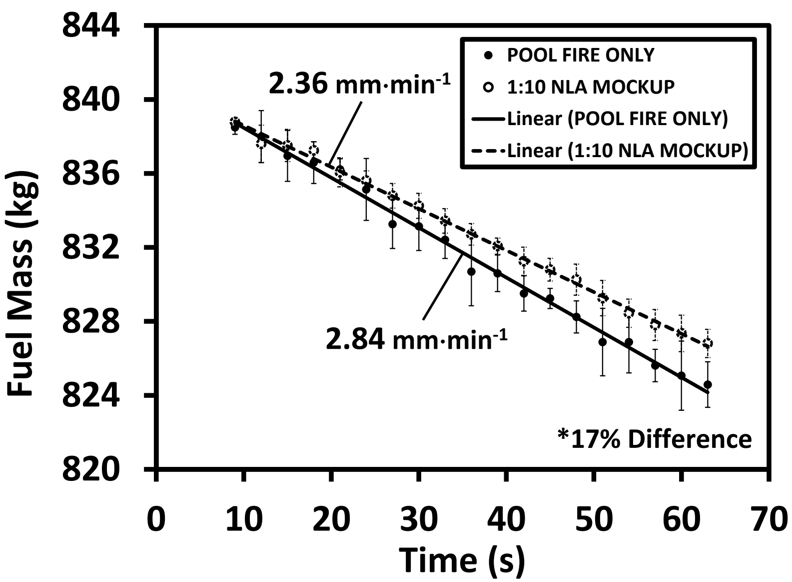
BETE Estimated Droplet Size Information:
10.7 lpm (2.82 gpm) @ 480 kPa (70 psi)



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

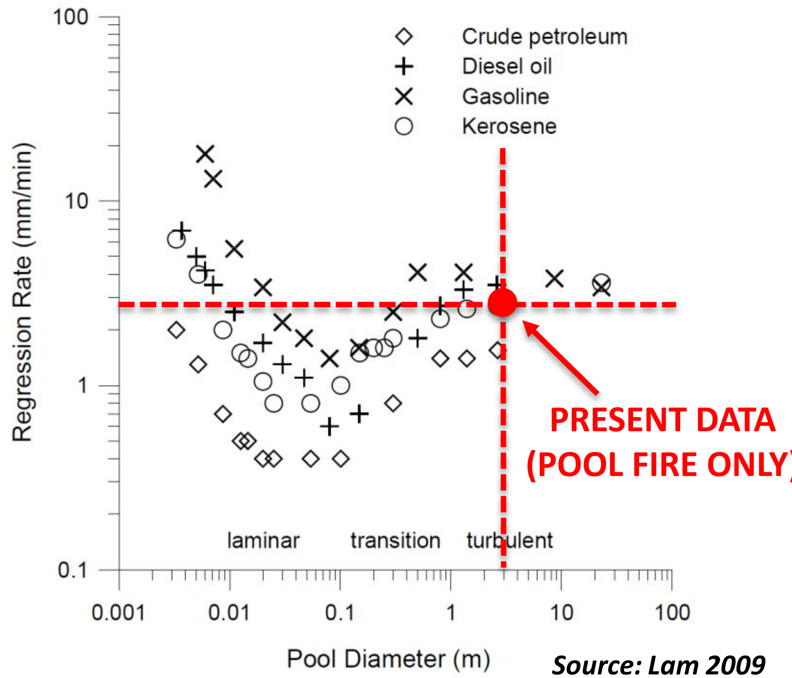
1:10 NLA Fuel Regression Results





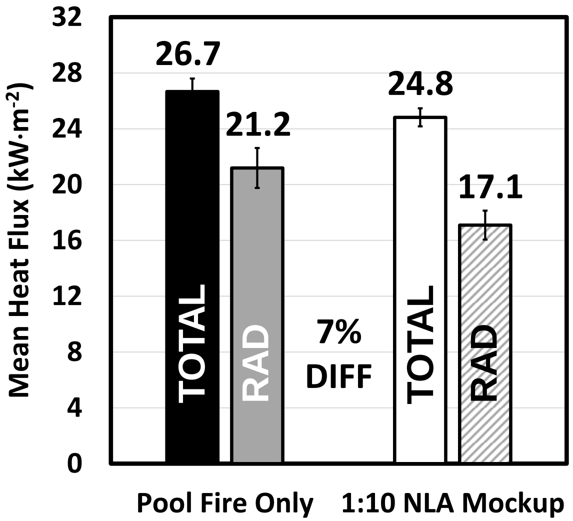
Pool Diameter	Burning Mode
< 0.05 m	convective, laminar
0.05 to 0.2 m	convective, turbulent
0.2 m to 1.0 m	radiative, turbulent, optically thin
> 1.0 m	radiative, turbulent, optically thick

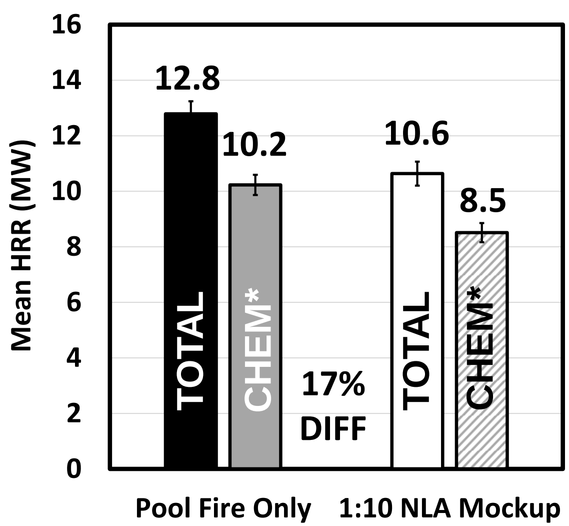
Source: Babrauskus 1983

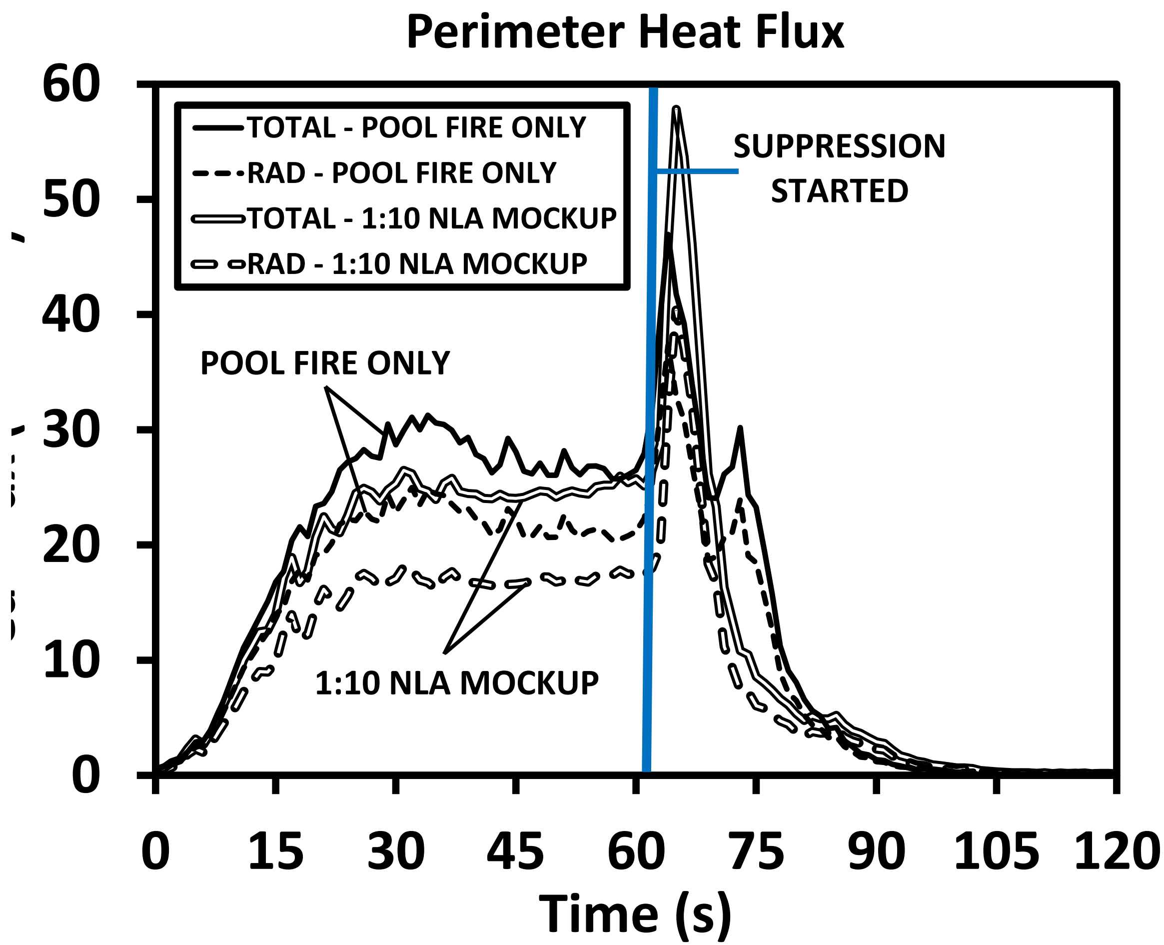


Source: Lam 2009

1:10 NLA Perimeter Heat Flux & Total HRR Results



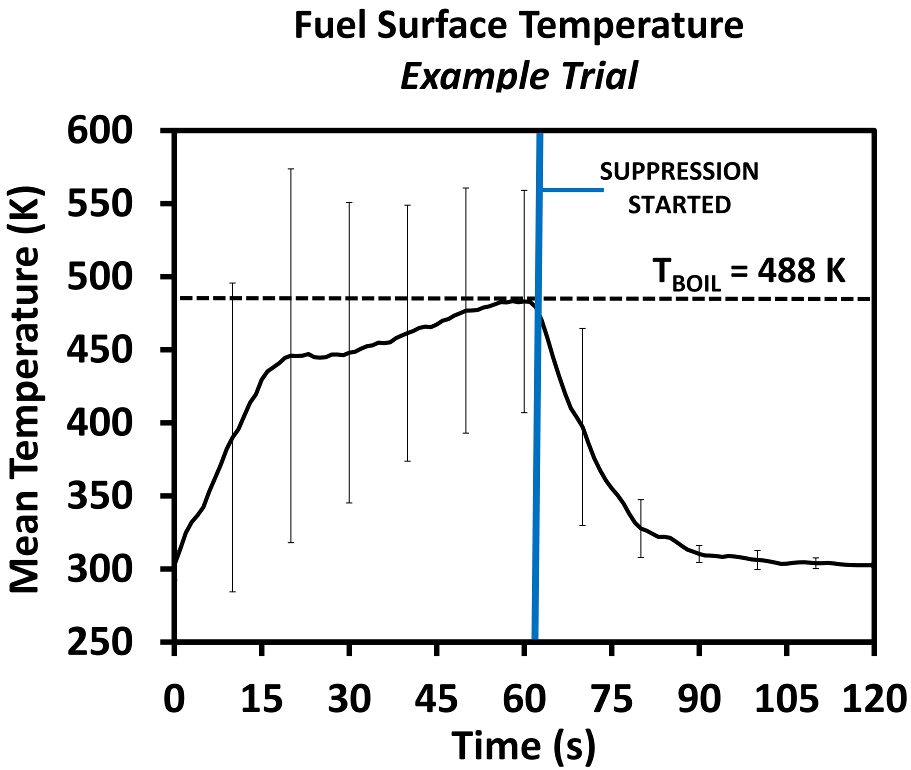


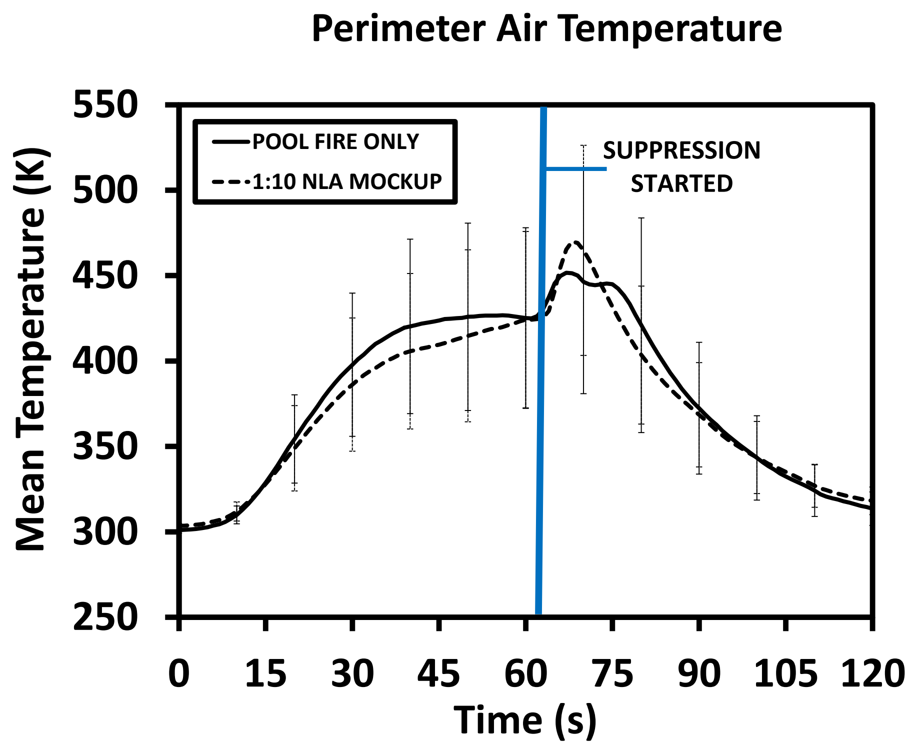


**Estimated*

Source: Blanchat et al. 2011

1:10 NLA Fuel Surface & Perimeter Temperature Results



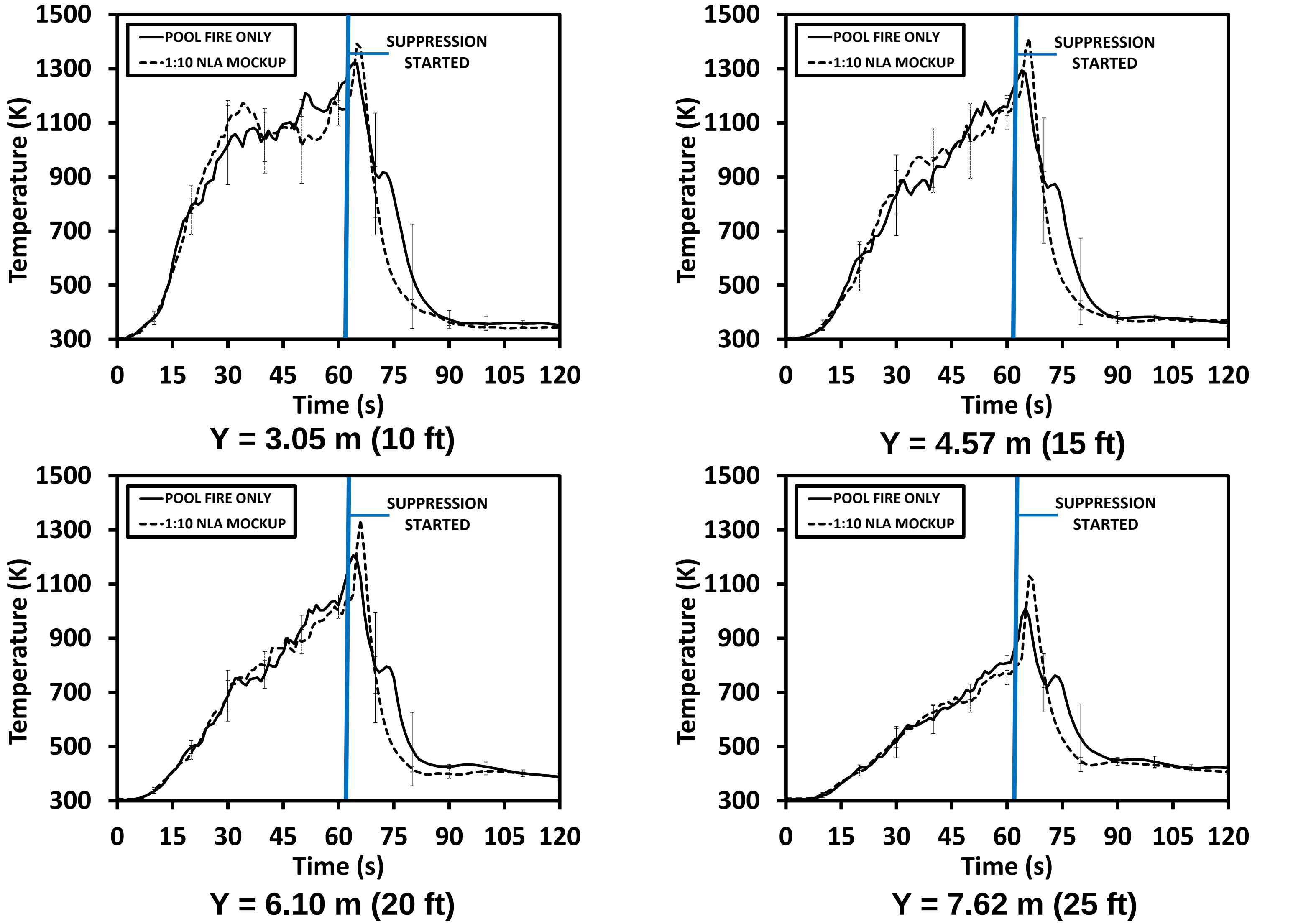


- Large deviation between sensors due to sensor alignment challenges and asymmetric fuel surface ignition

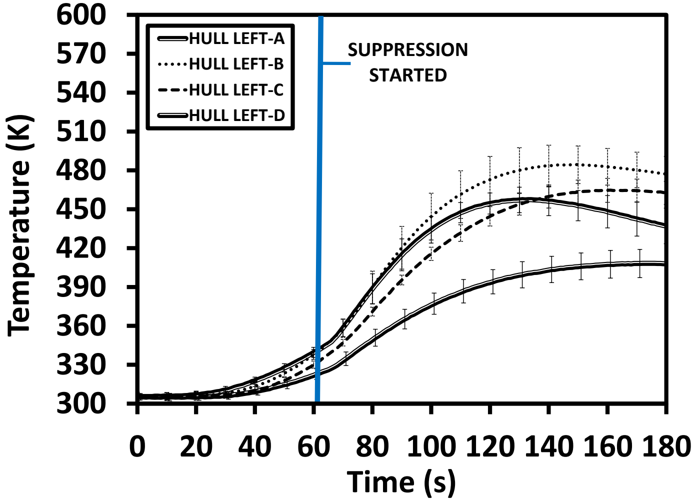
- Unremarkable difference between pool fire only and 1:10 NLA mockup fuel surface temperatures
- Similar response trend as adjacent heat flux sensors

Experiments

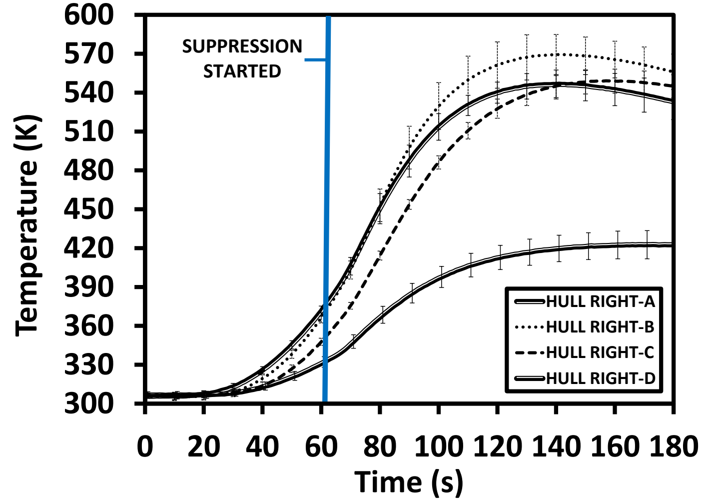
1:10 NLA Axial Fire Plume Temperature Results



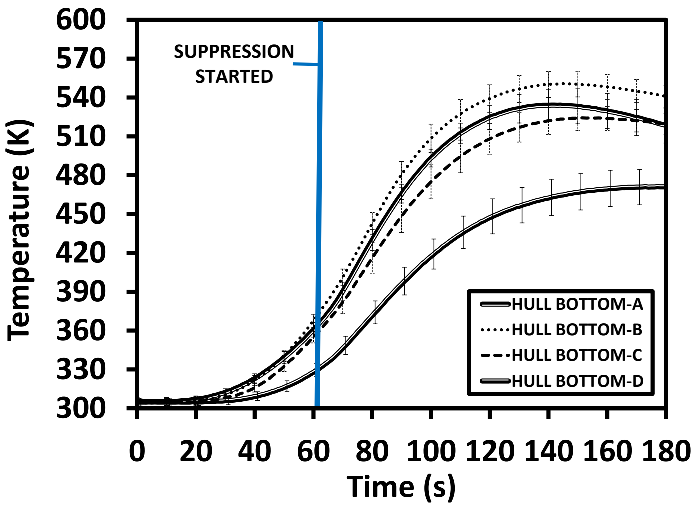
1:10 NLA Mockup Surface Temperature Results



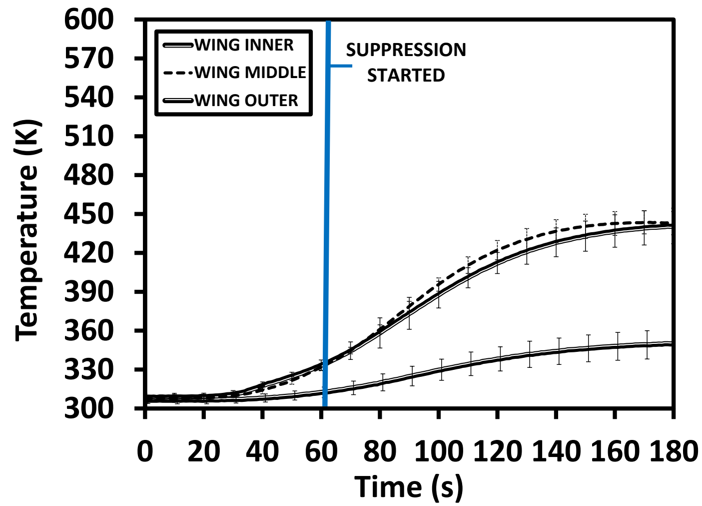
Mockup Left Hull



Mockup Right Hull

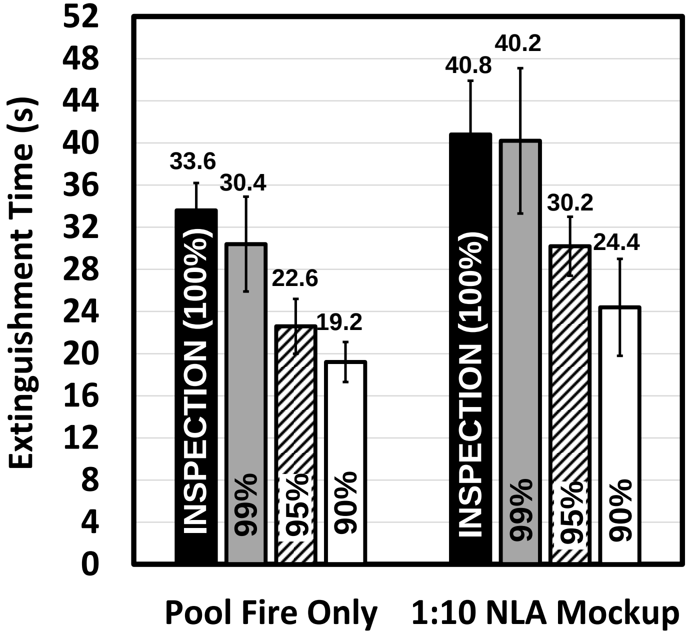


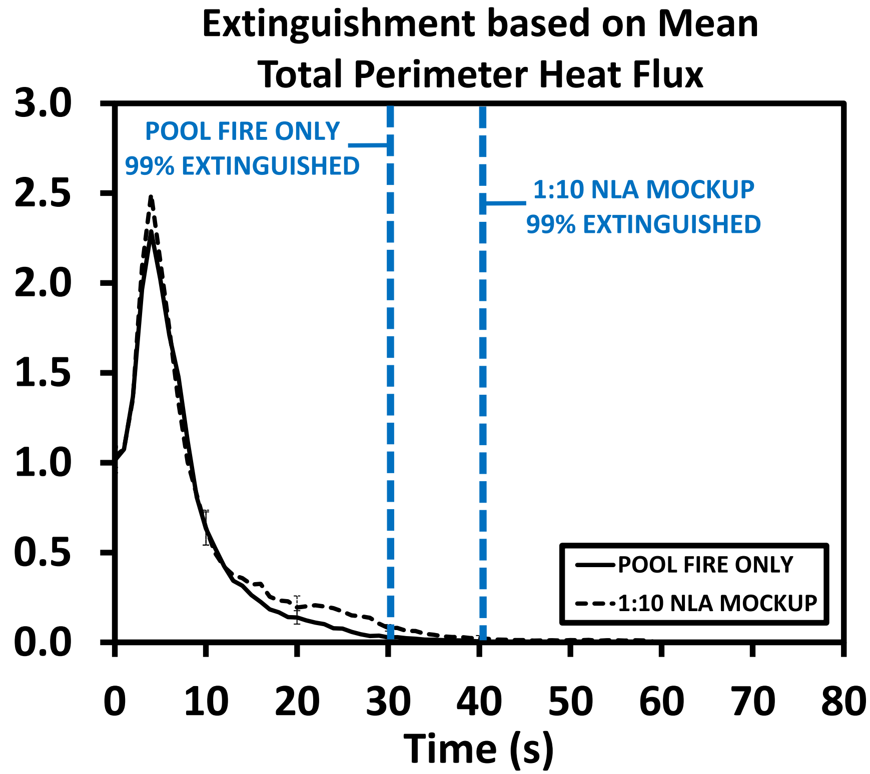
Mockup Bottom Hull



Mockup Wing Bottom

1:10 NLA Fire Suppression Results





Extinguishment Efficiency

	Pool Fire Only	1:10 NLA Mockup
99%	2.30 L/m² (0.056 gal/ft²)	3.08 L/m² (0.056 gal/ft²)
Inspection (100%)	2.54 L/m² (0.062 gal/ft²)	3.04 L/m² (0.074 gal/ft²)

≈25% DIFF

**USAF P-19 ≈2.45 L/m² (0.06 gal/ft²)*
Source: McDonald 2004

Experiments

1:10 Pool Fire Only Test Photos


1 – Pre-Burn


2 – Suppression Start Fire Intensification


3 – Mid-Suppression


4 – Almost Extinguished

1:10 NLA Test Photos

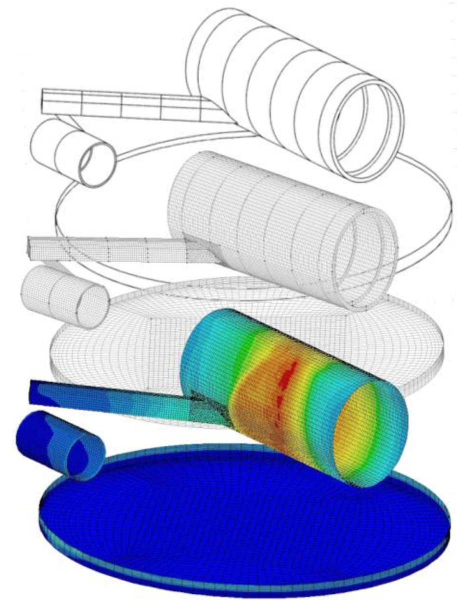
1 – Pre-Burn

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 2.6 GHz / 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

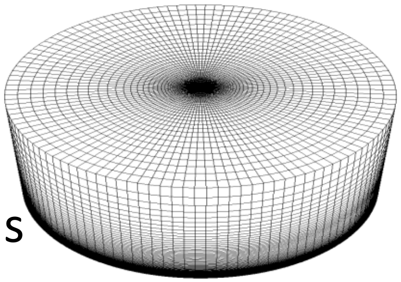
- Eulerian (Combustion) Model Framework
  - Partially premixed combustion based on the flamelet generated manifold diffusion flamelet approach
  - 22-species Jet A surrogate skeletal reaction mechanism based on the combustion of $C_{10}H_{22}$, C_6H_{14}, and C_6H_6 (Strelkova et al. 2008)
  - SST κ-ω (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

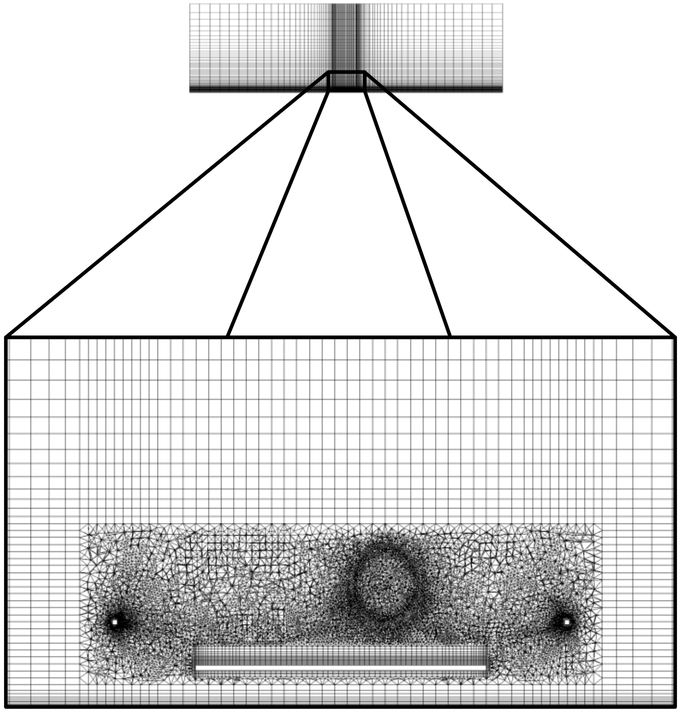
Multi-Block Hybrid Mesh Topology

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

Far-Field



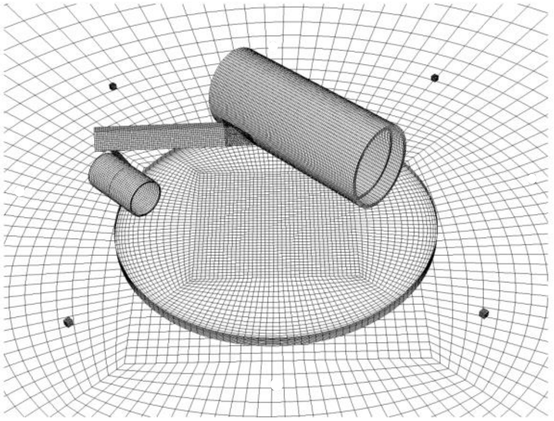
Far-Field Cross-Section



Near-Field Cross-Section

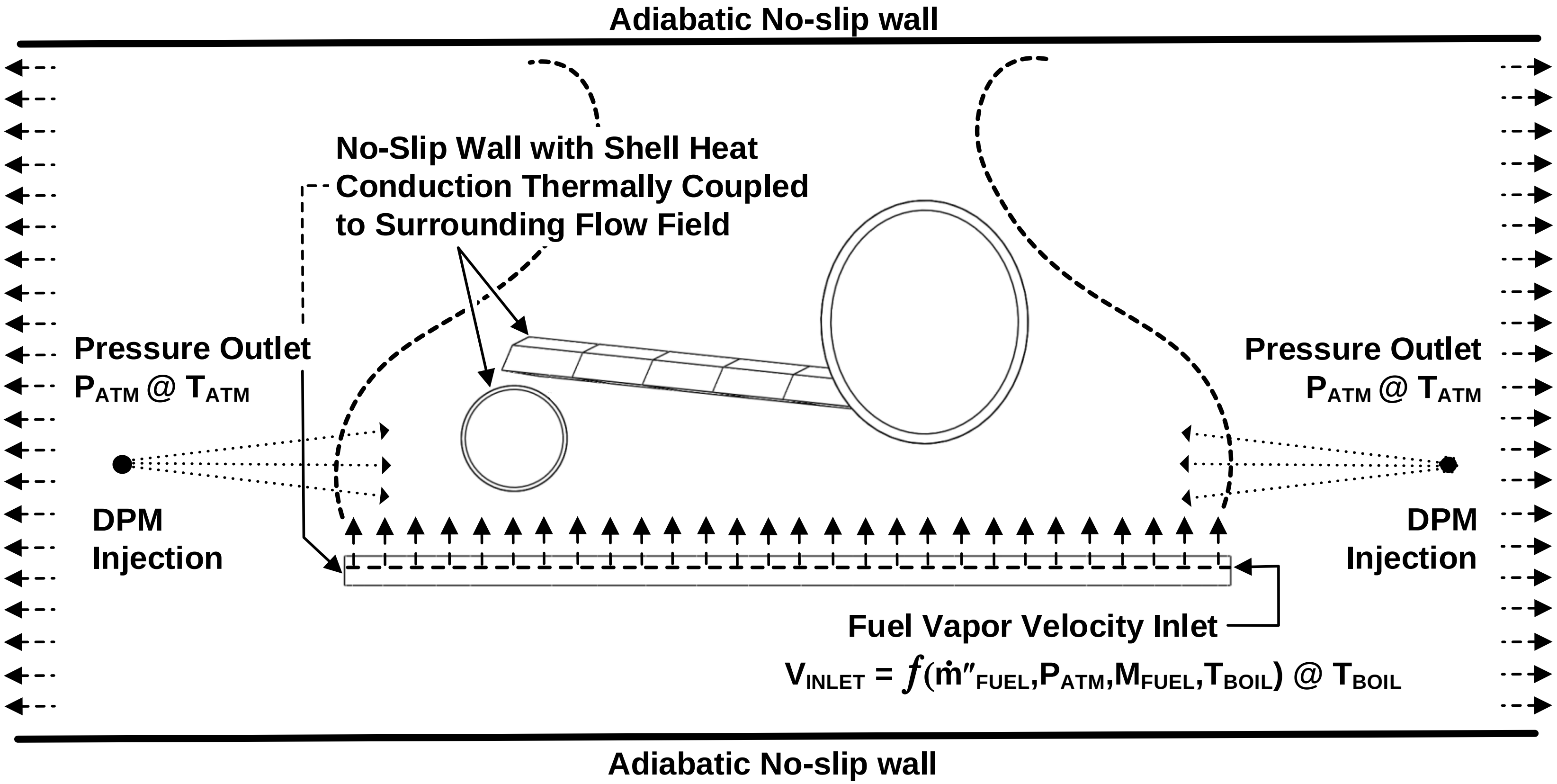
Pool Fire Only Mesh
≈ 1.46M Cells / 1.48M Nodes

1:10 NLA Mockup Mesh
≈ 3.05M Cells / 1.60M Nodes



1:10 NLA Mock-Up Near-Field

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

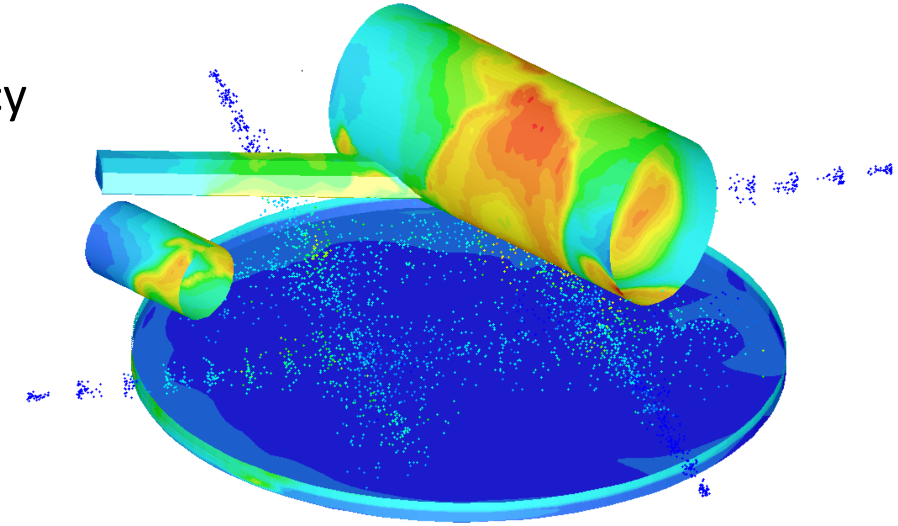
1:10 NLA CFD Model Preliminary Findings

Notable Similarities to Experiments

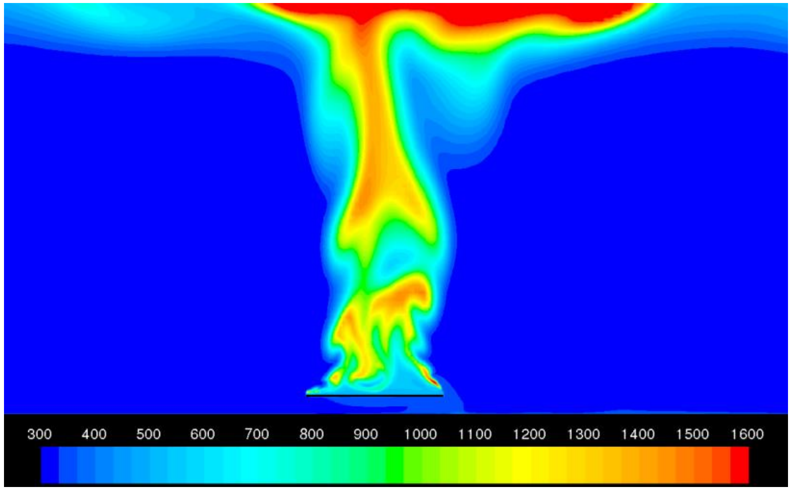
- Mean (pre-burn) perimeter air temperature, fire plume temperature, and total HRR
- Mean (pre-burn) perimeter heat flux
- Post-suppression start fire intensification
- Fire plume puffing frequency
- Mockup surface temperature profile trends compared to infrared camera data
- (Isothermal) agent delivery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

Notable Differences to Experiments

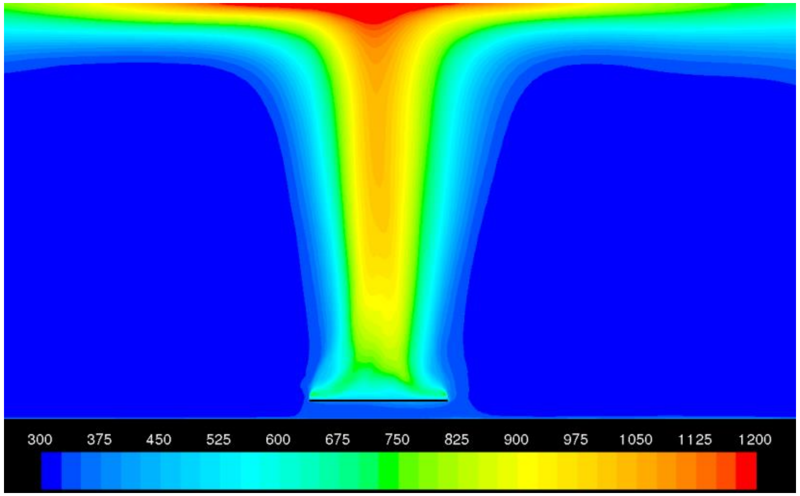
- Increased mockup surface heat-up rate
- Decreased rate of soot production



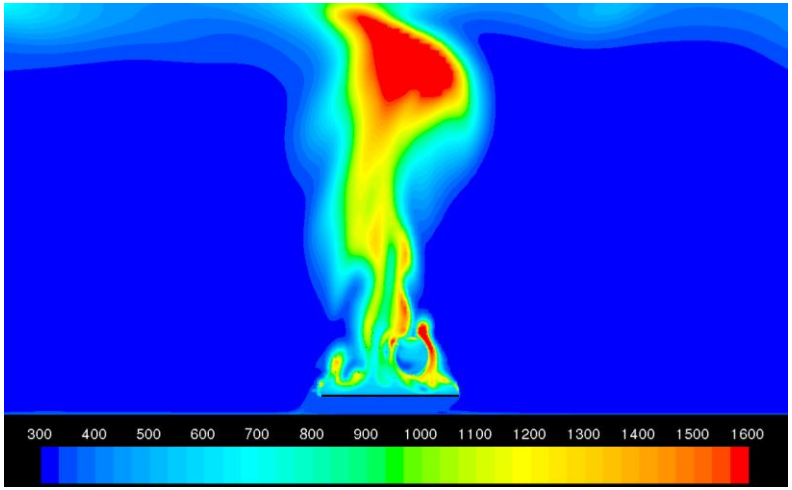
1:10 NLA CFD Model Sample Results



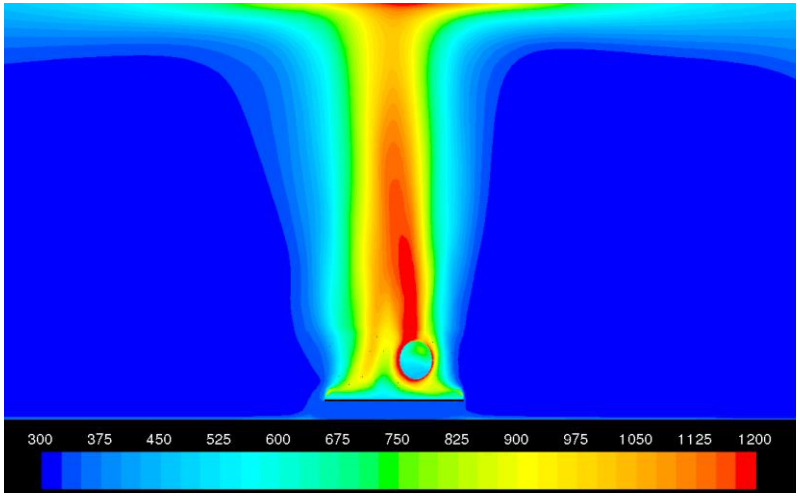
Pool Fire Only Instant Temperature (K)



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 1:10 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 open pool fire 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

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