

Ignited Fuel Spill Scenarios in F35 Hangar Designs
Revision 1

Prepared by:
Kyle Giubbini
NFPA 409 Technical Committee Member
R&D Engineer
Safespill
Houston, TX 77054

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1 Introduction

1.1 Purpose

The following report details calculations used to determine a worst-case spill fire scenario in an F35 hangar with a water-only sprinkler system compared to a hangar utilizing ILDFA for fire protection. The scenarios shown utilize information regarding large, open hydrocarbon pool fires and the delamination and ignition characteristics of composite aircraft components used on the F35 aircraft. Data related to large, open hydrocarbon pool fires is sourced from the SFPE Handbook, Section Three, Chapter 11 (Beyler). Data regarding delamination and ignition of composite aircraft components is sourced from research reports generated by the Air Force Research Laboratory (Bocchieri, May 2013) (Bocchieri, June 2013) and Federal Aviation Administration (Quintiere).

2 Hangar Layouts

The scenario examined involves the aircraft parking arrangements and hangar trench layouts for military aircraft hangars typically designed for housing F35B & F35C.

2.1 Hangar with Water-Only Sprinkler System

The assumed layout for this hangar utilizes rectangular trench layouts with a depth (from hangar door to office space) of 79 feet and width of 38 feet 6 inches. F35 Aircraft are parked at the center of each rectangular trench area, with a spacing (when wings are folded) of 10 feet from wingtip to wingtip. A crest (high point) is located at the center of the rectangular area and runs parallel to the hangar door. Slopes are built into the hangar surface to drive spilled liquid to trenches located beyond the nose and tail of the aircraft.

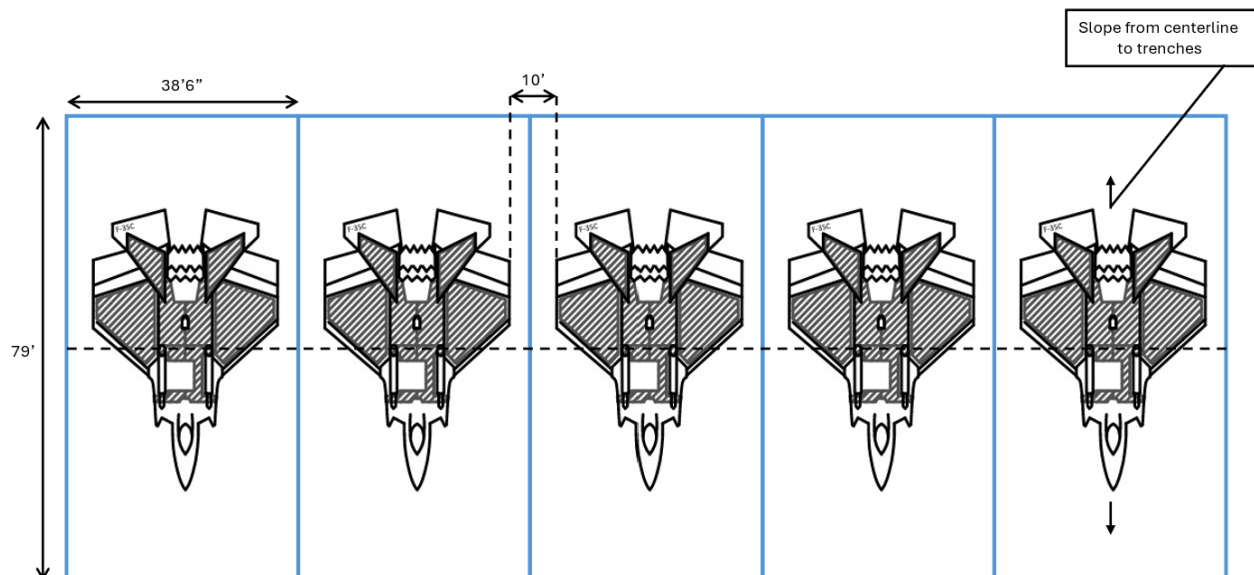


Figure 2-1: Dimensioned F35 Hangar with Trench Layout

The fire scenario described involves a 165-gallon spill of JP4 jet fuel from near the engine of the aircraft (Figure 2-2). A fully fueled F35 carries up to 3,000 gallons of fuel, so it is assumed that following the

initial spill, additional fuel would leak from the source of the spill throughout the duration of the event, continuing to feed the fire throughout the 3-minute duration of the events described.

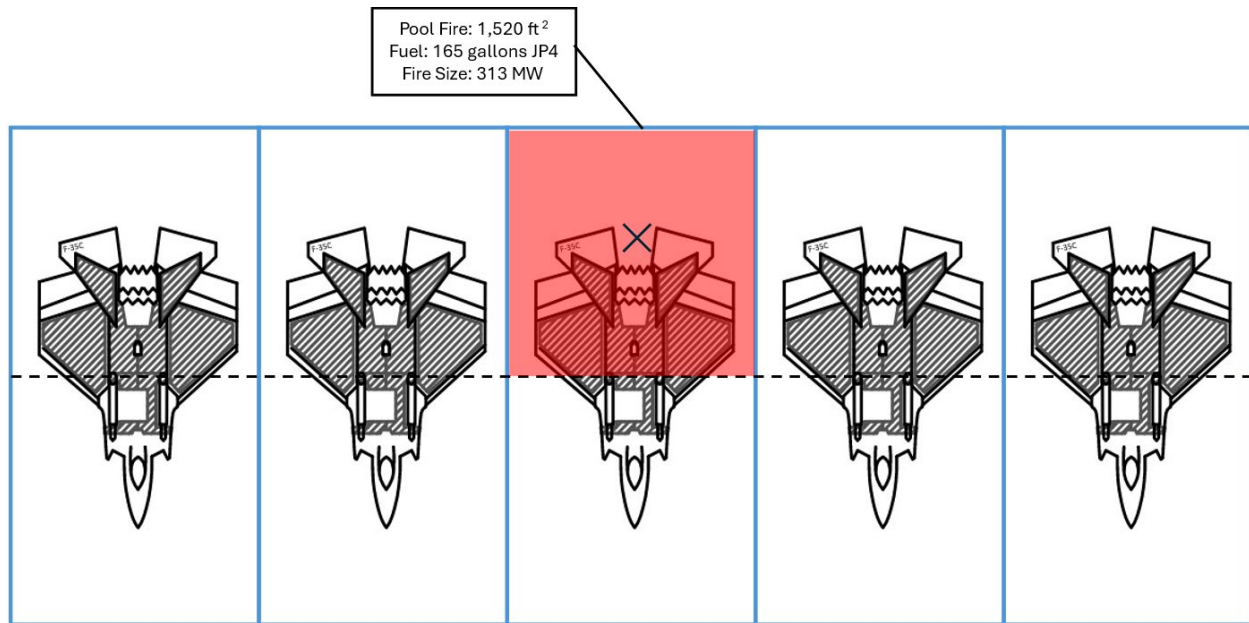


Figure 2-2: 165 Gallon JP4 Pool Fire in F35 Hangar

2.2 Hangar with ILDFA

In comparison, a scenario in which the hangar is installed with ILDFA is examined. In this scenario, the slope of the hangar is identical, but intermediate trenches at 38'6" are excluded as shown in Figure 2-3.

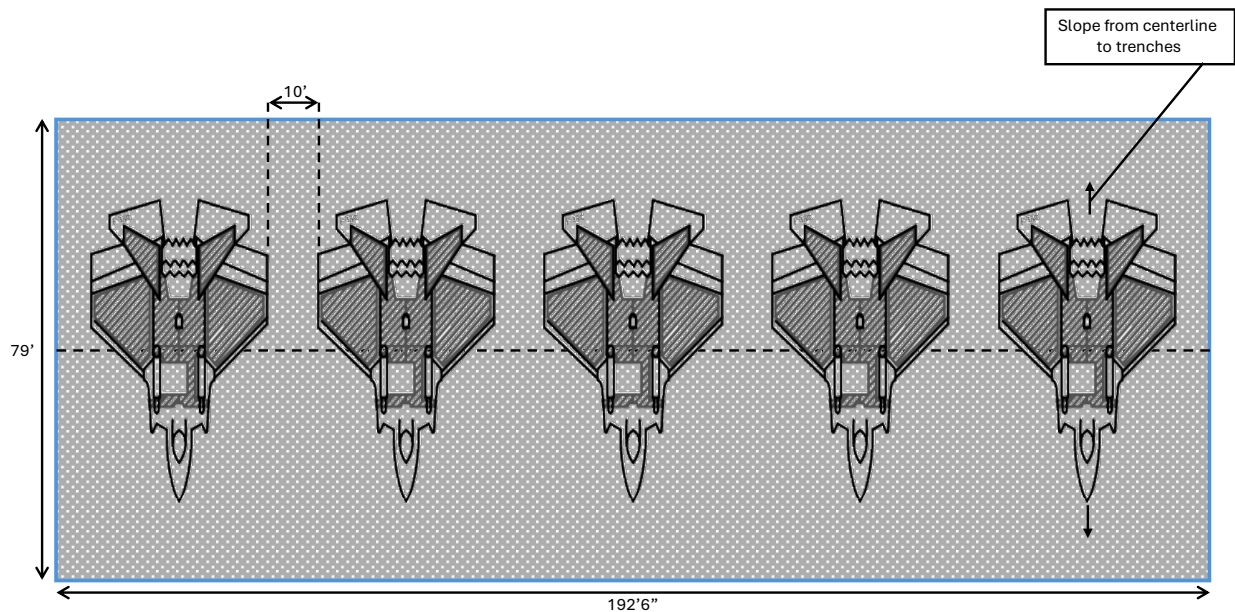


Figure 2-3: Layout for F35 Hangar with ILDFA Installed

3 Methods

3.1 Fire Scenario

In 2019, Safespill conducted a testing program at the request of the Chief Fire Protection Engineer for Naval Facilities Command (NAVFAC) and the Chief Fire Protection Engineer for the United States Department of the Air Force. This testing program centered around a benchmark test used for evaluating fire protection systems in aircraft hangars called the “wing tank drop test” (Zallen). This fire test involves an instantaneous release of 165 gallons of ignited JP4 jet fuel. Following the completion of Safespill’s testing program, the results were verified through 3rd party testing conducted by the Air Force Civil Engineering Center (AFCEC) (Wells).

For this report, a 165-gallon JP4 jet fuel fire is used as a representative and realistic fuel fire scenario in a hangar based on the test programs discussed above.

While JP4 fuel may be uncommon, it provides data consistent with ILDFA testing (Wells) and previous test programs (Zallen) related to liquid fires in aircraft hangars. While JP4 has a lower flash point than JP5 and JP8, other critical parameters such as mass burning rate and heat of combustion are nearly identical.

During these testing programs, fuel was ignited using either electrical glow plugs surrounded by alcohol soaked rags (Zallen) or nichrome wire embedded in wood wool (excelsior material) and energized using 15VAC (Wells). However, these reports listed other potential ignition scenarios that could occur in a hangar.

The 1987 Zallen report lists the following potential ignition sources:

- Non-explosion proof motors (used on hangar doors)
- High-voltage generators and start-carts
- Hydraulic carts
- Cartridge starts using black powders
- Running jet engines
- Static electricity
- Human error

The 2022 AFCEC report (Wells) states that “USAF maintenance aircraft hangars are designed for a worst-case fire threat scenario in which hundreds of gallons of fuel spill, pool, and ignite near an aircraft.”

Finally, an additional report referenced for this document (Bocchieri, May 2013) list the following potential fuel fire scenarios:

- a. Engine Nacelle Fire – occurs when a fuel or hydraulic line leaks within the nacelle and is ignited by contact with a hot surface
- b. Spill Fire – occurs when spilled fuel pools on the ground near or under the aircraft and ignites
- c. Wet Starts Fire – occurs on engine start, when fuel pumped to the engine fails to ignite in the combustor but ignites in the exhaust section. Historically these events are common but readily extinguished with flight line fire extinguishers and result in minimal damage to the aircraft
- d. Auxiliary Power Unit (APU) – occurs when a fuel or hydraulic line leaks within the APU compartment and is ignited by contact with a hot surface.

3.2 Water-Only Sprinkler System (No Low-Level Suppression)

In simulations not using ILDFA, suppression due to overhead water sprinkler systems is neglected. To properly account for the cooling effect of a sprinkler system, advanced fire modeling software would be required to determine critical performance factors, such as time to opening, distribution of sprinkler water, and effects to fire characteristics.

During a liquid fire in a hangar, the fire is shielded by the wings of the aircraft and water-only sprinkler discharge would only affect the size and intensity of the liquid fire **outside** of the footprint of the aircraft. While the sprinklers may reduce or eliminate the solid fire on the top surface of the aircraft, this contributes a fraction of the heat output of the liquid fire.

It is also important to note that current proposals for hangar installations utilizing water-only sprinkler systems with no low-level suppression systems call for a 0.2 gal/min/ft² over 5,000 ft² (See US Department of the Air Force “Sundown Policy for Foam Fire Suppression Systems and UFC 4-211-01, Change 4, Draft). Once a fire has grown beyond this area, sprinklers will be even less effective.

Finally, Safespill has conducted fire tests involving unshielded JP4 pool fires on bare concrete floors with water-only sprinkler systems.

The first test involved 30 gallons JP4 with an NFPA 409 prescribed water-only sprinkler density of 0.17 gal/min/ft². The second test involved 120 gallons JP4 with a water-only sprinkler density of 0.2 gal/min/ft².

Both tests utilized a sprinkler system height of 20 feet (much lower than a typical hangar ceiling) and the fire was neither controlled nor diminished by the sprinkler system. Rather, the sprinkler system generates large volumes of smoke that fill the space and contribute additional damage to building, aircraft, and personnel in the hangar.

The fire tests mentioned above are publicly available at the following web addresses:

<https://www.youtube.com/watch?v=u7-ZoVwSopo>

https://www.youtube.com/watch?v=2lrBJE99e_c

3.3 Ignited Composite Aircraft Components

Once ignited, it is assumed that burning aircraft components will contribute additional heat to the fire. The FAA report describes the average heat release rate of the composite aircraft components following ignition. Data is provided for ignited components at 25, 50, 75, and 100 kW/m². While the burning rate was sustained for heat fluxes as low as 8 kW/m², the critical heat release rate for sustained burning is estimated at 50 kW/m². In fire scenarios examined in Chapter 4, the average heat release rate of 250 kW/m² at 50 kW/m² heat flux is used to determine the contribution of ignited aircraft components to the overall fire.

There is also data provided to describe flame spread across the surface of the composite aircraft components. However, the flame spread (1 mm/sec) is neglected because this rate of spread is primarily observed in a vertical direction and is insignificant when compared to the spread of fire due to high heat fluxes from the pool fires examined.

3.4 Fire Size and Radiant Heat Flux

Calculations for the size and heat release rate from the liquid pool fire are based on data and equations from the SFPE Handbook.

Heat Release Rate for Liquid Pool Fires composed of Organic Liquids (3-25):

$$\dot{Q} = \Delta h_c \dot{m}_{\infty}'' (1 - e^{-k\beta D}) A$$

Where,

$\dot{Q}$ = pool fire heat release rate (kW)

$\dot{m}_{\infty}''$ = mass burning rate of fuel per unit surface area (kg/m²-sec) = 0.051 for JP4

Δh_c = heat of combustion of fuel (kJ/kg) = 43,500 for JP4

A = surface area of pool fire (m²)

$k\beta$ = empirical constant (m⁻¹) = 3.6 for JP4

D = Diameter of pool fire (m)

Radiative heat flux (3-274):

$$\dot{q}'' = \frac{\dot{Q}_r}{4\pi R^2}$$

Where,

$\dot{q}''$ = Radiative Heat Flux

$\dot{Q}_r$ = Total Radiative Energy Output defined by $\dot{Q}_r = \dot{Q} \times (0.21 - 0.0034 D)$

D = Diameter of pool fire (m)

R = distance from center of fire to target

3.5 Delamination and Auto-Ignition of Aircraft Components

Reports published by both the United States Air Force Civil Engineer Center (AFCEC) and United States Federal Aviation Administration (FAA) discuss the delamination and ignition of composite aircraft components.

Based on data from these sources, models were generated to determine the point at which radiant heat flux levels will delaminate and auto-ignite composite aircraft components.

3.5.1 Delamination Threshold

In the AFCEC report (Bocchieri, June 2013), IM7/RM3002 plates were shown to delaminate at various heat fluxes. It is also noted that “the time to delamination decreases rapidly with increasing heat flux”. At a heat flux of 15 kW/m² the composite delaminates within 230 seconds. At a heat flux of 25 kW/m² the composite delaminates within 130 seconds. At a heat flux of 35 kW/m² the composite delaminates within 77 seconds.

These values were plotted and fit with a curve as shown in Figure 3-1.

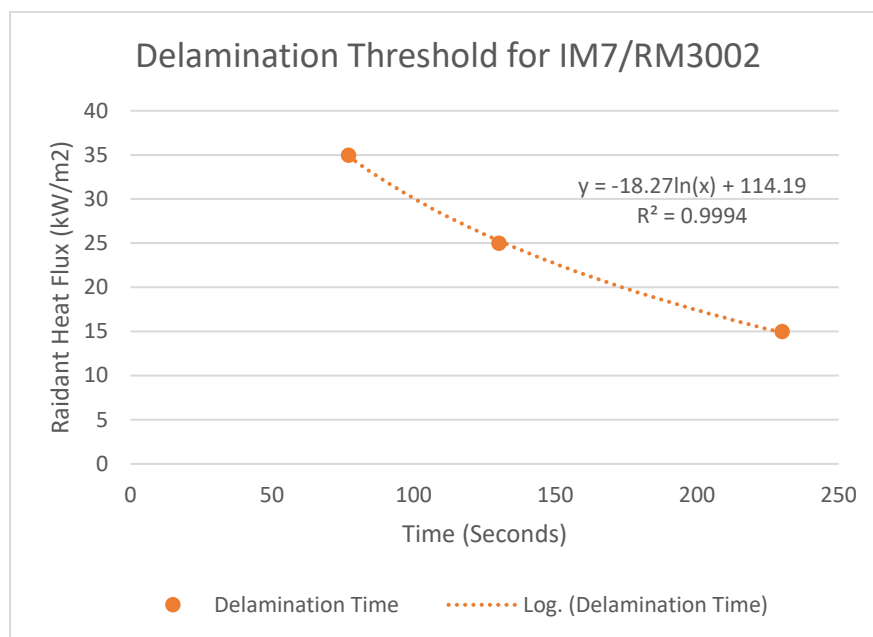


Figure 3-1: Delamination threshold for composite aircraft components fitted with logarithmic curve

The data is best fit with a logarithmic curve described by the equation:

$$y = -18.27 * \ln(x) + 114.19$$

Where,

x = Time in Seconds

y = Radiant Heat Flux in kW/m²

3.5.2 Auto-Ignition Threshold

In the DOT/FAA report (Quintiere), 8-276 Toray Composites plates were examined for flammability and fire hazard properties. In Chapter 2.4, both piloted and auto-ignition of the composite is demonstrated to occur following “onset of vaporization of the composite” at 300°C. Testing shows that the critical heat fluxes below which ignition cannot occur is 17.5 kW/m² for piloted ignition and about 31.5 kW/m² for auto ignition.

Based on observational data, the following equation is provided to determine auto-ignition of the composite:

$$t_{ig} = 23 \times 10^5 * q''^{-2}$$

Where,

t_{ig} = Time to auto-ignition in seconds

q'' = Incident Heat Flux in kW/m²

4 Results

Three fire scenarios were examined using the methods described in Chapter 3.

1. F35 Hangar with water-only sprinkler system, no additional fuel tank ruptures
2. F35 Hangar with water-only sprinkler system, additional fuel tank ruptures
3. F35 Hangar with ILDFA

For each scenario, the following assumptions were made:

- a. Initiation of fire consists of a 165-gallon, ignited, JP4 fuel fire from the engine of the aircraft (see Section 3.1).
- b. Fire is sustained by additional leaking JP4 for a duration of 3 minutes.
- c. Heat release rate and radiant heat flux for pool fires follow the equations described in 3.4.
- d. Delamination of aircraft components follows the equation described in 3.5.1.
- e. Auto-ignition of aircraft components follows the equation described in 3.5.2.
- f. Piloted ignition of aircraft components is neglected.
- g. Flame spread of aircraft components is neglected.
- h. Ignited aircraft components contributed a heat release rate of 250 kW/m^2 when ignited.
- i. For scenario 2, additional fuel leaks occur after 30 seconds of exposure to heat flux levels greater than 85 kW/m^2 .
- j. Cross-winds are neglected.
- k. Pool fires are bounded by trenches and do not contribute to overall fire from within trenches.
- l. Calculations are conducted in 2-dimensional layout, only the top surface of the aircraft is considered in delamination and ignition calculations.
- m. The entire top surface of the aircraft is composed of composite.

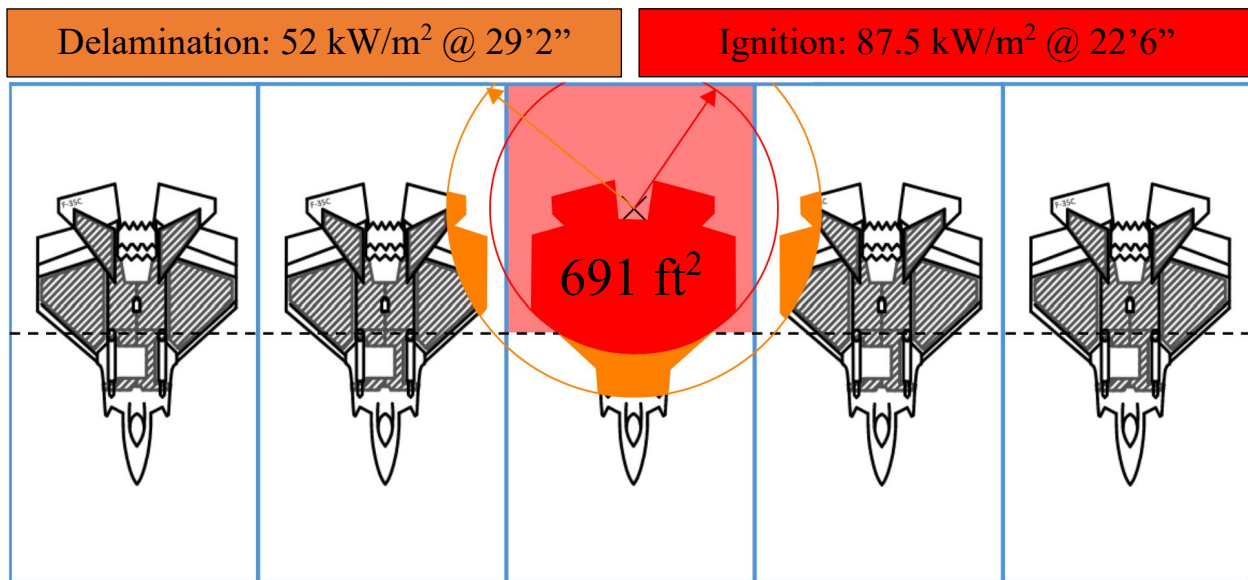
To generate calculations, the hangar layout was pixelated to 6" squares. Radiant heat flux was calculated for all pixels containing aircraft. This data was then colorized to display ignited and delaminated pixels. This data was then overlayed on hangar layouts for presentation.

4.1 Water-Only Sprinkler System without additional tank ruptures

With a water-only sprinkler system and no additional fuel fires, the following progression of fire was determined.

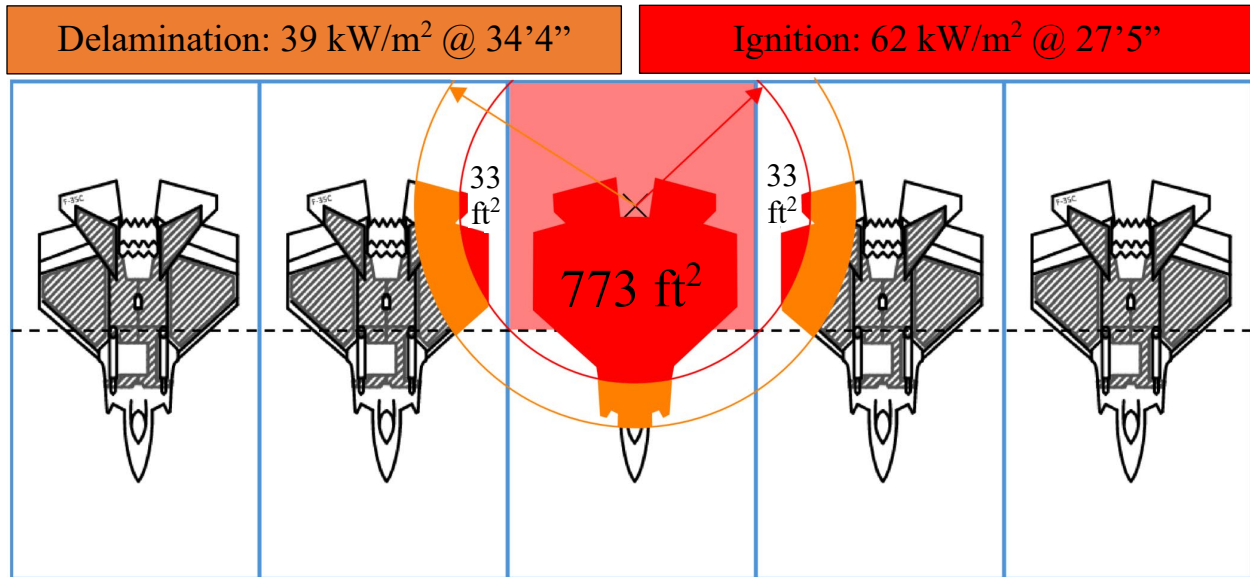
30 Seconds after Initiation of Pool Fire

Approximately 691 ft² of the involved aircraft are ignited and 95 ft² are delaminated. Adjacent aircraft experience delamination, approximately 67.5 ft² on each aircraft. Ignited aircraft components contribute an additional heat release rate of approximately 15 MW.



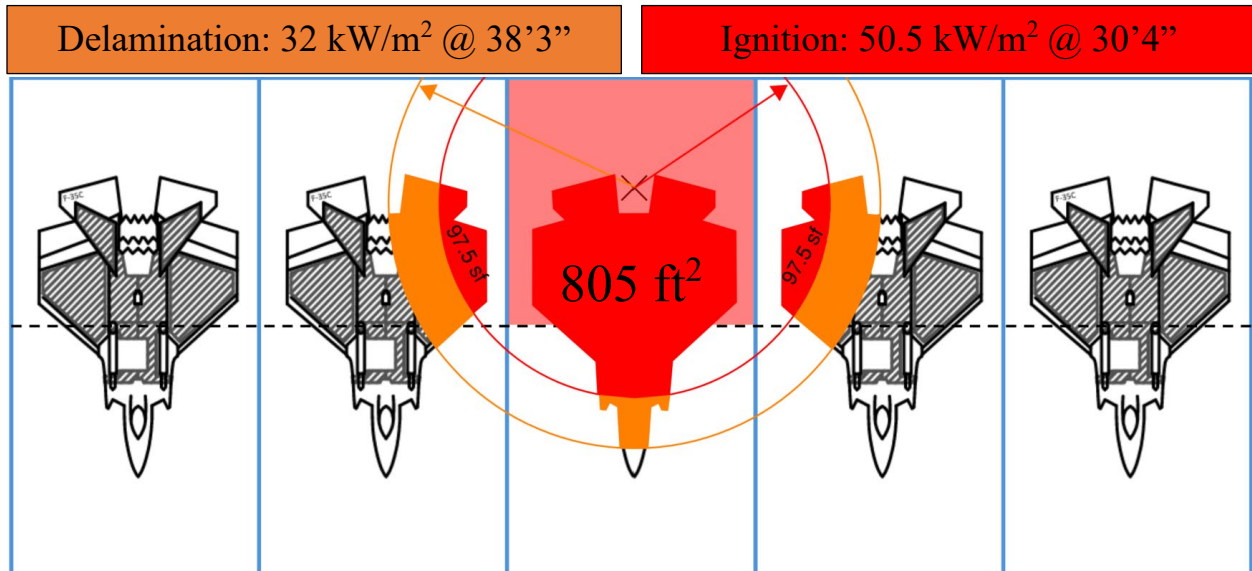
60 Seconds after Initiation of Pool Fire

Approximately 773 ft² of the involved aircraft are ignited and 64 ft² are delaminated. Adjacent aircraft ignite from radiant heat flux. Approximately 33 ft² of each adjacent aircraft are ignited, while 155 ft² of each aircraft are delaminated. Ignited aircraft components contribute an additional heat release rate of approximately 19.5 MW.



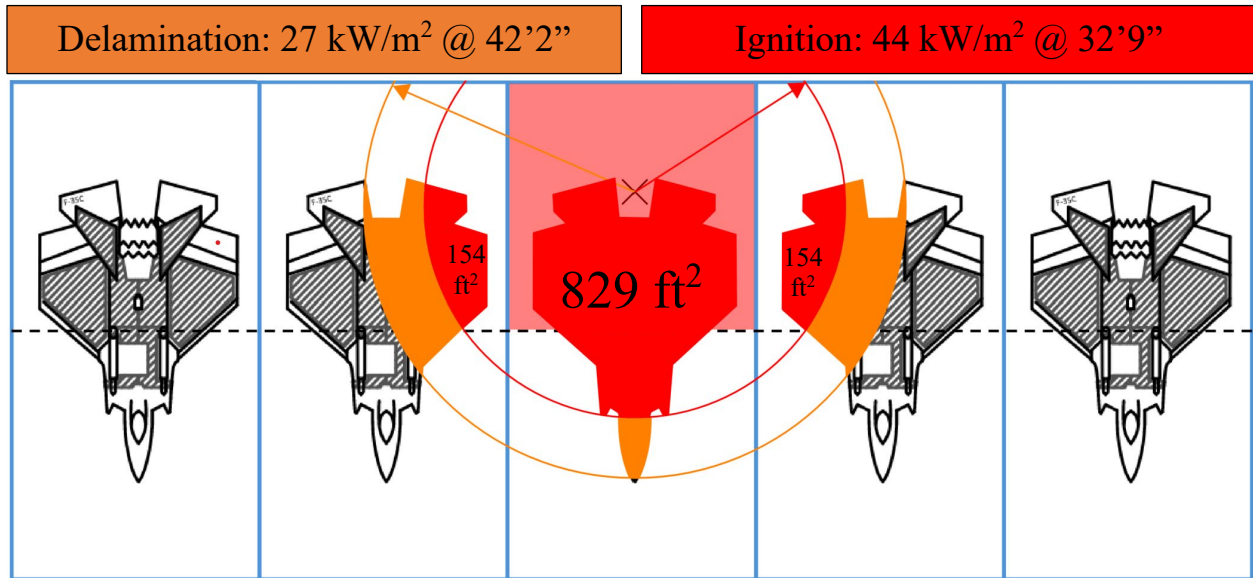
90 Seconds after Initiation of Pool Fire

Approximately 805 ft² of the involved aircraft are ignited and 48 ft² are delaminated. Approximately 97.5 ft² of each adjacent aircraft are ignited, while 188 ft² of each aircraft are delaminated. Ignited aircraft components contribute an additional heat release rate of approximately 23 MW.



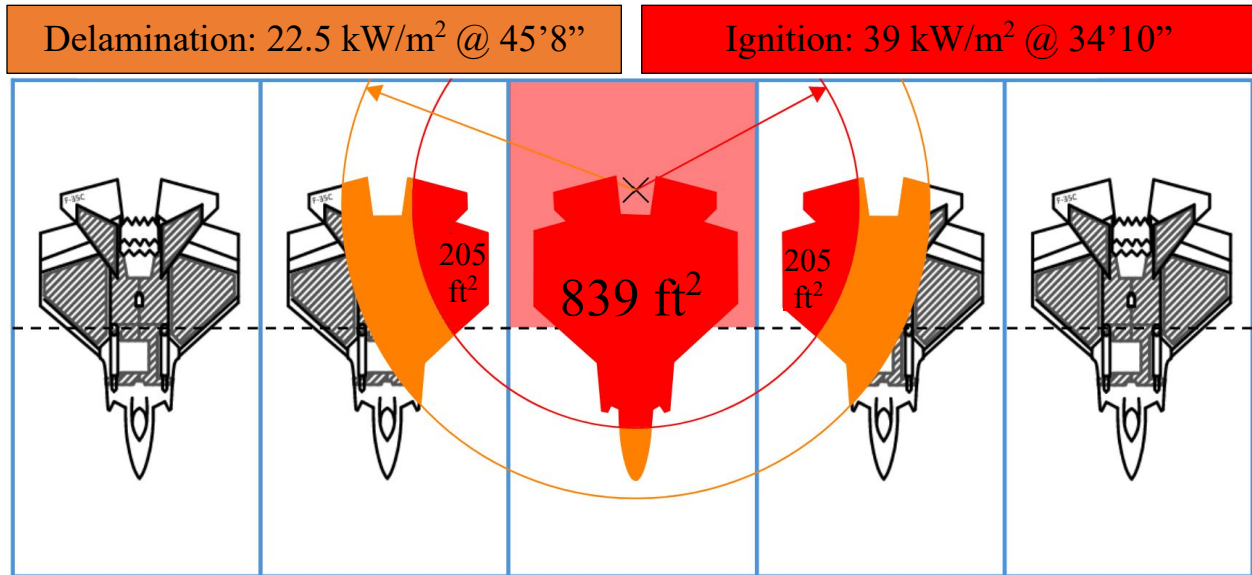
120 Seconds after Initiation of Pool Fire

Approximately 829 ft² of the involved aircraft are ignited and 38 ft² are delaminated. Approximately 154 ft² of each adjacent aircraft are ignited, while 237 ft² of each aircraft are delaminated. Ignited aircraft components contribute an additional heat release rate of approximately 26 MW.



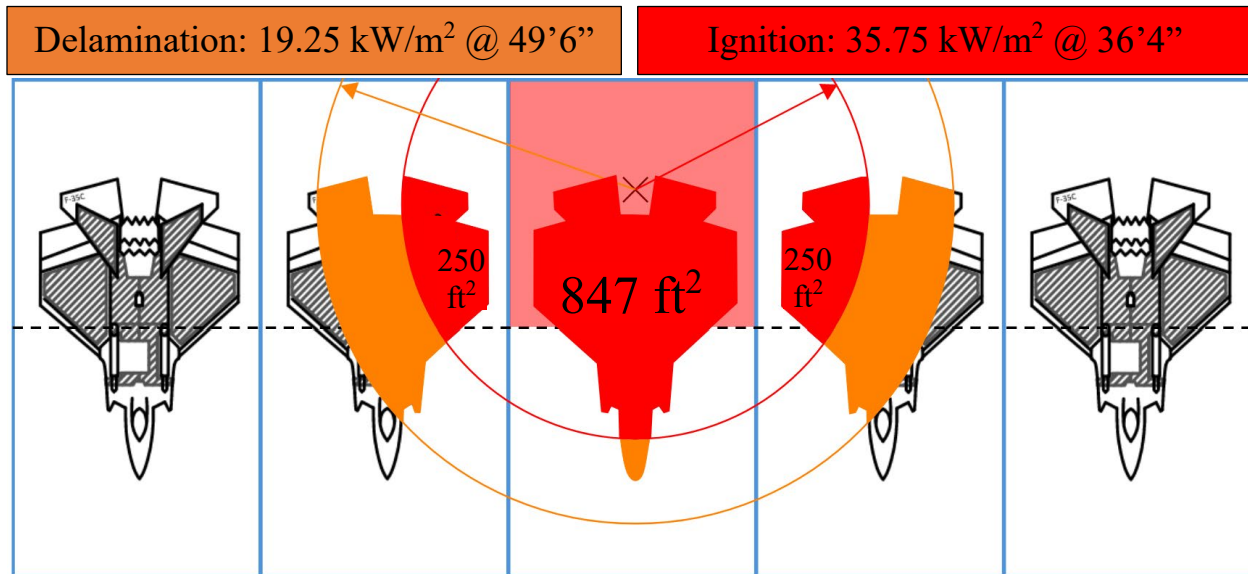
150 Seconds after Initiation of Pool Fire

Approximately 839 ft² of the involved aircraft are ignited and the remainder of the aircraft (31 ft²) is delaminated. Approximately 205 ft² of each adjacent aircraft are ignited, while 315 ft² of each aircraft are delaminated. Ignited aircraft components contribute an additional heat release rate of approximately 29 MW.



180 Seconds after Initiation of Pool Fire

Approximately 847 ft² of the involved aircraft are ignited and the remainder of the aircraft (23 ft²) is delaminated. Approximately 250 ft² of each adjacent aircraft are ignited, while 428 ft² of each aircraft are delaminated. Ignited aircraft components contribute an additional heat release rate of approximately 31 MW.

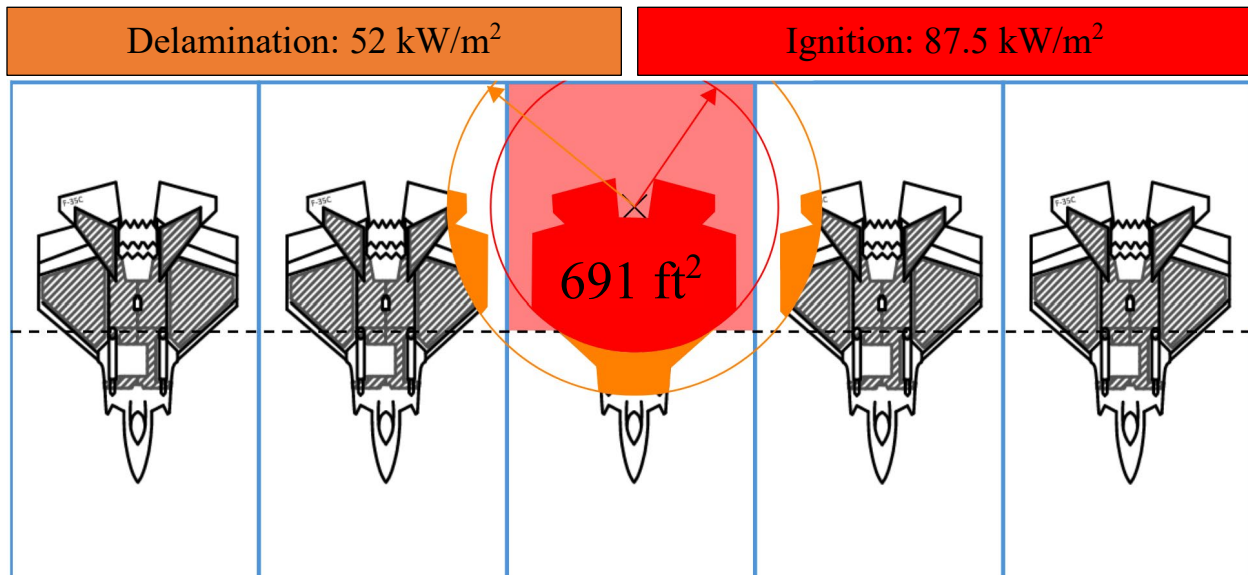


4.2 Water-Only Sprinkler System with additional tank ruptures

With a water-only sprinkler system the following progression of fire was determined, based on the assumption that additional fuel tanks will fail and lead to additional fuel fires when subjected to high radiant heat flux rates.

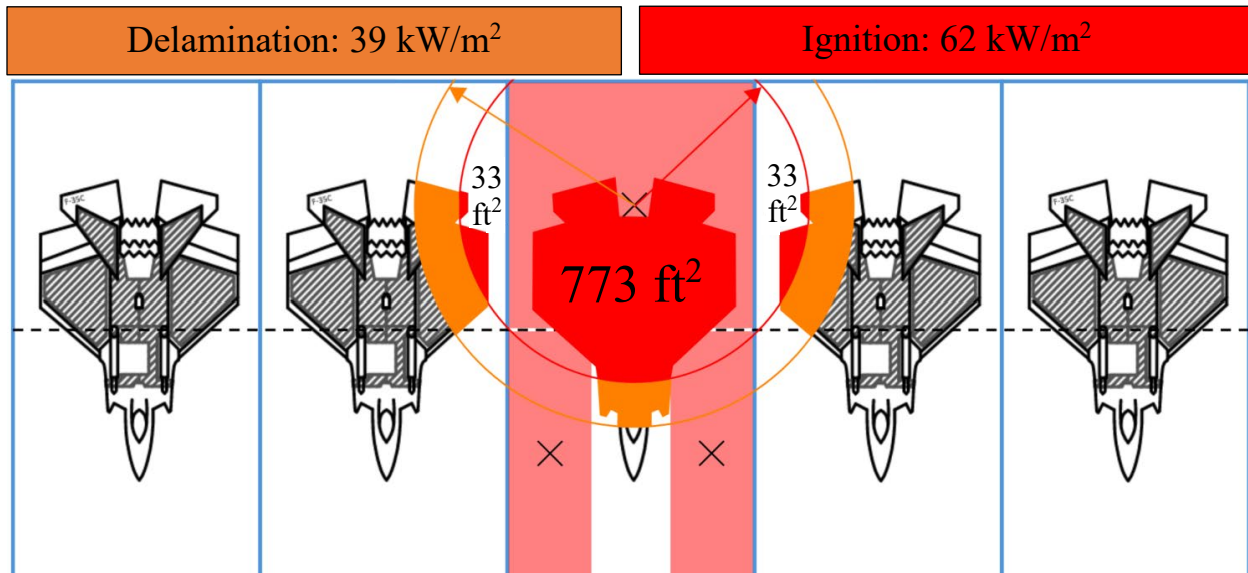
30 Seconds after Initiation of Pool Fire

Approximately 691 ft² of the involved aircraft are ignited and 95 ft² are delaminated. Adjacent aircraft experience delamination, approximately 67.5 ft² on each aircraft. Ignited aircraft components contribute an additional heat release rate of approximately 15 MW.



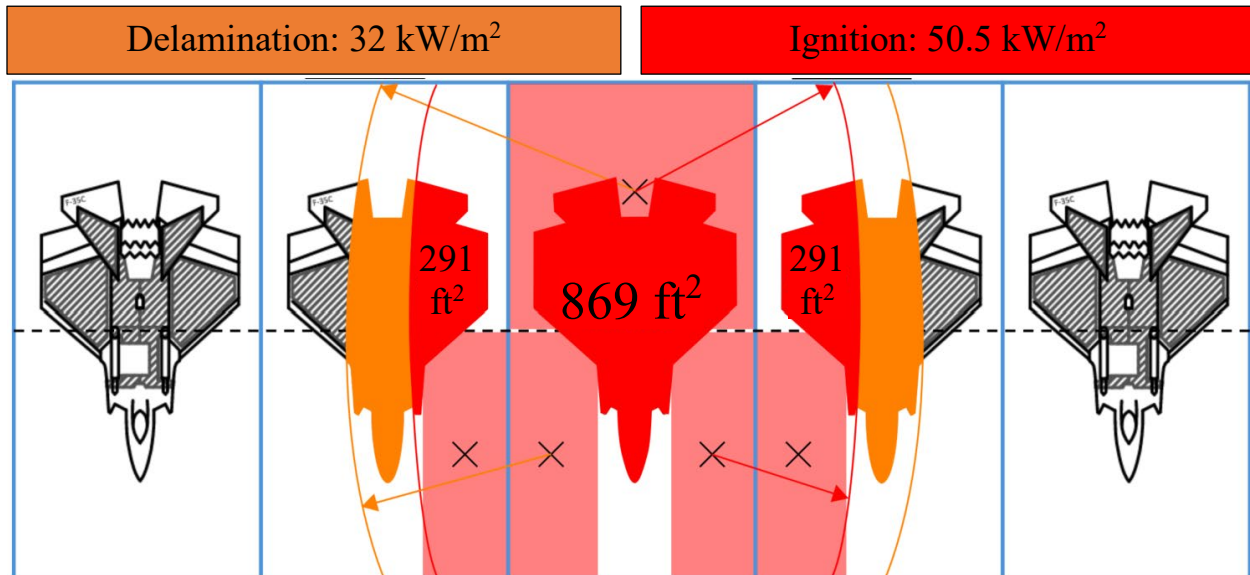
60 Seconds after Initiation of Pool Fire

Approximately 773 ft² of the involved aircraft are ignited and 64 ft² are delaminated. Adjacent aircraft ignite from radiant heat flux. Approximately 33 ft² of each adjacent aircraft are ignited, while 155 ft² of each aircraft are delaminated. Ignited aircraft components contribute an additional heat release rate of approximately 19.5 MW. Due to high radiant heat flux, additional pool fires begin near the nose of the aircraft. Each pool fire is approximated to cover 530 ft² and grow to a size of 110 MW.



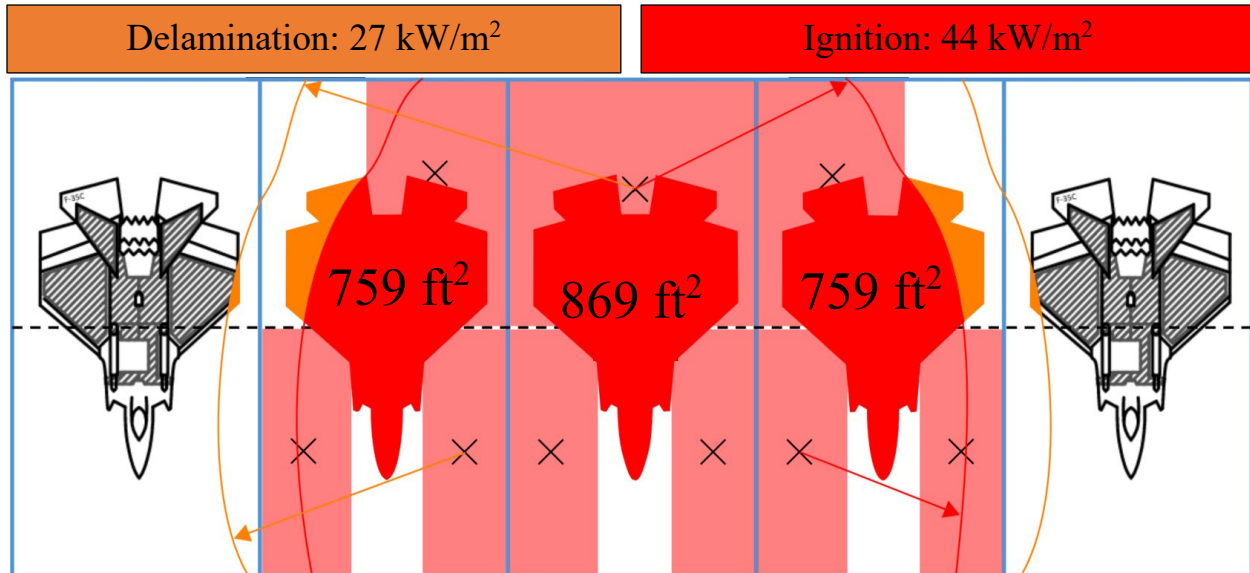
90 Seconds after Initiation of Pool Fire

The entire surface of the source aircraft is ignited, approximately 869 ft². Approximately 291 ft² of each adjacent aircraft are ignited, while 364 ft² of each aircraft are delaminated. Ignited aircraft components contribute an additional heat release rate of approximately 30 MW. Due to high radiant heat flux, additional pool fires begin near the nose of the adjacent aircrafts. Each pool fire is approximated to cover 530 ft² and grow to a size of 110 MW.



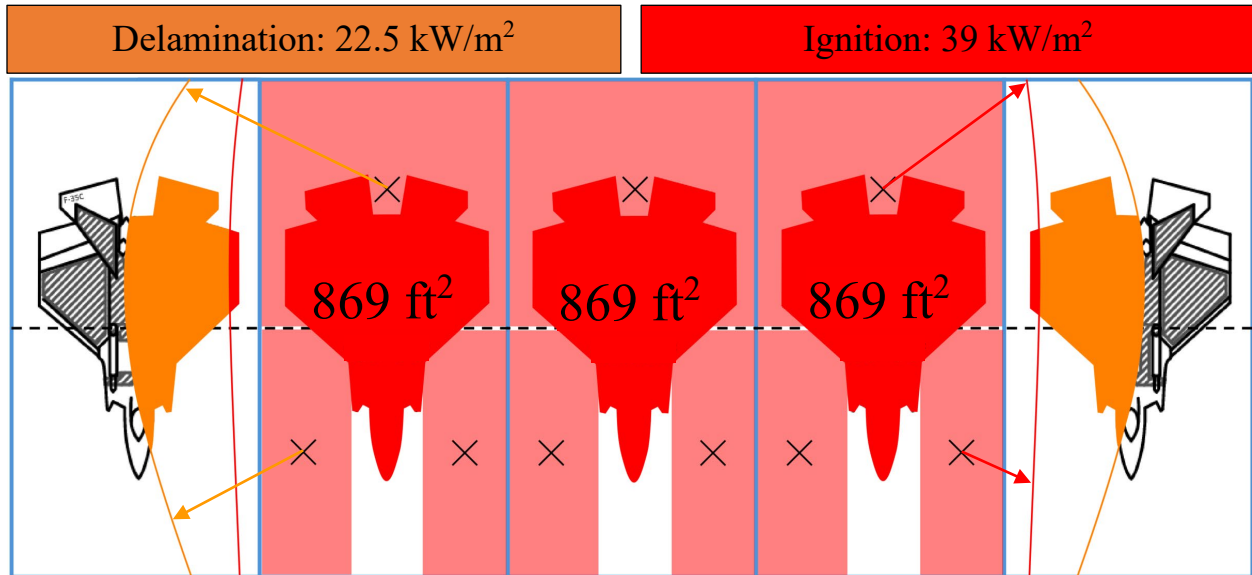
120 Seconds after Initiation of Pool Fire

Approximately 759 ft² of the adjacent aircraft are ignited and the remaining 109.5 ft² are delaminated. On the next aircraft, approximately 10 ft² of the wing tip is delaminated. Ignited aircraft components contribute an additional heat release rate of approximately 50 MW. Due to high radiant heat flux, additional pool fires begin near the tail of the adjacent aircrafts. Each pool fire is approximated to cover 485 ft² and grow to a size of 100 MW.



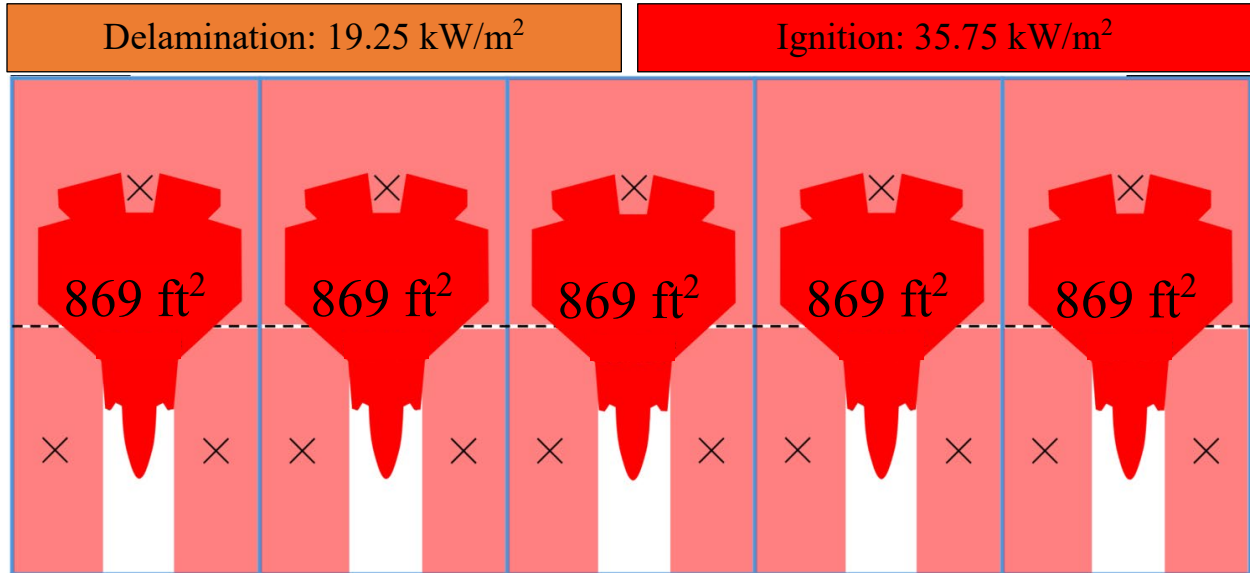
150 Seconds after Initiation of Pool Fire

The entire surface of the adjacent aircraft are ignited. Approximately 18 ft² of the next aircraft are ignited and 450 ft² of the aircraft are delaminated. Ignited aircraft components contribute an additional heat release rate of approximately 57 MW. Pool fires near the tail of the adjacent aircraft grow to 1,520 ft² and a heat release rate of 313 MW each.



180 Seconds after Initiation of Pool Fire

All 5 aircraft are fully ignited as fuel fires start on the 3rd adjacent aircraft. Based on the size and progression of the fire, the fire will continue to cascade to adjacent aircraft in the hangar (not shown in these figures).

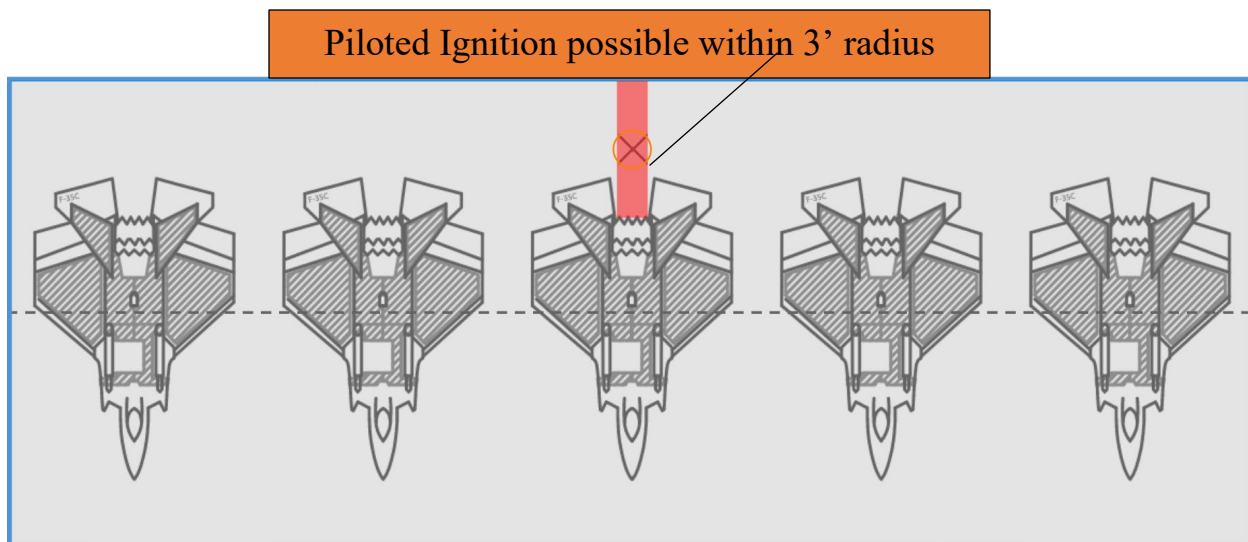


4.3 ILDFA Fire Protection

With ILDFA installed in the hangar, the liquid fire is quickly controlled and extinguished within 90 seconds. Throughout the duration of the event, the radiant heat flux on the aircraft are well below the delamination threshold. No additional aircraft are involved in the fire, and minimal damage occurs to the aircraft where the spill occurs. Data based on fire testing conducted by Air Force Civil Engineer Center (Wells) and Safespill (Giubbini).

30 Seconds after Initiation of Pool Fire

No delamination or ignition of the aircraft occurs. The peak radiant heat flux during the event is 14 kW/m^2 at 9'10" (3 meters). This peak is sustained for less than 10 seconds. Delamination occurs at heat fluxes greater than 52 kW/m^2 for a duration of 30 seconds. Auto-ignition requires heat fluxes greater than 87.5 kW/m^2 for a duration of 30 seconds. In the figure, the area within which **piloted** ignition could occur is shown. The radius where piloted ignition could occur is just 3 feet from the center of the fire.



5 Conclusion

Without adequate low-level suppression systems, simulations of liquid pool fire scenarios in F35 hangars show that substantial damage will occur not only to aircraft directly involved in the initial fuel fire, but also to adjacent aircraft. Water-only sprinkler protection is inadequate to extinguish fuel fires and shielding from aircraft prevents sprinkler water from penetrating the fire. In addition, currently proposed sprinkler coverage (0.2 gal/min/ft² over 5,000 ft²) is only capable of covering up to 3 aircraft in the hangar layout examined.

When additional fuel leaks are not considered, ignition and delamination will occur on more than half the body of the adjacent aircraft in the hangar.

With the addition of subsequent fuel fires on both the initial aircraft and adjacent aircraft, it is possible that all aircraft in the hangar may be destroyed or severely damaged.

In comparison, ILDFA provides superior fire protection in this scenario, quickly diminishing and ultimately extinguishing the fuel fire. Due to the short duration and diminished intensity of the fire, a worst-case event will be limited to the aircraft directly involved in the fuel fire. No damage will occur to adjacent aircraft in the hangar.

When considering both the financial and operation impact of this potential scenario, it is impossible to justify foregoing a low-level fire suppression system to protect our nation's high-value assets.

6 References

1. Beyler, C., “Fire Hazard Calculations for Large, Open Hydrocarbon Pool Fires,” *SFPE Handbook of Fire Protection Engineering*, 4th Edition, DiNenno, P.J. (ed.), National Fire Protection Association, Quincy, MA, 2008, pp. 3.271–3.319.
2. Bocchieri, R.; Cozart, Kristofor S.; Wells, Steven P.; Kirkpatrick, Steven W.; MacNeill, Robert A.; Dierdorf, Douglas S.; Enlow, Mark A.; Hawk, John R.; “Firefighting and Emergency Response Study of Advanced Composites Aircraft; Objective 1: Composite Material Damage in Minor Aircraft Fires,” Applied Research Associates, Air Force Civil Engineer Center, 18 May 2013.
3. Bocchieri, R.; Dierdorf, Douglas S.; Cozart, Kristofor S.; Wells, Steven P.; Steven W. Kirkpatrick,; Robert A. MacNeill; Hawk, John R.; “Experimental Investigation of Widespread Delamination Damage to Composite Materials Caused by Radiant Heating,” Applied Research Associates, Air Force Civil Engineer Center, 30 June 2013.
4. Quintiere, J.G.; Walters, R.N.; Crowley, S.; “Flammability Properties of Aircraft Carbon-Fiber Structural Composite,” US Department of Transportation, Federal Aviation Administration, October 2007.
5. Zallen, D.M., Morehouse, E.T., Dees, B.R., Walker, J.L., Campbell, P., “Fire Protection System for Hardened Aircraft Shelters Vol I of III: Discussion and Appendixes A-C,” Air Force Engineering and Services Center, October 1987.
6. Wells, S.; Horn, N.; Maraviglia, M; Luckarift, H.; Johnson, G.; Ashley, B.; “Fuel Spill Fire Testing of an Ignitable Liquid Drainage Floor Assembly (ILDFA) for Chemical-Free Fire Control Suppression,” Battelle Memorial Institute, ARCTOS Technology Solutions, Air Force Civil Engineer Center (AFCEC), 12 April 2022.
7. Giubbini, K.; Poole, J.; “Wing Tank Drop Test with Heat Flux Data,” Safespill, Poole Fire Protection, October 2020.
8. Heskestad, G., “Fire Plumes, Flame Height, and Air Entrainment,” *The SFPE Handbook of Fire Protection*, 3rd Ed., National Fire Protection Association, Quincy, MA, 2002.
9. “Estimating Burning Characteristics of Liquid Pool Fire, Heat Release Rate, Burning Duration, and Flame Height”, United States Nuclear Regulatory Commission, Version 1805.1, March 2011. Spreadsheet.