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Researching the Impact of Fire and Soot on Engine Performance

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Researching the Impact of Fire and Soot on Engine Performance

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Wildfires present a potential danger to populated areas every year. To combat these dangerous blazes, many agencies turn to aerial firefighting during the fire season. Aerial firefighting requires fixed wing aircraft to maneuver for a retardant drop while on the brink of stall. Due to the inherent safety risk in this procedure, the propulsion system of an aircraft must be responsive and reliable when the time comes to accelerate away from the drop zone. This paper focuses on predicting the effects of a fire on an engine's performance to better inform propulsion design decisions for aerial firefighting. Wildfires introduce two main hazards in the surrounding air environment: heat and particulates. Convection currents, generated due to the high heat that occurs near a fire, elevate hot air along with any soot and embers that are present. Firefighting aircraft fly in close proximity to the fires, so these effects are a significant design concern. A study to investigate the change of the thermodynamic properties of the surrounding air and the resulting effects on the thrust output of the engines is conducted. Likewise, the effects of particulate ingestion by the engines are discussed, along with the engine reliability issues that result from on-blade deposits. Finally, a flight plan for airtankers and lead planes is generated that limits engine exposure to wildfire heat and particulates through procedures such as a 10,000 feet cruise altitude, a 300 feet drop altitude, and flight path along the fire's edge. Through implementing these simple safety measures, firefighting aircraft will be both safer and more readily available to fight fires.

I. Nomenclature

RFP	=	request for proposal
AGL	=	above ground level
h_{drop}	=	altitude of retardant drop
T_{drop}	=	ambient temperature during retardant drop conditions
ρ_{drop}	=	ambient density during retardant drop conditions
ρ_{std}	=	ambient density at standard sea level conditions
P_{std}	=	ambient pressure at standard sea level conditions
R	=	the universal gas constant
P_{A_SSL}	=	engine power available at standard sea level conditions
P_{A_drop}	=	engine power available during retardant drop conditions
ConOps	=	concept of operations

II. Introduction

Wildfires differ from other natural disasters in that they are both prolonged in duration and highly mobile. These dangerous uncontrolled burns travel across wide swaths of land, leaving little more than a path of scorched Earth. In 2020 alone, wildfires burned more than 8,500,000 acres [1]. Due to the damage these blazes can cause to both forests and civilization, many government entities place a large emphasis on combating the flames. One of the most effective methods they employ to control wildfires is aerial firefighting. Aerial firefighting has been in use since 1955 [2]. This method involves the dispersal of a fire retardant over a fire by plane. Several techniques exist, such as fire spread control, point protection, and fire intensity reduction.

The research presented in this paper was inspired by the AIAA's 2022 Design Competition. The associated undergraduate team aircraft design category involves the design of a purpose-built responsive aerial firefighting

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aircraft. The flight conditions for the retardant drop mission provided in the request for proposal show the strenuous demand placed on aircraft while fighting fires. The document requires an airframe to possess a maximum drop speed of less than 150 knots at an altitude of less than 300 feet AGL [3]. Under these conditions, a large aircraft would be operating at speeds close to stall without sufficient altitude to recover. The airframe is essentially depleted of any energy, which presents an inherent safety concern.

It is very important to ensure the reliability of the installed propulsion system because of the potential for danger presented by an aircraft's depleted energy reserve. Unfortunately, the turboprop and turbofan engines of most aerial firefighters are operating in conditions they were never designed for. Any heat and soot generated from wildfires has the potential to disturb the operation of these delicate systems. This paper discusses the effects of a wildfire on the local air environment. The impacts of these effects on an aircraft's propulsion system are considered, and potential solutions are explored.

III. Effect on Surrounding Air Environment

The damage inflicted by wildfires on the ground is well known, but their effects extend far above the level of the surface. The sheer size of the fire generates vast amounts of heat and rising air. Additionally, the items that are burned on the surface create large plumes of smoke and soot particles. These side effects of wildfires are discussed in this section.

A. Heat Emission and Updrafts

It is no secret that wildfires are capable of producing immense amounts of heat. What starts out as discarded cigarettes, campfires, and lightning strikes can turn into a disaster level event, burning any trees, buildings, and automobiles in its path. Due to the intensity presented by these blazes, it can be difficult to accurately ascertain the temperatures produced. One way to estimate the surface temperatures is through the use of an Airborne Visible Infrared Imaging Spectrometer (AVIRIS). A joint group of faculty from the University of Utah, the University of California Santa Barbara, and the California Institute of Technology utilized this technique to map the 2003 Simi Fire [4]. They discovered that the temperatures generated from a wildfire were highest along the edges because of the abundance of fresh fuel. The fires behind this "front" were significantly cooler. Using AVRIS, this group found that the front temperatures were higher than 1100 K, while the interior temperatures were between 800-1000 K.

These temperature values are given for the surface, but firefighting aircraft will operate at a defined altitude. A model to predict the dispersion of this heat at altitude increments has been developed by researchers from the Pacific Northwest National Laboratory, the University of Maryland, Texas A&M University, and the University of Oklahoma [5]. Table 1 below shows the data they collected from a small wildfire outside of Amarillo, Texas on a hot day. It is worth noting that wildfires in this area are mostly fueled by tall grass, and do not possess maximum temperatures as high as the forest fires discussed above. Still, this data can be readily used to see the pattern of heat dissipation. At around 1200 meters, the recorded temperatures are equivalent, and the heat generated by the wildfire is no longer a concern.

Table. 1 Temperature values at altitude increments with and without a wildfire [5]

Altitude (m)	Temperature with Wildfire (K)	Temperature without Wildfire (K)
100	310	305
200	308	304
300	307	303
400	306	302
500	305	301
600	304	300
700	303	299
800	301	298
1200	296	296
1600	293	293
2000	289	289

This same research team also recorded updraft values and found that an updraft with an approximate velocity of 24 meters per second existed at an altitude of 1000 meters. This shockingly large wind gust has the potential to elevate particulates into the path of oncoming air traffic.

B. Particulate Emission

The particles generated by a wildfire depend heavily upon the items that are fueling it. Most often, this source is trees, vegetation, and other organic material. As these materials begin to combust, smoke clouds consisting of small particles form. The particles are mostly comprised of organic carbon, and they vary in size from 1 to 10 micrometers [6]. The smaller particles are more plentiful in wildfire smoke, and they also tend to stay in the air for longer periods of time [6]. Additionally, the smoldering areas of a wildfire continue to produce this smoke until fully extinguished, resulting in smoke arising from "contained" areas of a wildfire [6]. These particles, although harmful to humans, are a nonissue for firefighting aircraft until they combine with the convection currents generated by the fire.

When carried along by rising updrafts, the ash and soot generated by wildfires disperse in a pillar-like pattern called a smoke column. The height of these columns follows an interesting distribution, as shown in Figure 1 [7]. This figure, sourced from a study conducted by academic researchers and industry professionals, describes the height of smoke columns witnessed over a burning evergreen forest [7]. The research team used both pixel-weighted and AOD-weighted methods for finding the height of the smoke plumes, but the general trend found using both methods is the same. A maximum column height of around 6,000 meters was observed in this scenario, with a majority of the columns topping out around 1,000 meters. Around 80% of the smoke columns reach their maximum height before 3,000 meters. While several columns were observed to exceed that height, the majority will never reach it.

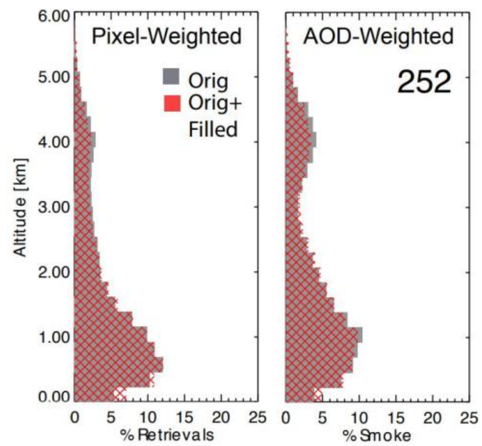

Fig. 1 Wildfire smoke plume height distribution above an evergreen forest [7]

Figure 2, also included in this study, shows the smoke columns heights above a woody savanna wildfire. This mix of burning trees and tall grasses produces a smoke layer that generally lays lower than that of the evergreen forest. The figure displays that the majority of the smoke columns in this scenario reach a maximum height below 1,500 meters. Almost no columns exceed 3,000 meters in height.

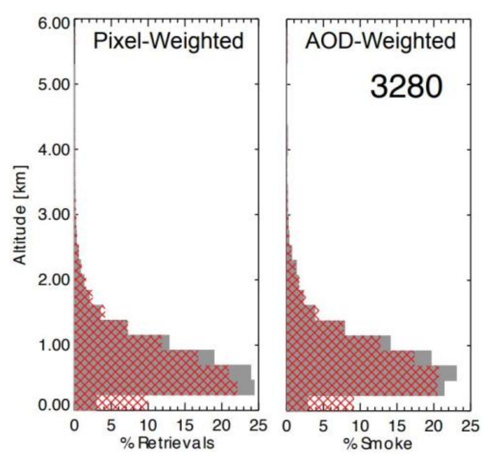

Fig. 2 Wildfire smoke plume height distribution above a woody savanna [7]

IV. Effect on Turbine Engines

Any changes to the local air environment directly affect the operation of aircraft gas-turbine propulsion systems. The effects of heating the air are calculable and are shown below. Unfortunately, analyzing the effects of the particulates generated by wildfires is less straightforward. Little data exists on interactions of aircraft engines with wildfire smoke columns. Luckily, the effect of another related topic is well documented: volcanic ash clouds. Volcanic ash has presented a risk to commercial aviation for years. The United States Geological Survey compiled 129 reports of aviation incidents involving volcanic ash that occurred between 1953 and 2009 [8]. Of these 129 incidents, 79 featured damage to the aircraft, while 9 involved in-flight engine failures. While the particulates generated by these two events are different in composition, the studied effects of volcanic ash can be used to estimate the effects of wildfire-generated contaminants.

A. Power Available Penalty

One of the major limiting factors in an aircraft's performance is the power available from the installed engines. This power output is especially important when performing aerial firefighting maneuvers requiring a fast acceleration after dropping a load of retardant. To calculate the effect of wildfire heat on the total power available during retardant drop, the temperature at the drop altitude must be found. The RFP provided for the AIAA Design Competition dictates a drop altitude below 300 feet AGL [3]. For the purpose of this calculation, a drop height of 250 feet will be used. Using linear interpolation with the data presented earlier, the temperature at 250 feet above a wildfire is found in Equation (1) below.

$$T_{drop} = \frac{T_0 - T_1}{h_0 - h_1} * h_{drop} + T_0 \tag{1}$$

$$T_{drop} = \frac{(1100\ K - 310\ K)}{(0\ m\ - 100\ m)} * \left(250\ ft * 0.3048\frac{m}{ft}\right) + 1100\ K =\ 498\ K \tag{1}$$

Using this temperature at the drop altitude, the corresponding density is found with Equation (2). Here, it is assumed that air is an ideal gas and that the fire has no effect on the pressure at the drop altitude. Further, the atmospheric properties at 250 feet AGL are assumed to be equivalent to the standard conditions at sea level.

$$\rho_{drop} = P_{std}/RT_{drop} = (101{,}325\ Pa)/(287\ J/kgK * 498\ K)\ = 0.709\ kg/m^3 \tag{2}$$

The power available of an aircraft propulsion system at set conditions can be corrected by using density ratios as shown below in Equation (3). This expression can be modified to estimate the power available during retardant drop as shown in Equation (4).

$$P_{A\_drop}/\rho_{drop} = P_{A\_SSL}/\rho_{std} \tag{3}$$

$$P_{A\_drop} = \rho_{drop} * P_{A\_SSL}/\rho_{std} = (0.709\ kg/m^3)(P_{A\_SSL})/(1.225\ kg/m^3) = 0.579P_{A\_SSL} \tag{4}$$

As shown in the above calculation, a potential 42.1% reduction in engine power output takes place at the drop conditions above a wildfire. This reduction in power available changes the stall dynamics of the aircraft. Power stalls now occur at a higher speed, meaning that the airframe may experience power stall before aerodynamic stall. The exact impact of any power loss is a complex topic which varies from airframe to airframe. It is worth noting that the effect of this temperature increase will likely only be experienced during a retardant drop, as the heat generated by a wildfire quickly dissipates with altitude as shown earlier in Table 1.

B. Material Deposits

As ash and soot particles travel through the compressor and turbine stages of an airbreathing engine, they are rapidly heated alongside the combustion products. This process can result in soot deposits forming along the compressor and turbine blades and vanes. This phenomenon is well documented with cases of volcanic ash, where the silica particles in the ash mixture result in glass deposits inside of the engine. Admittedly, the smoke generated by a wildfire is mostly comprised of carbon, which will not melt into glass. Still, a gradual buildup of soot can develop inside of the engine over time, resulting in similar effects. Figure 3 shows an example of a material deposit below.

Fig. 3 Volcanic ash deposits on high-pressure turbine vanes of a turbofan engine [9]

The image presented in Figure 3 is taken from a technical report compiled by Rolls-Royce after a Boeing 747 interacted with the volcanic ash resulting from Mount Galunggung in 1982. This aircraft suffered from a phenomenon known as compressor surge in all four engines, resulting in the temporary loss of power until the engines could be restarted [10]. Eventually, the plane landed safely with three engines. The engine failure was directly attributed to material deposits within the engine as seen above. The effects of the deposits are spread out across the length of the engine.

Compressor surge happens when the flow of air inside of an engine begins to change direction, typically in an oscillatory manner. To prevent this event, the compressor stage of a turbine engine operates at a certain pressure ratio. When particulates are ingested into a turbine engine, they begin to deposit along intake structures and vanes, resulting in changes to the engine area ratios. These changes reduce the pressure ratio generated by the compressor, which allows for compressor surge to occur [10]. While the smoke from a wildfire will take longer to generate these deposits, the effects of these material build-ups are serious, and they should be treated accordingly.

Turbofan engines are more receptive to material deposits than turboprop engines because of their air intake method. Turboprops generally pull-in air for the turbine core through a small intake slot, while turbofans' turbine core receives its air supply as it enters the large fan assembly. The difference in surface area results in more particulate ingestion for the turbofan, which in turn results in a larger risk of particulate deposition and compressor surge.

C. Blade Erosion

As soot and ash particles are ingested into a turbine engine's air intake, they have to pass through the rotating system of fan and compressor blades. Due to the rotational motion of these components, the tips of the blades have the highest tangential velocity, with some turbofans reaching fan tip speeds of 400 m/s [11]. This high blade speed results in a violent collision between the blades and any particulate that is pulled into their path. While the particulates are generally not massive, they can be plentiful. At high particulate densities, the area surrounding a turbofan fan begins to glow as the blade tips strike the debris. This effect is experimentally shown below in Figure 4.

Fig. 4 An example of the glow around the fan face caused by dust interactions [12]

The glowing effect shown in Figure 4 displays the large amount of energy the fan blades of a turbofan impart on the particles they contact. While the glow is outwardly present on fan blades, particle interactions are not exclusive to turbofans. These particle interactions also occur inside the compressor stage of all turbine engines. Over time, these constant impacts begin to erode the surface of the fan and compressor blades, causing irreversible damage. When the compressor blades begin to lose material, they can no longer maintain the proper pressure ratios needed to prevent compressor stall. When these particle interactions happen in conjunction with material deposition, as occurs in actual engine use, the likelihood of engine failures increases dramatically. Figure 5 below shows an example of the impact of a dusty environment on the compressor stage of a turboprop engine.

Fig. 5 Turboprop compressor blade erosion caused by dust interactions [13]

While the effects of blade erosion are well known, the impact that wildfire smoke and ash in particular will have on the blades of an airbreathing engine is not commonly studied. As stated earlier, much research is conducted on the impact of volcanic ash cloud ingestion due to its disruption of commercial flights. Additionally, another popular area of study is the impact of dusty and sandy environments, such as the example provided in Figure 5. This environment became relevant in part due to the large number of military flights through countries around the Middle East over the past 20 years. According to recent research surrounding the simulation of particulate ingestion, the severity of blade erosion is linked to the probability of a particle interacting with a fan or compressor blade [11]. This probability is linked to the size of the individual particles and the speed of the blades. Figure 6 below was provided with the study [11]. It shows the probability of a particle interacting with a turbofan's fan blade at 10,000 feet AGL with varying amounts of power applied.

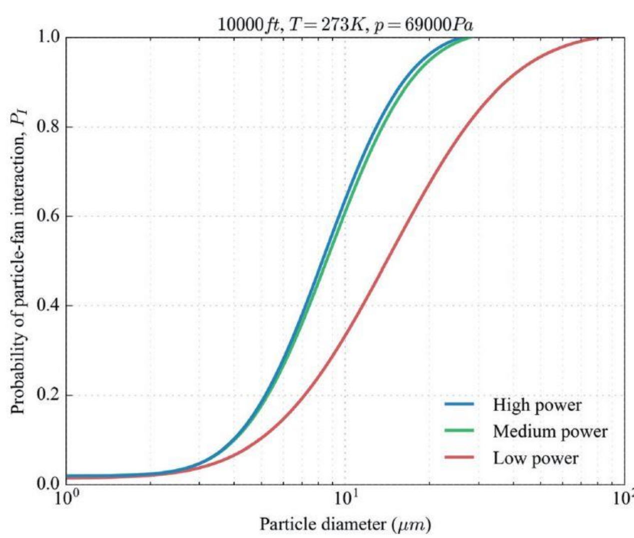

Fig. 6 Probability of particle fan interaction by particle size [11]

This model presented in Figure 6 can be used to determine the likelihood of wildfire smoke particles hitting the fan blades of a turbofan. As previously stated, the carbon deposits in wildfire smoke vary in size from 1 to 10 micrometers with the finer particles being more common [6]. Assuming that the engine is operating at medium power and that the particles have an average size of 4 micrometers, the probability of a particle-fan interaction occurring is about 10%. While this probability is lower than that for bigger particulates such as sand where an interaction is almost guaranteed, a large number of impacts can gradually accumulate during a prolonged exposure. This model is only for turbofans however, which lack the ability to filter air like turboprop engines. While smaller particles will still bypass a filter, the likelihood of them contacting the compressor blades is lower.

D. Other Effects

While material deposition and blade erosion are two of the main effects of particulate ingestion, several other effects have also been witnessed on occasion [12]. When particulates begin to create deposits inside of an airbreathing engine, they can also start to create obstructions within the engine's cooling system. By blocking cooling ports and passages, these material deposits can present a clear danger to engine operation. Another possible outcome of particulate ingestion is the contamination of any engine fluids such as oil, fuel, and bleed air. Contaminations in these fluids can result in material buildups elsewhere within the aircraft. Lastly, ingested particulates can interact with engine control systems, potentially resulting in damage to the sensors or engine. As these particles build up within the airbreathing engines, they have the potential to attach themselves to sensors and other control equipment. Any faulty temperature or pressure readings could result in disaster for the engine.

V. Maintenance and Preventative Care

Operating in elevated temperatures and ingesting wildfire ash and soot into an engine is almost unavoidable in aerial firefighting, and the consequences of doing so are high. Of the effects discussed in the previous section, almost all of them have the potential to cause an engine failure. In an aerial firefighting mission where aircraft are operating at the brink of stall, this risk is unacceptable. Methods of countering the potential adverse effects of operating around a wildfire are discussed in this section.

A. Avoidance

One of the most effective means of countering the effects of a wildfire on aircraft engines is to avoid the heat and particulates altogether. While some contact with increased heat and smoke is unavoidable, the amount of exposure can be mitigated through a carefully constructed flight plan. To create a procedure for avoiding the effects of a wildfire, the typical uses for aerial firefighting aircraft must first be considered. During a fire, the aircraft involved typically act in an airtanker, lead plane, or air attack role [14]. Airtankers carry and deliver a retardant payload. Lead planes serve as guides for the larger airtankers, highlighting the correct drop location. Lastly, air attack aircraft, or Air Tactical Group Supervisors, monitor the airspace surrounding a fire and coordinate the responding aircraft [14]. While all of these aircraft work together, their exposure levels to the surrounding environment vary by mission type. Still, some common techniques for reducing exposure across the board exist.

All of the aircraft types are affected by flying through the smoke and soot generated by a wildfire. One way to avoid these particulates is to increase altitude. While retardant drops must occur around 300 feet AGL, the cruise altitude of the aircraft on their way to and from the drop point is not as tightly controlled. The majority of any flight will occur at cruise, and wildfires have the potential to span thousands of acres. Therefore, adjusting the cruise altitude to avoid the smoke will significantly reduce the exposure of engines to harmful particulates. The smoke above a wildfire is dependent upon the type of fuel as shown in Figure 1 and Figure 2, but they both show a similar trend. For both the evergreen forest and the woody savannah, the chance of smoke exposure is significantly lessened after reaching 3,000 meters (~10,000 ft). At this altitude, almost none of the smoke from the woody savannah fire was present. Likewise, 80% of the evergreen forest smoke settled below this height. While even higher altitudes are better, this 10,000 feet altitude represents a reasonable minimum cruise height for limiting particulate ingestion by the engines.

Another way to minimize smoke ingestion by the engines is to adjust the flight path of the aircraft. As previously mentioned, the center sections of the fire that have already been burned tend to smolder, producing a majority of the total wildfire smoke [6]. To avoid this, any firefighting aircraft should fly around the outside edges of the fire whenever possible until the mission dictates otherwise. When response time is not an issue, this circumvention of the fire will help ensure the engines are not at risk of damage from particulate ingestion. This flight path plan, along with the 10,000 feet recommended minimum cruise altitude, should ensure that no unnecessary wear is caused on the engines.

Lastly, to counteract the extreme ambient temperatures and the corresponding loss of power during retardant drop, the drop should occur as close to 300 feet AGL as possible. The heat generated by a wildfire dissipates very fast as shown in Table 1. While the temperature at 250 feet is around 498 K, the temperature at 100 meters (~330 feet) is around 310 K. This substantial drop in temperature over an interval of 80 feet shows that every foot counts when choosing a drop altitude. By dropping at a lower temperature, the respective density is higher, resulting in a larger power available. This drop altitude is relevant to the mission of both airtankers and their lead planes.

Applying these avoidance techniques to the three classes of firefighting aircraft is not difficult. Airtankers, for example, typically perform one of two missions. They can drop retardant in a line to control the boundaries of the blaze, or they can drop retardant on an area of interest, such as an important building within the wildfire [15]. The ConOps for the line drop is shown below in Figure 7, and the ConOps for the point protection drop is shown below in Figure 8. Additionally, Table 2 describes the mission phases shown in each diagram. For both of these drop types, the aircraft can cruise at an altitude of 10,000 feet around the edges of the fire until it nears the drop zone. The line drop is simple; the aircraft descends to 300 feet AGL, lays a line of retardant along the edge of the fire, and ascends back to cruise altitude. The point protection drop is more complicated. The tanker will circumvent the fire until it reaches the point on the edge of the fire where it is closest to the drop zone. It then flies above the fire at cruise altitude, descends to 300 feet AGL when the drop point approaches, drops the retardant, and ascends to cruise altitude while following the quickest possible path out from above the wildfire. By limiting the amount of time within the fire, the risk of engine issues is lowered substantially.

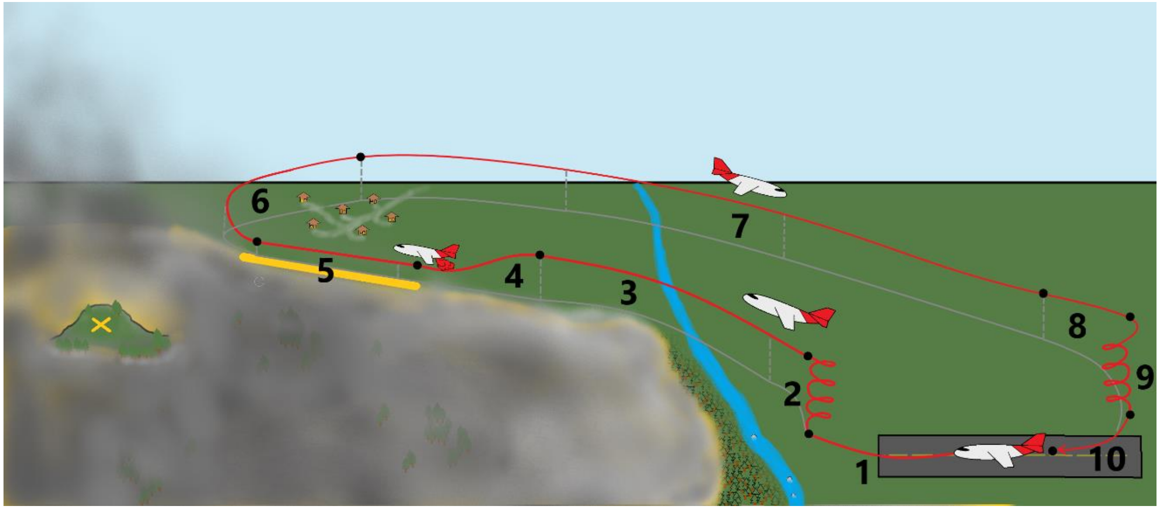

Fig. 7 Concept of operations for an airtanker performing a line drop

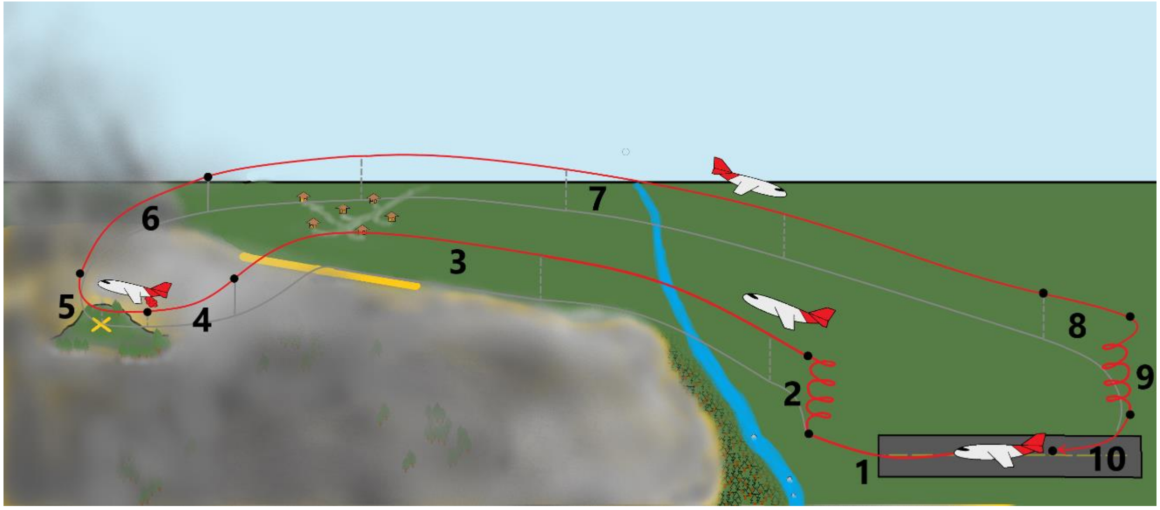

Fig. 8 Concept of operations for an airtanker performing a point protection drop

Table. 2 Description of mission phases for the presented airtanker ConOps

Mission Phase	Title	Description
1	Takeoff	Takeoff from runway with retardant payload.
2	Climb to Cruise Alt.	Climb to an altitude greater than 10,000 ft (~3,000 m).
3	Cruise	Cruise on a path around the edge of the fire.
4	Descend to Drop Alt.	Descend to an altitude around 300 ft.
5	Drop Retardant	Drop the retardant on the target.
6	Climb to Cruise Alt.	Climb to an altitude greater than 10,000 ft (~3,000 m).
7	Cruise	Cruise on a path around the edge of the fire.
8	Loiter	Await permission to land.
9	Descend to Ground	Descend to ground level.
10	Land/Replenish	Land the aircraft and replenish if needed.

Airtankers are often large, unmaneuverable, and heavily loaded, so lead planes are used to guide them on a gradual path towards the drop zone [14]. Due to this relationship, lead planes encounter many of the same environments as airtankers and can mitigate their risks likewise. A ConOps for a lead plane guiding an airtanker on a line drop is shown below in Figure 9. The mission phases shown in this diagram are described in Table 3. The main difference between the lead plane mission and the airtanker mission is shown in Phase 7b. Lead planes are not responsible for only one drop; they can guide-in multiple airtankers per flight depending on the needs of the fire. Their engines are at the greatest risk of damage because of this repeated exposure to the wildfire smoke and heat.

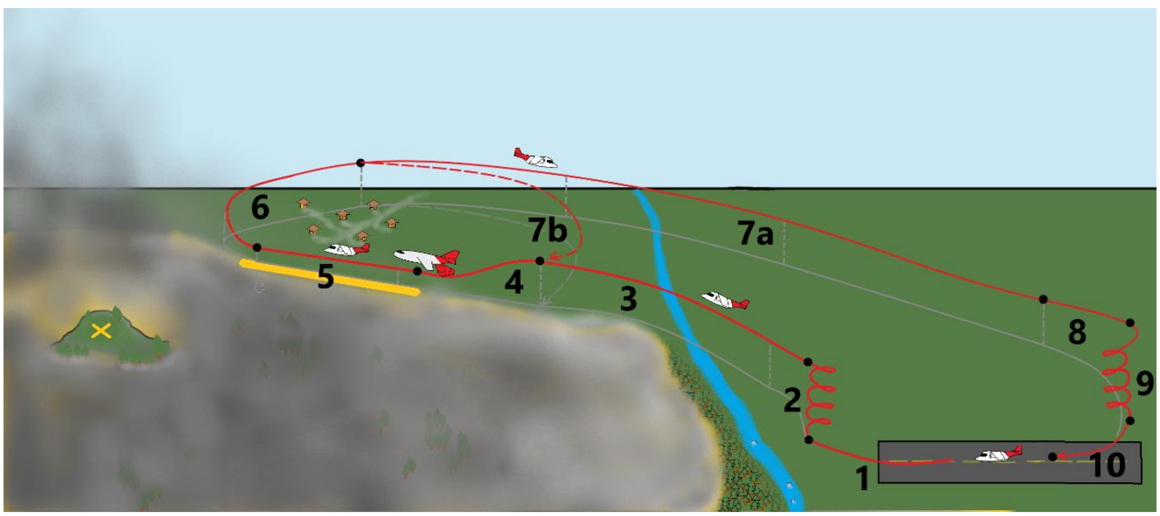

Fig. 9 Concept of operations for a lead plane guiding airtankers

Table. 3 Description of mission phases for the presented lead plane ConOps

Mission Phase	Title	Description
1	Takeoff	Takeoff from runway with retardant payload.
2	Climb to Cruise Alt.	Climb to an altitude greater than 10,000 ft (~3,000 m).
3	Cruise	Cruise on a path around the edge of the fire.
4	Descend to Drop Alt.	Descend to an altitude around 300 ft.
5	Drop Retardant	Guide an airtanker to the drop target.
6	Climb to Cruise Alt.	Climb to an altitude greater than 10,000 ft (~3,000 m).
7a	Cruise	Cruise on a path around the edge of the fire.
7b	Repeat Guide Phase	Guide the next air tanker to its drop site (Repeat Phase 4)
8	Loiter	Await permission to land.
9	Descend to Ground	Descend to ground level.
10	Land/Replenish	Land the aircraft and replenish if needed.

Lastly, aircraft fulfilling the air attack/air tactical group supervisor role typically have the longest time on target, but their mission does not require a close proximity to the fire. Instead of making retardant drop runs, these aircrafts observe and coordinate the lead planes and airtankers [14]. Since their role is removed from the frontlines of firefighting, it is easy for the air attack platform to avoid the negative effects of operating near a wildfire. If at all possible, these aircraft should be operating on the outside edge of a fire. This allows for the coordination of line drops and wildfire area control. If the ATGS is to supervise point protection drops, it can cruise above the 10,000 feet threshold to avoid the majority of the smoke. Due to the flexible mission of this aircraft, the performance of its engines can be easily preserved.

B. Maintenance

While avoidance of the wildfire effects is the best method of preserving airbreathing engines, the missions performed by aerial firefighting aircraft do not always allow for complete avoidance. As shown above, some aircraft roles are more prone to suffering engine damage from wildfire heat and smoke than others. Airtankers can mitigate many risks when controlling the spread of a fire by controlling the cruise altitude, limiting the drop altitude, and flying around a fire's edges. Unfortunately, these techniques are not always applicable. For the point protection drops, for example, the aircraft must fly above the fire to reach the intended target. In these cases, minimizing the time over the fire is key. Additionally, some missions are time sensitive and do not allow for circumventing a fire. The aircraft can end up cruising over a fire for an extended period of time. Due to the dangers presented by both point protection and time sensitive drops, the engines should be inspected when the aircraft returns to land.

Lead planes experience the same conditions as airtankers, but their exposure to the wildfire environment is increased by having to participate in repeated drops. It is beneficial to have multiple lead planes in a rotation due to the harsh nature of their role. When a lead plane returns to base after a full flight of guiding airtankers, it will need to have its engines inspected for damage. While both the airtankers and lead planes can warrant special maintenance, the air attack/air tactical group supervisor aircraft are able to avoid the majority of the heat and smoke. As such, no special maintenance should be required.

When inspecting the engines of aircraft that warrant maintenance, the condition of the fan blades (turbofan) or propeller blades (turboprop) should be evaluated. For a turbofan engine, the fan blades should show signs of wear if damage to the engine internals occurred. For a turboprop engine, it is recommended to inspect the air filtration system and the compressor blades. The previously described effects of particulates on airbreathing engines appeared to pair together. Compressor stall was an effect of both material deposition and compressor blade erosion. If no damage to the compressor stage of the engine is visible, the presence of material deposits is unlikely. After this visual inspection, the aircraft is ready to proceed with its usual maintenance schedule and replenish its fuel/retardant as needed.

VI. Conclusion

Flying above a wildfire can present some challenges for airbreathing engines, and in an aerial firefighting application, any change in engine performance can be costly. Wildfires generate heat in excess of 1100 K, but this heat dissipates quickly with altitude. At a standard drop altitude, the excess of heat results in an engine power available that is almost 40% lower than the power at standard conditions. The smoke generated by the fire is another concern, as it contains soot and ash. These carbon particles present a danger to both turbofan and turboprop engines, as the particles possess the potential to erode fan and compressor blades and form material deposits throughout the engine. When this occurs, the engine can suffer from compressor stall, which results in an engine out situation.

The effects of a wildfire, while severe, can be mitigated through proper flight plans. To avoid the power available penalty, firefighting aircraft should drop their retardant loads as close to 300 feet AGL as possible. Additionally, engine smoke ingestion can be prevented in most cases by cruising at 10,000 feet AGL to and from the target destination. A flight path around the currently burning edges of the fire increases this factor of safety, with aircraft minimizing their time above the smoldering center of the fire as the mission allows. Lastly, aircraft at increased risk for engine damage such as point protection airtankers and lead planes should have their turbine engines inspected for visual damage to the fan and compressor blades in between flights. Through understanding the effects of a wildfire on engine performance, and altering the flight plan accordingly, aerial firefighting aircraft can operate in a manner that allows for less maintenance downtime and safer operation in general.

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