Adapting Rotorcraft Mission Task Elements to Wildfire Applications

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ABSTRACT

Adapting mission task elements (MTE) to a wildfire environment would help characterize how aircraft handling qualities may change in the presence of a wildfire. It would also provide insight into how a (often retrofitted) vehicle may degrade in its operational environment, allowing pilots to be more informed making "go/ no go" calls in real-time during a crisis. This work focuses on rotorcraft applications, although some lessons learned may be relevant to fixed wing aircraft. A review of wildfire-related aviation casualties and pilot accounts from fighting wildfires informed critical areas of risk during each segment of a generalized Wildfire Scenario. MTEs from ADS-33/ MIL-DTL-32742 such as the Decelerating Approach, Depart/Abort, and Missed Approach were mapped to this scenario and then altered to focus on the relevant wildfire scenario. Slung loads (such as supplies, water, or fire suppressant) also change vehicle dynamics which may significantly impact handling qualities. One of the most challenging scenarios is when a rotorcraft must quickly climb to avoid terrain during or shortly after dropping water/fire suppressant. A custom MTE is presented that would challenge the vehicle in a similar way to this type of maneuver. Variations of conditions that could be explored using these MTEs are also discussed, as well as which variations would benefit the most from motion-based simulation.

INTRODUCTION

Applying recent developments in technology and research, especially in handling qualities, to fighting wildfires could reduce loss of life and property. Wildfire pilots are highly trained, but they also must rely significantly on experience and judgment to best utilize the resources around them which may be different for each fire. Because of the high-risk nature of the flights in and around wildfires, it is challenging to replicate the environment for training. Developing mission task elements tailored to wildfire firefighting has three advantages. It can 1) expose handling qualities or performance deficiencies in these highly demanding scenarios, 2) provide the pilot with more information on how the vehicle is likely to degrade in a given environment, and 3) be utilized in pilot training to help pilots adapt their experience from previous civil/military backgrounds to wildfire specific scenarios in lower risk environments. The wildfire environment is unique, and the objective of this paper is to discuss potential adaptations from existing mission task elements and mission scenarios to identify deficiencies that may surface in such situations.

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BACKGROUND

In August 2024, the World Resources Institute (WRI) calculated that the area burned globally by forest fires increased ~5.4% per year from 2001-2023. The years 2020, 2021, and 2023 set records and were reported as the fourth, third, and first worst years for global forest fires, respectively (Ref. 1). Additionally, even once inflation is accounted for, the cost of wildfire fighting has increased four times from the 1980s to 2018 (Ref. 2). With wildfires becoming more costly and prevalent, it is likely that less-experienced pilots will be called in to help alleviate fires or experienced pilots will be forced to work extended hours, increasing the probability of accidents.

In January 2025, the Palisades and Eaton fires burned through the LA area. From January 7-22, 2025, fire alerts detected in LA county were 130 times greater than the average from 2021-2024. WRI listed less rainfall combined with the strong Santa Ana winds as contributors (Ref. 3). Jeff Wise, a journalist and pilot, recorded the experience of flying a Chinook as a waterbomber during the Palisades fire (Ref. 4). Some key insights from this experience informed this work. First, the effect the loading and unloading of water may have on the dynamics of the rotorcraft is significant, especially if the refill or drop occurred in tight terrain, such as a canyon or terrain that requires the pilot to climb quickly after dropping the load. Climbing may be challenging if the load is not released as expected, causing the vehicle to be heavier or have a shifting center of gravity. This can be quite significant when the payload accounts for a large portion of the vehicle's weight. For example, Reference 4 describes a modified Chinook with a 3,000-gallon tank which can carry ~25,000 lbs. of water, or almost half of its 54,100 lbs. maximum gross weight (Ref. 5). Second, due to typically cooler temperature trends and weaker winds, pilots may be required to fly at night which degrades visuals that may already be compromised by smoke. Third, the airspace may be densely occupied by other responding aircraft (small or large) or present obstacles such as trees and power lines when performing low altitude operations. During the Palisades fire, a drone collided with a larger waterbomber, damaging the waterbomber and forcing it to land (Ref. 4). Wise recorded the pilot and crew flying largely with visuals obtained out of the helicopter window (visual flight rules, VFR) because of the risk of running into obstacles if the pilots were solely focused on instrumentation.

In 2019, Smithsonian's *Air and Space Magazine* also described the challenge of flying in low-altitude, rough terrain in an article titled "The Pilots Who Fight California Wildfires" (Ref. 6). Fire retardant must be dropped at slow airspeeds, at low altitudes and, often, in low visibility. Additionally, pilots must often make experience-based calls based on limited information. Pilot, Jim Barnes, elaborated:

> *While the official minimum for a retardant drop is 150 feet, 'your unofficial minimum might turn out to be much lower,' Barnes says. 'When you're diving deep into Tujunga Canyon, how can you tell?' As terrain closes in, standard flight instruments provide mainly distraction. 'At that point, I'm not even looking inside the cockpit anymore,' he says. 'All those gauges mean nothing to me if I smack a tree.' If lives on the ground are in imminent danger, standard safety guidelines don't usually apply. 'That's the time you really hang it all out there.* (Ref. 6)

While in this quote, Barnes was describing his experience flying a fixed-wing aircraft, the challenges are similar for rotorcraft. Helicopters may drop water directly on a target such as an endangered structure, but more often drop water onto flames along a path at about 50 knots from an altitude of 75-100 feet (Ref. 6).

There are many factors that make flying in proximity of wildfires different than flying in other environments. For example, heat gradients cause updrafts and turbulence (Ref. 6). When combined with the previously mentioned degraded visual environment and busy airspace, the result is a very high workload for the pilot. It is proposed that a combination of fixed-base simulations, motion-based simulations, and flight exercises could be used to prepare pilots for these extreme scenarios using adapted Mission Task Elements (MTEs) while reducing the number of "unknowns" that pilots may encounter for the first time in-field. This will allow them to develop skills to effectively fight fires while mitigating risk by becoming more familiar with the handling qualities challenges of the wildfire environment in safer conditions and by increasing the amount of data available to better predict how a vehicle may degrade in a specific scenario or environmental condition. Furthermore, experimentation in various conditions (fire/wind intensity, visibility, etc.) may highlight areas where handling qualities may be improved through piloting techniques, control system changes, or alterations to the vehicle design. Additionally, sole reliance on manufacturer specifications may not provide pilots with all necessary information about how their vehicle will degrade/react in extreme conditions, especially since most vehicles used for wildfire fighting are retrofitted rather than specifically designed for wildfire fighting missions-meaning they may be operating at the edge of their designed limits (Ref. 6).

Accident Summary

In 2015, the CDC released a summary of aviation-related wildfire firefighter fatalities from 2000-2013 (Ref 7). The report concluded, "The leading causes of fatal aircraft crashes were engine, structure, or component failure (24%); pilot loss of control (24%); failure to maintain clearance from terrain, water, or objects (20%); and hazardous weather (15%)." These leading causes all have flight dynamics or handling qualities implications. While not a comprehensive list, the following are illustrative examples of aviation-related wildfire accidents in no particular order (Table 1):

Table 1. Examples of Fixed and Rotary Wing Wildfire-Related Accidents (Refs. 8-14).

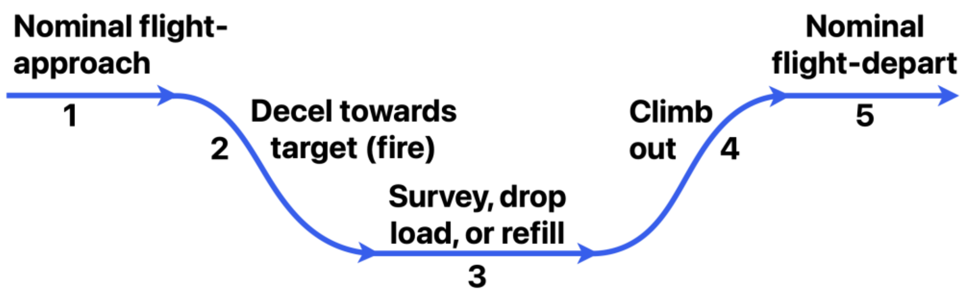
Description	Type	Fixed or Rotary Wing	Location	Year
Australian Transportation Safety Bureau (ATSB) investigators found that weather conditions were hazardous due to gusting winds and mountain wave activity. Aircraft tend to be vulnerable to atmospheric influence during retardant drops because they are low speed and low altitude maneuvers. A sudden shift from crosswind gusts to tailwind gusts reduced the aircraft's airspeed and significantly degraded its climb performance, preventing it from safely climbing and evading obstacles resulting in terrain collision (Ref. 8).	Weather-induced	Fixed (Lockheed EC-130Q)	New South Wales, Australia	2020
Two Cal Fire helicopters assisting with the Broadway Fire collided midair in mountainous terrain. A Sikorsky S-64E and Bell 407 unintentionally ended up on a converging flight path. During a descending maneuver, the Sikorsky S-64E was unaware of a Bell 407 below it. The Sikorsky was able to land with some damage. The Bell 407 was destroyed in the collision. (Ref. 9, 10).	Airspace awareness	Rotary (Bell 407 and Sikorsky S-64E)	Cabazon, CA, USA	2023
Crash on takeoff while transporting fire crew members and a forest service official from a wildfire area only accessible by rotorcraft. Terrain was very steep. Both pilots had 10,000+ hours of experience. It was later determined that the helicopter was overloaded (Ref. 11, 12).	Vehicle operational limits/terrain	Rotary (Sikorsky S-61N)	Trinity Alps, CA, USA	2008
Steep slopes and tall trees at the Elk Complex Fire created a challenging environment to deliver supplies for clean up to the Elk Complex area. Though the helicopter was equipped with a 150 ft longline to drop blivets, the marshal recommended a longer line the day of the drop, but the message was not received until the final approach. The main rotor struck a tree, and the vehicle and pilot were lost. One lesson learned, among other things, was the pilot's decreased ability to see out the right side of the aircraft during a slung load mission, where the pilot often flies from the left seat. The safety circle (generally recognized at 1.5 times the rotor diameter both on ground and in-flight) was not large enough to clear the trees (Ref. 13).	Terrain/obstacles/slung load	Rotary (Bell 205A-1)	Elk Complex, CA, USA	2007
A Z-8X helicopter crashed in Erhani Lake while refilling its water bucket. Witnesses saw the aircraft began to rotate a couple hundred feet above the water before the bucket was lowered. The spin increased and the helicopter descended. An explosion occurred before the helicopter impacted the water (Ref. 14).	Unknown, possible tail rotor mechanical failure	Rotary (Z-8X)	Dali, China	2021

Each of the events listed in Table 1 represents an example of pilot loss of control due to improper use of the aircraft, lack of situational awareness, degraded visuals, inclement weather, or a combination of such factors. These events can require pilots to either maneuver the vehicle in a way that was outside of conventional operation (tighter tolerances, more extreme angles for approach/take off, etc.) or in a non-typical environment. In some instances, knowing the vehicle's limitations and how they would degrade could have, theoretically, assisted pilots in responding to these deviations from normal operations.

This discussion builds on Refs. 15 and 16. Ref. 15 identified technology gaps for rotorcraft in wildfire applications. Ref. 16 explored wildfire turbulence modeling and control adaptations to reduce workload. Additionally, studies previously described in Ref. 16 to adapt ADS-33 MTEs to Advanced Air Mobility applications inspired this work. Applicable lessons learned to the wildfire environment from past VMS studies can also be found in Ref. 16. This work will use a similar approach of adapting traditional ADS-33/ MIL-DTL-32742 MTEs while focusing on the wildfire environment. Other works that informed this study were Ivler's Slung Load MTE (Ref. 17), the EMS MTE (Ref. 18) by Theodore et al., and Klyde's study on handling qualities for large aerial tankers used for wildfire suppression (Ref. 19).

EXAMPLE MISSION TASK ELEMENTS

A common mission scenario that had multiple wildfire applications emerged through the review of literature and accounts from pilots (such as those discussed in Background). This mission scenario, "Exploratory Wildfire Scenario (EWS)", is broken into five segments: 1) begin in a constant altitude approach with steady level flight, 2) descend and decelerate towards target (likely a fire, but other targets are possible such as a body of water for refilling a water bucket or an area of interest to survey), 3) perform a low altitude, low speed segment of flight, 4) quickly climb out and away from danger, (fire, approaching obstacles, terrain, etc.), and 5) return to nominal flight condition (Fig. 1). This mission scenario can also be performed with a slung load such as a box with supplies or a water bucket. Most tasks are completed in Segment 3, however, for the water drop application, the drop make begin in Segment 3, but continue into Segment 4.



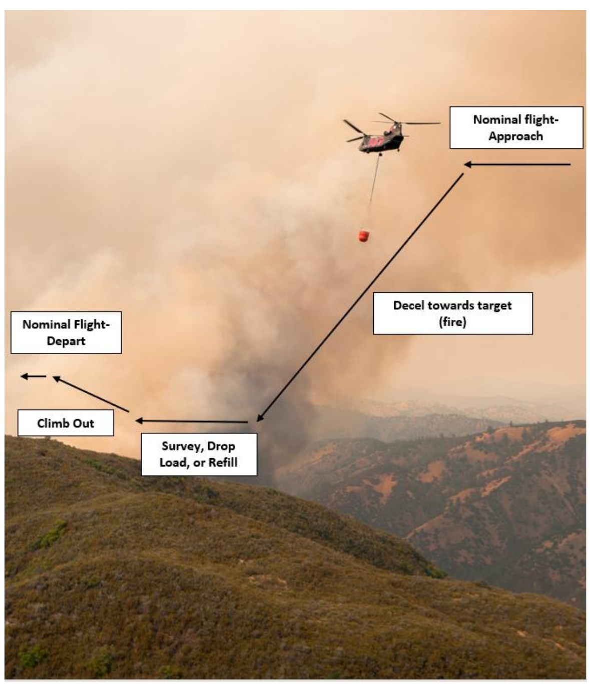


Figure 1. Exploratory Wildfire Mission Scenario (EWS) profile (top). EWS overlaid on CH-47 flight path preparing for water drop-Clearlake, CA. CH-47 enters from right (instead of left as in EWS profile above). ***Image credit: Ref. 20.***

EWS's five segments can be represented by three mission task elements that are modified from MIL-DTL-32742, Ref. 21. Each segment is described below. A single MTE may overlap more than one mission segment, especially if the MTE is intended to capture the transition from one segment to the next. The relevant segment(s) are highlighted after each MTE is introduced. An additional custom MTE accounting for the dynamics of the weight shift from climbing shortly after or during the release of a slung load is also described.

Segment 1: Approach

The pilot may experience unique environmental conditions (degraded visuals, turbulence, etc.), but otherwise, this segment of the flight is routine. The relevant segment is highlighted in Figure 2.

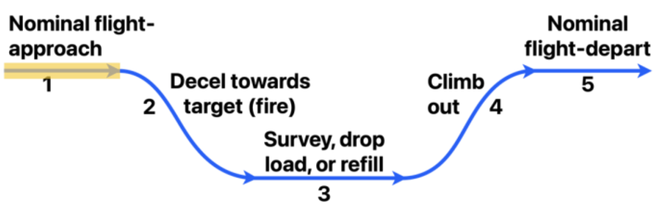


Figure 2. EWS Approach Segment 1.

Segment 2: Decelerating and Descending Towards Target

Most accidents that occurred in Segment 2 were due to high pilot workload or lack of situational awareness. An example of an incident in this segment is the Cabazon fire (Table 1) where one emergency aircraft was unaware of another in close vicinity and descended on top of it (Ref. 9 and 10). Other accounts such as Ref. 4, describe the challenges of watching instrumentation while maintaining awareness for power lines/trees/etc. during the descent. This segment is similar in many ways to the Decelerating Approach MTE as listed in Ref. 21. The relevant portion of EWS to the Decelerating Approach MTE is highlighted in Figure 3 and captures the end of Segment 1, the transition between Segment 1 and 2, and Segment 2. Table 2a shows the original text from MIL-DTL-32742 as currently written, and the EWS proposed revision for the MTE's Objective and Description. Performance Criteria for both MIL-DTL-32742 and EWS are shown in Table 2b. To differentiate, the original text from Ref. 21 will be listed as "MIL-DTL-32742 Decelerating Approach" and the revised text will be labeled "EWS Decelerating Approach". This naming scheme will be utilized through the rest of this work.

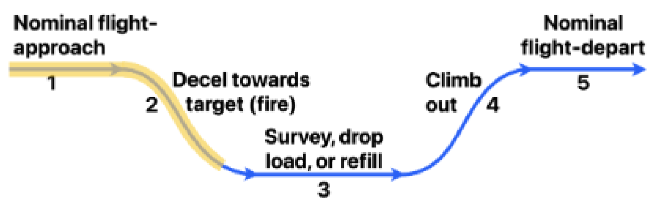


Figure 3. Portion of EWS that maps to the Decelerating Approach MTE.

Table 2a: Objective and Description of Decelerating Approach.

MIL-DTL-3274 Decelerating Approach	EWS Decelerating Approach
Objectives. • Check ability to perform precision glideslope and localizer tracking to very low decision height and groundspeed with a reasonable pilot workload. • Check ability to precisely control airspeed and to perform a deceleration while descending on the glideslope.	**Objectives.** • Check ability to descend to a very low decision height while maintaining groundspeed with a reasonable pilot workload. • Check ability to precisely control airspeed and to perform a deceleration while descending on the glideslope (only until switch to visual cueing at the altitude where obstacles become a concern).
Description of Maneuver. Starting on a 4-degree glideslope at an airspeed of 100 knots, perform a manual deceleration to an airspeed of 25 knots at an altitude of 50 ft. Guidance commands may be generated using onboard sensors, or from ground-based transmitters.	**Description of Maneuver.** Start the maneuver in level flight at 500 feet and 80 knots. Once established on the 4-degree glideslope decelerate to 50 knots at an altitude of 75 ft. (Glideslope should be used as long as possible, but visual cues may be necessary depending on environment.) *If this maneuver was attempted at a much steeper angle, the speed should be adjusted to ensure a safe approach. The ideal angle and speed combination should be explored through simulation as part of future work.

Table 2b. Performance Standards of Decelerating Approach.

Performance standards. MIL-DTL-32742 Decelerating Approach			**Performance standards.** EWS Decelerating Approach		
	Desired	Adequate		Desired	Adequate
Maintain glideslope within ± X ft:	12.5 feet	25 feet	Achieve final altitude within ± X ft:	12.5 feet	25 feet
Maintain airspeed within ±X knots of the reference:	5 knots	10 knots	Once final airspeed (50 kts) is achieved, maintain airspeed within ±X knots	5 knots	10 knots
Maintain localizer within:	50 feet	75 feet			

A key difference is that the MIL-DTL-32742 version of the Decelerating Approach currently relies heavily on supplemental instrumentation (such as a localizer) that likely would not be present, or if present, may not be practical to use while also watching for obstacles (such as trees or power lines). The form of the proposed EWS Decelerating Approach description is a hybrid of the proposed revision by Blanken, et al. (Ref. 22) and the Decelerating Approach in MIL-DTL-32742. The changes in both the description and metrics are intended to allow the MTE to be completed with less instrument or sensor-based cueing which is more representative of the wildfire environment. Additionally, the performance standards focus more on achieving the final required altitude and speed and relax the requirements during the deceleration phase, giving the pilots more autonomy and providing more compatibility with heavy use of visual cueing.

It should be noted that all numerical values listed in EWS Decelerating Approach are based on existing information but are intended to be notional. Before this work could be applied more broadly, it is highly recommended that a combination of fixed and motion-based simulations be conducted, along with test pilot feedback, to fine tune these values. The starting altitude was based on Refs. 6 and 23, and the starting airspeed was based on target airspeeds listed for similar altitudes in the MIL-DTL-32472 for the Missed Approach MTE. The final airspeed and altitude were chosen such that a payload could be accurately dropped (Refs. 6 and. 24). This will be further discussed under the Payload Drop and Ascend MTE. Margins for maintaining altitude were based on the performance standards in MIL-DTL-32472 and allow the pilot to avoid most telephone poles, tall trees, and some extreme environmental conditions directly above a fire (for desired standard) and most tall structures/homes and flames (for adequate standard). Figure 4 illustrates the potential proximity of the flames to the helicopter during the approach.

Figure 4. Helicopter dropping water on flames (Ref. 25). ***Credit: CAL FIRE.***

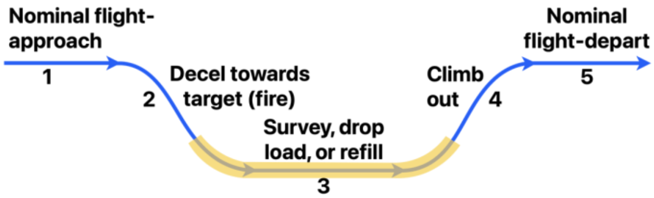
Segment 3: Survey, Drop, Load or Refill

Segment 3 should begin when the pilot reaches the required height to confidentially perform the drop/load/survey task. Seventy-five feet (Ref. 6) will be used as a placeholder for discussion purposes until future simulation efforts refine this guidance. This description best fits the survey application. If loading or unloading water/fire retardant, additional impacts from shifting loads may need to be accounted for. However, for simplicity, those effects will be broken up into a separate MTE described below under Payload Drop and Ascent.

The key risk in Segment 3, if a slung load is not present, is the precision required to fly very close to the terrain/terrain-based obstacles and the fire. Reference 7 states that failure to maintain clearance boundaries resulted in ~20% of wildfire-related aviation causalities. While Fig. 1 represents this segment as a simple, constant altitude sortie, the Depart/Abort MTE (Ref. 21) would demonstrate the ability to establish hover/constant low speed forward flight after a trim change (such as the transition between Segment 2 and Segment 3 or Segment 3 and Segment 4). Therefore, these transitions along with Segment 3 are highlighted in Figure 5 and show the portion of EWS that would be evaluated using the modified Depart/Abort MTE. The Depart/Abort MTE would also assess the pilot's ability to fly with high precision in a low-altitude setting. The Depart/Abort MTE description is shown in Fig. 6.

Figure 5. Portion of EWS evaluated with Depart/Abort MTE.

The Decel to Dash MTE (Ref. 21) is more similar in profile to the highlighted portion of Figure 5, and the Decel to Dash may also be relevant to explore in future work.



However, the Decel to Dash would likely require the pilot to be more aggressive/may be overly demanding for this application, and therefore, was not chosen as the focus of this study.

Because this MTE is being utilized to assess the ability to be precise in low altitude, but it does not directly map to the mission scenario, it is acceptable to use the Objectives, Description of maneuver, and Description of test course as proposed in MIL-DTL-32742 as written with one exception. The vehicle should be stabilized at 75 feet wheel height (or 75 feet height of the external load if a load is present), rather than 35 feet as 35 feet would likely be too close to flames/water/etc. Performance metrics can also remain as currently written apart from, "Maintain radar altitude below X ft" which should be revised to 150 feet for desired and 200 feet (doubled from current MIL-DTL-32742 standards) for adequate in both good visual environment (GVE) and degraded visual environments (DVE), as the MIL-DTL-32742 altitudes are likely more limiting than required for the wildfire application. While low-altitude maneuvering is needed in the wildfire scenario, wildfire pilots may need more flexibility to balance getting low enough to successfully perform tasks while avoiding ground-based hazards and the most extreme wildfire generated turbulence. Therefore, like the EWS Decelerating Approach, a minimum distance the wheels must stay from the ground is also included in the performance metrics to avoid power lines, trees, flames, etc. Table 3 shows these changes. Again, all values are intended as notional place holders until metrics can be refined.

a. Objectives.

- Check pitch axis and heave axis handling qualities during moderately aggressive maneuvering.
- Check for undesirable coupling between the longitudinal and lateral-directional axes.
- Check for harmony between the pitch axis and heave axis controllers.
- Check for overly complex power management requirements.
- Check for ability to re-establish hover after changing trim.
- With an external load, check for dynamic problems resulting from the external load configuration.

b. Description of maneuver. From a stabilized hover at 35 ft wheel height (or no greater than 35 ft external load height) and 800 ft from the intended endpoint, initiate a longitudinal acceleration to perform a normal departure. Abort the departure and decelerate to a hover such that at the termination of the maneuver, the cockpit shall be within 20 ft of the intended endpoint. It is not permissible to overshoot the intended endpoint and move back. If the rotorcraft stopped short, the maneuver is not complete until it is within 20 ft of the intended endpoint. The acceleration and deceleration phases shall be accomplished in a single smooth maneuver. For rotorcraft that use changes in pitch attitude for airspeed control, a target of approximately 20 degrees of pitch attitude should be used for the acceleration and deceleration. The maneuver is complete when control motions have subsided to those necessary to maintain a stable hover.

c. Description of test course. The test course shall consist of at least a reference line on the ground indicating the desired track during the acceleration and deceleration, and markers to denote the starting and endpoint of the maneuver. The course should also include reference lines or markers parallel to the course reference line to allow the pilot and observers to perceive the desired and adequate longitudinal tracking performance, such as the example shown in FIGURE 57.

d. Performance standards. Depart/Abort.

	Cargo/Utility		Externally Slung Load	
	GVE	DVE	GVE	DVE
DESIRED PERFORMANCE				
• Maintain lateral track within ±X ft:	10 ft	10 ft	10 ft	10 ft
• Maintain radar altitude below X ft:	75 ft	75 ft	75 ft*	75 ft*
• Maintain heading within ±X deg:	10 deg	10 deg	10 deg	10 deg
• Time to complete maneuver:	25 sec	25 sec	30 sec	30 sec
• Maintain rotor speed within:	OFE	OFE	OFE	OFE
ADEQUATE PERFORMANCE				
• Maintain lateral track within ±X ft:	20 ft	20 ft	20 ft	20 ft
• Maintain radar altitude below X ft:	100 ft	100 ft	100 ft*	100 ft*
• Maintain heading within ±X deg:	15 deg	15 deg	15 deg	15 deg
• Time to complete maneuver:	30 sec	30 sec	35 sec	35 sec
• Maintain rotor speed within:	SFE	SFE	SFE	SFE

* Altitudes refer to height of external load, maneuver at hover

Figure 6. Depart/Abort objectives, description of maneuver and test course, and performance standards (Ref. 21). Diagram of test course can be found in Appendix.

Table 3: Adapted Performance Metrics for Depart/Abort.

MIL-DTL-32742 Depart/Abort			EWS Depart/Abort		
	Desired	Adequate		Desired	Adequate
Maintain radar altitude below X ft:	75 feet	100 feet	Maintain radar altitude below X ft:	150 feet	200 feet
			Maintain wheel/slung load height above X ft:	60 feet	45 feet

Segment 4: Climb Out

Segment 4 describes the part of the mission scenario where the aircraft must transition from low altitude flight to a higher altitude above the most extreme environmental impacts from the fire, terrain, or other obstacles, minimally to a nominal operations height (<500 feet, below the air tankers and supervisor aircraft, Ref. 6). This maneuver maps to a tailored version of the Missed Approach MTE as listed in MIL-DTL-32742. For this exercise, preliminary values of a final flight height of 500 feet (Refs. 6 and 23) and a climb at V_y (best rate of climb) will be used for illustration of the maneuver. Primary risks in this segment are obstacles, especially in DVE, power limitations to climb quickly (performance implications that constrain handling qualities), or if the terrain does not allow for easy maneuvering. (A safety circle for obstacle avoidance is generally defined as 1.5 times the rotor diameter both on ground and in-flight (Ref. 13). This metric is used to evaluate adequate clearance. However, some scenarios may require more clearance.) An example incident that could be represented by the tailored EWS Missed Approach is the Trinity Alps fire accident (Table 1 and Ref. 11-12). The relevant part of the mission scenario captured by the adapted Missed Approach MTE (EWS Missed Approach) is highlighted in Fig. 7 (the end of Segment 3, Segment 4, the beginning of Segment 5 and the transitions between them). A load drop and changing vehicle dynamics introduces a more challenging scenario. That consideration will be further discussed under "Payload Drop and Ascent." Table 4a shows the MIL-DTL-32742 and the proposed revisions to the Objectives and Description of Maneuver, and Table 4b shows the MIL-DTL-32742 and EWS proposed Performance Metrics.

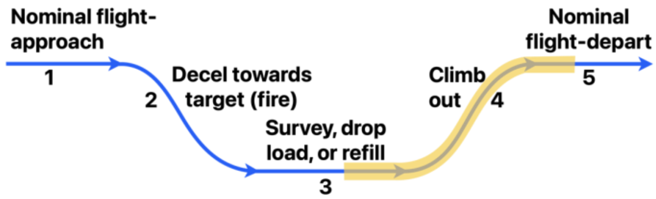


Figure 7. Portion of EWS1 evaluated with Missed Approach MTE

The EWS Missed Approach task is intended to assess the pilot workload during a climb in situations where pilot may have divided attention. If the pilot were flying in an environment with significant obstacles, ability to avoid those obstacles can be tested via the Slalom or Pull Up/Push Down MTE (Ref. 21) which is discussed in Table 7. Altitude margins were reduced to be more representative of the control needed during wildfire operations. Airspeed range in performance metrics was reduced in MIL-DTL-32742 compared to previous versions of ADS33 (Ref. 22). These slower speeds are more appropriate to stay closer to the "ideal" airspeed for dropping fire retardant (Refs. 6 and 24).

Table 4a: MIL-DTL-32742 Vs. EWS Missed Approach Objectives and Description.

MIL-DTL-32742 Missed Approach	EWS Missed Approach
Objectives. Check longitudinal flight control variations in a high-workload, divided-attention task.	**Objectives.** Check longitudinal flight control variations in a high-workload, divided-attention task.
Description of Maneuver. After performing an ILS approach to Decision Height, initiate a climb on runway heading to an altitude of 500 ft at an airspeed of 80 knots. At 500 ft, turn right to a heading 90 degrees from runway heading. Level off at 1,000 ft and accelerate to 100 knots. Once steady at this condition, turn right to a heading of 180 degrees from runway heading and climb to 2,000 ft. Once level at 2000 ft and steady on 100 knots, accelerate to 130 knots or V_H.	**Description of Maneuver.** Start flying at a constant altitude of 75 feet at 50 knots. Initiate a climb to 500 feet altitude at V_y (best rate of climb). Level vehicle and end maneuver when vehicle has stabilized for at least 3 seconds.

Table 4b: MIL-DTL-32742 Vs. EWS Missed Approach Performance Metrics.

MIL-DTL-32742 Missed Approach			EWS Missed Approach		
	Desired	Adequate		Desired	Adequate
Maintain altitudes within:	± 100 ft	± 200 ft	Maintain altitudes within:	± 15 ft	± 30 ft
Maintain target airspeeds within:	± 5 knots	± 10 knots	Maintain airspeeds during level segment of flight within:	± 5 knots	± 10 knots

Segment 5: Depart

Like the Approach, this portion of the flight may be subject to wildfire-specific environmental factors, but is otherwise, expected to be nominal flight conditions. Figure 8 highlights the relevant section of EWS.

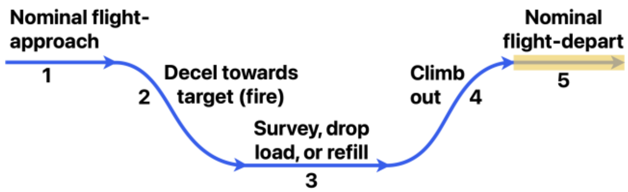


Figure 8: Segment 5 of EWS-Depart.

Assessing Transient Payload Drop Dynamics

A critical portion of the wildfire mission scenario involves the loading or unloading of payloads. A load placement MTE developed by Ivler, et al. was able to show a trade-off between the damping of slung loads and handling qualities (Ref. 17). The work also demonstrated that handling qualities tended to degrade with larger load mass ratios (LMRs) and longer sling lengths. This is a particularly important for wildfire fighting aircraft which may require larger suppressant loads at longer lengths for effective behavior in degraded environments and difficult terrain. Ivler's work was added to a proposal for revising handling quality standards (Ref. 22) and ultimately adopted into MIL-DTL-32742(AR), Ref. 21.

These updated standards are useful for assessing many transportation segments of wildfire mission scenarios involving slung loads; however, the transient dynamics associated with dropping a payload are not currently addressed. These may be important considerations, especially when a fire suppression payload has a large LMR that may dramatically change the inertial properties of the vehicle when jettisoned. Additionally, vehicle dynamics may also be impacted by control systems that do not properly account for changing load conditions. These effects may be exacerbated in mission scenarios with difficult terrain or obscured obstacles which could cause pilots to make aggressive (and potentially unexpected) maneuvers while dropping a payload. The following mission task element was developed to simulate this behavior for analysis. Performance standards can be found in Table 5.

Payload Drop & Ascent

a. **Objectives.**
   - Check ability to maintain airspeed, heading, and altitude during a payload drop.
   - Assess handling qualities of the transient dynamics from dropping a payload.

b. **Description of Maneuver.** Begin level unaccelerated flight at 55 knots with a distance of 500 feet to a ground-referenced target and an altitude of 100 feet above the terrain. If a slung load is in use, maintain a ground clearance of 100 feet for the load. Upon passing the ground-referenced target initiate the payload drop. For payloads that jettison instantaneously, immediately initiate and complete a 50-foot ascent within specified time, or the shortest time allowed by the constraints of the operational flight envelope (OFE). For loads that do not jettison instantaneously, a second ground-reference target will be placed at a distance commensurate with a one-half dissipation of the payload and the 50-foot ascent will instead be initiated there. Complete the maneuver in level flight and hold a stabilized altitude for 3 seconds.

c. **Description of test course.** The test course shall have one ground-referenced target for instantaneous payloads and two ground referenced targets for non-instantaneous payloads. These targets may be moved or supplemented to provide sufficient visual cueing for the specific vehicle and payload configuration in use. Markers should also be present for denoting desired and adequate boundaries of the full payload dissipation zone. A suggested test course for this maneuver is shown in Figure 9. Performance metrics for Payload Drop and Ascent can be found in Table 5.

Table 5: Performance – Payload Drop & Ascent.

	Desired	Adequate
• Maintain lateral track with ±X ft:	20 ft*	35 ft*
• Maintain a heading of ±X deg:	5 deg	10 deg
• Maintain airspeed within ±X knots:	5 knots	10 knots
• Except during the ascent, maintain an altitude within ±X ft:	5 ft	10 ft
• Complete the ascent and stabilize altitude within:	6 sec**	8 sec**

*Evaluation of lateral track constraints differ for instantaneous and non-instantaneous payloads. See notes in Figure 9 for the suggested test course.

** Times may be adjusted if constrained by the OFE.

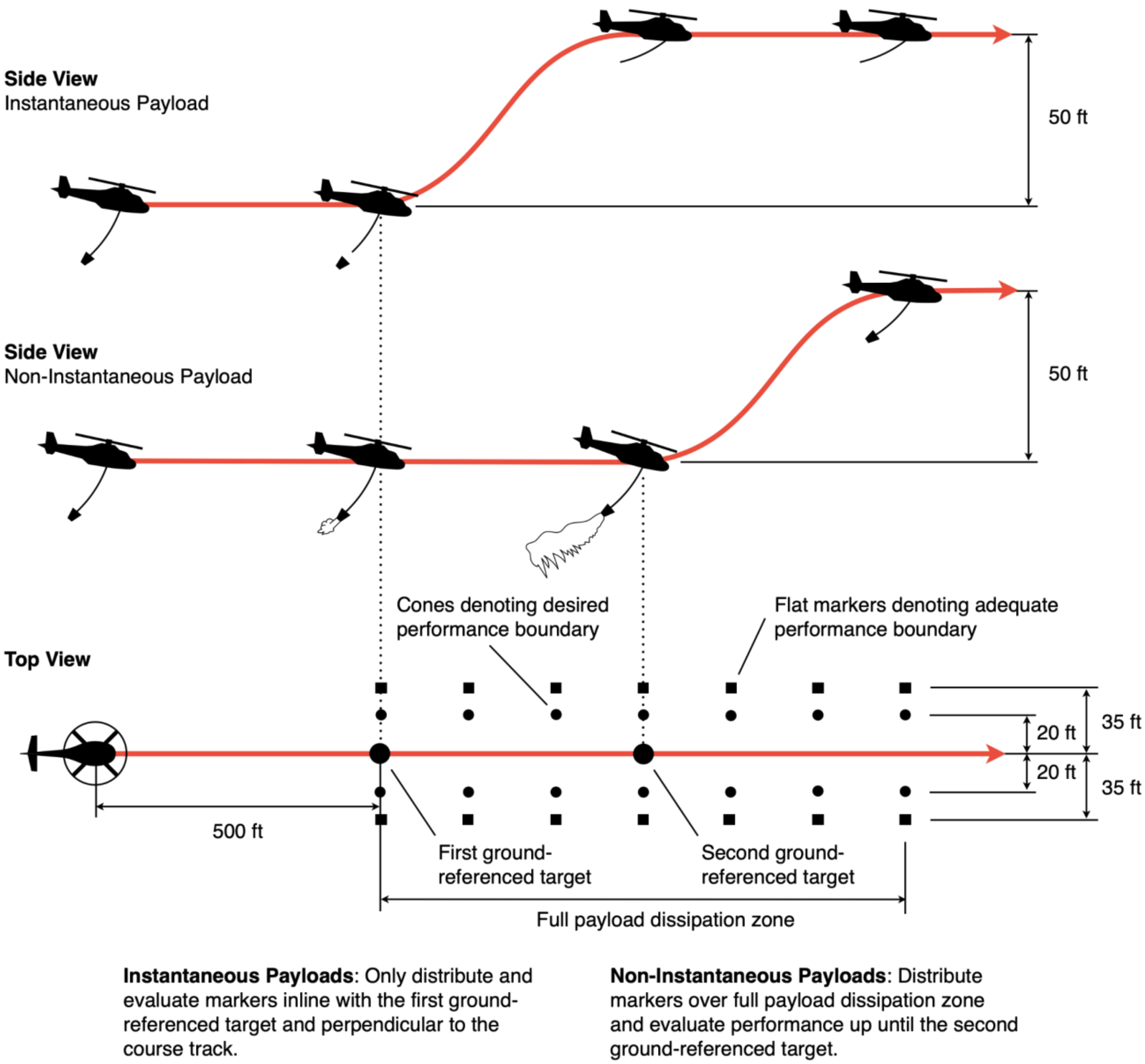


Figure 9. Suggested course for the Payload Drop & Ascent maneuver.

Airspeed and dimensions for the payload dissipation zone are based on work by Solarz & Jordan which assessed performance of a 660-gallon Bambi helibucket for various suppressants (Ref. 24). This study showed that the line length of a suppressant drop with a coverage level of three gallons per 100 square feet is maximized at airspeeds of approximately 50-60 knots, depending on the suppressant. Additionally, the study reported contour plots with drop pattern characteristics that were all approximately 50 feet wide for drop heights ranging from 83-149 feet. While lower drop heights increase coverage levels, an altitude of 100 feet was chosen as representative for the course since many wildfire drops may occur over difficult terrain and additional clearance may be required for adverse environmental conditions. Although the accuracy of the drop is not directly measured with this MTE, desired and adequate boundaries are provided at ±20 and ±35 feet, respectively. Assuming a perfect drop occurs when the MTE is executed as intended, drops on the desired and adequate boundaries represent perfect drop overlaps of approximately 60% and 30%, respectively. The desired boundaries were originally tighter, but expanded to provide better visual cueing after considering that a slung load may require the pilot to be 150+ feet above the course.

The 50-foot ascent is based on a common obstacle avoidance criterion used by the Federal Aviation Administration (FAA) for aircraft certification (Ref. 26, 27). Times to complete this maneuver were extended from those of the vertical maneuver MTE (Ref. 21). Based on a second-order transfer function with a natural frequency of 0.8 rad/sec and a damping ratio of 0.85, the peak acceleration for a 50-foot ascent in six seconds is estimated to be approximately

1G. Given the variety of possible configurations, a footnote for adjusting the times based on OFE constraints was added (see Table 5). Directional maintenance requirements were based on values common to several MTEs, while altitude maintenance requirements were adapted from the Vertical Maneuver (Ref. 21). Specifically, altitude requirements were relaxed given the divided attention required for maintaining heading, airspeed, and flying within the performance boundaries of the payload dissipation zone.

Combined Mission Scenario (Exploratory Wildfire Scenario Version 1 (EWS V1))

A representative mission scenario (sometimes referred to as a vignette) was created which combines the discussed MTEs. Performing this mission scenario is both a handling qualities exercise and allows aircraft performance to be evaluated. It would also reveal any challenges in segment transitions that were missed when performing the MTEs independently. EWS represents the general maneuver with multiple applications. EWS V1 specifically refers to the example case of dropping the water/fire suppressant, and utilizes the Payload Drop and Ascend as part of Segment 3 from EWS (See Figure 1). EWS V1 is illustrated in Figure 10. Other variation examples could include picking up water, avoiding obstacles in the flight path, and increasing the workload by simulating communication with/tracking awareness of other wildfire aircraft in area. The combined mission scenario (EWS V1) is as follows:

a. Objectives.
- Fly a representative mission scenario for a wildfire environment to assess deficiencies in vehicle performance, assess pilot workload/impact of split attention, and change in vehicle dynamics.

b. Description of maneuver. Above minimum clearance (AMC) is defined as altitude relative to the highest point for the intended target area. This notion is illustrated in Figure 10 where 0 ft AMC coincides with 500 ft mean seal level (MSL). Altitude is measured from the lesser of wheel height or, if present, the bottom of a slung load.

Fly at a constant altitude of 500 feet AMC at 100 knots. Initiate descent until an altitude of 75 feet AMC is reached, following the glideslope. Level out and fly a distance of 90 feet before initiating load drop. 500 feet after initiating load drop, climb to an altitude of 500 feet AMC and level off. Complete the maneuver in steady, level flight for three seconds.

A time limit is included because pilots may need to "get in and get out" before conditions change. Total time was estimated based on assumed speed of aircraft for payload drop and area of coverage (Ref. 24), but should be refined through simulation, pilot feedback, and tailored to size of rotorcraft and fire as needed. For the variation of this scenario that includes putting obstacles representing a tree or power line in the pilot's path and asking them to maneuver around it before completing the mission scenario, five seconds should be added for this variation to the desired and adequate criteria. Total time may need to be adjusted for survey scenarios or smaller rotorcraft.

c. Description of course. A target "box" is required to represent the fire to provide pilots with a reference point to aim the water drop. A 1-acre (209 x 209 feet) box is suggested as a preliminary target size, to be refined through simulation, for most single rotor fire-firefighting helicopters. If a significantly smaller or larger helicopter is used, the box size may need to be scaled accordingly. Performance metrics for EWS V1 are in Table 6.

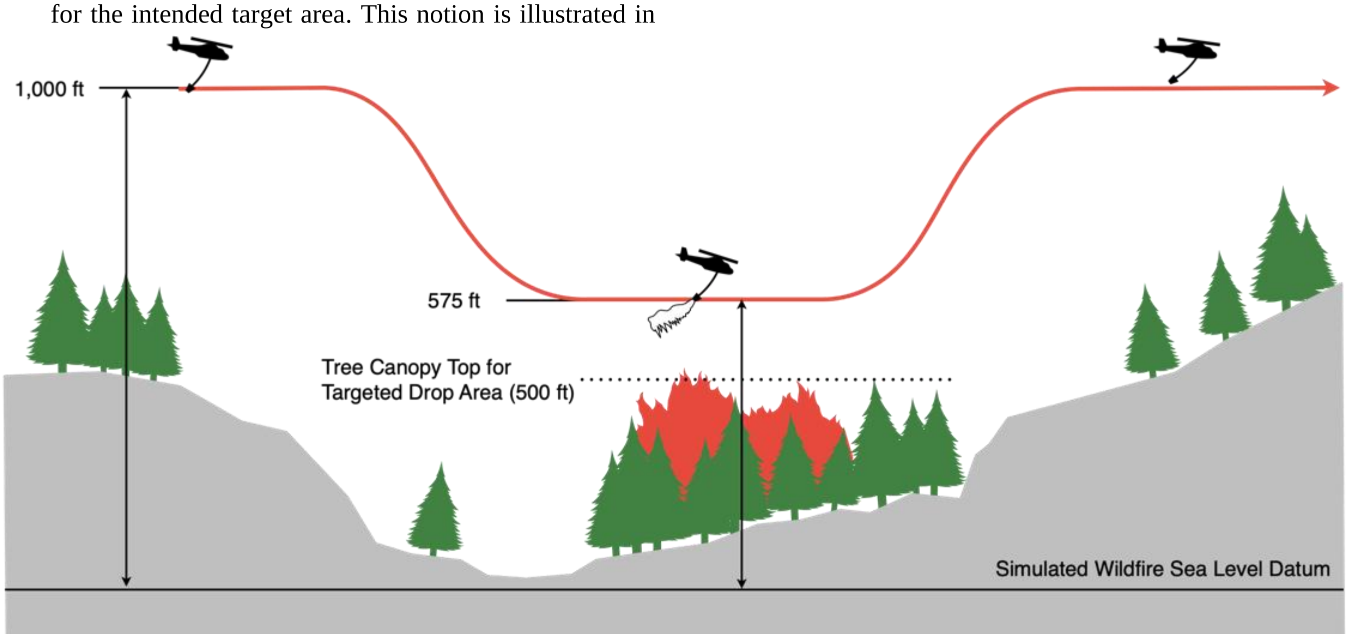


Figure 10. EWS V1 mission scenario suppressant drop.

Table 6: Performance Metrics for EWS V1-Water Drop EWS Variant.

	Desired	Adequate
Maintain AMC altitude within:	±15 ft	±30 ft
Coverage of fire "box"	90%	75%
In Segment 3, maintain 50 kts:	±5 knots	±10 knots
Total time to complete maneuver (including 3 second hold):	30 sec	45 sec

SIMULATION

Table 7 lists potential simulation cases that warrant exploration in either fixed- or motion-based simulation. Fixed-base simulation should be used to prioritize the test matrix for motion-based runs (using facilities such as the NASA Ames Vertical Motion Simulator) and refine the performance metrics. A preliminary prioritization for cases is included in Table 7 where those cases are ranked with "high" being the highest priority for motion-based simulation, "med" being secondary priority, and "low" being cases that could likely be sufficiently explored using fixed-based simulation. The rows in Table 7 include potential variables in the MTEs including visual grades, turbulence levels, terrain type, and component failure. These variables will be discussed in more detail below.

Table 7: Potential Simulation Cases for MTEs of Interest.

	Varying Visual Conditions (Clear Day, Light Smoke, Heavy Smoke, Nighttime Flying)	Varying Turbulence (Calm, General Atmospheric Winds, Wildfire Generated Turbulence and Winds)	Terrain Types (Shallow, moderate, and steep slopes, varying obstacles heights)	Component Failure	Notes
General Maneuvers					
Hover	med	high	low	low	Turbulence, especially generated by the wildfire likely to significantly impact ability to station keep. Higher levels of visual degradation would compromise ability to see reference targets. Unlikely to execute hover portion of mission if component failed.
Vertical Maneuver	high	high	low	low	See above notes under "Hover". Pilots may become spatially disoriented if visuals severely degraded.
Obstacle Avoidance					
Slalom	high	med	high	low	Performance criteria, specifically related to speed, could likely be relaxed in a wildfire environment. Degraded visuals are expected to be the primary concern, however, if vehicles are in very close proximity to obstacles, turbulence may also be a factor.
Pullup/Push Over	high	med	high	low	Obstacles of various heights should be simulated
Slope Landing and Liftoff	med	med	high	low	Historical data may exist. This should be evaluated before establishing priority. Motion relevant to assess spatial awareness.
Mission Specific					
EWS Decelerating Approach	high	high	med	low	Visualization levels and turbulence are more critical for low terrain MTEs. Motion key for spatial awareness.
EWS Depart/Abort	high	high	med	low	See above. This maneuver represents the most critical segment for mission success (survey, crew rescue, etc.) if there is no slung load which increases priority.
EWS Missed Approach	high	med	high*	med	Terrain variation prioritized for maneuvers that involve climbing. *Assuming no slung load
Payload Drop & Ascent	high	high	high	med	Payload Drop and Ascent should be prioritized over EWS Missed Approach if slung load is included.
Combined scenario	high	high	high	med	Comprehensive validation of flight envelope

Conditions

References 4 and 6 both emphasized how much pilots rely on visual cueing, rather than instrumentation, during the critical mission phase of the wildfire scenario. The main impact of handling qualities from degraded visuals is likely tied to planning and reaction time. Following MIL-DTL-32742 guidelines, visual environment grades are traditionally either GVE or DVE. Wildfire operations in the presence of ash or smoke would tend towards maneuvers in DVE conditions. However, specifically for these scenarios, the level of visual degradation may vary significantly and simulating this variation could prove beneficial. These variations could be represented through mapping to the Useable Cue Environment (UCE).

It is suggested that evaluation be performed with "light and heavy smoke" variation to determine the appropriate mapping to the UCE. Reference 28 claims that an optimal range for visibility is 1000 yards. Assuming this represents GVE, and nighttime flights requiring night vision assistance is DVE (Ref. 21), and that decreasing the visual distance would correlate to a similar reduction in reaction time, Table 8 presents a notional break out of how the presence of smoke may affect visual range for a wildfire scenario. However, this breakdown is only intended to provide starting values until appropriate levels can be further defined through simulation or more formal UCE evaluation. These conditions are included as variables in Table 7. Specific maneuvers of interest for this variable would be the MTEs that require the pilots to be precise in their altitude control (such as the Vertical Maneuver and Depart/Abort) and the obstacle avoidance MTEs such as the Slalom and Push Up/Pull Over.

A second set of conditions is presented in Table 7: Calm, General Atmospheric Turbulence and Winds, and Wildfire Generated Turbulence and Winds. High altitude maneuvers will help limit influence of wildfire driven turbulence, but they may not be feasible in many wildfire fighting applications. For this set of variables, low speed maneuvers like hover, those that require station keeping, and activities with slung loads, such as the Payload Drop and Ascent, would be the most likely to see large impacts on handling qualities ratings. Risk is greater as well in the low-altitude maneuvers such as Missed Approach and Slope Landing because of the proximity of the vehicle to a ground-based hazard (fire, tree, irregular terrain features, etc.).

Additional conditions may include uneven terrain with varying levels (shallow, moderate, steep) which would be most relevant in the EWS Missed Approach and Payload Drop and Ascent, as well as the MTEs testing obstacle avoidance, in order to gauge the pilots' ability to react to rapidly changing terrain and assess the handling qualities limits. Component failure may also be relevant to explore. While outside the scope of this effort, it would be worthwhile to explore the impact of the wildfire on hardware failure. Simulating these failures and how the vehicle would respond could inform pilot training by providing experience in a lower risk environment and help develop procedures to be followed in-field should such a failure occur, increasing the likelihood for the pilot to be able to maneuver away and land safely.

MTEs and Mission Scenarios

In addition to the MTEs mapped to EWS and the custom MTE, Payload Drop and Ascent, a few other existing MTEs were included in Table 7 for consideration. While beyond the scope of this work, these MTEs may also be adapted. Hover and Vertical Maneuver were chosen to assess station keeping ability and as a baseline to compare more complex maneuvers. Single axis vertical control would be relevant for the segment of the mission when the aircraft is trying to line up with a water source, fly closer to a target for visual inspection, or drop supplies. It should be confirmed via fixed-based simulation if it is necessary to isolate this from the custom Payload Drop and Ascent maneuver. This also may depend on if the assessment is focused on well-known, retrofitted vehicles or non-traditional or novel vehicles, like those that may be designed in the future specifically for fighting wildfires (Ref. 15). Existing knowledge should be leveraged when available. In the context of aerial firefighting, many aircraft are government surplus with a pedigree of flying and handling qualities testing, such as the UH-60 and UH-1H, among others. Although these vehicles are retrofitted to fight wildfires, they tend to retain performance capabilities similar to the original vehicles. (Although familiarity could also yield false confidence, if vehicles are operating closer to their design limits or in ways they were not designed for, thorough exploration is still warranted. The Trinity Alps fire (Ref. 11-12) crash involved an overloaded Sikorsky S-61, the civilian variant of the Sikorsky S-3 "Sea King"). However, assuming mostly vehicles with extensive military use backgrounds, running tests such as the Hover and Vertical Maneuver are likely to yield fewer original results compared to the Payload Drop and Ascent or Wildfire Mission Scenario.

Table 8: Conditions and Preliminary Corresponding Visual Distances.

Conditions	Visual Distance
Clear Day (GVE)	1000 yards
Light Smoke (DVE)	<500 yards (half visual distance and reaction time)
Heavy Smoke (DVE)	<250 yards (quarter visual distance and reaction time)
Nighttime Flying (DVE)	Requires use of night vision eyewear

The Slalom and Pull Up/Push Over maneuvers were selected as a reference that would allow researchers to explore handling qualities impacts related to obstacle avoidance. It should be noted that these are likely more demanding than needed, especially regarding the required speeds of the maneuvers. However, they are generally representative of the way a pilot might need to maneuver the vehicle to avoid colliding with rapidly changing terrain or obstacles. The Slope Landing and Liftoff may also provide value in the wildfire scenario, depending on the terrain. MIL-DTL-32742 Reference 21 calls for a clearly marked landing area which would need to be redefined for this environment. This maneuver would be representing a crew delivery/pick up (Helitack crews may either land near a remote fire or repel depending on terrain).

Fixed- versus Motion-Based Simulation

Starting with the preliminary set of MTEs identified in Table 7, computer simulations can be used to assess various portions of the tasks in the presence of turbulence, during the injection of component failures, or while operating with a slung load. For example, the ability of the vehicle's control system to station-keep in different levels of turbulence, how well a slalom course or glideslope can be followed, or whether significant couplings occur in a vertical maneuver when subjected to a component failure. This first pass can help identify which axes of the vehicle may have limited capabilities. Following this, fixed-base simulators can be used to assess the handling qualities of the vehicle in GVE versus DVE. While these tests would not provide the vestibular feedback that can greatly improve a pilot's perception of how a vehicle is responding to their inputs, it can uncover whether certain setups have larger changes from their respective control cases or result in unexpected trends worth additional investigation.

The identified cases of the test matrix which present the greatest concerns can then be assessed in a motion-based simulator or flight test to baseline handling qualities. While this provides valuable data, even more information may be obtainable if solutions to challenging vehicle characteristics are identified prior to testing. For example, a vehicle with a cross-axis coupling excited in turbulence might be correctable with an airframe or control law modification. If the change is found to be significant in computer simulation or fixed-base simulations, it may be worth considering for motion or flight testing. The prioritization in Table 7 is notional and should be updated after additional simulation work and feedback from pilots/industry.

FUTURE WORK

This paper proposes a series of new and modified MTEs that address a variety of essential tasks for rotorcraft-based wildfire operations. As previously stated, the MTEs presented in this document are not intended to be detailed final tasks but rather are intended to serve as a foundation for future studies to collaborate and iteratively improve upon. In the further development of these baseline MTEs, this study recommends the additional following topics for further investigation: turbulence modeling, environmental modeling, and control strategy.

Historical events demonstrate that operating rotorcraft in the wildfire environment exposes the aircraft, pilot, and passengers to significant risks. As previously highlighted, a quarter of all firefighting fatalities were aviation related. One area that warrants improvement is wildfire-driven turbulence modeling in the context of rotorcraft operations (Ref. 16). Fortunately, the literature has an extensive history of experimental measurements of wildfire turbulence, with well over 100 years of history on the topic (Ref. 29-30). In previous work, the authors of this study demonstrated how existing historical data can be leveraged to inform low-order turbulence modeling for the wildfire environment (Ref. 16). This turbulence model was generated via a sum-of-sines approach to best fit existing experimental data. However, the turbulence model presented previously was greatly limited as the modeling approach only accounted for replicating the PSD signature of the wildfire turbulence, thus ignoring spatial coherence of the flow field. An additional limitation of the previously presented turbulence model was the requirement of extrapolating the high-frequency content of the available experimental data. One significant limiting factor experienced in generating this turbulence model was that much of the literature has focused extensively on characterizing the dynamics of wildfire-driven turbulence rather than on turbulence modeling in the context of vehicle flight dynamics. For instance, many published experimental measurements for wildfire turbulence were obtained with sampling frequencies too low for rotorcraft-based handling quality applications. As such, the authors recommend that further development of wildfire turbulence models happen through the close collaboration of wildfire experimentalist experts and the rotorcraft handling qualities community. Through this close multi-disciplinary collaboration, the community must identify best practices for utilizing existing and future experimental datasets for turbulence model derivation and validation.

In addition to improving wildfire turbulence modeling, further efforts must be taken to ensure wildfire MTEs best replicate the wildfire environment when additional environmental data sets are available. In improving the proposed baseline MTEs in this study, future work includes modeling shared airspaces with both crewed and uncrewed vehicles, accounting for irregular/changing terrain, and maintaining safe distances from tree and power lines.

SUMMARY AND CONCLUDING REMARKS

This work is intended to be a preliminary discussion of adapting traditional mission task elements that could be used to represent a wildfire scenario. Because many wildfire fighting vehicles are retrofitted, rather than designed specifically for the wildfire environment, and are also being used in extreme environmental conditions, it is important to understand the true limits of the vehicle and how the vehicle's handling qualities and performance will degrade in that environment. This work has the potential to reduce fatalities by enabling pilots to practice these high-risk missions in a lower risk environment. A general wildfire scenario ("Exploratory Wildfire Scenario", EWS) was proposed, and the adapted versions of the Decelerating Approach, Depart/Abort, and Missed Approach were mapped to this scenario. A Payload Drop & Ascent MTE is proposed to assess handling qualities of the transient dynamics from dropping a payload. This may be especially useful for wildfire fighting vehicles with large LMRs. Modeling, simulation, and testing of these MTEs can help refine metrics. Future work includes fixed-based simulations which will inform which MTEs and conditions to prioritize in motion-based simulation or flight testing. Additionally, maturing turbulence and control methods should be explored. Lastly, additional video footage, wind data, or vehicle performance data obtained during wildfire events would further mature these studies.

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APPENDIX

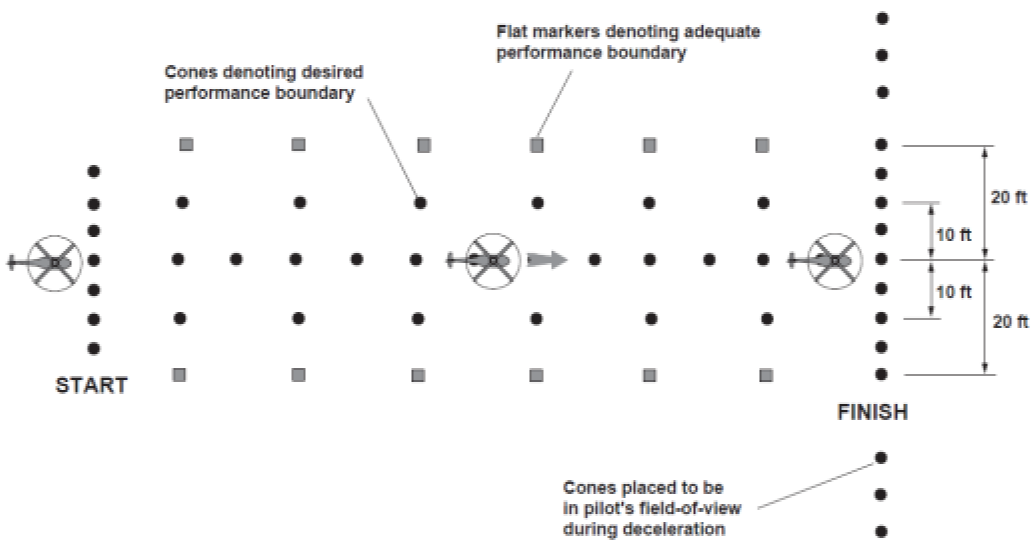

Figure A1: Depart/Abort test course diagram (Ref. 21).

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