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Simulation of the Passenger and Crew Exposure Resulting from the Thermal Runaway of Portable Electronic Devices in the Cabin and Cockpit †

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Abstract

Passengers routinely carry numerous Portable Electronic Devices (PEDs) powered by lithium-ion batteries, which present hazards when subjected to thermal runaway, including emission of toxic gases, smoke generation and potential fires. The LOKI-PED project investigates the severity of such events in aircraft cabins by experimentally characterizing combustion gases, validating a zonal cabin model and predicting exposure to harmful substances and smoke. PEDs were deliberately forced into thermal runaway in both burn chamber and A320 cabin mockup tests, enabling the quantification of emitted carbon dioxide and toxic compounds such as carbon monoxide, formaldehyde, hydrogen fluoride, and hydrogen chloride. These measurements were correlated to CO_2 peak concentrations, enabling a factor-based scaling approach for full-scale cabin simulations. A validated zonal model was then used to predict the temporal and spatial spread of gases and smoke in the cabin, cockpit and galley. Results show that while cabin ventilation generally keeps exposure below harmful levels, the cockpit and galley are significantly more vulnerable. The study highlights the importance of rapid crew response, limitations on PED battery capacities and operational mitigation strategies to ensure flight safety.

Keywords: thermal runaway; lithium-ion battery; portable electronic device (PED); cabin; cockpit; exposure; zonal simulation

1. Introduction

Modern air travel involves the widespread presence of portable electronic devices (PEDs) such as smartphones, tablets, laptops, e-book readers, power banks and smartwatches, all powered by lithium-ion batteries. These batteries are favored for their high energy density but present hazards when subjected to failure. Lithium-ion cells can overheat, swell, vent flammable and toxic gases, ignite or even explode. In the confined environment of an aircraft, such events pose significant risks to passengers, crew and the safe operation of the flight. While the release of harmful substances during a lithium-ion thermal runaway event is well documented, the manner in which these gases dilute and spread inside an aircraft is insufficiently understood. Ventilation systems, airflow patterns, cabin volume and passenger proximity all influence exposure levels. During thermal runaway, devices emit a mixture of combustion gases including carbon dioxide, carbon monoxide, formaldehyde, hydrogen fluoride, hydrogen chloride and other substances

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that can reach harmful concentrations depending on the size of the space and available ventilation. Understanding how these gases disperse, how quickly dangerous thresholds are reached and how smoke affects visibility is therefore essential. The LOKI-PED project addresses these knowledge gaps by conducting a comprehensive investigation combining PED thermal runaway tests, full-scale cabin tracer gas measurements and zonal modeling of gas dispersion [1]. The project quantifies hazardous substances emitted by PED thermal runaway, establishes correlations between CO_2 and toxic compounds, and validates a zonal cabin model capable of predicting exposure and visibility loss under various cabin, cockpit and galley conditions.

2. Methodology

Several thermal runaway investigations performed by the FAA have provided valuable qualitative insight into PED behavior [2]. However, these studies generally lack the quantitative data necessary to predict how vented gases spread throughout an aircraft cabin. To address this limitation, the LOKI-PED project employs a multi-step methodology to obtain quantitative exposure data and establish predictive correlations (Figure 1).

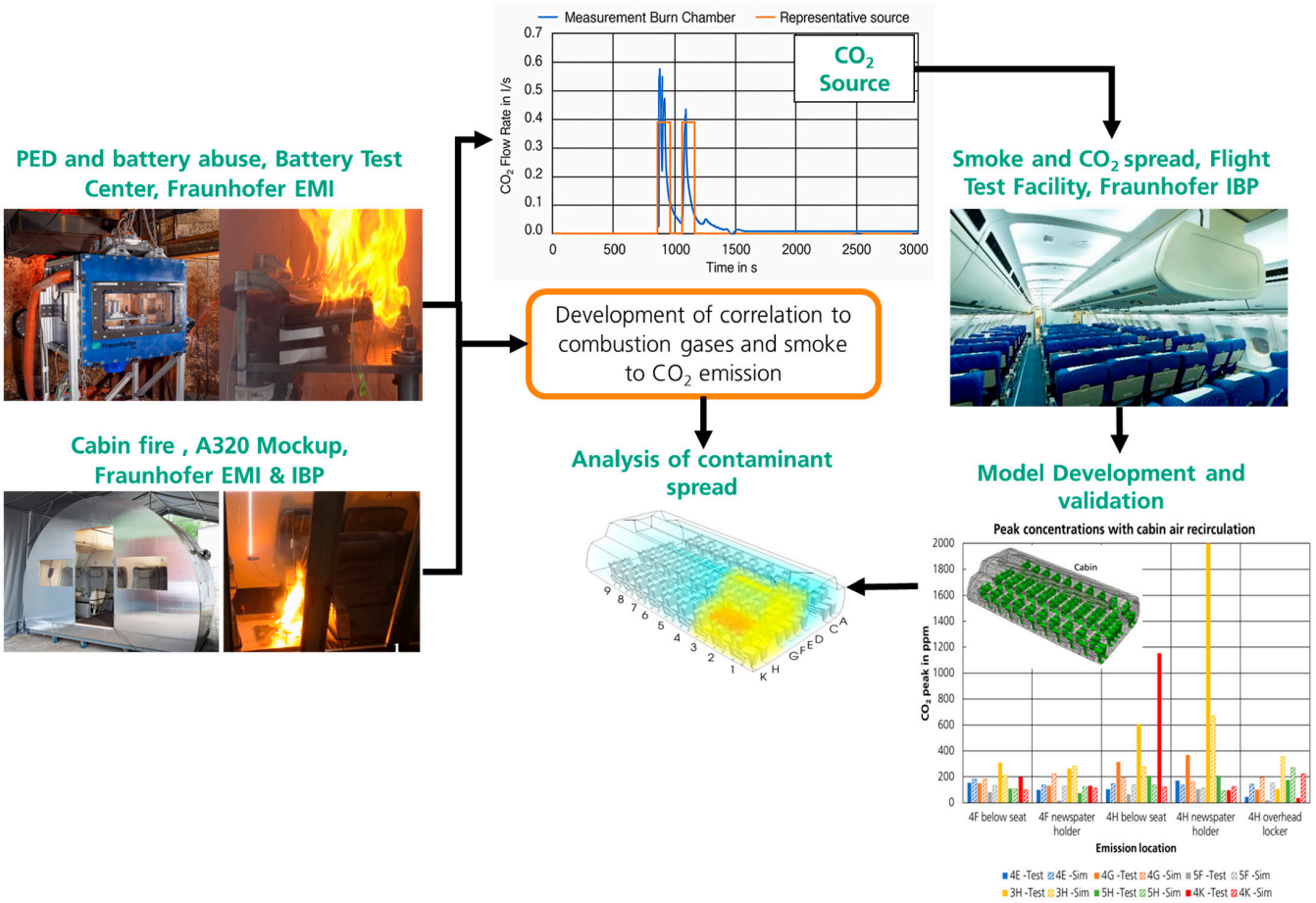


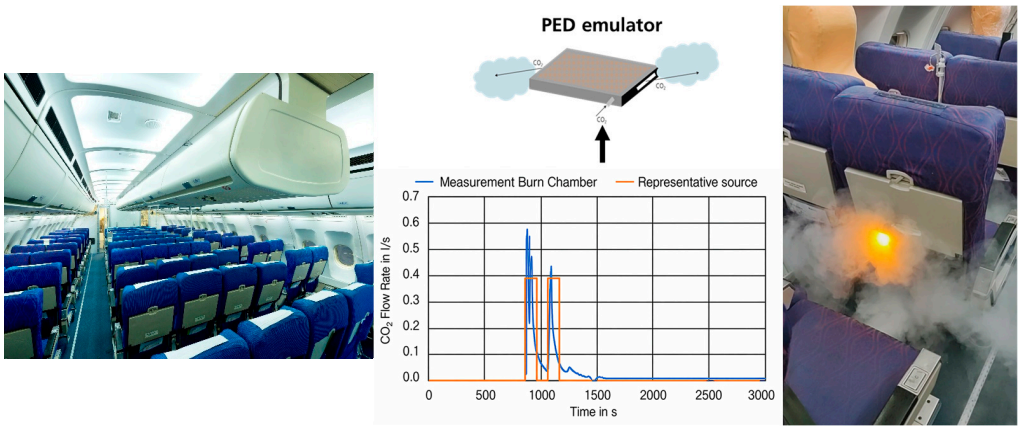
Figure 1. Methodological approach.

Battery Test Center: The methodology began with burn chamber testing at Fraunhofer EMI, where PEDs were deliberately forced into thermal runaway to measure the detailed composition of emitted gases. These experiments established representative emission profiles and peak toxic gas fractions for later scaling [3].

Cabin Fire—A320 Mockup: Thermal runaway tests were then conducted by Fraunhofer EMI in a ventilated two-seat row A320 cabin mockup provided by Fraunhofer IBP to observe gas release under realistic aircraft ventilation. Laptops were subjected to ther-

mal runaway in a two-row business-class seating arrangement, with ventilation set to 5 L/s per PAX and no recirculation, reproducing airflow comparable to an A320 economy class 3-3 configuration. These tests provided data on cabin exhaust gas composition, CO_2 concentration over time and smoke visibility behavior [3].

Flight Test Facility: Full-scale cabin measurements were conducted in a wide-body front fuselage demonstrator at the Fraunhofer IBP Flight Test Facility (Figure 2a). Because real PED fires could not be triggered in this test facility due to fire safety measures, a PED emulator was used to release CO_2 and smoke according to the emission profiles derived directly from the PED burn test data (Figure 2b). This allowed controlled measurement of spatial and temporal tracer gas (CO_2) propagation across the cabin, galley and cockpit.



(**a**) (**b**) (**c**)

Figure 2. Flight test facility—wide-body front fuselage demonstrator (**a**), PED emulator and CO_2 injection profile (**b**), and PED emulator and smoke generator in newspaper holder (**c**).

The PED emulator in the cabin was placed in five different locations (Figure 3). These were, for the PAX at seat 4F, below seat 3F and in the newspaper holder of seat 3F, and for the PAX at seat 4H, below seat 3H, in the newspaper holder of seat 3H, and in the overhead bin above seat 4H. A total of nine CO_2 measurement sensors were installed in the cabin, around the PED emulator and at various distances from the PED emulators. Figure 3 also shows the PED emulator's locations in the galley and cockpit, as well as the locations of the CO_2 measurement sensors in the galley and cockpit. Tests in the Flight Facility were performed with recirculation cabin ventilation (899 m^3/h fresh air and 899 m^3/h recirculated air) as well as with fresh air only ventilation (899 m^3/h fresh air). Smoke and CO_2 were injected during the test at the PED emulator locations mentioned above (Figure 2c). CO_2 concentrations were measured and later used for model validation.

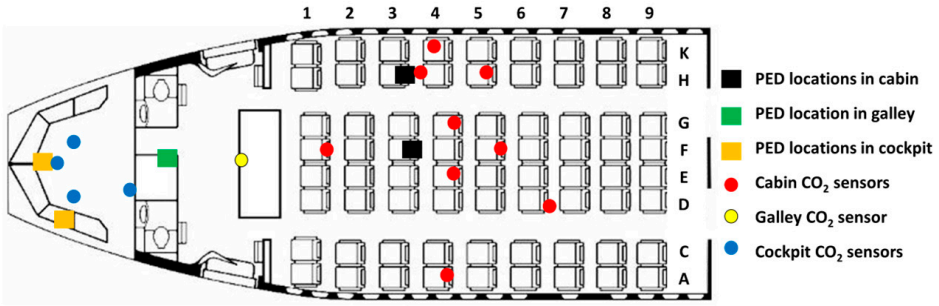


Figure 3. Location of PEDs and CO_2 sensors in cabin, galley and cockpit.

Model Development and Validation: A zonal model of the aircraft was developed using the zonal approach [4,5]. The Fraunhofer model generation tool was used to generate

a 3D zonal model from the CAD model (Figure 4). In the zonal modeling technique, the air volume is typically subdivided into a few hundred zones that exchange air, enthalpy and tracer components. The thermal runaway incident was modeled by introducing 70 L of CO_2 (two injection events in total, as derived from the PED burn tests, Figure 2b) into the appropriate zone, depending on the event location. The temporal and spatial dilution of CO_2 due to the aircraft's ventilation system was simulated for the cabin, galley and cockpit. The model was validated against test data obtained from the Fraunhofer Flight Test Facility.

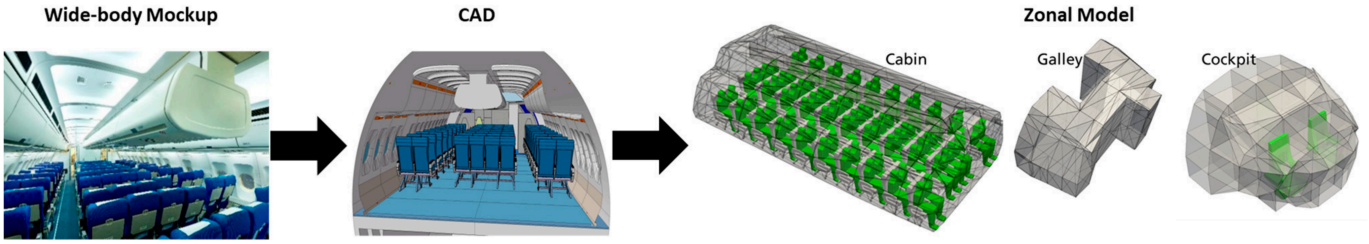


Figure 4. Zonal models of cabin, galley and cockpit.

To link PED burn test emissions with full-scale cabin simulations, toxic gas concentrations measured during thermal runaway were expressed as fractions relative to CO_2. This enabled the scaling of harmful species according to simulated CO_2 levels. Smoke density and visibility grade were also correlated to excess CO_2 concentration using video analysis from A320 mockup tests. Acute Exposure Guideline Levels (AEGL-2, 10 min values) were used as the primary toxicological reference for assessing hazard severity [6].

Finally, a simulative study was conducted using the validated zonal model to predict contaminant concentrations, exposure levels and visibility reduction for thermal runaway events occurring in the cabin, galley and cockpit. These simulations enabled assessment of the potential severity of PED thermal runaway under operational ventilation conditions and provided the basis for evaluating mitigation strategies.

3. Analysis of Contaminant and Smoke Spread

3.1. Peak Contaminant Concentration in Cabin, Galley and Cockpit

Figure 5 shows the predicted CO_2 spread and exposure limits when the peak concentration is reached in the emission zone for the cases with the largest spread and highest local concentration. The worst cases under realistic ventilation of the cabin, galley and cockpit were observed in the following scenarios:

- **Cabin**: Cabin in fresh air mode (899 m^3/h fresh air) with the PED emission in the newspaper holder at seat 4H
- **Galley**: Galley (252 m^3/h fresh air) with the cabin in fresh air mode (899 m^3/h fresh air), PED located below the oven racks
- **Cockpit**: Cockpit (700 m^3/h), PED on the left side of the pilot

The color scales are mapped to exposure thresholds of contaminants produced during combustion. The CO_2 equivalent of the 10 min AEGL-2 for CO is 1076 ppm, and that of 10 min AEGL-2 of HCHO is 2531 ppm. Typically, elevated concentrations occur within a two-seat radius from the emission location in the cabin (Figure 5a,b). However, in the galley and cockpit, a comparatively larger volume percentage is exposed to elevated concentrations during the peak (Figure 5c,d).

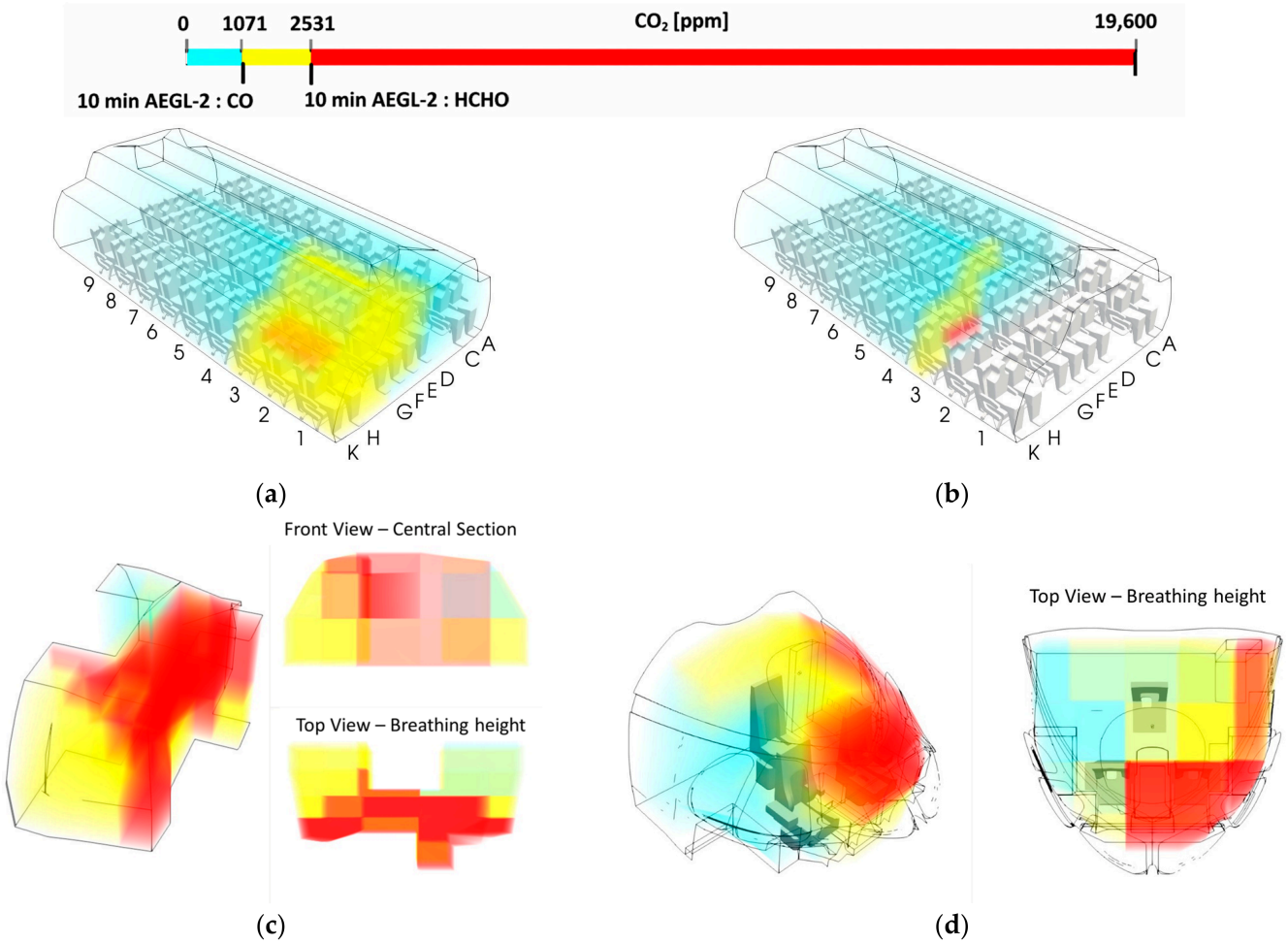


Figure 5. Spatial peak contaminant concentration in Cabin (**a**,**b**), Galley (**c**) and Cockpit (**d**).

3.2. Temporal Evolution of CO_2-Concentration in Cabin, Galley and Cockpit

The temporal evolution of the maximal CO_2 concentration (zone of the burning PED) and the average concentration in the cabin, galley and cockpit were evaluated and compared to the 10 min AEGL-2 equivalent for CO and HCHO. In the cabin (Figure 6a), the AEGL-2 threshold is exceeded at peak contaminant concentration, but does not persist over the critical exposure duration. Even at the peak concentration, 95% of the cabin volume remains below the AEGL-2 limit. Therefore, long-lasting adverse health effects or impaired ability to escape would not be expected. In the galley (Figure 6b), both the maximum and average concentrations at the peak exceed the 10 min exposure limit during the first event. The accumulated exposure in the maximum zone of the galley exceeds the 10 min AEGL-2 value for CO at 150 s. In the cockpit (Figure 6c) at the end of 10 min, the time- and space-averaged concentration in the cockpit remains below the AEGL-2 limit for CO. However, in the area of maximum concentration, the 10 min AEGL-2 limit is already exceeded within less than one minute during the first thermal runaway event. Thus, it is essential that pilots quickly equip themselves with breathing equipment in the event of a PED fire in the cockpit.

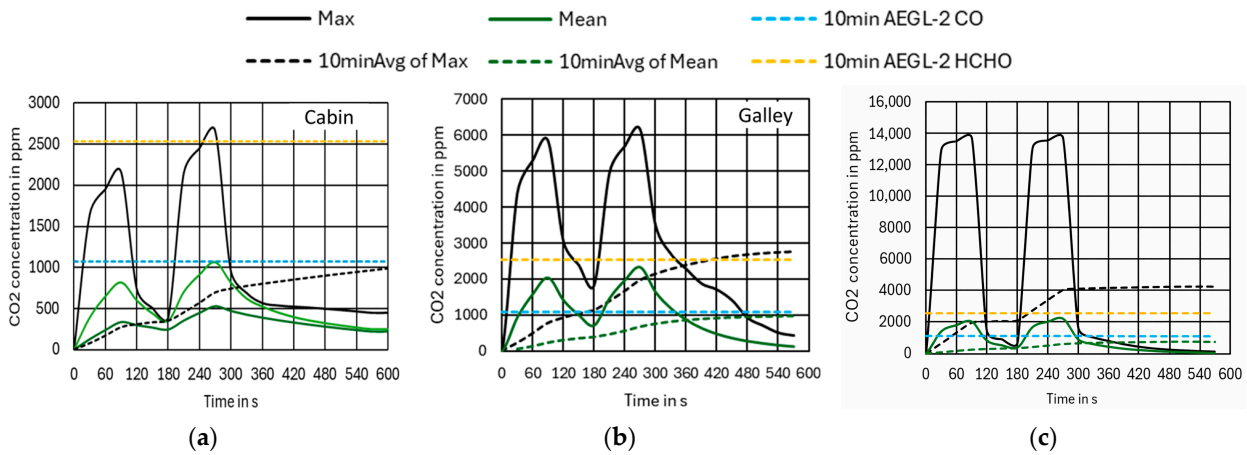


Figure 6. Temporal evolution of the maximal CO_2-concentration and the average concentration in the cabin (**a**), galley (**b**) and cockpit (**c**).

3.3. Smoke Spread and Visibility in Cabin, Galley and Cockpit

Smoke visibility was correlated to excess CO_2 concentration using video analysis from A320 mockup PED thermal runaway tests. For the evaluation, four stages of visibility were defined:

- 3 ≥ no visibility;
- 2 = distinct smoke with (partially) impaired visibility;
- 1 = light smoke with hardly any visibility deterioration;
- 0.7029 ≤ full visibility.

Figure 7 shows the expected visibility reduction in the cabin (a), galley (b) and cockpit (c) at peak concentration for the worst cases under the realistic ventilation conditions stated in Section 3.1.

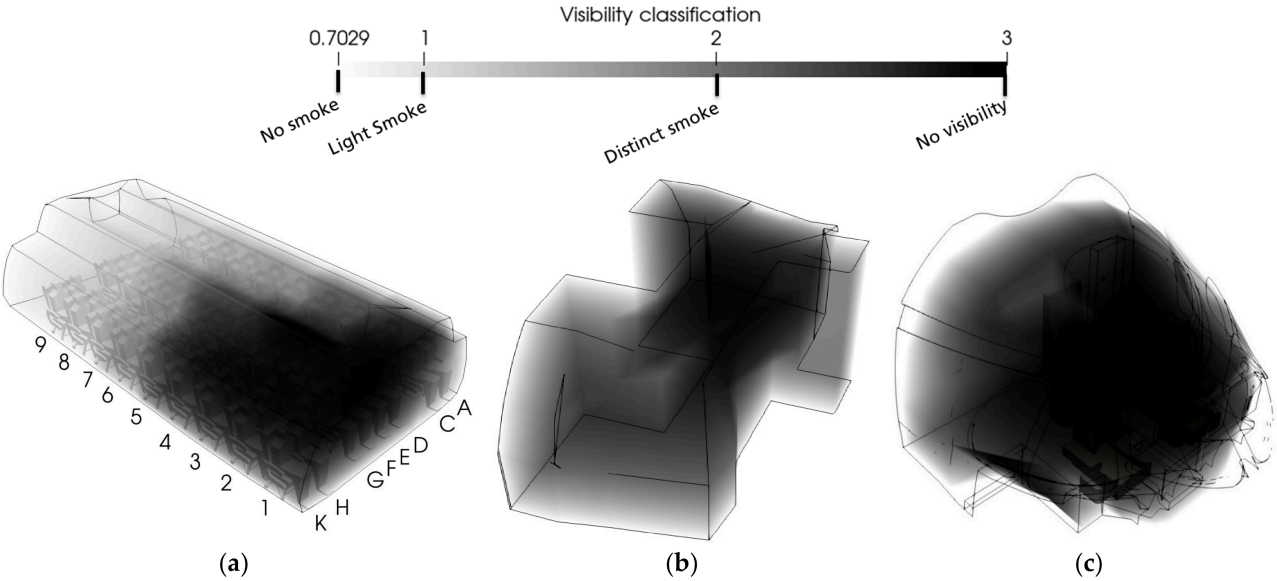


Figure 7. Visibility at peak spatial concentration: Cabin (**a**), Galley (**b**), Cockpit (**c**).

Figure 8 shows the temporal evolution of visibility derived from the corresponding temporal development of CO_2 concentration in the cabin (a), galley (b) and cockpit (c). In the cabin, the area surrounding the PED event experiences a short-term impairment of visibility during the peak concentrations of both injection events. However, after each event, the visibility in the zones with maximum concentration gradually improves, returning to

approximately visibility grade 2. The mean smoke density in the cabin briefly deteriorates beyond grade 2 following the second event, indicating a short-term reduction in overall cabin visibility (Figure 8a). In the galley, smoke accumulates more rapidly and to a significantly higher density due to the confined geometry. The galley fills with dense smoke soon after the first event. Smoke begins to dissipate after 360 s (after the second event) (Figure 8b). The cockpit also shows fast visibility degradation. Within 30 s of the first thermal runaway event, smoke spreads throughout the cockpit volume, and visibility is effectively lost. This rapid onset highlights the limited buffer time available to the flight crew in such scenarios. It takes approximately 3 min before the visibility grading improves to below grade 2 (after the second event), indicating a partial recovery of visibility (Figure 8c).

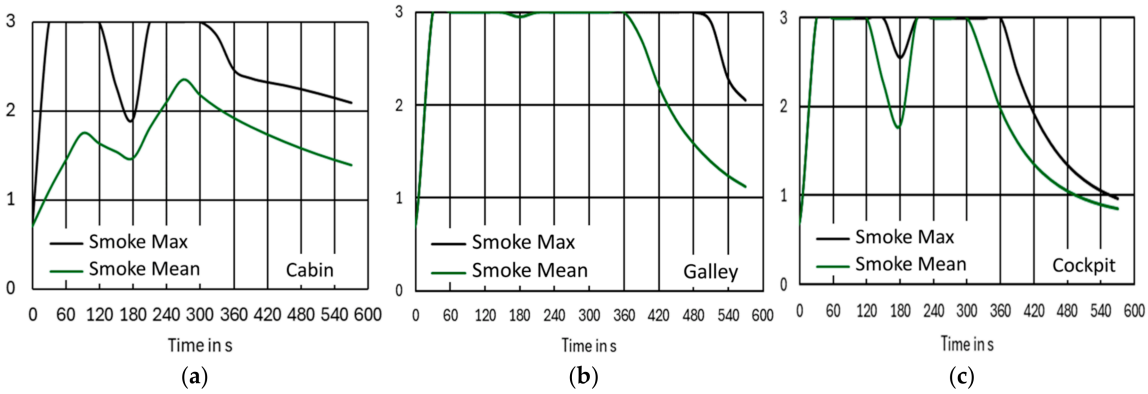


Figure 8. Temporal evolution of visibility based on the temporal evolution of CO_2-concentration: Cabin (**a**), Galley (**b**), Cockpit (**c**).

4. Discussion

The entire analysis was based on a single representative emission profile for a burning PED (the profile of a laptop with a 100 Wh battery capacity (Figure 2b).

Exposure to a burning PED in the cabin:

Distances of approximately two seats around the PED show increased exposure levels and should therefore be taken into account in the event of a PED thermal runaway. At these seats, the most critical threat is reaching the AEGL-2 limit for CO; consequently, respiratory irritation may occur.

The question of whether exposure to a burning PED is harmful cannot be answered with 100% certainty for all possible scenarios. However, the measurements performed in the cabin within the LOKI-PED project suggest the following:

- In the plume of the burning PED, increased levels of hazardous substances are likely. This plume is typically accompanied by visible smoke.
- In the near field, the margin to the AEGL-2 exposure level is around 50% during the first thermal runaway and is almost entirely used if the event propagates. Hence, the 100 Wh limit appears reasonable in terms of potential exposure.
- Farther away from the burning PED, no long-lasting harmful effects are expected. Therefore, passengers close to the event should be relocated at least two seats away.
- A PED burning in the cabin does not pose a threat to the cockpit.

Exposure to a burning PED in the cockpit and galley:

The tested profile leads to harmful concentrations of combustion products in both the cockpit and galley. Visibility reduction and inhalation of toxic gases are major risks in the event of a PED battery thermal runaway. It is essential to mitigate these risks. For example, flight crew members should equip themselves with the available supplemental oxygen

systems with a full-face mask. PEDs showing early symptoms of a battery thermal runaway should be relocated to the passenger cabin as quickly as possible to avoid exposing the pilots to hazardous gases and smoke that could reduce visibility.

The risk assessment associated with moving the item differs depending on whether it must be removed from the cockpit or moved within the cabin to be cooled. In the cockpit, the risk of not removing the device may exceed the risk associated with handling it. To reduce the severity of thermal runaway events, the battery capacity limit for PEDs permitted on the flight could be lowered.

5. Conclusions

The LOKI-PED project provides a comprehensive assessment of the hazards posed by PED thermal runaway in aircraft environments through combined experimental and modeling approaches. The validated zonal model provides a means to predict gas and smoke dispersion in cabin, cockpit and galley scenarios.

Key findings include:

- Cabin exposure is generally safe beyond two seats from the burning PED; therefore, passengers seated more than two seats away are typically not at risk.
- Cockpit and galley exposures can exceed AEGL-2 limits rapidly, posing significant risks and hence requiring an immediate response.
- Visibility loss is strongly correlated with excess CO_2, enabling predictive modeling.
- Operational mitigation measures include prompt use of oxygen masks, careful relocation of overheating PEDs and consideration of battery size restrictions.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Data can be made available upon request.

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Conflicts of Interest: The authors have no conflicts of interest.

Abbreviations

PED	Portable Electronic Devices
AEGL	Acute Exposure Guideline Levels
LOKI	Lithium batteries in pOrtable electronic devices—risK of fIre and smoke

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