NASA/TM-20250009504

Advanced Vision Systems for Degraded Cockpit Environments

Ru-Ching Chen
Glenn Research Center, Cleveland, Ohio

November 2025

NASA STI Program Report Series

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA scientific and technical information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NTRS Registered and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION.
  Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM.
  Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT.
  Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION.
  Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- SPECIAL PUBLICATION.
  Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION.
  English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include organizing and publishing research results, distributing specialized research announcements and feeds, providing information desk and personal search support, and enabling data exchange services.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at http://www.sti.nasa.gov

NASA/TM-20250009504

Advanced Vision Systems for Degraded Cockpit Environments

Ru-Ching Chen
Glenn Research Center, Cleveland, Ohio

National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

November 2025

Acknowledgments

Special thanks to members of the Graphics and Visualization Lab (GVIS) at NASA Glenn Research Center as well as Craig Little at NASA Armstrong Flight Research Center. This work was funded by a FY2025 Center Innovation Fund.

This report is a formal draft or working paper, intended to solicit comments and ideas from a technical peer group.

Trade names and trademarks are used in this report for identification only. Their usage does not constitute an official endorsement, either expressed or implied, by the National Aeronautics and Space Administration.

Level of Review: This material has been technically reviewed by technical management.

This report is available in electronic form at https://www.sti.nasa.gov/ and https://ntrs.nasa.gov/

NASA STI Program/Mail Stop 050
NASA Langley Research Center
Hampton, VA 23681-2199

Advanced Vision Systems for Degraded Cockpit Environments

Ru-Ching Chen

National Aeronautics and Space Administration
Cleveland, Ohio, USA

September 21, 2025

Abstract

Losing sight in a smoke-filled cockpit is a catastrophic failure with a history of fatal consequences. Today's standard-issue equipment simply is not designed to solve the problem. This paper makes the case for a new safety paradigm built on vision restoration, moving beyond the limitations of mere preservation. We explore this by weighing the trade-offs between three emerging technological pathways: integrated AR masks, conjunctive HMDs, and fully immersive VR systems. The analysis navigates the complex design choices inherent in each approach. An integrated mask, for example, offers a streamlined emergency response but concentrates the risk on a single point of electronic failure. In contrast, modular systems provide flexibility but introduce their own significant human factors and integration hurdles. The most technologically complete approach, immersive VR, promises a perfect, smoke-immune view, but its viability hinges on achieving a nearly unprecedented level of system reliability. Moving any of these concepts from the lab to the flight deck presents a formidable challenge. We conclude by outlining a research agenda that calls for focused work on sensor fusion, low-power display optics, and critical human factors questions. The paper argues that a modernized regulatory framework is also essential for charting a clear and predictable certification path for this next generation of life-saving technology.

1. Introduction

Smoke-in-cockpit emergencies pose a catastrophic and persistent risk in modern aviation. This technical memorandum explores the emerging vision systems being developed to counter that threat. We begin by analyzing why current mitigation strategies, particularly the standard-issue oxygen masks, are operationally and ergonomically insufficient. While they provide breathable air, they fail to solve the fundamental problem of a pilot's vision being completely and dangerously obscured. This creates a critical and unresolved capability gap in emergency response, where crews have the means to breathe but not to see, a distinction that has proven fatal in multiple accidents. From that baseline, the analysis centers on three competing architectural paradigms for a viable solution: integrated Augmented Reality (AR) masks, conjunctive Head-Mounted Displays (HMDs) designed for use with existing equipment, and fully immersive Virtual Reality (VR) headsets. To assess the feasibility of these concepts, we examine the core enabling technologies in detail, weighing the performance trade-offs of different sensing modalities, like Infrared and Millimeter-Wave Radar, and advanced display optics.

Of course, a technical solution is only valuable if it can be certified. A significant portion of this document, therefore, is dedicated to outlining a plausible path to regulatory approval under the frameworks of the Federal Aviation Administration (FAA) and the European Union Aviation Safety Agency (EASA). This includes addressing the key hurdles of system integrity, human factors validation, and establishing an Equivalent Level of Safety (ELOS). The memorandum concludes by weaving these threads together, clarifying the complex trade-offs between architectures to highlight the essential questions the aviation community must answer to bring this life-saving technology to the flight deck.

Though statistically rare, in-flight fires are often catastrophic, frequently culminating in a complete loss of aircraft control [1]. The danger extends beyond the flames to the rapid and total degradation of the cockpit environment. This inevitably leads to the failure of the single most critical instrument a pilot has: their own vision. When all other systems are compromised, a pilot's ability to see their instruments and maintain an external view is the final safeguard against disaster. To lose that capability is to lose control of the aircraft, regardless of the crew's skill or the integrity of any remaining systems.

2. Historical Precedent and Case Studies

Even before the era of complex digital avionics, in-flight fires posed fundamental challenges that still define the problem today. The cases that follow are archetypal examples of hidden fires, delayed detection, and flawed design philosophies, showing the devastating consequences that can result.

2.1. Case Study: Air Canada Flight 797 (McDonnell Douglas DC-9-32), June 2, 1983

The loss of Air Canada Flight 797 is a foundational case study in this area. It tragically illustrates the lethal mathematics of slow detection and exposes deep flaws in both cabin safety standards and the emergency equipment available to crews.

2.1.1. Root Cause Analysis

The U.S. National Transportation Safety Board (NTSB) investigation [2, 3] concluded that the accident had three probable causes: a fire from an unknown source, an underestimation of its severity, and misleading reports to the captain about its progress. Investigators focused on the aircraft's aft lavatory, where the fire was first spotted. They meticulously analyzed several potential ignition sources, including the lavatory flush motor, nearby wiring, and even a discarded cigarette, but could not positively identify what started the fire.

That ambiguity is itself a critical finding. It highlights how destructive in-flight fires can be, often erasing all evidence of how they started. The NTSB did determine that the fire had spread unseen inside the lavatory walls and into the hidden space above the cabin ceiling. This stealthy path of propagation made it impossible for the cabin crew to know its true scale or fight it effectively.

2.1.2. Event Timeline and Crew Actions

The event's timeline is a stark lesson in why every second counts. At 18:51 EDT, the first sign of an electrical problem appeared when three circuit breakers for the lavatory's flush motor tripped.

The flight crew knew about the tripped breakers, but with no other warnings, they didn't treat it as a critical emergency.

It wasn't until around 19:02 EDT that a flight attendant told the captain about a "fire in the washroom". This critical 10-minute delay gave a small, smoldering fire enough time to grow into an uncontrollable blaze. The crew's response was made even more difficult because reports from the cabin suggested the situation was improving. This conflicting information delayed the captain's decision to begin an emergency descent.

2.1.3. Technology and Human Factors Evaluation

The NTSB report pointed to serious human factors problems with the crew's personal protective equipment (PPE). During the descent, the captain wore his oxygen mask and smoke goggles, but he reported that his goggles steamed up, making it nearly impossible to see the flight instruments at the worst possible moment. For the cabin crew, the fact that they had no self-contained breathing gear was a critical failure. The NTSB believed that a flight attendant with a full-face smoke mask might have been able to attack the fire more aggressively when it first started.

The crew's decisions also showed weaknesses in emergency procedures. The first officer, using his own judgment outside of any checklist, shut down the air conditioning packs because he thought they were fueling the fire. While a logical move under extreme stress, this action had an unintended and dangerous consequence: it shut off the only system capable of clearing smoke from the cockpit, making the pilots' situation even worse. This is a classic human factors problem, where crews under intense pressure and with limited information may deviate from procedures in ways that have unforeseen and negative results.

2.1.4. Outcome and Results

The flight crew performed an exceptional emergency landing at the Greater Cincinnati Airport (CVG). But within 90 seconds of the doors opening, an influx of fresh air fed the flames, causing a flash fire that instantly consumed the cabin. Twenty-three of the 46 people on board died from smoke inhalation and burns [4]. The fire completely destroyed the aircraft [5].

2.1.5. Industry & Regulatory Reaction

The catastrophic loss of life, which occurred even after a successful landing, acted as a catalyst for the global aviation regulatory community. The NTSB released a series of urgent recommendations that led directly to major improvements in cabin safety. Following this, the FAA required smoke detectors in all aircraft lavatories, automatic fire extinguishers in trash bins, floor-level emergency lighting, and stricter fire-resistance standards for cabin materials [2]. The accident also pushed for long-overdue upgrades to crew protective breathing equipment [3].

The response from regulators was sweeping, yet it was also entirely reactive. The new rules mandated technologies and standards that were mostly available before the accident but had been set aside due to cost concerns.

2.2. Case Study: ValuJet Flight 592 (McDonnell Douglas DC-9-32), May 11, 1996

The crash of ValuJet Flight 592 was more than just an accident caused by improperly handled cargo. It represented a catastrophic breakdown of a core aircraft design and certification philosophy, made worse by a complete collapse of the safety culture at a maintenance contractor.

2.2.1. Root Cause Analysis

The NTSB determined the probable cause was a fire ignited by one or more chemical oxygen generators that were improperly shipped as cargo in the forward Class D cargo hold [6]. The investigation uncovered an extensive cascade of technical failures. It began with ValuJet's maintenance contractor, SabreTech, whose employees failed to install required safety caps on the firing pins of expired but still fully charged oxygen generators.

This critical error was compounded by falsified paperwork [7]. SabreTech employees wrongly labeled the shipping box as "Oxy Cannisters - Empty" and did not declare the contents as hazardous material. Furthermore, the generators themselves were packed inadequately, placed loosely in cardboard boxes with only bubble wrap for protection. This left them vulnerable to activation from routine ground handling or in-flight vibrations. Once triggered, the generators started a chemical reaction that produced extreme heat, well over 260 °C, along with pure oxygen [8]. This created a self-sustaining, oxygen-fed fire in a cargo hold that was never designed to contain it.

2.2.2. Event Timeline and Crew Actions

Investigators believe the fire started not long after the plane was airborne [9]. For about six minutes, the crew had no idea a fire was raging below them. The first sign of trouble came at 14:10 EDT, when the cockpit voice recorder (CVR) picked up a loud bang and the pilots noticed electrical fluctuations. That sound was later identified as a tire in the cargo hold exploding from the heat.

The crew reacted immediately, recognizing the severity of the problem and declaring an emergency to return to Miami. But the fire was spreading with incredible speed. Because the cockpit-cabin interphone was not working, a flight attendant had to open the cockpit door to report the fire, which allowed thick smoke to pour onto the flight deck.

2.2.3. Technology and Human Factors Evaluation

The central technological failure in this accident was the design philosophy behind the Class D cargo compartment. These compartments were designed to suppress a fire by being hermetically sealed, which would theoretically starve a fire of oxygen. This design is completely ineffective and, in fact, dangerous when a fire involves an oxidizer like a chemical oxygen generator, which creates its own oxygen supply. The very design meant to provide safety was rendered useless. The NTSB was unequivocal in its finding, stating that the FAA's failure to require smoke detection and fire suppression systems in these holds was a direct cause of the accident. The crew was flying an aircraft with an invisible, uncontrollable fire raging right beneath their feet.

The human factors failures at SabreTech were just as severe and were systemic. The investigation painted a picture of a maintenance culture under intense pressure to meet deadlines. There was inadequate training on handling hazardous materials, a shortage of critical supplies like the safety caps, and a work environment that allowed for the falsification of maintenance records. This case showed how a poor safety culture at a third-party vendor could introduce a fatal flaw into the aviation system, bypassing all of an airline's own safety protocols.

2.2.4. Outcome and Results

The fire's intensity was devastating; it burned through the cabin floor, severing flight control cables and leading to a catastrophic loss of control. The aircraft crashed at high speed into the Florida Everglades. All 110 people on board, 105 passengers and 5 crew members, were killed. The aircraft was a total loss.

2.2.5. Industry & Regulatory Reaction

The aftermath of the ValuJet crash brought swift and profound changes from regulators. The FAA immediately issued an emergency rule that banned the transport of chemical oxygen generators as cargo on passenger flights [9]. More importantly, the accident forced a complete overhaul of the philosophy behind aircraft certification and safety. The FAA mandated a costly and complex program to retrofit all existing Class D cargo holds across the passenger fleet, upgrading them to Class C standards, which include smoke detectors and active fire suppression systems [10]. The crash also put the FAA's oversight of new, low-cost airlines and their outside maintenance contractors under a microscope, triggering a fundamental shift in the agency's focus away from promoting the industry and toward prioritizing safety above all else.

2.3. Swissair Flight 111 (McDonnell Douglas MD-11), September 2, 1998

The loss of Swissair Flight 111 marked a turning point for in-flight fire investigations. Here, the threat was not an outside element like cargo, but something that originated from within the aircraft's own complex and certified systems. This accident brought to light deep, systemic flaws in how materials were certified, how emergency checklists were designed, and how the industry understood fires in hidden, inaccessible parts of an airplane.

2.3.1. Root Cause Analysis

After a monumental, multi-year investigation, the Transportation Safety Board of Canada (TSB) concluded that the accident was caused by a fire that started above the cockpit ceiling [5]. Investigators believe the most likely sequence began with an electrical arc from damaged wiring. This arc ignited the flammable cover material, a metallized polyethylene terephthalate (MPET) film, on the nearby thermal acoustic insulation blankets. Once lit, the fire spread quickly across the surface of the MPET blankets, which provided a significant source of fuel [11]. The fire then ignited other flammable materials in the area. While investigators could not pinpoint the exact wire that caused the initial arc, they strongly suspected wiring connected to a recently installed In-Flight Entertainment Network (IFEN), which had been certified through a Supplemental Type Certificate (STC).

2.3.2. Event Timeline and Crew Actions

The first sign of trouble was an unusual smell in the cockpit, which the crew noticed at 01:10 UTC [12]. A critical 13 minutes passed between that first sensory clue and the start of a rapid cascade of systems failures, which began showing up on the flight data recorder (FDR) at 01:24 UTC. By that time, the fire was already out of control.

Based on the limited information they had, the crew's first thought was that the smell was coming from the air conditioning system, a common and usually harmless issue. They acted deliberately, declaring a "Pan Pan Pan" international urgency signal, putting on their oxygen masks, and starting a diversion to Halifax, Nova Scotia. Critically, the pilots had no idea how large or intense the fire was that raged in the hidden space just above their heads. They made the procedurally correct decision to prepare for an overweight landing by dumping fuel, but this action used up vital minutes while the fire was busy destroying the aircraft's wiring and critical systems.

2.3.3. Technology and Human Factors Evaluation

The Swissair 111 investigation revealed profound failures in both how technology was certified and in human factors engineering.

- Material Flammability Standards: At the heart of the technological failures was the inadequacy of the standards for certifying material flammability [13]. The MPET-covered insulation blankets had passed the required FAA vertical burn tests, yet they proved to be highly flammable in a real-world fire. They were the main reason the fire was able to spread. The TSB concluded that the certification standards were dangerously insufficient because they did not replicate realistic fire scenarios. This accident shattered the industry's long-held assumption that certified materials were inherently "fire-safe."
- Lack of Detection in Hidden Areas: The aircraft had no smoke or fire detectors in the cockpit ceiling area, often called the "attic." This meant the flight crew had to rely entirely on their sense of smell, an unreliable and lagging indicator, to detect the fire. They were blind to the threat until it was far too late.
- Checklist Complexity and Philosophy: The crew was confronted with an impossible task. They started the "Smoke/Fumes of Unknown Origin" checklist, a complicated procedure that instructed them to systematically shut down individual electrical busses to try and find the source. This focus on troubleshooting consumed precious time and mental energy. The TSB was highly critical of this approach, pointing out that the final step in the checklist was to "Land at the nearest suitable airport," which downplayed the urgency of the situation. The mental load on the pilots was simply overwhelming as they navigated a diversion at night, talked to ATC, and worked through a complex diagnostic checklist while their environment deteriorated around them.

2.3.4. Outcome and Results

The fire led to the progressive failure of essential flight instruments, displays, and flight control systems [14]. The aircraft's recorders stopped working about six minutes before it crashed. At that point, the crew was likely fighting a fully developed fire in the cockpit with almost no working instruments. The aircraft eventually went out of control and crashed into the Atlantic Ocean near Peggy's Cove, Nova Scotia. All 229 people on board, 215 passengers and 14 crew members, were killed. While the aircraft was destroyed, an unprecedented recovery effort managed to bring 98% of the wreckage by weight back up from the ocean floor.

2.3.5. Industry & Regulatory Reaction

The TSB's findings set off a paradigm shift in aviation safety. Regulators ordered a massive, worldwide program to remove and replace MPET-covered insulation blankets from thousands of aircraft. The accident spurred the development of the Enhanced Airworthiness Program for Airplane Systems (EAPAS) and new rules for Electrical Wiring Interconnection Systems (EWIS), which fundamentally changed how aircraft wiring is designed, installed, and maintained. The process for approving STCs also came under intense scrutiny.

Most importantly, the accident forced a global rethinking of emergency checklist philosophy. This led to the widespread adoption of new procedures that prioritize landing immediately over time-consuming troubleshooting whenever there is an unconfirmed sign of smoke or fire. The TSB also made far-reaching recommendations about CVR recording times and the need for firefighting plans that include ways to detect and suppress fires in inaccessible areas.

2.4. Case Study: UPS Airlines Flight 6 (Boeing 747-400F), September 3, 2010

The crash of UPS Flight 6 completely redefined the industry's understanding of a worst-case fire scenario. The accident showed that a fire involving large amounts of lithium-ion batteries could create an unsurvivable environment so quickly that it rendered traditional procedures and equipment tragically useless.

2.4.1. Root Cause Analysis

The final report from the United Arab Emirates General Civil Aviation Authority (GCAA) concluded that an un-contained cargo fire started when the contents of a cargo pallet auto-ignited [15]. This pallet was carrying a large shipment that included over 81,000 lithium batteries.

The danger with lithium batteries is a failure mode called thermal runaway. This is a violent and self-sustaining chemical reaction that produces extreme heat, potentially over 2000 °C, and flammable gases. Critically, the reaction also creates its own oxygen, which makes it immune to standard fire suppression techniques like Halon gas or oxygen starvation. The investigation also discovered that the fire-resistant liner of the Class E cargo hold failed. This allowed the fire to burn through the aircraft's structure and destroy critical systems at a rapid pace.

2.4.2. Event Timeline and Crew Actions

The first warning, a "FIRE MAIN DK FWD" EICAS message, appeared at 19:15, just 22 minutes after the flight departed from Dubai. The crew's response was immediate and professional. They declared an emergency, put on their oxygen masks, activated the cargo fire suppression system, and started turning back to Dubai. But, the situation got worse with shocking speed. Just three minutes after the first warning, the cockpit started to fill with thick, continuous smoke. The crew reported they could no longer see their radios or flight displays. The fire then burned quickly through the aircraft's ceiling, destroying primary flight controls and making the captain's control column useless for controlling the plane's pitch.

2.4.3. Technology and Human Factors Evaluation

From a human factors perspective, this accident is one of the most important case studies on record for in-flight fires.

- Crew Protective Equipment (PPE): The standard-issue crew oxygen masks proved to be fatally inadequate. At 19:20, only five minutes into the emergency, the captain's oxygen supply failed. He had to leave his seat to get the Emergency Reserve Oxygen System (EROS) mask, which was stowed behind him. In the toxic, oxygen-starved air of the smoke-filled cockpit, he was quickly overcome by hypoxia and collapsed, incapacitated for the rest of the flight. This left the First Officer to manage a crippled aircraft in a zero-visibility environment, completely alone. The event was a stark demonstration of how critical vision is; without the ability to see his instruments or anything outside, the First Officer's immense skill and effort were ultimately not enough.

- Checklist and Procedural Load: The crew followed the checklist for a main deck cargo fire, which involved depressurizing the cabin and staying at a high altitude to try and starve the fire of oxygen. This procedure, which was designed for conventional fires, is completely useless against a large-scale lithium battery fire that fuels itself through chemical reactions. This pointed to a critical failure of emergency procedures to evolve with new cargo threats. The cognitive, physiological, and physical workload placed upon the First Officer was beyond human limits.

2.4.4. Outcome and Results

The First Officer made heroic efforts to save the plane. He was being guided by radio from another pilot who was relaying instructions from ATC. But without any visual references or primary flight controls, a safe landing was impossible. He overflew the Dubai airport and was trying to set up an approach to a different airport when he completely lost control. The aircraft crashed in an unpopulated area near a military base. Both crew members, Captain Douglas Lampe and First Officer Matthew Bell, were killed. The Boeing 747-400F was destroyed.

2.4.5. Industry & Regulatory Reaction

The accident sent shockwaves through the air cargo industry and its regulators [16]. It led to an immediate reassessment of the serious risks involved in transporting lithium batteries in bulk. The FAA and the International Civil Aviation Organization (ICAO) soon issued stricter rules for the packaging, labeling, and quantity of lithium battery shipments [17]. The GCAA's final report included 36 safety recommendations. These called for better fire detection and suppression systems in cargo holds. Most significantly, the report recommended international cooperation to mandate "vision assurance devices or technology for improved pilot visibility during continuous smoke". The NTSB, which had already recommended automatic fire extinguisher systems in cargo holds, repeated its call with a new sense of urgency.

2.5. Case Study: Asiana Airlines Flight 991 (Boeing 747-400F), July 28, 2011

When Asiana Flight 991 was lost less than a year after the UPS 6 tragedy, it was devastating proof that the lithium battery threat was not just an isolated event. Instead, it was a systemic and global risk to all air cargo operations.

2.5.1. Root Cause Analysis

The South Korean Aviation and Railway Accident Investigation Board (ARAIB) concluded the crash was the result of a large, uncontained fire [18]. The fire led to parts of the fuselage separating from the aircraft in mid-air, which caused the pilots to lose control. Because both flight recorders were lost in deep water, investigators could not find the precise source of ignition. However, the investigation did find that the fire started on or near two pallets in the back of the main deck. These pallets were carrying declared dangerous goods, which included 400 kg of lithium-ion batteries and other flammable liquids like paint. The fire broke out in a Class E cargo compartment, a type which, by design, does not have an active fire suppression system.

2.5.2. Event Timeline and Crew Actions

The crew sent their first report of a fire on the main deck at 03:54 local time, about 50 minutes after taking off from Seoul [19]. They sent an ACARS message and made a radio call, immediately declared an emergency, put on their oxygen masks, and started a rapid descent. They tried to divert to the nearest suitable airport, Jeju. From that point, the timeline was alarmingly brief. Over the next 17 minutes, the crew reported that it was getting harder to control the aircraft, mentioning heavy vibrations and a loss of flight controls. All radio contact was lost at 04:11. The entire time from the first sign of fire to the crash was only 18 minutes, which was not nearly enough time to reach a safe landing.

2.5.3. Technology and Human Factors Evaluation

This accident drove home the lessons from both the ValuJet 592 and UPS 6 crashes: passive fire containment simply does not work for high-energy fires. The Class E cargo compartment, which was designed to rely on depressurization and the integrity of its liner, stood no chance of containing the blaze. The investigation also brought up human factors concerns about how the crew handled the emergency checklist. Evidence suggested they might have mistakenly used the checklist for the Boeing 747 Combi, which is a mixed passenger and cargo plane, instead of the correct one for their all-cargo freighter. This error could have delayed critical actions like depressurizing the cabin. It serves as another example of the immense mental pressure and potential for mistakes when crews have to manage a crisis that is escalating so quickly.

2.5.4. Outcome and Results

The uncontrolled fire caused a structural failure and an in-flight breakup of the aircraft. The Boeing 747-400F crashed into the East China Sea, killing both pilots. The airframe was completely destroyed.

2.5.5. Industry & Regulatory Reaction

Coming so soon after the UPS 6 accident, the loss of Asiana 991 provided irrefutable proof of a systemic vulnerability in the industry. It showed that any airline carrying bulk lithium batteries under the existing rules was exposed to the same risk of a fast, uncontrollable, and catastrophic fire. The ARAIB issued 20 comprehensive safety recommendations aimed at Asiana Airlines, the Korean regulator (MOLIT), Boeing, and ICAO. These recommendations called for stricter rules on separating hazardous cargo, the development of active fire suppression systems for Class E holds, better simulator training for fire emergencies, and improvements to make flight recorders more survivable and easier to find.

2.6. Case Study: Japan Airlines Boeing 787 (Boston, January 7, 2013)

The battery fire on a Japan Airlines Boeing 787 in Boston was a landmark event. Even though it happened on the ground and no one was hurt, it exposed critical weaknesses in how new technologies were being certified. In many ways, it was a fortunate “successful failure” that likely prevented a catastrophe in the air.

2.6.1. Root Cause Analysis

The NTSB traced the probable cause to an internal short circuit inside a single cell of the lithium-ion battery that powered the Auxiliary Power Unit (APU) [20]. This failure in one cell set off a thermal runaway that spread to the cells next to it. As a result, the entire battery overheated, vented flammable electrolytes, and began to smoke and burn.

2.6.2. Event Timeline and Crew Actions

The incident took place on the ground at Boston's Logan International Airport [21]. The aircraft was parked at the gate, and all passengers and crew had already gotten off. A cleaning crew first noticed smoke in the aft cabin. At the same time, a maintenance manager in the cockpit saw that the APU had shut down on its own. A mechanic went to investigate and, upon opening the aft electronics bay, found heavy smoke and flames coming from the APU battery case.

2.6.3. Technology and Human Factors Evaluation

At its core, the NTSB investigation uncovered a catastrophic failure in the aircraft certification process [22]. The NTSB's report placed the blame squarely on "Boeing's failure to incorporate design requirements to mitigate the most severe effects of an internal short circuit... and the Federal Aviation Administration's failure to identify this design deficiency during the type design certification process". The safety analyses that the manufacturer conducted, and the FAA accepted, simply did not properly consider the possibility that a short circuit in a single battery cell could cascade into a full-blown thermal runaway. Such an event could breach the battery case and create a serious fire hazard. The fundamental assumptions that formed the basis of the battery system's safety case were proven to be wrong. This event was a stark lesson in the profound risks of integrating novel, high-energy technologies into aircraft without a certification process strong enough to anticipate their unique and most severe failure modes.

2.6.4. Outcome and Results

Because the fire happened on the ground in a controlled setting, airport rescue and firefighting crews were able to contain it successfully. There were no fatalities or serious injuries. The damage was limited to the APU battery and the area immediately around it in the aft electronics bay.

2.6.5. Industry & Regulatory Reaction

The combination of this incident and a nearly identical in-flight battery fire on an All Nippon Airways 787 just nine days later forced the FAA and regulators around the world to take a drastic step: they grounded the entire global fleet of Boeing 787s [23]. The grounding lasted for more than three months, until a certified fix was developed and put in place. This solution required a complete redesign of the battery and its housing. The new design featured better insulation between the cells, a much stronger, sealed steel containment box, and a dedicated venting system. This system was designed to channel any smoke or flammable gases directly overboard, keeping them from getting into the cabin or other parts of the aircraft.

2.7. EgyptAir Flight 804 (Airbus A320-232), May 19, 2016

The investigation into the loss of EgyptAir Flight 804 stands out due to a significant and very public disagreement between the lead investigative body and its international partners. This conflict has clouded the official findings. However, the technical evidence points to a rapid, oxygen-fueled fire that started within the cockpit itself. This raises the deeply concerning possibility that a piece of essential safety equipment became the catalyst for the catastrophe.

2.7.1. Root Cause Analysis

The investigation resulted in two conflicting conclusions:

- Egyptian EAAID Conclusion: The Egyptian Aircraft Accident Investigation Directorate (EAAID) came to the conclusion that the fire was started by the detonation of "explosive materials" that had been placed in the forward galley [24]. They argued that this explosion damaged the crew's oxygen system, and the resulting oxygen leak fed and accelerated the fire.

- French BEA Dissenting Conclusion: The French Bureau of Enquiry and Analysis for Civil Aviation Safety (BEA), which took part as the representative for the aircraft's country of manufacture, strongly disagreed [25]. The BEA's analysis of CVR, FDR, and ACARS data led them to believe a fire most likely broke out inside the cockpit, starting at or near the First Officer's oxygen mask. The leading scenario from the BEA suggests the fire was fueled by a high-pressure oxygen leak from the mask's supply line and was possibly ignited by a pilot's cigarette, a practice the airline had reportedly not banned. The BEA's conclusion aligns more closely with the sequence of fault messages and the sounds from the CVR.

2.7.2. Event Timeline and Crew Actions

The flight was routine until its final moments. At 00:26 UTC, the aircraft's ACARS system started sending out a series of automated fault messages, beginning with "SMOKE LAVATORY SMOKE" [26]. Over the next three minutes, more messages followed in quick succession, indicating smoke in the avionics bay and failures in multiple flight control computers and cockpit window systems. Sounds consistent with a fire were recorded on the CVR, including the First Officer yelling "Fire". The crew never transmitted a distress call to air traffic control. This suggests they were either instantly overwhelmed by the event or were completely focused on trying to fight it. Radar data shows the aircraft then went into a series of sharp, uncontrolled turns as it descended rapidly from its cruising altitude of 37,000 feet.

2.7.3. Technology and Human Factors Evaluation

The BEA's analysis points to a catastrophic combination of a latent technical flaw and a critical human factors problem.

- Crew Oxygen System as a Hazard: The primary technological vulnerability lay in the crew oxygen system itself. This system is essential for survival during a smoke or depressurization event. However, a leak in a high-pressure supply line or mask can create a localized environment of pure oxygen. In such an atmosphere, materials that normally do not burn can ignite with ease, and a fire can spread with explosive speed, much like a blowtorch. This case study presents the alarming idea of safety equipment becoming the main accelerant in a disaster.

- Human Factors and Safety Culture: The potential ignition source the BEA pointed to, a lit cigarette, underscores a major failure in safety culture. The disaster seems to have been caused by a precise combination of a known maintenance issue (the oxygen mask in question had been replaced just three days earlier and might have been faulty) and a hazardous crew behavior (smoking in the cockpit).

2.7.4. Outcome and Results

The aircraft crashed into the eastern Mediterranean Sea, killing all 66 passengers and crew members on board. The Airbus A320 was destroyed.

2.7.5. Industry & Regulatory Reaction

The public disagreement between the Egyptian and French authorities severely hampered the investigation and its aftermath. This conflict delayed a final, consensus-based report for more than eight years, a delay that hinders the global safety system's ability to absorb lessons learned and implement timely corrective actions. In its own dissenting report, the BEA issued a safety recommendation that EASA and other regulators should formally assess the risks posed by a lit cigarette in proximity to crew oxygen equipment. The recommendation further urged them to amend certification and operational regulations as needed based on the results of that assessment.

Table 1: Summary of Incidents

Date	**Flight / Aircraft**	**Aircraft Type**	**Primary Causal Factor**	**Outcome (# Fatalities)**	**Key Technology/Human Factors Deficiency Noted**
02-Jun-83	Air Canada 797	McDonnell Douglas DC-9-32	Undetermined lavatory fire propagating in a hidden area	Landed, 23 fatalities post-landing	Detection latency (> 10 min); PPE vision impairment (goggles steamed); Lack of cabin crew PBE
11-May-96	ValuJet 592	McDonnell Douglas DC-9-32	Improperly stored chemical oxygen generators in cargo	Crash, 110 fatalities	Invalidated containment concept (Class D hold); Lack of cargo smoke detection/suppression
02-Sep-98	Swissair 111	McDonnell Douglas MD-11	Electrical arc igniting flammable (certified) insulation blankets	Crash, 229 fatalities	Inadequate material flammability standards; Lack of detection in hidden areas; Flawed checklist philosophy
03-Sep-10	UPS Airlines 6	Boeing 747-400F	Thermal runaway of bulk lithium-ion battery cargo	Crash, 2 fatalities	Extreme fire propagation speed; Complete loss of cockpit visibility; PPE oxygen supply failure
28-Jul-11	Asiana Airlines 991	Boeing 747-400F	Fire involving bulk lithium-ion batteries and flammable liquids	Crash, 2 fatalities	Inadequate Class E cargo containment; Corroborated Li-ion battery threat; Checklist confusion
07-Jan-13	Japan Airlines B787	Boeing 787-8	Internal short circuit and thermal runaway of APU Li-ion battery	Contained on ground, 0 fatalities	Flawed certification process for new battery technology; Inadequate system safety analysis
19-May-16	EgyptAir 804	Airbus A320 232	Disputed: Likely cockpit fire fueled by leaking crew oxygen mask	Crash, 66 fatalities	Safety equipment (O2 mask) as a fire accelerant; Poor safety culture (cockpit smoking)

3. Current State of the Art

The story of how we developed protective breathing and vision equipment for pilots is one of technological convergence, driven by the unique and ever-changing challenges of flight. The earliest ideas for this kind of gear did not come from aviation at all, but from 19th-century industrial workplaces like mines and fire departments [27]. In those settings, basic asbestos masks, filter hoods, and hose-fed breathing systems were the first real attempts to keep people alive in toxic air. The core engineering problems we still face today, supplying breathable air and protecting the eyes, were identified more than a hundred years ago.

With the advent of aviation, a whole new set of needs appeared. The first open-cockpit aircraft subjected pilots to extreme cold, deafening engine noise, and sprayed oil. For protection, the leather flying helmet and separate goggles quickly became standard. A crucial but accidental discovery was that the leather also gave pilots a bit of fire protection, an early sign of the future role this gear would play [28]. As planes flew higher and faster, especially during and after World War II, the physiological danger of hypoxia became a major concern. This led to military-driven innovations in sophisticated oxygen delivery systems, creating a new branch of technology focused on life support at extreme altitudes.

A key turning point came when aviation technology was cross-pollinated back to its conceptual roots. Companies like Scott Aviation, which had perfected high-altitude breathing gear for air crews, saw its potential and adapted it for firefighters. This moment marked the merging of two separate lines of development and is the direct ancestor of the pilot oxygen mask used today.

The arrival of pressurized, enclosed cockpits in transport aircraft fundamentally changed the primary threat. The danger was no longer external exposure but internal hazards, especially in-flight fires. The focus shifted from simply surviving the elements to surviving the aircraft itself. This new reality pushed for the development of purpose-built smoke protection. In the 1960s, the FAA's Civil Aeromedical Institute (CAMI) started making and testing dedicated passenger smoke hoods with advanced, heat-resistant materials like polyimide films [29–31]. This work marked a critical split in design philosophy: protective equipment was no longer just an adaptation of high-altitude systems but was being designed from scratch to fight the specific dangers of smoke and fire [32].

This history is important because it reveals that the three primary types of equipment analyzed in this report are not just iterative upgrades of one another. They represent three distinct evolutionary branches, each offering a unique engineering and philosophical solution to the life-threatening problem of cockpit smoke. The standard oxygen mask and goggle combination is an adaptation of a system first designed for hypoxia. The integrated smoke hood is a direct descendant of the self-contained breathing apparatus (SCBA) used by firefighters, built specifically for surviving a toxic fire. EVAS®, however, is a radical departure. It is a specialized tool that focuses only on preserving a pilot's vision by physically changing the immediate environment rather than protecting the user within it. To properly appreciate the strengths, weaknesses, and operational roles of each, it is essential to understand these different origins.

3.1. Standard Oxygen Mask and Separate Smoke Goggle Combinations

On the flight decks of most commercial and military transport aircraft, the standard protective breathing equipment (PBE) is a combination of a quick-donning oxygen mask and a separate pair of anti-smoke goggles. This setup is so widespread because it serves a dual purpose, offering protection from both high-altitude depressurization and in-flight smoke. The problem, however, is that the system is fundamentally an adaptation of life-support gear. This fact introduces serious human factors and integration challenges when pilots are forced to rely on it during a smoke emergency.

3.1.1. Principle of Operation and Key Engineering Specifics

The system has two main, separate components: the oxygen mask itself and the smoke goggles.

- Oxygen Mask and Regulator: The heart of the system is the quick-donning oronasal mask, which covers the pilot's nose and mouth. To be certified for use in transport aircraft, these masks must pass the minimum performance standards outlined in TSO-C78a [33]. One of the most critical requirements is that a pilot must be able to put the mask on with one hand in five seconds or less, a standard born from the need for rapid protection after a sudden decompression. The mask gets its oxygen from the aircraft's fixed supply through a regulator, which is certified under its own standard, TSO-C89a [34].

  The regulator itself is a sophisticated piece of equipment. In its normal "diluter-demand" mode, it conserves oxygen by mixing it with ambient cockpit air, adjusting the ratio based on the cabin's altitude [35, 36]. But for a smoke emergency, this mode would be dangerous, as it would pull contaminated air into the mask. For this reason, procedures and regulations require the crew to switch to 100% oxygen and select the "emergency" or positive pressure setting. Doing so forces a continuous stream of pure oxygen into the mask, creating a higher pressure inside than outside. This positive pressure is the key to safety, as it actively prevents smoke or toxic fumes from leaking in around the face seal.

- Smoke Goggles: The second part of the system is the smoke goggles, a separate piece of gear designed to be worn over the oxygen mask. Their job is to create a seal that protects the pilot's eyes from irritants. Airworthiness rules are specific: the goggles cannot have any "appreciable adverse effect on vision" and must be able to fit over corrective eyeglasses [37]. While some goggle models are certified under their own FAA TSO [38], many are approved based on recognized industrial safety standards like ANSI Z87.1 [39]. Most feature anti-fog coatings and are made with impact-resistant polycarbonate lenses [40].

3.1.2. Systems Integration Challenges (Communications and Audio Alerts)

Getting the mask and goggle system to work seamlessly within the complex flight deck environment is a serious challenge, especially when it comes to communication.

- Microphone Integration and Switching: The oxygen mask has its own microphone, which is crucial for communication. Most designs are set up to automatically activate this microphone and deactivate the pilot's headset boom mic as soon as the mask is pulled from its stowage box [41]. While this is supposed to be a smooth transition, it creates a potential point of failure. If the switch fails, the pilot might find themselves unable to transmit on the radio or interphone.

- Degraded Speech Intelligibility: The most critical problem with this system is how badly it degrades audio quality. The mask's physical structure muffles the pilot's voice, and because the microphone is so close to the mouth and nose, it picks up the loud, rhythmic sounds of pressurized breathing [41]. This combination pumps significant noise into the communication system. The result is that it becomes very difficult for crew members to understand each other and for Air Traffic Control (ATC) to understand their transmissions. This is not just anecdotal; an NTSB report on a Boeing 757 incident specifically mentioned that communicating with ATC was difficult with the oxygen masks on [42]. Technical studies back this up, showing that oxygen masks significantly change the acoustic properties of human speech, which directly harms intelligibility [43]. In the real world, pilots may have to hold their breath just to hear an incoming message or to make a clear call, which adds yet another layer of stress to an already overwhelming situation.

- Auditory Perception of Alerts: Finally, the mask and oxygen system create a great deal of noise and distraction. The mask itself can block peripheral sounds, and combined with the hiss of the oxygen and the intense focus required in an emergency, it can be easy for a pilot to miss or misinterpret critical audio alerts from the aircraft. This kind of auditory masking can dangerously delay a crew's recognition of a secondary or cascading failure.

3.1.3. Human Factors Deep Dive

Because the system is made of multiple components and must be used under extreme stress, it creates a very demanding situation from a human factors perspective.

- Stowage and Accessibility: Regulations say that PBE must be "conveniently located" and "easily accessible for immediate use" [44]. While the oxygen mask itself is usually in a good spot, incident reports show that the separate smoke goggles are often tucked away in less convenient places. This can waste critical seconds as a pilot, in a cockpit that may be quickly filling with smoke, has to fumble to find them [45].
- Donning Sequence Complexity: Putting the full system on is a complex sequence of motor tasks. A pilot must remove their headset, grab and put on the mask, inflate the harness to secure it, put the headset back on, find the goggle container, take out the goggles, and finally secure them over the mask and head. Trying to perform this series of actions perfectly with one hand, while the other hand is flying the plane, is incredibly difficult under stress. The NTSB's investigation into the UPS Flight 6 crash in Dubai, a key accident involving cockpit smoke, found that the flight crew struggled significantly with this exact sequence [46]. Investigators noted problems with getting a proper fit, the difficulty of needing two hands, and the pilots' inability to find and use the mask's selectors by feel alone [47]. In another incident involving a Cessna 525B, a BEA report noted that the crew never even managed to put their goggles on, most likely because the task seemed too complex under the immense time pressure of the emergency [48].
- In-Use Performance and Task Compatibility: Even when a pilot manages to get everything on correctly, the system's performance can be poor. Some goggle designs do not create an effective seal against the shape of the oxygen mask, which allows smoke to get trapped inside and makes them useless [49]. The bulk of the mask and goggles can also be uncomfortable, and the goggle frame itself can create blind spots or limit the pilot's field of view, making a proper instrument scan more difficult [50].

All of these issues combine to place a significant mental burden on the pilot. They are forced to dedicate precious mental energy to simply managing the equipment, from struggling to communicate to fumbling for selectors by feel, all while trying to compensate for a limited field of view. This happens at the exact moment when all of their focus should be on flying the aircraft, navigating, and troubleshooting the emergency [51]. The system's flaws are not just inconveniences; they are a direct result of its history. This equipment was first designed as a high-altitude life-support system and was later adapted for the unique challenges of a cockpit fire. Its design DNA prioritizes solving the physiological problem of hypoxia. Smoke protection was effectively a "bolted-on" feature, which is why we see this cascade of human factors problems in real-world emergencies.

3.1.4. Regulatory and Certification Basis

This equipment is governed by a complex, multi-layered regulatory framework.

- Airworthiness Standards: The foundational requirements are laid out in 14 CFR 25.1439 for FAA-regulated aircraft and the corresponding CS-25 standard for EASA [37, 52]. These regulations require the installation of PBE for the flight crew and specify that it must offer protection from smoke, CO_2, and other harmful gases. The rules explicitly permit either a fully integrated mask or a standard mask with "accessory equipment to cover the eyes." They also formalize the requirements for communication and a minimum 15-minute oxygen supply.
- Operating Rules: For airlines, 14 CFR 121.337 builds upon the airworthiness rules [44]. It gets into the specifics of operational use, confirming the 15-minute supply and communication standards, and adds the need for interphone communication with flight attendants. Critically, it also requires flight crew members to perform pre-flight checks on their equipment to ensure it is working properly and has adequate oxygen pressure.
- Technical Standard Orders (TSO): The FAA relies on TSOs to set the minimum performance, quality, and manufacturing standards for specific pieces of hardware. The oxygen mask itself must meet TSO-C78a [33], and its regulator must meet TSO-C89a [34]. These TSOs provide assurance that the individual components have been rigorously tested against a baseline safety standard, and they form the basis for certifying the hardware.

3.2. Analysis of Integrated Full-Face Smoke Hoods (PBE)

Unlike the adapted mask and goggle system, integrated full-face smoke hoods were designed from the ground up for one specific purpose: providing comprehensive protection during a fire. Commonly known as Protective Breathing Equipment (PBE), these single-unit devices are specialized tools for firefighting and emergency management, prioritizing rapid, error-proof use and complete isolation from a toxic environment.

3.2.1. Principle of Operation and Key Engineering Specifics

The all-in-one, self-contained design is what truly defines a smoke hood.

- Integrated Construction: A PBE combines the head covering, a wide-view visor, the breathing apparatus, and a neck seal into one cohesive unit [53]. This design completely eliminates the need for a crew member to assemble separate pieces of gear in the middle of an emergency. The hood itself is made from heat-resistant materials like polyimide films, which protect the wearer's head and face from extreme temperatures and the danger of melting or dripping plastics [29]. The visor is usually a flexible, clear panel that provides a wide field of view, often cited by manufacturers as 270 degrees [54].
- Self-Contained Oxygen Source: A critical difference from the flight deck masks is that PBEs carry their own oxygen supply and do not connect to the aircraft's fixed system. This portability is vital for a crew member who needs to move through the cabin to fight a fire. These units provide breathable air in one of two ways:
  - Compressed Oxygen: Many modern PBEs use small, lightweight cylinders of compressed aviator-grade oxygen. This method has a significant advantage: as the gas expands, it

  - provides a cool supply of air, which helps reduce the effects of heat stress on the user [54].
  - Chemical Oxygen Generation: Other designs rely on a chemical reaction to create oxygen, often using a potassium superoxide (KO_2) cartridge [55]. Although this method is effective, the chemical reaction gives off a great deal of heat, which can make the unit uncomfortably warm for the wearer.

- Carbon Dioxide Removal: Since the hood creates a closed-loop breathing system, the wearer's exhaled carbon dioxide (CO_2) has to be scrubbed from the air to prevent poisoning. This is done with panels inside the hood that contain a chemical absorbent, typically lithium hydroxide (LiOH), which captures and neutralizes the CO_2 [56].

3.2.2. Systems Integration Challenges

Because the PBE is a self-contained, portable device, it faces a different set of integration challenges than the equipment mounted on the flight deck.

- Communication: The biggest integration problem is communication. The hood is designed to allow for spoken communication, but the sound is muffled by the material, and the acoustics inside are not clear. Manufacturers might claim that speech is intelligible over short distances, and heavy-duty models are often designed to work with a megaphone [57]. However, the system has no direct electronic link to the aircraft's radios. This makes it fundamentally unusable for the pilot who is actively flying the plane and needs to maintain clear, two-way contact with ATC. This single limitation is what defines the PBE's role as a tool for cabin crew, or for a flight crew member who has handed off control of the aircraft to go fight a fire.

3.2.3. Human Factors Deep Dive

From a human factors standpoint, the smoke hood presents a clear trade-off. It offers outstanding ease of use and protection, but it also brings unique physiological and psychological stresses into the picture.

- Stowage and Donning: PBEs are made to be stored efficiently. They are typically folded, vacuum-sealed in a moisture-resistant pouch, and placed inside a compact, clearly marked box. Their biggest human factors win is how simple and fast they are to put on. The single-unit design gets rid of the complex, error-prone sequence of the mask and goggle combo, replacing it with a straightforward "open, activate, and pull over the head" motion. Manufacturers consistently claim a donning time under 15 seconds, which is a critical advantage for reducing mental load and the chance for error under the intense stress of a fire. Even though real-world times will vary with training and stress levels, the procedure's built-in simplicity makes it far more reliable than its multi-piece alternative [58].

- In-Use Performance (Physiological and Psychological Burden):

  - Heat Stress and Humidity: The same closed-loop design that offers excellent protection also traps the heat and moisture from the wearer's breath. This can cause the temperature and humidity inside the hood to rise quickly, creating a real risk of heat stress. This is especially true if the crew member is doing something physically demanding, like fighting a fire [59]. The maximum internal temperature is a key performance metric outlined in the equipment's TSO.

  - Claustrophobia and Anxiety: For some people, the experience of having their entire head enclosed in a sealed hood can trigger feelings of claustrophobia or anxiety [60]. In a life-or-death emergency, these psychological effects could easily be magnified and might impair a person's ability to perform.
  - Auditory and Visual Performance: The material of the hood naturally muffles outside sounds. This could make it harder for a crew member to locate a fire by sound or to hear instructions from others. And while the large visor offers a wide field of view, the flexible material is more likely to create optical distortions than rigid goggles, which is a concern that has been brought up in certification discussions [61].

The smoke hood's design is a perfect example of a role-specific engineering compromise. It gives top priority to foolproof, fast donning and total protection from a toxic atmosphere. These benefits, however, come at the cost of the high-fidelity, electronically integrated communications that a pilot flying the aircraft absolutely needs. This trade-off makes the smoke hood an exceptional tool for its intended job of firefighting, but a poor substitute for the dedicated system on the flight deck.

3.2.4. Regulatory and Certification Basis

The FAA and EASA have a specific set of TSOs (and their European counterparts, ETSOs) for regulating PBEs. These standards differ based on the intended user's role and expected workload.

- TSO-C99 and TSO-C116: This equipment is primarily governed by two TSOs. TSO-C99, titled "Flight Deck (Sedentary) Crewmember Protective Breathing Equipment," is for units that would be used by a pilot remaining at their station [62]. TSO-C116, "Crewmember Portable Protective Breathing Equipment," covers the portable units that crew members use to actively fight a fire [63]. The main difference is in the performance standards. TSO-C116 outlines a more demanding workload profile to simulate the higher breathing rate and physical effort of firefighting, which ensures the 15-minute oxygen supply will be sufficient even under strenuous activity [64].

- Performance Standards: Both TSOs lay out critical performance benchmarks. These include the 15-minute oxygen supply, limits on how much CO_2 can build up inside the hood, the flammability and heat resistance of the materials, and a maximum time for donning the unit (which is specified as 15 seconds in TSO-C116) [64].

- International Harmonization: The leading PBE manufacturers typically get their equipment certified by multiple international bodies, such as the FAA (TSO), EASA (ETSO), the UK's CAA, and China's CAAC. This reflects a widely harmonized global standard for this type of safety equipment.

3.3. Analysis of Inflatable Vision Units (EVAS®)

The Emergency Vision Assurance System, or EVAS®, represents a complete paradigm shift in how the industry addresses the threat of cockpit smoke. Unlike traditional equipment that is designed to shield the user from a dangerous environment, EVAS is an Inflatable Vision Unit (IVU) that instead alters the immediate environment. Its purpose is to preserve the single most critical pilot function during a smoke event: vision. It is a last-resort safety tool, built to prevent a loss-of-control accident when dense, continuous smoke makes the flight instruments and the outside view impossible to see.

3.3.1. Principle of Operation and Key Engineering Specifics

Instead of filtering air or supplying oxygen, EVAS works by physically displacing smoke.

- Smoke Displacement Mechanism: The core of the system is a transparent bag that inflates. When a pilot deploys it, the bag fills the space between their head and the instrument panel, which physically pushes the smoke-filled air out of their line of sight [65]. This process creates a small, localized pocket of clear air. The IVU's clear plastic walls then act as a window through which the pilot can see the instruments.
- System Components and Deployment: The whole system is self-contained in a compact aluminum case, roughly the size of a flight manual and weighing about six pounds [66]. Inside the case are the IVU, a battery-powered pump, and a high-efficiency particulate air (HEPA) filter rated at 0.3 microns. To activate it, the pilot pulls a tab. The pump then draws in cockpit air, runs it through the HEPA filter to strip out all the smoke particles, and uses the resulting clean air to inflate the IVU. The entire inflation process takes less than 30 seconds. The internal battery is powerful enough to keep the unit inflated for at least two hours, giving the crew more than enough time to divert and land the aircraft.

3.3.2. Systems Integration Challenges

The biggest integration challenge for EVAS is its total dependence on other pieces of protective equipment.

- Synergy with Breathing Equipment: EVAS is a vision-enhancement system only; it offers no protection for the pilot's lungs. The system was explicitly designed to be used along with a standard pilot oxygen mask and smoke goggles. This means that while EVAS solves the critical problem of lost vision, the crew still has to deal with all the communication and human factors issues that come with their breathing equipment. It is a powerful tool to supplement traditional PBE, not replace it.
- Physical Cockpit Integration: The stowed unit has to be installed where a pilot can easily get to it in an emergency, but where it will not interfere with normal flight operations. Once it is deployed, the IVU takes up a large part of the pilot's personal workspace. This is a factor that must be carefully considered during the ergonomic design and certification of its installation.

3.3.3. Human Factors Deep Dive

Using EVAS means accepting a significant human factors trade-off. While it guarantees a clear view of the most critical instruments, it does so at the cost of inducing severe "tunnel vision."

- Stowage and Deployment: The system is designed to be deployed manually in a straightforward way. But like any piece of emergency gear, proficiency and muscle memory are everything. Pilots need regular training to make sure they can find, deploy, and activate the unit quickly and correctly when facing the immense stress of a real smoke emergency.
- In-Use Performance (The "Tunnel Vision" Trade-Off):
  - Unparalleled Vision Assurance: The most significant human factors benefit of EVAS is that it gives a pilot a perfectly clear and unobstructed view of their primary flight

  instruments (the "basic T" configuration) and a look forward through the windscreen, even in zero-visibility smoke. In a situation like the UPS Flight 6 accident, where dense smoke made the instruments completely unreadable even with oxygen masks on, a capability like this could be the one thing that determines a successful outcome.
  - Induced Tunnel Vision and Its Consequences: The IVU's design inherently creates a narrow, focused window to the instrument panel, which completely cuts off the pilot's peripheral vision [67]. This has serious implications for both their task performance and overall situational awareness:
    - Instrument Scan Impairment: Pilots lose the ability to perform a normal instrument scan just by moving their eyes. If they need to see something outside the IVU's immediate window, they have to physically move the whole unit or their head. This is a slower process that takes more physical and mental effort.
    - Degraded Situational Awareness: Losing peripheral vision means the pilot is essentially blind to the rest of the cockpit. They cannot see switches on other panels or the throttle quadrant without deliberately moving their head away from the primary instruments. They also lose track of what the other crew member is doing and the general state of the cockpit environment.
    - Increased Cognitive Workload: EVAS certainly reduces the workload of trying to read instruments through smoke, but it adds a new kind of mental burden. The pilot has to actively manage this very limited field of view and consciously plan their head movements to get the information they need. This can add to their stress and mental effort [68].

This trade-off points to a fundamental shift in safety philosophy. Traditional PBE is designed to protect the operator so they can function inside a hostile environment. EVAS works from a different premise. It prioritizes the single most critical task, instrument flight, above everything else. It essentially accepts that the wider cockpit environment is lost and instead creates a small, task-specific "safe zone" just for vision. Accepting a major human factors penalty like tunnel vision in return for a guaranteed capability is a unique and powerful way to manage risk, a strategy born from the lessons of accidents where just being able to breathe was not enough.

3.3.4. Regulatory and Certification Basis

When it comes to regulation, EVAS has a different story than the mandated PBE found on aircraft.

- Certified but Not Mandated: EVAS is fully certified by the FAA. Its installation has been approved on a wide range of aircraft, covering over 120 different models from business jets to large transport-category airliners. The FAA itself has acknowledged the system's value, even retrofitting its own aircraft fleet to meet the recommendations for continuous smoke protection found in Advisory Circular AC 25.9a [69].

- Voluntary Adoption: Even with its proven effectiveness and strong support from pilot unions and safety bodies, especially after the UPS Flight 6 accident, regulators have not required the installation of EVAS across the commercial fleet. Its adoption has been driven by the voluntary initiative of safety-conscious operators like UPS, FedEx, and JetBlue [70, 71]. The push has also come from airframe manufacturers such as Gulfstream, Bombardier, and Dassault, which now offer it as a standard or optional feature. This reflects a common pattern in aviation safety, where the implementation of "above-and-beyond" technologies often happens long before any regulatory mandates are put in place.

4. Architectural Approaches for Advanced Vision Systems

The history of in-flight fires and the human factors data both point to the same conclusion: our current strategy of trying to preserve what little vision a pilot has left in a smoke-filled cockpit is not enough. To truly solve this problem, we need a paradigm shift, moving from vision preservation to vision restoration. This memorandum will conduct a rigorous technical analysis of the emerging Augmented Reality (AR) and Virtual Reality (VR) systems that make this shift possible. We believe these technologies offer a necessary and viable solution, one that can give pilots a clear, synthetic view of their flight path and instruments. This would allow them to effectively "see through the smoke" and maintain control of the aircraft all the way to a safe landing.

There are three main architectural paths for developing an advanced vision system for a degraded cockpit. Each one represents a distinct design philosophy with its own unique set of trade-offs in human factors, systems engineering, reliability, and the complexity of certification. The choice of which path to take is the most fundamental decision in the system's design, as it will shape everything about its operational characteristics and how it is brought to market.

To make a fair comparison, the architectural concepts discussed below are illustrated with a mix of currently certified products, adaptations of existing aerospace technologies, and conceptual models based on mature, high-fidelity systems. This approach provides a tangible way to compare each philosophy, recognizing that they are at different stages of market readiness but that each one represents a valid and distinct engineering path toward solving the problem.

4.1. Integrated Systems (AR Goggle/Mask)

4.1.1. Conceptual Design and Component Integration

In an integrated system, the oxygen delivery and vision systems are combined into a single, inseparable head-worn unit. This approach takes a holistic view of the problem, creating one piece of equipment to handle both life support and vision. Key components like the oxygen mask faceplate, a see-through AR display, a micro-camera, and onboard processing electronics are all physically and functionally unified. The goal is a seamless, all-in-one emergency device.

4.1.2. Case Study: Klatt Works SAVED System

A practical, real-world example of the integrated architecture can be seen in the Smoke Assured Vision Enhanced Display (SAVED) system, developed by Klatt Works [72]. This system is a retrofit module that connects directly to existing, certified pilot oxygen masks. It uses dual 720p high-resolution displays to project flight symbology and a video feed from a nose-mounted camera onto a see-through combiner inside the mask. This setup allows a pilot to see critical flight information and maintain an external view even when the cockpit is full of smoke. The system has already earned a Supplemental Type Certificate (STC) for several Boeing transport aircraft, including the 777, 767, and 757. With certifications for other aircraft types in progress, it has demonstrated a viable and accepted path to regulatory approval.

4.1.3. System-Level Advantages and Disadvantages

Advantages:

- Optimized Human Factors: The biggest advantage of this approach is how much it simplifies the emergency procedure. A pilot only needs to perform one single, streamlined action to get

Table 2: Comparative Matrix of Flight Crew Protective Equipment

Criterion	**Oxygen Mask & Goggles**	**Integrated Smoke Hood (PBE)**	**Inflatable Vision Unit (EVAS)**
Donning Time & Complexity	5-15 seconds (target); High complexity, multi-step sequence. High potential for error under stress.	<15 seconds; Low complexity, single-unit action. Highly robust and error-resistant.	<30 seconds (inflation); Low complexity deployment. Requires coordination with mask donning.
Communication Intelligibility (Internal/External)	Poor to Fair. Severely degraded by breathing noise and physical muffling, impacting crew coordination and ATC comprehension.	Fair (Internal). Allows for oral speech but is muffled. Not integrated with external aircraft radios.	N/A. Dependent on the underlying breathing equipment being used (i.e., Poor to Fair with standard mask).
Field of View (FoV)	Good to Fair. Potentially restricted by goggle frame. Susceptible to fogging and smoke ingress if seal is poor.	Excellent (Peripheral). Wide, panoramic view (e.g., 270°). Can be subject to optical distortion from flexible visor.	Severely Restricted. Induces ”tunnel vision,” eliminating all peripheral view.
Cognitive Burden	High. Managing degraded communications, complex donning, and potential visual obstructions adds significant mental workload.	Moderate. Simple to use, but potential for claustrophobia and auditory isolation. Managing heat buildup.	Moderate to High. Eliminates visual search burden in smoke but adds workload for scanning via head/unit movement.
Physiological Burden	Low. Minimal physical stress beyond the pressure of the face seal.	Moderate to High. Potential for significant heat stress and humidity buildup. Risk of claustrophobia.	Low. Minimal physical burden.
Task Compatibility (Pilot Flying)	Primary system. Required for radio communication, despite flaws.	Unsuitable. Lack of radio integration and potential for auditory/visual distortion.	Supplemental system. Essential for maintaining instrument reference in dense smoke but impairs full panel scan.
Task Compatibility (Firefighting)	Poor. Cumbersome two-piece system with potential for poor seal and entanglement.	Excellent. Designed for this role. Provides full head protection, portability, and robust contamination seal.	N/A. Not a protective device; used only from a fixed seat.
Primary Protection Method	Respiratory (100% O2) & Vision (sealed goggles).	Respiratory (self-contained O2) & Full Head/Vision Protection (sealed hood).	Vision Preservation via Smoke Displacement.

both their life support and vision system working. This drastically reduces their cognitive load and the time it takes to get the equipment running in a high-stress situation.

- Guaranteed Alignment: Because the optics are built directly into the mask's structure, the system guarantees a perfect and repeatable alignment. The oxygen mask's seal on the pilot's face will always line up correctly with the display's optical path. This gets rid of the risk that the two pieces of gear could interfere with each other or become misaligned, which could compromise either the oxygen seal or the pilot's ability to see clearly.
- Simplified Unit Certification: Since the system is a self-contained unit, it can be tested and certified as a single piece of equipment. This could potentially make the airworthiness approval process for the device itself much simpler.

Disadvantages:

- Single Point of Failure: The tight integration of life support and vision systems also creates a critical single point of failure. If any electronic component fails, whether it is the display, the processor, or the power supply, the entire vision system becomes useless. This reality pushes the reliability and integrity requirements for the electronic components to an extremely high level.
- Increased Head-Worn Weight and Bulk: Putting all the necessary components like displays, optics, and processors directly onto the mask makes it heavier and can shift its center of gravity. This can cause pilot fatigue and neck strain, especially if it is used for a long time or under G-forces, a problem well-documented with military HMDs [73].
- Thermal Management Challenges: Concentrating power-hungry components like processors and bright displays inside an enclosed, head-worn unit creates a major challenge for managing heat. If that heat is not dissipated effectively, it can lead to component degradation, system failure, and discomfort or even injury to the user [74].
- Higher Lifecycle and Upgrade Costs: The all-in-one design means that the entire unit has to be replaced or go through a major recertification just to upgrade a single part, like a better display or a faster processor. Over the long term, this can lead to higher lifecycle costs when compared to a more modular system.

4.2. Conjunctive Systems (Standalone HMD & Oxygen Mask)

4.2.1. Conceptual Design and Modularity

The conjunctive architecture takes a fundamentally different approach, keeping the vision system and the life support system as two distinct pieces of equipment. In this model, a standalone Augmented or Virtual Reality Head-Mounted Display is designed to be used concurrently, or "in conjunction," with a standard, certified pilot oxygen mask. This modular philosophy allows each component to be developed, certified, and upgraded independently of the other.

4.2.2. Illustrative Examples: AerAware and F-35 HMDS

The viability of this concept can be illustrated by looking at two technologies from different ends of the aerospace spectrum.

- AerAware: Developed by Universal Avionics and AerSale, the AerAware system is an FAA-certified Enhanced Flight Vision System (EFVS) for the Boeing 737NG [75]. Its architecture, which pairs a high-transparency AR display (the SkyLens HWD) with a powerful, externally mounted camera system, shows that a high-performance, certified HMD can be designed to work alongside other cockpit equipment. While it is marketed for improving visibility in bad weather, the core design could be adapted for a smoke-in-cockpit scenario. The key engineering challenges would be ensuring the HMD fits perfectly over an oxygen mask without interfering with its seal, and confirming that its sensors can effectively penetrate dense smoke.
- F-35 Gen III Helmet Mounted Display System (HMDS): While it is a military system of far greater complexity, the F-35 helmet serves as a high-fidelity benchmark for what a standalone HMD can do [76–78]. It completely replaces the traditional Head-Up Display (HUD), projecting all flight data and sensor imagery directly onto the pilot's visor. Its most revolutionary feature is a network of six infrared cameras around the aircraft that are stitched together to give the pilot a seamless 360-degree view, literally allowing them to "look through" the floor of the plane. A civil system could use a simplified version of this idea: a standalone HMD fed by external sensors, designed from the start to be compatible with a separate oxygen mask.

4.2.3. System-Level Advantages and Disadvantages

Advantages:

- Modularity and Flexibility: The HMD and oxygen mask can be developed and upgraded on separate tracks. An airline could adopt a next-generation HMD without having to replace its entire inventory of certified oxygen masks. This provides greater flexibility and could lead to lower lifecycle costs.
- Leverages Existing Certified Technology: This approach can be built on the foundation of already-certified technologies like the AerAware HMD and the standard pilot oxygen masks that have been in use for decades. This could potentially reduce development risk and shorten the timeline for certification.
- Distributed Weight and Thermal Load: With a modular system, critical components like processing units and power supplies can be located in an avionics rack instead of on the pilot's head. This dramatically reduces the weight a pilot has to wear, improves comfort, and makes it much easier to manage the heat generated by the electronics.

Disadvantages:

- Complex Donning Procedure: From a human factors perspective, the main drawback is the need for two separate actions in an emergency. A pilot must first put on their oxygen mask and then, as a second step, place the HMD over it. This adds complexity and takes more time to get the full system up and running.
- Interface and Seal Integrity: The biggest engineering challenge for this approach is to design a perfectly synergistic and non-interfering fit between the HMD and the oxygen mask [79]. The design must absolutely guarantee that the HMD's harness and structure will not compromise the critical seal of the oxygen mask under any circumstances. Solving this hardware and human factors interface is a crucial part of the system's development [80].

- Optical Alignment Challenges: It is very difficult to ensure a precise and repeatable alignment between the HMD's virtual display and the pilot's eyes, especially when both pieces of equipment are being put on under extreme stress. Even a small misalignment can cause parallax errors, visual discomfort, or spatial disorientation, which would make the system less effective when it is needed most.

4.3. Immersive Systems (VR Headset)

4.3.1. Conceptual Design and Synthetic World Generation

The immersive system represents the most radical departure from traditional cockpit design. This approach uses a fully enclosed Virtual Reality (VR) headset that completely blocks out all light from the real world, entirely replacing a pilot's natural vision with a computer-generated synthetic environment. The foundation of this virtual world is a high-fidelity Synthetic Vision System (SVS) database, which is driven by precise data from the aircraft's GPS and Inertial Navigation System (INS). This primary view can then be augmented with real-time information from other sensors, like radar, to show nearby traffic or obstacles that are not in the database. In this setup, the pilot wears a separate, low-profile oxygen mask underneath the VR headset.

4.3.2. Conceptual Case Study: Adaptation of Full Flight Simulator Technology

Although no immersive system is certified for in-cockpit use today, a high-fidelity benchmark for the technology already exists in modern Full Flight Simulators (FFS) from companies like CAE and L3Harris. These simulators generate a complete, high-resolution, 360-degree synthetic world that totally replaces a pilot's view of the outside. They have already perfected the core technologies that an immersive architecture would need:

- High-Integrity Synthetic Vision: The terrain and obstacle databases used in FFS are certified, high-resolution, and identical to what an SVS would require.
- Real-Time Rendering: They use powerful image generators that can render the synthetic world at high frame rates with very little latency, which is critical for preventing disorientation.
- Pilot Acceptance: Thousands of pilots already spend hours training in these fully immersive environments. This proves that flying in a purely synthetic world is fundamentally viable from a human factors standpoint.

From an engineering perspective, creating a certifiable immersive system for the cockpit is really a challenge of miniaturizing and hardening this mature, ground-based technology. The goal is to fit it into a reliable, head-worn device that can meet the extremely strict integrity requirements of DO-178C and DO-254.

4.3.3. System-Level Advantages and Disadvantages

Advantages:

- Total Elimination of Visual Obscurants: The most powerful advantage of this approach is that it makes smoke, fumes, or glare completely irrelevant. It guarantees a pilot a perfect, high-contrast, “clear day” view of the outside world, no matter what the actual conditions are inside or outside the cockpit.

- Unlimited Field of Regard: Because the world is synthetically generated, it can be rendered in 360 degrees. This opens the door to capabilities similar to the F-35's Distributed Aperture System. A pilot could look in any direction, even down through the floor or behind the aircraft, and see a synthetic view of the terrain, dramatically enhancing their situational awareness.
- Fully Controlled Visual Environment: By getting rid of all external visual noise, the HMI can be perfectly optimized. There are no competing real-world cues, so the system can be designed to show only the most critical information in the clearest possible way. This has the potential to reduce distraction and a pilot's cognitive load [81].

Disadvantages:

- System Integrity and Reliability Requirements: This architecture's complete dependence on its own systems is its biggest technical and certification challenge. Any failure of the VR system, whether it is a power loss, a processor crash, or a software bug, would cause an immediate and total loss of all visual reference for the pilot, compelling an immediate transition to standby instruments under duress [82].
- Vestibular Mismatch and Cybersickness: A major human factors hurdle is the conflict between what a pilot is seeing and what their body is feeling. The eyes see a stable or moving synthetic world, but the inner ear's vestibular system feels the actual motion of the aircraft. This sensory mismatch is known to cause severe motion sickness, nausea, and disorientation, a condition often called cybersickness [83].
- "Keyhole Effect" and Perceptual Tunneling: While the system gives a pilot an unlimited field of regard (where they can look), the field of view (what they can see at any one moment) is still restricted by the headset's optics. This can create a "keyhole" or "tunnel vision" effect, robbing the pilot of the peripheral vision cues that are so important for maintaining spatial awareness.
- Negative Transfer of Training: There is also a risk that the skills and reflexes a pilot develops while flying in a purely virtual world might not transfer well to the real world. In a worst-case scenario, this could even lead to a negative transfer of training, where a pilot makes an incorrect action after the emergency is over because of habits formed in the virtual environment [83].

The choice between these architectures is not merely technical but strategic, reflecting a balance between near-term feasibility and long-term capability. Ultimately, selecting an architecture comes down to a strategic assessment of different risk-mitigation philosophies and engineering priorities. The Integrated approach focuses on streamlined human factors in a single device but concentrates the risk of electronic failure. The Conjunctive approach uses modularity and existing certified components but creates the challenge of ensuring a perfect interface between two separate systems. The Immersive approach offers the most complete solution for restoring vision but also requires the highest possible level of system integrity. Each path presents its own unique set of complex, but potentially solvable, engineering and certification challenges.

Table 3: Comparison of Advanced Vision System Architectures

Feature	**Integrated System (AR)**	**Conjunctive System (AR)**	**Immersive System (VR)**
Concept	Oxygen mask and AR display are a single, unified unit.	Standalone AR HMD is worn over a standard oxygen mask.	Fully enclosed VR headset replaces outside view; separate oxygen mask.
Donning Procedure	Single action for both oxygen and vision.	Dual action: first mask, then HMD.	Dual action: first mask, then VR headset.
Human Factors (Pros)	Fast, simple donning; guaranteed optical/mask alignment.	Potentially lighter HMD; leverages familiar oxygen mask.	Eliminates all visual distractions; perfect, high-contrast view.
Human Factors (Cons)	Increased head-worn weight and bulk; potential for heat buildup.	Risk of physical interference; complex donning; alignment challenges.	High risk of cybersickness; ”keyhole” perception; potential for negative training transfer.
System Engineering (Pros)	Self-contained unit simplifies device-level certification.	Modular (independent upgrades); leverages existing certified tech; processing can be off-head.	Simplifies sensor requirements (primarily SVS/GPS); immune to obscurants.
System Engineering (Cons)	Single point of failure; monolithic upgrades are costly.	Complex mechanical and electrical integration; alignment integrity.	Total reliance on system integrity; requires unprecedented reliability.
Primary Failure Mode	Loss of entire unit (vision and potentially oxygen monitoring).	Visual misalignment or loss of HMD function; compromised mask seal.	Instantaneous and total spatial disorientation (complete blindness).
Est. TRL (Civil Aviation)	TRL 8-9 (System proven through successful operation)	TRL 6-7 (System prototype demonstrated in operational environment)	TRL 4-5 (Component validation in lab/relevant environment)

5. Core Technology Deep Dive

The effectiveness of any advanced vision system ultimately comes down to the performance and integration of its core technologies. Choosing the right sensors, displays, and optical components is a complex balancing act between performance, reliability, power needs, size, and cost. This section offers a technical analysis of these key building blocks, with a focus on how their specific characteristics impact the system's ability to save lives in a degraded cockpit environment.

5.1. Sensing Modalities for Obscurant Penetration

In a smoke-filled cockpit, the most basic challenge is getting reliable data about the outside world through a medium that is visually opaque. No single sensor technology can do it all; each has its own strengths and weaknesses. For this reason, a robust and certifiable system will have to use a multi-modal sensing approach, combining different sensors and using intelligent fusion algorithms to create a single, high-integrity image for the pilot.

5.1.1. Infrared (LWIR/MWIR)

- Capability: Infrared cameras, also known as thermal imagers, work by detecting the differences in heat radiated by objects. This makes them extremely good at "seeing" through smoke, haze, and darkness, as these obscurants are mostly transparent to thermal energy [84, 85]. An IR camera can clearly pick up the heat signatures from runway lights, airport buildings, terrain, and other aircraft, giving a pilot the critical visual cues they need for an approach and landing. Long-Wave Infrared (LWIR), which operates in the 8-14 micrometer band, is generally better for detecting objects at normal earth temperatures and is more effective at penetrating moisture in the air. Mid-Wave Infrared (MWIR), in the 3-5 micrometer band, can provide a higher resolution image and is more sensitive to hotter objects like jet engines, but it is typically more expensive because the sensor needs to be cryogenically cooled [86].

- Limitations: The main weakness of infrared imaging is a phenomenon called thermal crossover. This happens when an object and its background reach the same temperature, causing the object's thermal signature to blend in and essentially vanish from the IR view [87]. A classic example is a runway at dawn or dusk, when its temperature might perfectly match the surrounding terrain. IR sensors also cannot see color or read painted markings like runway numbers unless there is a temperature difference between the paint and the surface. Finally, they can have trouble telling the difference between materials that have similar thermal properties.

5.1.2. Millimeter-Wave (MMW) Radar

- Capability: MMW radar systems, which usually operate at frequencies between 30 and 300 GHz, have an unmatched ability to penetrate atmospheric obscurants. They can see through dense smoke, fog, rain, and dust far better than IR or visible light sensors [88]. They are also excellent for providing very precise range and velocity data for terrain and obstacles.

- Limitations: The main problem with using MMW radar as a primary vision system has always been its lower angular resolution when compared to optical sensors. This can create a "blurry" or hard-to-interpret image that doesn't have the crispness a pilot needs for precise manual control. Newer high-frequency systems are getting better all the time, but creating a visually intuitive, video-like “picture” for landing is still a major technical challenge [89].

5.1.3. Synthetic Vision System (SVS)

- Capability: An SVS is different because it does not sense the real world at all. Instead, it creates a clean, 3D graphical picture of the outside world. It does this by rendering a high-resolution database of terrain, obstacles, and airports, using the aircraft’s exact position as determined by GPS and an Inertial Navigation System (INS) [90, 91]. The great advantage of an SVS is that it is completely immune to any and all obscurants in the cockpit or atmosphere, always providing a perfect “clear day” view.

- Limitations: The integrity of an SVS display is completely tied to the accuracy of its database and its navigation source. An error in the GPS/INS position or an outdated database can cause the system to show a “convincingly wrong” image. This is a critical danger, as a pilot can easily be misled by a compelling but false picture, leading to spatial disorientation and wrong control inputs. A stark example of this risk comes from an Australian Transport Safety Bureau (ATSB) investigation into a Pilatus PC-12 incident [92, 93]. A bad radio altimeter input made the SVS show the runway rising up to meet the plane. This incident makes it clear that any SVS used for primary flight guidance has to be cross-checked by an independent sensor to guarantee its integrity.

5.1.4. The Imperative of Sensor Fusion

Because each of these sensor types has its own limitations, a safe and reliable vision system cannot rely on just one. The only workable solution is sensor fusion. This approach combines data from multiple, different sensors using sophisticated algorithms, like extended Kalman filters, to create a single, unified, high-integrity picture for the pilot. A well-designed fusion system uses the strengths of each sensor to make up for the weaknesses of the others [94].

- Example Fusion Logic: In a typical setup, the SVS would provide the basic, clear-day synthetic view of the world. The image from the LWIR sensor would be overlaid and fused with it, adding real-time thermal cues that confirm the location of runway lights, spot other aircraft from their hot engines, or identify hazards on the ground that are not in the database. The MMW radar would serve as a powerful, all-weather integrity check, constantly verifying the aircraft’s position against the terrain database and detecting any large obstacles that are not supposed to be there. The fusion algorithm’s job is to continuously evaluate the confidence level of each sensor’s input and weigh them accordingly to generate the final, trusted image that the pilot sees [95].

Table 4: Comparison of Sensing Modalities

Modality	**Smoke Penetration**	**Resolution**	**Update Rate**	**Day/Night Capability**	**Detects Painted Markings**	**Primary Limitation**	**Integrity Check Role**
LWIR	Excellent	High	High	Yes	No	Thermal Crossover	Good (Confirms thermal signatures)
MWIR	Good	Very High	High	Yes	No	Cost; Atmospheric Attenuation	Fair (High-temp targets)
MMW Radar	Superior	Low-Medium	Medium-High	Yes	No	Angular Resolution; Image Intuiveness	Excellent (All-weather position)
SVS	Immune	Very High	High	Yes	Yes	Database/GPS Integrity Failure	None (Requires external check)

5.2. Human-Machine Interface (HMI) for High-Stress Environments

The HMI, which covers the symbology and information shown on the display, is just as critical as the hardware it runs on. In the chaos of a cockpit emergency, the HMI has to be designed for instant understanding and minimal mental effort. It is not a feature-rich primary flight display; it is an emergency lifeline.

5.2.1. Symbology Design Principles for Emergency Operations

- Primacy of Flight Path and Attitude: The most vital information for preventing a loss of control is the aircraft's energy state and its path through the air. For this reason, the flight path vector, a clear attitude indicator or horizon line, airspeed, altitude, and heading must be the largest and most easily understood elements on the display. All other system information is secondary.

- Conformal and Intuitive Symbology: Whenever it makes sense, the symbology should be conformal, meaning it is spatially fixed and overlays the real-world or sensor-view feature it represents [96]. For example, a synthetic box showing the runway landing zone should be drawn directly on top of the IR or SVS image of the runway. This approach reduces the mental workload of trying to merge two different frames of reference, the display symbology and the outside world, into a single picture [97].

5.2.2. Decluttering Strategies and Information Prioritization

Information overload is a direct threat to safety in a high-stress situation. A pilot's attention is a limited resource that must be focused only on the most critical tasks: flying the plane and navigating to a safe landing [98].

- Dedicated Emergency Mode: The system needs to have a simple, one-touch "Emergency" or "Smoke" mode. When a pilot activates it, this mode should instantly declutter the display. It must remove all non-essential information like engine data, communication frequencies, or system status pages, and show only the bare minimum needed for survival: attitude, airspeed, altitude, heading, and a clear flight path to the nearest suitable airport [99].

- Heuristic and Context-Aware Decluttering: A more advanced HMI could use smart automation to manage display clutter based on the phase of flight. For instance, during a final approach, the system could automatically dim or hide navigation data that is no longer needed, helping the pilot focus even more on the flight path vector and runway cues [100].

5.2.3. Mitigating Cognitive Tunneling

While a good HMI can make it easier to read instruments through smoke, it can also introduce a new risk known as cognitive tunneling. This happens when a pilot becomes so focused on the compelling AR symbology that they tune out everything else, including other environmental cues, crew communications, or peripheral information. Dealing with this risk requires a two-part solution that involves both the HMI design and specialized training.

- HMI Design Philosophy: The "Emergency" mode must do more than just declutter. It should be built on design principles that help manage the pilot's attention. This could involve using subtle cues in the peripheral vision or "attentional guides" that gently pull the pilot's awareness back to a broader instrument scan. The idea is to provide a lifeline of critical data without completely capturing the pilot's focus.

- Specialized Training Protocols: Simulator-based training is absolutely essential. Scenarios must be created to specifically train pilots how to use the system correctly in a high-stress environment. This training needs to focus on strategies for dividing attention between the AR display and other aircraft systems, reinforcing crew resource management (CRM) protocols, and practicing the transition to standby instruments in case the system fails.

5.2.4. Future HMI Evolution: The Challenge of Interactive Control

The primary, certifiable job of the HMI described so far is to be a non-interactive, "read-only" lifeline that feeds critical visual data to the pilot. Its core design philosophy is built on simplicity and reliability for the essential task of keeping control of the aircraft.

Looking further down the road, however, a potential second-generation capability could emerge: direct interaction with virtual cockpit controls. This would allow a pilot to use hand gestures to manipulate virtual switches, tune radios, or interact with the flight management system. Such a feature would be invaluable if smoke were to completely hide the physical controls. But getting there means solving the very difficult technical problem of tracking a pilot's hands and fingers through a visually opaque medium.

- Millimeter-Wave (MMW) Radar: MMW radar is the most promising technology for tracking through smoke.
  - Principle: Radar sends out radio waves that can pass through the soot and carbon particles in smoke that block visible and infrared light. These waves bounce off solid objects, like a hand, letting a sensor build a 3D image of its shape and movement.
  - Challenges: The biggest hurdle is getting the extremely high resolution needed to tell individual fingers apart. This would require a sophisticated, high-frequency radar system and complex processing algorithms. While some consumer-grade gesture-recognition radars exist, making a system reliable enough for a safety-critical aviation environment is a huge technological jump.
- Ultrasonic Sensing: This technology uses high-frequency sound waves to create an image.
  - Principle: An emitter sends out sound waves that reflect off objects and return to a microphone. The system then maps the object's location and shape based on these echoes.
  - Challenges: A cockpit fire creates a turbulent, chaotic environment. The dense, swirling smoke and intense heat would severely scatter and distort the sound waves, which would result in a noisy, low-quality, and unreliable image.
- Thermal Imaging: This method uses a long-wave infrared camera to see heat signatures. While thermal cameras have some ability to penetrate smoke, they are not a dependable solution for this particular job.
  - Principle: The camera would try to detect the heat coming from the pilot's hand.
  - Challenges: A cockpit fire throws off a chaotic thermal background. The smoke itself is hot, and surfaces all over the cockpit will be radiating intense, fluctuating heat. In this kind of environment, the thermal signature of a human hand would be effectively

camouflaged, making it almost impossible for a system to reliably pick it out from the background noise.

Given these major technical hurdles, interactive hand tracking should be seen as a long-term research and development goal, not a near-term system requirement. Maturing the sensing and processing technologies to a level of integrity high enough for a safety-critical flight deck will be the next phase in the evolution of emergency vision systems. This work can be pursued once the basic capability of passive vision restoration is successfully fielded.

5.2.5. Building Pilot Trust and Communicating System Integrity

The technical reliability of an advanced vision system is only half the battle. Its true effectiveness depends on the pilot's trust in the information it provides. Human-machine trust is a fragile and dynamic thing. A good HMI must not only present data but also manage a healthy, calibrated level of trust, especially under pressure.

- The Trust Paradox: The system faces two opposite risks. The first is "brittle trust," where a minor, non-critical glitch like a momentary screen flicker causes the pilot to lose all confidence and abandon the system, even if it is still 99% functional. The opposite risk is "over-trust," where a very compelling and normally reliable display lulls a pilot into complacency. This makes them vulnerable to accepting a wrong but plausible image without question.
- HMI for Trust Calibration: To handle these risks, the HMI philosophy must focus on being transparent about the system's health and any uncertainty.
  - Integrity Status Annunciation: The display needs simple, clear symbology that shows the operational status of the vision system and its sensors (SVS, IR, MMW). This lets the pilot know at a glance the basis for the image they are seeing.
  - Graceful Degradation: The HMI must clearly show when the system is working in a degraded mode. For example, if the IR sensor fails, the symbology should change to indicate that the image is now coming only from the SVS. This inherently communicates a change in the data's integrity level, allowing the pilot to adjust their confidence accordingly and cross-check with other information.

6. Regulatory and Certification Pathway

Introducing any new system that a pilot will use as a primary flight reference, especially in an emergency, demands a clear and rigorous path to certification. While advanced AR and VR vision systems are a new type of technology for commercial cockpits, they can be certified within the existing FAA and EASA regulatory frameworks. The strategy involves using established standards and proving that the new system provides a level of safety that is at least equivalent to the systems it helps or replaces.

6.1. Establishing a Certification Basis (FAA/EASA)

A certification basis is the specific set of airworthiness rules that a new design must follow. For a novel piece of equipment like an emergency vision system, this basis will be built by combining existing software and hardware standards, adapting performance standards from related technologies, and making a specific case for an equivalent level of safety.

6.1.1. Applicability of DO-178C and DO-254

These two standards are the bedrock for developing any airborne software and electronic hardware. There is no negotiating compliance.

- DO-178C, Software Considerations in Airborne Systems and Equipment Certification: The software that controls the display, sensor fusion, and HMI symbology is the heart of the system. Since it would be the pilot's only visual reference in an emergency, its failure would be catastrophic. For this reason, it would be classified at the highest criticality level: Design Assurance Level A (DAL A). This level of rigor demands exhaustive testing and verification, including 100% Modified Condition/Decision Coverage (MC/DC) of the code, extensive documentation, and independent reviews at every stage of the software's life.
- DO-254, Design Assurance Guidance for Airborne Electronic Hardware: In the same way, the complex electronic hardware, including the processors, graphics chips, and display drivers, would also need to follow a corresponding DAL A certification process. This requires a structured and verifiable design process to make sure the hardware is robust and reliable in all foreseeable conditions.

It is impossible to overstate what meeting DAL A requirements means for a project. This is not just a technical checklist; it is a massive financial and programmatic commitment that shapes the entire development cycle. The exhaustive verification, traceability, and independent reviews required for this level of integrity can add years to a development schedule and millions of dollars to the cost. This business reality heavily influences system design. The sheer cost and complexity of DAL A certification mean that an architecture with a simpler, more easily verifiable software and hardware design might have a significant commercial advantage, potentially deciding which approach is actually viable to bring to market.

6.1.2. Technical Standard Orders (TSOs) for EFVS/HMDs

No TSO exists today specifically for a smoke-penetrating vision system. However, existing standards for similar technologies give us a valuable head start in defining performance requirements. TSOs for Enhanced Flight Vision Systems, like TSO-C164a, and for Head-Up Displays, like TSO-C113, set the bar for things like display latency, accuracy, symbology, and reliability. These standards, which were written mainly for low-visibility weather operations, would need to be adapted and expanded with specific new requirements for performing in dense smoke and for use as a primary emergency flight reference.

6.1.3. Framework for Demonstrating Equivalent Level of Safety (ELOS)

Because this system is so new, the most probable path to certification will be through an Equivalent Level of Safety (ELOS) finding, which is allowed by regulations like 14 CFR § 21.21(b)(1) [101]. An ELOS finding is granted when a manufacturer can show that even though their design does not literally meet an existing rule, it still provides a level of safety equal to or better than that rule.

The core of the ELOS argument would be a side-by-side risk assessment. The current system, a standard oxygen mask, has no electronic failure modes, but it is almost useless for seeing in a dense smoke event. This makes a catastrophic outcome highly likely, as proven by accidents like UPS Flight 6. The proposed electronic vision system does introduce new, quantifiable ways to fail, such as a power loss or a software bug. The ELOS case must prove through analysis, simulation, and testing that the overall risk to the aircraft is lower with the new system. This means showing that the probability of a safe landing during a smoke event is significantly higher with the advanced vision system than without it, even after factoring in the system's own potential ways of failing.

6.2. Key Certification Hurdles

The path to certifying these systems will be a challenge, and it will require working closely with regulators to get through several key hurdles.

6.2.1. System Integrity and Reliability

The manufacturer must be able to prove that the system is exceptionally robust and that its failure modes are well understood and have been properly addressed.

- Failure Modes and Effects Analysis (FMEA): A complete, bottom-up FMEA is a non-negotiable starting point. This analysis has to systematically identify every possible way each component could fail, from the sensors to the power supply. For each failure, the analysis must then trace the effect it would have on the system and the pilot, and assign it a criticality level.
- Critical Failure Modes: The most hazardous failure modes must get special attention. These include:
  - Total System Failure: A blank screen, which would force the pilot to fall back on other procedures, if that's even possible.
  - Frozen or Lagging Image: A static or delayed image that no longer matches the aircraft's current state, which could easily lead to wrong control inputs.
  - Erroneous but Plausible Image: This is the most dangerous way for a system to fail. It is when the system shows incorrect information that looks right, such as the wrong attitude or position, like what happened in the PC-12 SVS incident. Preventing this requires robust, independent integrity monitoring.
  - Partial Display Failure: The loss of critical symbology, like the airspeed tape or horizon line, while other parts of the display keep working. This could seriously mislead the pilot.

6.2.2. Human Factors Validation

This is arguably the most critical and closely watched part of the certification process. The system cannot be approved on its technical merits alone; it has to be proven usable and effective for line pilots in realistic emergency situations.

- Demonstrating Reduced Cognitive Load: The manufacturer has to provide objective evidence that the system makes the pilot's mental workload lighter, not heavier, during an emergency. This means going beyond just asking pilots what they think and using structured, objective testing [102].
- Proposed Human-in-the-Loop Testing Protocol: A solid validation plan must include high-fidelity, full-mission simulator trials with a statistically meaningful number of line pilots. The protocol would look something like this:

  - Baseline Scenarios: Pilots would fly difficult smoke-in-cockpit emergencies with their vision completely blocked, using only the standard oxygen mask and standby instruments. Key performance data, like flight path deviation and procedure execution times, would be recorded along with workload data from tools like the NASA-TLX survey or heart rate monitoring.
  - System Scenarios: The same pilots would then fly the exact same scenarios using the proposed advanced vision system.
  - Comparative Analysis: The data from both sets of scenarios would be statistically compared to prove objectively that the vision system leads to better performance, lower workload, and a higher rate of successful outcomes. This kind of robust, objective data is what regulatory authorities like the FAA and EASA will need to see in the human factors validation report to provide a quantitative basis for approving the system [103].

6.2.3. Installation Approval (Supplemental Type Certificate)

To install this system on aircraft already in service, a Supplemental Type Certificate (STC) is needed, which brings its own unique set of challenges.

- Physical Integration: The STC process requires approval for every physical change to the aircraft. This includes mounting external sensors like cameras or radar antennas, installing processing units in avionics bays, and all the structural modifications and wiring that go with them.
- Electrical Load and Avionics Interface: The analysis must also prove that the aircraft's electrical system can handle the extra power drain from the vision system in all flight conditions. Engineers must also define and validate the system's connection to existing avionics buses, like ARINC 429, to ensure it gets accurate flight data without interfering with other critical aircraft systems.

Beyond getting the vision system itself certified, securing an STC for its installation is a complex engineering challenge in its own right. Every type of aircraft presents a unique integration puzzle, which means each one needs its own tailor-made and expensive certification program. The process involves detailed aerodynamic analysis to make sure external sensors do not disturb the airflow over the skin of the aircraft. It also requires structural analysis for all the mounting hardware and rigorous testing to confirm a seamless integration with the plane's electrical and avionics systems. The fact that a separate STC program is needed for each target airframe is a major financial and logistical hurdle that will heavily shape the strategy for bringing this technology to market.

Table 5: Key Certification Hurdles and Proposed Validation Strategies

Hurdle	**Description of Hurdle**	**Applicable Regulation/Standard**	**Proposed Validation Method**	**Evidence to be Produced**
System Integrity	Risk of system failure leading to loss of visual reference or display of hazardous misleading information (HMI).	FAR §25.1309, DO-178C/DO-254 (DAL A)	Comprehensive FMEA; Fault injection testing in simulator; Design of independent integrity monitors using dissimilar sensors.	FMEA Report; System Safety Assessment; Software/Hardware Accomplishment Summaries; Integrity Monitor Design Document.
Human Factors	Risk that the system increases cognitive load, is difficult to interpret, or induces disorientation under stress.	AC 25.11, AC 20-167A	High-fidelity, human-in-the-loop simulator trials comparing baseline (mask only) vs. system performance with line pilots.	Human Factors Validation Test Plan & Report; Statistical analysis of pilot performance and workload (NASA-TLX); Pilot questionnaires.
Installation (STC)	Complexity of retrofitting sensors, processors, and displays onto existing aircraft structures and avionics architectures.	FAR Part 21, Subpart E	Detailed installation design; Structural and electrical load analysis; Avionics interface testing in an integration lab.	STC Data Package including engineering drawings, structural analysis reports, electrical load analysis, and ground/flight test plans.
Sensor/Database Integrity	Risk of SVS presenting a ”convincingly wrong” image due to database errors or GPS/INS failure.	TSO-C164a, AC 20-167A	Cross-checking of SVS position with independent sensors (IR/MMW); Database integrity verification process per DO-200A.	Sensor Fusion Integrity Analysis Report; Database Validation Plan and Report.

7. Conclusions and Recommendations

The analysis in this memorandum confirms what the historical record shows: smoke-in-cockpit events are a catastrophic and unresolved threat to aviation safety. The current strategy, which relies on oxygen masks to preserve vision, is fundamentally not enough for the dense, fast-moving smoke conditions seen in key accidents. A complete loss of vision is an unsurvivable event. The maturation of AR and VR technology, however, now offers a viable path to a new safety paradigm, one based on restoring vision rather than just preserving it.

7.1. Summary of Findings

Our analysis confirms that a total loss of vision from dense cockpit smoke is an unsurvivable condition for which current equipment is an inadequate countermeasure. The rise of AR/VR technology presents a viable path toward a new safety paradigm built on vision restoration. A comparative look at the potential architectures shows a complex landscape of trade-offs, with no single approach offering a perfect solution. The best path forward will depend on solving the key safety and engineering challenges that are unique to each design philosophy.

- Integrated AR Systems make a strong case from a human factors perspective by combining life support and vision restoration into a single, quickly-donned unit with guaranteed optical alignment. This holistic design, however, creates a single point of failure in its electronics. It also introduces significant design challenges related to head-worn weight, power, and thermal management that must be solved to meet certification standards.
- Conjunctive AR Systems offer a flexible, modular architecture that separates the certified life-support system from the vision system. This could potentially lower lifecycle costs and distribute head-worn weight. The critical challenge for this approach is designing a robust and reliable physical and functional interface between the HMD and the oxygen mask, ensuring the mask's life-sustaining seal is never compromised during the multi-step donning procedure.
- Immersive VR Systems represent a technologically complete solution, offering a perfect, synthetic view that is immune to all environmental obscurants. The viability of this approach is contingent upon achieving a level of system integrity and reliability far exceeding current standards for avionics. Any failure would result in a complete and instantaneous loss of vision, a catastrophic failure mode that presents a formidable certification challenge.

7.2. Recommendations for Future Research and Development

To speed up the development and adoption of this life-saving technology, the entire aviation ecosystem will need to work together. With that in mind, this section frames the path forward not as a simple roadmap, but as a series of open questions for the industry to solve collaboratively. To encourage a neutral look at all possible solutions, research and development should move forward on parallel tracks that address the unique challenges of each architectural paradigm. A comprehensive R&D strategy should not pick a winner too early, but should instead work to advance the core technologies that all three approaches will need. The following areas represent the most critical challenges where a focused, community-wide research effort could have the greatest impact:

7.2.1. Technology Gaps

- Power Architecture for Head-Worn Systems: A key question for the industry is how to design and certify a highly reliable, redundant power source for head-worn systems. Any investigation must solve the need for an independent, backup battery while making sure the solution does not add an unacceptable amount of weight or heat stress to the pilot's head.
- High-Fidelity MMW Imaging: We need to explore further how much investment and research it would take to advance Millimeter-Wave radar technology so that it can produce high-resolution, high-frame-rate, video-like imagery. An MMW sensor with the clarity of an optical camera would be the ultimate all-weather, smoke-penetrating integrity monitor for an SVS and a powerful sensor in its own right.
- Display System Efficiency: The industry needs a concerted research effort to break the cycle of trade-offs between power, heat, and brightness that currently limits AR display development. This includes research into making waveguide combiners more optically efficient and improving the brightness efficiency of microdisplays like MicroLED and OLED. The goal is to create lightweight, low-power, daylight-viewable HMDs that are suitable for the aviation environment.
- Robust Sensor Fusion Algorithms: A central challenge is still the development of certifiable (DAL A) sensor fusion software that can intelligently combine data from SVS, IR, and MMW sources. A critical part of this research must be to develop HMI principles for handling dangerous conflicts between sensor inputs, ensuring the pilot gets clear and actionable information, not debilitating ambiguity.
- Standardized HMD-Mask Interface Protocols: For Conjunctive Systems, a critical area of research is the creation of a standardized physical and electronic interface for head-worn displays and certified oxygen masks. This would mean creating a design standard, similar to an ARINC or RTCA standard, to ensure that any compliant HMD can be paired with any compliant mask without compromising its seal or function. This would greatly reduce the integration challenge for manufacturers.

7.2.2. Human Factors Research

- Cognitive Performance in Extreme Stress: We need continued high-fidelity simulator studies to better quantify a pilot's cognitive load and performance when using different HMI symbology and decluttering strategies during a smoke-in-cockpit event. The goal is to define an optimized, minimalist HMI standard for emergency use.
- Long-Term Immersive Environment Effects: For future VR-based systems, we need foundational research to understand the long-term physiological and psychological effects on pilots who have to operate for long periods in a fully synthetic world. This includes studies on how to mitigate cybersickness, prevent negative transfer of training, and maintain situational awareness.
- Vestibular-Visual Synchronization in VR: To make Immersive Systems viable, foundational research is needed to solve the problem of cybersickness in the dynamic environment of an aircraft. This work should include developing predictive filtering and motion compensation algorithms that can sync the visual data in the VR headset with the pilot's inner-ear sensations

of aircraft movement. This is essential to make sure the system is physiologically tolerable for extended emergency use.

7.2.3. Regulatory Framework Development

- Establish a New Technical Standard Order (TSO): The aviation community should consider whether a collaborative effort between regulators like the FAA and EASA could lead to the development of a new TSO created specifically for "Emergency Vision Assurance Systems" (EVAS). This proposed category is intended to be distinct from any single trademarked system and would create a regulatory framework for the full spectrum of advanced architectures, from the AR and VR systems to the smoke displacement technologies analyzed in this memorandum. Such a TSO would set minimum performance standards for sensor capability, display latency, system integrity (including failure mode rules), and HMI design principles. A dedicated TSO would harmonize requirements across the industry and streamline the certification process for future systems, giving manufacturers a clear and predictable regulatory path to follow.

Bibliography

[1] Arvind K. Chaturvedi and Donald C. Sanders. *Aircraft fires, smoke toxicity, and survival: An overview.* Tech. rep. FAA/AM-95/08. Washington, D.C.: Federal Aviation Administration, Feb. 1995. URL: `https://www.faa.gov/sites/faa.gov/files/data_research/research/med_humanfacs/oamtechreports/AM95-08.pdf`.

[2] National Transportation Safety Board. *Aircraft Accident Report-Air Canada Flight 797, Mc-Donnell Douglas DC-9-32, C-FTLU, Greater Cincinnati International Airport, Covington, Kentucky, June 2, 1983 (Supersedes NTSB/AAR-84/09).* en. Tech. rep. NTSB/AAR-86/02. Washington, D.C., June 1983.

[3] Jim Burnett. *Safety Recommendation(s) A-83-70 through -81.* Oct. 1983.

[4] Jim Burnett. *Safety Recommendation(s) A-84-76 through -78.* July 1984. URL: `https://www.ntsb.gov/safety/safety-recs/recletters/A84_76_78.pdf`.

[5] Transportation Safety Board of Canada. *Aviation Investigation Report In-Flight Fire Leading to Collision with Water.* en. Tech. rep. A98H0003. Sept. 1998.

[6] *McDonnell Douglas DC-9-32 — Federal Aviation Administration.* Dec. 2022. URL: `https://www.faa.gov/lessons_learned/transport_airplane/accidents/N904VJ`.

[7] *Fugitive Sought in 1996 ValuJet Crash.* en-us. Story. Apr. 2018. URL: `https://www.fbi.gov/news/stories/new-reward-for-fugitive-in-1996-valujet-crash-040518`.

[8] Peter B. Heller. *ValuJet Flight 592 crash investigation — Research Starters — EBSCO Research.* en. 2024. URL: `https://www.ebsco.com`.

[9] National Transportation Safety Board. *In-Flight Fire and Impact with Terrain, ValuJet Airlines Flight 592, Dc-9-32, N904VJ, Everglades, Near Miami, Florida.* en. Tech. rep. NTSB/AAR-97/06. Washington, D.C., Aug. 1997.

[10] Jim Hall. *Safety Recommendation(s) A-97-56 through -77.* Sept. 1997. URL: `https://www.ntsb.gov/safety/safety-recs/recletters/a97_56_77.pdf`.

[11] Transportation Safety Board of Canada. *Swissair Flight 111 Abbreviated Investigation Chronology - Transportation Safety Board of Canada.* eng. Last Modified: 2019-06-14. URL: `https://www.bst.gc.ca/eng/medias-media/fiches-facts/A98H0003/chronology_a98h0003.html`.

[12] *McDonnell Douglas MD-11 — Federal Aviation Administration.* URL: `https://www.faa.gov/lessons_learned/transport_airplane/accidents/HB-IWF`.

[13] Steve Lilley. *SYSTEM FAILURE CASE STUDIES: Wire to Wire.* Feb. 2010. URL: `https://sma.nasa.gov/docs/default-source/safety-messages/safetymessage-2010-02-07-swissair111crash.pdf?sfvrsn=dead1ef8_4`.

[14] Transportation Safety Board of Canada. *Swissair 111 Investigation Report - Executive Summary - Transportation Safety Board of Canada.* eng. Last Modified: 2019-06-14. URL: `https://www.tsb.gc.ca/eng/medias-media/fiches-facts/A98H0003/sum_a98h0003.html`.

[15] General Civil Aviation Authority of the United Arab Emirates. *Uncontained Cargo Fire Leading to Loss of Control Inflight and Uncontrolled Descent Into Terrain.* Tech. rep. AAIS Case Reference: 13/2010. 2022.

[16] VisionSafe. *Special Edition The Loss of Flight 006.* Sept. 2013. URL: `https://www.visionsafe.com/docs/media/smoke/SmokeSignals_SpecialEdition3.pdf`.

[17] *The Dangers of Lithium Battery Fires – And What to Do in Flight.* en-US. URL: `https://nbaa.org/aircraft-operations/safety/in-flight-safety/handling-of-hazardous-materials/lithium-batteries/dangers-lithium-battery-fires-flight/`.

[18] Aircraft and Railway Accident Investigation Board. *Crash Into The Sea After An In-Flight Fire.* Tech. rep. ARAIB/AAR1105. Sept. 2012. URL: `https://skybrary.aero/bookshelf/books/2143.pdf`.

[19] Mark Lacagnina. *In-Flight Inferno.* en-US. Jan. 2016. URL: `https://flightsafety.org/asw-article/in-flight-inferno/`.

[20] National Transportation Safety Board. *Auxiliary Power Unit Battery Fire.* Tech. rep. NTSB/AIR-14/01. Washington, D.C., Nov. 2014. URL: `https://www.ntsb.gov/investigations/AccidentReports/Reports/AIR1401.pdf`.

[21] National Transportation Safety Board. *Airworthiness Group Chairman's Addendum.* Nov. 2014. URL: `https://www.ntsb.gov/investigations/AccidentReports/Documents/Airworthiness_Factual_Addendum.pdf`.

[22] Joseph M Kolly, Joseph Panagiotou, and Barbara A. Czech. *The Investigation of a Lithium-Ion Battery Fire Onboard a Boeing 787 by the US National Transportation Safety Board.* en. Tech. rep. URL: `https://www.isasi.org/resources/Documents/technical-papers/2013/ISASI%20NTSB%20Kolly.pdf`.

[23] *JAL B 787 smoke event at gate.* URL: `https://data.ntsb.gov/Docket/?NTSBNumber=DCA13IA037`.

[24] Ministry Of Civil Aviation. *Final Report EgyptAir A320 Aircraft crash in the Mediterranean.* Tech. rep. EGAI2016-01. Oct. 2024. URL: https://bea.aero/fileadmin/user_upload/SU-GCC.pdf.

[25] Bureau of Enquiry and Analysis for Civil Aviation Safety. *Oxygen fire in cockpit study.* Tech. rep. BEA2016-0093. Dec. 2023. URL: https://bea.aero/fileadmin/documents/etudes/feucockpitEN/BEA2016-0293_OXYGEN-FIRE_study.pdf.

[26] Kyra Dempsey. *Masks, Smoke, and Mirrors: The untold story of EgyptAir flight 804.* en. June 2025. URL: https://admiralcloudberg.medium.com/masks-smoke-and-mirrors-the-untold-story-of-egyptair-flight-804-42c788fcac2d.

[27] *A brief history of our breathing apparatus.* en-GB. URL: https://www.london-fire.gov.uk/museum/london-fire-brigade-history-and-stories/equipment-and-uniforms/a-brief-history-of-our-breathing-apparatus/.

[28] Graham Rood. "A BRIEF HISTORY OF FLYING CLOTHING". en. In: *Journal of Aeronautical History* (Jan. 2014). URL: http://aerosociety.com/Assets/Docs/Publications/The%20Journal%20of%20Aeronautical%20History/2014-01_Rood_Aircrew_clothing.pdf.

[29] E. Arnold Higgins. *Summary Report of the history and events pertinent to the Civil Aeromedical Institute's evaluation of providing smoke/fume protective breathing equipment for airline passenger use.* Tech. rep. FAA/AM-87/05. Washington, D.C.: Federal Aviation Administration, June 1987. URL: https://www.faa.gov/sites/faa.gov/files/data_research/research/med_humanfacs/oamtechreports/AM87-05.pdf.

[30] John A. Vaughn and Kenneth W. Welsh. *Visual evaluation of smoke-protective devices.* Tech. rep. FAA/AM-76/05. Washington, D.C.: Federal Aviation Administration, May 1976. URL: https://www.faa.gov/sites/faa.gov/files/data_research/research/med_humanfacs/oamtechreports/AM76-05.pdf.

[31] John A. Vaughn. *The optical properties of smoke-protective devices.* Tech. rep. FAA/AM-78/41. Washington, D.C.: Federal Aviation Administration, 1978. URL: https://www.faa.gov/sites/faa.gov/files/data_research/research/med_humanfacs/oamtechreports/AM78-41.pdf.

[32] Ernest B. McFadden and Roger C. Smith. *Protective smoke hood studies.* Tech. rep. FAA/AM-70/20. Washington, D.C.: Federal Aviation Administration, Dec. 1970. URL: https://www.faa.gov/sites/faa.gov/files/data_research/research/med_humanfacs/oamtechreports/AM70-20.pdf.

[33] *Crewmember Demand Oxygen Mask.* Technical Standard Orders (TSO). May 2008. URL: https://drs.faa.gov/browse/excelExternalWindow/549B6A1FDC1A968386257451004F88AC.0001.

[34] *Crewmember Oxygen Regulators, Demand.* Technical Standard Orders (TSO). Apr. 2008. URL: https://drs.faa.gov/browse/excelExternalWindow/E0DB1281B9EE9C688625741F00558B6E.0001.

[35] *OXYGEN REGULATORS, DEMAND.* European Technical Standard Order. Oct. 2003. URL: https://www.easa.europa.eu/download/etso/ETSO-C89_CS-ETSO_0.pdf.

[36] *CREWMEMBER DEMAND OXYGEN MASK.* European Technical Standard Order. Feb. 2018. URL: https://www.easa.europa.eu/download/etso/ETSO-C78a_CS-ETSO_13.pdf.

[37] *14 CFR 25.1439 – Protective breathing equipment.* en. URL: https://www.ecfr.gov/current/title-14/part-25/section-25.1439.

[38] *322-72: ZODIAC AEROSPACE Anti-Smoke Goggle Lens, Clear, For Fixed Wing Aircraft.* URL: https://shop.boeing.com/aviation-supply/p/322-72=2J.

[39] *Aerox Smoke Goggles.* en. URL: https://www.mypilotstore.com/mypilotstore/sep/9346.

[40] *Sweep On 2000.* en. URL: https://www.collinsaerospace.com/what-we-do/industries/business-aviation/cabin/oxygen-and-psu-systems/crew-oxygen-systems/crew-masks/sweep-on-2000.

[41] Ian Blair Fries. *Oxygen masks 101.* en. Text. Jan. 2016. URL: https://www.aopa.org/news-and-media/all-news/2016/september/pilot/oxygen-masks-101.

[42] Clinton Crookshanks. *Aviation Investigation Final Report.* Tech. rep. ENG08IA011. Federal Aviation Administration, Aug. 2008. URL: https://data.ntsb.gov/carol-repgen/api/Aviation/ReportMain/GenerateNewestReport/76023/pdf.

[43] Benjamin Elie et al. "Modeling the Effect of Military Oxygen Masks on Speech Characteristics". en. In: *Interspeech 2021.* ISCA, Aug. 2021, pp. 3306–3310. DOI: 10.21437/Interspeech.2021-1650. URL: https://www.isca-archive.org/interspeech_2021/elie21_interspeech.html.

[44] *14 CFR 121.337 – Protective breathing equipment.* en. URL: https://www.ecfr.gov/current/title-14/part-121/section-121.337.

[45] Hugh Tillman. *Cockpit Smoke - AVweb.* en-US. Section: Features. Sept. 2020. URL: https://avweb.com/features/cockpit-smoke/.

[46] Deborah Hersman. *Safety Recommendation(s) A-11-87 through -91.* Sept. 2011. URL: https://www.ntsb.gov/safety/safety-recs/recletters/A-11-087-091.pdf.

[47] Victor Wicklund and Michael Romanowski. *PS-AIR-25.1441-03.* Policy Statement. URL: https://www.faa.gov/sites/faa.gov/files/2022-08/PS-AIR-25.1441-03_0.pdf.

[48] *Serious incident to the Cessna Citation 525B registered F-HCIC on 22 July 2013 at 10 NM north west of Paris Orly airport climbing through FL 180.* en. Investigation Report f-ic13072.en. Oct. 2018. URL: https://bea.aero/uploads/tx_elydbrapports/f-ic130722.en.pdf.

[49] Wonsup Lee et al. "Ergonomic Design and Evaluation of a Pilot Oxygen Mask". en. In: *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* 57.1 (Sept. 2013), pp. 1673–1677. ISSN: 1071-1813, 2169-5067. DOI: 10.1177/1541931213571371. URL: https://journals.sagepub.com/doi/10.1177/1541931213571371.

[50] Federal Aviation Administration. *Pilot Vision.* URL: https://www.faa.gov/pilots/safety/pilotsafetybrochures/media/pilot_vision.pdf.

[51] Frank Albers et al. "The effects of wearing pilots' oxygen masks on cognitive performance". en. In: *Ergonomics* (June 2025), pp. 1–11. ISSN: 0014-0139, 1366-5847. DOI: 10.1080/00140139.2025.2511871. URL: https://www.tandfonline.com/doi/full/10.1080/00140139.2025.2511871.

[52] *Large Aeroplanes.* en. Certification Specification. June 2021. URL: https://www.easa.europa.eu/en/document-library/certification-specifications/group/cs-25-large-aeroplanes.

[53] *Protective Breathing Equipment.* en. URL: `https://www.collinsaerospace.com/what-we-do/industries/business-aviation/cabin/oxygen-and-psu-systems/portable-oxygen-systems/protective-breathing-equipment/protective-breathing-equipment`.

[54] *PROTECTIVE BREATHING EQUIPMENT (PBE).* URL: `https://essexindustries.com/products/protective-breathing-equipment-pbe/`.

[55] *Smoke Hoods.* URL: `https://skybrary.aero/articles/smoke-hoods`.

[56] Essex Industries. *Crewmember Protective Breathing Equipment (PBE).* Aug. 2015. URL: `http://www.essexindustries.com/wp-content/uploads/2016/02/Original-PBE-PRM-01-Rev-21-Date-8-28-15.pdf`.

[57] Essex Industries. *PROTECTIVE BREATHING EQUIPMENT.* URL: `https://essexindustries.com/wp-content/uploads/2019/09/PBE-Brochure-2019.pdf`.

[58] Jerry Davis et al. "Developing Empirical Donning Times for Smoke Hoods". en. In: *Athens Journal of Technology & Engineering* 2.4 (Nov. 2015), pp. 231–240. ISSN: 22418237. DOI: `10.30958/ajte.2-4-1`. URL: `https://www.athensjournals.gr/technology/2015-2-4-1-Davis.pdf`.

[59] *Proximity suits and heat stress: How to prevent it?* en-US. Oct. 2021. URL: `https://otegotextile.com/news/prevent-heat-stress-in-proximity-suits/`.

[60] *Cockpit Smoke Hoods.* en-US. Section: Equipment Reviews. May 2008. URL: `https://avweb.com/features_old/cockpit-smoke-hoods/`.

[61] European Aviation Safety Agency. *ETSO approval for CS-ETSO applicable to Protective Breathing Equipment (ETSO-C99).* Consultation Paper ETSO.Dev.C99#1. Sept. 2007.

[62] *Flight Deck (Sedentary) Crewmember Protective Breathing Equipment.* Technical Standard Orders (TSO). June 2008. URL: `https://drs.faa.gov/browse/excelExternalWindow/B3135D7ADDCB0C2D8625745D00530B2F.0001`.

[63] *Crewmember Portable Protective Breathing Equipment.* `https://drs.faa.gov/browse/excelExternalWindow/2D1AC8B163160D45862576030070A93F.0001`. Technical Standard Orders (TSO). July 2009.

[64] *CREWMEMBER PROTECTIVE BREATHING EQUIPMENT.* European Technical Standard Order. Oct. 2024. URL: `https://www.easa.europa.eu/download/etso/ETSO-C116_CS-ETSO_0.pdf`.

[65] *Mitigations : FAA Cargo Fire Safety.* URL: `https://www.fire.tc.faa.gov/CargoSafety/Hazards/3-Lithium_Ion_Batteries_Shipped_In_Bulk_UN_3480/Operational_Risks/1-Cargo_on_Freighter_Aircraft/Mitigations/2-Flight_Deck_Smoke_Protection`.

[66] VisionSafe Corporation. *EVAS.* URL: `https://flightsafety.org/wp-content/uploads/2018/09/VisionSafe-Corporation-EVAS-Exh-Website.pdf`.

[67] Fernando Vargas-Martín and Eli Peli. "Eye movements of patients with tunnel vision while walking". eng. In: *Investigative Ophthalmology & Visual Science* 47.12 (Dec. 2006), pp. 5295–5302. ISSN: 0146-0404. DOI: `10.1167/iovs.05-1043`.

[68] Alexander J Baughman, Kyoung Jae Kim, and Andrew F J Abercromby. "Assessments of Physiology And Cognition in Hybrid-reality Environments (APACHE) – Physical Workload Approximation". en. In: *51st International Conference on Environmental Systems* (July 2022). URL: `https://ttu-ir.tdl.org/bitstreams/6bca837e-2ada-4c04-9ce1-2f5867ec3304/download`.

[69] Federal Aviation Administration. *AC 25-9A - Smoke Detection, Penetration, and Evacuation Tests and Related Flight Manual Emergency Procedures.* Jan. 1994. URL: `https://www.faa.gov/documentLibrary/media/Advisory_Circular/AC_25-9A.pdf`.

[70] Mark Huber. *VisionSafe EVAS Now On More Than 1,000 Gulfstreams.* en. Oct. 2019. URL: `https://www.ainonline.com/aviation-news/general-aviation/2019-10-20/visionsafe-evas-now-more-1000-gulfstreams`.

[71] *VisionSafe Frequently Asked Questions.* URL: `https://www.visionsafe.com/faqs.html`.

[72] *SAVED.* URL: `https://www.klattworks.com/saved/`.

[73] *HMDs: Helmet Mounted Display.* en. URL: `https://www.baesystems.com`.

[74] Alexandra Watkins et al. *Immersive and Wearable Thermal Rendering for Augmented Reality.* arXiv:2503.20646 [cs]. Mar. 2025. DOI: `10.48550/arXiv.2503.20646`. URL: `http://arxiv.org/abs/2503.20646`.

[75] *AerAware EFVS.* URL: `https://universalavionics.com/home/products/enhanced-vision/aeraware-efvs`.

[76] *HMDS Helmet Mounted Display System.* URL: `https://www.jsf.mil/hmds`.

[77] *Joint Strike Fighter F-35 Helmet Mounted Display System.* URL: `https://www.elbitsystems.com/air-space/aircraft-systems/helmet-mounted-display/joint-strike-fighter-f-35`.

[78] *F-35 Gen III Helmet Mounted Display System.* en. URL: `https://www.collinsaerospace.com/what-we-do/industries/military-and-defense/displays-and-controls/airborne/helmet-mounted-displays/f-35-gen-iii-helmet-mounted-display-system`.

[79] Clarence E. Rash et al. *Helmet-Mounted Displays: Sensation, Perception and Cognition Issues: (614362011-001).* en. Institution: American Psychological Association. 2009. DOI: `10.1037/e614362011-001`. URL: `https://doi.apa.org/doi/10.1037/e614362011-001`.

[80] J. Rieneke C. Schreinemakers et al. "Oxygen mask related nasal integument and osteocartilagenous disorders in F-16 fighter pilots". eng. In: *PloS One* 8.3 (2013), e56251. ISSN: 1932-6203. DOI: `10.1371/journal.pone.0056251`.

[81] Agnieszka A. Tubis et al. "Risk Assessment for the Development of Emergency Scenarios for Tram Driver Training". en. In: *Applied Sciences* 14.22 (Nov. 2024), p. 10444. ISSN: 2076-3417. DOI: `10.3390/app142210444`. URL: `https://www.mdpi.com/2076-3417/14/22/10444`.

[82] Robert L Thomas, Jorge L. D. Albelo, and Michael Wiggins. "Enhancing Pilot Training Through Virtual Reality: Recognizing and Mitigating Aviation Visual and Vestibular Illusions". en. In: *International Journal of Aviation, Aeronautics, and Aerospace* 10.3 (Jan. 2023). ISSN: 2374-6793. DOI: `10.58940/2374-6793.1839`. URL: `https://commons.erau.edu/ijaaa/vol10/iss3/10`.

[83] Tim Marron et al. "Virtual Reality & Pilot Training: Existing Technologies, Challenges & Opportunities". en. In: *Journal of Aviation/Aerospace Education & Research* 33.1 (2024). URL: `https://commons.erau.edu/jaaer/vol33/iss1/1/`.

[84] *Advantages of LWIR and MWIR.* URL: `https://www.gst-ir.net/news-events/infrared-knowledge/389.html`.

[85] John Oncea. *SWIR, MWIR, And LWIR: One Use Case For Each.* Aug. 2023. URL: `https://www.photonicsonline.com/doc/swir-mwir-and-lwir-one-use-case-for-each-0001`.

[86] *The Differences Between SWIR, MWIR, and LWIR Cameras.* en-US. Jan. 2023. URL: `https://www.axiomoptics.com/blog/the-differences-between-swir-mwir-and-lwir-cameras/`.

[87] V. Dhar et al. "Comparison of the performance of LWIR and MWIR thermal imagers for varying ambient temperature and humidity conditions". In: Orlando, Florida, United States, May 2011, 80140P. DOI: `10.1117/12.884372`. URL: `http://proceedings.spiedigitallibrary.org/proceeding.aspx?doi=10.1117/12.884372`.

[88] *Vision: Possible.* en-US. URL: `https://www.ti.com/about-ti/newsroom/company-blog/vision-possible.html`.

[89] Yair Richter and Nezah Balal. "High-Resolution Millimeter-Wave Radar for Real-Time Detection and Characterization of High-Speed Objects with Rapid Acceleration Capabilities". en. In: *Electronics* 13.10 (May 2024), p. 1961. ISSN: 2079-9292. DOI: `10.3390/electronics13101961`. URL: `https://www.mdpi.com/2079-9292/13/10/1961`.

[90] Russell V Parrish et al. *Aspects of Synthetic Vision Display Systems and the Best Practices of the NASA's SVS Project.* en. Technical Publication TP-2008-215130. National Aeronautics and Space Administration, May 2008. URL: `https://ntrs.nasa.gov/citations/20080018605`.

[91] E Bailey and V Parrish. *Technical Challenges In the Development of a NASA Synthetic Vision System Concept.* en. Technical Memorandum TM-20020094319. National Aeronautics and Space Administration, Jan. 2002. URL: `https://ntrs.nasa.gov/citations/20020094319`.

[92] *Synthetic vision display error involving Pilatus PC-12, VH-OWA, Meekatharra Airport, Western Australia, 18 June 2016.* ATSB Transport Safety Report AO-2016-064. Canberra, Australia: Australian Transport Safety Bureau, Jan. 2017. URL: `https://www.atsb.gov.au/publications/investigation_reports/2016/aair/ao-2016-064`.

[93] *Confusion of Compelling, But Erroneous, PC-12 Synthetic Vision Display.* en. Jan. 2017. URL: `https://aerossurance.com/safety-management/pc12-synthetic-vision-failure/`.

[94] Takuma Nakamura et al. "Vision Sensor Fusion for Autonomous Landing". en. In: *AIAA Information Systems-AIAA Infotech @ Aerospace.* Grapevine, Texas: American Institute of Aeronautics and Astronautics, Jan. 2017. ISBN: 978-1-62410-449-7. DOI: `10.2514/6.2017-0674`. URL: `https://arc.aiaa.org/doi/10.2514/6.2017-0674`.

[95] Kun Yue. "Multi-sensor data fusion for autonomous flight of unmanned aerial vehicles in complex flight environments". en. In: *Drone Systems and Applications* 12 (Jan. 2024), pp. 1–12. ISSN: 2564-4939. DOI: `10.1139/dsa-2024-0005`. URL: `https://cdnsciencepub.com/doi/10.1139/dsa-2024-0005`.

[96] Ofer Klein et al. "Use of 3D conformal symbology on HMD for a safer flight in degraded visual environment". In: Baltimore, Maryland, USA, May 2012, 83600Q. DOI: `10.1117/12.918871`. URL: `http://proceedings.spiedigitallibrary.org/proceeding.aspx?doi=10.1117/12.918871`.

[97] Kristen K Liggett. “The Effects of Helmet-Mounted Display Symbology on the Opto-Kinetic Cervical Reflex and Frame of Reference”. en. In: *RTO HFM Symposium* RTO-MP-086 (Apr. 2002). URL: `https://www.faa.gov/sites/faa.gov/files/about/office_org/headquarters_offices/avs/MP-086-44.pdf`.

[98] Max Friedrich and Mark Vollrath. “Human–Machine Interface Design for Monitoring Safety Risks Associated with Operating Small Unmanned Aircraft Systems in Urban Areas”. en. In: *Aerospace* 8.3 (Mar. 2021), p. 71. ISSN: 2226-4310. DOI: `10.3390/aerospace8030071`. URL: `https://www.mdpi.com/2226-4310/8/3/71`.

[99] Mark St. John et al. “Heuristic Automation for Decluttering Tactical Displays”. en. In: *Human Factors: The Journal of the Human Factors and Ergonomics Society* 47.3 (Sept. 2005), pp. 509–525. ISSN: 0018-7208, 1547-8181. DOI: `10.1518/001872005774860014`. URL: `https://journals.sagepub.com/doi/10.1518/001872005774860014`.

[100] Thomas Münsterer et al. “Sensor-enhanced 3D conformal cueing for safe and reliable HC operation in DVE in all flight phases”. In: ed. by Jeff J. Güell and Jack Sanders-Reed. Baltimore, Maryland, USA, June 2014, p. 90870I. DOI: `10.1117/12.2050377`. URL: `http://proceedings.spiedigitallibrary.org/proceeding.aspx?doi=10.1117/12.2050377`.

[101] *Final Equivalent Level of Safety ELOS-VLA.0991-01 (and ELOS-EVLA.0991), Fuel Pumps*. Equivalent Safety Finding. European Union Aviation Safety Agency, 2022. URL: `https://www.easa.europa.eu/en/document-library/product-certification-consultations/final-equivalent-level-safety-elos-vla0991-01`.

[102] Kelene A. Fercho et al. *Federal Aviation Administration Aircraft Evaluation Division Operations and Human Factors Evaluation Aid for Enhanced Flight Vision Systems*. en. Tech. rep. Medium: application/pdf. Federal Aviation Administration: Office of Aerospace Medicine, Nov. 2024. DOI: `10.21949/1527442`. URL: `https://rosap.ntl.bts.gov/view/dot/85381`.

[103] Lawrence J Prinzel III et al. *Human Factors Research Needs for In-Time Aviation Safety Management Systems (IASMS) Design: Enabling the NASA “Sky for All” Future Airspace Vision*. en. Technical Memorandum TM-20230002092. National Aeronautics and Space Administration, Feb. 2023. URL: `https://ntrs.nasa.gov/api/citations/20230002092/downloads/Prinzel_HFES_2023_Final_Proposal_v2.pdf`.