

ABSTRACT

Title of Thesis: EVALUATION OF LOW-PRESSURE
WATER-BASED TRENCH DRAIN FIRE
SUPPRESSION SYSTEMS IN AIRCRAFT
HANGARS USING FDS MODELING

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Master of Science, 2023

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The 2020 National Defense Authorization Act (NDAA) prohibition of PFAS-containing AFFF fire protection systems by 2024 has motivated the U.S. Department of Defense to study other alternatives. In this study, the current low-expansion AFFF foam fire suppression systems with trenches layout in NAVFAC facilities are modeled as water-based systems to determine the scale, coverage, and extinguishment times that can be expected from such systems. A reduced spacing of the trenches is then simulated to determine how spacing of the floor nozzles affects fire suppression and control. Additionally, a model of a previously identified floor-level low-pressure water mist nozzle with the incorporation of trenches is studied to validate its possibility of being a replacement option for the current NAVFAC systems. Each simulation consists of three components: fire model, sprinkler/water mist model, and extinction model. Each model is evaluated separately before inputting into the final simulations to determine the most accurate

representation and minimize uncertainties. The final simulations with sprinkler nozzles show successful extinguishment up to 23 MW and better performance at earlier activation time and in setups with the current trench spacing. Little to no difference is observed between the two fuel spill fire scenarios at the same activation time and trench spacing. On the other hand, the low-pressure water mist systems do not meet adequate performance in the final hangar simulations.

EVALUATION OF LOW-PRESSURE WATER-BASED TRENCH DRAIN FIRE
SUPPRESSION SYSTEMS IN AIRCRAFT HANGARS USING FDS MODELING

by

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Thesis submitted to the Faculty of the Graduate School of the
University of Maryland, College Park, in partial fulfillment
of the requirements for the degree of
Master of Science
2023

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Acknowledgements

First, I would like to thank Dr. Milke for creating a warm environment in the Fire Protection Engineering department and for being a great mentor throughout my time at the University of Maryland. His guidance and humor have always been greatly appreciated, especially during tough times. Second, I would like to thank Dr. Trouvé for being my co-advisor. His comments during our meetings have helped me navigate and grow throughout this research. Third, I would like to thank Dr. Fernando Raffan-Montoya for being not only my third committee member but also a great professor in my two undergraduate classes. Last but not least, I would like to give a special thanks to Dr. Yujeong Kim for her knowledge and friendship this year.

Additionally, I want to express my sincere gratitude to Battelle, the U.S Air Force, and the U.S. Navy for funding this project. I appreciate Dr. Bridgett Ashley, Julie Bryant, and Steven Wells for their inputs during our monthly meetings. I also appreciate the contacts at Viking, especially Martin Workman and Shawn Feenstra, for their support. In addition, I would like to thank the contacts at NAVFAC, especially Joe Simone and Stephen So, for their input and organizing a tour for me to see the fire suppression systems at NAS Pax River.

This year would have been especially tough without my graduate friends, especially those in cubicle aisle one. Thank you, Jeff, and Kelliann, for forcing me out of my comfort zone and trying new things. I will cherish the memories we have made throughout the year, and I look forward to more adventures together. Thank you, Genevieve, for your wisdom and kindness. I always appreciate our talk as rarely as it happens.

I would not have made it here without my family. I would like to thank my parents for always supporting and encouraging me, and my little sister for letting me annoy her once a week. I would like to give a special shout out to Quintin B. Squintin for being my “punching bag” and supplying me with caffeine throughout this year. I love and appreciate you lots.

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List of Abbreviations

AIT: Auto Ignition Temperature

AFCEC: Air Force Civil Engineering Center

AFFF: Aqueous Film Forming Foam

CFD: Computational Fluid Dynamics

DoD: Department of Defense

FDS: Fire Dynamics Simulator

HRR: Heat Release Rate

LES: Large-Eddy Simulation

MLRPUA: Mass Loss Rate Per Unit Area

NAVFAC: Naval Facilities Engineering Systems Command

NDAA: National Defense Authorization Act

NIST: National Institute of Standards and Technology

NFPA: National Fire Protection Association

PFAS: Per- and Polyfluoroalkyl chemicals

SCLF: Slice file

UFC: Unified Facilities Criteria

Chapter 1 Introduction

The fire suppression systems containing Aqueous Film Forming Foam (AFFF) have been used widely by the Department of Defense (DoD) and the aviation community since the 1970s as a means of protection in aircraft hangars. These systems are particularly effective against liquid fuel (class B) fires. However, compounds such as per- and polyfluoroalkyl substances (PFAS) in firefighting foam have been found to be problematic for not only the environment but also human health [1, 2, 3]. Environmental concerns as well as the frequency of accidental discharge incidents, such as activations of foam systems without a fire being present, motivate the U.S. Navy and U.S. Air Force to study the feasibility of other alternative fire suppression systems for aircraft hangars.

1.1 Motivation

One of the most dangerous fire hazards in aircraft hangars is jet fuel spills due to their high heat release and potential damage to expensive aircraft and other structures. In U.S. Navy facilities, this hazard is currently protected by trench systems that are spaced throughout the hangar floor with nozzles that discharge low expansion AFFF foam. The AFFF-charge systems effectively control fires and minimize aircraft damage compared to ceiling-mounted high expansion HiEx systems. However, PFAS found in foam poses high risks to the environment as well as human health due to its toxicity and inability to degrade [2]. This leads to the 2020 National Defense Authorization Act (NDAA) prohibition of PFAS-containing AFFF fire protection systems beginning

October 1, 2024. Furthermore, a study on a 17-year window of discharge incidents from commercial airlines and U.S. DoD hangars reports an average of 11.8 accidental foam discharges occurred per year [2]. An earlier study estimates on average a minimum of \$6.4M cost per accidental foam discharge incident [1]. Concerns raised by environmental, health, and monetary issues motivate the DoD to pursue other alternatives to AFFF foam system while meeting requirements for fire control. A previous study by Steranka (2021) funded by the U.S. Air Force has considered water mist [4]; however, this study explores the feasibility of sprinkler system alternatives, specifically in Navy aircraft hangars with trench systems.

This report consists of two phases. Phase I involves simulations of the current Navy fire suppression system to evaluate the effectiveness of a water-based system to control fire. After the initial simulation of the current trench system, the trench spacing will be reduced in the model to study its effect on fire suppression. Phase II includes simulations of compatible COTS low-pressure water mist systems with the trench system.

1.2 Computational Modeling Background

In this study, Fire Dynamics Simulator (FDS) version 6.7.9 developed by the National Institute of Standards and Technology (NIST) is used for computational modeling purposes. Another software developed by NIST, Smokeview version 6.7.21, and Pyrosim 2022 version 2322.3.1208 developed by Thunderhead Engineering is used

to visualize the results of FDS. Lastly, MATLAB R2022b is utilized to process and manipulate FDS results in matrix form.

FDS, a computational fluid dynamics (CFD) model, divides the computational domain into several control volumes and represents thermally driven fluid flows through numerically solving a form of Navier-Stokes equations appropriate for low-speed flow [5]. The hydrodynamic model preferred by FDS is the Large Eddy Simulation (LES) approach due to its ability to not only solve physics accurately but also decrease computational time. FDS uses a “single-step, mixing-controlled chemical reaction” which uses air, fuel, and products as “lumped species” [5]. The radiation transport model FDS utilizes a technique similar to finite volume methods (FVM) for convective heat transport [5]. Further information about numerical methods and governing equations can be found in FDS Technical Reference Guide [6].

FDS models with multiple meshes can be processed through parallel processing in which each mesh is assigned to a single-core processor. For parallel processing in this study, Zaratan (available at <https://hpcc.umd.edu>), a high-performance computing cluster at UMD is used. The flow field in each mesh is computed by FDS on Zaratan as an MPI process via Message Passing Interface (MPI) [10]. In this study, individual components of the model will be evaluated in FDS to determine the most accurate representation and minimize uncertainties.

1.3 Scope of Work

The focus of this study is to use FDS and Smokeview to model and visualize the current Navy trench drain fire suppression system using only water. The model utilizes the hangar dimensions and specifications in the Unified Facilities Criteria (UFC) 4-211-01 with trenches with maximum spacing 15.2 m intervals and floor nozzles located in trench drains with maximum spacing 7.6 m [7]. Figure 1-1 shows the schematic of the trench systems with nozzle layout in a pull-in hangar [7].

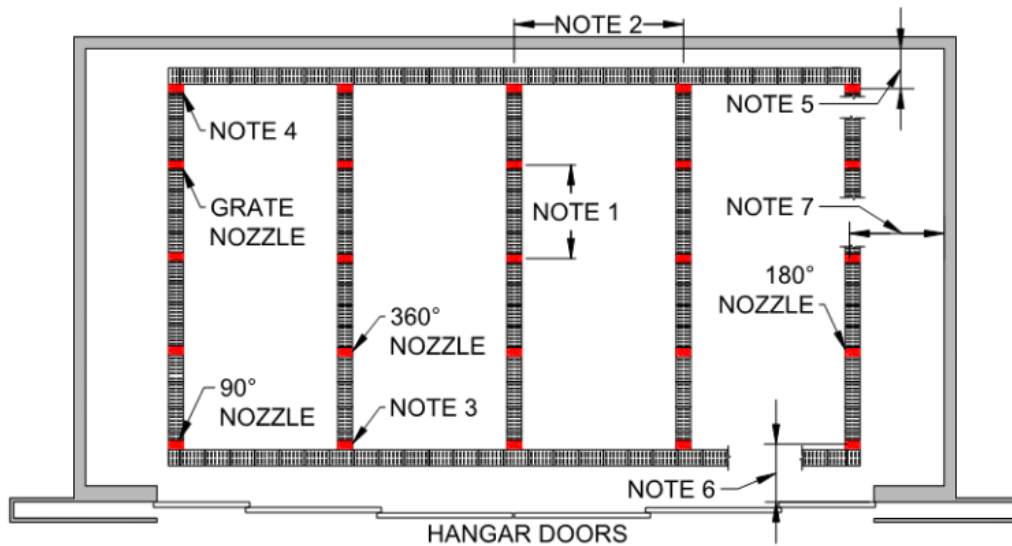


Figure 1-1. Schematic of trench systems with nozzle layout in a pull-in hangar.

Modeling of the current system in a range of uncontained JP-8 spills (0.06 m^3 to 0.62 m^3) serves as a baseline to determine the scale, coverage, and extinguishment times that can be expected from nozzles at the floor that expel only water. The spacing of the trenches will then be reduced to 7.6 m to determine how the spacing of the floor nozzles affects fire suppression and control. In a previous study by Steranka (2021), she

identifies VID Fire-kill Model F102-1, a low-pressure water mist telescopic pop-up commercial-off-the-shelf (COTS) nozzle, to be a replacement option to the current NAVFAC system [4]. A model of VID Fire-kill Model F102-1 with the incorporation of trenches will be included in this research. The results of computer simulations will be utilized to support large-scale field testing following this study.

Chapter 2 Literature Review

2.1 Navy Fire Suppression Systems

Currently, the Navy uses trench systems that are spaced throughout the hangar floor with nozzles that discharge low AFFF in case of a fire. The trenches serve as a means of removing hazardous fuel and fire suppression system discharge as well as conveying fire suppression piping to low level system discharge devices [7]. Prior to the AFFF system, the Navy used overhead sprinkler systems as a means of fire suppression system, but those systems were not sufficient in protecting aircraft in case of a fire. While a ceiling mounted HiEx or AFFF overhead system was considered an option, the floor mounted system minimized firefighting agent damage to aircraft stored in the area. Previous floor nozzle designs including fixed and pop-up designs failed to provide adequate performance. As a result, the Viking Grate Nozzle, a standard COTS nozzle, was developed as a joint effort between the Navy and Viking in the late nineties. While providing a low-profile spray pattern, the nozzle is mounted in a commercially available trench system and is able to support heavy loads in aircraft hangars. It also applies AFFF in a circular pattern with 7.6 m radius while including no moving parts to ensure mechanical reliability [8]. In addition, this nozzle discharges AFFF in a spray pattern of approximately 0.3 to 0.46 meters above the floor in a 360° radius. Further design requirements for foam trench systems follow UFC 4-211-01 requirements. Current system specifications require that a 3% AFFF solution must discharge for 10-

minutes at 40 to 60 psi and the detection-to-discharge delay shall not exceed 30 seconds at any nozzle in the trench system. Figure 2-1 shows a typical nozzle layout on a trench.

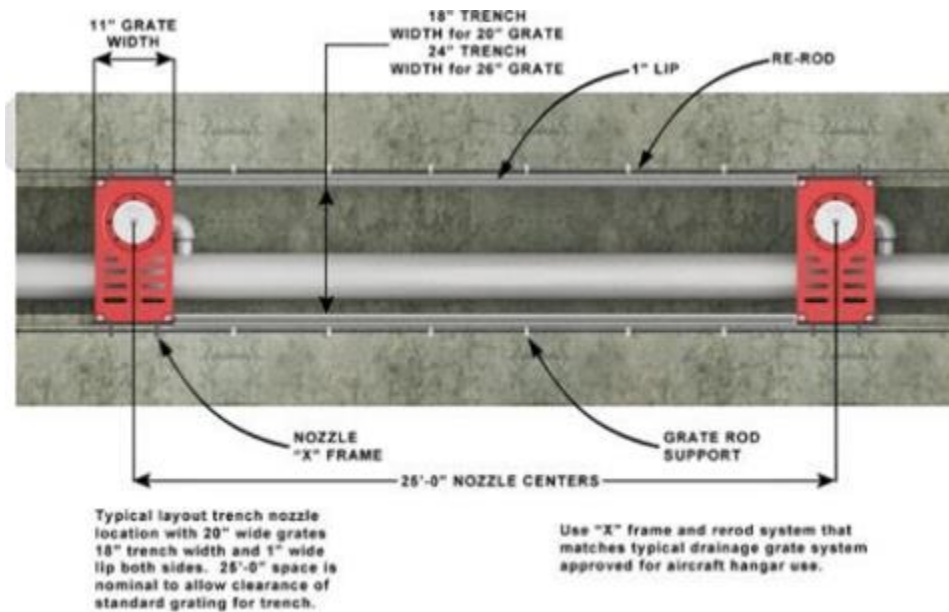


Figure 2-1. Typical nozzle layout on a trench.

2.2 Previous Modeling Effort

Since the 2020 NDAA, other alternative systems have been studied to replace foam-based fire suppression systems in aircraft hangars. The Air Force Civil Engineer Center (AFCEC) at Tyndall AFB has made significant effort in investigating alternative water-based technologies including modeling and evaluation of water mist for fire suppression. An initial study conducted by Steranka (2021) encompasses market research, FDS modeling, and feasibility analysis of COTS water mist technologies resulting in the selection of a high-pressure water mist system employing both floor and ceiling nozzles [4]. Additional study by Lee (2023) focuses on the modeling of a

Marioff's Hi-Fog, high-pressure water mist fire suppression system. This study evaluates the performance of two different system nozzle configurations, ceiling only and a combination of ceiling and floor, in a total of twelve model scenarios [9]. There is no previous study in the simulation of potential sprinkler system designs for hangar applications nor incorporation of trench drain systems.

2.3 COTS Research

A previous study by Steranka (2021) identifies several COTS water mist systems that might be appropriate to replace the current low expansion AFFF floor systems in Navy facilities [4]. As an example, VID model Fire-kill F102, is a low-pressure water mist nozzle designed specifically for the protection of aircraft hangars. This study further examines the use of this nozzle in combination with the trench system in case of fuel spill fire scenarios.

Currently, there is no floor sprinkler nozzle designed for the protection of aircraft hangars. For that reason, Viking Grate Nozzle GN200, the foam nozzle used in current Navy fire suppression systems, is examined in this study as a sprinkler nozzle for a water-based system. Viking Grate Nozzle GN202, a recent update of the GN200 model for the use of fluorine-free foam, can also be examined as a sprinkler nozzle. However, due to the time constraint of this study, only model GN200 is studied.

Chapter 3 Fire Model

3.1 Description of Fuel

The fuel used throughout this study is JP-8, a kerosene-based fuel mixed with additives for military uses. Due to its nonhomogeneous and complex structures, JP-8 is simplified in FDS using the default single step, mixing controlled combustion model of lumped species. A single fuel species is made up of C, H, O, and N that reacts with oxygen to form H_2O , CO_2 , soot, and CO. FDS requires minimum inputs including chemical formula, mass loss rate per unit area (MLRPUA) or heat release rate per unit area (HRRPUA), CO yield, radiative fraction, and soot yield to create a burner vent. Previous work by Steranka (2021) identifies the chemical formula for the fuel species JP-8 to be $C_{11}H_{21}$ and the value of the post combustion CO yield to be 0.01 [4]. The value of MLRPUA is dependent on various parameters such as the depth of the spill, quantity of liquid spilled, floor material, and fuel temperature. The literature provides a wide range of values for MLRPUA for JP-8 with limited data being available for uncontained pool spill scenarios which are the subject of this study. A MLRPUA value of 0.01 kg/s/m^2 is noted by Gottuk and White for large diameter uncontained JP-8 fires [10].

The spill area of all scenarios is calculated from an estimation rule from Benfer et al. (2012) which approximates 4.83 m^2 spill area per cubic meter of liquid for a spill volume for spills less than 0.09 m^3 and 1.35 m^2 spill area per volume liquid for a spill volume 0.095 m^3 [11]. As such, the spill area for 0.06 m^3 , 0.21 m^3 , and 0.62 m^3 spill is

found to be approximately 79.4 m², 74.2 m², and 222.3 m², respectively. Previous work by Lee (2023) identifies the spread rate for an uncontained spill to be 6 cm/s, which is used to model all scenarios in this study [9]. The radiative fraction values of JP-8 are based on the radiative fraction values of kerosene ranging from 0.4 to 0.04 for pool fires with diameters from 1 m to 50 m [10]. The values of soot yield for JP-8 range from 0.01 to 0.2 based on data from experiments with dodecane [4]. The exact value of the radiative fraction and soot yield is further examined in section 3.2.

3.2 Radiation Model

3.2.1 Radiation Model Description

Thermal radiation is a crucial factor in modeling sprinkler and water mist suppression systems due to the ability to absorb and disperse thermal radiation of water droplets. The equation that governs radiation transport for an absorbing, emitting and scattering medium is defined in the FDS Technical Guide as:

$$s \cdot \nabla I_\lambda(x, s) = -\kappa(x, \lambda)I_\lambda(x, s) - \sigma(x, \lambda)I_\lambda(x, s) + B(x, \lambda) + \frac{\sigma(x, \lambda)}{4\pi} \int_{4\pi} \Phi(s', s)I_\lambda(x, s')ds' \quad (\text{Eq. 3.1})$$

where $I_\lambda(x, s)$ is the radiation intensity at wavelength, λ ; s is the direction vector of the intensity; and $\kappa(x, \lambda)$ and $\sigma_s(x, \lambda)$ are the local absorption and scattering coefficients, respectively. $B(x, \lambda)$ is the emission source term, describing how much heat is emitted by the local mixture of gas, soot, and particles. The terms on the right-hand side of

equation 3.1 represent the energy loss by absorption, energy loss by scattering, emission source, and in-scattering from other directions, respectively [12].

The net contribution from thermal radiation in the energy equation is based on the following equation:

$$\dot{q}_r''' \equiv -\nabla \cdot \dot{q}_r''(x) = \kappa(x) \left[\int_{4\pi} I(x, s') ds' - 4\pi I_b(x) \right] \quad (\text{Eq. 3.2})$$

where $\kappa(x)$ is the absorption coefficient, $I_b(x)$ is the source term, and $I(x, s)$ is the solution of the radiation transport equation for non-scattering gray gas. Equation 3.3 provides the solution of the radiation transport equation for non-scattering gray gas based on the source term:

$$s \cdot \nabla I(x, s) = \kappa(x) [I_b(x) - I(x, s)] \quad (\text{Eq. 3.3})$$

Additional information on each term in Equation 3.3 as well as thermal radiation can be found in FDS Technical Reference Guide [12].

FDS provides three options to model thermal radiation. The first option, or radiation model 1 as referred to throughout this study, corresponds to the LES default which is an optically thick model that requires a specified value for radiative fraction (χ_r) “RADIATIVE_FRACTION” on the “REAC” or “COMB” line. As solving the flame temperature in the radiation transport equation (RTE) is not well-resolved for large-scale fire simulations, this option provides an alternative way to specify explicitly the amount of thermal radiation released from the total combustion energy. In grid cells where $X_r \dot{q}_r'''$ is greater than 10 kW/m³, the source term in RTE is adjusted to ensure that the net radiative emission from the fire is the specified radiative fraction multiplied

by the total combustion energy generated in this region. The second option, or radiation model 2, corresponds to optically thick model with unspecified radiative fraction where FDS assumes the flame temperature is well-resolved and there is no correction needed to calculate the RTE source term. The last option, or radiation model 3, is the optically thin model with a specified radiative fraction where the reabsorption of thermal radiation by cold combustion product gases is neglected. This model is desired in open space scenarios and can be turned on by specifying “OPTICALLY_THIN=T” on the RADI line. These models are further studied in the subsequent subsection.

3.2.2 Radiation Model Validation Test

To determine the appropriate radiation model and study the effect of soot yield and radiative fraction on the development of a fire, a series of tests was performed in a computational domain of size 24 m x 24 m x 15 m with a uniform 0.1 m grid. The domain was constructed of a concrete floor and open boundaries everywhere else. A 0.06 m³ uncontained JP-8 spill fire was used throughout these tests. The fire was represented by a 10.1 m diameter circular burner with prescribed surface temperature of 220°C and MLPUA of 0.01 kg/s/m². The fire was started at the center of

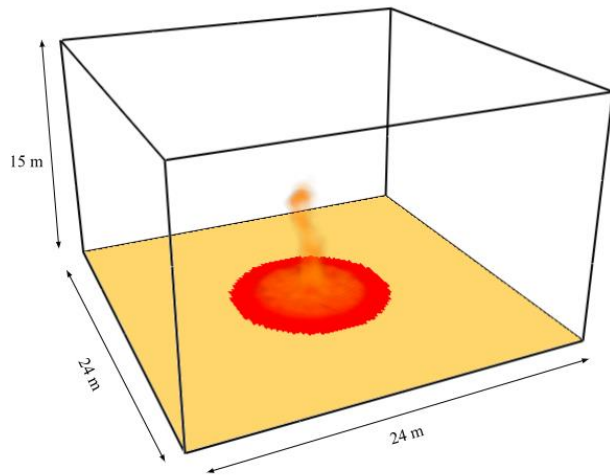


Figure 3-1. Radiation Model Tests Setup.

the burner and spread radially outward at a rate of 0.06 m/s. Figure 3-1 shows the experimental setup.

The run time for each test was 60 seconds during which the fire was in a transient phase. Devices were placed across the centerline of the pool surface to measure the total heat flux. The total heat flux results from simulations were then compared to the total heat flux estimated from the following heat balance:

$$q_{net} = (\dot{m}_{pan} / \dot{m}_{spill}) \dot{m}_{fuel} H_{V,sens} \quad (\text{Eq. 3.4})$$

where $\dot{m}_{pan} / \dot{m}_{spill}$ is the ratio of the maximum mass burning rate of a pan fire over the maximum burning rate of an uncontained spill, $\dot{m}_{fuel}$ is the burning rate of the fuel, and $H_{V,sens}$ is the sensible heat of vaporization of JP-8. Figure 3-2 shows the result of the first test which examines radiation model 1 with a range of radiative fraction from 0.05 to 0.3 and a constant soot yield of zero. It can be observed that as the radiative fraction approaches zero, the simulated total heat flux approaches the estimated total heat flux value. Figure 3-3 represents not only the use of radiation model 2 but also the effect of soot yield on optically thick radiation model. As the value of soot yield increases, the total heat flux moves away from the estimated total heat flux.

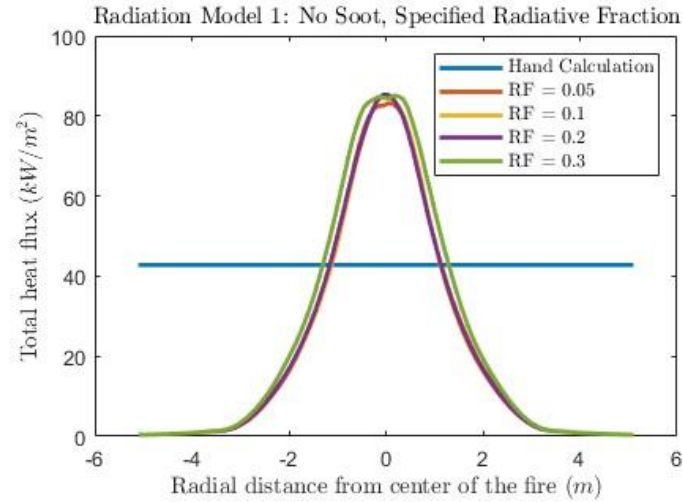


Figure 3-2. Total heat flux at pool surface versus radial distance from center of the fire. Varying radiative fraction and no soot yield.

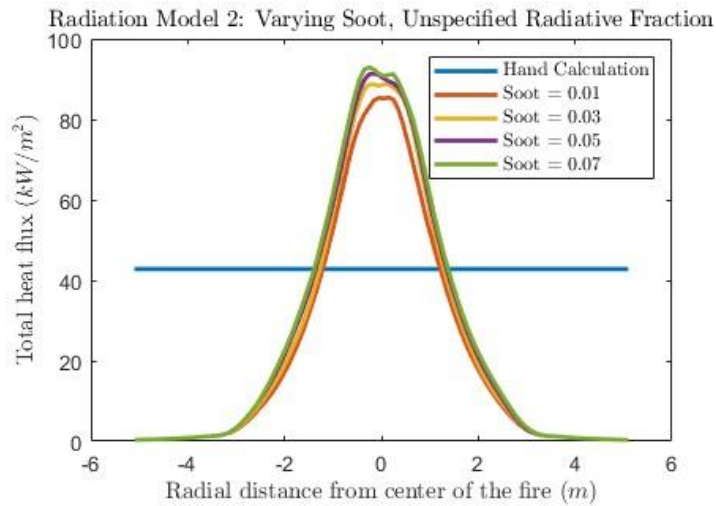


Figure 3-3. Total heat flux at pool surface versus radial distance from center of the fire. Varying soot yield and no radiative fraction.

Figure 3-4 shows the total heat flux across the burner with radiation model 3. The value of soot yield does not influence the total heat flux output by this model as it ignores the emission and absorption of cold gases in the domain. Since this model only accounts

for the emission inside the flame sheet, as radiative fraction increases, the value of total heat flux increases and approaches the estimated value.

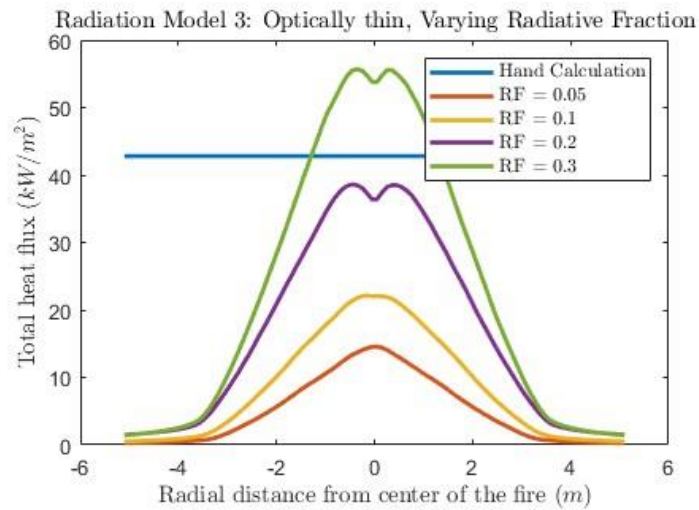


Figure 3-4. Total heat flux at pool surface versus radial distance from center of the fire. Optically thin model.

The result of radiation model 3 test shows that optically thin model approaches the desired total heat flux and hence can be used. However, the absorption and emission of thermal radiation by hot and cold smoke are important effects that need to be considered in the final hangar configuration. Therefore, radiation model 1 with a radiative fraction value of 0.05 and no soot yield is the most appropriate option to model thermal radiation. Table 3-1 summarizes the final inputs applicable to all uncontained spill fire scenarios.

Table 3-1. Uncontained Fire Final FDS Inputs

Heat of combustion, H_c (kJ/kg)	42800
MLRPUA, $\dot{m}''$ (kg/s/m ²)	0.01
Radiative fraction (χ_r)	0.05
Soot yield	0.0
CO yield	0.01
Spread rate (m/s)	0.06
Surface temperature, T_s (°C)	220

3.3 Length-scale Analysis

3.3.1 Scenario 1: 0.06 m³ spill

A length-scale analysis was performed to study the grid sensitivity of the 0.06 m³ uncontained spill fire. The setup in the previous section was repeated with additional grid sizes, ranging from 0.05 m to 0.5 m. An additional computational domain of size 48 m x 48 m x 15 m with uniform 0.1 m grid, or $dx = 0.1$ m (X3 Domain) in the legend of all plots, was also assessed to study the effect of air entrainment on fire development. The hand calculation for heat release rate is based on the following equation:

$$\dot{Q} = \frac{\dot{m}''}{H_c} \quad , \quad (\text{Eq. 3.5})$$

and the hand calculation of flame height is estimated from Heskestad correlation as follows:

$$\frac{L_f}{D} = 3.7(\dot{Q}^*)^{\frac{2}{5}} - 1.02 ; \dot{Q}^* = \frac{\dot{Q}}{\rho_{\infty} c_p T_{\infty} \sqrt{g} D^{\frac{5}{2}}} \quad (\text{Eq. 3.6})$$

where ρ_∞ , c_p , and T_∞ are the ambient density, specific heat, and temperature. $\dot{Q}^*$ is a quantity that relates the fire's heat release rate with the diameter of its base [8]. Figure 3-5 shows fire development in terms of heat release rate and flame height over time. The results in all grid cases approach the estimated heat release rate and flame height, and continue to grow since it was still in transient phase. Devices are placed across the burner surface to measure the total heat flux, resulting in Figure 3-6. The estimation of total heat flux was discussed in the previous section. The result confirms that the smaller the grid, the more accurate the measured total heat flux. The gas velocity and temperature along the centerline of the fire is also measured as a function of the elevation, z , as shown in Figure 3-7. Little to no difference is observed between the gas velocity and temperature along the centerline of the fire of the 0.1 m grid case and 0.01 m (X3 Domain) case, confirming the fact that there is no significant entrainment effect if a computational domain increases. The smaller computational domain is valid and should be used to reduce costs.

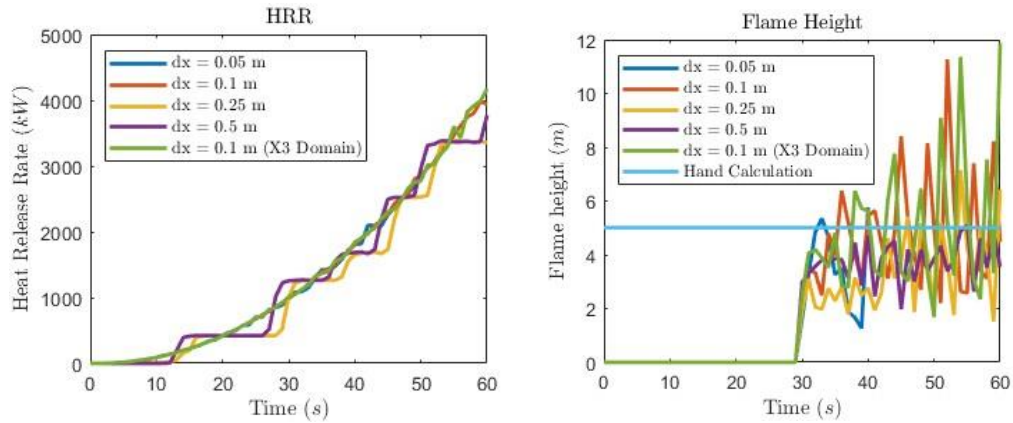


Figure 3-5. Heat Release Rate and Flame Height of 0.06 m³ JP-8 spill as a function of time.

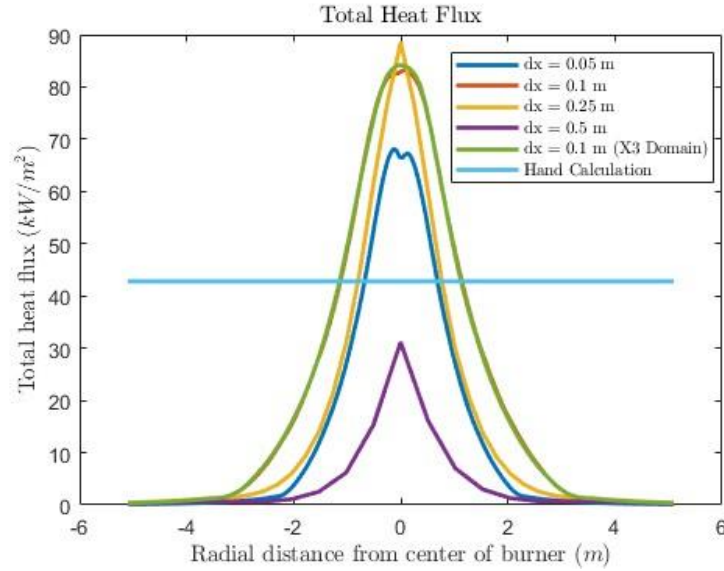


Figure 3-6. 0.06 m³ spill: Total heat flux across burner with various grid size.

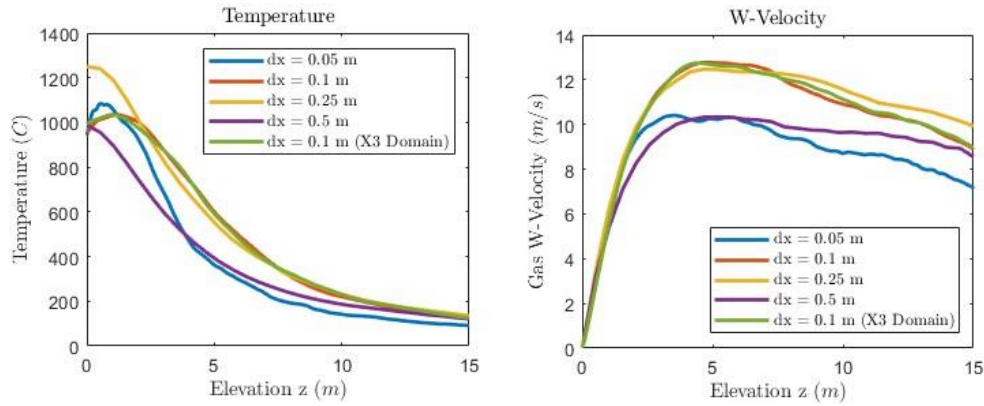


Figure 3-7. 0.06 m³ spill: Temperature and Gas velocity measured along centerline of the fire.

Table 3-2 summarizes the computational time for each fire simulation. Due to computational cost, the simulation time of 0.05 m grid case ends at 40.8 seconds. However, from Figure 3-3, if allowed to run the full 60 seconds, the fire development in this case matches that in other grid size cases. The difference in computational time between 0.05 m grid and 0.1 m grid suggests that the latter should be used in the final

hangar simulation. However, the grid size will be adjusted based on the length-scale analysis of the floor nozzles.

Table 3-2. 0.06 m³ Fire Computing Time

Cell size (m)	T_END	Time (h)
0.05	40.8	3456
0.1	60	277
0.1 (X3 Domain)	60	1158
0.25	60	6.8
0.50	60	3.3

3.3.2 Scenario 2: 0.6 m³ spill

A similar length-scale analysis was conducted to study the grid dependency of the 0.6 m³ uncontained spill fire. The analysis was orchestrated in a computational domain of size 34 m x 34 m x 15 m with a uniform grid size ranging from 0.05 m to 0.5 m. A larger domain of size 78 m x 78 m x 15 m with a uniform 0.1 m grid, or dx = 0.1 m (X3 Domain) as labeled in the legends of all plots, was also utilized to study the effect of air entrainment on the fire development. Both domains were constructed of open boundaries and a concrete floor. The 0.6 m³ JP-8 fuel spill fire was placed in the center of the domains and was represented by a 16.8 m diameter circular burner with prescribed surface temperature of 220°C and MLPUA of 0.01 kg/s/m². Similar to

previous fire scenario, the fire was lit at the center of the burner and spread outward at a rate of 0.06 m/s.

Figure 3-8 shows the heat release rate and flame height development of the fire over the simulation time. Figure 3-9 plots the total heat flux versus the radial distance from the center of the burner. The temperature and gas velocity along the centerline of the burner are shown in Figure 3-10. All plots show consistent results with results previously observed with 0.06 m³ spill case. The heat release rate converges between different grid sizes, and the flame height in all cases approaches the estimated flame height value. As the grid size gets smaller, the measured total heat flux across the burner reaches the estimated total heat flux value. Finally, there is little to no temperature and gas velocity difference between the two computational domains, confirming the previous observation on size of a computational domain versus the effect of air entrainment on the development of a fire.

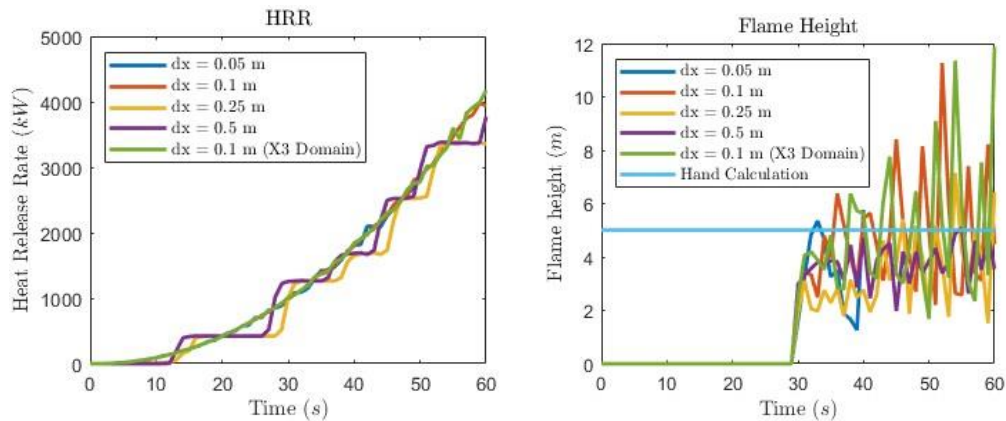


Figure 3-8. Heat Release Rate and Flame Height of 0.6 m³ JP-8 spill as a function of time.

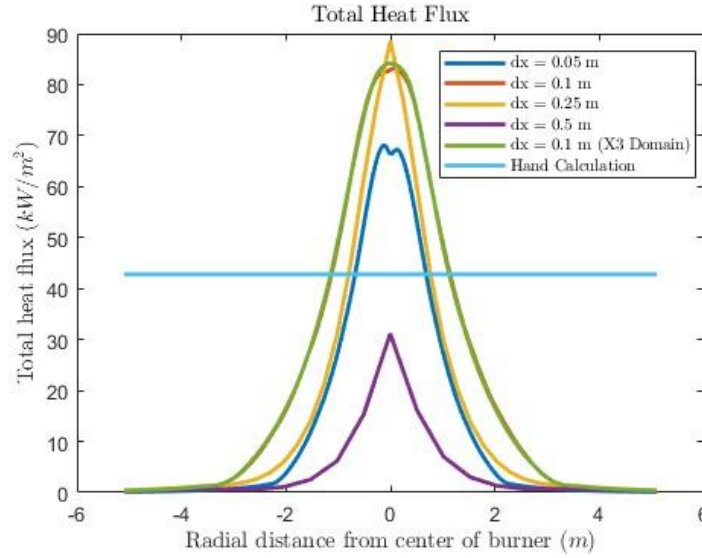


Figure 3-9. 0.6 m³: Total heat flux across burner with various grid size.

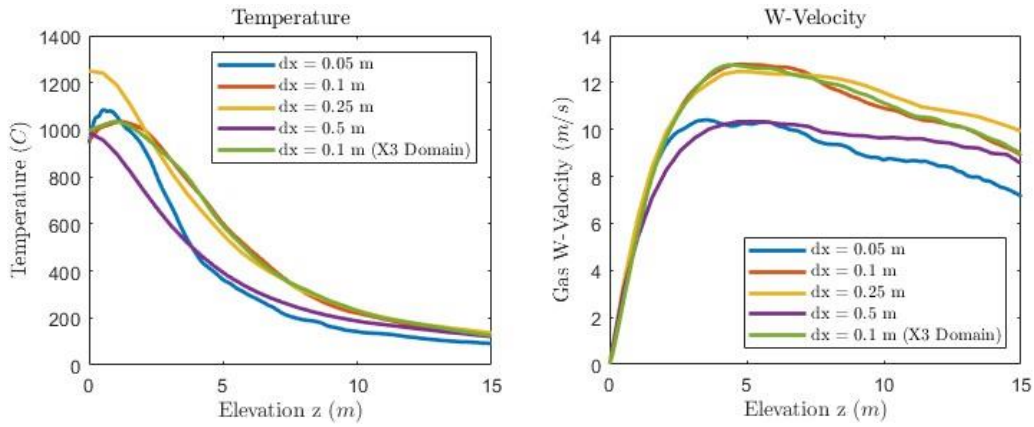


Figure 3-10. 0.6 m³: Temperature and Gas velocity measured along centerline of the fire.

Table 3-3 summarizes the computational time for each fire simulation. The simulation time of 0.05 m grid case ends at 49.2 seconds due to computational time limit. The gap between simulation times again suggests that 0.1 m grid should be used to lessen the computational cost; however, the final grid size must accommodate the result of grid dependency tests for nozzles.

Table 3-3. 0.6 m³ Fire Computing Time

Cell size (m)	T_END	Time (h)
0.05	49.2	10368
0.1	60	605
0.1 (X3 Domain)	60	2501.5
0.25	60	2.3
0.50	60	0.17

Chapter 4 Nozzle Model

There are two ways to set up a multi-orifice nozzle in FDS: by prescribing a single nozzle with a complex pattern or by placing multiple nozzles with different orientation vectors at the same location. This section provides information on how particles are introduced and resolved in FDS as well as validation tests for two nozzles of interest: the Viking Grate Nozzle, a sprinkler nozzle, and the VID Fire-kill Model F102, a low-pressure water mist nozzle.

4.1 Description of FDS Nozzle and Lagrangian Particle Model

FDS uses nozzles which have pre-defined input parameters such as the k-factor, operating pressure, initial velocity, and spray angle to introduce water droplets into the computational domain. Multi-orifice nozzles can be modeled by specifying a single nozzle with a complex spray pattern or by placing multiple nozzles at a single point with varying orientations based on orifice direction. While the values of k-factor and operating pressure are provided in the manufacturer's product data sheet, the values of initial velocity and spray angle are obtained from either available experimental data or numerical estimation. Spray angle is a parameter that FDS uses to specify two angles that outline a conical spray pattern through which droplets are injected. These droplets are also introduced from a prescribed radial distance r_0 , or OFF_SET value, from a nozzle to prevent numerical instabilities resulted from having a large amount of water droplets within one grid cell.

Liquid droplets in FDS that are too small to resolve on the numerical grid are tracked as Lagrangian particles. A liquid droplet in FDS is defined by specifying the name of the evaporated gas species. In this study, water vapor characteristics such as density and specific heat are built into the FDS library. A single simulated droplet in FDS is used to represent a large number of droplets produced by a nozzle in reality to reduce computational cost. The value of PARTICLES_PER_SECOND, 500 by default, restricts the number of droplets that one simulated droplet represents. FDS uses the Rosin-Rammler lognormal distribution as the default size distribution of droplets, as described equation 4.1:

$$F_v(D) = \begin{cases} 1/\sqrt{2\pi} \int_0^D \frac{1}{\sigma D'} \exp\left(-\frac{[\ln(D'/D_{v,0.5})]^2}{2\sigma^2}\right) dD' & (D \leq D_{v,0.5}) \\ 1 - \exp(-0.693(D/D_{v,0.5})^\gamma) & (D > D_{v,0.5}) \end{cases} \quad (\text{Eq. 4.1})$$

where $D_{v,0.5}$ is volumetric median diameter and γ and σ (both empirically determined) are used to control the width of distribution [6]. The acceleration and position of the particle are determined from equations 4.2 and 4.3:

$$\frac{du_p}{dt} = g - \frac{1}{2} \frac{\rho C_d A_{p,c}}{m_p} (u_p - u) |u_p - u|, \quad (\text{Eq. 4.2})$$

$$\frac{dx_p}{dt} = u_p, \quad (\text{Eq. 4.3})$$

where u is the gas velocity, ρ is the gas density, u_p is the velocity of the bulk particle within a grid cell and $A_{p,c}$ is the cross-sectional area of the bulk particle [6]. The drag coefficient, C_d , is a function of the local Reynolds number based on particle diameter as follows:

$$C_d = \begin{cases} 24/Re_D & Re_D < 1 \\ 24(0.85 + 0.15Re_D^{0.687})/Re_D & 1 < Re_D < 1000. \\ 0.44 & 1000 < Re_D \end{cases} \quad (\text{Eq. 4.4})$$

A drag reduction model is applied in cells where the local droplet value fraction exceeds 1×10^{-5} to account for the aerodynamic interactions between particles. The reduced drag coefficient is determined from the equation:

$$C_d = \frac{C_{d,0}F}{F_0}, \quad (\text{Eq. 4.5})$$

where $C_{d,0}$ is the single particle drag coefficient and F/F_0 is the hydrodynamic force ratio of the trailing particle to an isolated particle [12]. Additional information on the hydrodynamic force ratio can be found in the FDS Technical Guide [12].

4.2 Viking Grate Nozzle – Sprinkler Model

The Viking Grate Nozzle Model GN200 is a multi-orifice floor-level foam nozzle currently used in the protection of aircraft hangar at U.S. Navy facilities. A schematic of these systems is provided in Figure 1-1. For the purpose of this study, this nozzle is considered a multi-orifice sprinkler nozzle and is modeled by placing multiple nozzles at a single point with varying orientation based on orifice direction. There are three variations (90°, 180°, and 360°) of this nozzle due to the requirements on location and spacing of nozzle in the UFC. Each variation has a different number of orifices and different k-factors. The values of k-factor, pressure, and number of orifices are taken from Viking's product data sheet and summarized in Table 4-1 [13, 14]. Due to the chosen method of modeling this nozzle, the k-factor prescribed in FDS is equal to the k-factor from the manufacturer data sheet divided by the respective number of orifices.

Table 4-1. Viking Grate Nozzle: Manufacturer's K-Factor and Number of Orifices

Nozzle Variation	K-Factor (L/min/bar ^{1/2})	Number of Orifices
90°	100	11
180°	173	19
360°	337	36

4.2.1 Single Micronozzle Spray Characteristics Calibration

Due to its original use as a foam nozzle, there is no previous experimental data on droplet characterization of Viking Grate Nozzle. A series of tests is conducted to calibrate the spray of this nozzle following a bucket test data provided by Viking.

A standard bucket test was conducted by Viking to determine the distribution of water of a 180° nozzle along a pathway that is perpendicular to the trench as shown in Figure 4-1. The test tabulated the amount of gallons per minute per square feet of water distributed in 1-foot increments from the trench. This bucket data in gpm/ft² was later converted to kg/s/m² to be comparable with FDS simulation results. The



Figure 4-1. Viking Bucket Test Setup

water collection was done with 1 ft x 1 ft (0.3 m x 0.3 m) buckets that are in accordance with UL and FM standards of testing water density from sprinklers. The 180° nozzle

was raised 1 ft (0.3 m) above the floor to match the height of the collection buckets [15].

The validation model in FDS is setup similar to the Viking Bucket Test described above to calibrate unknown values such as initial velocity, droplet diameter, offset value, and spray angle. Assuming that the data collected in the buckets comes primarily from the middle stream and that there is no contribution of water from other neighboring streams, the validation model is conducted with a single nozzle representing this stream. Due to limited data, it is also assumed that the calibrated input values are equivalent through all three variations of the Viking Grate Nozzle.

4.2.1.1 First Initial Velocity and Droplet Diameter Calibration

A computational domain of 10 m x 2 m x 1 m with uniform 0.1 m grid was used to perform the first initial velocity and droplet diameter calibration. A single nozzle was placed at 0.3 m elevation, 1 m from XMIN, and orientated in the positive x-direction. The value of humidity was set at 100% to prevent any evaporation of droplets. For this test, the value of OFFSET, SPRAY_ANGLE, SPRAY_PATTERN_BETA, and SPRAY_PATTERN_MU was fixed at 0.1 m; 0, 20; 500; and 0, respectively. These values would be calibrated in later tests.

The value of droplet diameter is calculated to be 0.56 mm using the following equations:

$$\frac{D_{v,0.5}}{d} = 1.53 (We)^{-\frac{1}{3}}, \quad (\text{Eq. 4.6})$$

$$We = \frac{\rho_p u_p^2 d}{\sigma}, \quad (\text{Eq. 4.7})$$

where d is the orifice diameter of the nozzle, We is the orifice Webber number or the ratio of inertial forces to surface tension forces, ρ_p is the density of water, u_p is the discharge velocity, and σ is the liquid surface tension. However, droplets in sprinkler sprays have a diameter at approximately 1 mm. Thus, larger values (1 mm, 1.5 mm, 2 mm) of droplet diameter are also tested to examine the effect of droplet diameter to the water distribution of a nozzle.

The value of particle velocity is approximated in three different ways. The first way follows Sheppard correlation results in a particle velocity of 10 m/s [16]:

$$V_0 \approx 0.6 \sqrt{\frac{P}{\rho}} = 10 \text{ m/s} \quad (\text{Eq. 4.8})$$

The second way flows Bernoulli which approximate the maximum initial velocity from the nozzle, resulting in a value of 23.7 m/s:

$$V_0 = \sqrt{\frac{2\Delta P}{\rho}} = 23.7 \text{ m/s} \quad (\text{Eq. 4.9})$$

The third and last approximation follow conservation of flow through each orifice:

$$Q_{total} = 19 * q_{micronozzle} \quad (\text{Eq. 4.10})$$

$$V_0 = \frac{q_{micronozzle}}{\rho \frac{\pi}{4} d^2} = 23.9 \text{ m/s} \quad (\text{Eq. 4.11})$$

Since the third approximation is similar to Bernoulli, only results from Sheppard and Bernoulli were used in further tests. The result of the first calibration, as shown in Figure 4-2, requires additional calibration on initial velocity value. It is observed that as the particle velocity increases, the shape of distribution becomes wider. As the droplet diameter increases, the peak value of distribution increases.

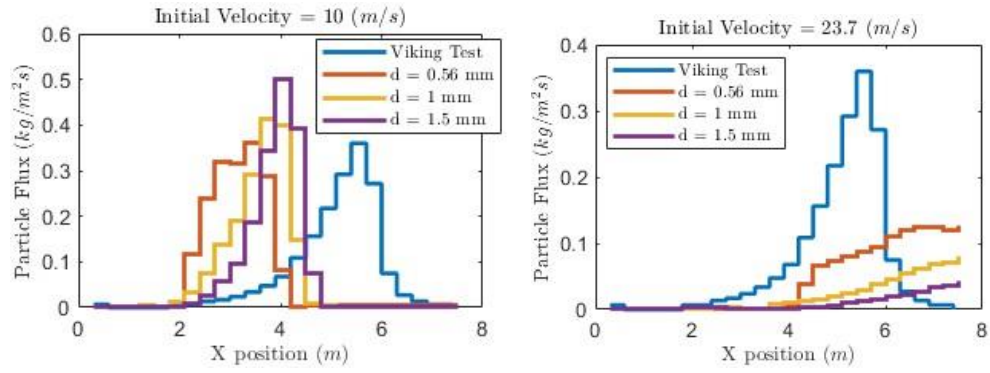


Figure 4-2. Sheppard (Left) and Bernoulli (Right) Calibration

An additional initial velocity value of 12 m/s was evaluated. The result in Figure 4-3 shows that an initial velocity of 12 m/s and a droplet velocity of 2 mm matches Viking bucket test data best.

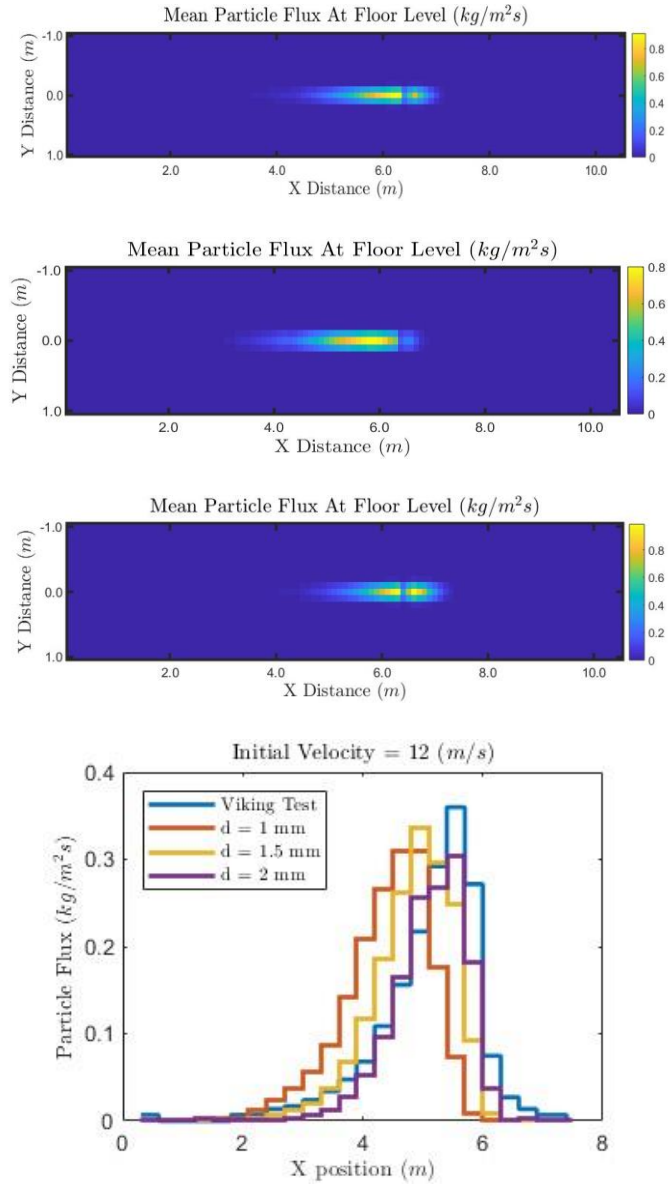


Figure 4-3. $V_0 = 12$ m/s calibration. Top to bottom: 1 mm, 1.5 mm, and 2 mm

4.2.1.2 Length Scale Analysis

A length scale analysis is conducted to study the grid dependency of water distribution following the initial droplet diameter and initial velocity calibration. The previous computational domain and nozzle location setup were used with updated droplet diameter of 2 mm and initial velocity of 12 m/s. Table 4-2 shows the computational time for each nozzle simulation. The computational time increases as grid size gets smaller. The computational time of 0.0125 m grid is about 63 times the computational time of 0.025 m grid.

Table 4-2. Viking Grate Nozzle Computing Time

Cell size (m)	Time (h)
0.0125	1972
0.025	31
0.05	1.5
0.1	0.25

The result in Figure 4-4 shows a good convergence in terms of peak value and about 1 m of uncertainty for the range of water distribution between 0.05 m, 0.025 m, and 0.0125 m grid size. The 0.025 m grid is used to reduce computational cost in further testing.

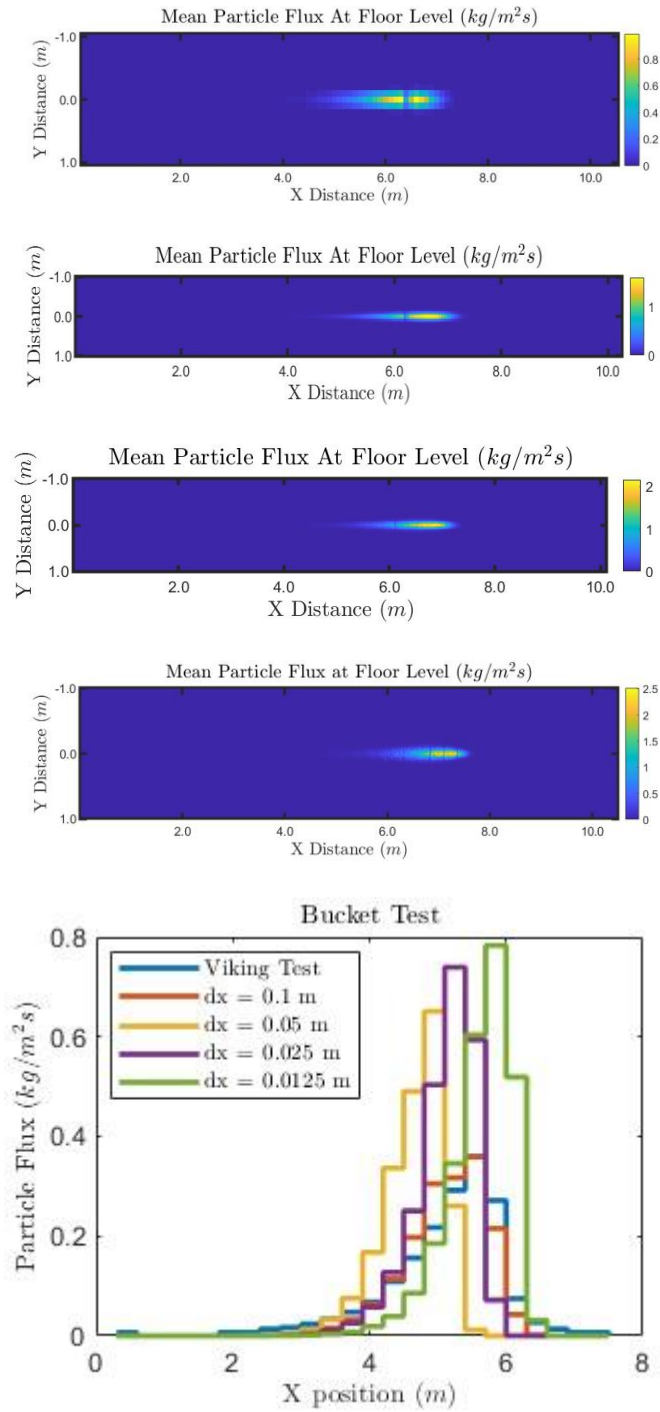


Figure 4-4. Viking Grate Nozzle: Grid Analysis. Top to bottom: 0.01 m grid, 0.05 m grid, 0.025 m grid, and 0.0125 m grid

4.2.1.3 Second Initial Velocity and Droplet Diameter Calibration

The first droplet diameter and initial velocity was repeated with a 0.025 m grid. The result shown in Figure 4-5 shows that an initial velocity value of 12 m/s is the best match for the range of distribution. However, due to the use of finer grid size, there is minor difference observed in the shape as well as peak value of distribution among different droplet diameter plots. A droplet diameter of 1.5 mm was chosen to run further tests on other parameters.

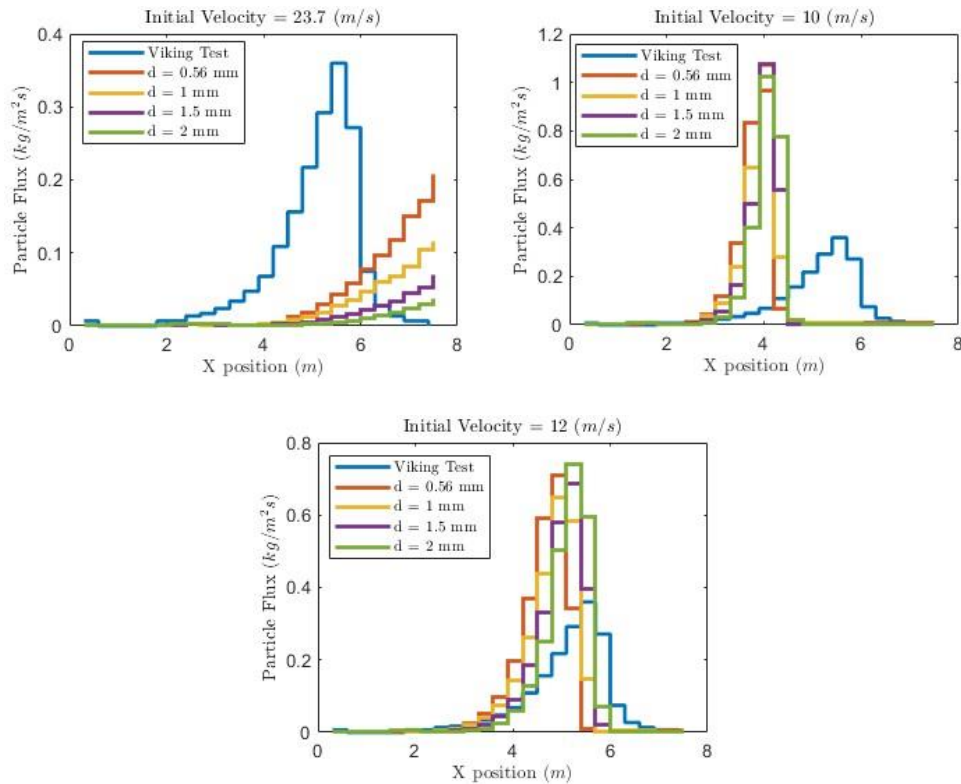


Figure 4-5. Second Droplet Diameter and Initial Velocity Calibration

4.2.1.4 OFFSET and SPRAY_PATTERN_BETA

Additional tests were done to justify the value of other spray parameters such as OFFSET and SPRAY_PATTERN_BETA. The control parameters for offset value tests are summarized in Table 4-3. Three offset values (0.05 m, 0.10 m, and 0.15 m) were examined. The result in Figure 4-6 shows little to no change to bucket test value between different offset values.

Table 4-3. Control parameters for offset value test

Droplet Diameter (mm)	Spray Angle (°)	SPRAY_PATTERN_BETA	INITIAL_VELOCITY (m/s)
1.5	0,20	500	12

The value of SPRAY_PATTERN_BETA which controls the width of distribution of droplet was also examined. The range of SPRAY_PATTERN_BETA is 0 to 1000 with 0 being the widest distribution. The

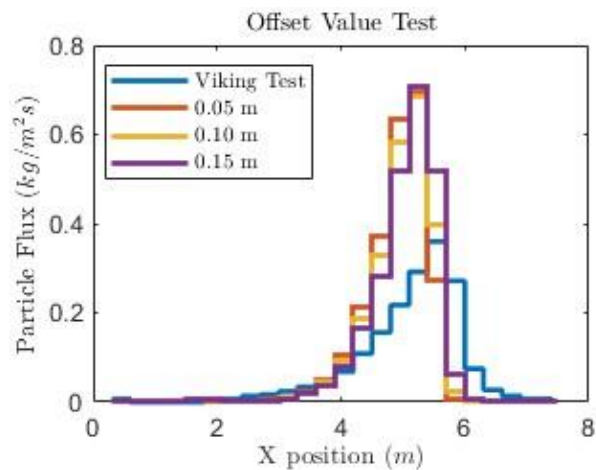


Figure 4-6. Viking Offset Value Test

control parameters for this test are summarized in Table 4-4. Figure 4-7 shows the bucket test data between various SPRAY_PATTERN_BETA values. The higher the

value of SPRAY_PATTERN_BETA, the finer the spray. Compared to actual Viking Test data, a SPRAY_PATTERN_BETA value of 100 is the best match.

Table 4-4. Control parameters for SPRAY_PATTERN_BETA test

Droplet Diameter (mm)	Spray Angle (°)	Offset (m)	INITIAL_VELOCITY (m/s)
1.5	0,20	0.1	12

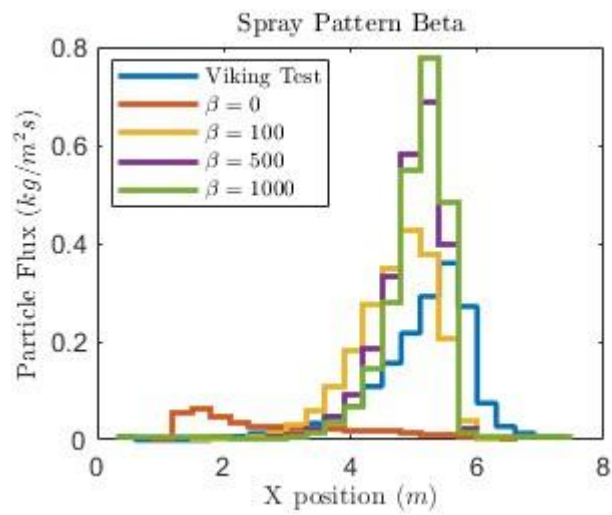


Figure 4-7. Viking SPRAY_PATTERN_BETA Value Test

4.2.1.5 Final Initial Velocity and SPRAY_PATTERN_BETA Calibration

From the results of previous calibration, one can observe that the bucket test value is more sensitive to the change in initial velocity and SPRAY_PATTERN_BETA than the change in offset or droplet diameter. Additional calibration on initial velocity and SPRAY_PATTERN_BETA is performed. The control parameters for these tests are summarized in Table 4-5. Figure 4-8 shows the final bucket data calibration. An initial velocity of 12.5 m/s and SPRAY_PATTERN_BETA of 85 results in the best match to Viking Test data.

Table 4-5. Control parameters for final calibration

Droplet Diameter (mm)	Spray Angle (°)	Offset (m)	INITIAL_VELOCITY (m/s)
1.5	0,20	0.1	12.5

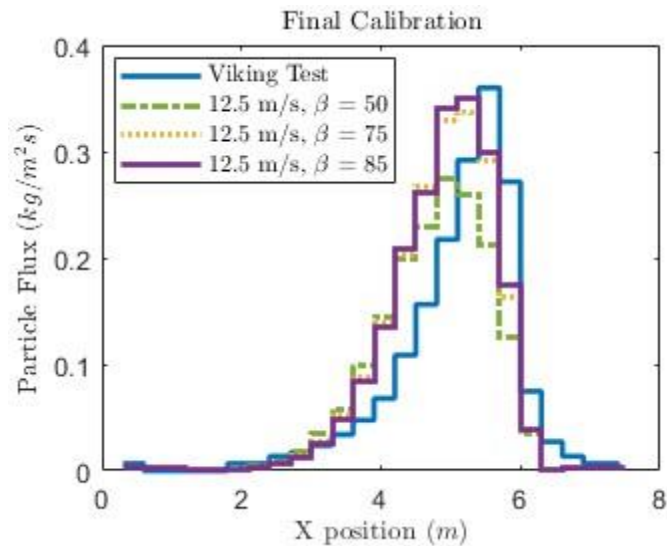


Figure 4-8. Viking Bucket Test Final Calibration

The final FDS inputs for Viking Grate Nozzle are summarized in Table 4-6, and Figure 4-9 displays a full 180° Viking Grate Nozzle in FDS created with the final inputs. Figure 4-10, produced by Viking tests, shows the pattern of Viking Grate Nozzle 180°. The pattern delivered by the nozzle as shown in Figure 4-10 is consistent with the pattern illustrated in Figure 4-9.

Table 4-6. Viking Grate Nozzle 180 ° Final FDS Inputs

Pressure (bar)	2.8
k-factor (L/min/bar ^{1/2})	9
Droplet Diameter (mm)	1.5
Spray Angle (°)	0,20
Offset, r ₀ (m)	0.1
INITIAL_VELOCITY, V ₀ (m/s)	12.5
SPRAY_PATTERN_BETA	85
SPRAY_PATTERN_MU	0

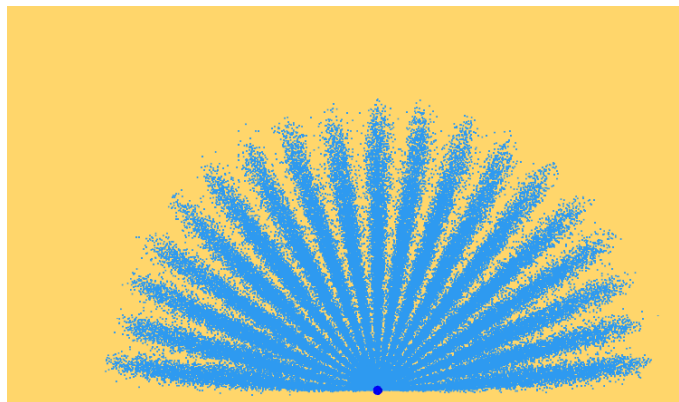


Figure 4-9. Plan view of simulated Viking Grate Nozzle 180°

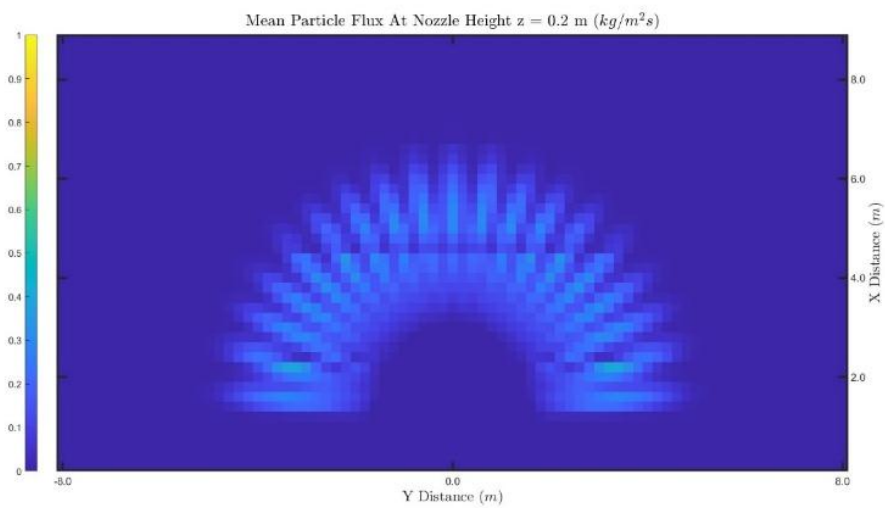
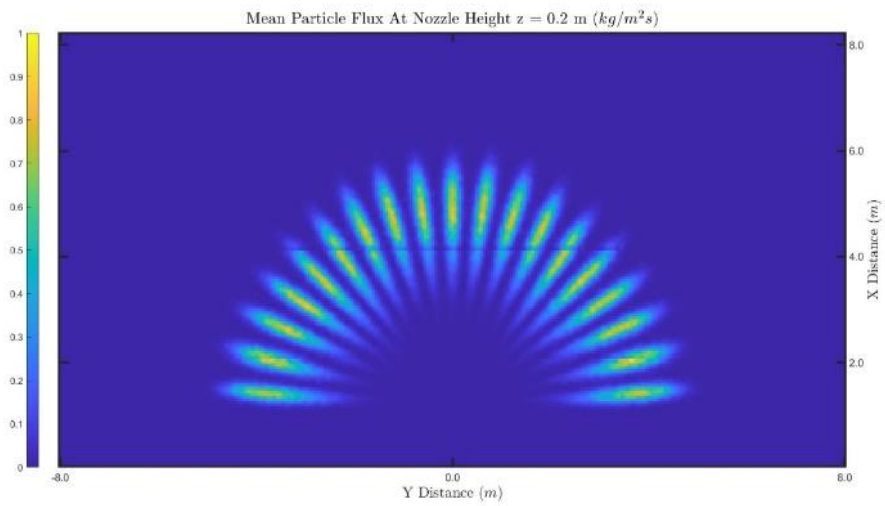
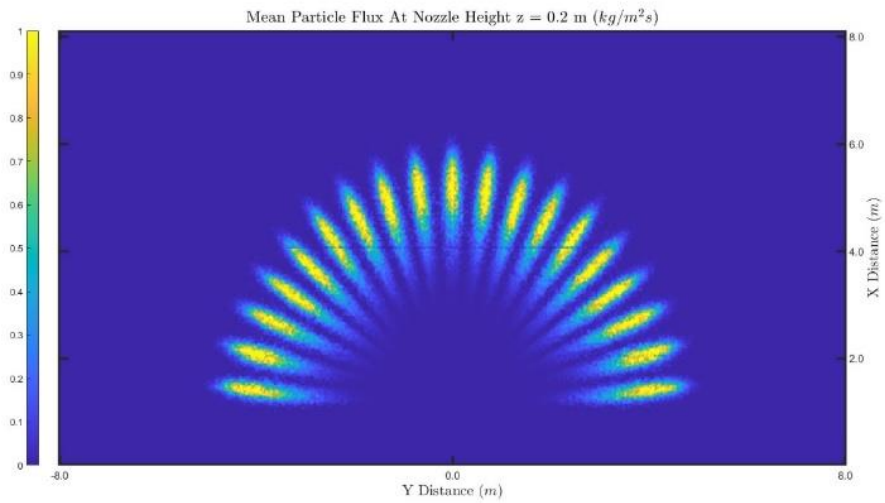


Figure 4-10. Viking Grate Nozzle 180° in reality

4.2.2 Full Nozzle Length Scale Analysis

Additional tests are performed in a computational domain of size 8 m by 16 m by 1 m to determine the length scale of a 180° Viking Grate Nozzle. The nozzle is placed 1 m from the horizon of the computational domain and at 0.2 m height. Figure 4-11 shows the mean particle flux measured at 0.2 m with uniform 0.025 m, 0.05 m, 0.1 m, and 0.2 m grid. As the grid size increases, the spray pattern becomes less well-resolved, confirming the fact that a smaller grid size is necessary for the performance of the spray. However, as shown in Table 4-7, using a uniform 0.025 m grid size or an even smaller grid is not cost-wise feasible in the final hangar simulations. The use of

hybrid meshes is essential to optimize both the spray performance and computational time.



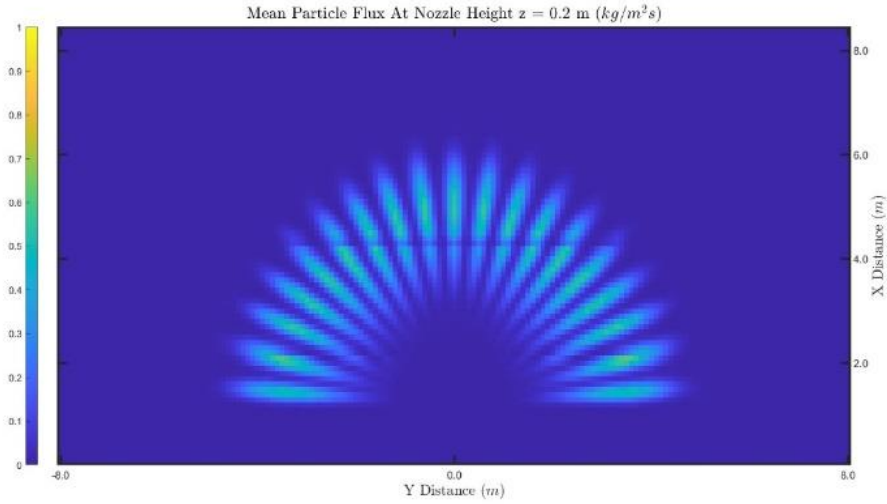


Figure 4-11. Mean Particle Flux of Viking Grate Nozzle using different grid sizes. From top to bottom: 0.025 m, 0.05 m, 0.1 m, and 0.2 m

The same computational domain is used to compare the water distribution of the three-hybrid mesh design with that of a uniform 0.025 m grid. The first hybrid mesh

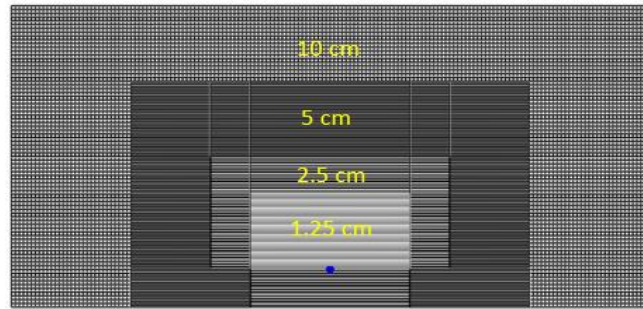


Figure 4-12. Hybrid 1 Setup.

design, Hybrid 1, as shown in Figure 4-12, has a 0.0125 m grid up to 2 m away from the nozzle, 0.025 m grid from 2 m to 3 m away from the nozzle, and 0.05 m grid from 3 m to 6 m away from the nozzle. The second hybrid mesh design, Hybrid 2, has a 0.025 m grid up to 2 m away from the nozzle, 0.05 m grid from 2 to 3 m away from the nozzle, and 0.10 m grid from 3 m to 5 m away from the nozzle. The third and last hybrid mesh design, Hybrid 3, has a 0.025 m grid up to 2 m away from the nozzle, and

0.05 from 2 to 5 m away from the nozzle. Figures 4-13 and 4-14 show the mean particle flux measured along the centerline of the nozzle as well as 1 m away from the nozzle. Table 4-7 includes the computational time of simulations using hybrid mesh designs. From Figures 4-5 and 4-6 as well as Table 4-3, Hybrid 3 shows convergence in terms of water distribution with uniform 0.025 m grid and Hybrid 1 while Hybrid 3 costs about 5 and 17 times less respectively in computational time to run. As a result, Hybrid 3 is chosen to be the final length scale design for a Viking Grate Nozzle in the final hangar simulations.

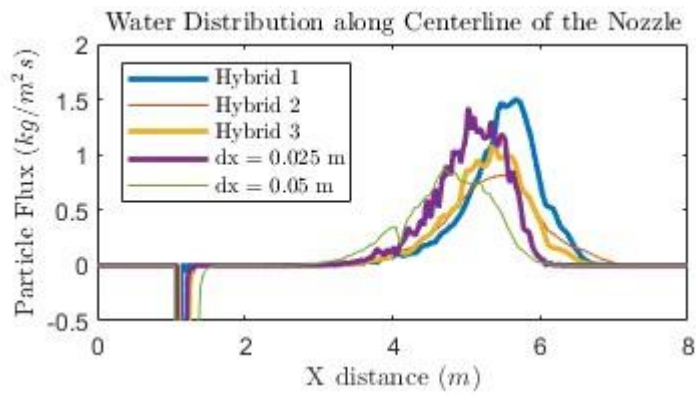


Figure 4-13. Water distribution along the centerline of the nozzle

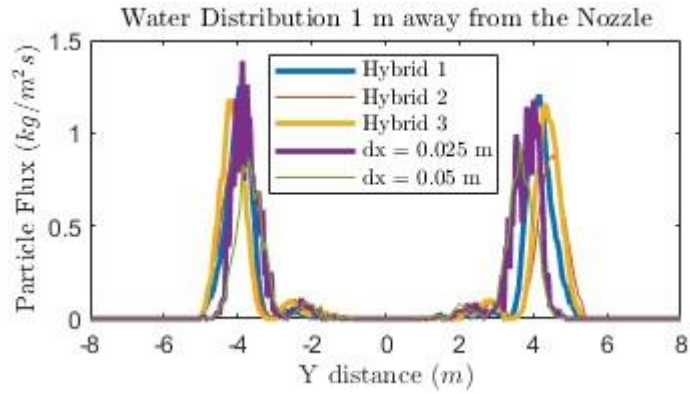


Figure 4-14. Water distribution 1 m away from the nozzle.

Table 4-7. VID Fire-kill Model F-102 Computing Time

Cell size (m)	Time (h)
0.025	288
0.05	18.8
0.1	1.5
0.2	0.2
Hybrid 1	1034
Hybrid 2	74.8
Hybrid 3	61

4.2.3 Droplet Movement Validation

One key difference between sprinkler and water mist systems is the size of the droplet. Water mist droplets are small and more likely to adhere to a surface due to the high surface area to volume ratio. On the other hand, large sprinkler droplets are more prone to spreading due to their greater weight and momentum. When water droplets hit the floor, they are assigned random directions. FDS uses the input parameter `HORIZONTAL_VELOCITY` to control the speed at which droplets move horizontally

after impact. A study by Simmons et al (2004) provides a correlation to estimate the velocity of the droplet based on energy conservation. The speed is estimated to be 0.3 m/s using equation 4.12:

$$v = \left(\frac{2\sigma \cos(\theta)}{\rho d} \right)^{\frac{1}{2}} \quad (\text{Eq. 4.12})$$

where v is the velocity of the droplet, σ is the surface tension coefficient of the fluid, θ is the contact angle, ρ is the density of fluid, and d is the diameter of the droplet [17]. The estimation of speed above is an underestimation as in reality, water droplets may travel faster due to the interaction with the incoming water jet. At one point in time, the water accumulated on the floor will reach a quasi-steady state and form a thin film. The thickness of this film, h , is determined to be 2e-4 m using equation 4.13:

$$(1 - \cos(\theta)) \cdot \sigma = \rho \cdot g \cdot h \quad (\text{Eq. 4.13})$$

from the same study by Simmons et al [17]. As a result, the parameter MINIMUM_FILM_THICKNESS is specified to be 2e-4 m on the MISC line for simulations with Viking Grate Nozzle.

4.3 VID Fire-kill F102 – Water Mist Model

VID Fire-kill Model F102 is a multi-orifice, low-pressure water mist floor pop-up nozzle designed for the protection of aircraft hangar. The nozzle contains four orifices: one centered facing directly horizontal, and three oriented at a 45-degree angle as shown in Figure 4-15. The



Figure 4-15. VID Fire-kill Model F102

modeling of this nozzle in FDS utilizes characteristics previously developed by Steranka (2021) with a single nozzle and a spray pattern table assuming equal flow out of each orifice [4]. Since Steranka's study, the manufacturer has updated information on the k-factor and operating pressure of this nozzle. Therefore, a newly updated k-factor value of 12 L/min/bar^{1/2} and operating pressure value of 10 bar is used [18]. The final FDS input characteristics of this nozzle are summarized in Table 4-8.

Table 4-8. VID Fire-kill Model F102 Nozzle FDS

Inputs		
Pressure (bar)		10
k-factor (L/min/bar ^{1/2})		12
Initial velocity, V0 (m/s)		35, 20
Spray angle, ϕ (°)		60
Number of perimeter micronozzles and orientation (°)		3, 45°
Droplet size distribution	Dv,50 (μm)	200
	γ	2
	σ	0.58
Offset, r0 (m)		0.1

4.3.1 Length Scale Analysis

A computational domain of size 8 m x 4 m x 1.5 m was used to perform a grid dependency test of the nozzle. All boundaries are open except the floor which was set to be concrete. The nozzle was placed at 0.1 m from the left boundary 0.2 m above the floor. Humidity was set at 100 to prevent evaporation of droplets. At various x- and z-locations as well as along the centerline of the nozzle, the mean particle flux of the nozzle and mean gas velocity were recorded and analyzed through FDS slice files. Additionally, the water distribution on the floor along the centerline of the nozzle and the water distribution on the floor x-distance away from the nozzle were plotted to

differentiate the effect of various grid sizes. The length scale analysis utilizes three different grid sizes including 0.1 m, 0.05 m, 0.025 m.

Figures 4-16 to 4-18 show the mean particle flux of the nozzle at various z-location with each row representing 0.1 m, 0.05 m, and 0.025 m grid, respectively. Figure 4-19 shows the gas velocity at floor level. As the grid size gets smaller, the spray of the nozzle is more defined, and more particles are visible on the slice file. On the other hand, the computational time also increases.

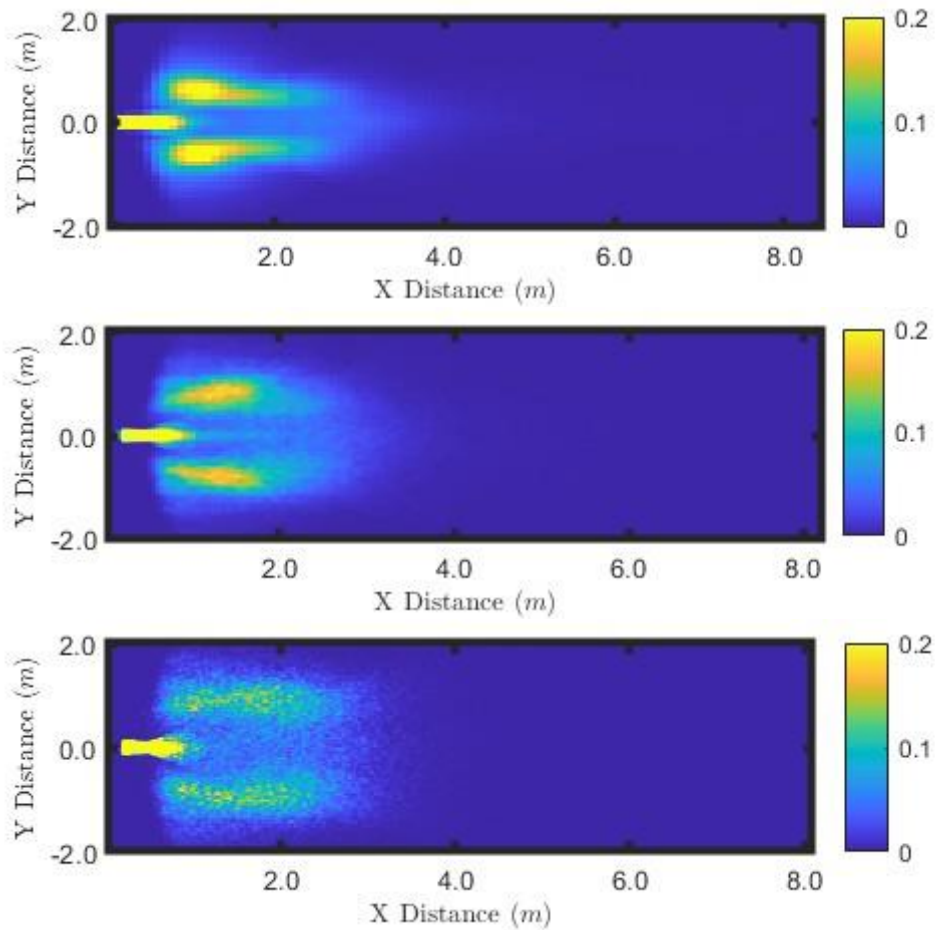


Figure 4-16. Mean particle flux at Floor Level. Top to bottom: 0.1 m, 0.05 m, 0.025 m

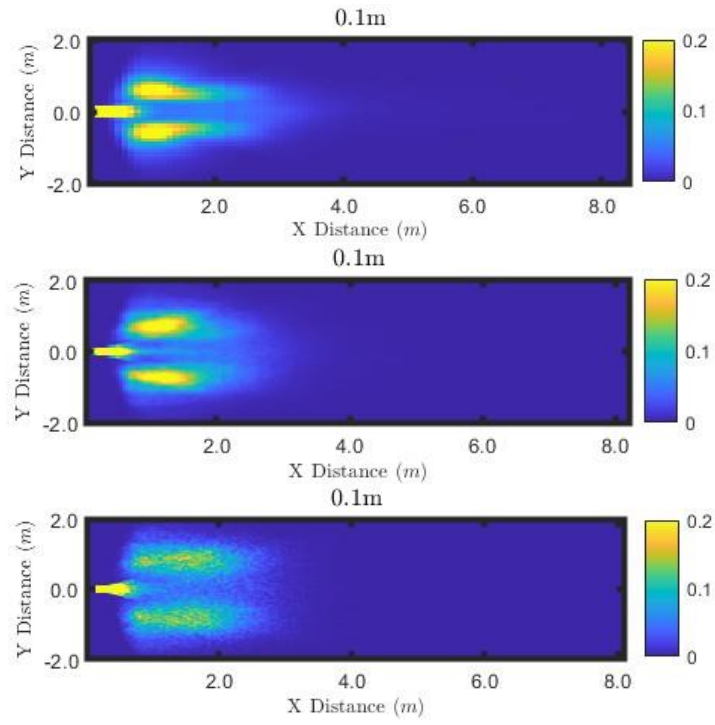


Figure 4-17. Mean particle flux at 0.1 m above the floor. Top to bottom: 0.1 m, 0.5 m, 0.025 m

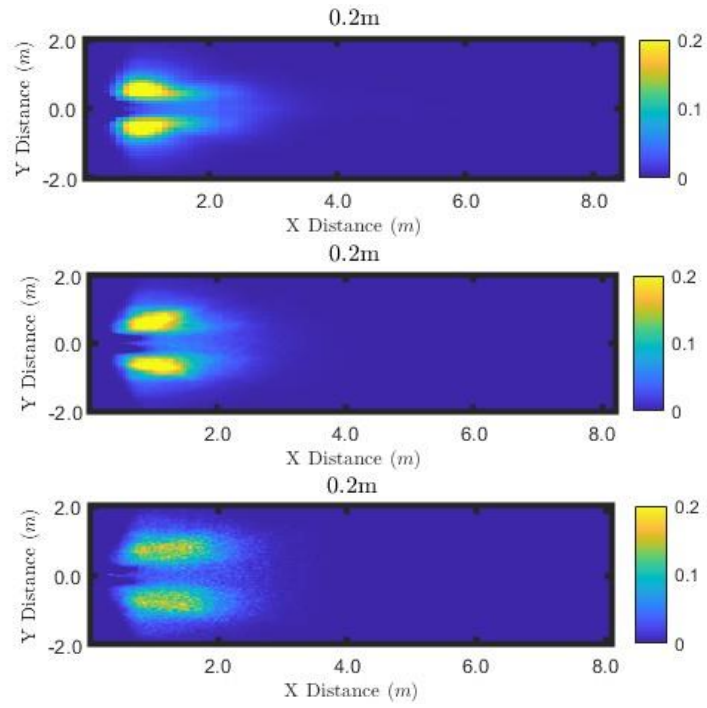


Figure 4-18. Mean particle flux at 0.2 m above the floor. Top to bottom: 0.1 m, 0.5 m, 0.025 m

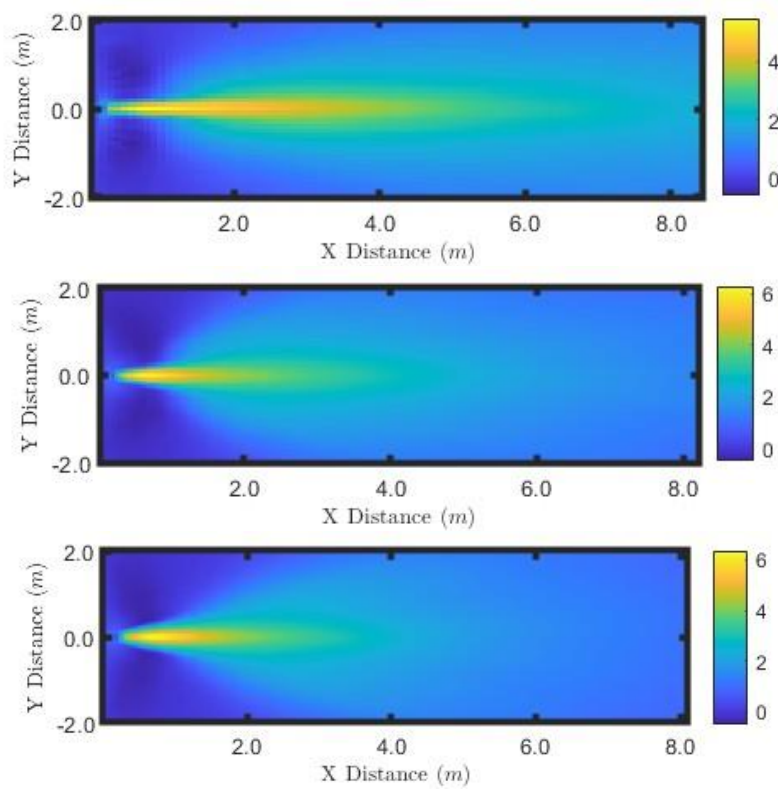


Figure 4-19. Mean gas velocity at floor level above the floor. Top to bottom: 0.1 m, 0.5 m, 0.025 m

Figure 4-20 shows the mean particle flux along the centerline of the nozzle with each row representing 0.1 m, 0.05 m, and 0.025 m grid, respectively. Figure 4-21 shows the mean particle flux, or water distribution, on the floor along the centerline of the nozzle. There is a good agreement between the curves representing 0.05 m and 0.025 m grid. The peak value of mean particle flux of both curves is close to $5 \text{ kg/m}^2\text{s}$, while the peak value of the 0.1 m grid curve is approximately $2.8 \text{ kg/m}^2\text{s}$. This agreement between the two smaller grid sizes supports previous observation on the mean particle flux at various z-locations.

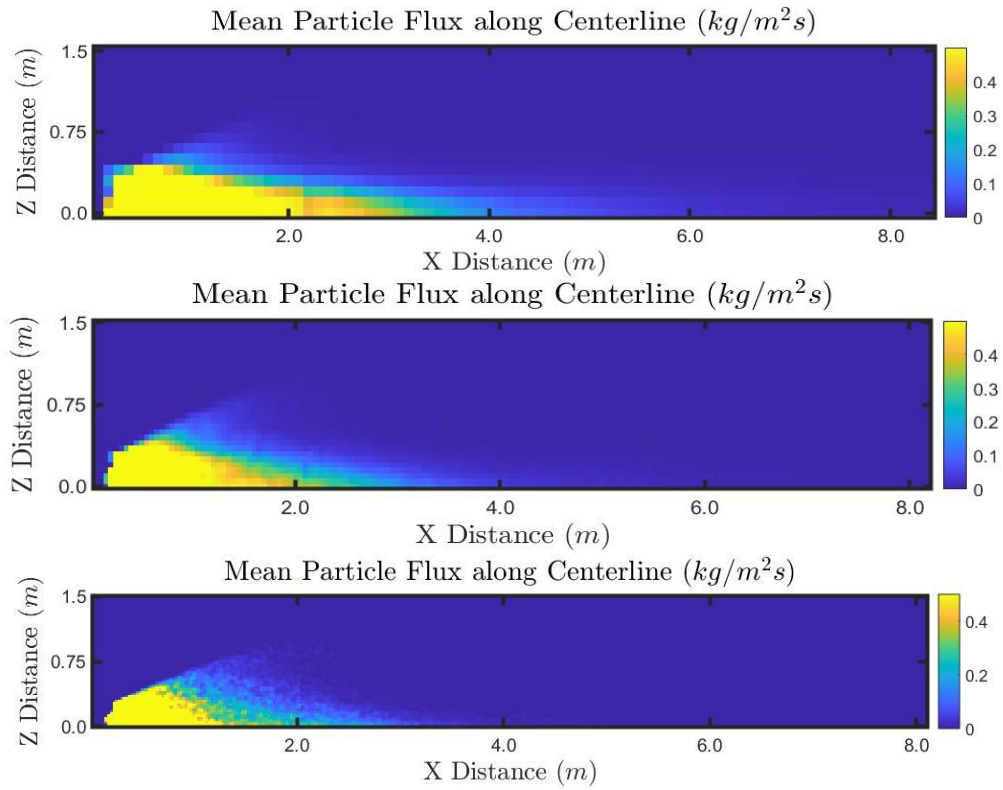


Figure 4-20. Mean particle flux at 0.2 m above the floor. Top to bottom: 0.1 m, 0.5 m, 0.025 m

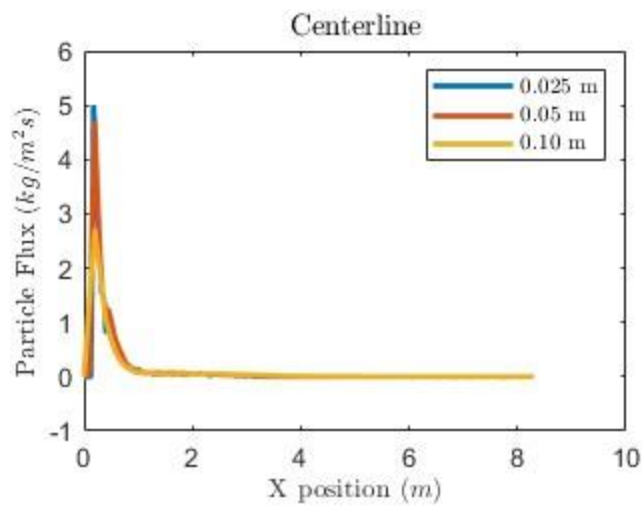


Figure 4-21. Water distribution on the floor along the centerline of the nozzle.

Figure 4-22 shows the mean particle flux at various x-locations with each column representing 0.1 m, 0.05 m, and 0.025 m grid, respectively. Figure 4-23 displays the water distribution on the floor x-distance away from the nozzle. Even though the 0.025 m grid has more variations, there is a good convergence between the 0.05 m and 0.025 m curves. The fluctuations of 0.025 m curve are a result of using a finer grid size and thus increases the ability of FDS to pick up more droplets.

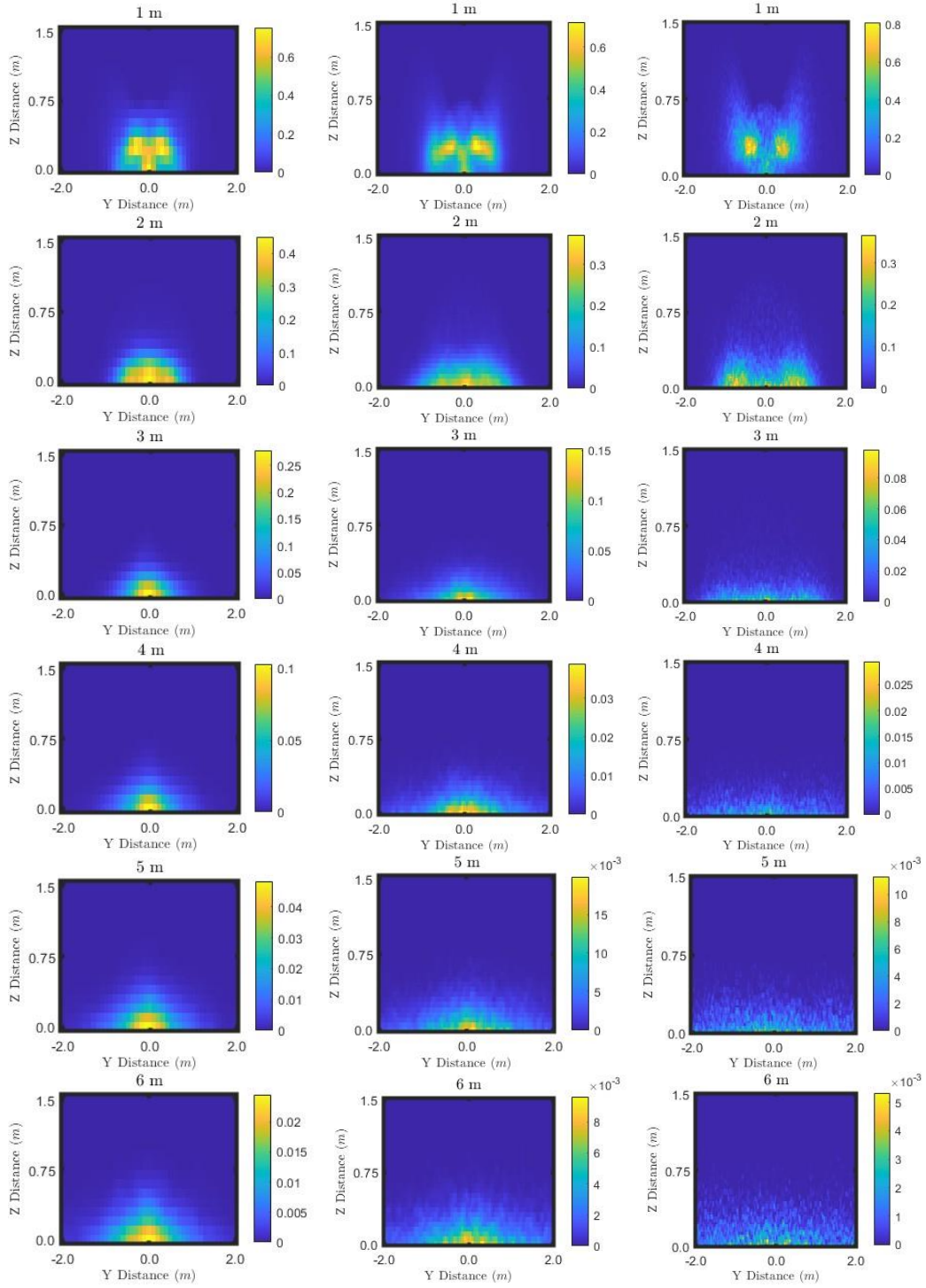


Figure 4-22. Mean particle flux at various x-distance away from the nozzle. Left to Right: 0.1 m grid, 0.05 m grid, and 0.025 m grid.

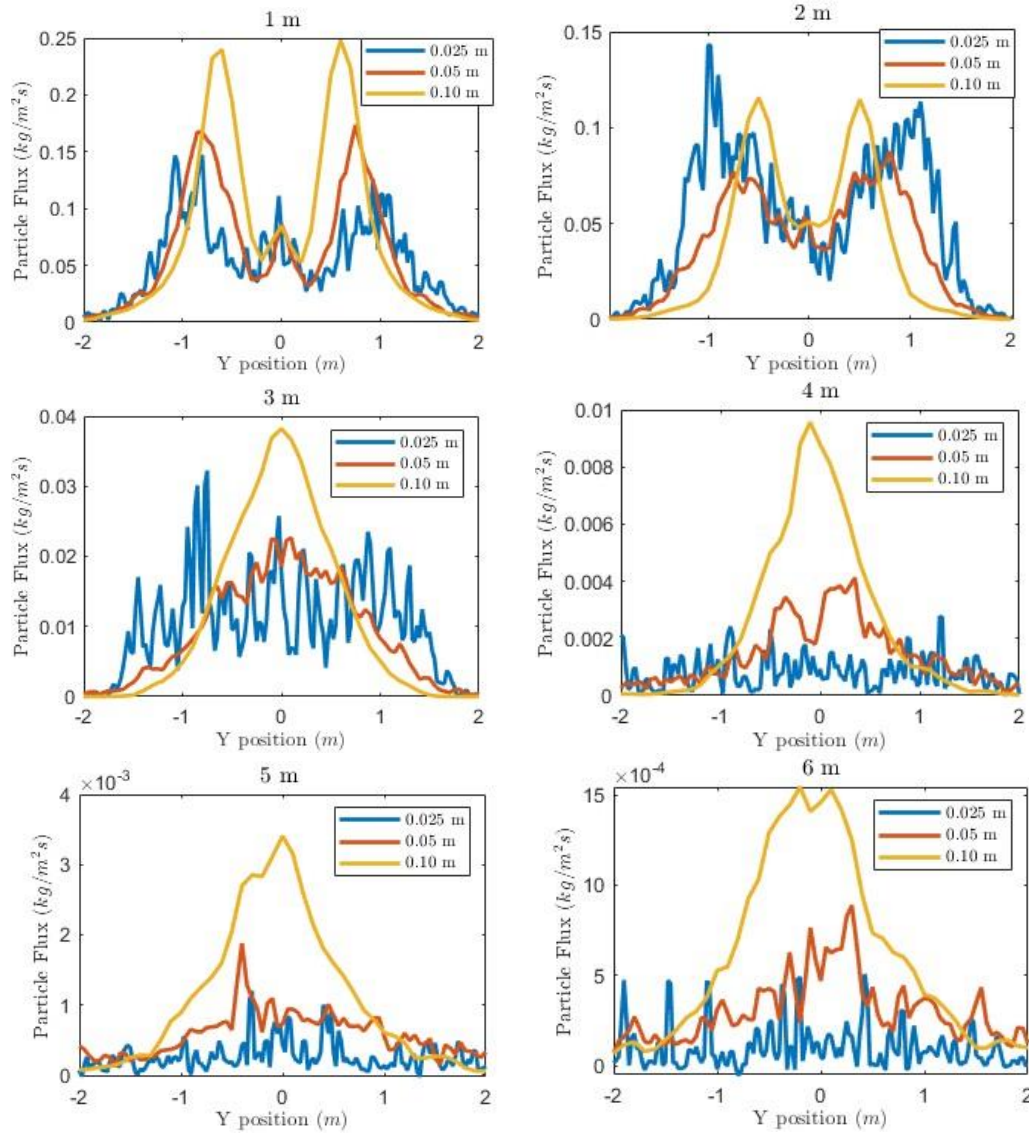


Figure 4-23. Water distribution on the floor x-distance (1 m to 6 m) away from the nozzle.

The computational time for each nozzle simulation is provided in Table 4-9. As the grid size becomes finer, computational time increases. Even though the 0.025 m and 0.5 m grid size show good convergence throughout the analysis, the computational time of 0.025 m grid is approximately ten times the computational time of 0.05 m grid. This

observation indicates that a 0.05 m grid should be used in the final hangar simulations to reduce the computational cost.

Table 4-9. VID Fire-kill Model F-102
Computing Time

Cell size (m)	Time (h)
0.025	190
0.05	18.8
0.1	2

Chapter 5 Evaporation and Extinction Model

5.1 Evaporation Model Description

The evaporation model in FDS is based on a series of equations that describe the mass and energy transfer between the gas and liquid. These equations are defined in the FDS Technical Guide [12] as follows:

$$\frac{dm_p}{dt} = -A_{p,s} h_m \rho_f (Y_{\alpha,l} - Y_{\alpha,g}) , \quad (\text{Eq. 5.1})$$

$$\rho_g V \frac{dY_{\alpha,g}}{dt} = -(1 - Y_{\alpha,g}) \frac{dm_p}{dt} , \quad (\text{Eq. 5.2})$$

$$\frac{dT_p}{dt} = \frac{1}{m_p c_p} [\dot{q}_r + A_{p,s} h_g (T_g - T_p) + A_{p,s} h_w (T_w - T_p) + \frac{dm_p}{dt} h_v] , \quad (\text{Eq. 5.3})$$

$$\frac{dT_g}{dt} = \frac{1}{m_p c_p} [A_{p,s} h_g (T_p - T_g) - \frac{dm_p}{dt} (h_{\alpha,p} - h_{\alpha,g})] . \quad (\text{Eq. 5.4})$$

The subscript α represents the gas species that formed from the droplets in a given grid cell over a time step of the gas phase solver. Assuming droplet temperature is uniform, Equation 17 shows the evaporation rate as a function of the liquid equilibrium vapor mass fraction, $Y_{\alpha,l}$, the local gas phase vapor mass fraction, $Y_{\alpha,g}$, droplet temperature, T_p , and the local gas temperature, T_g . The subscript g represents the average of the quantity in the cell occupied by the droplet while the subscript p refers to the liquid droplet. The variable T_s is the surface temperature if the droplet is attached to a solid. Since the droplet is resolved to be a homogeneous liquid of species α , m_p is the mass of the droplet, $A_{p,s}$ is the surface area of the liquid droplet, h_m is the mass transfer coefficient, ρ_g is the gas density, ρ_f is the particle film density, c_p is the liquid specific

heat, c_g is the gas specific heat, h_g is the heat transfer coefficient between the droplet and the gas, $\dot{q}_r$ is the rate of radiative heating of the droplet, $h_{\alpha,p}$ is the vapor specific enthalpy at the particle temperature, and $h_{\alpha,g}$ is the vapor specific enthalpy at the gas temperature. The liquid equilibrium vapor mass fraction is determined from the Clausius-Clapeyron equation:

$$X_{\alpha,l} = \exp \left[\frac{h_v W_\alpha}{R} \left(\frac{1}{T_b} - \frac{1}{T_p} \right) \right]; Y_{\alpha,l} = \frac{X_{\alpha,l}}{X_{\alpha,l} \left(1 - \frac{W_a}{W_\alpha} \right) + \left(\frac{W_a}{W_\alpha} \right)} \quad (\text{Eq. 5.5})$$

where $X_{\alpha,l}$ is the equilibrium vapor volume fraction, W_α is the molecular weight of the gaseous species α , W_a is the molecular weight of air, R is the universal gas constant, and T_b is the boiling temperature of the liquid at standard atmospheric temperature [2].

The mass transfer coefficient, h_m , is based on the empirical relationships between the Spalding mass transfer number B_M , the low mass flux Sherwood number Sh_0 , the Sherwood number with blowing Sh , the binary diffusion coefficient between the liquid vapor and surrounding gas D_{lg} , the length scale of the droplet diameter L , the Reynolds number of the droplet Re_D the Reynolds number based on length scale Re_L , and the Schmidt number Sc from the following equations:

$$h_m = \frac{Sh D_{lg}}{L} \frac{B_M}{Y_{\alpha,l} - Y_{\alpha,g}}, \quad (\text{Eq. 5.6})$$

$$Sh = \frac{\ln(1+B_M)}{B_M} Sh_0, \quad (\text{Eq. 5.7})$$

$$Sh_0 = \begin{cases} 2 + 0.6Re_D^{\frac{1}{2}}Sc^{\frac{1}{3}} \\ 0.037Re_L^{\frac{4}{5}}Sc^{\frac{1}{3}} \end{cases}, \quad (\text{Eq. 5.8})$$

$$B_M = \frac{Y_{\alpha,l} - Y_{\alpha,g}}{1 - Y_{\alpha,l}}, \quad (\text{Eq. 5.9})$$

Another empirical relationship based on the Nusselt number Nu describe the heat transfer coefficient h :

$$h = \frac{Nuk}{L}, \quad (\text{Eq. 5.10})$$

$$Nu = \frac{\ln(1+B_M)}{B_M} Nu_0, \quad (\text{Eq. 5.11})$$

$$Nu_0 = \begin{cases} 2 + 0.6Re_D^{\frac{1}{2}}Pr^{\frac{1}{3}} \\ 0.037Re_L^{\frac{4}{5}}Pr^{\frac{1}{3}} \end{cases}. \quad (\text{Eq. 5.12})$$

where Nu_0 is the low mass flux Nusselt number, k is the thermal conductivity of the gas, and Pr is the Prandtl number which is assumed to be 0.7 for all cases [12]. The mass and energy exchange between liquid droplets and surrounding gas (or solid surfaces) is computed droplet by droplet. Additional information about this exchange of mass and energy can be found in FDS Technical Guide [12].

A validation test for the evaporation model of FDS version 6.7.9 was performed by Lee (2023) using the modified version of the example case `water_evaporation_4_np100.fds` from the FDS library [5, 6]. The test results showed agreement with steady state FDS

measurements and confirmed the accuracy of FDS evaporation model in FDS version 6.7.9. Therefore, no further validation test is needed in this study.

5.2 Extinction Model Description

For water mist systems, there are two options for predicting extinction in FDS that are constructed based on the critical flame temperature (CFT). This critical flame temperature can be resolved from the limiting oxygen index (LOI) as described in Beyler's chapter of the SFPE Handbook [19]. The adiabatic flame temperature of a stoichiometric mixture of fuel and oxygen at the LOI can be attained using:

$$T_{OI} = T_{\infty} + Y_{OI} \left(\frac{\frac{\Delta H}{r_{O_2}}}{\bar{c}_p} \right) \quad ; \quad Y_{OI} = \frac{X_{OI} W_{O_2}}{X_{OI} W_{O_2} + (1 - X_{OI}) W_{N_2}} \quad (\text{Eq. 5.13})$$

where $\bar{c}_p$ is the average specific heat of the gases that are calculated based on the composition of the combustion products:

$$\bar{c}_p = \frac{1}{T_f - T} \sum_{\alpha} \int_T^{T_f} Y_{\alpha} c_{p,\alpha}(T') dT' \quad (\text{Eq. 5.14})$$

The first extinction model, 'EXTINCTION 1' in the FDS input file, considers oxygen

Table 5-1. FDS Extinction Criteria Inputs	
LOI [mol/mol]	0.135
CFT [°C]	1527 ^a

^a[16]

concentration and temperature of a given grid cell as the only factors for combustion. On the other hand, in the second extinction model, 'EXTINCTION MODEL 2,' both the oxygen and fuel content at the initial grid cell conditions must raise the temperature of the grid cell to critical flame temperature for combustion to occur. This study focuses on Extinction Model 2 which uses the values of LOI and CFT provided in Table 5-1.

In the default mixing-controlled combustion, FDS assumes that fuel and oxygen react independently of local temperature, reaction concentration, and strain rate. This assumption is a limitation in the extinction model and can create unrealistic re-ignition in a previously extinguished grid cell where unburnt fuel gas meets sufficient oxygen elsewhere in the domain. To prevent this unrealistic burning, `AUTO_IGNITION_TEMPERATURE` (AIT) can be set on the REAC line to state a value below which combustion will not occur. The AIT of JP-8 is found from the literature to be 230°C and is used throughout this study [2]. For ignition to occur, either an `AIT_EXCLUSION_ZONE` must be specified, or the burner surface temperature is raised above the prescribed AIT. A series of validation tests are conducted to determine the most appropriate way to ignite a fire in the subsequent section. These are not applicable to sprinkler nozzles i.e., Viking Grate Nozzles as sprinkler systems work by wetting the area, while water mist systems work based on their cooling capabilities from droplet evaporation.

5.3 Ignition Method Validation Test without Nozzle Activation

A validation test is conducted to verify the best method of ignition without any nozzles. A 79 m² burner representing a 0.06 m³ uncontained spill is placed at the center of a computational domain of size 15 m by 16 m by 10 m with

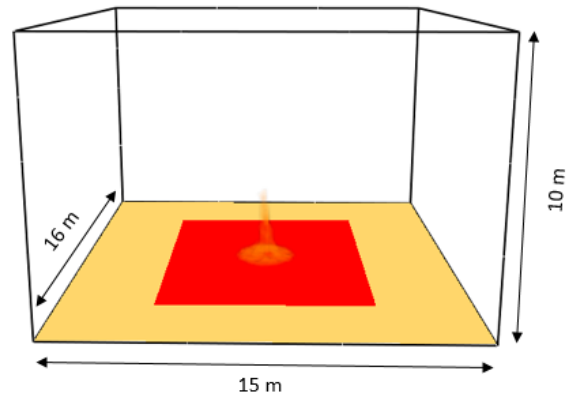


Figure 5-1. Validation Test Setup.

a uniform 0.1 m grid as shown in Figure 5-1. This fire is lit at the center and grows radially outward at a rate of 0.6 m/s to a steady state value of 34 MW. Note that in this case, the spread rate is accelerated to ten times faster so that the fire can reach its steady state value. Two methods of ignition are studied. The first method is called “Ramp” using which the surface temperature of the burner raises to 700 K for combustion to occur then gradually decreases to the AIT. The second method is “Exclusion Zone” in which a 15 m by 16 m by 3 m auto ignition exclusion zone is specified. The control method “No Ramp” is similar to the first with the exception that the surface temperature is constantly at 700 K. Figure 5-2 shows the heat release rate of the fire over time using each of these ignition methods. While the fire ignited using the control “No Ramp” method reaches expected steady state value, it does not maintain at this value and reaches a lower steady state value at around 30 MW. The “Ramp” method curve does not have a gradual growth rate similar to the other two, and its steady state bounces between 30 to 35 MW between 12 to 30 seconds. Only “Exclusion Zone” method

correctly prescribes the fire and maintained it at 34 MW. For this reason, “Exclusion Zone” is concluded to be the best way to prescribe a fire without any nozzle activations. However, further testing is needed to verify the appropriate ignition method in cases with nozzle activations.

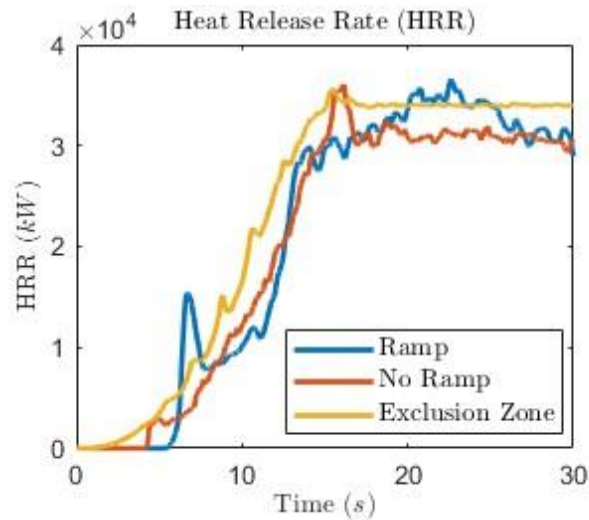


Figure 5-2. Heat Release Rate over time of a 34 MW fire using different ignition methods.

5.4 Extinction Validation Test

In this section, several small-scale validation tests are conducted to verify the logistics in fire cases with nozzle activations. All tests are conducted in computational domains with open boundaries and concrete floors. The humidity level is set to be 65% to resemble normal conditions.

5.4.1 Viking Grate Nozzle

The validation test with Viking Grate Nozzles is conducted in a computational domain of size 16 m by 16 m by 10 m. A square burner with a side of 3.6 m is placed in the center of the domain and prescribed to grow to 1 MW at 10 seconds of the simulation time. Two Viking Grate Nozzles 180° are placed 15 m away from each other and 0.5 m from the edge of the computational domain. These nozzles are set to activate at 10 seconds to allow the fire to grow to the prescribed HRR. The meshes are set up to match the length-scale analysis previously done in section 4.2.1. Figure 5-3 shows the setup test for Viking Grate Nozzles.

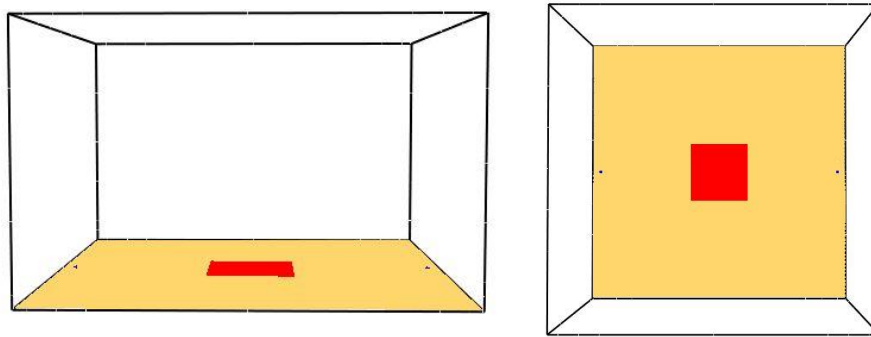


Figure 5-3. Small-scale extinction setup for Viking Grate Nozzle.

The fire is prescribed using surface temperature method in which the fire ramps up to 700 K in the first 7 seconds and then decreases below AIT at 8 seconds. Figure 5-4 shows the heat release rate measured throughout the simulation time of 30 seconds.

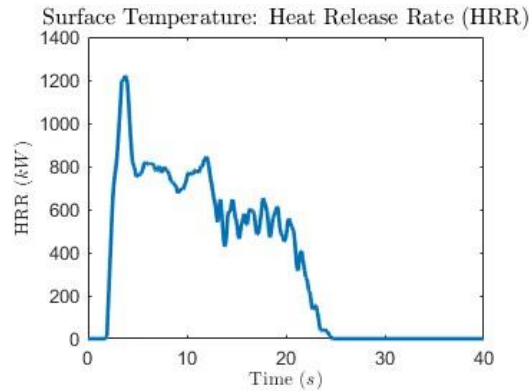


Figure 5-4. Heat Release Rate over time of a 1 MW fire with Viking Grate Nozzles activate at 10 seconds.

The fire grows to 1200 kW then decreases to approximately 800 kW at the end of 10 seconds which is smaller than what is originally prescribed. However, this result is consistent with the result in section 5.3 in which the fire prescribed using the surface temperature ramp method reaches the prescribed HRR but does not maintain this value at a steady state. However, this case shows successful extinction as the fire is completely extinguished at about 15 seconds after the nozzles activate.

5.4.2 VID Fire-kill Nozzle

For a small-scale test with low pressure water mist, a computational domain of size 9 m x 16 m x 10 m and a square burner with a side of 1 m at the center of the domain is used. Four VID nozzles are installed 2 m from each other on a branch line and 7.6 m across from each other. Figure 5-5 shows the test setup with VID Fire-kill Nozzles.

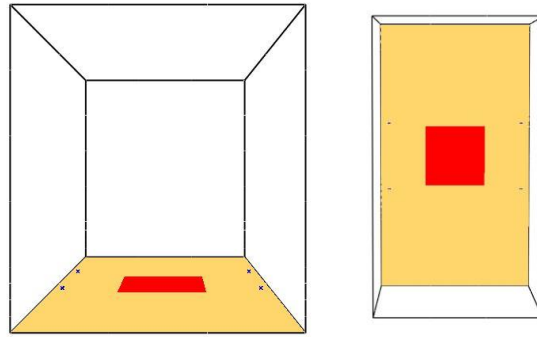


Figure 5-5. Small-scale extinction setup for VID Fire kill Nozzle.

Both fires prescribed by the surface temperature ramp and AIT exclusion zone are studied. In the surface temperature method, the fire ramps up to 700 K in the first seven seconds of the simulation then decreases below AIT at 8 seconds. In the AIT exclusion zone method, an AIT exclusion zone that covers a 0.5 m radius around the burner and 2 cells above the burner is added. One notable difference in these tests compared to previous tests done with Viking Grate Nozzle is that the fire is prescribed to reach 500 kW instead of 1 MW in its steady state. Figure 5-6 shows the heat release rate measured throughout the simulation time of 30 seconds for both cases.

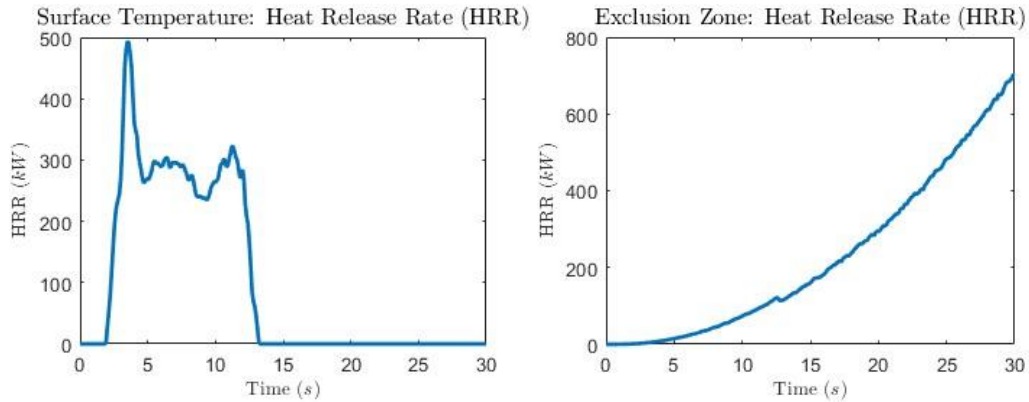


Figure 5-6. Heat Release Rate for Surface Temperature (left) and Exclusion Zone (right) case.

Again, in the surface temperature ramp method, the fire reaches its prescribed HRR but eventually decreases to 300 kW in its steady state. This case shows successful extinction 5 seconds after nozzles activation. In the AIT exclusion zone case, the fire continues to grow and reach 700 kW at the end of the 30 seconds simulation. There is no sign of water mist and fire interacting with each other in this case. This result is interesting as the use of AIT exclusion zone does not work as applied for this case with water mist. It is recognized that additional guidance on this method could be beneficial and if applied can yield a different outcome. This result suggests that further investigation can be done to examine the water mist evaporation model and the use of AIT exclusion zone to prescribe a fire. Due to the time constraints of this project, the surface temperature ramp method will be used to prescribe fires with VID Fire-kill nozzles in the final hangar simulations.

Chapter 6 Model Inputs

6.1 Hangar and Plane Construction

In final simulations with a full-size hangar, a computational domain of size 64 m x 37 m x 10 m is utilized. Within this computational domain, a rectangular-shaped hangar of size 64 m x 29 m x 10 m with a door of size 63.7 m width x 7.62 m height is created based on dimensions listed for a hangar type I in UFC 411-01 [7]. Figure 6-1 shows the computational domain along with the hangar construction.

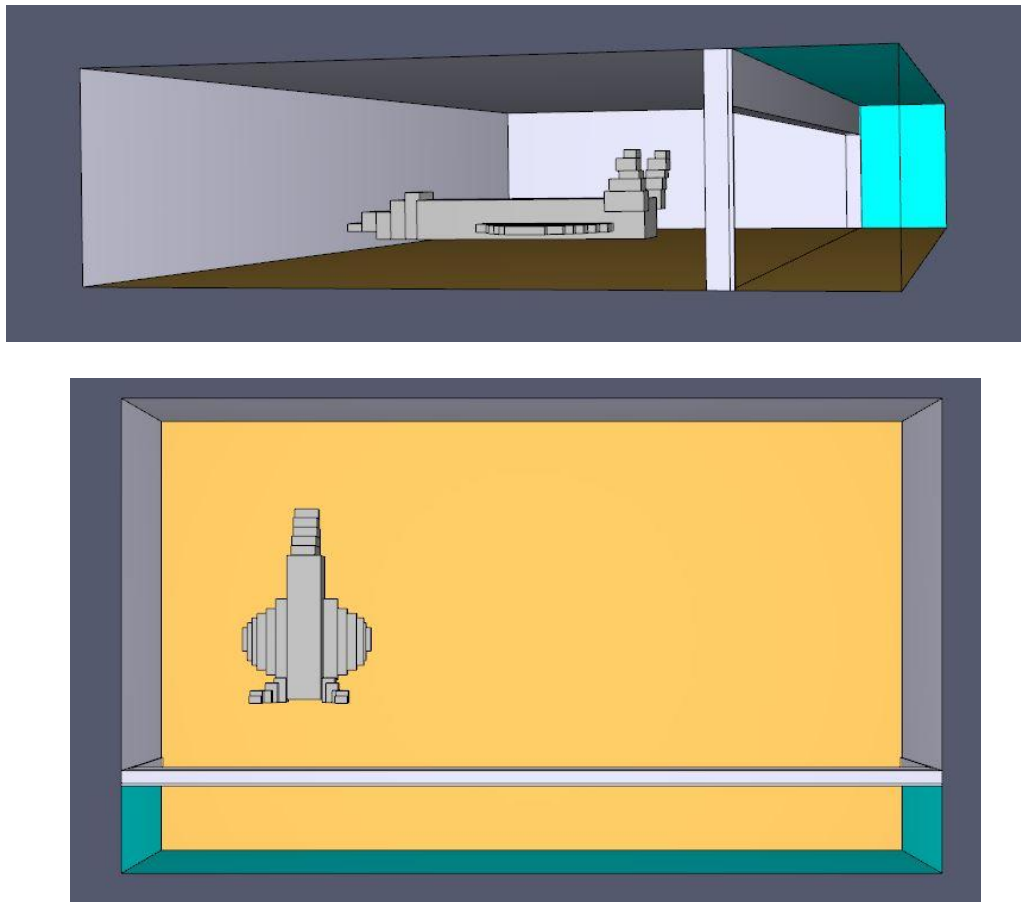


Figure 6-1. Final hangar simulation setup.

The hangar walls and roof are assigned corrugated metal properties, while the floor is set to be concrete. The properties of these constructed materials are listed in Table 6-1. An open area of size 64 m x 8 m x 10 m is also added to allow air entrainment. All boundaries of this area are assigned OPEN except the concrete bottom surface.

Table 6-1. Properties of constructed materials.

Material	Conductivity	Density	Specific heat	Thickness
	[W/m/K]	[kg/m ³]	[kJ/kg/K]	[m]
Concrete	1.8	2200	1.04	0.1
Corrugated metal	52	7800	0.47	0.2
Composite	1.2	1512	2.2	0.0032

Two trench setups are studied. The first is the current spacing of 15.2 m, and the second is the reduced spacing of 7.6 m. The trenches are 0.66 m in width. Figure 6-2 shows the trench of both cases.

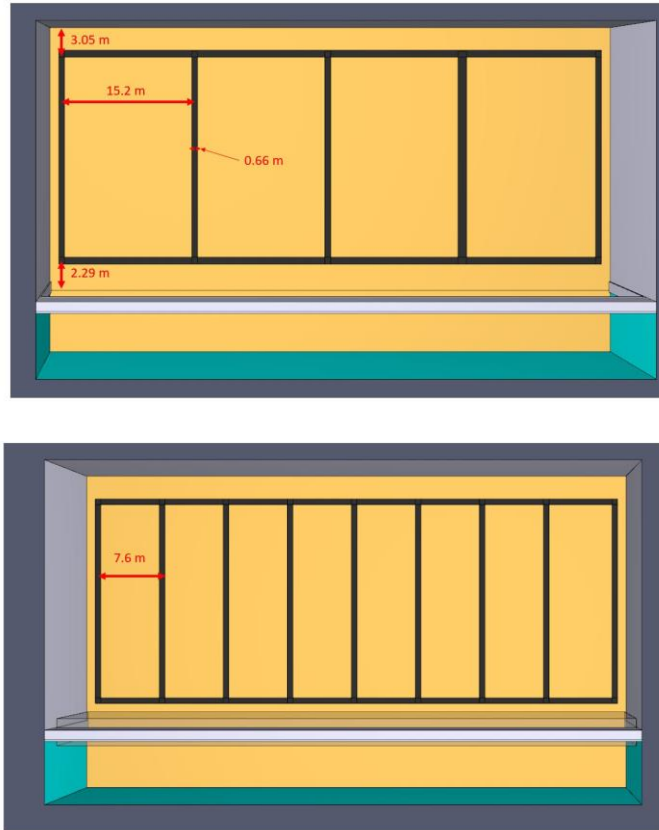


Figure 6-2. Trench setup: 15.2 m (Top) and 7.6 m (Bottom).

This study utilizes the same F-35 plane previously studied by Steranka (2021) and Lee (2023) [4, 9]. The F-35 plane is made with rectangular obstructions and assigned composite material with the properties listed in Table 6-1. The plane has a length of 16 m, a fuselage height of 2 m, a tail height of 4 m, and a wingspan of 11 m. Devices are placed on the plane to measure gauge heat flux as shown in Figure 6-3. The gauge heat flux is prescribed in FDS with “GAUGE_TEMPERATURE = 15” and “GAUGE_EMISSIVITY = 0.95.” Additionally, incident heat flux is also measured at the same locations. Incident heat flux does not account for radiation leaving the surface,

and the temperature used for the convective flux portion is the actual surface temperature as opposed to a user defined gauge temperature. Both of these measurements are to be used as benchmarks in full-scale tests done by the U.S. Air Force.

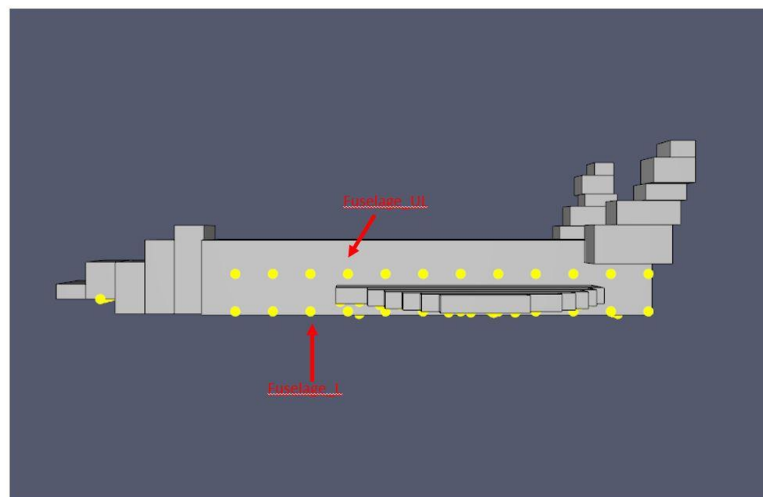
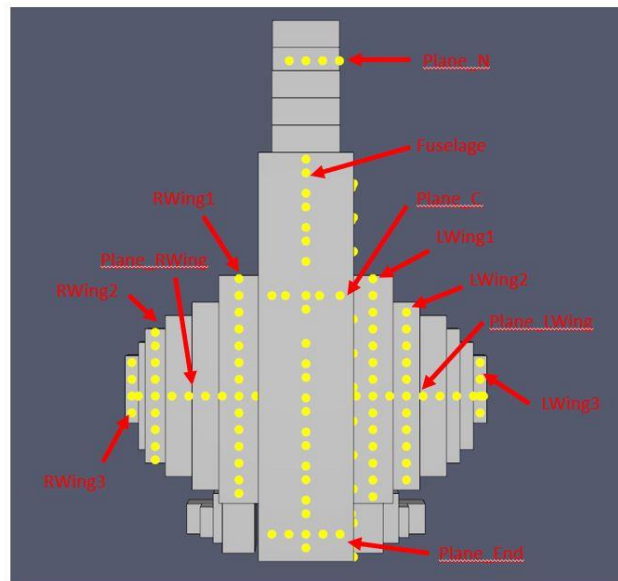


Figure 6-3. Location of devices on the plane.

6.2 Nozzle Installation

6.2.1 Viking Grate Nozzle

The Viking Grate Nozzles layout on the trench is created based on the requirements in UFC 411-01 [7]. Eight nozzles are placed in the center of the trenches and spaced 7.6 m from each other. The nozzle spacing stays the same for both trench cases. Figure 6-4 illustrates the nozzle layout for both setups.

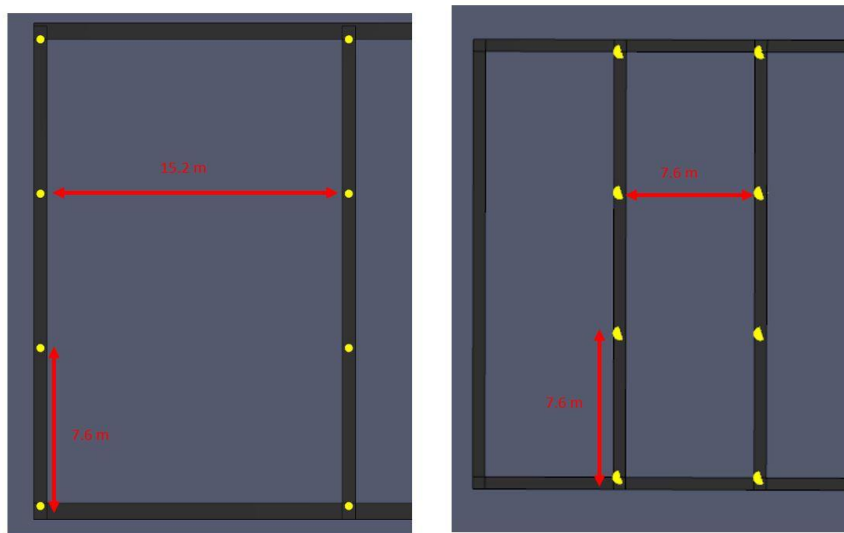


Figure 6-4. Viking Grate Nozzle Layout: 15.2 m (Left) and 7.6 m (Right).

6.2.2 VID Fire-kill Nozzle

The layout of the VID Fire-kill Nozzle is created based on the manufacturer's product data sheet [18]. Twenty-four nozzles are placed in the center of the trenches and spaced 2 m from each other. Due to the maximum spacing of 8 m across required

for this nozzle, only the 7.6 m trench spacing setup is used. Figure 6-5 illustrates the layout of VID Fire-kill nozzles on 7.6 m trench spacing.

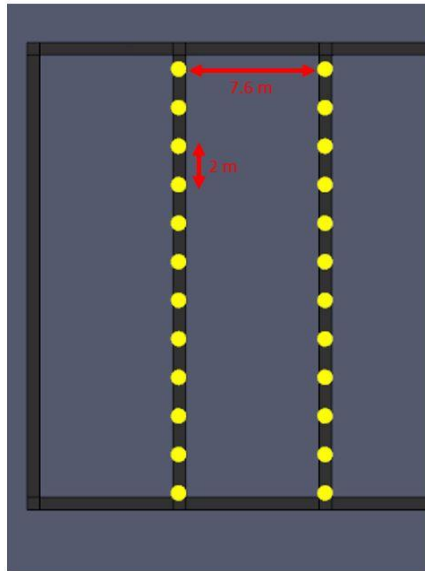


Figure 6-5. VID Fire-kill Nozzles Layout.

6.3 Fire Location

The fire scenarios in both trenches' setups simulate fuel spills located in the middle of the area bounded by the trench. Figure 6-6 shows the fire's location and point of ignition for all scenarios. The fire in case a) is represented by a 79 m² square burner, while the fire in case b) is represented by a 222 m² square burner. With the reduction of trench spacing, some of the fuel is lost through the trenches. Cases c) and d) are modeled with worst-case scenarios, assuming the fuel spreads at the same rate in all direction. Case c) is represented by a 48 m² square burner, and case d) is a rectangular burner with its area being the area bounded by the trenches.

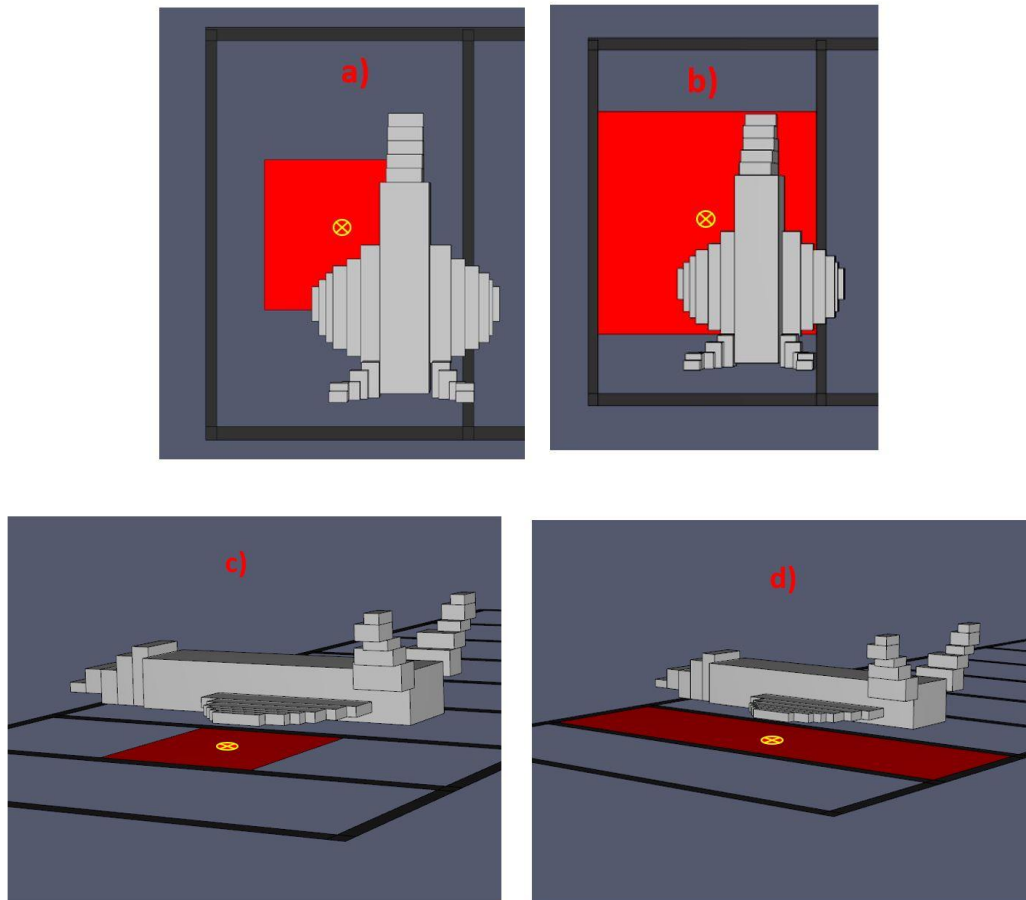


Figure 6-6. Location of the fire and Point of Ignition for:

- a) 15.2 m trench spacing 0.06 m³ spill
- b) 15.2 m trench spacing 0.6 m³ spill
- c) 7.6 m trench spacing 0.06 m³ spill
- d) 7.6 m trench spacing 0.6 m³ spill

6.4 Performance Criteria

The performance criteria for sprinkler cases with Viking Grate Nozzle are based on two requirements for low expansion AFFF foam systems. The first requirement cites 30 seconds for the most remote nozzle to

Table 6-2. Critical Heat Fluxes to Plane

Heat Flux [kW/m ²]	Time until Delamination [s]
15	129
25	74

activate [7]. The second requirement states 60 seconds for full coverage of a foam blanket [20]. In this study, the first requirement is interpreted as there is a 30 seconds delay of nozzle activation, while the second requirement is used to evaluate the time it takes for the water-based system to provide full floor coverage. Each scenario will be tested with two nozzle activation times: 30 seconds and 60 seconds. In addition, reduction of HRR, time to complete extinguishment and incident heat fluxes to the plane are also evaluated. Table 6-2 lists the critical heat flux values for the plane composite material [4]. On the other hand, the performance of low-pressure water mist systems with VID Fire-kill nozzles is only evaluated based on reduction of HRR and incident heat fluxes measured on the plane. The simulation results are used to develop a test matrix for full-scale experiments. The final acceptable level of protection will be determined by the U.S. Air Force based on these experiments.

Chapter 7 Results

UMD's High Performance Computing (HPC) cluster Zaratan is utilized to run final hangar simulations. The total simulation time for 30 seconds and 60 seconds nozzle activation is 60 seconds and 90 seconds, respectively.

7.1 Viking Grate Nozzle

7.1.1 Trench spacing 15.2 m – 0.06 m³ spill – 30 seconds activation

Figure 7-1 shows the heat release rate and mass loss rate of the fuel of 0.06 m³ spill case with nozzles activated at 30 seconds. At the time of nozzle activation, the fire is at about 5 MW and continues to grow to 7 MW. It takes about 20 seconds from the nozzle activation time to complete extinguishment as shown in the temperature SLCF file in Figure 7-2.

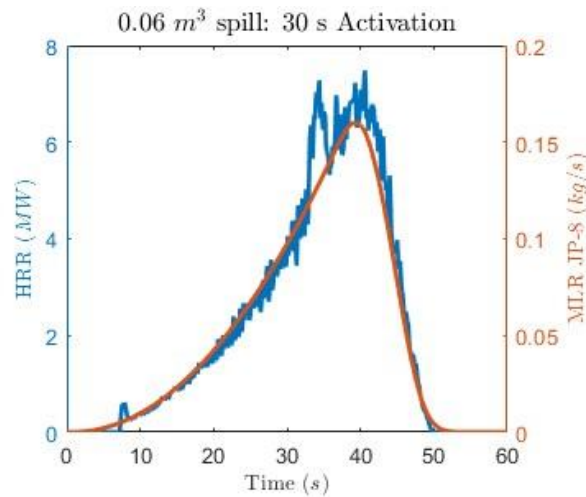


Figure 7-1. Heat Release Rate and MLR JP-8 for Viking Grate Nozzle with trench spacing 15.2 m – 0.06 m³ spill – 30 seconds activation.

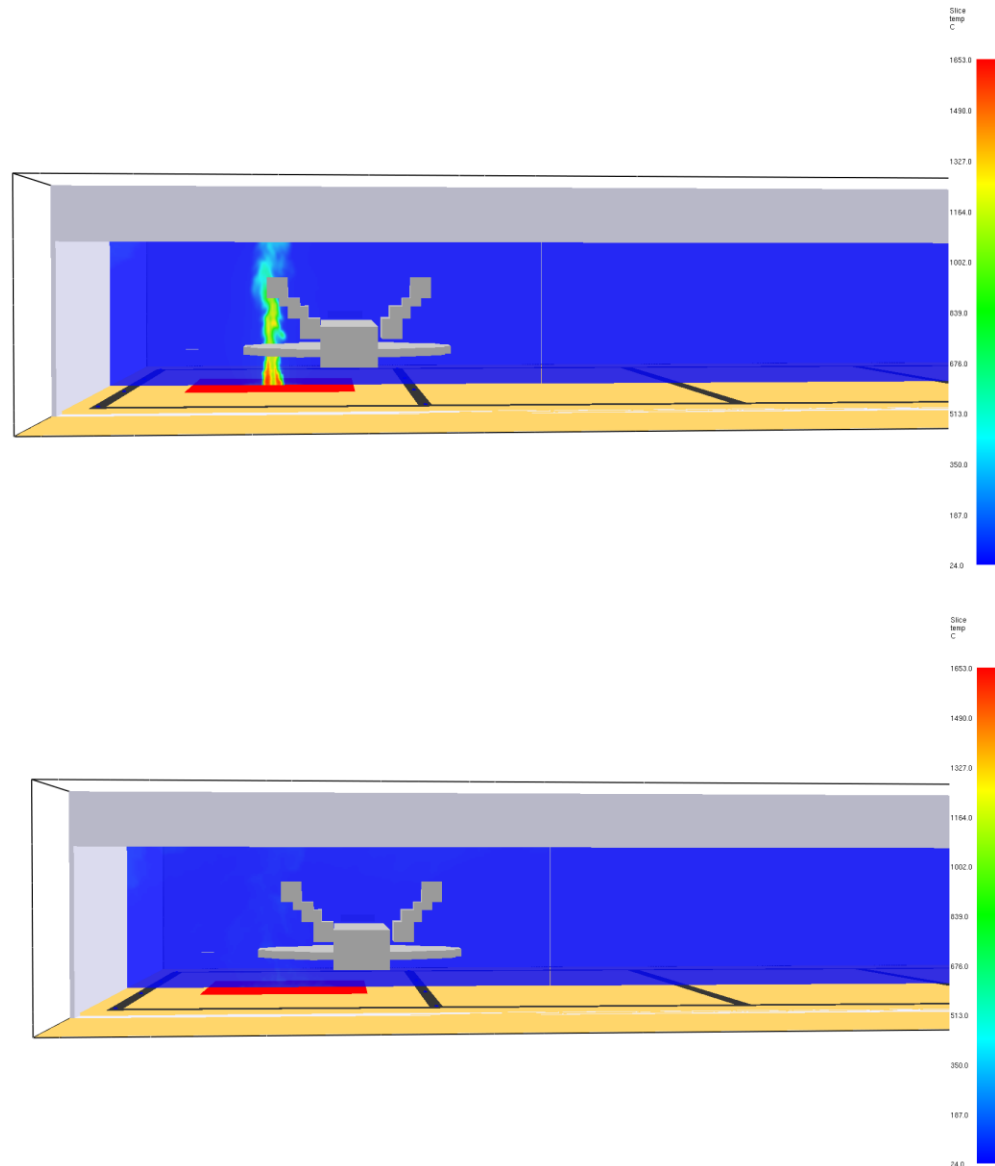


Figure 7-2. Temperature SCLF file for Viking Grate Nozzle with 0.06 m³ spill and 30 seconds activation at 30 seconds (Top) and 50 seconds (Bottom).

The highest heat flux measurement is observed at Fuselage Left at about 11 kW/m². Figure 7-3 shows the incident and gauge heat flux measured at this location. Additional measurements at other locations are provided in Appendix A. Overall, both incident

and gauge heat flux measurements are similar in value. The incident heat flux measurement is slightly higher due to its inability to account for radiation leaving the surface.

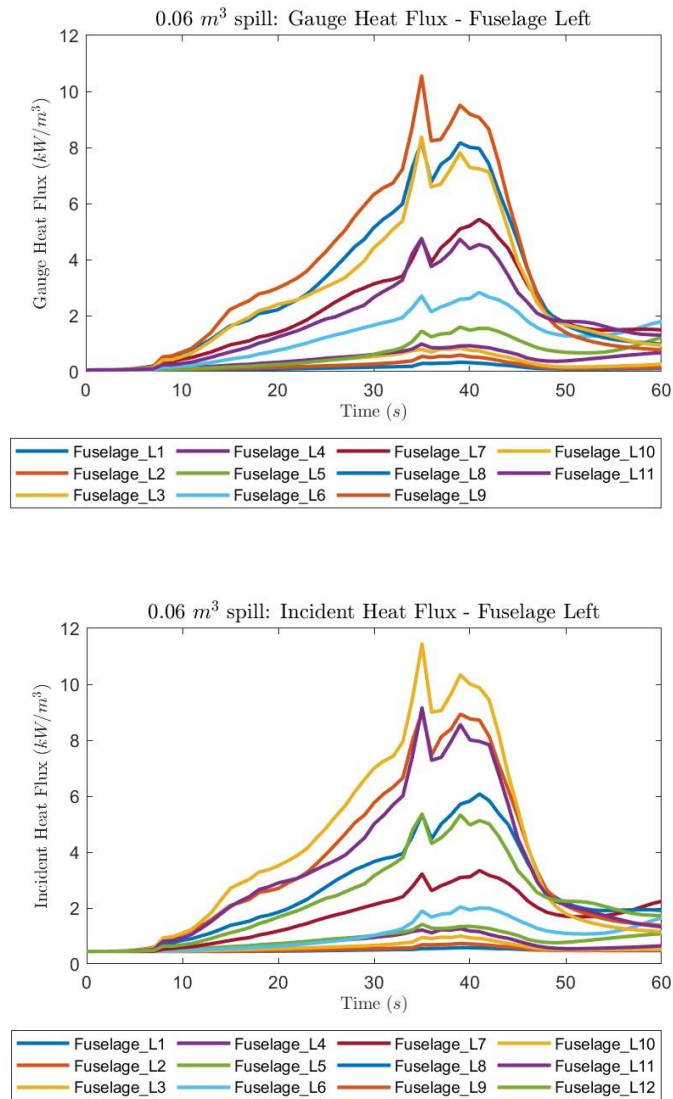


Figure 7-3. Gauge Heat Flux (Top) and Incident Heat Flux (Bottom) measured at Fuselage Left.

7.1.2 Trench spacing 15.2 m – 0.06 m³ spill – 60 seconds activation

Figure 7-4 shows the heat release rate as well as mass loss rate of the fuel of 0.06 m³ spill case with nozzles activated at 60 seconds. At the time of nozzle activation, the heat release rate of the fire is at about 15 MW and continues to grow to 23 MW. Similar to previous case, it takes about 20 seconds from the nozzle activation time to complete extinguishment as shown in the temperature SLCF file in Figure 7-5.

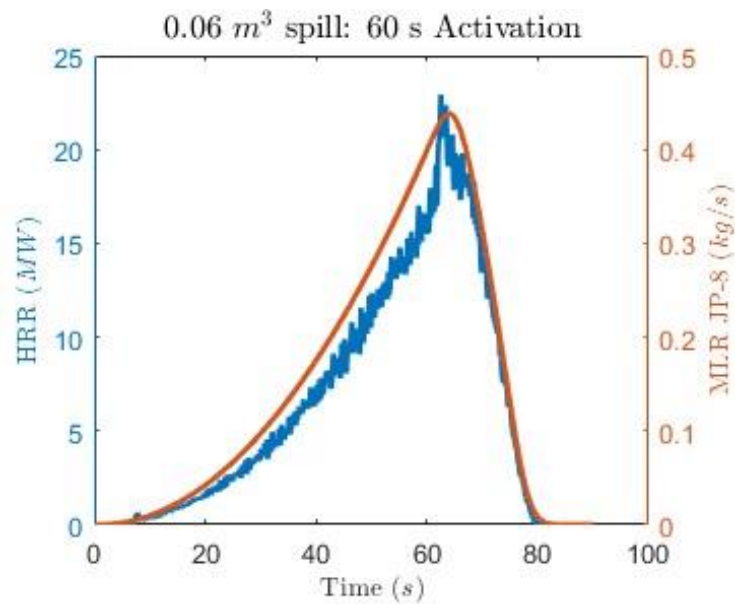


Figure 7-4. Heat Release Rate and MLR of JP-8 for Viking Grate Nozzle with trench spacing 15.2 m – 0.06 m³ spill – 60 seconds activation.

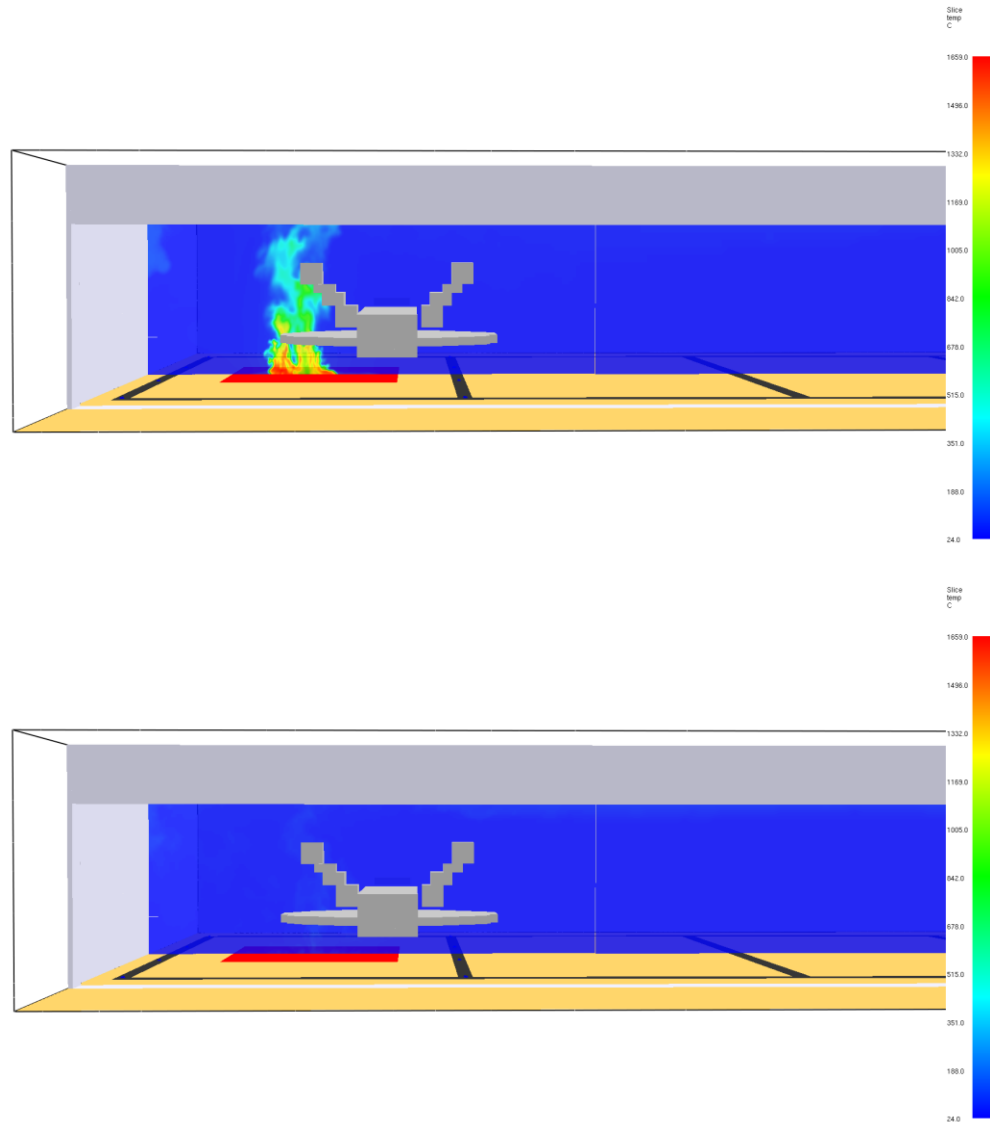


Figure 7-5. Temperature SCLF file for Viking Grate Nozzle with 0.06 m³ spill and 60 seconds activation at 60 seconds (Top) and 81 seconds (Bottom).

As expected, the heat fluxes to the plane increases as the activation delay increases. Fuselage Left still experiences the highest heat flux measured at about 24 kW/m². Figure 7-3 shows the incident and gauge heat flux measured at this location. Additional

measurements at other locations are provided in Appendix A. Both activation times for 0.06 m³ spill and 15.2 m comply with performance criteria laid out in section 6.4.

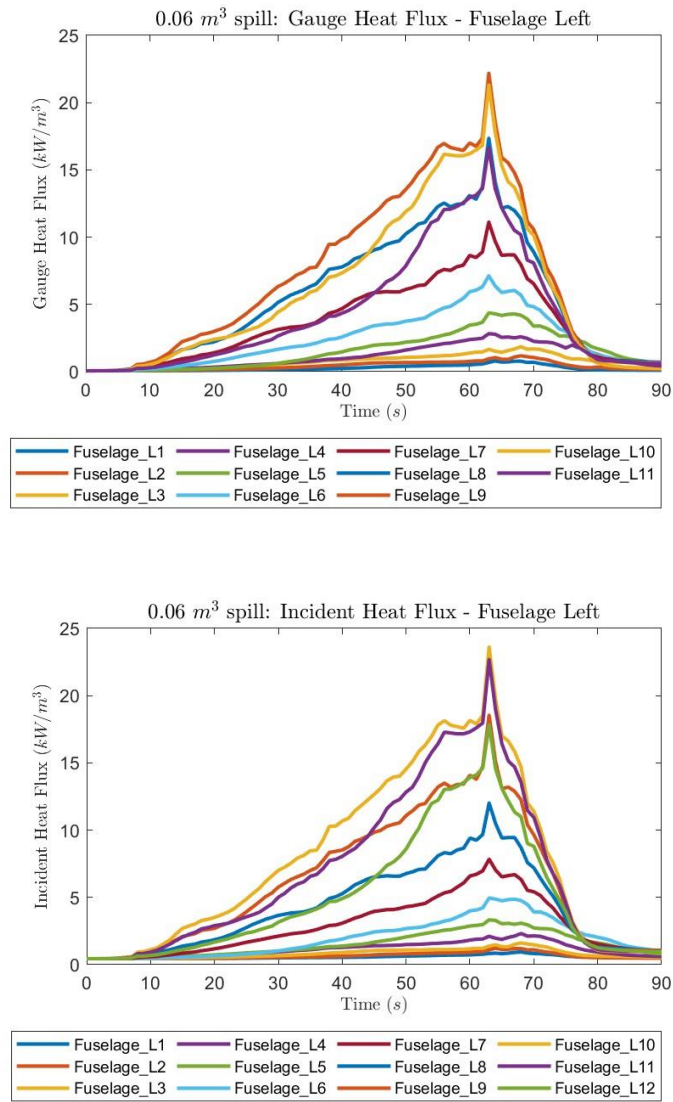


Figure 7-6. Gauge Heat Flux (Top) and Incident Heat Flux (Bottom) measured at Fuselage Left.

7.1.3 Trench spacing 15.2 m – 0.6 m³ spill – 30 seconds activation

Figure 7-7 shows the heat release rate and mass loss rate of JP-8 of 0.6 m³ spill case with nozzles activated at 30 seconds. The fire grows to about 8 MW until it is completely extinguished. Again, it takes about 20 seconds for the water to completely cover the burner and suffocate the fire as shown in the temperature SLCF file in Figure 7-8.

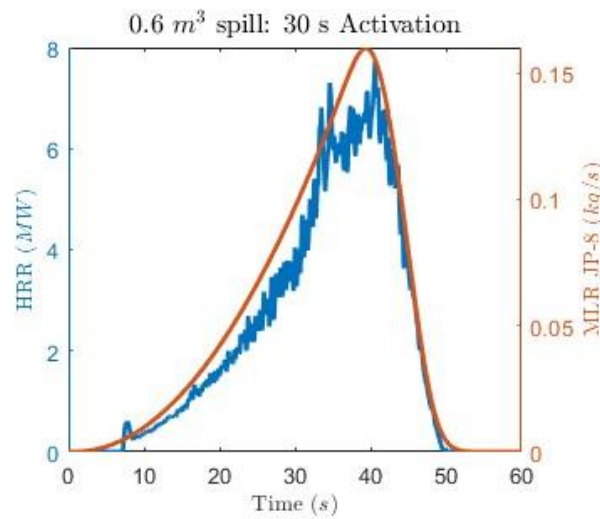


Figure 7-7. Heat Release Rate and MLR of JP-8 for Viking Grate Nozzle with trench spacing 15.2 m – 0.6 m³ spill – 30 seconds activation.

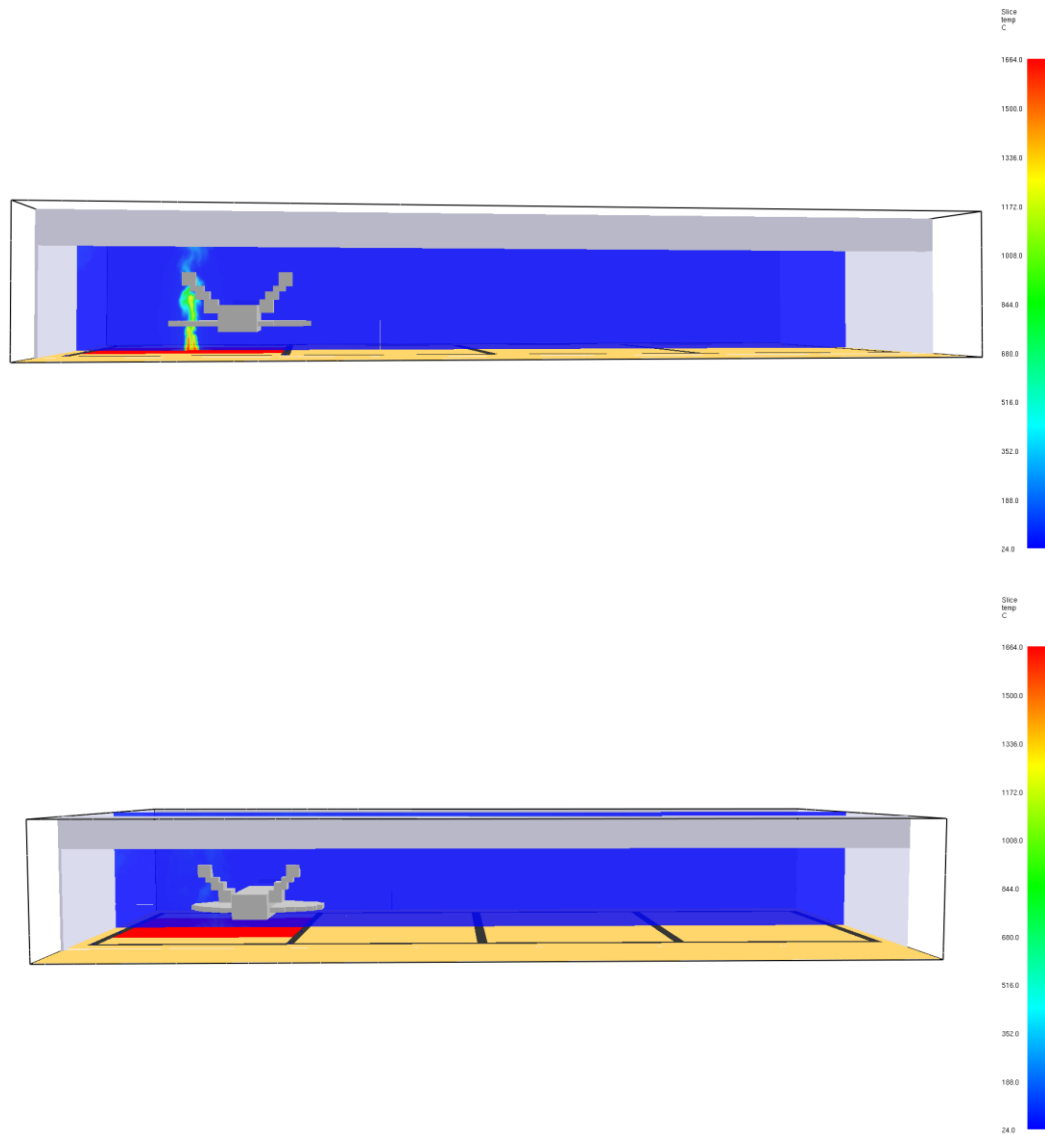


Figure 7-8. Temperature SCLF file for Viking Grate Nozzle with 0.6 m³ spill and 30 seconds activation at 30 seconds (Top) and 50 seconds (Bottom).

The heat flux measured for this case is similar to the case in section 7.1.1 with the highest heat flux being 12 kW/m² measured at Fuselage Left. Figure 7-9 shows the incident and gauge heat flux measured at this location. Additional measurements at other locations are provided in Appendix A.

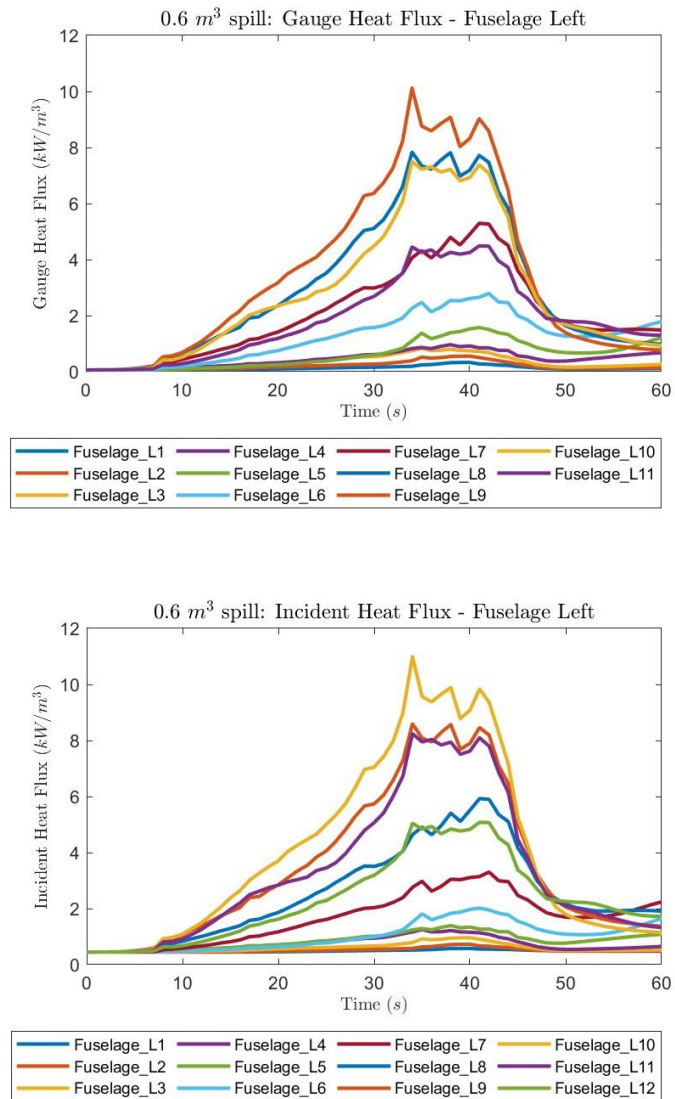


Figure 7-9. Gauge Heat Flux (Top) and Incident Heat Flux (Bottom) measured at Fuselage Left.

7.1.4 Trench spacing 15.2 m – 0.6 m³ spill – 60 seconds activation

Similar to previous cases, extinguishment for this case happens around 20 seconds after the nozzles activate as shown in Figure 7-10 with the HRR and MLR of JP-8 curve and Figure 7-11 with the temperature SLCF file at various times of interest.

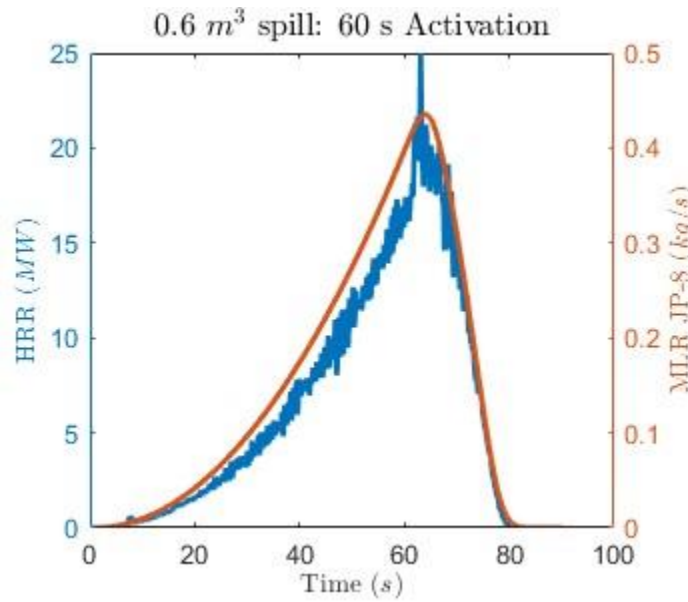


Figure 7-10. Heat Release Rate and MLR of JP-8 for Viking Grate Nozzle with trench spacing 15.2 m – 0.6 m³ spill – 60 seconds activation.

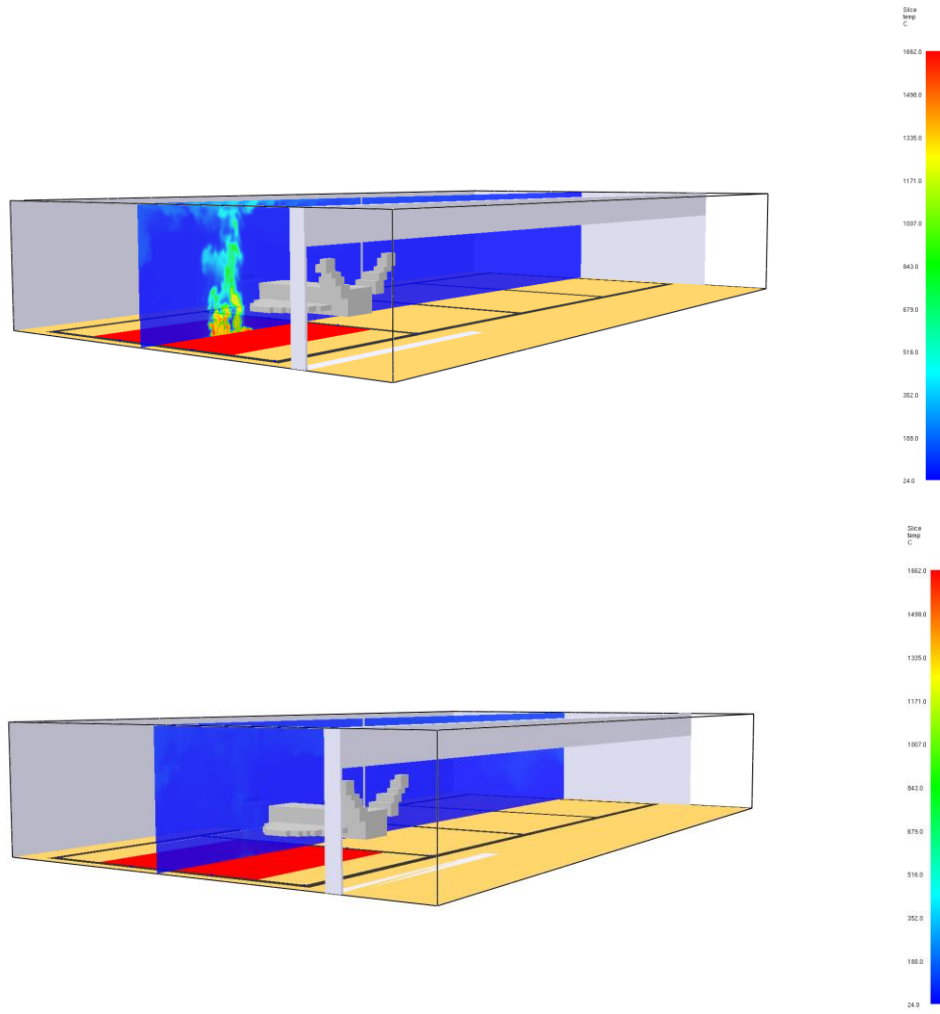


Figure 7-11. Temperature SCLF file for Viking Grate Nozzle with 0.6 m³ spill and 60 seconds activation at 60 seconds (Top) and 81 seconds (Bottom).

The heat flux measurements in this case are similar to that of case 7.1.2 with Fuselage Left experiencing the highest heat flux measured at about 24 kW/m². Figure 7-12 shows the incident and gauge heat flux measured at this location. Additional measurements at other locations are provided in Appendix A.

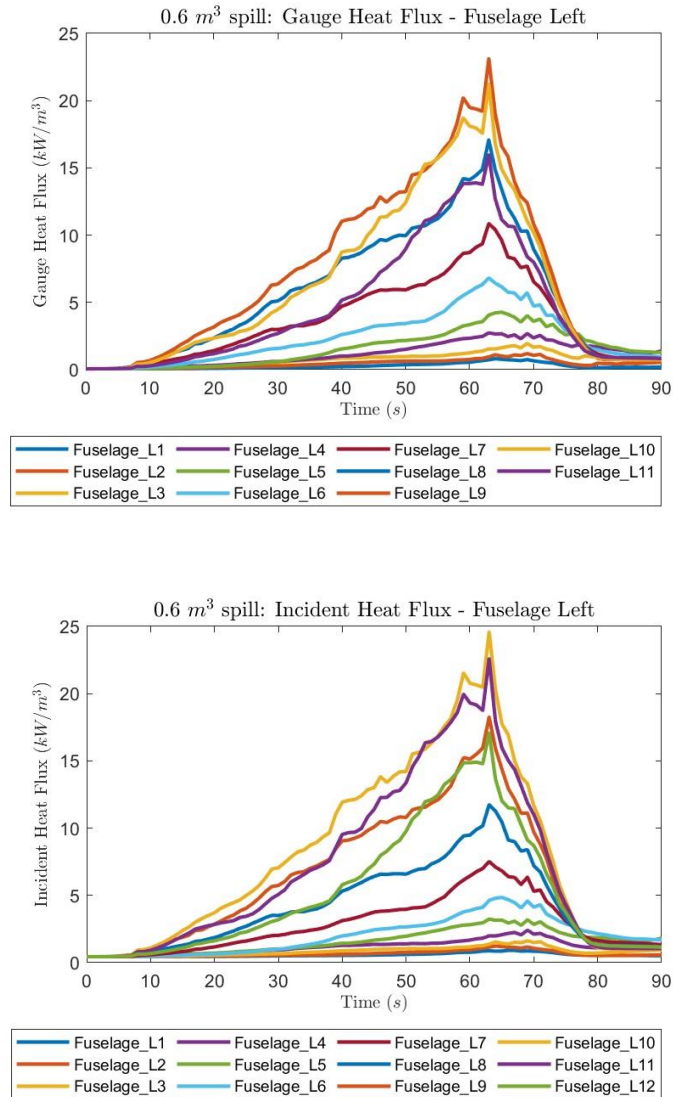


Figure 7-12. Gauge Heat Flux (Top) and Incident Heat Flux (Bottom) measured at Fuselage Left.

7.1.5 Trench spacing 7.6 m – 0.06 m³ spill – 30 seconds activation

Compared to the cases with 15.2 trench spacing, the fire in this case extinguishes much faster, at about 5 seconds after the nozzles activate as shown in Figure 7-13 with the HRR and MLR of JP-8 curve and Figure 7-14 with the temperature

SLCF file. There is an immense spike in heat release rate right after the nozzles set to activate at 30 seconds. This observation is physical as the activation of nozzles brings in additional air to the already burning fuel.

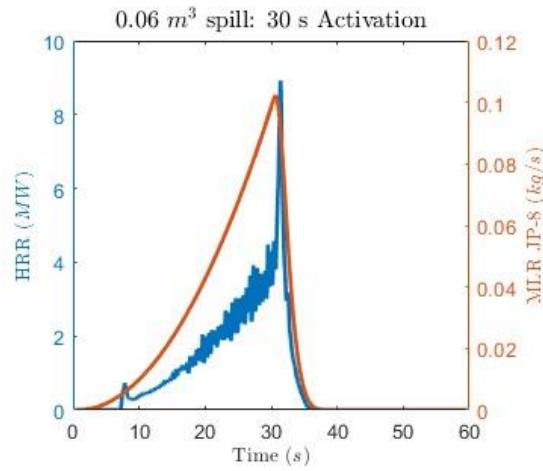


Figure 7-13. Heat Release Rate and MLR of JP-8 for Viking Grate Nozzle with trench spacing 7.6

m – 0.06 m³ spill – 30 seconds activation.

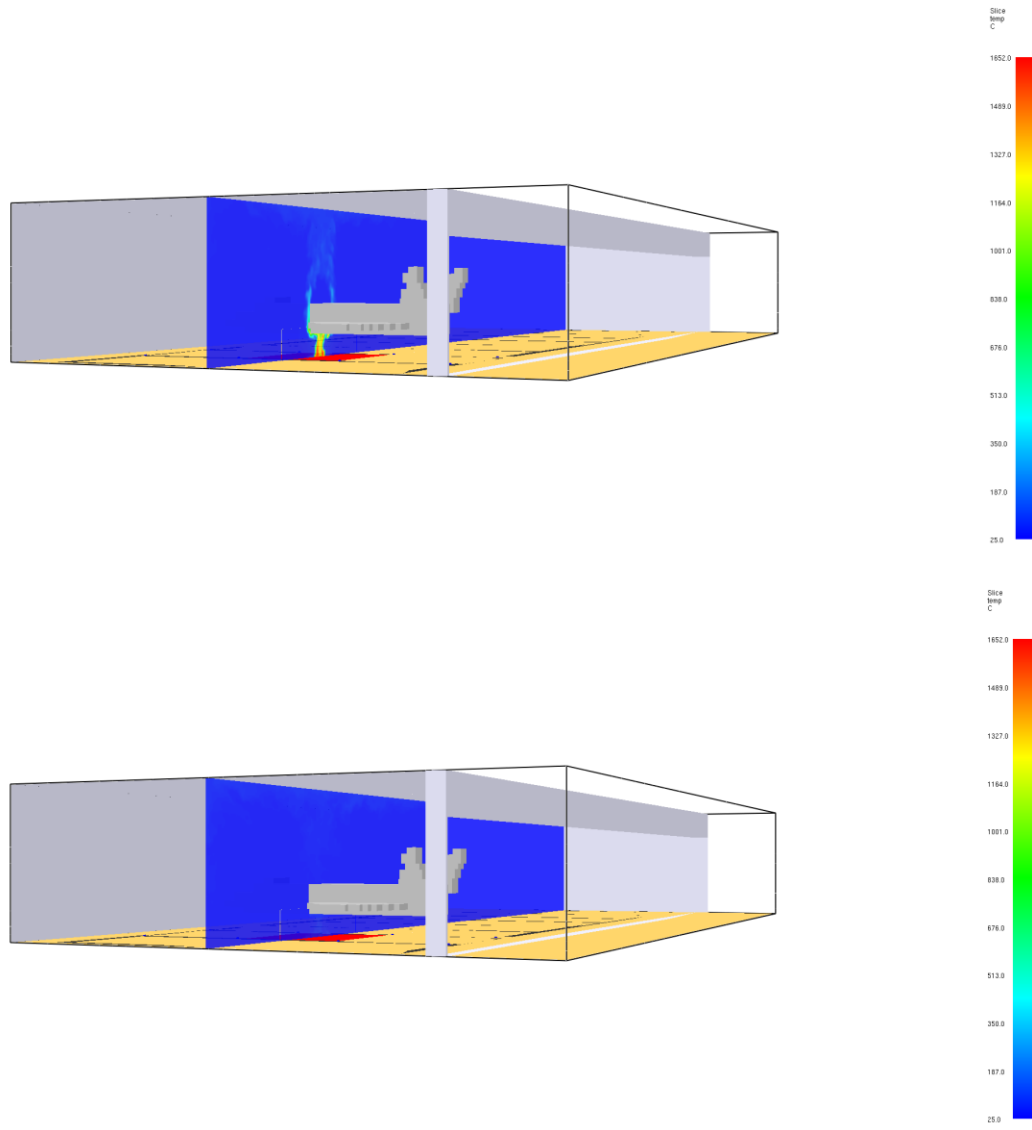


Figure 7-14. Temperature SCLF file for Viking Grate Nozzle with trench spacing 7.6 m - 0.06 m³ spill and 30 seconds activation at 30 seconds (Top) and 36 seconds (Bottom).

Since the burner is directly underneath the fuselage. It is expected that the fuselage would experience the highest heat flux, and the heat fluxes experienced on both sides of the plane are symmetrical. The heat flux measured at the fuselage in this case reaches 110 kW/m² as shown in Figure 7-15. This value is much higher than the performance

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criteria identified in section 6.4 and indicates that several locations on the plane might be severely damaged. Additional measurements at other locations are provided in Appendix A.

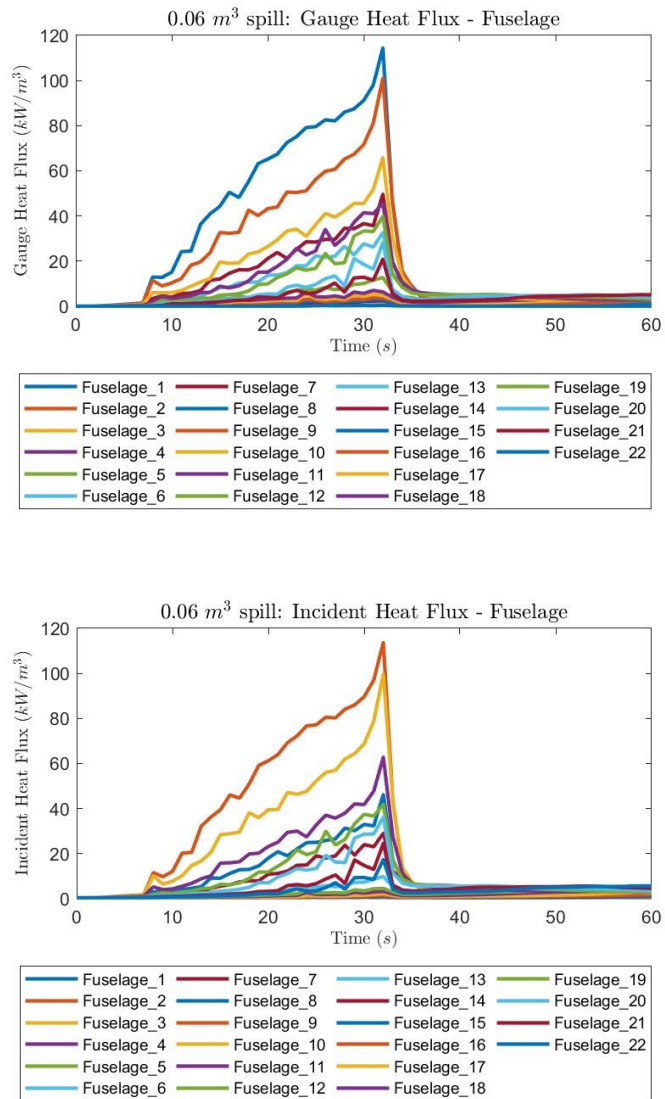


Figure 7-15. Gauge Heat Flux (Top) and Incident Heat Flux (Bottom) measured at Fuselage.

7.1.6 Trench spacing 7.6 m – 0.06 m³ spill – 60 seconds activation

In this case, the fire is extinguished about 10 seconds after the nozzles activate as shown in Figure 7-16 with HRR and MLR of JP-8 curve and Figure 7-17 with temperature SLCF file. The HRR curve in this case does not have a spike similar to the previous case due to a much higher HRR at the time of the nozzle activation.

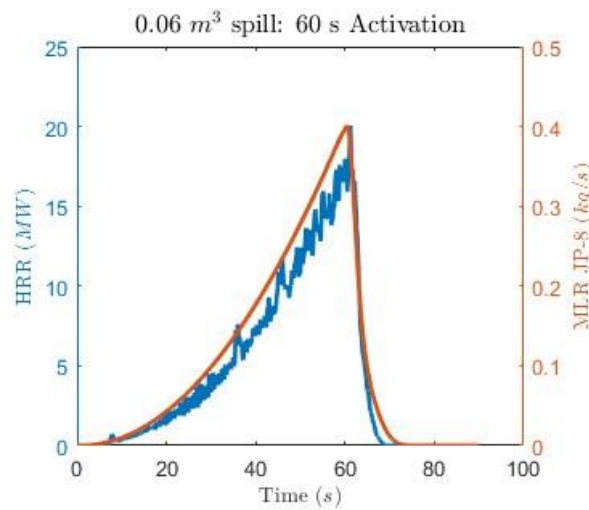


Figure 7-16. Heat Release Rate and MLR of JP-8 for Viking Grate Nozzle with trench spacing 7.6 m – 0.06 m³ spill – 60 seconds activation.

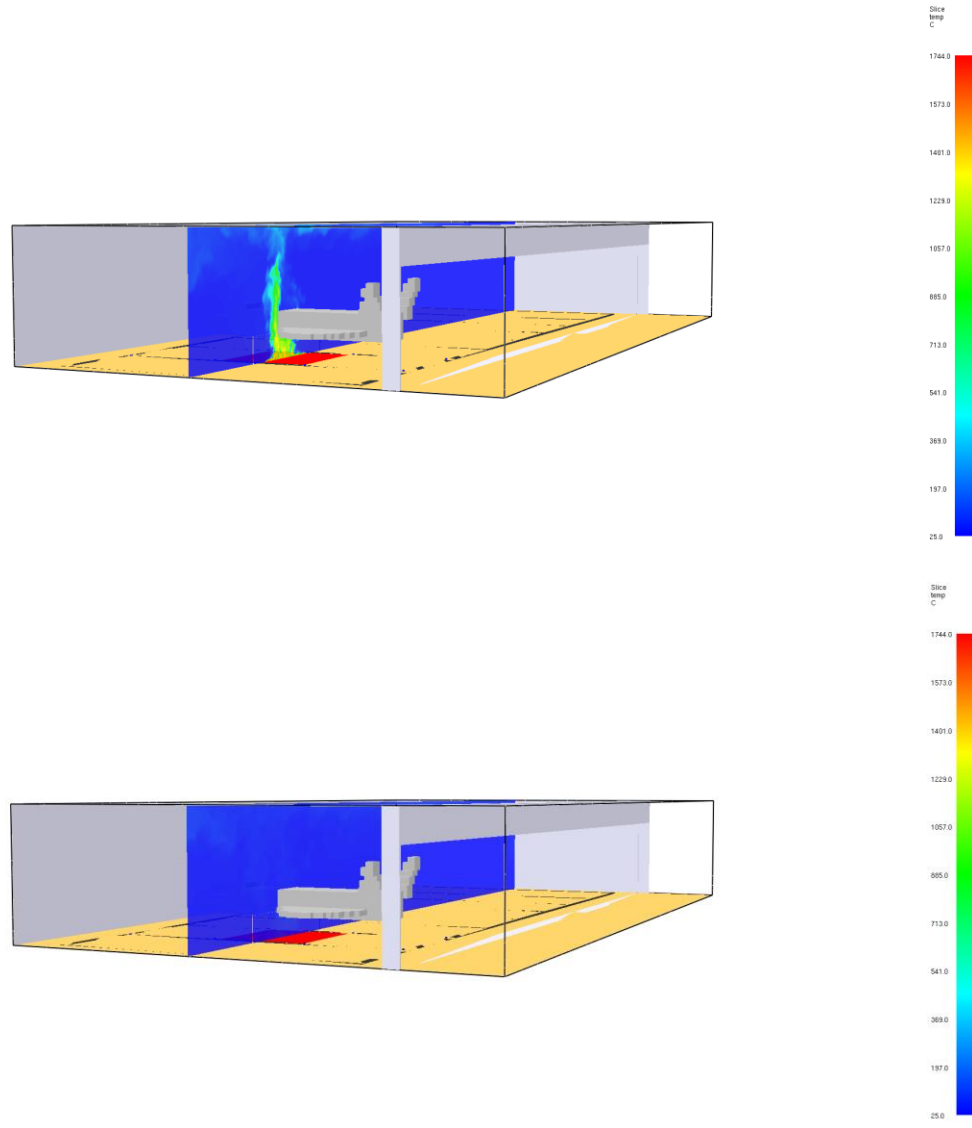


Figure 7-17. Temperature SCLF file for Viking Grate Nozzle with 0.06 m³ spill and 60 seconds activation at 60 seconds (Top) and 69 seconds (Bottom).

The plane fuselage still experiences the highest heat flux that reaches 110 kW/m², similar to the highest heat flux in 30 seconds activation case. However, with the delay of nozzle activation time, the plane undergoes this heat flux for about 30 seconds, a much longer time compared to the 30 seconds activation case that results in the plane

being severely damaged. Additional measurements at other locations are provided in Appendix A.

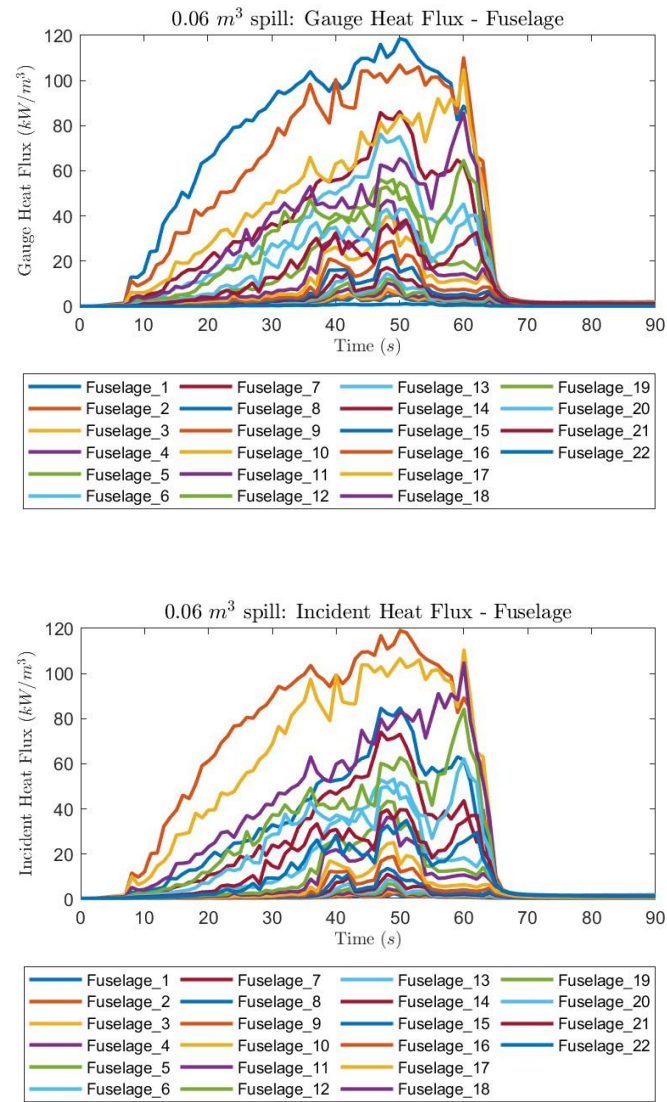


Figure 7-18. Gauge Heat Flux (Top) and Incident Heat Flux (Bottom) measured at Fuselage.

7.1.7 Trench spacing 7.6 m – 0.6 m³ spill – 30 seconds activation

Despite having a fire with a slightly higher HRR, this case has a similar result to the case in section 7.1.5 with fire being extinguished about 5 seconds after the nozzles activate as shown in Figure 7-19 that plots the HRR and MLR of JP-8 curve over time. The HRR spike is consistent with the previously observed spike in the case in section 7.1.5. Figure 7-20 illustrates the temperature SLCF file across the middle of the burner at the times of interest.

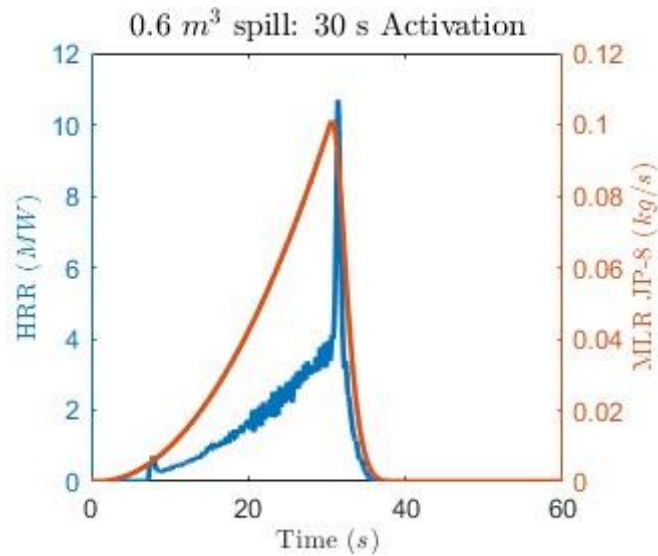


Figure 7-19. Heat Release Rate and MLR of JP-8 for Viking Grate Nozzle with trench spacing 7.6 m – 0.6 m³ spill – 30 seconds activation.

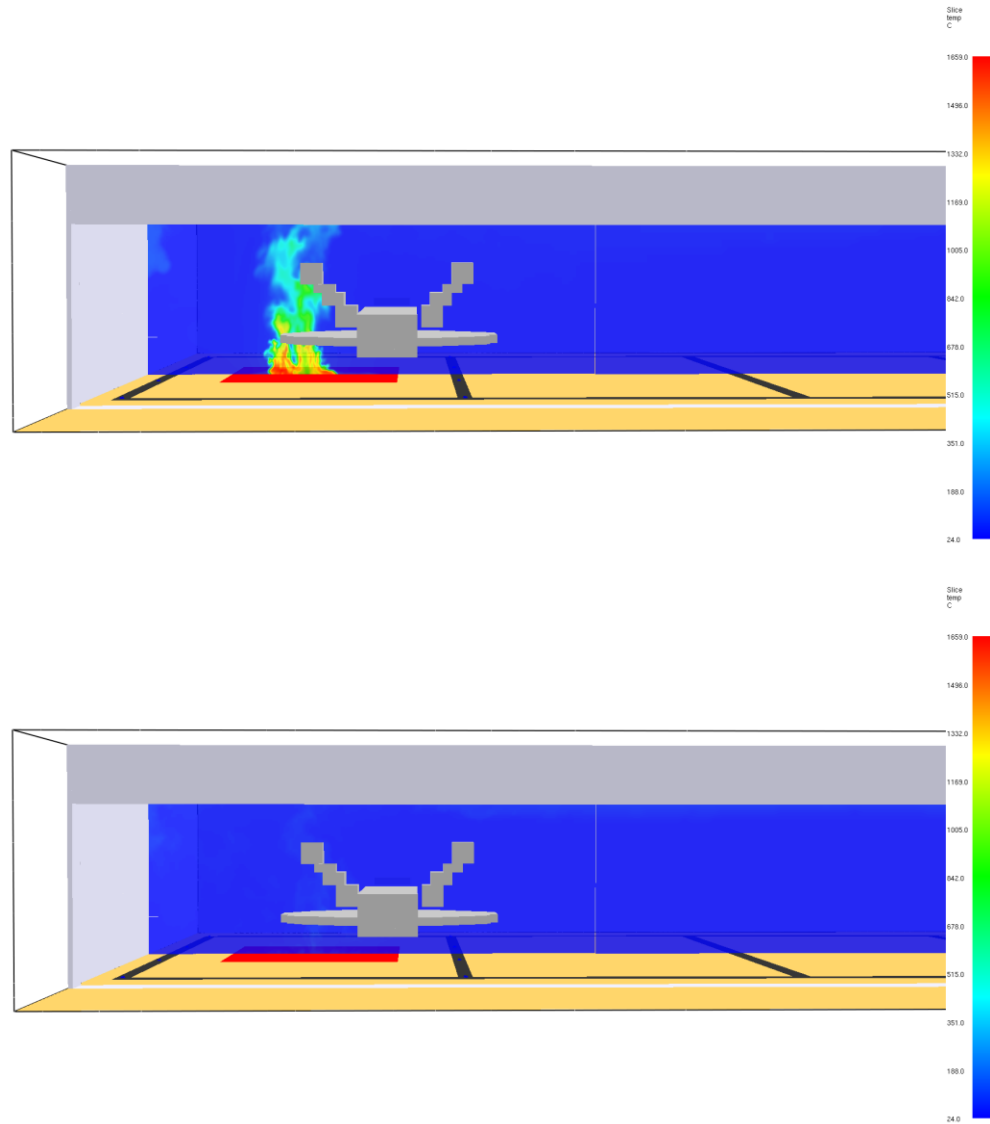


Figure 7-20. Temperature SCLF file for Viking Grate Nozzle with 0.6 m³ spill and 30 seconds activation at 30 seconds (Top) and 36 seconds (Bottom).

The heat fluxes experienced on the plane in this case are also comparable to that in the case of 0.06 m³ spill and 30 seconds nozzle activation. As shown in Figure 7-21, the highest heat flux experienced by the fuselage is approximately 120 kW/m². Additional measurements of other parts of the plane are provided in Appendix A.

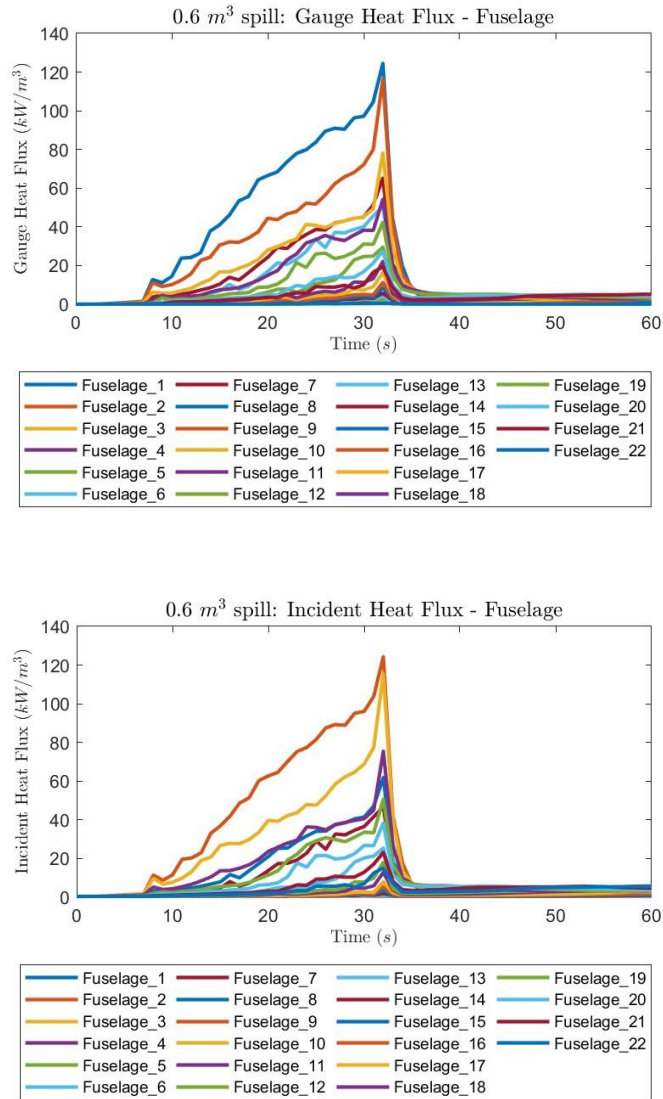


Figure 7-21. Gauge Heat Flux (Top) and Incident Heat Flux (Bottom) measured at Fuselage.

7.1.8 Trench spacing 7.6 m – 0.6 m³ spill – 60 seconds activation

The results including time to extinguishment after nozzle activation and heat fluxes to the plane in this case are akin to that of 0.06 m³ spill with nozzles activate at 60 seconds. The fire is completely extinguished about 10 seconds after nozzle activation as shown

in Figure 7-22 with HRR and MLR of JP-8 curve and Figure 7-23 with temperature
SLCF file at times of interest.

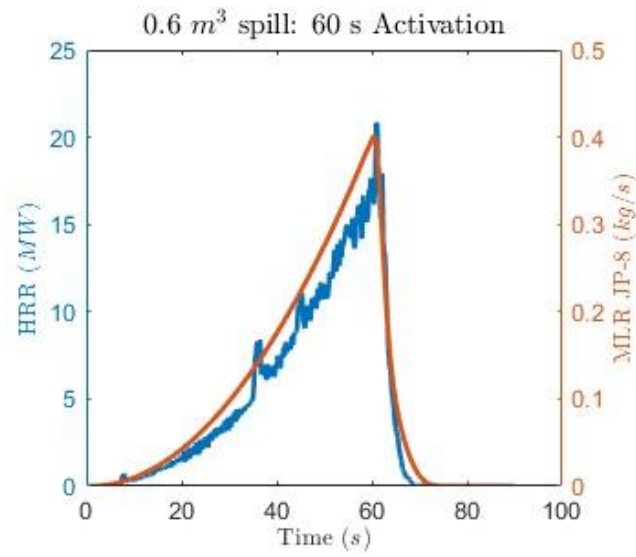


Figure 7-22. Heat Release Rate and MLR of JP-8 for Viking Grate Nozzle with trench spacing 7.6
m – 0.6 m³ spill – 60 seconds activation.

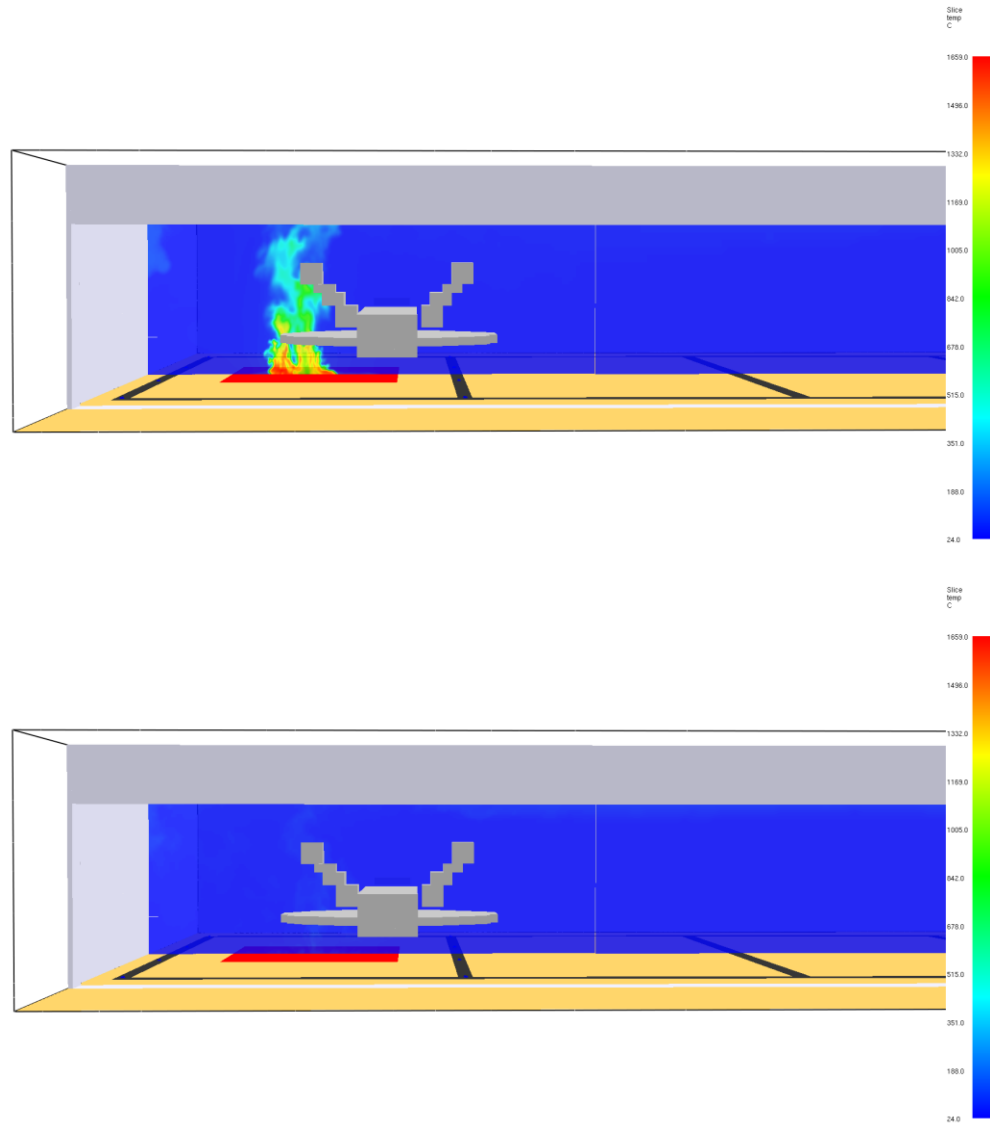


Figure 7-23. Temperature SCLF file for Viking Grate Nozzle with 0.6 m³ spill and 60 seconds activation at 60 seconds (Top) and 81 seconds (Bottom).

Figure 7-24 shows the highest heat fluxes experienced at the plane fuselage. Additional measurements at other locations are provided in Appendix A.

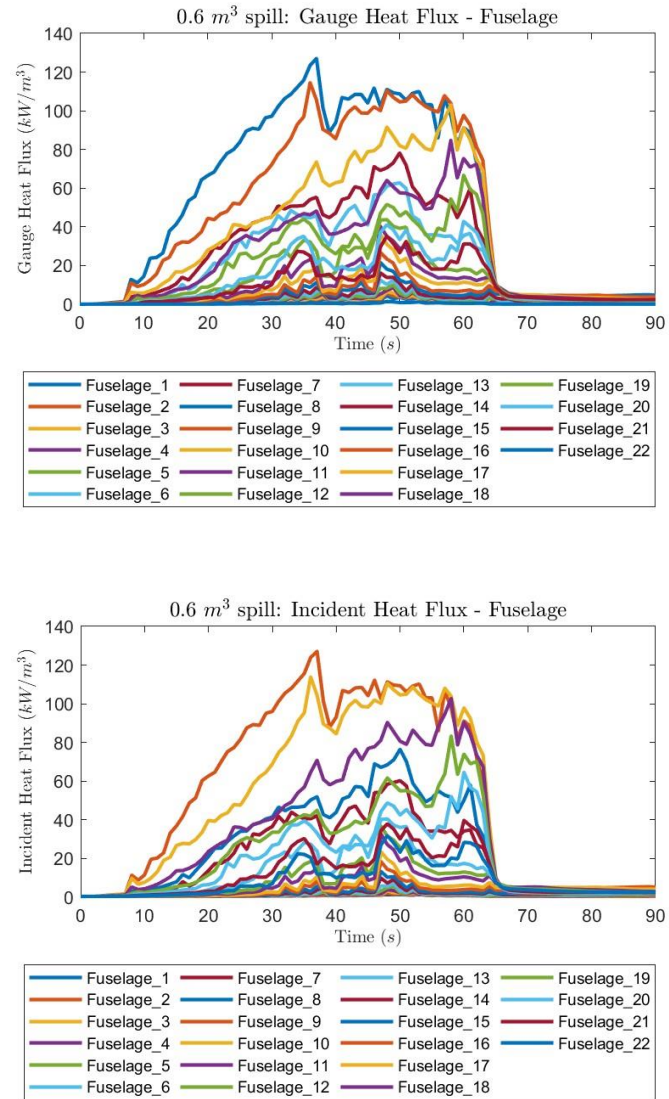


Figure 7-24. Gauge Heat Flux (Top) and Incident Heat Flux (Bottom) measured at Fuselage.

7.1.9 Summary of Results

The results for all scenarios with the Viking Grate Nozzle are summarized in Table 7-1.

Table 7-1. Viking Grate Nozzle Final Simulation Results.

Spill Volume [m ³]	Activation Time [s]	Trench Spacing [m]	Peak HRR [MW]	Time of Extinguishment [s]	Peak Heat Flux to the Plane [kW/m ²]	Critical Damage to the Plane [Y/N]
0.06	30	15.2	7	50	11	N
		7.6	9	36	110	Y
	60	15.2	23	81	24	N
		7.6	20	70	110	Y
0.6	30	15.2	8	50	12	N
		7.6	11	36	120	Y
	60	15.2	25	81	24	N
		7.6	21	70	130	Y

The results above show that reducing the trench spacing shortens the extinguishment time by almost threefold; however, the heat fluxes measured on the plane are also increased by a factor of 10. While the location of the fire in the standard 15.2 m trench spacing is not directly underneath the plane, the location of the fire in the 7.6 m trench spacing is. This examples the drastic difference in heat flux measurements between the two cases.

7.2 VID Fire-Kill F-102

7.2.1 Trench spacing 7.6 m – 0.06 m³ spill – 30 seconds activation

7.2.1.1 Numerical Instabilities

In this scenario, the full-scale simulation with the plane ends with a numerical instability at 33.05 seconds. Further investigation of this issue indicates that FDS might not solve the pressure across the simulation accurately. Figure 7-26 shows the pressure SCLF at the time of the numerical instability. It can be observed that there is a clear separation of pressure between the left, middle, and right side of the plane with a very large variation of approximately 1000 to 2000 Pa. A burst of pressure can be expected from the nozzle activation due to the evaporation of droplets; however, the difference observed is unexpectedly large and might be the cause of the numerical instability.

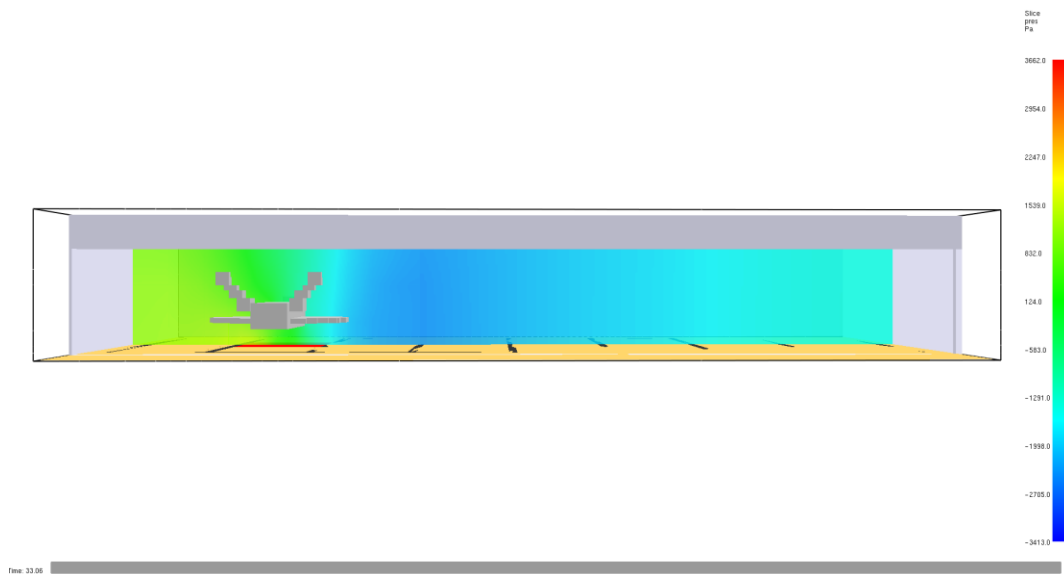


Figure 7-26. Pressure SCLF at 33.05 seconds (Numerical Instability Time)

FDS uses MAX_PRESSURE_ITERATIONS with a default value of 10 to control the maximum number of pressure iterations for each half of the time step. This parameter is tested with values ranging from 100 to 10,000 in full-scale simulation with the plane to investigate the accuracy of pressure solver. However, all simulations end with the same numerical instability at 33.05 seconds, suggesting that the issue might not be from the pressure solver itself. It can be theorized that the plane geometry contributes to the numerical instability as the previous small-scale extinction with water mist systems works without this numerical instability. Previous work by Lee (2023) reports numerical instabilities with high-pressure water mist simulations ran on FDS v6.7.9 that could be solved from running the same simulations on an older FDS v6.7.4 [9]. The same solution can potentially be applied in this case. These theories are tested in the subsequent sections.

7.2.1.2 No Plane Simulation

The simulation with VID Fire-kill nozzles is done without the plane to test the fire extinguishment of the water mist systems. The result in Figure 7-26 with HRR and MLR of JP-8 curves shows unsuccessful fire extinguishment as the fire continues to grow to about 25 MW at the end of the simulations. Additional visualizations with temperature SCLF at times of interest are provided in Figure 7-27.

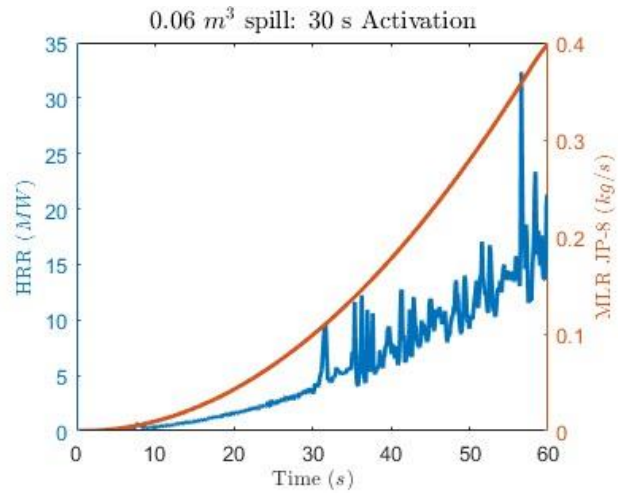


Figure 7-26. Heat Release Rate and MLR of JP-8 for VID Fire-kill Nozzle with trench spacing 7.6

m – 0.6 m³ spill – 30 seconds activation – No Plane on v6.7.9

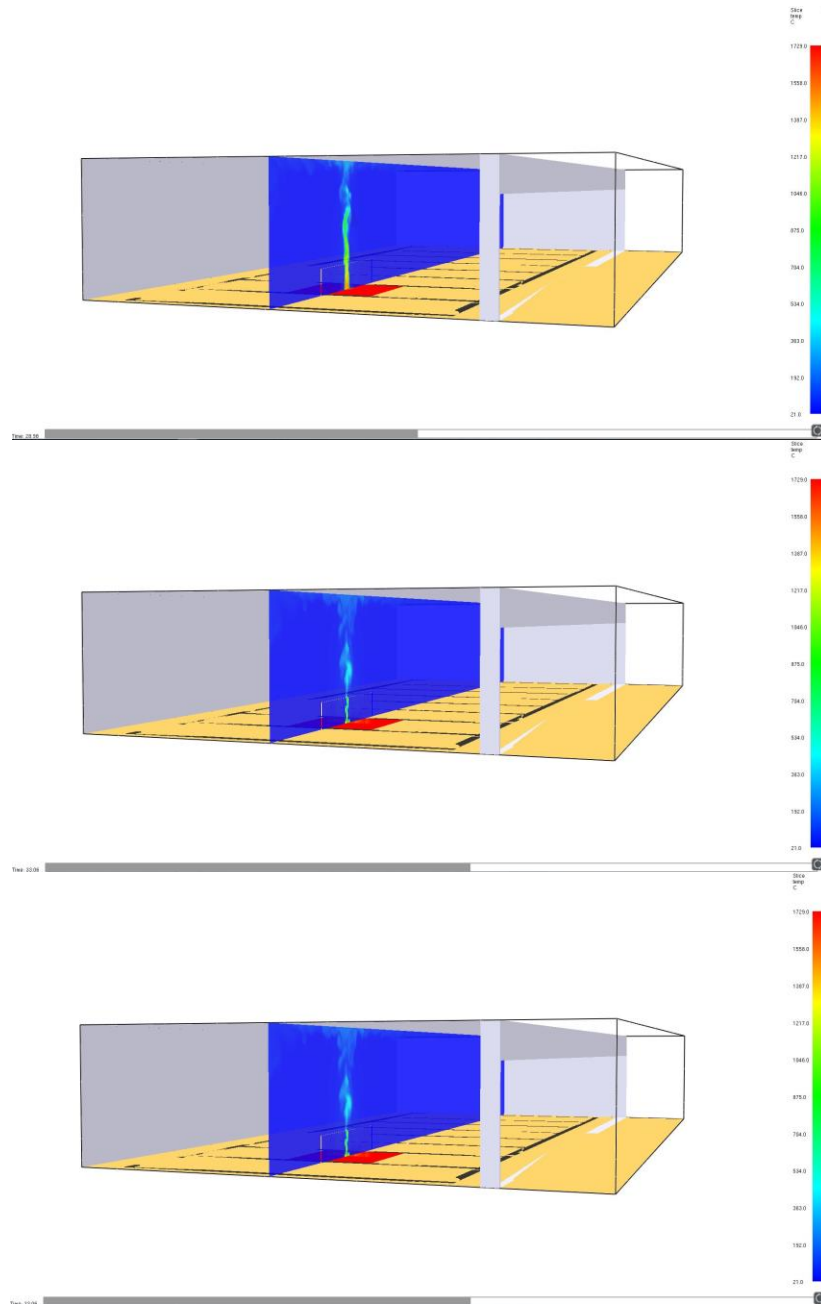


Figure 7-27. Temperature SCLF file for Viking Grate Nozzle with 0.06 m³ spill and 30 seconds activation at times of interest. From top to bottom: 29 seconds (before the nozzle activation), 33 seconds, and 58 seconds.

7.2.1.3 Full-scale Simulation on FDS v6.7.4

The full-scale simulation with a plane runs successfully without a numerical instability on FDS v6.7.4, suggesting that a change in the evaporation model between the two versions might be the cause of the numerical instability issue. On the other hand, the result of this simulation is consistent with the result shown in the previous test without the plane that is run with v6.7.9. The HRR and MLR of JP-8 shown in Figure 7-28 match those shown in Figure 7-26.

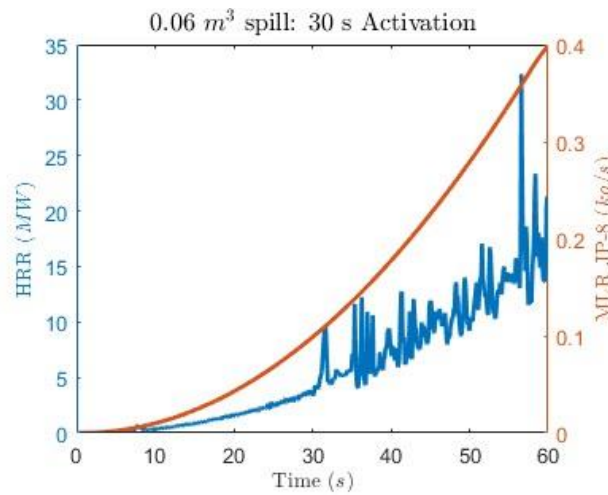


Figure 7-28. Heat Release Rate and MLR of JP-8 for VID Fire-kill Nozzle with trench spacing 7.6

m – 0.6 m³ spill – 30 seconds activation – v6.7.4

The maximum heat flux is observed at Fuselage at about 120 kW/m², as shown in Figure 7-29. Additional heat flux measurements elsewhere on the plane are provided in Appendix B.

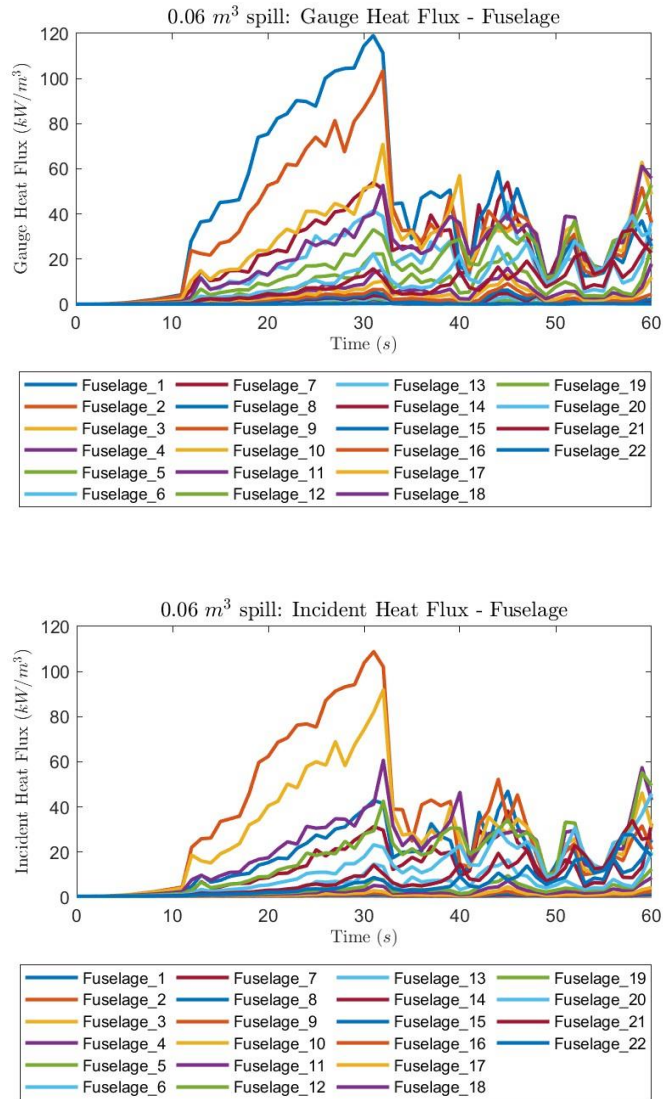


Figure 7-29. Gauge Heat Flux (Top) and Incident Heat Flux (Bottom) measured at Fuselage.

Due to the inadequate performance of low-pressure water mist systems with VID Fire-kill F-102 model in the 0.06 m³ spill case, no further simulations with a larger spill or later activation times are needed. While these water mist systems are compatible with

the current NAVFAC setup, they do not provide the same performance as the sprinkler systems.

Chapter 8 Conclusion

8.1 Summary

In this study, the current low expansion AFFF foam suppression systems with trenches used in the U.S. Navy facilities are simulated as sprinkler systems to investigate the performance of such water-based systems in fuel spill fire scenarios. Additional simulations with COTS floor-level low-pressure water mist systems previously identified by a study by Steranka (2021) with the incorporation of trench systems are conducted to compare the suppression level of low-pressure water mist systems with that of sprinkler systems. Each simulation consists of three models: fire model, sprinkler, or water mist model, and extinction model.

The fire model of two fire scenarios, 0.06 m^3 and 0.6 m^3 uncontained JP-8 fuel spill, are created based on information such as chemical formula, MLRPUA/HRRPURA, CO yield and spread rate found in literature. Three radiation options in FDS along with radiative fraction and soot yield values are investigated through total heat flux measurement across burner. From this investigation, the optically thick option with a specific radiative fraction of 0.05 and no soot yield is deemed to be the best option to model uncontained fuel spill scenarios. Additionally, a length-scale analysis is performed to ensure the model is well-resolved.

In the sprinkler model, several calibration tests are conducted to determine the spray characteristics of Viking Grate Nozzles based on a bucket test result provided by Viking. A length-scale analysis is also performed to determine the appropriate grid size

that captures the spray details while being relatively low-cost. As a result, a hybrid mesh design is adapted. On the other hand, the water mist model utilizes a spray pattern of VID Fire-kill F-102 nozzle previously developed by Steranka (2021). With updated information on k-factor and operating pressure from the manufacturer, a length-scale analysis is conducted and found that a 0.05 cm grid size is applicable to capture the spray pattern in the near field of the nozzle.

In the extinction model, several tests are orchestrated to study two methods of ignition for water mist systems: surface temperature ramp and AIT exclusion zone, with and without nozzle activations. The AIT exclusion zone is determined to be the best ignition method without nozzle activation. However, this method proposes many unwanted results such as the lack of water and fire interaction in tests with nozzle activation. Essentially, the surface temperature ramp is used in final hangar simulations to minimize any unexpected drawbacks.

The final simulations with Viking Grate Nozzles show successful extinguishment for fires up to 23 MW. There are essentially no differences between two fuel spill cases with the same activation time. Additionally, an earlier activation time will minimize damage to the plane as the heat fluxes measured in earlier activation cases are almost two times lower than that experienced in later activation cases. While reducing the trench spacing shortens the extinguishment time by almost triple, the heat fluxes measured on the plane are much higher than the critical heat flux associated with the plane material, suggesting that the plane might suffer from critical damage. Overall, the current setup with 15.2 m trench spacing is chosen to be the better option.

The final simulation with the low-pressure water mist systems and VID Fire-kill F-102 nozzle results in unsuccessful extinguishment with 0.06 m³ JP-8 spill case. While the water mist systems are applicable with the trench systems, they do not provide adequate protection against jet fuel spill fires.

8.2 Limitations and Future Work

There are several limitations to the models applied throughout this study. The most notable limitations are:

1. Similar to previous work, a constant MLRPUA or HRRPUA is applied. This fire model does not account for reduction of burning rate.
2. For sprinkler cases with Viking Grate Nozzle, a reduction of burning rate parameter $E_COEFFICIENT$ is set to be 1 m²/(kg-s). The value for this parameter must be obtained experimentally; however, due to Viking Grate Nozzle's intent use as a foam nozzle, there is no experimental data to calibrate this parameter. The value is approximate from literature.
3. The fire scenarios throughout this study are modeled as worst-case scenarios due to FDS inability to model free-flowing fuel.

From the limitations of this study, several areas of future work can be explored:

1. Investigation of liquid pyrolysis model. If the fuel is given reaction parameters via the MATL line i.e., liquid pyrolysis model is activated, there is no need to set any additional suppression parameters. This investigation can potentially

solve the issue with limited experimental data to calibrate E_COEFFICIENT parameter.

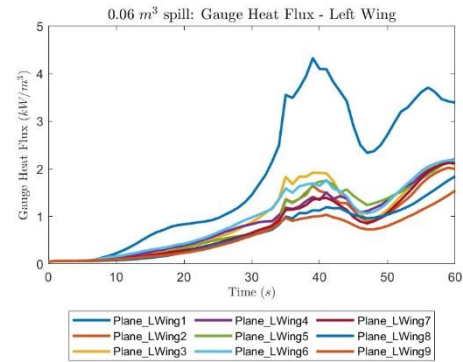
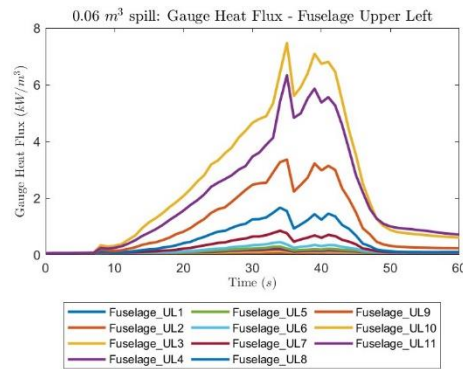
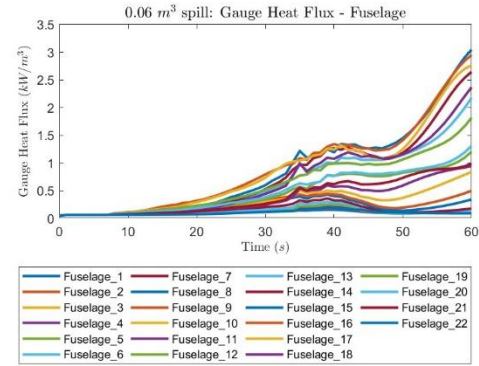
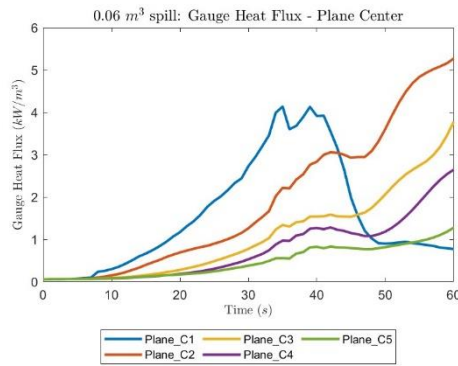
2. Development of a design guidelines for AIT_EXCLUSION_ZONE. The ignition method with AIT_EXCLUSION_ZONE can be the most accurate method to prescribe a fire; however, additional testing needs to be done to investigate its sensitivity with grid resolution and size of the burner.
3. Improvement to MATLAB script to read SCLF file with multi meshes setup.
4. Understanding of numerical instability issue with water mist systems in FDS v6.7.9.

Appendices

Appendix A. Additional Measurements for Viking Grate Nozzle

Any measurements below 1 kW/m^2 are considered insignificant and discarded from this section. For cases with trench spacing 7.6 m , since the burner is placed directly underneath and center of the plane, the heat fluxes experienced on both sides of the plane are symmetrical. Thus, only the left side measurements are recorded.

A.1 Trench spacing 15.2 m – 0.06 m^3 spill – 30 seconds activation



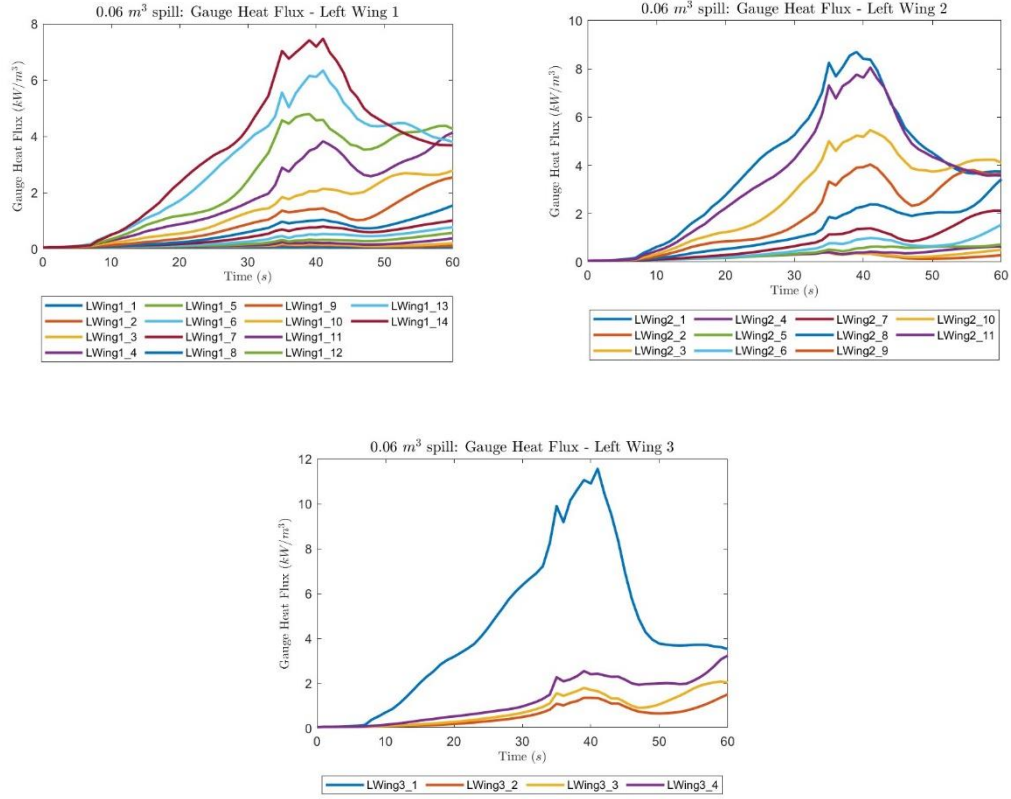
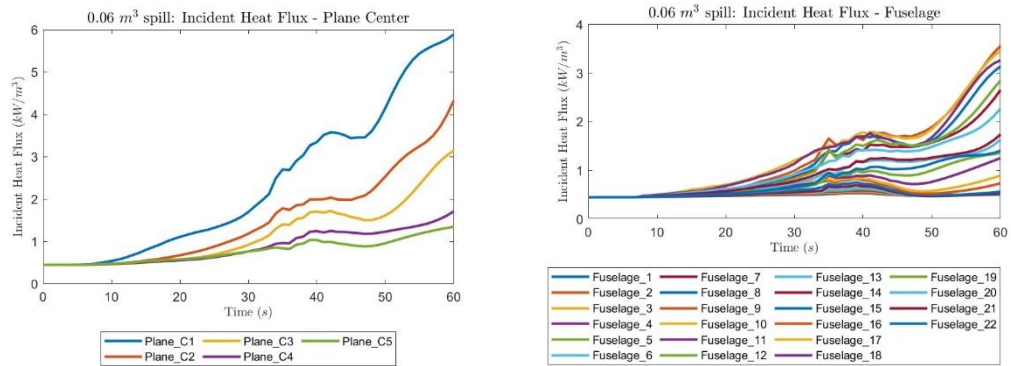


Figure A-1. Trench spacing 15.2 m – 0.06 m³ spill – 30 seconds activation – Gauge Heat Flux to the Plane.



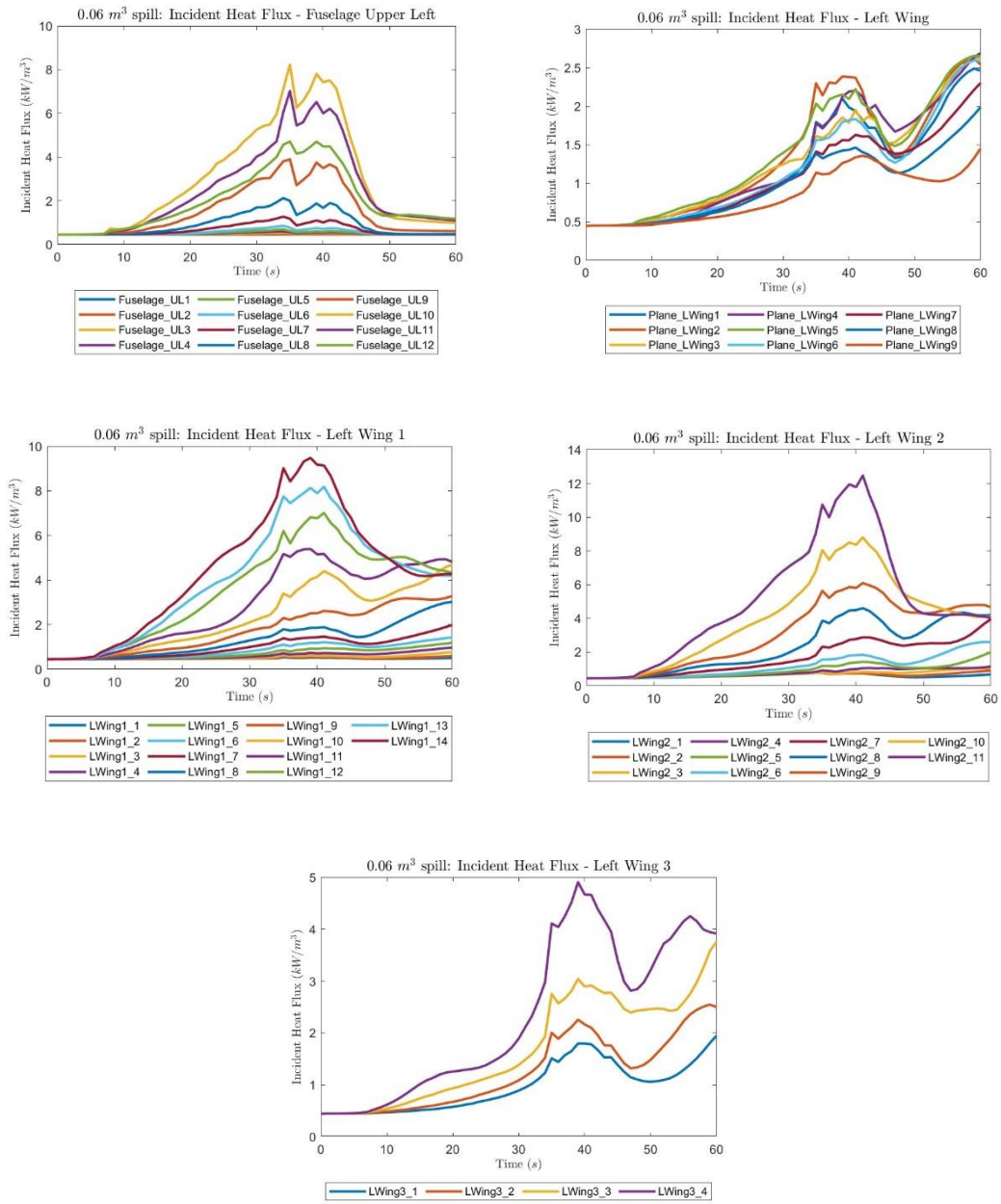
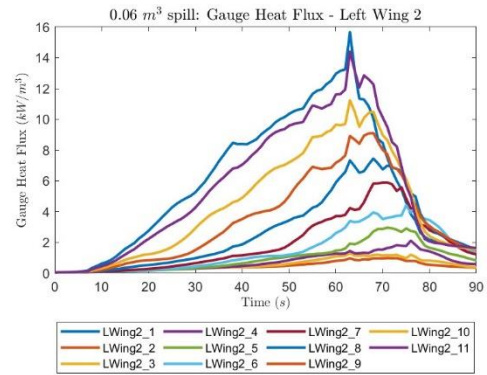
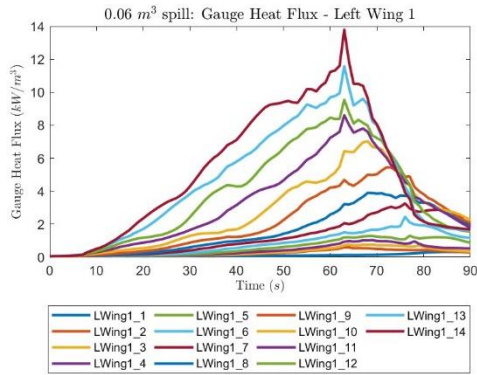
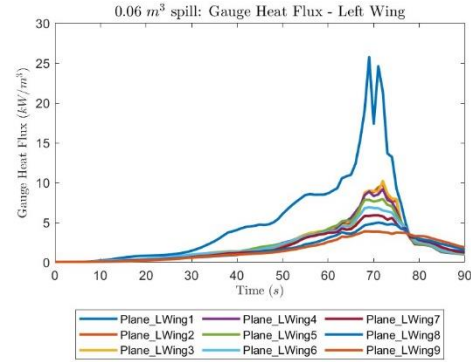
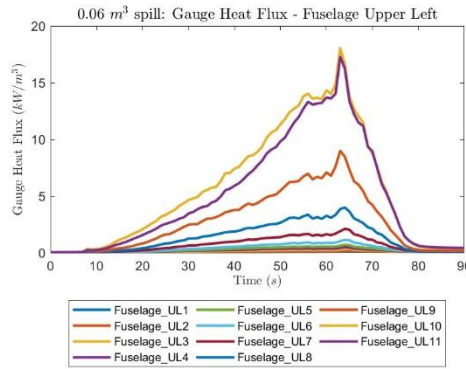
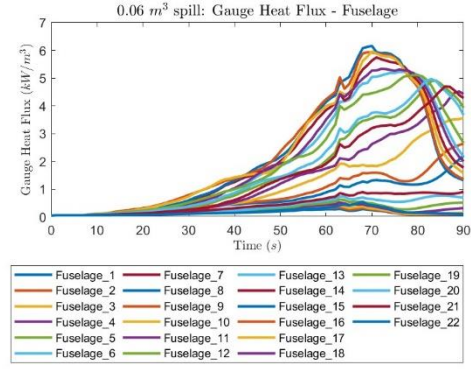
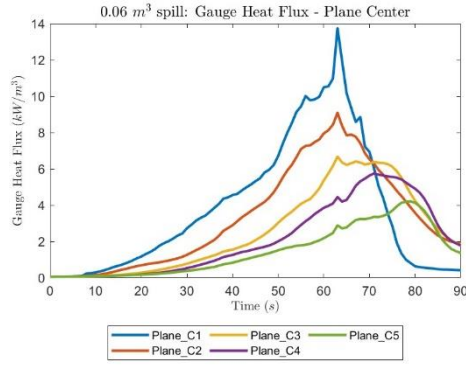


Figure A-2. Trench spacing 15.2 m – 0.06 m³ spill – 30 seconds activation – Incident Heat Flux to the Plane.

A.2 Trench spacing 15.2 m – 0.06 m³ spill – 60 seconds activation



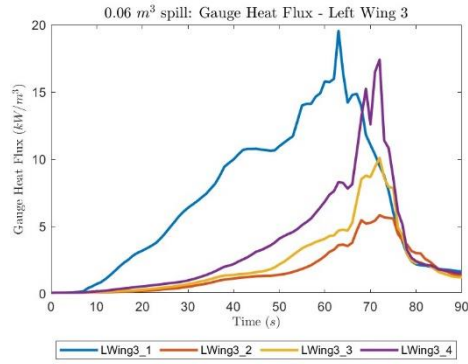
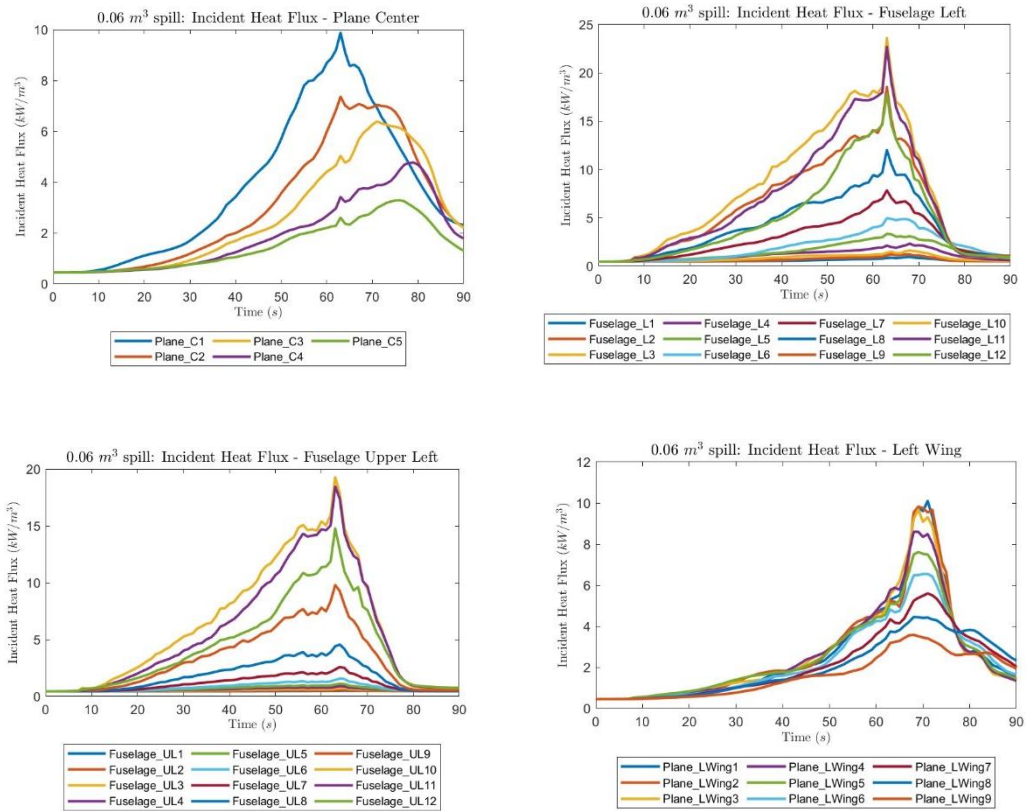


Figure A-3. Trench spacing 15.2 m – 0.06 m³ spill – 60 seconds activation – Gauge Heat Flux to the Plane.



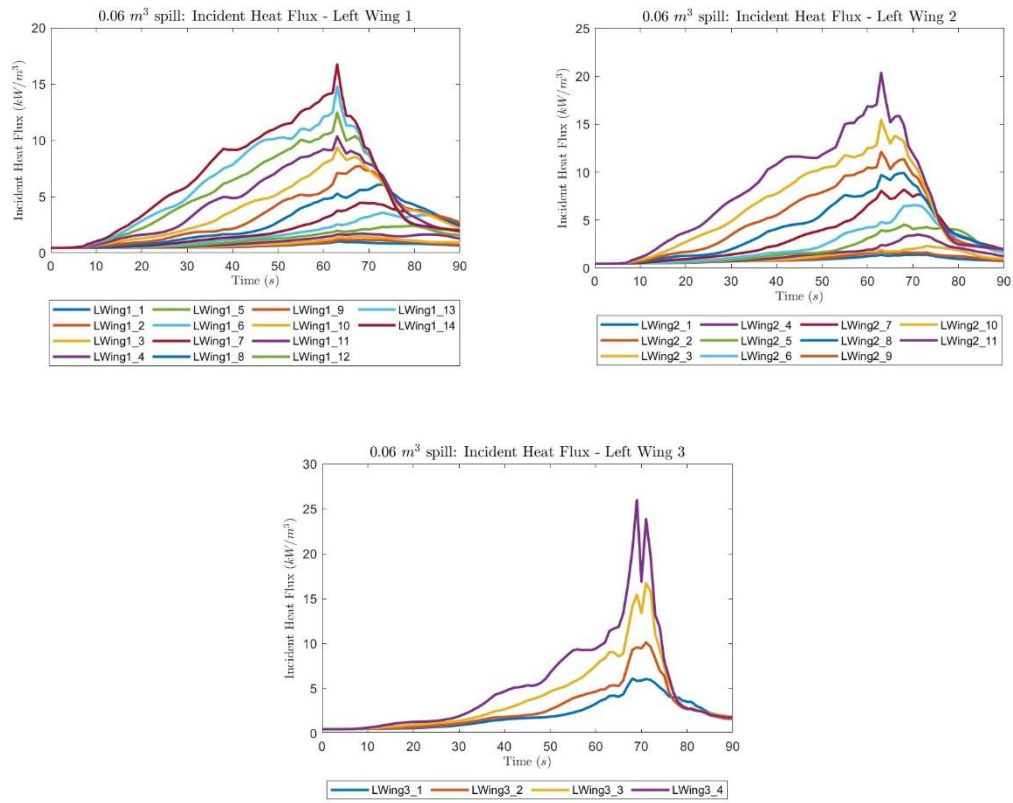
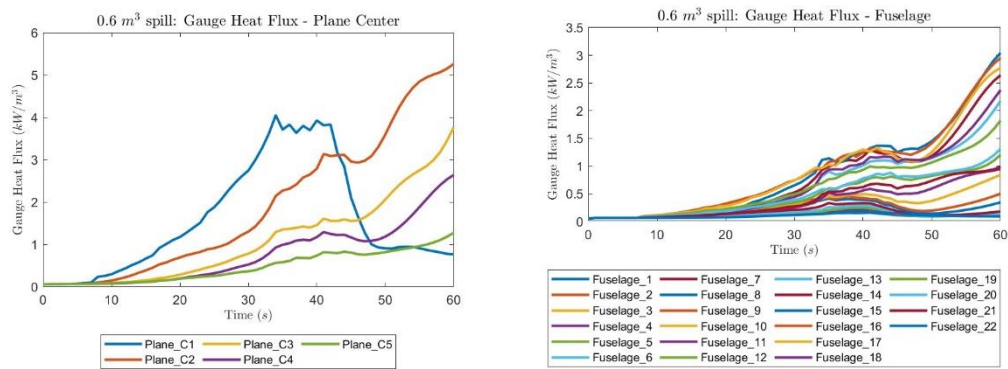


Figure A-4. Trench spacing 15.2 m – 0.06 m³ spill – 60 seconds activation – Incident Heat Flux to the Plane.

A.3 Trench spacing 15.2 m – 0.6 m³ spill – 30 seconds activation



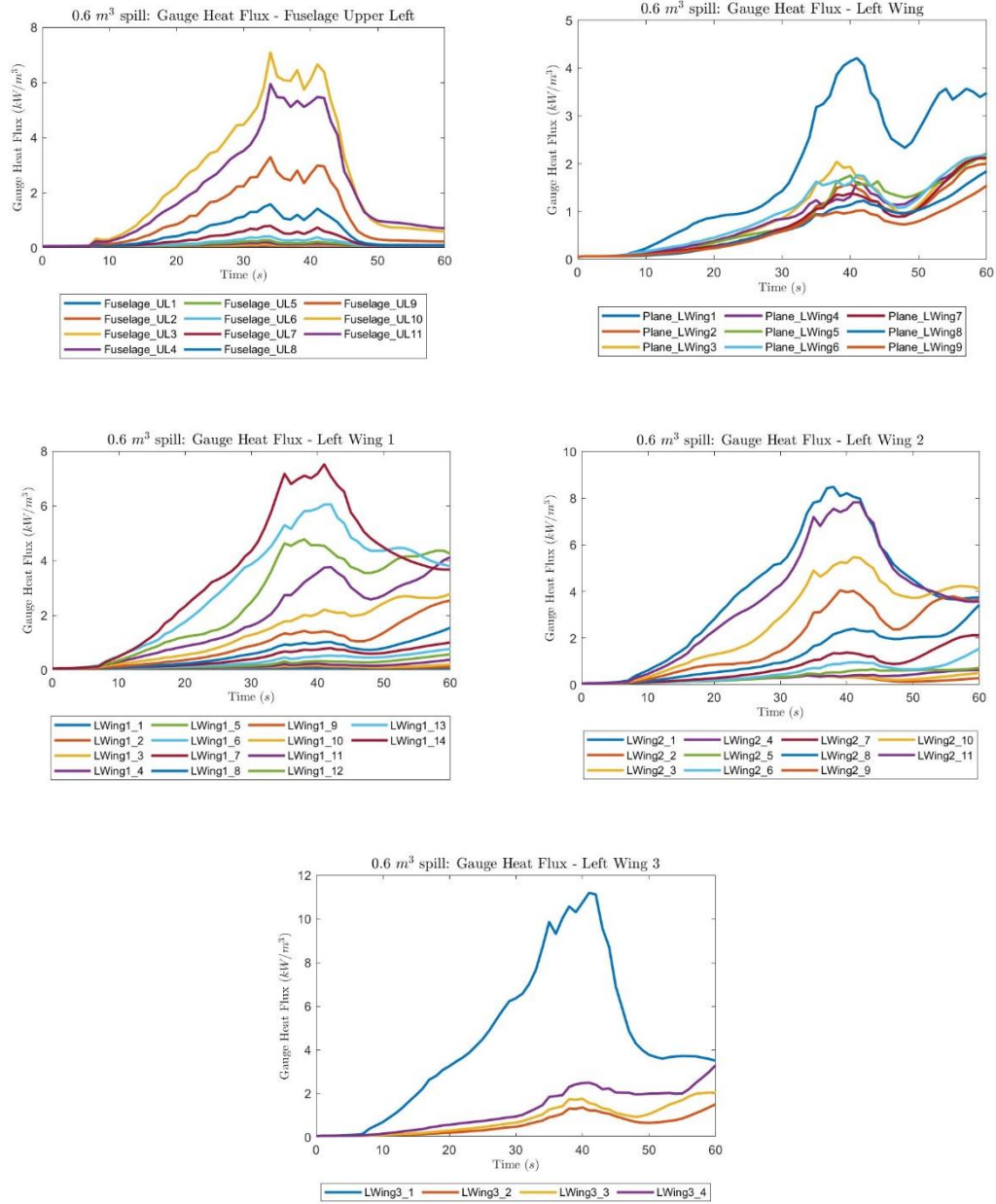
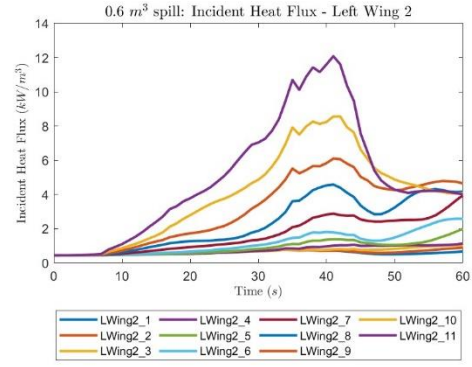
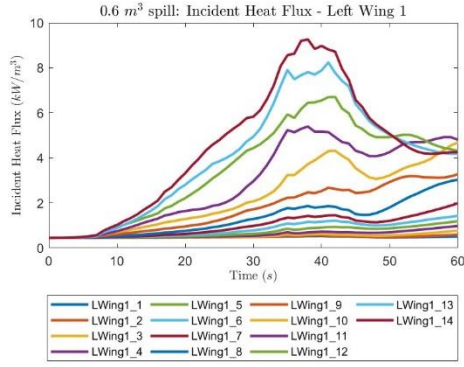
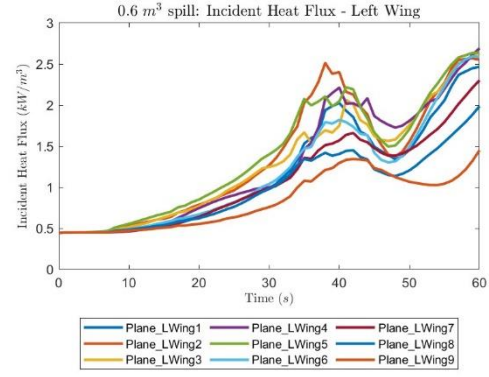
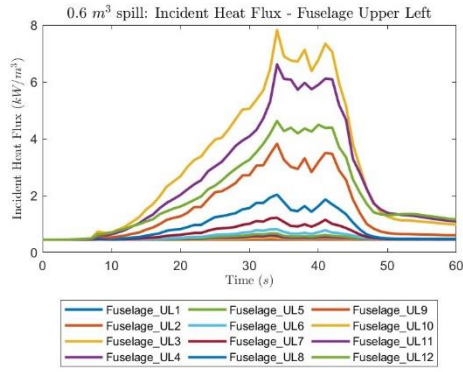
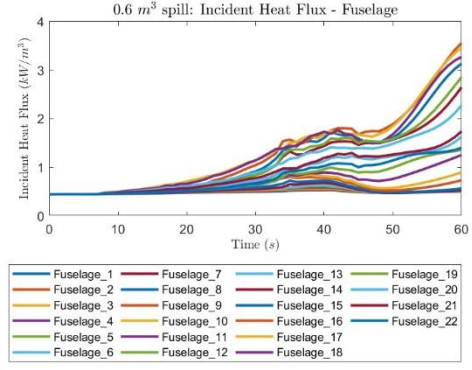
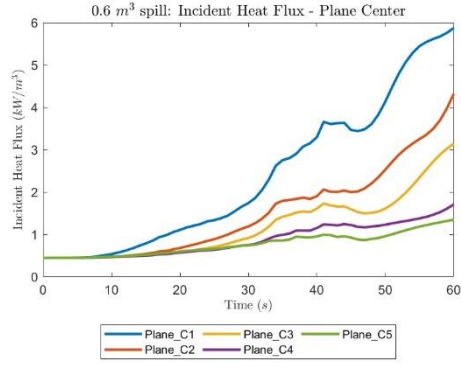


Figure A-5. 3 Trench spacing 15.2 m – 0.6 m³ spill – 30 seconds activation – Gauge Heat Flux to the Plane.



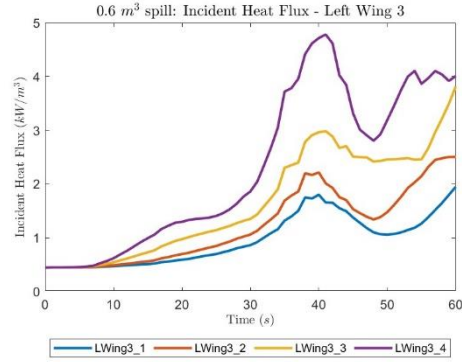
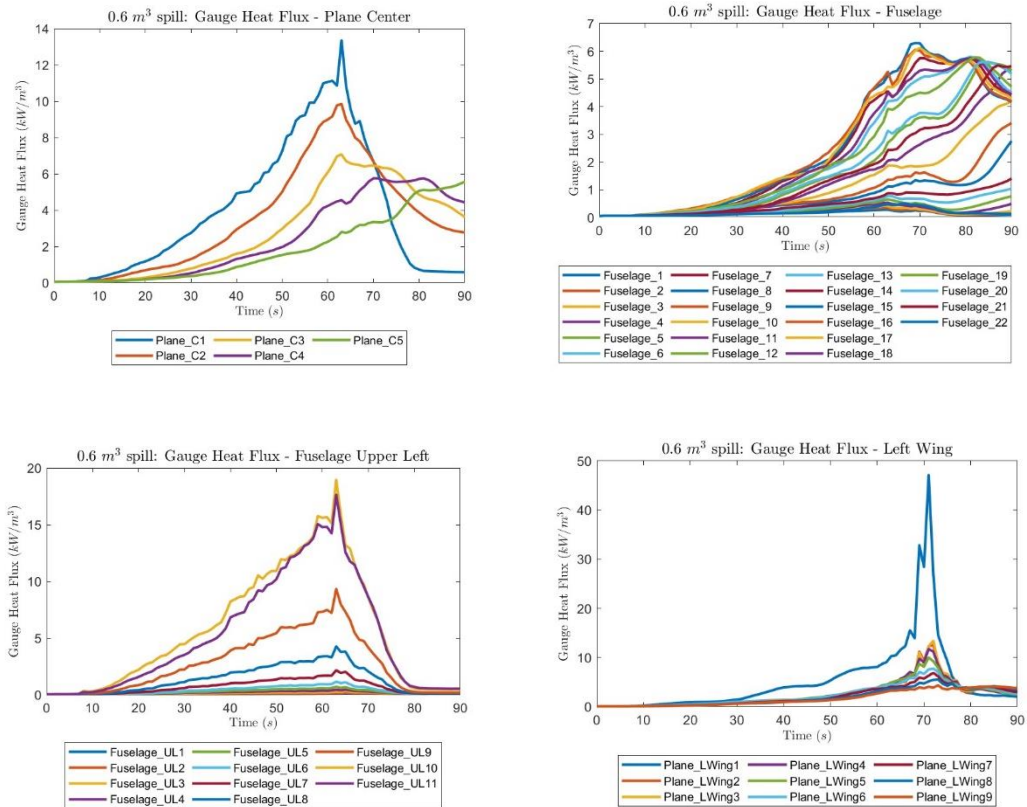


Figure A-6. 3 Trench spacing 15.2 m – 0.6 m³ spill – 30 seconds activation – Incident Heat Flux to the Plane.

A.4 Trench spacing 15.2 m – 0.6 m³ spill – 60 seconds activation



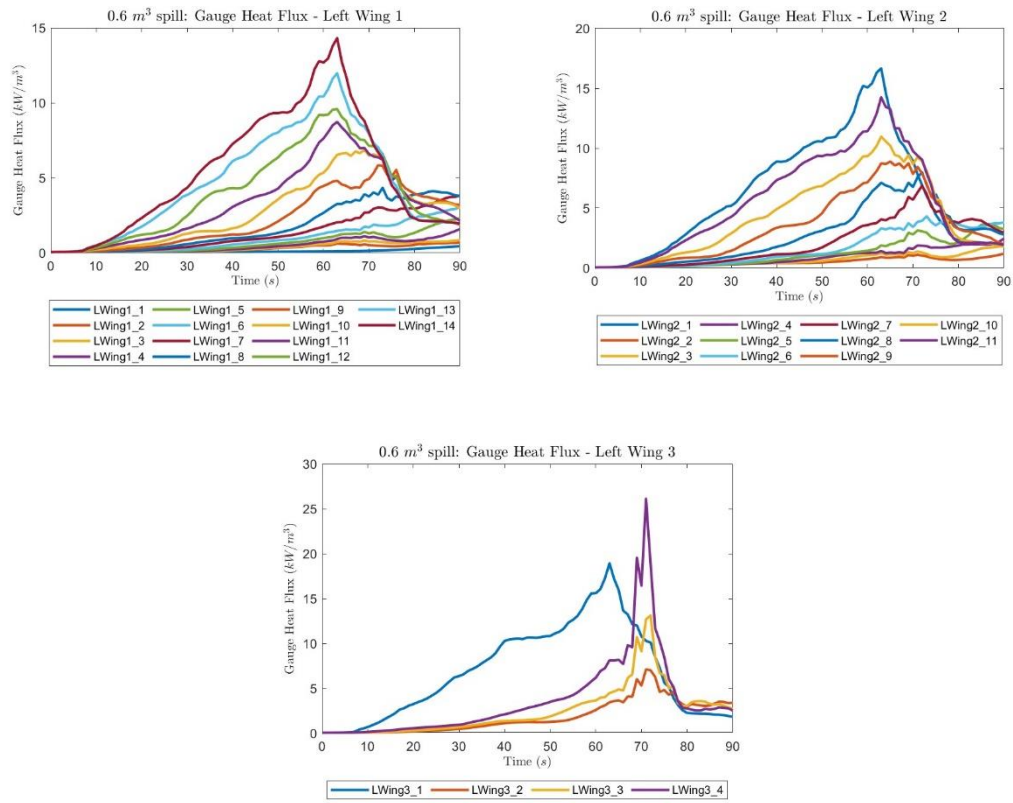
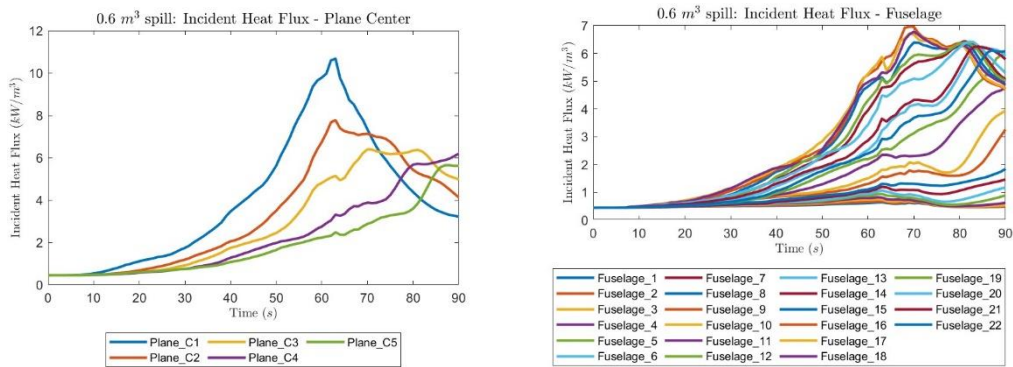


Figure A-7. Trench spacing 15.2 m – 0.6 m³ spill – 60 seconds activation – Gauge Heat Flux to the Plane.



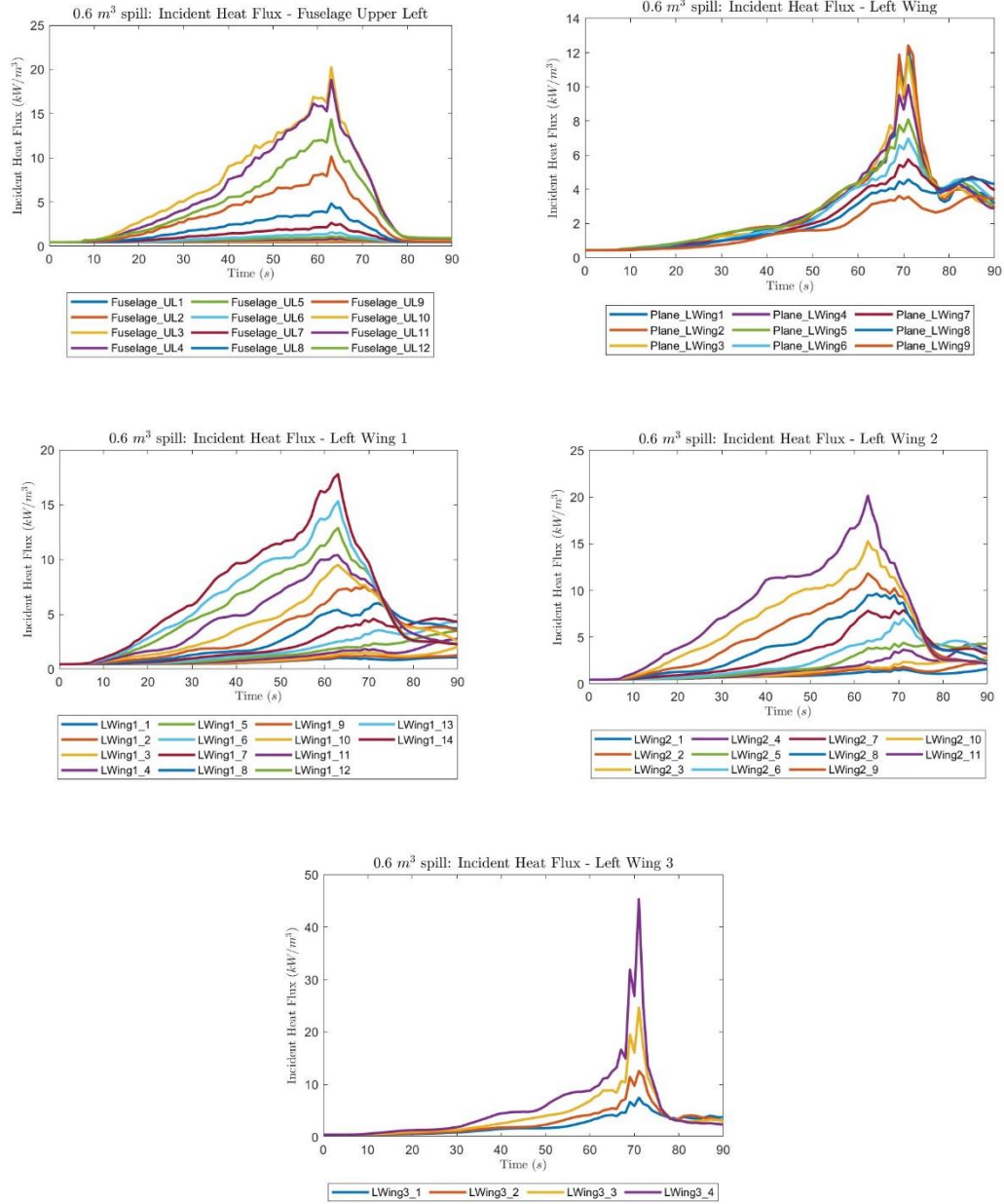
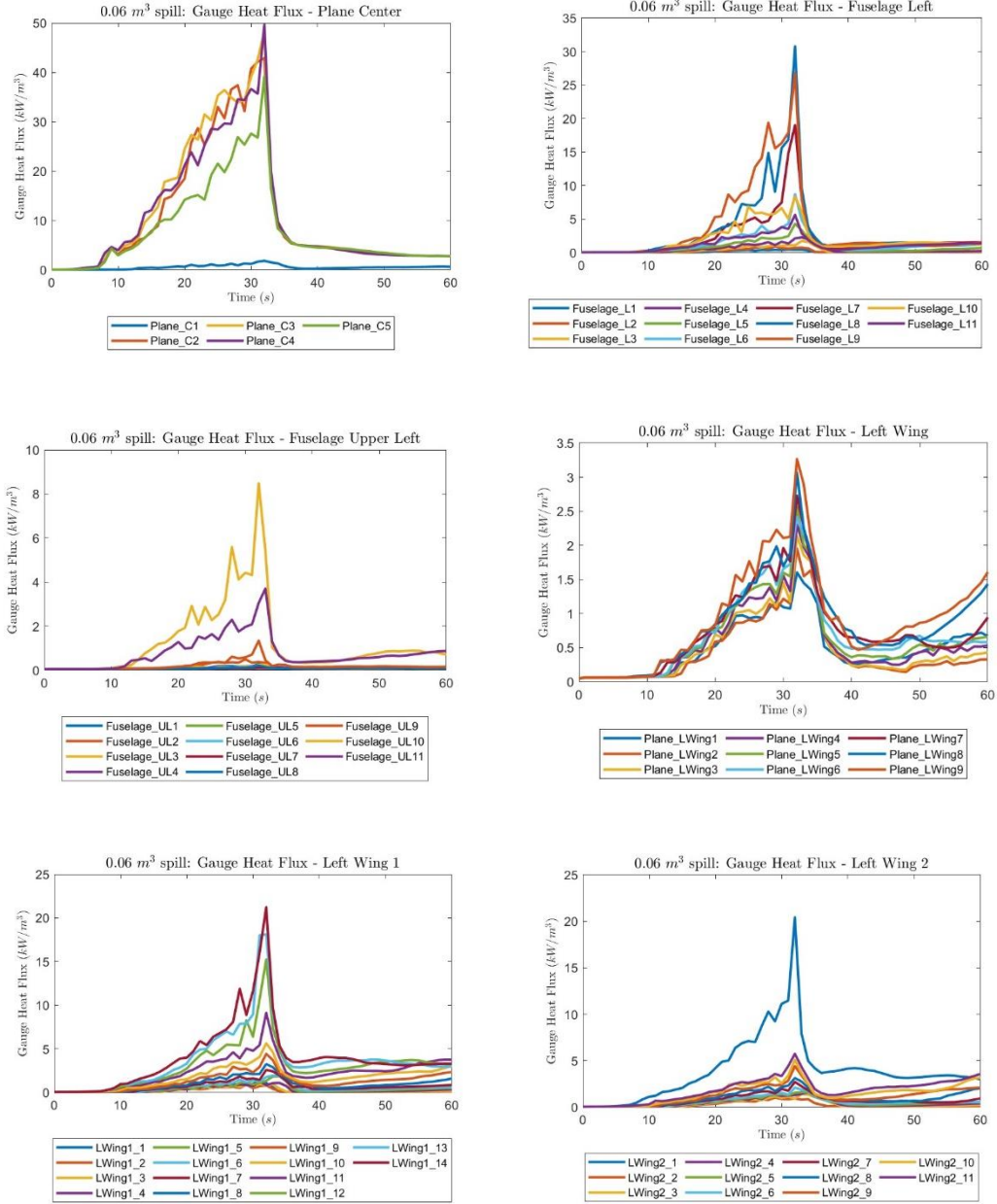


Figure A-8. Trench spacing 15.2 m – 0.6 m³ spill – 60 seconds activation – Incident Heat Flux to the Plane.

A.5 Trench spacing 7.6 m – 0.06 m³ spill – 30 seconds activation



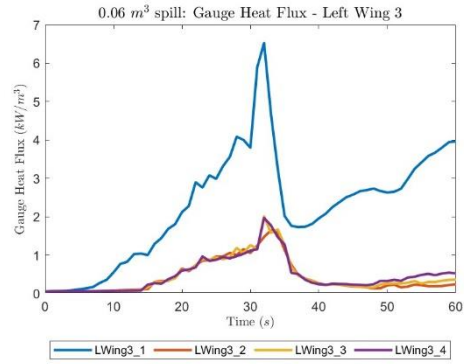
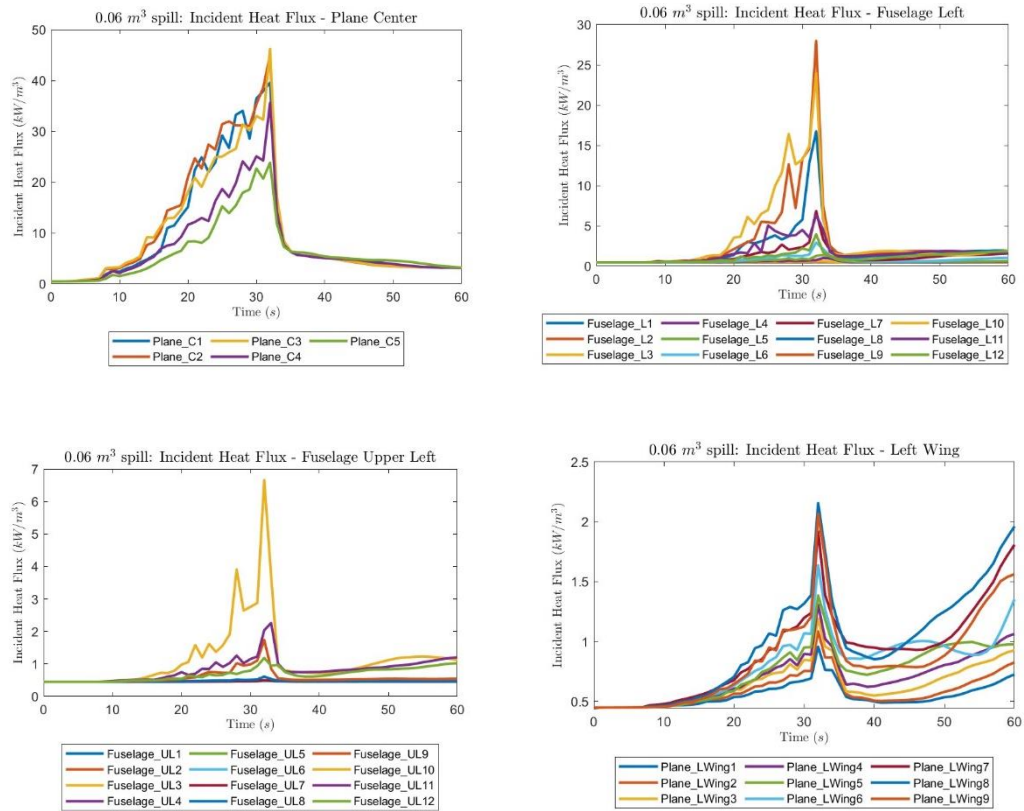


Figure A-9. Trench spacing 7.6 m – 0.06 m³ spill – 30 seconds activation – Gauge Heat Flux to the Plane.



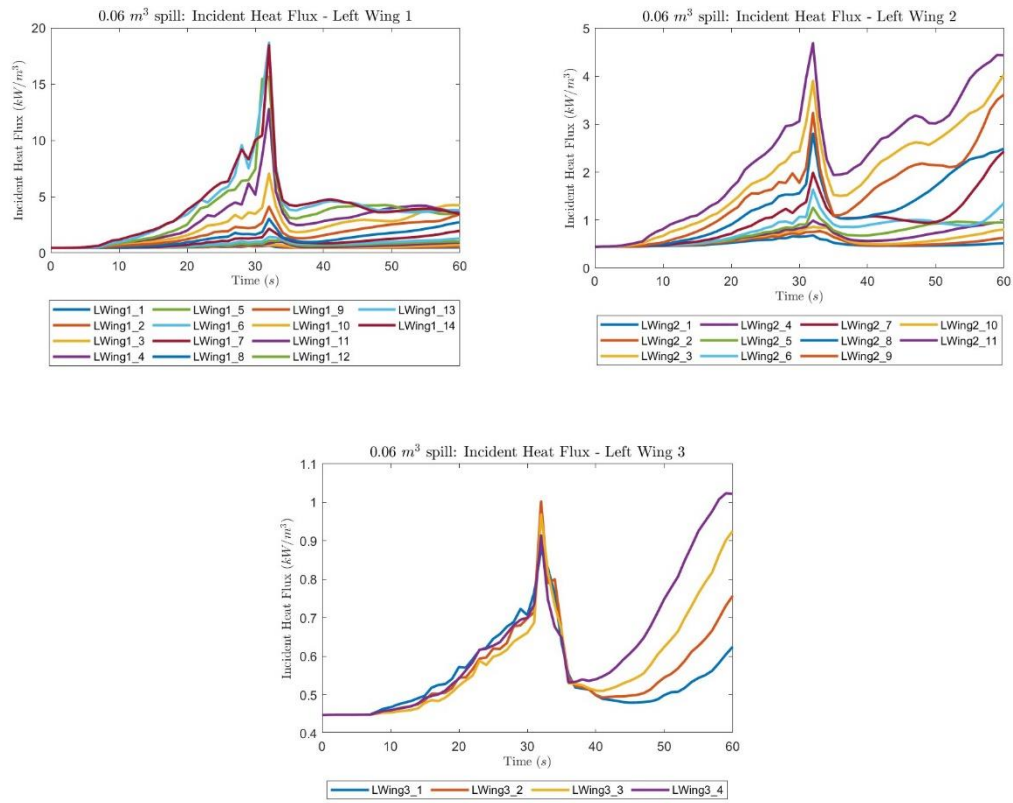
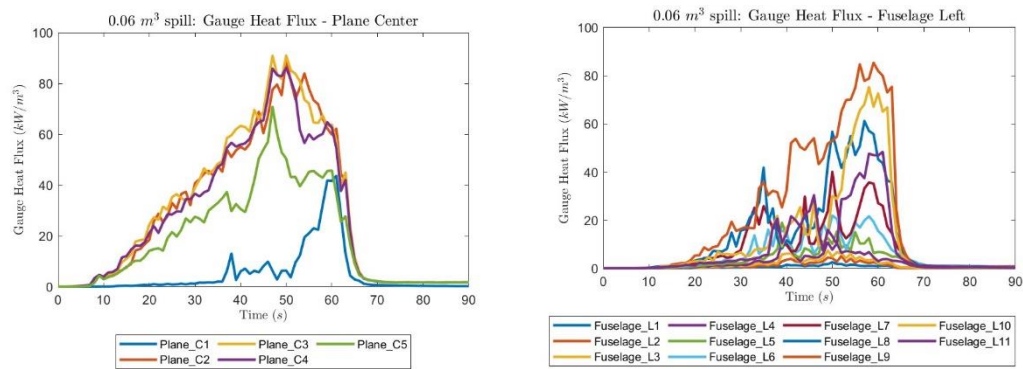


Figure A-10. Trench spacing 7.6 m – 0.06 m³ spill – 30 seconds activation – Incident Heat Flux to the Plane.

A.6 Trench spacing 7.6 m – 0.06 m³ spill – 60 seconds activation



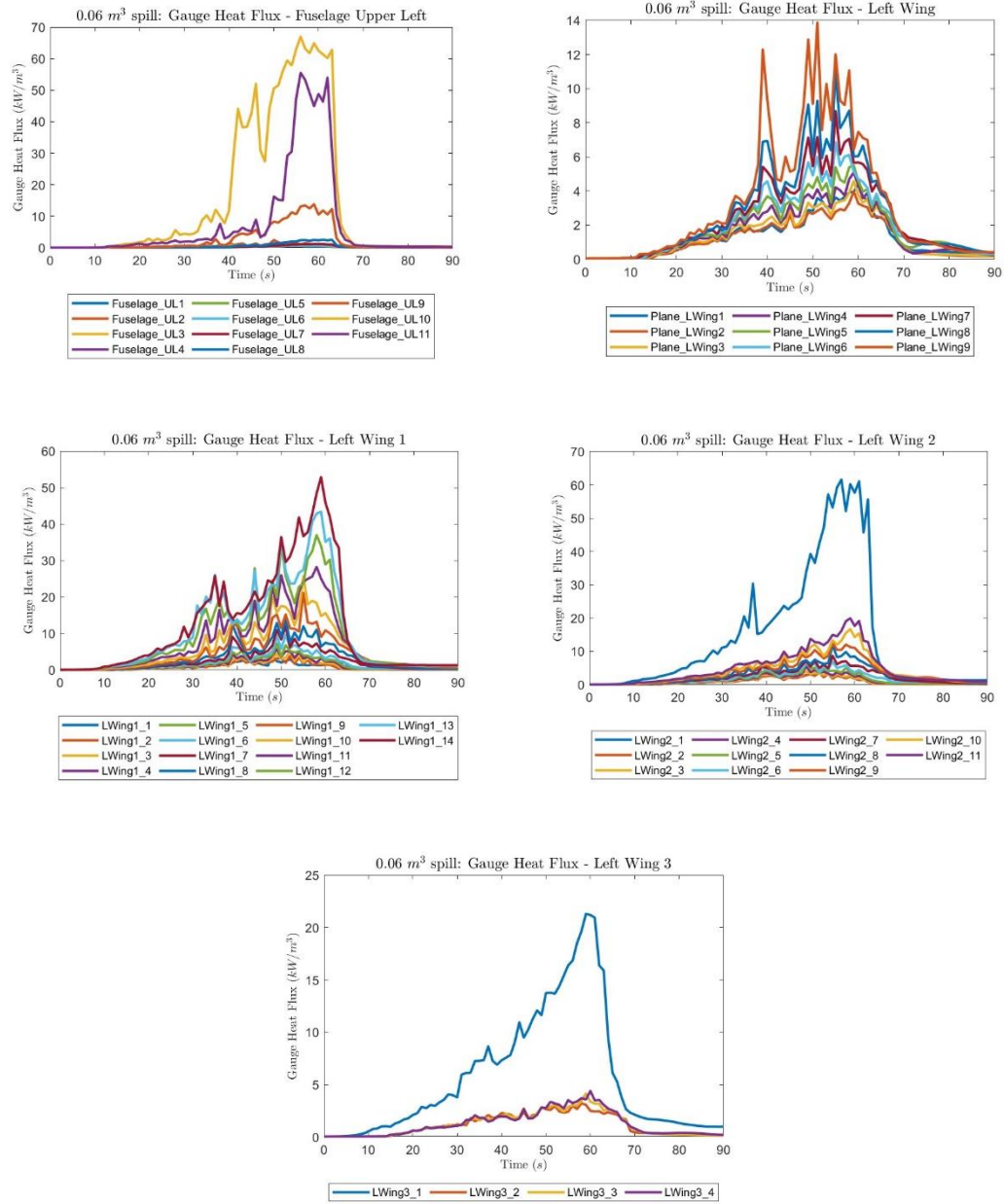
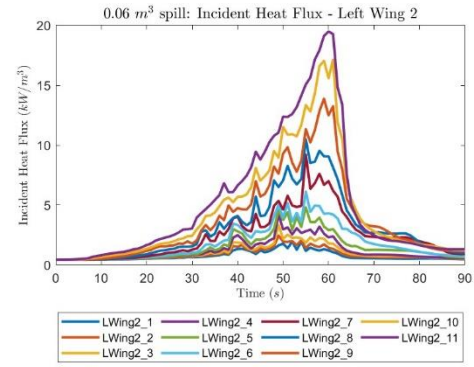
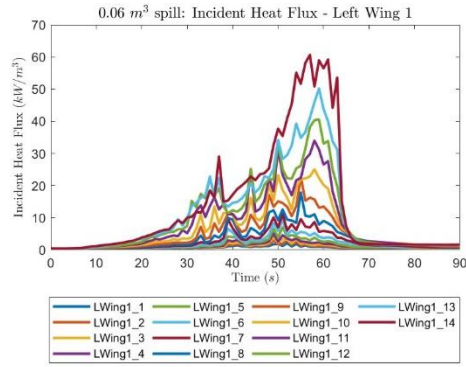
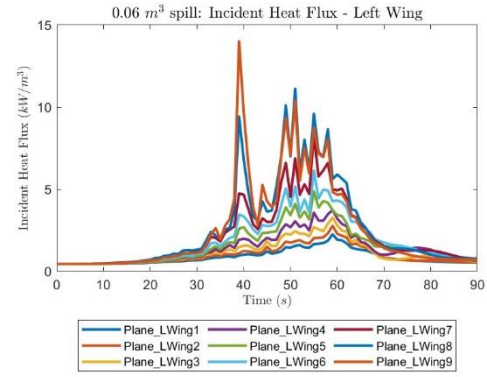
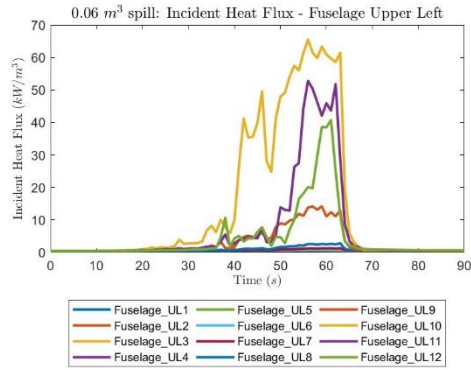
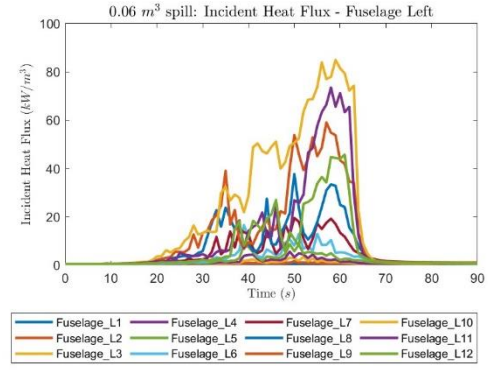
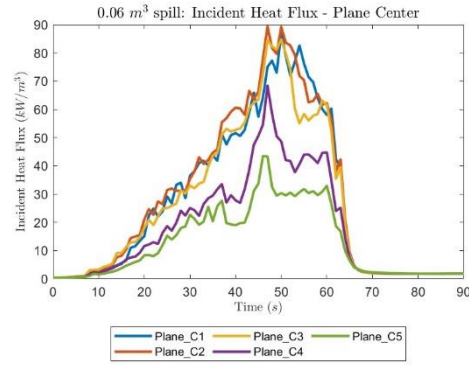


Figure A-11. Trench spacing 7.6 m – 0.06 m³ spill – 60 seconds activation – Gauge Heat Flux to the Plane.



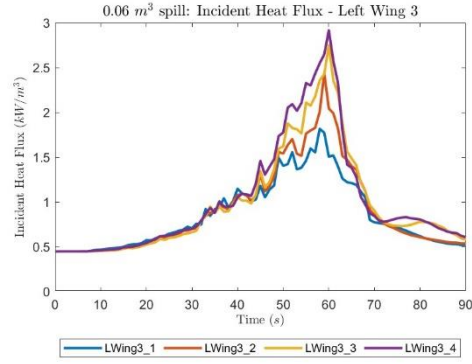
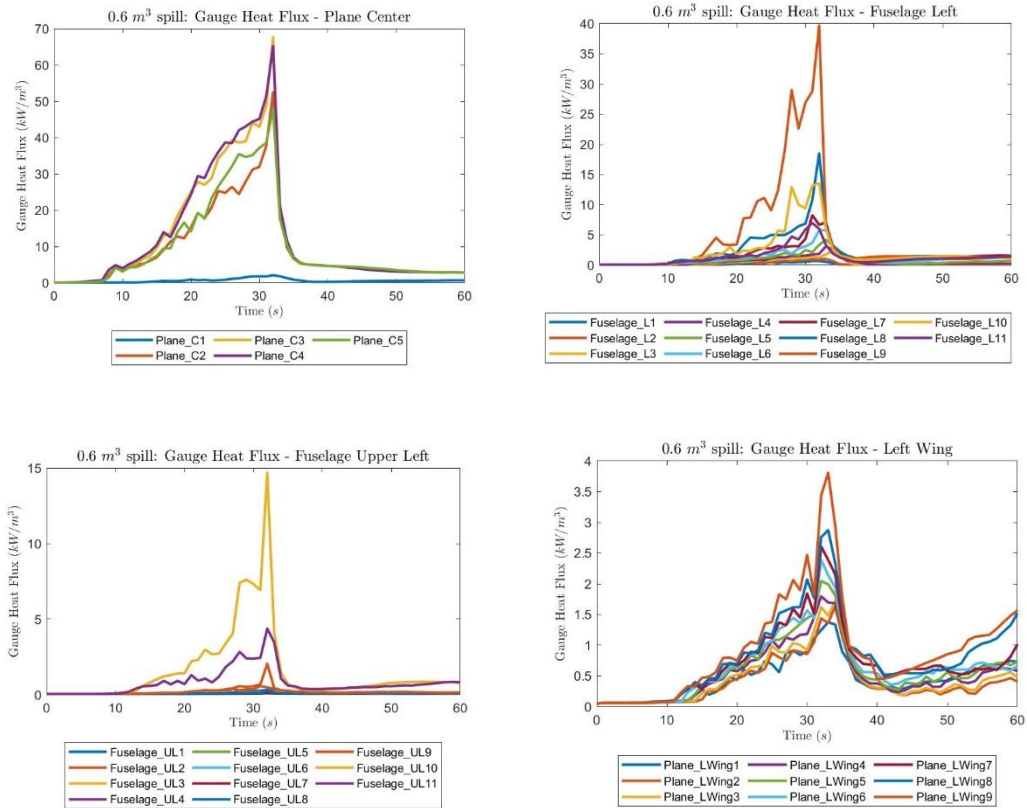


Figure A-12. Trench spacing 7.6 m – 0.06 m³ spill – 60 seconds activation – Incident Heat Flux to the Plane.

A.7 Trench spacing 7.6 m – 0.6 m³ spill – 30 seconds activation



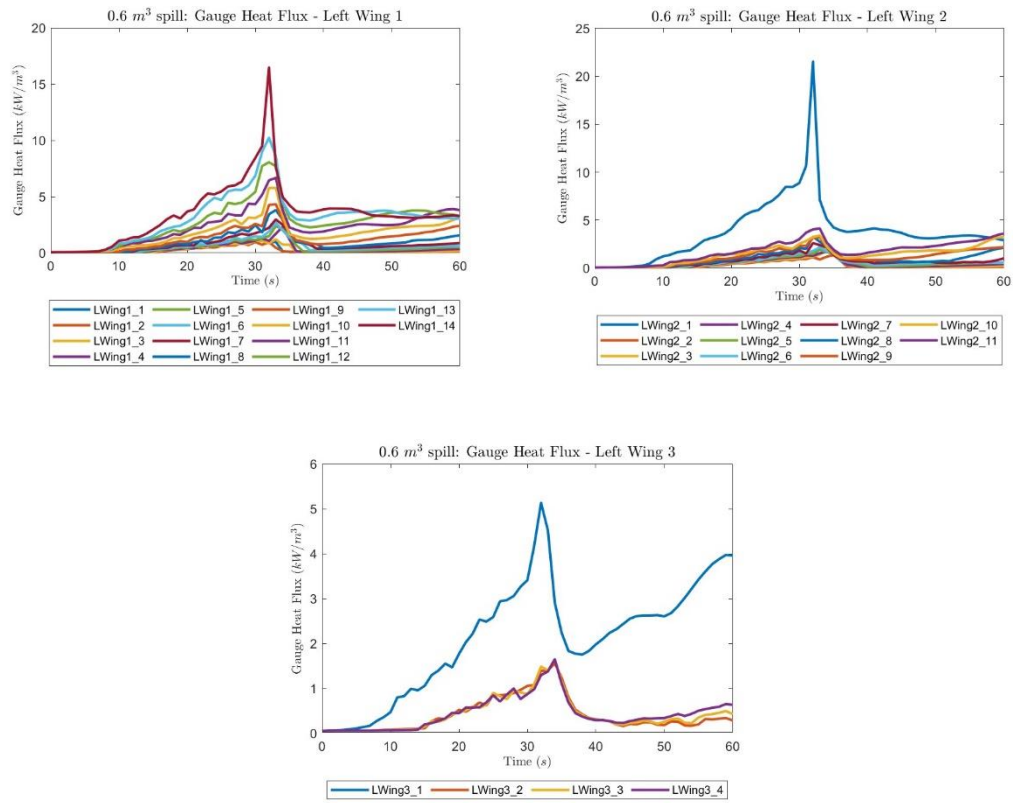
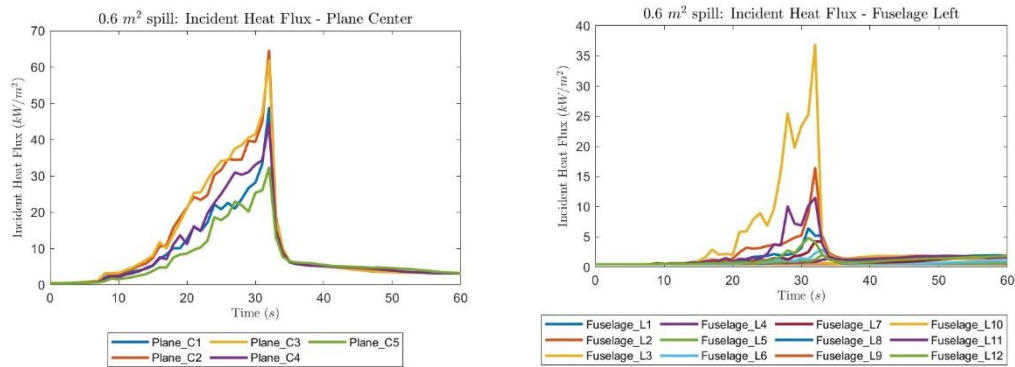


Figure A-13. Trench spacing 7.6 m – 0.6 m³ spill – 30 seconds activation – Gauge Heat Flux to the Plane.



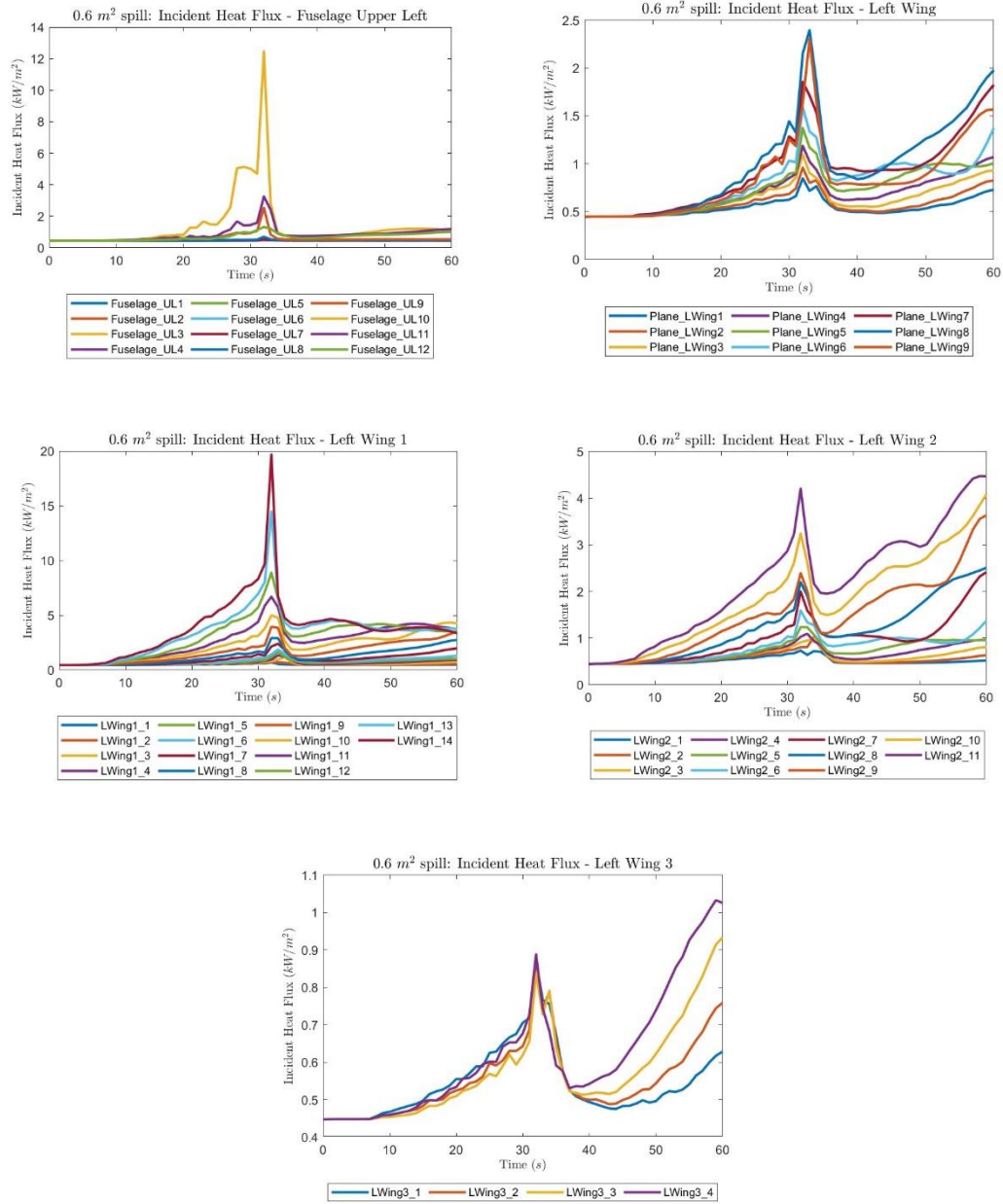
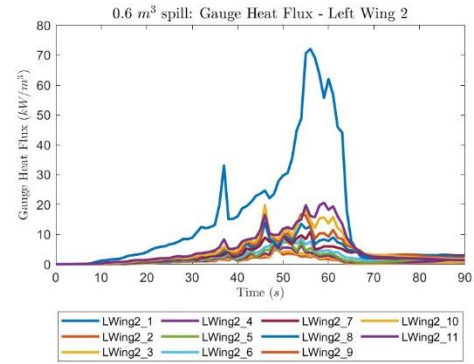
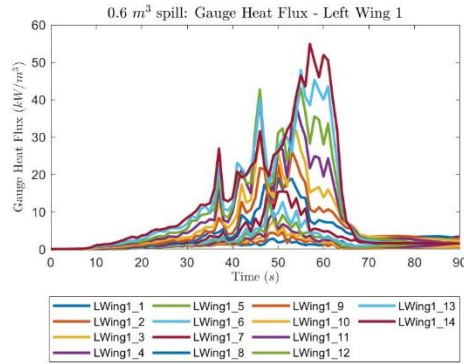
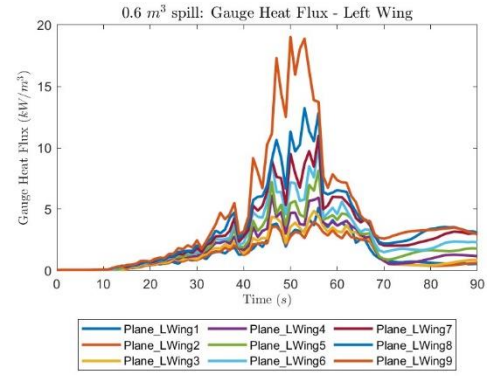
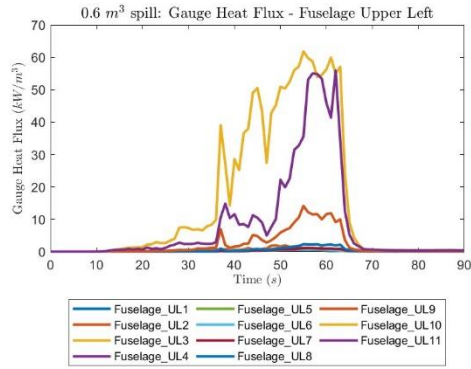
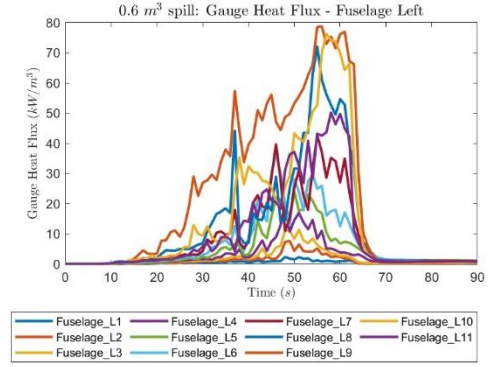
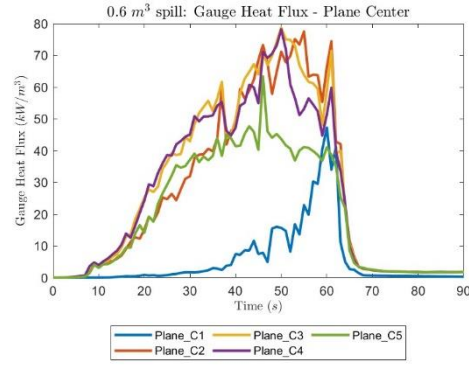


Figure A-14. Trench spacing 7.6 m – 0.6 m³ spill – 30 seconds activation – Incident Heat Flux to the Plane.

A.8 Trench spacing 7.6 m – 0.6 m³ spill – 60 seconds activation



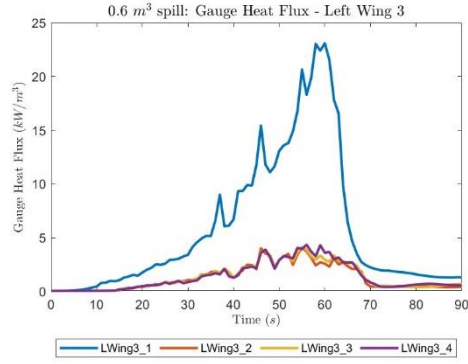
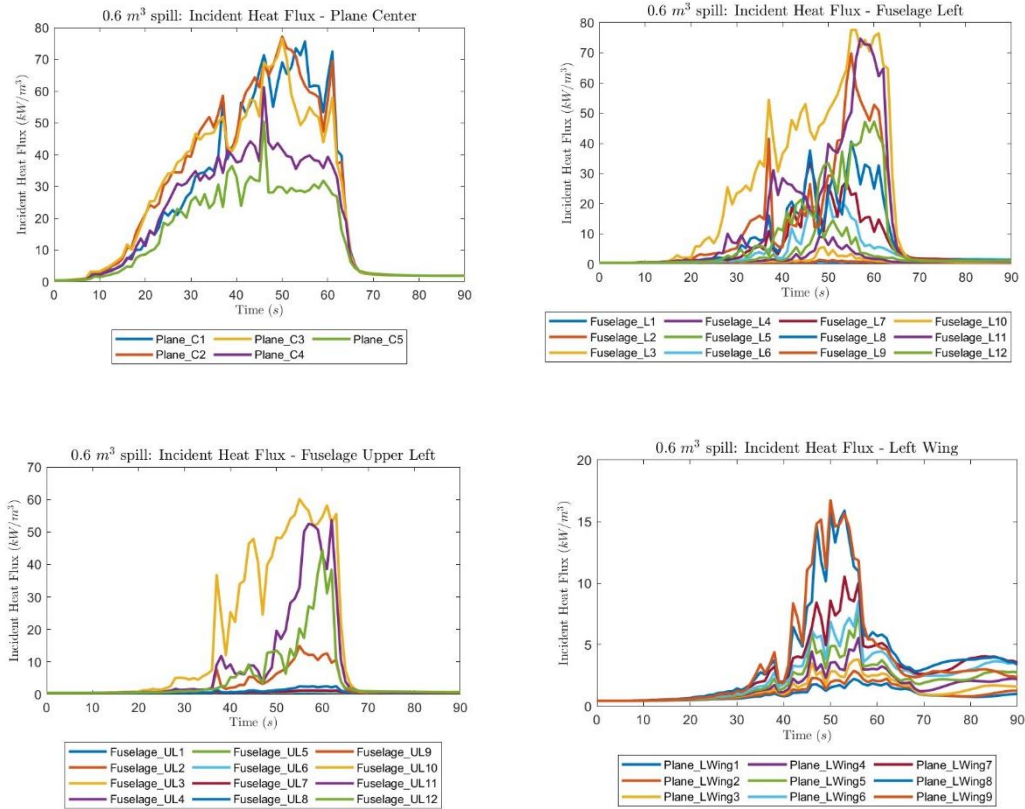


Figure A-15. Trench spacing 7.6 m – 0.6 m³ spill – 60 seconds activation – Gauge Heat Flux to the Plane.



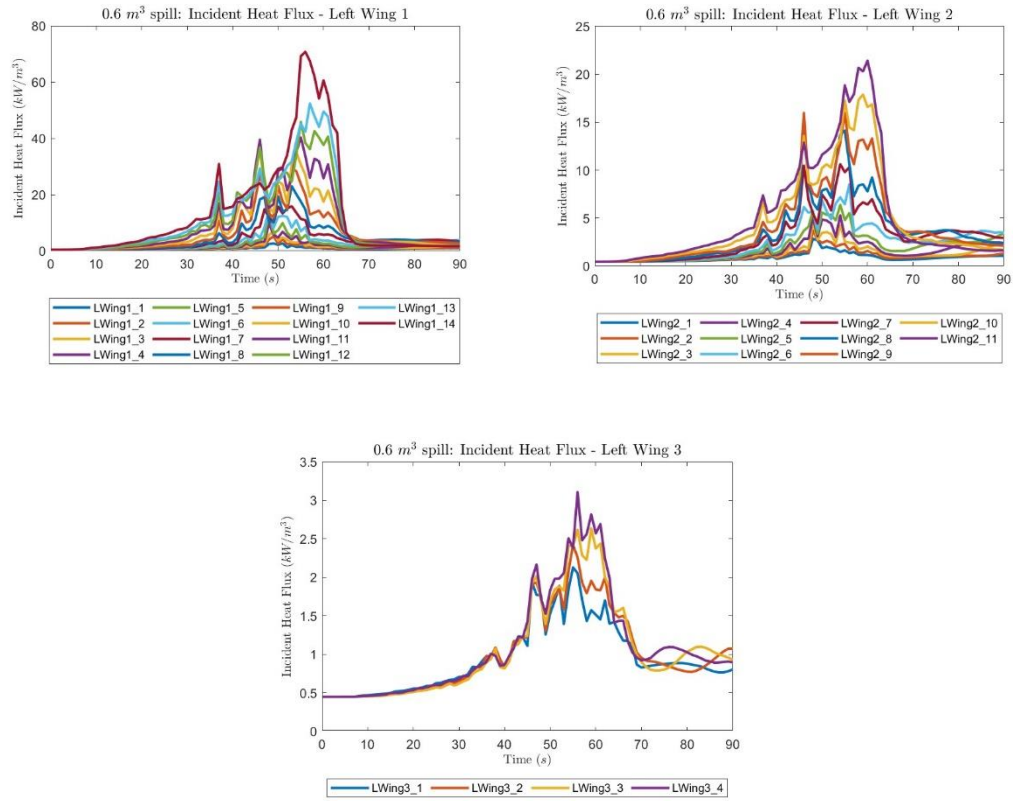
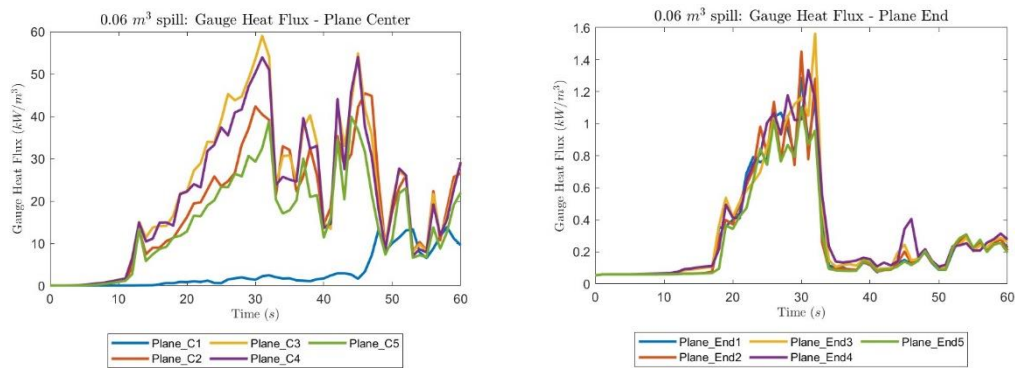
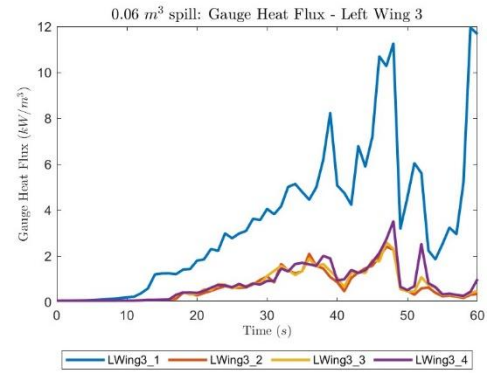
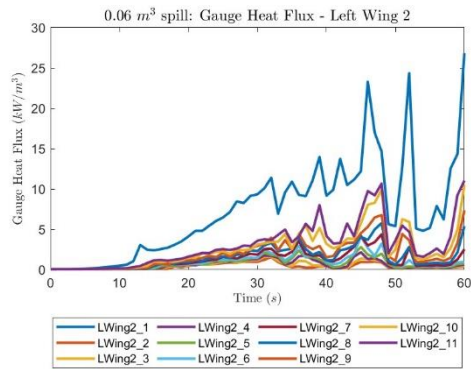
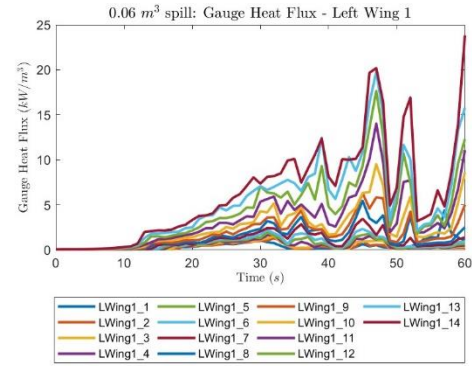
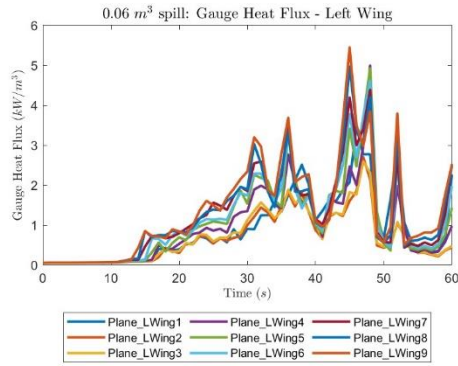
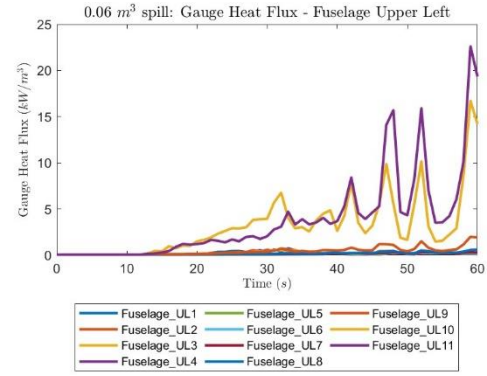
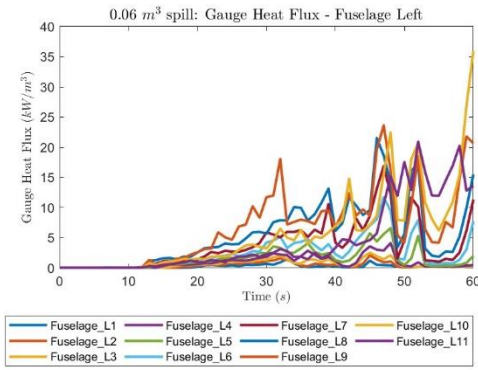


Figure A-16. Trench spacing 7.6 m – 0.6 m³ spill – 60 seconds activation – Incident Heat Flux to the Plane.

Appendix B. Additional Measurements for VID Fire-kill F-102 Nozzle





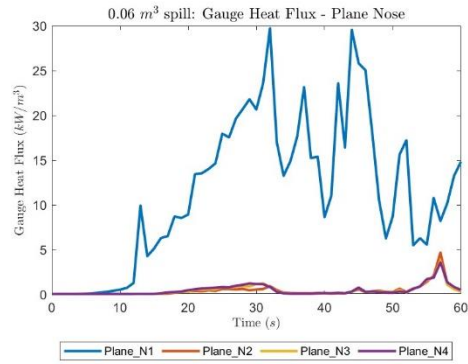
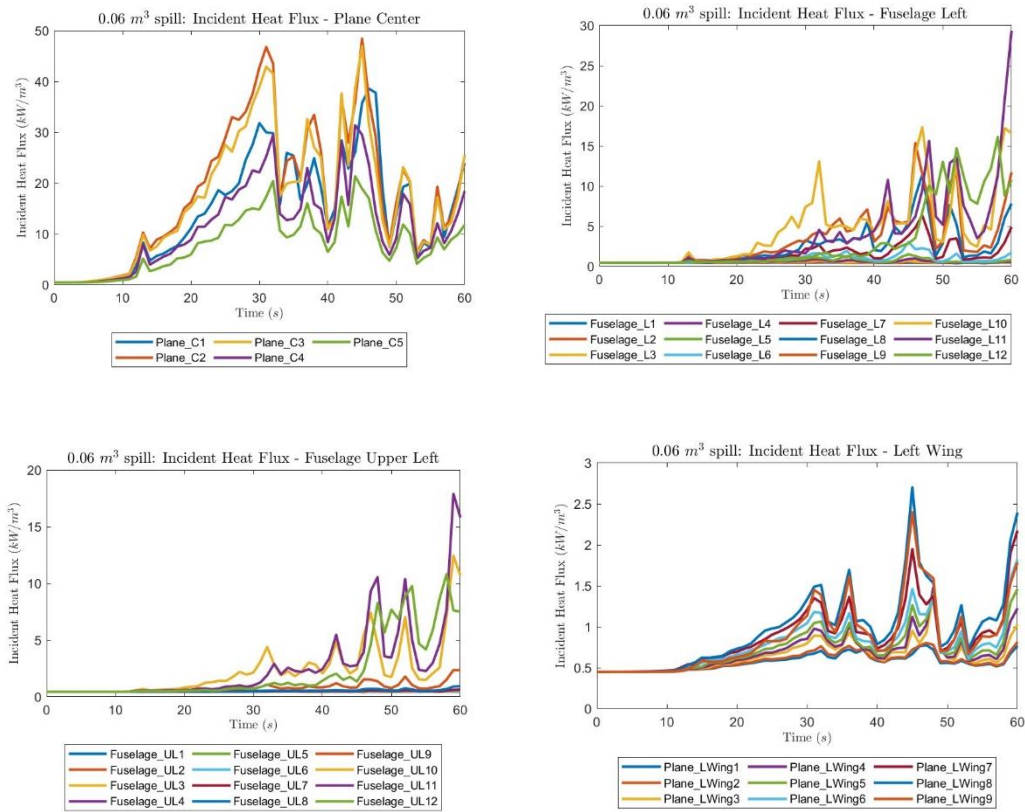


Figure B-1. Trench spacing 7.6 m – 0.06 m³ spill – 30 seconds activation – Gauge Heat Flux to the Plane.



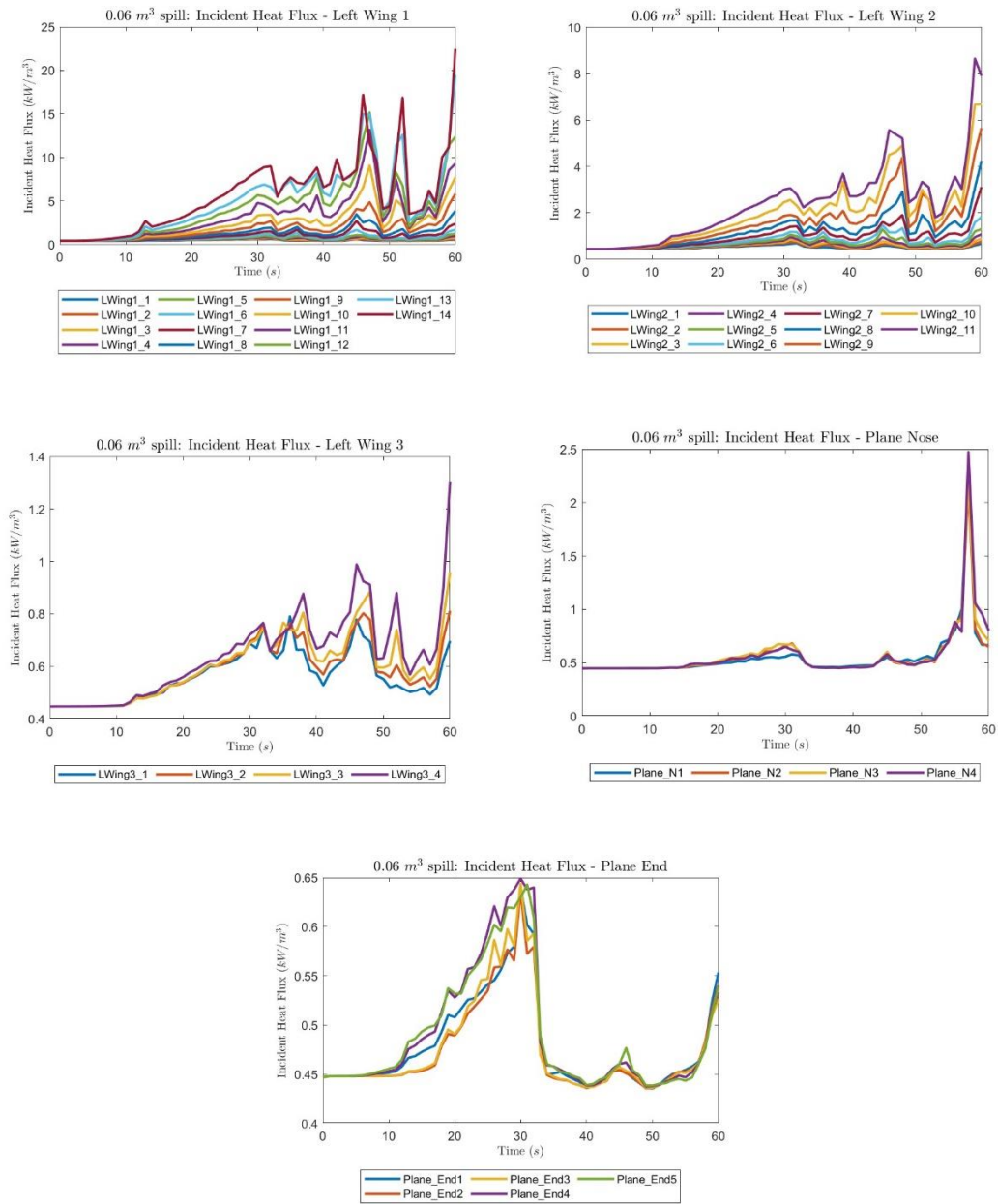


Figure B-2. Trench spacing 7.6 m – 0.06 m³ spill – 30 seconds activation – Incident Heat Flux to the Plane.

Appendix C. FDS Code

C.1 Simulation Constraints – Viking Nozzle

```
&MISC SIMULATION_MODE='LES',  
      TMPA=25.,  
      HUMIDITY=65.,  
      PARTICLE_CFL=.TRUE.,  
      MINIMUM_FILM_THICKNESS=0.0002,  
      POROUS_FLOOR=F/  
&RADI RADIATION=T/
```

C.2 Simulation Constraints – VID Fire-kill Nozzle

```
&MISC SIMULATION_MODE='LES',  
      TMPA=25.,  
      HUMIDITY=65.,  
      PARTICLE_CFL=.TRUE./  
&RADI RADIATION=T/  
&COMB EXTINCTION_MODEL='EXTINCTION 2' /  
  
&TIME T_END=60./  
  
&DUMP DT_RESTART=15., DT_PL3D=10.0, DT_DEVC=1.0, DT_HRR=0.1,  
WRITE_XYZ=.TRUE.,  
      PLOT3D_QUANTITY(1:5)='TEMPERATURE','W-VELOCITY','HRRPUV',  
      'MASS FRACTION','VOLUME FRACTION',  
      PLOT3D_SPEC_ID(4)='OXYGEN', PLOT3D_SPEC_ID(5)='WATER VAPOR'/
```

C.3 Hangar Configuration – 15.2 m trench

// Hangar Construction

```
&MATL ID='CORRUGATED METAL',  
      SPECIFIC_HEAT=0.47,  
      CONDUCTIVITY=52.0,  
      DENSITY=7800.0/  
  
&MATL ID='CONCRETE',  
      SPECIFIC_HEAT=1.04,  
      CONDUCTIVITY=1.8,  
      DENSITY=2200.0/
```

```

&SURF ID='WALL',
  COLOR='LAVENDER',
  DEFAULT=.TRUE.,
  MATL_ID(1,1)='CORRUGATED METAL',
  MATL_MASS_FRACTION(1,1)=1.0,
  THICKNESS(1)=0.2/

```

```

&SURF ID='FLOOR',
  MATL_ID(1,1)='CONCRETE',
  MATL_MASS_FRACTION(1,1)=1.0,
  THICKNESS(1)=0.1/
/Hangar Door

```

```

&OBST ID='Door Wall', XB=0.0, 64.0, -1.2,0.0, 0.0, 10.0/
&HOLE ID='Door',    XB=0.15,63.85,-2.0,1.0, 0.0, 7.62/

```

```

/Trench Setup

```

```

&VENT ID='TrenchOut1',SURF_ID='FLOOR', XB= 1.0, 63.0, 2.0,2.80,0.0,0.0,
COLOR='GRAY 20'/
&VENT ID='TrenchOut2',SURF_ID='FLOOR', XB= 1.0, 63.0,25.64,26.44,0.0,0.0,
COLOR='GRAY 20'/
&VENT ID='TrenchOut3',SURF_ID='FLOOR', XB= 1.0, 1.66, 2.0,26.3,0.0,0.0,
COLOR='GRAY 20'/
&VENT ID='TrenchOut4',SURF_ID='FLOOR', XB=62.34, 63.0, 2.0,26.3,0.0,0.0,
COLOR='GRAY 20'/
&VENT ID='TrenchIn1',SURF_ID='FLOOR', XB= 16.2,16.86, 2.0,26.3,0.0,0.0,
COLOR='GRAY 20'/
&VENT ID='TrenchIn2',SURF_ID='FLOOR', XB= 31.4,32.06, 2.0,26.3,0.0,0.0,
COLOR='GRAY 20'/
&VENT ID='TrenchIn3',SURF_ID='FLOOR', XB= 46.6,47.6, 2.0,26.3,0.0,0.0,
COLOR='GRAY 20'/

```

```

/Hangar Walls and Roof

```

```

&VENT ID='Vent #1', SURF_ID='WALL', XB=0.0,0.0,-1.0,29.0,0.0,10.0/ xmin
&VENT ID='Vent #2', SURF_ID='WALL', XB=64.0,64.0,-1.0,29.0,0.0,10.0/ xmax
&VENT ID='Vent #3', SURF_ID='OPEN', XB=0.0,64.0,-8.0,-8.0,0.0,10.0/ ymin
&VENT ID='Vent #4', SURF_ID='WALL', XB=0.0,64.0,29.0,29.0,0.0,10.0/ ymax
wall back
&VENT ID='Vent #5', SURF_ID='WALL', XB=0.0,64.0,-1.0,29.0,10.0,10.0/ ceiling
&VENT ID='Vent #6', SURF_ID='FLOOR', XB=0.0,64.0,-1.0,29.0,0.0,0.0/ floor

```

/Outdoor Space for air entrainment

```
&VENT ID='Vent #7', SURF_ID='OPEN', XB=0.0,0.0,-8.0,-1.0,0.0,10.0/  
&VENT ID='Vent #8', SURF_ID='OPEN', XB=64.0,64.0,-8.0,-1.0,0.0,10.0/  
&VENT ID='Vent #9', SURF_ID='FLOOR', XB=0.0,64.0,-8.0,-1.0,0.0,0.0/  
&VENT ID='Vent #10', SURF_ID='OPEN', XB=0.0,64.0,-8.0,-1.0,10.0,10.0/
```

C.4 Hangar Configuration – 7.6 m trench

// Hangar Construction

```
&MATL ID='CORRUGATED METAL',  
  SPECIFIC_HEAT=0.47,  
  CONDUCTIVITY=52.0,  
  DENSITY=7800.0/
```

```
&MATL ID='CONCRETE',  
  SPECIFIC_HEAT=1.04,  
  CONDUCTIVITY=1.8,  
  DENSITY=2200.0/
```

```
&SURF ID='WALL',  
  COLOR='LAVENDER',  
  DEFAULT=.TRUE.,  
  MATL_ID(1,1)='CORRUGATED METAL',  
  MATL_MASS_FRACTION(1,1)=1.0,  
  THICKNESS(1)=0.2/
```

```
&SURF ID='FLOOR',  
  MATL_ID(1,1)='CONCRETE',  
  MATL_MASS_FRACTION(1,1)=1.0,  
  THICKNESS(1)=0.1/
```

/Hangar Door

```
&OBST ID='Door Wall', XB=0.0, 64.0, -1.2,0.0, 0.0, 10.0/  
&HOLE ID='Door',    XB=0.15,63.85,-2.0,1.0, 0.0, 7.62/
```

/Trench Setup

```
&OBST ID='TrenchOut1', XB=1.0 ,63.0 ,2.0 ,2.66,0.0,0.0, COLOR='GRAY 20' ,  
SURF_ID='FLOOR'/
```

&OBST ID='TrenchOut2', XB=1.0 ,63.0 ,25.64,26.3,0.0,0.0,COLOR='GRAY 20',
 SURF_ID='FLOOR'/
 &OBST ID='TrenchOut3', XB=1.0 ,1.66 ,2.0 ,26.3,0.0,0.0, COLOR='GRAY 20' ,
 SURF_ID='FLOOR'/
 &OBST ID='TrenchOut4', XB=62.34,63.0 ,2.0 ,26.3,0.0,0.0,COLOR='GRAY 20',
 SURF_ID='FLOOR'/
 &OBST ID='TrenchIn1', XB=8.6 ,9.26 ,2.0 ,26.3,0.0,0.0, COLOR='GRAY 20' ,
 SURF_ID='FLOOR'/
 &OBST ID='TrenchIn2', XB=16.2 ,16.86,2.0 ,26.3,0.0,0.0, COLOR='GRAY 20',
 SURF_ID='FLOOR'/
 &OBST ID='TrenchIn3', XB=23.8 ,24.46,2.0 ,26.3,0.0,0.0, COLOR='GRAY 20',
 SURF_ID='FLOOR'/
 &OBST ID='TrenchIn4', XB=31.4 ,32.06,2.0 ,26.3,0.0,0.0, COLOR='GRAY 20',
 SURF_ID='FLOOR'/
 &OBST ID='TrenchIn5', XB=39.0 ,39.66,2.0 ,26.3,0.0,0.0, COLOR='GRAY 20',
 SURF_ID='FLOOR'/
 &OBST ID='TrenchIn6', XB=46.6 ,47.26,2.0 ,26.3,0.0,0.0, COLOR='GRAY 20',
 SURF_ID='FLOOR'/
 &OBST ID='TrenchIn7', XB=54.2 ,54.86,2.0 ,26.3,0.0,0.0, COLOR='GRAY 20',
 SURF_ID='FLOOR'/

/Hangar Walls and Roof

&VENT ID='Vent #1', SURF_ID='WALL', XB=0.0,0.0,-1.0,29.0,0.0,10.0/ xmin
 &VENT ID='Vent #2', SURF_ID='WALL', XB=64.0,64.0,-1.0,29.0,0.0,10.0/ xmax
 &VENT ID='Vent #3', SURF_ID='OPEN', XB=0.0,64.0,-8.0,-8.0,0.0,10.0/ ymin
 &VENT ID='Vent #4', SURF_ID='WALL', XB=0.0,64.0,29.0,29.0,0.0,10.0/ ymax
 wall back
 &VENT ID='Vent #5', SURF_ID='WALL', XB=0.0,64.0,-1.0,29.0,10.0,10.0/ ceiling
 &VENT ID='Vent #6', SURF_ID='FLOOR', XB=0.0,64.0,-1.0,29.0,0.0,0.0/ floor

/Outdoor Space for air entrainment

&VENT ID='Vent #7', SURF_ID='OPEN', XB=0.0,0.0,-8.0,-1.0,0.0,10.0/
 &VENT ID='Vent #8', SURF_ID='OPEN', XB=64.0,64.0,-8.0,-1.0,0.0,10.0/
 &VENT ID='Vent #9', SURF_ID='FLOOR', XB=0.0,64.0,-8.0,-1.0,0.0,0.0/
 &VENT ID='Vent #10', SURF_ID='OPEN', XB=0.0,64.0,-8.0,-1.0,10.0,10.0/

C.5 Fire Model

&REAC FUEL= 'JP-8',
 FORMULA = 'C11H21',
 HEAT_OF_COMBUSTION = 42800,

RADIATIVE_FRACTION = 0.05,
SOOT_YIELD= 0,
CO_YIELD= 0.01,
CRITICAL_FLAME_TEMPERATURE=1527,
AUTO_IGNITION_TEMPERATURE=230./

&SURF ID='FIRE',
HRRPUA=430,
E_COEFFICIENT=1,
TMP_FRONT=700,
RAMP_T='RAMP TEMP'/

&RAMP ID='RAMP TEMP',T=0.0,F=0.0/
&RAMP ID='RAMP TEMP',T=1.0,F=1.0/
&RAMP ID='RAMP TEMP',T=9.0,F=1.0/
&RAMP ID='RAMP TEMP',T=10.0,F=0.3/ 220

&VENT ID='BURNER',
SURF_ID='FIRE',
XB=4.48,13.38,9.7,18.6,0.0,0.0,
XYZ=8.93,14.15,0.0,
COLOR='RED',
SPREAD_RATE=0.06/

C.6 Viking Grate Nozzle

// Viking Nozzle

/ Spray
&SPEC ID='WATER VAPOR'/
&PART ID='VIKING WATER DROPLETS',
SPEC_ID='WATER VAPOR',
QUANTITIES(1:4)='PARTICLE DIAMETER','PARTICLE
TEMPERATURE','PARTICLE AGE','PARTICLE VELOCITY',
DIAMETER=1500,
HORIZONTAL_VELOCITY=0.3,
SAMPLING_FACTOR=100/

/ Viking Grate Nozzle Characteristics
&PROP ID='VikingGrateNoz',
OFFSET=0.1,
PARTICLES_PER_SECOND=530,
PART_ID='VIKING WATER DROPLETS',

K_FACTOR=9,
OPERATING_PRESSURE=2.8,
SPRAY_ANGLE=0.,20.,
SPRAY_PATTERN_BETA=85.,
SPRAY_PATTERN_MU=0.,
PARTICLE_VELOCITY=12.5,
SMOKEVIEW_ID='viking'/

/ Stream locations -- Activates at t=30 S

/180 deg nozzle

/Center Left 1

&DEVC XYZ=1.33,10.44,0.0, PROP_ID='VikingGrateNoz', ID='CL1_Stream1',
ORIENTATION=0.077, 0.982,0.174, QUANTITY="TIME", SETPOINT=30. /
&DEVC XYZ=1.33,10.44,0.0, PROP_ID='VikingGrateNoz', ID='CL1_Stream2',
ORIENTATION=0.238, 0.956,0.174, QUANTITY="TIME", SETPOINT=30. /
&DEVC XYZ=1.33,10.44,0.0, PROP_ID='VikingGrateNoz', ID='CL1_Stream3',
ORIENTATION=0.393, 0.903,0.174, QUANTITY="TIME", SETPOINT=30. /
&DEVC XYZ=1.33,10.44,0.0, PROP_ID='VikingGrateNoz', ID='CL1_Stream4',
ORIENTATION=0.536, 0.826,0.174, QUANTITY="TIME", SETPOINT=30. /
&DEVC XYZ=1.33,10.44,0.0, PROP_ID='VikingGrateNoz', ID='CL1_Stream5',
ORIENTATION=0.665, 0.726,0.174, QUANTITY="TIME", SETPOINT=30. /
&DEVC XYZ=1.33,10.44,0.0, PROP_ID='VikingGrateNoz', ID='CL1_Stream6',
ORIENTATION=0.776, 0.606,0.174, QUANTITY="TIME", SETPOINT=30. /
&DEVC XYZ=1.33,10.44,0.0, PROP_ID='VikingGrateNoz', ID='CL1_Stream7',
ORIENTATION=0.865, 0.470,0.174, QUANTITY="TIME", SETPOINT=30. /
&DEVC XYZ=1.33,10.44,0.0, PROP_ID='VikingGrateNoz', ID='CL1_Stream8',
ORIENTATION=0.931, 0.321,0.174, QUANTITY="TIME", SETPOINT=30. /
&DEVC XYZ=1.33,10.44,0.0, PROP_ID='VikingGrateNoz', ID='CL1_Stream9',
ORIENTATION=0.971, 0.163,0.174, QUANTITY="TIME", SETPOINT=30. /
&DEVC XYZ=1.33,10.44,0.0, PROP_ID='VikingGrateNoz', ID='CL1_Stream10',
ORIENTATION=0.985, 0.000,0.174, QUANTITY="TIME", SETPOINT=30. /
&DEVC XYZ=1.33,10.44,0.0, PROP_ID='VikingGrateNoz', ID='CL1_Stream11',
ORIENTATION=0.971,-0.163,0.174, QUANTITY="TIME", SETPOINT=30. /
&DEVC XYZ=1.33,10.44,0.0, PROP_ID='VikingGrateNoz', ID='CL1_Stream12',
ORIENTATION=0.931,-0.321,0.174, QUANTITY="TIME", SETPOINT=30. /
&DEVC XYZ=1.33,10.44,0.0, PROP_ID='VikingGrateNoz', ID='CL1_Stream13',
ORIENTATION=0.865,-0.470,0.174, QUANTITY="TIME", SETPOINT=30. /
&DEVC XYZ=1.33,10.44,0.0, PROP_ID='VikingGrateNoz', ID='CL1_Stream14',
ORIENTATION=0.776,-0.606,0.174, QUANTITY="TIME", SETPOINT=30. /
&DEVC XYZ=1.33,10.44,0.0, PROP_ID='VikingGrateNoz', ID='CL1_Stream15',
ORIENTATION=0.665,-0.726,0.174, QUANTITY="TIME", SETPOINT=30. /

&DEVC XYZ=1.33,10.44,0.0, PROP_ID='VikingGrateNoz', ID='CL1_Stream16',
 ORIENTATION=0.536,-0.826,0.174, QUANTITY="TIME", SETPOINT=30. /
 &DEVC XYZ=1.33,10.44,0.0, PROP_ID='VikingGrateNoz', ID='CL1_Stream17',
 ORIENTATION=0.393,-0.903,0.174, QUANTITY="TIME", SETPOINT=30. /
 &DEVC XYZ=1.33,10.44,0.0, PROP_ID='VikingGrateNoz', ID='CL1_Stream18',
 ORIENTATION=0.238,-0.956,0.174, QUANTITY="TIME", SETPOINT=30. /
 &DEVC XYZ=1.33,10.44,0.0, PROP_ID='VikingGrateNoz', ID='CL1_Stream19',
 ORIENTATION=0.077,-0.982,0.174, QUANTITY="TIME", SETPOINT=30. /

/Center Left 2

&DEVC XYZ=1.33,18.04,0.0, PROP_ID='VikingGrateNoz', ID='CL2_Stream1',
 ORIENTATION=0.077, 0.982,0.174, QUANTITY="TIME", SETPOINT=30. /
 &DEVC XYZ=1.33,18.04,0.0, PROP_ID='VikingGrateNoz', ID='CL2_Stream2',
 ORIENTATION=0.238, 0.956,0.174, QUANTITY="TIME", SETPOINT=30. /
 &DEVC XYZ=1.33,18.04,0.0, PROP_ID='VikingGrateNoz', ID='CL2_Stream3',
 ORIENTATION=0.393, 0.903,0.174, QUANTITY="TIME", SETPOINT=30. /
 &DEVC XYZ=1.33,18.04,0.0, PROP_ID='VikingGrateNoz', ID='CL2_Stream4',
 ORIENTATION=0.536, 0.826,0.174, QUANTITY="TIME", SETPOINT=30. /
 &DEVC XYZ=1.33,18.04,0.0, PROP_ID='VikingGrateNoz', ID='CL2_Stream5',
 ORIENTATION=0.665, 0.726,0.174, QUANTITY="TIME", SETPOINT=30. /
 &DEVC XYZ=1.33,18.04,0.0, PROP_ID='VikingGrateNoz', ID='CL2_Stream6',
 ORIENTATION=0.776, 0.606,0.174, QUANTITY="TIME", SETPOINT=30. /
 &DEVC XYZ=1.33,18.04,0.0, PROP_ID='VikingGrateNoz', ID='CL2_Stream7',
 ORIENTATION=0.865, 0.470,0.174, QUANTITY="TIME", SETPOINT=30. /
 &DEVC XYZ=1.33,18.04,0.0, PROP_ID='VikingGrateNoz', ID='CL2_Stream8',
 ORIENTATION=0.931, 0.321,0.174, QUANTITY="TIME", SETPOINT=30. /
 &DEVC XYZ=1.33,18.04,0.0, PROP_ID='VikingGrateNoz', ID='CL2_Stream9',
 ORIENTATION=0.971, 0.163,0.174, QUANTITY="TIME", SETPOINT=30. /
 &DEVC XYZ=1.33,18.04,0.0, PROP_ID='VikingGrateNoz', ID='CL2_Stream10',
 ORIENTATION=0.985, 0.000,0.174, QUANTITY="TIME", SETPOINT=30. /
 &DEVC XYZ=1.33,18.04,0.0, PROP_ID='VikingGrateNoz', ID='CL2_Stream11',
 ORIENTATION=0.971,-0.163,0.174, QUANTITY="TIME", SETPOINT=30. /
 &DEVC XYZ=1.33,18.04,0.0, PROP_ID='VikingGrateNoz', ID='CL2_Stream12',
 ORIENTATION=0.931,-0.321,0.174, QUANTITY="TIME", SETPOINT=30. /
 &DEVC XYZ=1.33,18.04,0.0, PROP_ID='VikingGrateNoz', ID='CL2_Stream13',
 ORIENTATION=0.865,-0.470,0.174, QUANTITY="TIME", SETPOINT=30. /
 &DEVC XYZ=1.33,18.04,0.0, PROP_ID='VikingGrateNoz', ID='CL2_Stream14',
 ORIENTATION=0.776,-0.606,0.174, QUANTITY="TIME", SETPOINT=30. /
 &DEVC XYZ=1.33,18.04,0.0, PROP_ID='VikingGrateNoz', ID='CL2_Stream15',
 ORIENTATION=0.665,-0.726,0.174, QUANTITY="TIME", SETPOINT=30. /
 &DEVC XYZ=1.33,18.04,0.0, PROP_ID='VikingGrateNoz', ID='CL2_Stream16',
 ORIENTATION=0.536,-0.826,0.174, QUANTITY="TIME", SETPOINT=30. /

&DEVC XYZ=1.33,18.04,0.0, PROP_ID='VikingGrateNoz', ID='CL2_Stream17',
 ORIENTATION=0.393,-0.903,0.174, QUANTITY="TIME", SETPOINT=30. /
 &DEVC XYZ=1.33,18.04,0.0, PROP_ID='VikingGrateNoz', ID='CL2_Stream18',
 ORIENTATION=0.238,-0.956,0.174, QUANTITY="TIME", SETPOINT=30. /
 &DEVC XYZ=1.33,18.04,0.0, PROP_ID='VikingGrateNoz', ID='CL2_Stream19',
 ORIENTATION=0.077,-0.982,0.174, QUANTITY="TIME", SETPOINT=30. /

/Center Right 1

&DEVC XYZ=16.53,10.44,0.0, PROP_ID='VikingGrateNoz', ID='CR1_Stream1',
 ORIENTATION=-0.077, 0.982,0.174, QUANTITY="TIME", SETPOINT=30. /
 &DEVC XYZ=16.53,10.44,0.0, PROP_ID='VikingGrateNoz', ID='CR1_Stream2',
 ORIENTATION=-0.238, 0.956,0.174, QUANTITY="TIME", SETPOINT=30. /
 &DEVC XYZ=16.53,10.44,0.0, PROP_ID='VikingGrateNoz', ID='CR1_Stream3',
 ORIENTATION=-0.393, 0.903,0.174, QUANTITY="TIME", SETPOINT=30. /
 &DEVC XYZ=16.53,10.44,0.0, PROP_ID='VikingGrateNoz', ID='CR1_Stream4',
 ORIENTATION=-0.536, 0.826,0.174, QUANTITY="TIME", SETPOINT=30. /
 &DEVC XYZ=16.53,10.44,0.0, PROP_ID='VikingGrateNoz', ID='CR1_Stream5',
 ORIENTATION=-0.665, 0.726,0.174, QUANTITY="TIME", SETPOINT=30. /
 &DEVC XYZ=16.53,10.44,0.0, PROP_ID='VikingGrateNoz', ID='CR1_Stream6',
 ORIENTATION=-0.776, 0.606,0.174, QUANTITY="TIME", SETPOINT=30. /
 &DEVC XYZ=16.53,10.44,0.0, PROP_ID='VikingGrateNoz', ID='CR1_Stream7',
 ORIENTATION=-0.865, 0.470,0.174, QUANTITY="TIME", SETPOINT=30. /
 &DEVC XYZ=16.53,10.44,0.0, PROP_ID='VikingGrateNoz', ID='CR1_Stream8',
 ORIENTATION=-0.931, 0.321,0.174, QUANTITY="TIME", SETPOINT=30. /
 &DEVC XYZ=16.53,10.44,0.0, PROP_ID='VikingGrateNoz', ID='CR1_Stream9',
 ORIENTATION=-0.971, 0.163,0.174, QUANTITY="TIME", SETPOINT=30. /
 &DEVC XYZ=16.53,10.44,0.0, PROP_ID='VikingGrateNoz', ID='CR1_Stream10',
 ORIENTATION=-0.985, 0.000,0.174, QUANTITY="TIME", SETPOINT=30. /
 &DEVC XYZ=16.53,10.44,0.0, PROP_ID='VikingGrateNoz', ID='CR1_Stream11',
 ORIENTATION=-0.971,-0.163,0.174, QUANTITY="TIME", SETPOINT=30. /
 &DEVC XYZ=16.53,10.44,0.0, PROP_ID='VikingGrateNoz', ID='CR1_Stream12',
 ORIENTATION=-0.931,-0.321,0.174, QUANTITY="TIME", SETPOINT=30. /
 &DEVC XYZ=16.53,10.44,0.0, PROP_ID='VikingGrateNoz', ID='CR1_Stream13',
 ORIENTATION=-0.865,-0.470,0.174, QUANTITY="TIME", SETPOINT=30. /
 &DEVC XYZ=16.53,10.44,0.0, PROP_ID='VikingGrateNoz', ID='CR1_Stream14',
 ORIENTATION=-0.776,-0.606,0.174, QUANTITY="TIME", SETPOINT=30. /
 &DEVC XYZ=16.53,10.44,0.0, PROP_ID='VikingGrateNoz', ID='CR1_Stream15',
 ORIENTATION=-0.665,-0.726,0.174, QUANTITY="TIME", SETPOINT=30. /
 &DEVC XYZ=16.53,10.44,0.0, PROP_ID='VikingGrateNoz', ID='CR1_Stream16',
 ORIENTATION=-0.536,-0.826,0.174, QUANTITY="TIME", SETPOINT=30. /
 &DEVC XYZ=16.53,10.44,0.0, PROP_ID='VikingGrateNoz', ID='CR1_Stream17',
 ORIENTATION=-0.393,-0.903,0.174, QUANTITY="TIME", SETPOINT=30. /

&DEVC XYZ=16.53,10.44,0.0, PROP_ID='VikingGrateNoz', ID='CR1_Stream18',
ORIENTATION=-0.238,-0.956,0.174, QUANTITY="TIME", SETPOINT=30. /
&DEVC XYZ=16.53,10.44,0.0, PROP_ID='VikingGrateNoz', ID='CR1_Stream19',
ORIENTATION=-0.077,-0.982,0.174, QUANTITY="TIME", SETPOINT=30. /

/Center Right 2

&DEVC XYZ=16.53,18.04,0.0, PROP_ID='VikingGrateNoz', ID='CR2_Stream1',
ORIENTATION=-0.077, 0.982,0.174, QUANTITY="TIME", SETPOINT=30. /
&DEVC XYZ=16.53,18.04,0.0, PROP_ID='VikingGrateNoz', ID='CR2_Stream2',
ORIENTATION=-0.238, 0.956,0.174, QUANTITY="TIME", SETPOINT=30. /
&DEVC XYZ=16.53,18.04,0.0, PROP_ID='VikingGrateNoz', ID='CR2_Stream3',
ORIENTATION=-0.393, 0.903,0.174, QUANTITY="TIME", SETPOINT=30. /
&DEVC XYZ=16.53,18.04,0.0, PROP_ID='VikingGrateNoz', ID='CR2_Stream4',
ORIENTATION=-0.536, 0.826,0.174, QUANTITY="TIME", SETPOINT=30. /
&DEVC XYZ=16.53,18.04,0.0, PROP_ID='VikingGrateNoz', ID='CR2_Stream5',
ORIENTATION=-0.665, 0.726,0.174, QUANTITY="TIME", SETPOINT=30. /
&DEVC XYZ=16.53,18.04,0.0, PROP_ID='VikingGrateNoz', ID='CR2_Stream6',
ORIENTATION=-0.776, 0.606,0.174, QUANTITY="TIME", SETPOINT=30. /
&DEVC XYZ=16.53,18.04,0.0, PROP_ID='VikingGrateNoz', ID='CR2_Stream7',
ORIENTATION=-0.865, 0.470,0.174, QUANTITY="TIME", SETPOINT=30. /
&DEVC XYZ=16.53,18.04,0.0, PROP_ID='VikingGrateNoz', ID='CR2_Stream8',
ORIENTATION=-0.931, 0.321,0.174, QUANTITY="TIME", SETPOINT=30. /
&DEVC XYZ=16.53,18.04,0.0, PROP_ID='VikingGrateNoz', ID='CR2_Stream9',
ORIENTATION=-0.971, 0.163,0.174, QUANTITY="TIME", SETPOINT=30. /
&DEVC XYZ=16.53,18.04,0.0, PROP_ID='VikingGrateNoz', ID='CR2_Stream10',
ORIENTATION=-0.985, 0.000,0.174, QUANTITY="TIME", SETPOINT=30. /
&DEVC XYZ=16.53,18.04,0.0, PROP_ID='VikingGrateNoz', ID='CR2_Stream11',
ORIENTATION=-0.971,-0.163,0.174, QUANTITY="TIME", SETPOINT=30. /
&DEVC XYZ=16.53,18.04,0.0, PROP_ID='VikingGrateNoz', ID='CR2_Stream12',
ORIENTATION=-0.931,-0.321,0.174, QUANTITY="TIME", SETPOINT=30. /
&DEVC XYZ=16.53,18.04,0.0, PROP_ID='VikingGrateNoz', ID='CR2_Stream13',
ORIENTATION=-0.865,-0.470,0.174, QUANTITY="TIME", SETPOINT=30. /
&DEVC XYZ=16.53,18.04,0.0, PROP_ID='VikingGrateNoz', ID='CR2_Stream14',
ORIENTATION=-0.776,-0.606,0.174, QUANTITY="TIME", SETPOINT=30. /
&DEVC XYZ=16.53,18.04,0.0, PROP_ID='VikingGrateNoz', ID='CR2_Stream15',
ORIENTATION=-0.665,-0.726,0.174, QUANTITY="TIME", SETPOINT=30. /
&DEVC XYZ=16.53,18.04,0.0, PROP_ID='VikingGrateNoz', ID='CR2_Stream16',
ORIENTATION=-0.536,-0.826,0.174, QUANTITY="TIME", SETPOINT=30. /
&DEVC XYZ=16.53,18.04,0.0, PROP_ID='VikingGrateNoz', ID='CR2_Stream17',
ORIENTATION=-0.393,-0.903,0.174, QUANTITY="TIME", SETPOINT=30. /
&DEVC XYZ=16.53,18.04,0.0, PROP_ID='VikingGrateNoz', ID='CR2_Stream18',
ORIENTATION=-0.238,-0.956,0.174, QUANTITY="TIME", SETPOINT=30. /

&DEVC XYZ=16.53,18.04,0.0, PROP_ID='VikingGrateNoz', ID='CR2_Stream19',
ORIENTATION=-0.077,-0.982,0.174, QUANTITY="TIME", SETPOINT=30. /

/90deg nozzle

/Top Left

&DEVC XYZ=1.33,25.64,0.0, PROP_ID='VikingGrateNoz', ID='TL_Stream1',
ORIENTATION=0.978,-0.068,0.174, QUANTITY="TIME", SETPOINT=30. /
&DEVC XYZ=1.33,25.64,0.0, PROP_ID='VikingGrateNoz', ID='TL_Stream2',
ORIENTATION=0.958,-0.207,0.174, QUANTITY="TIME", SETPOINT=30. /
&DEVC XYZ=1.33,25.64,0.0, PROP_ID='VikingGrateNoz', ID='TL_Stream3',
ORIENTATION=0.919,-0.342,0.174, QUANTITY="TIME", SETPOINT=30. /
&DEVC XYZ=1.33,25.64,0.0, PROP_ID='VikingGrateNoz', ID='TL_Stream4',
ORIENTATION=0.860,-0.469,0.174, QUANTITY="TIME", SETPOINT=30. /
&DEVC XYZ=1.33,25.64,0.0, PROP_ID='VikingGrateNoz', ID='TL_Stream5',
ORIENTATION=0.785,-0.587,0.174, QUANTITY="TIME", SETPOINT=30. /
&DEVC XYZ=1.33,25.64,0.0, PROP_ID='VikingGrateNoz', ID='TL_Stream6',
ORIENTATION=0.693,-0.693,0.174, QUANTITY="TIME", SETPOINT=30. /
&DEVC XYZ=1.33,25.64,0.0, PROP_ID='VikingGrateNoz', ID='TL_Stream7',
ORIENTATION=0.587,-0.785,0.174, QUANTITY="TIME", SETPOINT=30. /
&DEVC XYZ=1.33,25.64,0.0, PROP_ID='VikingGrateNoz', ID='TL_Stream8',
ORIENTATION=0.469,-0.860,0.174, QUANTITY="TIME", SETPOINT=30. /
&DEVC XYZ=1.33,25.64,0.0, PROP_ID='VikingGrateNoz', ID='TL_Stream9',
ORIENTATION=0.342,-0.919,0.174, QUANTITY="TIME", SETPOINT=30. /
&DEVC XYZ=1.33,25.64,0.0, PROP_ID='VikingGrateNoz', ID='TL_Stream10',
ORIENTATION=0.207,-0.958,0.174, QUANTITY="TIME", SETPOINT=30. /
&DEVC XYZ=1.33,25.64,0.0, PROP_ID='VikingGrateNoz', ID='TL_Stream11',
ORIENTATION=0.068,-0.978,0.174, QUANTITY="TIME", SETPOINT=30. /

/Top Right

&DEVC XYZ=16.53,25.64,0.0, PROP_ID='VikingGrateNoz', ID='TR_Stream1',
ORIENTATION=-0.978,-0.068,0.174, QUANTITY="TIME", SETPOINT=30. /
&DEVC XYZ=16.53,25.64,0.0, PROP_ID='VikingGrateNoz', ID='TR_Stream2',
ORIENTATION=-0.958,-0.207,0.174, QUANTITY="TIME", SETPOINT=30. /
&DEVC XYZ=16.53,25.64,0.0, PROP_ID='VikingGrateNoz', ID='TR_Stream3',
ORIENTATION=-0.919,-0.342,0.174, QUANTITY="TIME", SETPOINT=30. /
&DEVC XYZ=16.53,25.64,0.0, PROP_ID='VikingGrateNoz', ID='TR_Stream4',
ORIENTATION=-0.860,-0.469,0.174, QUANTITY="TIME", SETPOINT=30. /
&DEVC XYZ=16.53,25.64,0.0, PROP_ID='VikingGrateNoz', ID='TR_Stream5',
ORIENTATION=-0.785,-0.587,0.174, QUANTITY="TIME", SETPOINT=30. /
&DEVC XYZ=16.53,25.64,0.0, PROP_ID='VikingGrateNoz', ID='TR_Stream6',
ORIENTATION=-0.693,-0.693,0.174, QUANTITY="TIME", SETPOINT=30. /
&DEVC XYZ=16.53,25.64,0.0, PROP_ID='VikingGrateNoz', ID='TR_Stream7',
ORIENTATION=-0.587,-0.785,0.174, QUANTITY="TIME", SETPOINT=30. /

&DEVC XYZ=16.53,25.64,0.0, PROP_ID='VikingGrateNoz', ID='TR_Stream8',
 ORIENTATION=-0.469,-0.860,0.174, QUANTITY="TIME", SETPOINT=30. /
 &DEVC XYZ=16.53,25.64,0.0, PROP_ID='VikingGrateNoz', ID='TR_Stream9',
 ORIENTATION=-0.342,-0.919,0.174, QUANTITY="TIME", SETPOINT=30. /
 &DEVC XYZ=16.53,25.64,0.0, PROP_ID='VikingGrateNoz', ID='TR_Stream10',
 ORIENTATION=-0.207,-0.958,0.174, QUANTITY="TIME", SETPOINT=30. /
 &DEVC XYZ=16.53,25.64,0.0, PROP_ID='VikingGrateNoz', ID='TR_Stream11',
 ORIENTATION=-0.068,-0.978,0.174, QUANTITY="TIME", SETPOINT=30. /

/Bottom Left

&DEVC XYZ=1.33,2.66,0.0, PROP_ID='VikingGrateNoz', ID='BL_Stream1',
 ORIENTATION=0.978, 0.068,0.174, QUANTITY="TIME", SETPOINT=30. /
 &DEVC XYZ=1.33,2.66,0.0, PROP_ID='VikingGrateNoz', ID='BL_Stream2',
 ORIENTATION=0.958, 0.207,0.174, QUANTITY="TIME", SETPOINT=30. /
 &DEVC XYZ=1.33,2.66,0.0, PROP_ID='VikingGrateNoz', ID='BL_Stream3',
 ORIENTATION=0.919, 0.342,0.174, QUANTITY="TIME", SETPOINT=30. /
 &DEVC XYZ=1.33,2.66,0.0, PROP_ID='VikingGrateNoz', ID='BL_Stream4',
 ORIENTATION=0.860, 0.469,0.174, QUANTITY="TIME", SETPOINT=30. /
 &DEVC XYZ=1.33,2.66,0.0, PROP_ID='VikingGrateNoz', ID='BL_Stream5',
 ORIENTATION=0.785, 0.587,0.174, QUANTITY="TIME", SETPOINT=30. /
 &DEVC XYZ=1.33,2.66,0.0, PROP_ID='VikingGrateNoz', ID='BL_Stream6',
 ORIENTATION=0.693, 0.693,0.174, QUANTITY="TIME", SETPOINT=30. /
 &DEVC XYZ=1.33,2.66,0.0, PROP_ID='VikingGrateNoz', ID='BL_Stream7',
 ORIENTATION=0.587, 0.785,0.174, QUANTITY="TIME", SETPOINT=30. /
 &DEVC XYZ=1.33,2.66,0.0, PROP_ID='VikingGrateNoz', ID='BL_Stream8',
 ORIENTATION=0.469, 0.860,0.174, QUANTITY="TIME", SETPOINT=30. /
 &DEVC XYZ=1.33,2.66,0.0, PROP_ID='VikingGrateNoz', ID='BL_Stream9',
 ORIENTATION=0.342, 0.919,0.174, QUANTITY="TIME", SETPOINT=30. /
 &DEVC XYZ=1.33,2.66,0.0, PROP_ID='VikingGrateNoz', ID='BL_Stream10',
 ORIENTATION=0.207, 0.958,0.174, QUANTITY="TIME", SETPOINT=30. /
 &DEVC XYZ=1.33,2.66,0.0, PROP_ID='VikingGrateNoz', ID='BL_Stream11',
 ORIENTATION=0.068, 0.978,0.174, QUANTITY="TIME", SETPOINT=30. /

/Bottom Right

&DEVC XYZ=16.53,2.66,0.0, PROP_ID='VikingGrateNoz', ID='BR_Stream1',
 ORIENTATION=-0.978, 0.068,0.174, QUANTITY="TIME", SETPOINT=30. /
 &DEVC XYZ=16.53,2.66,0.0, PROP_ID='VikingGrateNoz', ID='BR_Stream2',
 ORIENTATION=-0.958, 0.207,0.174, QUANTITY="TIME", SETPOINT=30. /
 &DEVC XYZ=16.53,2.66,0.0, PROP_ID='VikingGrateNoz', ID='BR_Stream3',
 ORIENTATION=-0.919, 0.342,0.174, QUANTITY="TIME", SETPOINT=30. /
 &DEVC XYZ=16.53,2.66,0.0, PROP_ID='VikingGrateNoz', ID='BR_Stream4',
 ORIENTATION=-0.860, 0.469,0.174, QUANTITY="TIME", SETPOINT=30. /

```

&DEVC XYZ=16.53,2.66,0.0, PROP_ID='VikingGrateNoz', ID='BR_Stream5',
ORIENTATION=-0.785, 0.587,0.174, QUANTITY="TIME", SETPOINT=30. /
&DEVC XYZ=16.53,2.66,0.0, PROP_ID='VikingGrateNoz', ID='BR_Stream6',
ORIENTATION=-0.693, 0.693,0.174, QUANTITY="TIME", SETPOINT=30. /
&DEVC XYZ=16.53,2.66,0.0, PROP_ID='VikingGrateNoz', ID='BR_Stream7',
ORIENTATION=-0.587, 0.785,0.174, QUANTITY="TIME", SETPOINT=30. /
&DEVC XYZ=16.53,2.66,0.0, PROP_ID='VikingGrateNoz', ID='BR_Stream8',
ORIENTATION=-0.469, 0.860,0.174, QUANTITY="TIME", SETPOINT=30. /
&DEVC XYZ=16.53,2.66,0.0, PROP_ID='VikingGrateNoz', ID='BR_Stream9',
ORIENTATION=-0.342, 0.919,0.174, QUANTITY="TIME", SETPOINT=30. /
&DEVC XYZ=16.53,2.66,0.0, PROP_ID='VikingGrateNoz', ID='BR_Stream10',
ORIENTATION=-0.207, 0.958,0.174, QUANTITY="TIME", SETPOINT=30. /
&DEVC XYZ=16.53,2.66,0.0, PROP_ID='VikingGrateNoz', ID='BR_Stream11',
ORIENTATION=-0.068, 0.978,0.174, QUANTITY="TIME", SETPOINT=30. /

```

C.7 VID Fire-kill Nozzle

```

/ Spray
&SPEC ID='WATER VAPOR'/
&PART ID='WATERF-102',
    SPEC_ID='WATER VAPOR',
    DIAMETER = 200,
    GAMMA_D = 2,
    SAMPLING_FACTOR = 500,
    QUANTITIES(1:3)='PARTICLE DIAMETER','PARTICLE
TEMPERATURE','PARTICLE AGE'/

&PROP ID='F-102 Nozzle',
    OFFSET=0.1,
    PARTICLES_PER_SECOND=2500,
    PART_ID='WATERF-102',
    K_FACTOR=12,
    OPERATING_PRESSURE=10,
    SPRAY_PATTERN_TABLE='F-102 Characteristics'/

&TABL ID='F-102 Characteristics', TABLE_DATA = 0,30,0,360,35,0.25 /
&TABL ID='F-102 Characteristics', TABLE_DATA = 15,75,-30,30,20,0.25/
&TABL ID='F-102 Characteristics', TABLE_DATA = 15,75,90,150,20,0.25/
&TABL ID='F-102 Characteristics', TABLE_DATA = 15,75,210,270,20,0.25/

/ Stream locations -- Activates at t=30 S
/Nozzle Left

```

&DEVC ID='FLOOR MIST NOZZLE 1', XYZ=8.93,24.9,0.2, ORIENTATION=
 1,0,0, QUANTITY='TIME',SETPOINT=30., PROP_ID='F-102 Nozzle'/
 &DEVC ID='FLOOR MIST NOZZLE 2', XYZ=8.93,22.9,0.2, ORIENTATION=
 1,0,0, QUANTITY='TIME',SETPOINT=30., PROP_ID='F-102 Nozzle'/
 &DEVC ID='FLOOR MIST NOZZLE 3', XYZ=8.93,20.9,0.2, ORIENTATION=
 1,0,0, QUANTITY='TIME',SETPOINT=30., PROP_ID='F-102 Nozzle'/
 &DEVC ID='FLOOR MIST NOZZLE 4', XYZ=8.93,18.9,0.2, ORIENTATION=
 1,0,0, QUANTITY='TIME',SETPOINT=30., PROP_ID='F-102 Nozzle'/
 &DEVC ID='FLOOR MIST NOZZLE 5', XYZ=8.93,16.9,0.2, ORIENTATION=
 1,0,0, QUANTITY='TIME',SETPOINT=30., PROP_ID='F-102 Nozzle'/
 &DEVC ID='FLOOR MIST NOZZLE 6', XYZ=8.93,14.9,0.2, ORIENTATION=
 1,0,0, QUANTITY='TIME',SETPOINT=30., PROP_ID='F-102 Nozzle'/
 &DEVC ID='FLOOR MIST NOZZLE 7', XYZ=8.93,12.9,0.2, ORIENTATION=
 1,0,0, QUANTITY='TIME',SETPOINT=30., PROP_ID='F-102 Nozzle'/
 &DEVC ID='FLOOR MIST NOZZLE 8', XYZ=8.93,10.9,0.2, ORIENTATION=
 1,0,0, QUANTITY='TIME',SETPOINT=30., PROP_ID='F-102 Nozzle'/
 &DEVC ID='FLOOR MIST NOZZLE 9', XYZ=8.93, 8.9,0.2, ORIENTATION=
 1,0,0, QUANTITY='TIME',SETPOINT=30., PROP_ID='F-102 Nozzle'/
 &DEVC ID='FLOOR MIST NOZZLE 10', XYZ=8.93, 6.9,0.2, ORIENTATION=
 1,0,0, QUANTITY='TIME',SETPOINT=30., PROP_ID='F-102 Nozzle'/
 &DEVC ID='FLOOR MIST NOZZLE 11', XYZ=8.93, 4.9,0.2, ORIENTATION=
 1,0,0, QUANTITY='TIME',SETPOINT=30., PROP_ID='F-102 Nozzle'/
 &DEVC ID='FLOOR MIST NOZZLE 12', XYZ=8.93, 2.9,0.2, ORIENTATION=
 1,0,0, QUANTITY='TIME',SETPOINT=30., PROP_ID='F-102 Nozzle'/

/Nozzle Right

&DEVC ID='FLOOR MIST NOZZLE 13', XYZ=16.53,24.9,0.2, ORIENTATION=-
 1,0,0, QUANTITY='TIME',SETPOINT=30., PROP_ID='F-102 Nozzle'/
 &DEVC ID='FLOOR MIST NOZZLE 14', XYZ=16.53,22.9,0.2, ORIENTATION=-
 1,0,0, QUANTITY='TIME',SETPOINT=30., PROP_ID='F-102 Nozzle'/
 &DEVC ID='FLOOR MIST NOZZLE 15', XYZ=16.53,20.9,0.2, ORIENTATION=-
 1,0,0, QUANTITY='TIME',SETPOINT=30., PROP_ID='F-102 Nozzle'/
 &DEVC ID='FLOOR MIST NOZZLE 16', XYZ=16.53,18.9,0.2, ORIENTATION=-
 1,0,0, QUANTITY='TIME',SETPOINT=30., PROP_ID='F-102 Nozzle'/
 &DEVC ID='FLOOR MIST NOZZLE 17', XYZ=16.53,16.9,0.2, ORIENTATION=-
 1,0,0, QUANTITY='TIME',SETPOINT=30., PROP_ID='F-102 Nozzle'/
 &DEVC ID='FLOOR MIST NOZZLE 18', XYZ=16.53,14.9,0.2, ORIENTATION=-
 1,0,0, QUANTITY='TIME',SETPOINT=30., PROP_ID='F-102 Nozzle'/
 &DEVC ID='FLOOR MIST NOZZLE 19', XYZ=16.53,12.9,0.2, ORIENTATION=-
 1,0,0, QUANTITY='TIME',SETPOINT=30., PROP_ID='F-102 Nozzle'/
 &DEVC ID='FLOOR MIST NOZZLE 20', XYZ=16.53,10.9,0.2, ORIENTATION=-
 1,0,0, QUANTITY='TIME',SETPOINT=30., PROP_ID='F-102 Nozzle'/

```

&DEVC ID='FLOOR MIST NOZZLE 21', XYZ=16.53, 8.9,0.2, ORIENTATION=-
1,0,0, QUANTITY='TIME',SETPOINT=30., PROP_ID='F-102 Nozzle'/
&DEVC ID='FLOOR MIST NOZZLE 22', XYZ=16.53, 6.9,0.2, ORIENTATION=-
1,0,0, QUANTITY='TIME',SETPOINT=30., PROP_ID='F-102 Nozzle'/
&DEVC ID='FLOOR MIST NOZZLE 23', XYZ=16.53, 4.9,0.2, ORIENTATION=-
1,0,0, QUANTITY='TIME',SETPOINT=30., PROP_ID='F-102 Nozzle'/
&DEVC ID='FLOOR MIST NOZZLE 24', XYZ=16.53, 2.9,0.2, ORIENTATION=-
1,0,0, QUANTITY='TIME',SETPOINT=30., PROP_ID='F-102 Nozzle'/

```

C.8 Plane and Devices

/F-35 plane obstruction

```

&MATL ID = 'COMPOSITE',
    CONDUCTIVITY = 1.2,
    SPECIFIC_HEAT = 2.2,
    DENSITY = 1514 /

```

```

&SURF ID ='PLANE',
    MATL_ID = 'COMPOSITE',
    THICKNESS = 0.0032,
    COLOR = 'SILVER'/

```

```

&OBST XB = 11.6,14.4,5.2,17.2,1.6,3.6, SURF_ID = 'PLANE' / FUSALAGE
&OBST XB = 12,14,17.2,18,1.6,4, SURF_ID = 'PLANE' / NOSE
&OBST XB = 12,14,18,18.8,1.6,3.6, SURF_ID = 'PLANE' / NOSE
&OBST XB = 12,14,18.8,19.6,1.6,3, SURF_ID = 'PLANE' / NOSE
&OBST XB = 12,14,19.6,20.4,2,3, SURF_ID = 'PLANE' / NOSE
&OBST XB = 12,14,20.4,21.2,2,2.4, SURF_ID = 'PLANE' / NOSE

```

```

&OBST XB = 10.4,11.6,6.8,13.6,2,2.4 , SURF_ID = 'PLANE' / LHS WING
&OBST XB = 9.6,10.4,7.2,12.8,2,2.4, SURF_ID = 'PLANE' / LHS WING
&OBST XB = 8.8,9.6,7.6,12.4,2,2.4, SURF_ID = 'PLANE' / LHS WING
&OBST XB = 8.4,8.8,8,12,2,2.4, SURF_ID = 'PLANE' / LHS WING
&OBST XB = 8,8.4,8.4,11.6,2,2.4, SURF_ID = 'PLANE' / LHS WING
&OBST XB = 7.6,8,9.2,11.2,2,2.4, SURF_ID = 'PLANE' / LHS WING

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&OBST XB = 14.4,15.6,6.8,13.6,2,2.4 , SURF_ID = 'PLANE' / RHS WING
&OBST XB = 15.6,16.4,7.2,12.8,2,2.4, SURF_ID = 'PLANE' / RHS WING
&OBST XB = 16.4,17.2,7.6,12.4,2,2.4, SURF_ID = 'PLANE' / RHS WING
&OBST XB = 17.2,17.8,8,12,2,2.4, SURF_ID = 'PLANE' / RHS WING
&OBST XB = 17.8,18,8.4,11.6,2,2.4, SURF_ID = 'PLANE' / RHS WING
&OBST XB = 18,18.4,9.2,11.2,2,2.4, SURF_ID = 'PLANE' / RHS WING

```

&OBST XB = 10.6,11.6,5,7,3,4, SURF_ID = 'PLANE' / LHS TAIL
 &OBST XB = 10,11,5,6.6,4,4.6, SURF_ID = 'PLANE'/LHS TAIL
 &OBST XB = 9.6,10.6,5,6,4.6,5, SURF_ID = 'PLANE'/LHS TAIL
 &OBST XB = 9,10,5,6,5,5.6, SURF_ID = 'PLANE' / LHS TAIL
 &OBST XB = 9,10,5,5.6,5.6,6, SURF_ID = 'PLANE' /LHS TAIL

&OBST XB = 14.6,15.6,5,7,3,4, SURF_ID = 'PLANE' / RHS TAIL
 &OBST XB = 15,16,5,6.6,4,4.6, SURF_ID = 'PLANE'/RHS TAIL
 &OBST XB = 15.6,16.5,5,6,4.6,5, SURF_ID = 'PLANE'/RHS TAIL
 &OBST XB = 16,17,5,6,5,5.6, SURF_ID = 'PLANE' / RHS TAIL
 &OBST XB = 16,17,5,5.6,5.6,6, SURF_ID = 'PLANE' /RHS TAIL

// Heat Flux Measurements for Plane
 / Incident Heat Flux

&DEVC ID = 'Plane_End1', XYZ = 12,6,1.6 , IOR = -3, QUANTITY = 'INCIDENT
 HEAT FLUX' /
 &DEVC ID = 'Plane_End2', XYZ =12.5,6,1.6 , IOR = -3, QUANTITY = 'INCIDENT
 HEAT FLUX' /
 &DEVC ID = 'Plane_End3', XYZ = 13,6,1.6 , IOR = -3, QUANTITY = 'INCIDENT
 HEAT FLUX' /
 &DEVC ID = 'Plane_End4', XYZ =13.5,6,1.6 , IOR = -3, QUANTITY = 'INCIDENT
 HEAT FLUX' /
 &DEVC ID = 'Plane_End5', XYZ =14.0,6,1.6 , IOR = -3, QUANTITY = 'INCIDENT
 HEAT FLUX' /

&DEVC ID = 'Fuselage_1', XYZ=13,5.6,1.6, QUANTITY = 'INCIDENT HEAT
 FLUX',IOR = -3/
 &DEVC ID = 'Fuselage_2', XYZ=13,6,1.6, QUANTITY = 'INCIDENT HEAT
 FLUX',IOR = -3/
 &DEVC ID = 'Fuselage_3', XYZ=13,6.6,1.6, QUANTITY = 'INCIDENT HEAT
 FLUX',IOR = -3/
 &DEVC ID = 'Fuselage_4', XYZ=13,7,1.6, QUANTITY = 'INCIDENT HEAT
 FLUX',IOR = -3/
 &DEVC ID = 'Fuselage_5', XYZ=13,7.6,1.6, QUANTITY = 'INCIDENT HEAT
 FLUX',IOR = -3/
 &DEVC ID = 'Fuselage_6', XYZ=13,8,1.6, QUANTITY = 'INCIDENT HEAT
 FLUX',IOR = -3/
 &DEVC ID = 'Fuselage_7', XYZ=13,8.6,1.6, QUANTITY = 'INCIDENT HEAT
 FLUX',IOR = -3/
 &DEVC ID = 'Fuselage_8', XYZ=13,9,1.6, QUANTITY = 'INCIDENT HEAT
 FLUX',IOR = -3/

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/Gauge Heat Flux
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