

LOKI-PED [EASA.2022.C09]

**REPORT ON RISK ASSESSMENT, DISCUSSION OF REGULATIONS, AND
ASSESSMENT OF THE APPLICABLE PROVISION**

LOKI-PED Risk Assessment, Discussion of Regulations, Assessment of the Applicable Provisions

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1 Preface

Due to their strong thematic interdependence, work packages 3 and 4 are treated jointly in this deliverable following prior agreement with EASA. Addressing them separately would result in excessive cross-referencing and reduced clarity. Specifically, the contents of Deliverables D3.1, D3.2 and D4 are combined and discussed in an integrated manner:

D-3.1: Technical analysis and quantification of the effects of the batteries' types, energy capacity and numbers on the hazards created

D-3.2: Report containing data that supports the establishment of limits on the quantity and energy capacity of the batteries and assessment of the consequence of modifying current limitations on PED on board.

D-4: Assessment of the applicable provisions.

2 Introduction

The objective of Work Package (WP) 3 is to quantitatively assess the risks associated with thermal runaway in lithium-ion batteries contained in portable electronic devices (PEDs) carried in the passenger cabin and on the flight deck.

Conducting such a risk analysis is challenging, primarily due to limited availability of data. To address this gap and provide a foundation for evaluating the hazards and consequences associated with such events, experimental investigations and numerical simulations were carried out as part of the LOKI-PED project. The risk assessment in WP 3 builds upon results of these experiments and simulations conducted in WP 1 and WP 2, which are presented in consolidated form in Deliverables D1.7 and D2.4.

Statistical probabilities of an event are estimated based on observed frequencies, as outlined in WP 3, using data from three main sources: (i) incident reports from airlines, (ii) complementary information from official databases, and (iii) survey data on passenger behavior. It should be noted that deriving probabilities of occurrence from observed frequencies involves uncertainty, as this approach assumes that past and future conditions remain unchanged.

An additional objective of WP 3 is to conduct sensitivity analyses considering variations in the number of devices transported by each passenger and their energy capacities, and to quantify their impact on the calculated risks. This task is aimed at capturing future variability in passenger behavior and anticipated technological developments.

Although power tools were investigated experimentally in WP 1 and WP 2, WP 3 revealed a lack of data availability on the frequency of events originating by this type of devices. Consequently, power tools are not taken into account in the present risk assessment. In contrast, as noted in Deliverable D1.7, numerous thermal incidents have been linked to power banks. Although not considered for the other tasks, power banks are considered here for the risk assessment comparative purposes, particularly with regard to incident frequency.

The aim of WP 4 is to evaluate the identified risk scenarios against current regulatory provisions and to identify potential gaps. This evaluation is presented in the concluding section of this deliverable, while specific regulations –

especially those addressing mitigation measures – will also be discussed in the preceding chapters.

3 Methodological Approach

In the context of this assessment, risk is defined as the product of the probability of an event and its consequences:

$$\text{Risk} = \text{Probability} \times \text{Consequences}$$

The probability (or likelihood) of a thermal runaway event is based on statistical probability, using historical data from past events. The primary challenge in this analysis was to identify a suitable data basis that not only reflects the number of PED-related incidents in a given time but also differentiates between the different types of portable electronic devices (PEDs) investigated within the LOKI-PED project, and to relate these incident numbers to the total number of flights or flight hours.

The consequences component refers to the potential effects of a thermal runaway event involving lithium-ion batteries. In this assessment, consequences were analyzed based on the associated hazards, specifically fire, smoke, and toxic gas release. For risk classification, the determining factor was the most severe outcome observed in each scenario.

For visualization and classification, risk is represented in the form of a risk matrix (Figure 1), also referred to as a consequence–likelihood matrix, following established approaches in ISO standards [1] and EASA’s Certification Specifications for Large Aeroplanes (CS-25) [2].

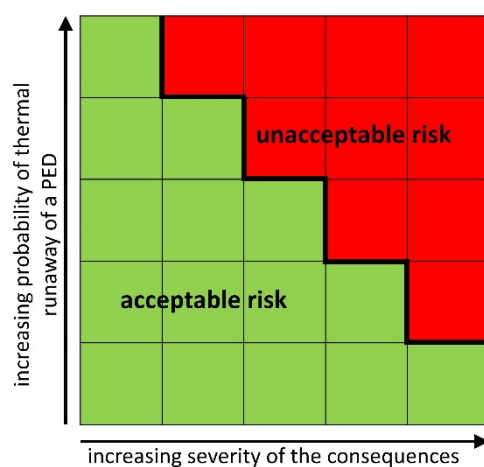


Figure 1: Risk matrix.

The risk acceptance criteria applied in this study are aligned with the classification scheme outlined in CS-25 [2], which states that: »A logical and acceptable inverse relationship must exist between the average probability per flight hour and the severity of failure condition effects«, such that:

- (1) Failure conditions with no safety effect have no probability requirements.
- (2) Minor failure conditions may be probable.
- (3) Major failure conditions must be no more frequent than remote.
- (4) Hazardous failure conditions must be no more frequent than extremely remote.
- (5) Catastrophic failure conditions must be extremely improbable.

It is important to note that risk matrices inherently introduce artificial discontinuities due to the use of discrete categories for severity and likelihood. Thus, minor variations in input parameters can lead to disproportionate shifts in risk classification, potentially misrepresenting the continuous nature of real-world risk. This effect must be carefully considered when interpreting the results, especially considering the various assumptions made during probability estimation, consequence evaluation, and the underlying simulations that inform the consequence assessment.

Finally, the risk classification used in this deliverable is based on the worst credible case, not on hypothetical extremes. It is assumed that all relevant mitigation measures (e.g. emergency equipment) and crew procedures are in place and function as intended. A more detailed assessment and discussion of emergency procedures and mitigation measures is provided in Deliverable D6.4.

4 Probability of Occurrence of a Thermal Runaway of PEDs

The experiments conducted within the LOKI-PED project were designed to investigate the consequences of thermal runaway events, both under laboratory conditions and in a (simulated) aircraft setup. To this end, thermal runaway was deliberately induced, meaning the probability of occurrence was artificially set to 1. These experiments therefore do not permit conclusions about the probability of such events occurring under real operational conditions. Instead, estimates of the probability of occurrence are derived from observed frequencies of events based on incident reports.

It should be noted that observed frequencies of an event indicate how often the event has actually occurred within a given dataset or over a specific period. In contrast, the probability of occurrence is a theoretical measure of the likelihood that the event will happen in the future. In the risk assessment domain, it is common practice to estimate probabilities from observed frequencies, particularly when sufficient and reliable historical data is available. However, this approach has limitations, especially for rare events, incomplete or biased data, or when system conditions may change over time. While observed frequencies offer valuable empirical input, directly equating them to probabilities of occurrence can be misleading under such circumstances. Therefore, careful consideration of context, data quality, and potential changes is essential when using observed frequencies to estimate probabilities. In cases of limited data or changing conditions, it is standard practice to supplement empirical estimates with expert judgment or scenario analysis, and to document the associated assumptions and uncertainties.

Although power tools were among the PED types investigated and analyzed experimentally in LOKI-PED work packages 1 and 2 (see deliverables D1.7 and D2.4), no sufficient data are available on the frequency of incidents involving these devices, which is why they were not further treated in the following risk assessment. In contrast, power banks, while not originally within the project's defined scope, are frequently mentioned in incident reports and represent a significant portion of documented thermal events (see deliverable D1.7). For this reason, they are included in the discussion and as a relevant point of comparison, particularly with regard to incident frequency and overall risk potential.

4.1 Thermal Runaway Probability by device Type

The probability of a thermal runaway of a device is expressed as a statistical probability (i.e. posteriori probability). This means that historical event data is being used to calculate a frequency of incidents¹ from which the probability is then estimated as an empirical approximation of future likelihood (see further explanation above in chapter 4). This can be expressed e.g. as number of incidents per passenger, per departures (i.e. flights), or airtime. As described in Deliverable 1.7, there do exist reports and databases in which incidents are compiled, but it cannot be assumed that these are complete. For instance, the FAA website [4] explicitly states that its information should not be considered a complete listing. More critically, however, there is usually no reference to the underlying number of flights, airtime or passenger numbers to which these incident reports relate, making it impossible to calculate probabilities.

For this reason, data from the TRIP (Thermal Runaway Incident Program) [5] database is used, as it represents the most comprehensive source currently available, with the added benefit that the participating airlines are known. This allows for the retrieval of supplementary information, such as the number of enplaned passengers, total airtime, or number of departures, from the U.S. Bureau of Transportation Statistics (BTS) [6], particularly from the BTS-100 dataset, if not already reported in TRIP publications. The Thermal Runaway Incident Program (TRIP) Annual Report – 2021 [3] is, at the time of preparing this deliverable, the most detailed report available as it provides a comprehensive overview of the thermal runaway incidents for the years 2017 to 2021 of the 8 participating passenger airlines and relates them to the number of passengers enplaned and the number departures (Table 1). In this report, thermal incidents are defined as events involving "a fire, violent rupture, explosion, or a dangerous evolution of heat" [3]. Based on this data, it is possible to calculate the incident probability per million passengers ($P_{\text{incident_per_million_PAX}}$) and per flight ($P_{\text{incident_per_flight}}$) respectively:

$$P_{\text{incidents_per_million_PAX}} = \frac{\text{thermal incidents}}{\text{passengers enplaned [Millions]}}$$

and

¹ A thermal incident is defined as "a fire, violent rupture, explosion, or a dangerous evolution of heat." [3].

$$P_{\text{incidents_per_flight}} = \frac{\text{thermal incidents}}{\text{departures performed}}$$

Between 2017 and 2021, TRIP data combined with BTS records yields a statistical incident probability of: $P_{\text{incident_per_million_PAX}} = 0.09$ and $P_{\text{incident_per_flight}} = 1,09\text{E-}05$.

For the analyses and discussions in the following, it is assumed that these values are representative and thus can be extrapolated to other airlines, in particular also European airlines.

Table 1: Thermal incidents of reporting TRIP participants and related flight data for the years 2017-2021 (adapted from [3]).

	2017	2018	2019	2020	2021	Total
Total thermal incidents	37	41	47	31	60	216
Total Passengers enplaned [millions]	550.17	580.35	600.65	235.56	441.70	2,408.43
Departures performed	4,353,321	4,547,296	4,638,888	2,668,227	3,531,155	19,738,887
Incidents per million passengers	0.07	0.07	0.08	0.13	0.14	0.09

The data in Table 1 does not specify the device types involved in the reported incidents, an essential detail for refined risk analysis. While other compilations identify device types, they usually lack corresponding traffic data, making probability calculations infeasible. However, it is reasonable to assume that the proportional distribution of device types is consistent across different data sources. This allows the TRIP-derived incident probabilities to be disaggregated by device type using available breakdowns.

Figure 2 shows the incidents by year and by relevant device type. The data is derived from the TRIP report 2021 [3] and includes incidents reported by TRIP participants as well as incidents extracted from the FAA databases. The resulting percentage shares of each device type in the total number of incidents are as follows:

- Portable charger or powerbank 29.9%
- Cell phone: 18.3%
- Laptop: 11.0 %
- Tablet: 3.3%

The share of all device types considered in LOKI-PED consequently is 62.5% of the total number of incidents.

Combining these proportions with the base value of $P_{\text{incident_per_million_PAX}} = 0.09$, calculated using the data from Table 1 gives the respective incident per-type probability per million passengers:

- $P_{\text{powerbank_incident_per_million_PAX}} = 0.027$
- $P_{\text{phone_incident_per_million_PAX}} = 0.016$
- $P_{\text{laptop_incident_per_million_PAX}} = 0.010$
- $P_{\text{tablet_incident_per_million_PAX}} = 0.003$

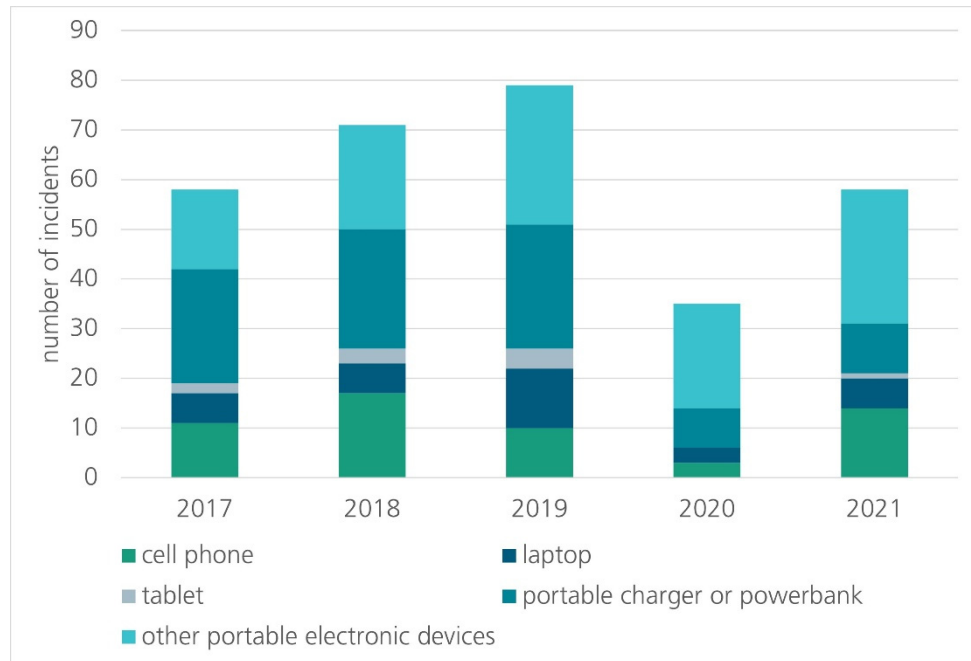


Figure 2: Number of thermal incidents by type and year for the years 2017-2021. The data is based TRIP including incident data reported by the FAA.

These per-type probabilities can be used to estimate the probability of an incident involving a particular device per flight, based on aircraft capacity.

However, it should be noted that this does not account for the fact that larger aircraft, which carry more passengers, are typically used on long-haul routes and thus have longer flight times than smaller aircraft.

As a good approximation, cabin crew members can be considered additional passengers.

$$P_{\text{incident_in_plane_type}} = P_{\text{incident_per_million_PAX}} \cdot \frac{(\text{number}_{\text{PAX}} + \text{number}_{\text{cabin_crew}})}{1,000,000}$$

Taking a single-aisle aircraft corresponding in size to an Airbus A320neo with a maximum passenger capacity of 194² and 4 cabin crew members as an

² <https://aircraft.airbus.com/en/aircraft/a320-family/a320neo> (accessed 27.02.2025)

example, the incident probabilities are as shown in Figure 3. Since, as shown above, the proportion of devices considered in LOKI-PED is 62.5% of all incidents, the incident probability is 0.056 per million passengers and thus the probability of an incident with one of these devices in this A320neo example is 1.11E-05.

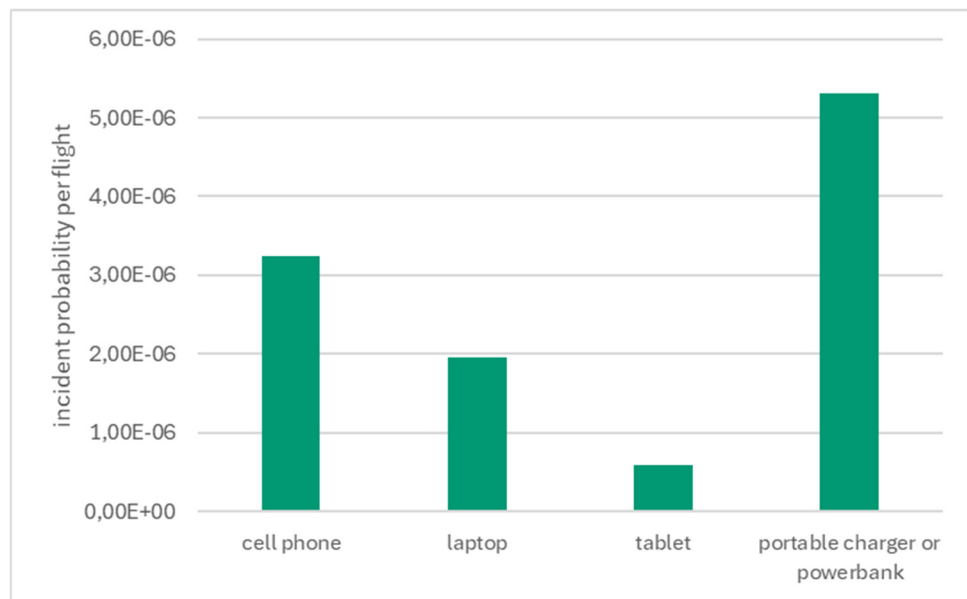


Figure 3: Incident probability by device type on an Airbus A320neo per flight. The estimation is based on the maximum passenger capacity (including the cabin crew).

In line with CS-25 guidelines, which require risk to be expressed per flight hour, the incident probability per flight is divided by the average flight duration. The airtime per flight (in minutes) is provided in the dataset used to compile the numbers in [3] on which Table 1 is based and is publicly available from the U.S. Bureau of Transportation Statistics [5]. Based on the observation period, the average flight duration was determined to be 134 minutes, corresponding to approximately 2.23 hours. This value is used to convert the probability from a per-flight basis to a per-hour basis, as shown in Figure 4. Based on the available data, the probability of a thermal incident involving one of the device types examined in the LOKI-PED project has been determined to be 4.94E-06 per flight hour.

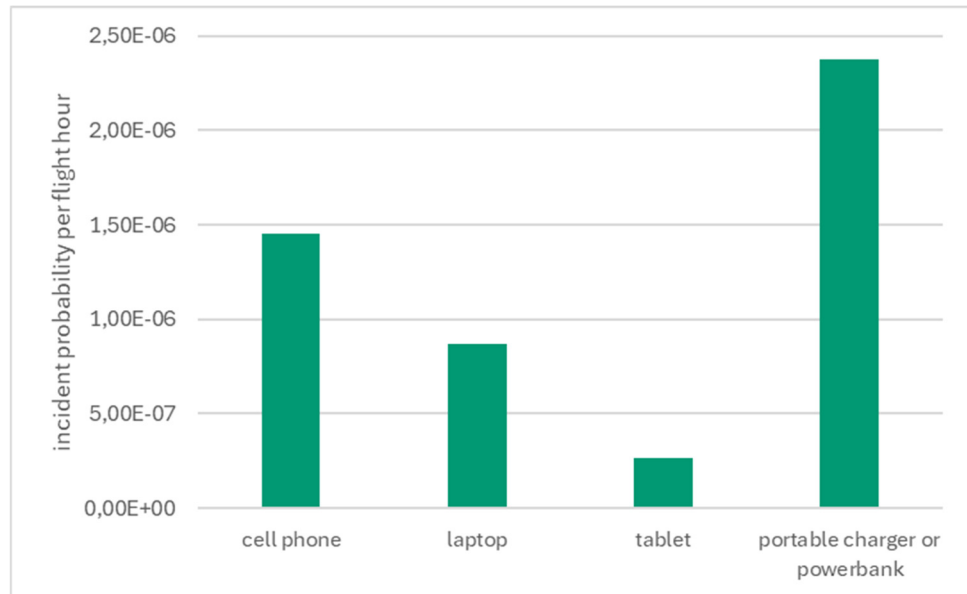


Figure 4: Incident probability by device type on an Airbus A320neo per flight hour. The estimation is based on the maximum passenger capacity (including the cabin crew).

4.2 Passenger Behavior

The likelihood of a thermal incident involving PEDs on board an aircraft is obviously closely linked to the number and types of devices carried. As PEDs such as smartphones and laptops have been part of everyday life for many years, it can be assumed that the vast majority of passengers carry them in their hand luggage and bring them on board aircraft. However, reliable data on the actual quantity and types of PEDs carried by passengers is scarce. A useful indication is provided by a series of surveys conducted by UL Standards & Engagement in 2023 [7] involving over 8000 adult US citizens. The results, summarized in Table 2, offer insight into the typical number and types of PEDs passengers may carry. It is important to note that this survey data originates from a different population than incident statistics discussed earlier. Nonetheless, it is assumed that passenger behavior is representative, and that passenger behavior in the EU is essentially comparable to that of respondents in these US-focused surveys.

Based on the figures in Table 2, the number of specific PEDs on board can be estimated, depending on aircraft size, maximum passenger capacity, and crew size.

Table 2: Passenger behavior expressed as percentage of passengers that bring a specific PED on board (data from [7]).

Devices containing lithium batteries	Percentage of PAX bringing devices containing lithium batteries on board
Cell phone	82%
Laptop	41%
Tablet	36%
Portable charger or power bank	31%

Understanding the prevalence and distribution of device types among passengers not only helps to estimate current risk levels but also provides a basis for exploring potential future scenarios. For instance, shifts in usage patterns, such as an increased prevalence of high-capacity devices, or regulatory measures restricting certain device types could significantly alter the overall risk of landscape. Such considerations are valuable for anticipating developments and informing regulatory or operational decisions.

4.3 Weighted Probability

In addition to passengers, it can be assumed that cockpit and cabin crew also carry devices - both for private and professional use. While the number and type of electronic devices intended for work-related use are directly subject to airline requirements, crew behavior regarding privately used devices is assumed to be similar to that of passengers.

Using the incident frequencies calculated in chapter 4.1 and these passenger behavior data from chapter 4.2, a weighted probability of an incident involving a single device can be derived:

$$P_{incident_per_device} = \frac{P_{incidents_per_million_PAX}}{devices\ carried\ per\ million\ PAX}$$

The results for the different device types are shown in Figure 5. These weighted probabilities facilitate a sensitivity analysis (see chapter 7), as they allow for the determination of not only the number of passengers (and crew members) within a specific scenario but also the quantity of each type of device carried. This enables the analysis of various scenarios to assess current regulations and identify potential gaps.

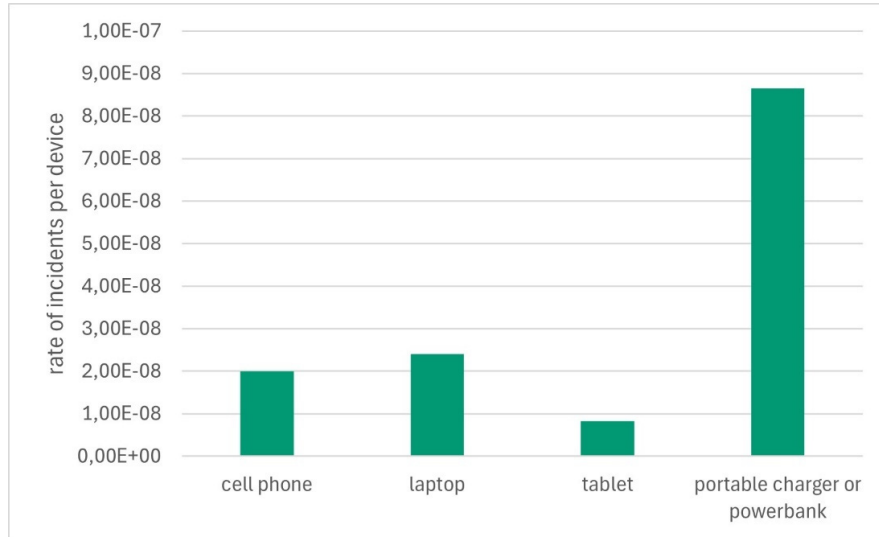


Figure 5: Weighted probability expressed incident probability per individual device.

The rate of incidents per device for a tablet is 8.28E-09, while for a cell phone, it is 2.00E-08, and for a laptop, it is 2.40E-08. In contrast, the rate of incidents per device for a portable charger is more than three times higher, at 8.65E-08. This strongly suggests that power banks have a substantially higher probability of undergoing thermal runaway compared to PEDs. Therefore, despite their relatively low numbers on board, they warrant special attention.

4.4 Limitations of the Probability Estimation

Overall, the probability assessment relies on a combination of heterogeneous data sources, as no single dataset covers all the required parameters. Due to the limited availability of comprehensive and consistent data sources, the probability assessment of thermal runaway events in PEDs necessarily draws multiple datasets from different origins. While this approach introduces certain uncertainties, the combination of TRIP reports and BTS flight statistics represents the best available basis to quantify incident likelihood in a meaningful and transparent manner.

Despite these efforts and methodological workarounds, some potentially important distinctions could not be reflected. In particular, no incident data is available for power tools, even though they were among the devices experimentally investigated in the project. Furthermore, incident probabilities cannot currently be broken down by battery capacity, number of cells per device, or cell type, parameters that would be valuable for conducting sensitivity analyses, particularly in view of anticipated developments in PED designs.

5 Consequences of a Thermal Runaway of PEDs

Since the PEDs considered in the cockpit and cabin are the same consumer-grade type of devices, the difference in incident probability is primarily attributable to the varying number of devices present in each compartment and not on the environmental conditions of the specific compartment. However, the hazards associated with a potential thermal runaway of these devices can lead to very different consequences in the flight deck compared to the cabin. This is partly due to differences in smoke and gas spread characteristics, and the different ventilation situation, but more importantly, the risk assessment fundamentally changes when, for example, a flight crew member - rather than a passenger - is visually impaired by smoke or incapacitated by toxic gases.

Given the expected differences in consequence of severity depending on the location of the event, thermal runaway in the flight deck and in the passenger cabin is assessed as two separate scenarios. Accordingly, two distinct risk matrices have been developed to reflect their specific safety implications.

To assess these consequences consistently, the severity classification framework defined in the EASA Certification Specifications CS-25 Amendment 28 (specifically CS 25.1309) [2] is applied. This includes the severity categories shown in Figure 2a of the specification »Relationship Between Severity of the Effects and Classification of Failure Conditions« (reproduced here as Figure 6), along with the explanatory text in the document.

Although PEDs are not part of the aircraft's certified systems, their failure may give rise to conditions, such as smoke, fire, or toxic emissions, that are comparable in effect to system failures. The potential consequences of thermal runaway events are therefore evaluated based on their potential impact on the aircraft, its occupants and the cabin crew, and the flight crew.

Quantitative data on the consequences of thermal runaway events were obtained in Work Package 2 using a five-step approach. This combines controlled experiments, where PEDs were intentionally forced into thermal runaway, with tracer gas tests and validated simulations to analyze the spatial and temporal dispersion of combustion gases. The resulting data allows for the assessment of passenger and crew exposure to hazardous gases and smoke-induced visibility reduction, using equivalent CO₂ concentrations as a reference metric, since emissions of other substances from burning PEDs correlate linearly with CO₂ release. The overall methodology and results are presented in Deliverable D2.4

Severity of the Effects	Effect on Aeroplane	No effect on operational capabilities or safety	Slight reduction in functional capabilities or safety margins	Significant reduction in functional capabilities or safety margins	Large reduction in functional capabilities or safety margins	Normally with hull loss
	Effect on Occupants excluding Flight Crew	Inconvenience	Physical discomfort	Physical distress, possibly including injuries	Serious or fatal injury to a small number of passengers or cabin crew	Multiple fatalities
	Effect on Flight Crew	No effect on flight crew	Slight increase in workload	Physical discomfort or a significant increase in workload	Physical distress or excessive workload impairs ability to perform tasks	Fatalities or incapacitation
Classification of Failure Conditions		No Safety Effect	Minor	Major	Hazardous	Catastrophic

Figure 6: Severity classification. Figure reproduced from CS-25 Amendment 28 [2].

A thermal runaway scenario involving a laptop was emulated and simulated to assess the spread of smoke and gases within the aircraft cabin, the galley, and the flight deck. The scenarios considered a laptop equipped with a 100 Wh battery, resulting in the release of approximately 70 liters of gas and 30 liters of smoke. Two ignition events, including a reignition, were modeled. To capture spatial variability, the emission source was positioned at five different locations within the cabin, one location in the galley, and two different positions in the flight deck. Additionally, two passenger cabin ventilation conditions were analyzed: one with fresh air supply only, and another combining fresh air with recirculated air.

To ensure a conservative risk assessment, the following analysis focuses on those scenarios that produced the most severe consequences within the simulated conditions. This includes, for example, configurations where the emulator position led to maximum gas and smoke exposure. These scenarios are considered representative for evaluating the highest relevant impact on safety under realistic assumptions.

To facilitate a more nuanced discussion, the hazards of smoke and toxic gases are initially considered separately in the following sections. This approach follows the structure and presentation in Deliverable D2.4 allowing for a detailed examination of each hazard type and their respective consequences. Nonetheless, it should be noted that in practical scenarios, smoke and toxic gases typically occur together, and their combined effects must be kept in mind when interpreting the results.

The following sections assess the consequences of thermal runaway events separately for the cabin, galley, and flight deck, addressing the hazards of toxic gases, smoke, and fire in each case.

5.1 Consequences in The Passenger Cabin

5.1.1 Toxic Gases

The simulation results regarding the concentration and limits of toxic gases, expressed as CO₂ equivalent, from deliverable D2.4 can be summarized as follows:

- The worst case with no attempt to mitigate the event, i.e., the highest gas concentration and widest spread of toxic gases, occurs when the emission source is in the seat literature pocket (seat 4H in Figure 7) in fresh-air-only ventilation mode. In this scenario a first fire followed by a second reignition is modelled.
- Typically, elevated concentrations are observed within a two-seat radius from the emission site, potentially affecting about 24-30 passengers. Highest concentrations were found in the direct vicinity of the incident.
- Validation of the simulation results revealed that toxic gas concentrations in the direct plume may be considerably higher as predicted by the simulation.
- In peak concentration, different toxic gas exposure limits were exceeded.
- In no instance did the concentrations reach levels that would pose a lethal threat.
- The momentary peak concentration for the CO AEGL³-2 limit (which corresponds to the lowest CO₂ equivalent among all gases considered) and HCHO were exceeded; however, the 10 min. exposure duration was not met. Thus, the AEGL-2 thresholds were numerically not

³ AEGL-2 (Acute Exposure Guideline Level 2): The airborne concentration of a substance above which the general population, including susceptible individuals, could experience irreversible or other serious, long-lasting health effects or an impaired ability to escape. Defined by the U.S. Environmental Protection Agency (EPA).

exceeded. The 10-min AEGL-2 CO exposure in the direct vicinity of the thermal runaway was very close to being exceeded (see Figure 7).

- If passengers in the exposed area are relocated within 90 s to a non-contaminated zone, short-term exposure may still exceed the 10 min AEGL-2 limit during thermal runaway, but further accumulation is prevented, resulting in overall exposure remaining clearly below the 10 min AEGL-2 level.
- The spread of toxic gases from a lithium battery thermal runaway event in the cabin into the flight deck was minimal. It can therefore be concluded that the toxic gases released during the thermal runaway of a lithium battery in a PED located in the passenger cabin do not pose a direct threat to the flight crew.

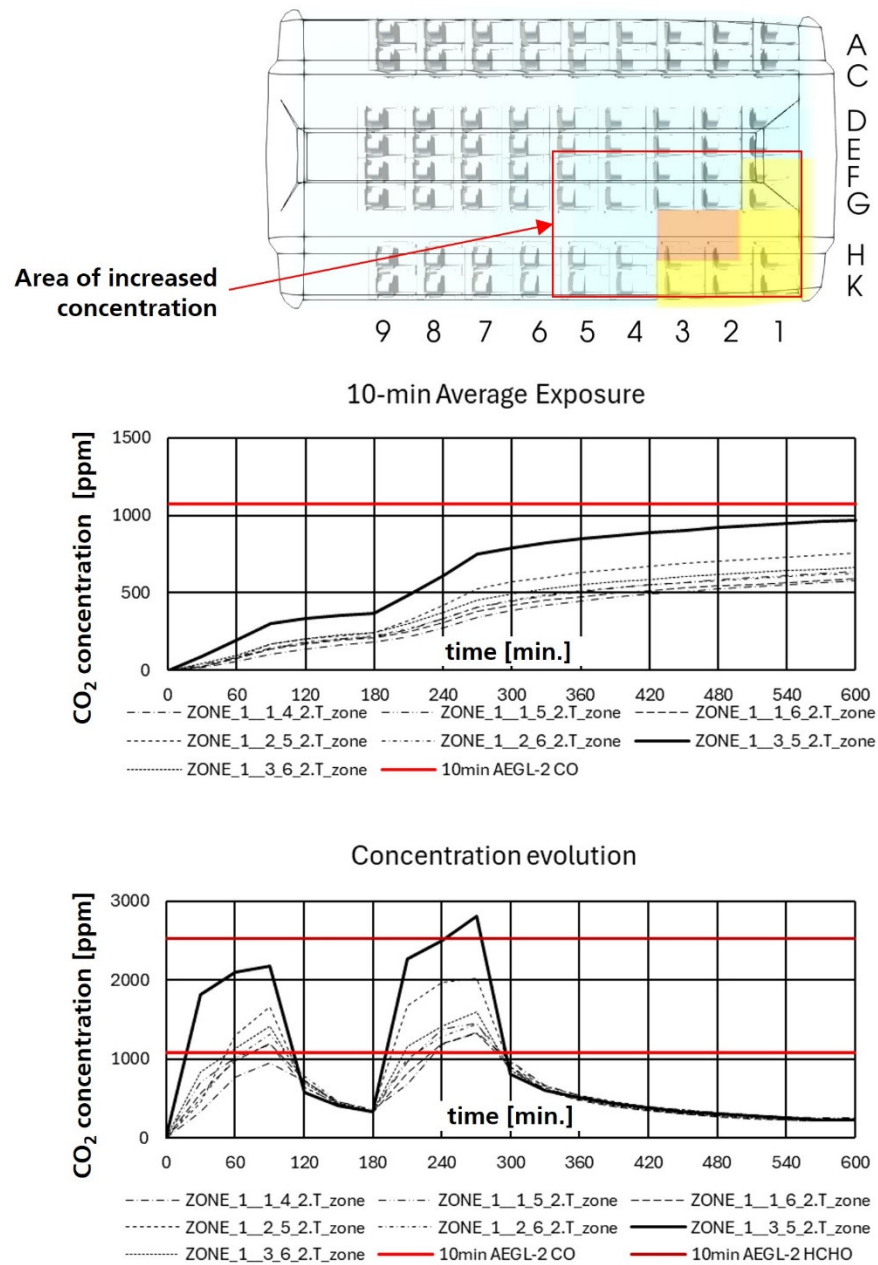


Figure 7: Simulation of exposure in case of an untreated 100Wh laptop fire. Simulation shows fire in 4H newspaper holder i.e. the rear seat of 3H (top). Simulation of 10-minutes average tracer gas exposure (middle). Simulation of tracer gas concentration evolution (bottom).

The following section systematically narrows down the classification by process of elimination, followed by a discussion of the remaining options based on EASA CS-25 Amendment 28 [2]. Toxic gases released during a cabin incident

do not affect the aircraft systems or structure but primarily pose a hazard to the occupants. Passengers and cabin crew are most directly exposed through inhalation, while possible effects on the flight crew must also be considered, as their duties during flight imply a potentially higher criticality compared to the cabin crew.

If a lithium-ion battery in a PED undergoes thermal runaway in the cabin, resulting in the release of hazardous gases and possibly smoke, the consequences on the occupants are classified at least as **“minor”**, even when gas concentrations remain below occupational exposure limits (e.g. MAK values). This is because passengers and cabin crew may still experience transient physical discomfort, such as mild eye or throat irritation or anxiety, without sustaining injuries. Additionally, the flight crew may face a slight increase in workload, typically limited to communication between the cabin and flight deck.

Conversely, this implies that a classification as **“no safety effect”** is not justifiable. On the other hand, assuming timely detection of the event and effective fire-fighting, neither multiple fatalities among passengers or cabin crew, nor fatalities or incapacitation of the flight crew are expected; therefore, classification as **“catastrophic”** is not applicable.

Based solely on the gas concentration potentially entering the flight deck from a thermal runaway smoke event originated in the cabin, which remains below the MAK threshold, a classification above **“minor”** is not justified.

Exceeding the AEGL-2 level would mark the onset of serious or potentially irreversible health effects, which, according to Figure 6, would result in a classification as **“hazardous”**. In the simulation, the CO AEGL-2 threshold was only narrowly not exceeded, making it realistic to assume that a slight exceedance, and thus a **“hazardous”** classification also lies well within the realm of possibility, considering some assumptions have been made when performing the simulations in Figure 7. This outcome would apply if reignition of the PED could not be prevented or if passengers in the affected area could not be relocated. Preventing reignition – even without relocation of passengers – limits accumulated exposure to values clearly below the 10 min AEGL-2 level (Figure 8, right). Relocation of passengers within 90 s leaves an even larger margin to the 10 min average exposure (Figure 8, left). Preventing reignition and/or relocating passengers from the immediate vicinity would thus substantially lower exposure, keeping it well below the AEGL-2 threshold and thus supporting a classification as **“major”**.

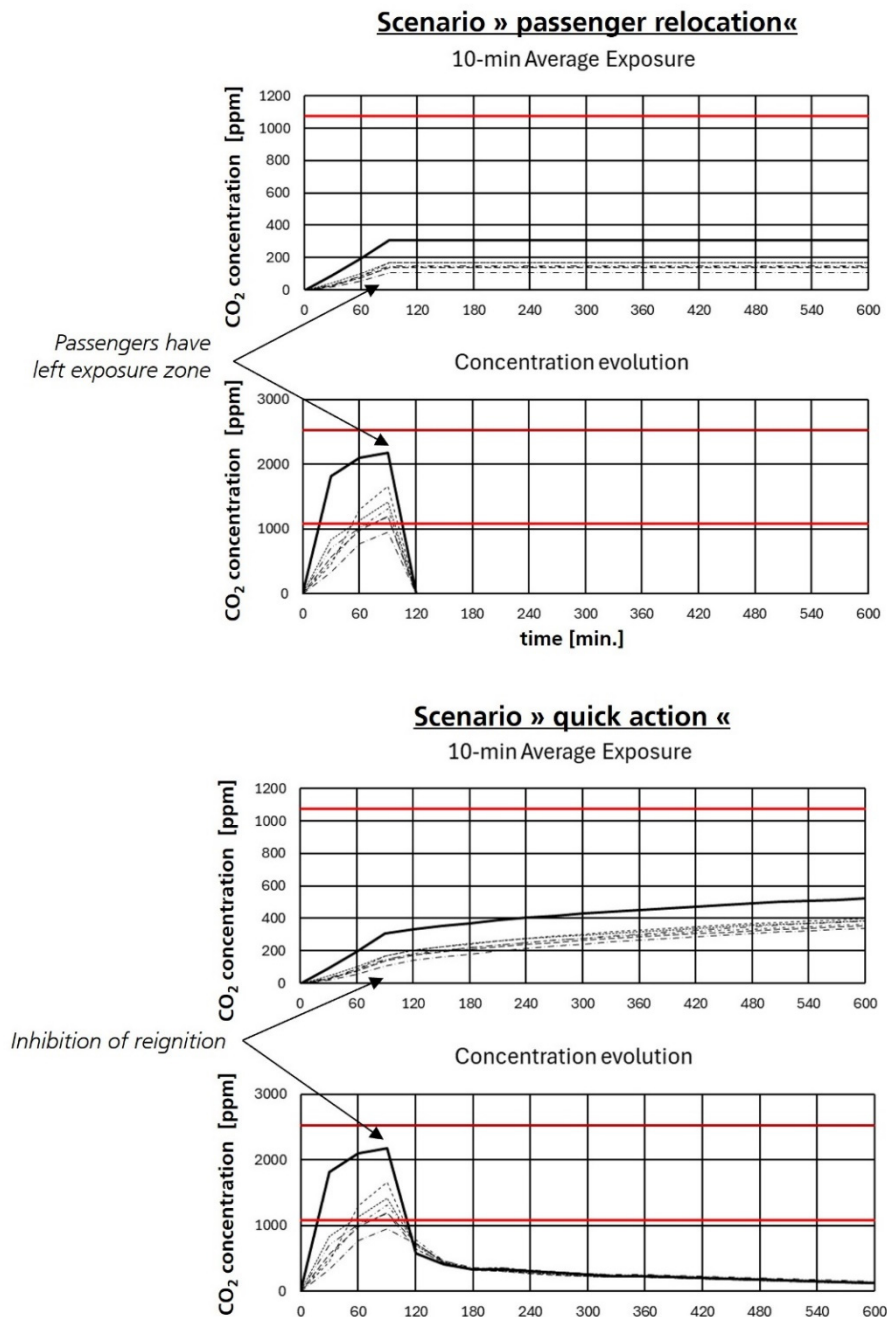


Figure 8: Simulation of a 100 Wh laptop fire scenario. The fire originates in the 4H newspaper holder, located behind seat 3H. Two scenarios are shown: (top panels) passengers are evacuated from the exposure zone; (bottom panels) prompt cabin crew action prevents PED reignition. Each case shows the 10-minute average tracer gas exposure (top) and the tracer gas concentration evolution (bottom). In both cases, exposure remains below the AEGL-2 limit.

However, even if passengers were relocated within the first minutes, thus avoiding the excessive inhalation of gases released during the reignition, or if reignition could be inhibited, localized exposure to elevated concentrations in the immediate plume may still pose a significant threat to crew members involved in locating, extinguishing, or removing the device, as well as to passengers in the direct vicinity. Exposure to these elevated concentrations of irritant or toxic gases may lead to physical distress or even serious injury. This is particularly relevant given that it cannot be reliably assumed that respiratory protection will be worn during the initial mitigation attempt. Therefore, classification as **“hazardous”** remains justified.

5.1.2 Visibility Reduction Due to Smoke

The simulation results regarding the concentration of smoke and the caused visibility reduction from deliverable D2.4 can be summarized as follows:

- Visibility reduction due to smoke can reach the LOKI-PED visibility classification 3, i.e. no visibility.
- Typically, elevated smoke density is observed within a two-seat radius from the emission site, potentially affecting 24-30 passengers.

Temporary visibility reduction in the cabin ranging from slight to moderate is more than a mere inconvenience but does not compromise occupant safety or significantly impair cabin crew performance. Although the reduced visibility may momentarily hinder the crew’s ability to locate the affected PED and initiate mitigation procedures, visibility is restored within 30 seconds (see D2.4). As no injuries or distress are expected and all required actions remain feasible, the consequences are consistent with the definition of being **“minor”** according to Figure 6.

However, in scenarios where available equipment or crew training is insufficient to rapidly identify and address the source of the incident, a classification of **“major”** may be justified, particularly if mitigation is delayed or the exposure duration increases.

A **“hazardous”** classification is excluded, as the smoke itself does not result in serious or fatal injuries, nor does it prevent the cabin crew from performing their safety-related duties.

5.1.3 Fire

In case of fire, serious burn injuries are possible for passengers in close proximity (especially the owner of the PED) to the device or for crew members involved in fire suppression. According to Figure 6, the potential for serious or fatal injury to even a small number of occupants justifies classification as **“hazardous”**. While fatal outcomes are improbable, the resulting injuries must still be considered serious.

A classification as **“major”** could only be justified if it can be reliably assumed that protective equipment such as fire-resistant gloves is available and correctly used, and the crew is adequately trained to intervene without injury. Even under these ideal conditions, however, passengers in close proximity to the device remain exposed to fire-related hazards. Taken together, these uncertainties ultimately warrant a **“hazardous”** classification.

A **“minor”** classification is not applicable in scenarios involving open flames and the potential for direct exposure.

While fire propagation cannot be entirely ruled out in theory, the scenario is not considered representative of a worst credible case. Escalation to a **“catastrophic”** outcome, such as uncontrolled fire spread resulting in multiple fatalities or the loss of the aircraft, is regarded as unrealistic, given the assumptions of early detection, trained crew, and the availability of fire suppression equipment.

5.1.4 Summary

The consequences of a thermal runaway of a PED in the passenger cabin are classified as **“hazardous”**, as the initial mitigation requires direct handling of the burning or smoldering device without guaranteed respiratory protection and without the possibility to immediately suppress the fire at its source. Toxic gas concentrations in the immediate plume may significantly exceed the average cabin values predicted by simulation, increasing the exposure risk for crew members. Furthermore, serious burn injuries are possible due to potential direct contact with flames or hot device surfaces during the transfer into a containment bag or liquid filled receptacle. These risks fulfill the criteria for a **“hazardous”** condition, as defined in AMC 25.1309 [2], due to the realistic potential for serious injury to a small number of passengers or cabin crew members.

5.2 Consequences in the Galley

5.2.1 Toxic Gases

As shown in the simulations presented in D2.4, the worst-case scenario, i.e., the highest concentration and widest spread of the tracer gas CO₂, occurs under the fresh-air-only ventilation regime. Near the incident, the 10-minutes AEGL-2 threshold for CO is exceeded. Also in the galley, higher peak concentrations can be expected within the direct plume.

Following the same line of argumentation as in 5.1.1, an incident occurring in the galley would also warrant classification as **“hazardous”**, based on the release of toxic gases. The main difference is that direct exposure of passengers is not expected in this scenario. However, it cannot be guaranteed that the first responding crew member will be wearing respiratory protection and would therefore be exposed to toxic gases.

5.2.2 Visibility Reduction Due to Smoke

The simulation results from deliverable D2.4 regarding smoke concentration and visibility reduction can be summarized as follows: Despite active ventilation, a significant reduction in visibility must be expected if a PED catches fire in the galley. The galley quickly fills with dense smoke, which only begins to dissipate after approximately 180 seconds, shortly before a second event introduces additional smoke.

As argued in 5.1.2, smoke release and associated visibility loss in the galley would also justify a **“major”** classification.

5.2.3 Fire

Following the same line of argumentation as in 5.1.3, serious burn injuries are possible for crew members involved in fire suppression, thus justifying a classification of a **“hazardous”**. A classification as **“major”** could only be justified if it can be reliably assumed that protective equipment such as fire-resistant gloves is available and correctly used, and the crew is adequately trained to intervene without injury. A **“minor”** classification is not applicable in scenarios involving open flames and the potential for direct exposure.

5.2.4 Summary

The consequences of a thermal runaway of a PED in the galley are classified as **“hazardous”**, as initial mitigation requires direct handling of the burning or smoldering device, without guaranteed respiratory protection and without guaranteed protection against burn injuries.

The main concern with a thermal runaway occurring in the galley is that the area may be unattended, leading to delayed detection and a loss of valuable response time. While this implies that no person is directly exposed during the initial phase, it also allows toxic gases and smoke to accumulate, making mitigation more difficult once the event is discovered.

5.3 Consequences in the Cockpit

5.3.1 Toxic Gases

The simulation results for a 100Wh Laptop from deliverable D2.4 regarding the concentration of toxic gases show that peak values exceed the 10-minute AEGL-2 thresholds for carbon monoxide (CO) and formaldehyde (HCHO). While the time- and space-averaged CO concentration in the cockpit remains below the AEGL-2 limit after ten minutes, localized peak concentrations exceed the threshold in less than one minute, that means already during the first thermal runaway, i.e. before the reignition.

Exceeding the AEGL-2 limits for carbon monoxide (CO) and formaldehyde (HCHO) does not result in immediate fatality but may lead to incapacitation of the flight crew. Such impairment, especially during critical phases of flight, can result in **“catastrophic”** consequences, including potential loss of aircraft control.

The immediate and correct use of oxygen masks with independent air supply can mitigate toxic exposure and reduce the severity of the event to **“hazardous”**, as crew members are then protected from the health effects of the gases. However, the situation remains **“hazardous”** due to the considerable increase in workload, restricted communication, and the persistent risk of delays or errors in donning the oxygen mask.

In cruise flight, where workload is generally lower and sufficient time is available to respond, the consequences may be further limited to a **“major”** condition, assuming oxygen masks are donned promptly, since the primary impact is a significant but manageable increase in workload.

Overall, in the worst credible case, AEGL-2 exceedance for CO and HCHO in the cockpit must be considered at least **“hazardous”** and potentially **“catastrophic”** if both pilots are simultaneously impaired due to errors or delays in using oxygen masks during critical phases of flight.

5.3.2 Visibility Reduction Due to Smoke

The simulation results for a 100Wh Laptop from deliverable D2.4 regarding the concentration of smoke and the caused visibility reduction can be summarized

as follows: within 30s the cockpit fills with smoke, and no more visibility is left. It takes 3 minutes until the grading is below 2 ("distinct smoke").

A complete loss of cockpit visibility due to dense smoke can lead to loss of aircraft control during critical flight phases such as takeoff or landing. This scenario justifies a classification as **"catastrophic"**, as the inability to maintain visual awareness of flight instruments or external references may result in a complete breakdown of flight crew performance.

Even in cruises, where autopilot systems are typically engaged, the situation remains at least **"hazardous"**, as temporary loss of visibility can still severely impair situational awareness and safe operation.

Protective breathing equipment or oxygen masks do not mitigate visibility loss. While they protect against toxic inhalation, they do not restore or improve visual conditions in the cockpit. Therefore, the hazard posed by smoke remains critical.

5.3.3 Fire

Even under the assumption that the crew acts immediately to remove the PED undergoing thermal run away from the cockpit to limit the consequences, the risk of burn injuries must still be considered. Handling a burning or smoldering PED involves direct contact with flames or hot surfaces. Due to the realistic potential for burn injury, the consequences remain classified at least as **"hazardous"**.

5.3.4 Summary

The consequences of a thermal runaway of a PED in the cockpit are classified as **"hazardous"** and may reach **"catastrophic"** severity under unfavorable conditions. Simulation results show that a 100 Wh laptop fire can lead to local exceedance of AEGL-2 limits for carbon monoxide (CO) and formaldehyde (HCHO) within less than one minute, posing a realistic risk of flight crew incapacitation. Such impairment, especially during critical flight phases, can result in loss of aircraft control.

The formation of dense smoke can completely obscure cockpit visibility within seconds. In contrast to the passenger cabin, impaired visibility in the cockpit has far more severe implications, as it can immediately affect the pilots' ability to maintain situational awareness and aircraft control. Even during cruise, where workload is lower, the event remains **"hazardous"** due to degraded visibility and increased operational workload.

Handling the burning or smoldering device additionally entails realistic potential for burning injuries. Considering toxic exposure, loss of visibility, and the need for immediate corrective action under high workload, a PED thermal runaway in the cockpit fulfills the criteria for a **“hazardous”** to **“catastrophic”** condition as defined in AMC 25.1309 [2].

5.4 Synthesis of the Consequence Analysis

This section consolidates the key consequences of thermal runaway events in cabin, galley, and flight deck scenarios together with selected considerations that emerged during the analysis. The objective is to provide an interim synthesis that captures both findings and reasoning, thereby supporting the subsequent risk assessment.

Although the 10-minute AEGL-2 thresholds were exceeded in some scenarios, it is unlikely that individuals would remain exposed to toxic gases for the full 10 minutes, especially since such events are typically accompanied by visible smoke. Either individuals escape exposure within a short time by donning breathing protection, as the responding cabin crew would do, or – like in the case of passengers – they are reseated or moved away from the danger zone by the crew. It should be noted, however, that in a fully booked aircraft, capacity constraints may arise, meaning that relocating affected passengers might not be feasible.

Nevertheless, it is essential that cabin crew members, particularly the first responder, immediately don respiratory protection when addressing a thermal runaway event, i.e., before approaching or handling the PED, as toxic gas concentrations in the plume may be considerably higher and may reach hazardous levels in less than 10 minutes. If preference is given to immediate response, the attacker’s duty should be limited to the acute firefighting and then a protected crew member should take over while the attacker moves away. Equally important is the prompt relocation of passengers in the immediate vicinity of the incident to reduce their exposure.

In the cockpit, relocation is not a viable option. Therefore, the primary mitigation must focus on the rapid removal of the device from the flight deck (see Deliverable D2.4). Even when pilots are wearing oxygen masks providing protection from toxic gases, this action is necessary, especially due to the visibility reduction caused by smoke, which oxygen masks do not mitigate.

While the inhalation of toxic gases can be mitigated through respiratory protection, this option is not available to passengers. This is particularly critical given the potentially high concentrations of toxic gases in the direct plume. As

a precautionary measure, safety instructions should emphasize that passengers must not attempt to handle a device in thermal runaway due to the risk of burn injuries and should avoid leaning over or placing their face near the affected device.

More broadly, consideration should be given to limiting the permitted battery capacity of personal electronic devices carried on board. This could significantly reduce the volume of toxic gases and smoke released in the event of a thermal runaway, thereby minimizing the associated risks. Currently, the carriage in the cabin of lithium-ion batteries in portable electronic devices is subject to international regulations, which generally permit batteries up to 100 Wh without restriction and allow two batteries in the range of 100–160 Wh with operator approval, while batteries above 160 Wh are prohibited (see chapter 8 for details on the regulations). These thresholds apply equally to passengers, cabin crew, and flight crew.

Given the confined space of the flight deck, leading to a quick accumulation of toxic gases and smoke in case of an incident, the criticality of crew performance, and the limited options for relocation or evacuation, consideration should be given to introducing more stringent limitations for PEDs in the cockpit compared to the cabin. In particular, the carriage of personal devices by flight crew could be reduced to the operationally necessary minimum (e.g., company-issued electronic flight bags), and the maximum permitted battery capacity could be set lower than in the passenger cabin. Such a measure would decrease the potential volume of toxic gas release and smoke production in the event of a thermal runaway, thereby mitigating both health and visibility risks in the flight deck.

6 Risk Assessment

Building on the probability assessment and the consequence evaluation presented in the previous chapters, the following section derives a risk classification for thermal runaway events in PEDs. This is done by plotting the values in a risk matrix (Figure 9), from which the resulting risk level is derived.

Both the classification of consequences, ranging from no safety effect to catastrophic along the x-axis, and the categorization of probability per flight hour, from 1.0E-11 (extremely improbable) to 1.0E-01 (not applicable), follow the definitions provided in EASA Certification Specifications CS-25, Amendment 28 [2]. The resulting risk level, and whether it is deemed acceptable (green) or unacceptable (red), is adopted directly from the criteria set out in this document.

		consequences				
		no safety effect	minor	major	hazardous	catastrophic
1.0E-01	N.A.	green	red	red	red	red
1.0E-03	probable	green	green	red	red	red
1.0E-05	remote	green	green	green	red	red
1.0E-07	extremely remote	green	green	green	green	red
1.0E-09	extremely improbable	green	green	green	green	green
1.0E-11		green	green	green	green	green

Figure 9: Risk matrix for a thermal runaway of a PED in the passenger cabin. The classification of probability and consequences is based on the EASA CS-25 Amendment 28 (AMC 25.1309) document, according to which a risk (i.e., the relationship between the probability of an event and the severity of its consequences) is defined as acceptable (marked in green) or unacceptable (marked in red).

Based on the calculation presented in Section 4.1, the likelihood of a thermal incident involving one of the device types examined in the LOKI-PED project (cell phone, laptop, tablet) and also power bank in the passenger cabin of a fully occupied Airbus A320neo (194 passengers plus 4 cabin crew members) is $4.97\text{E-}06$ per flight hour. This corresponds to a **“remote”** probability classification. As outlined in Section 5.1.4, the consequences of a thermal runaway event in the cabin are classified as **“hazardous”**. Combining these two dimensions, the resulting risk falls within the unacceptable range, according to the risk classification scheme defined in EASA CS-25 Amendment 28 (Figure 10).

By contrast, for much larger aircraft such as the Airbus A350, with its significantly higher passenger capacity of 480 passengers plus 10 cabin crew, or even the world’s largest passenger aircraft A380, accommodating up to 868 passengers and 18 cabin crew, the probability of a thermal incident increases to $1.23\text{E-}05$ and $2.22\text{E-}05$ per flight hour, respectively (see also chapter 7), placing them in the **“probable”** category, while the severity of consequences remains unchanged.

It should be noted that this assessment is rather conservative. A phone or tablet undergoing thermal runaway would likely produce less smoke and less toxic gases than a laptop or power bank. However, such devices could still cause comparable burn injuries during handling, which justifies maintaining the **“hazardous”** consequence classification. On the other hand, deliverable D1.7 shows that even under laboratory conditions intentionally triggered thermal runaway, while all PEDs produced smoke, only 15 out of 26 cases were classified as fire events. For laptops specifically, 13 out of 18 test cases resulted in fire.

It is therefore essential to aim at limiting the severity of consequences as much as possible, and at least to strive to keep them within the **“major”** category. Suited mitigation means include, for example, the use of fire-protective gloves and respiratory protection by the cabin crew, and the instruction of passengers not to touch a PED undergoing thermal runaway or to inhale the emitted plume (see also subchapters 5.1.3, 5.2.3, and chapter 8). A more detailed assessment and discussion of emergency procedures and mitigation measures is part of LOKI-PED work packages 5 and 6 and provided in Deliverable D6.4.

Furthermore, it should be noted that risk classification in this context cannot be made with absolute precision. While the use of a risk matrix offers a structured approach, it may give the impression of greater clarity than is achievable. In reality, a number of assumptions must be made regarding input parameters such as passenger behavior, device type, battery characteristics, gas spread, and crew response. These assumptions introduce uncertainties that limit the precision of any resulting classification. Nevertheless, this analysis suggests that

the overall risk in the passenger cabin is at least close to the threshold of acceptability. If the number of PEDs carried on board increases in the future or if battery capacities continue to grow, leading to larger amounts of gas and smoke in the event of thermal runaway, the resulting risk could shift further into the range defined as unacceptable (see chapter 7).

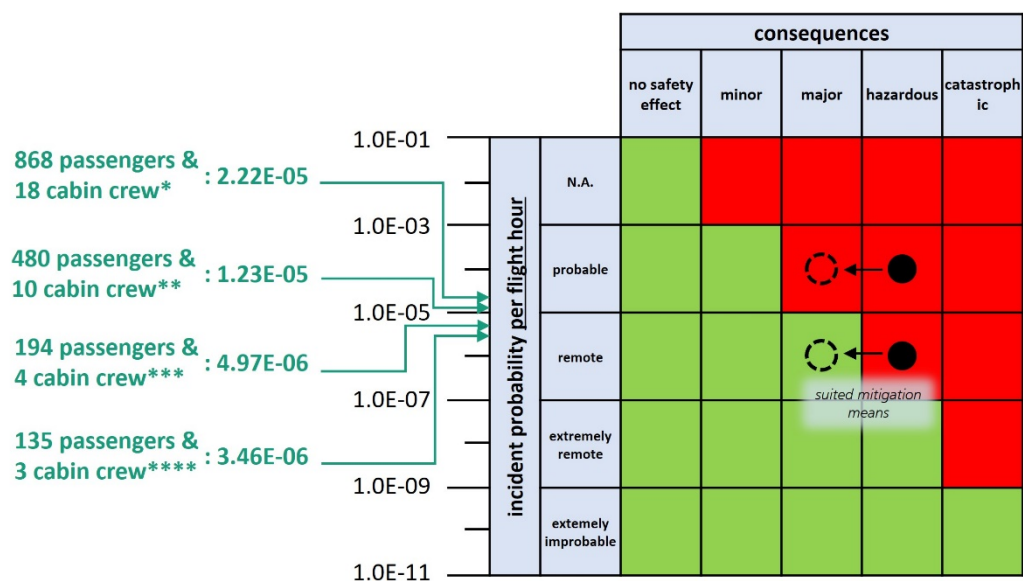


Figure 10: Risk matrix accounting for different passenger capacities (& crew number) corresponding to aircraft such as the Airbus A220-100****, A320neo***, A350**, and A380*. The assessment of consequences remains identical across all aircraft types. The effects of applying suited mitigation means are represented by dashed markers in the risk matrix.

Given the typically very small number of PEDs present in the galley during flight, the overall probability of such an incident can be assessed as very low, likely falling into the **“remote”** or even **“extremely remote”** category. When combined with the classification of the consequences as **“hazardous”** (see chapter 5.2.4), the resulting risk associated with a PED thermal runaway in the galley lies at the boundary between the unacceptable and acceptable ranges, i.e., it may still be considered unacceptable or only just within the acceptable range. As in the passenger cabin, efforts should be made to reduce the potential consequences to at least the **“major”** level. This should be more readily achievable in the galley, as the chance of individual passengers being affected is small, and it is realistic to ensure adequate protection of cabin crew through the use of protective breathing equipment and fire-resistant gloves.

In the same way, incident probability and the assessment of consequence severity can be combined for the risk assessment on the flight deck. It is assumed that, regardless of aircraft type, two pilots are present, each carrying

one mobile phone, one tablet, one laptop, and one portable power bank. Under these conservative assumptions, the incident probability per flight hour falls within the **“remote”** category, close to **“extremely remote”**. When combined with the consequence assessment established in chapter 5.3, this results in a risk classification as **non-acceptable**, both during the critical flight phases (with the consequences classified as **“catastrophic”**) and during the remainder of the flight (classified as **“hazardous”**) (Figure 11). Even when considering that the critical flight phases are relatively short in duration, so that the probability of an incident occurring specifically during these phases may be considered extremely remote, the risk assessment still remains not acceptable, given that the potential consequences are classified as **“catastrophic”**. It is therefore essential to introduce appropriate mitigating measures and procedures to limit the consequences of a thermal runaway event on the flight deck.

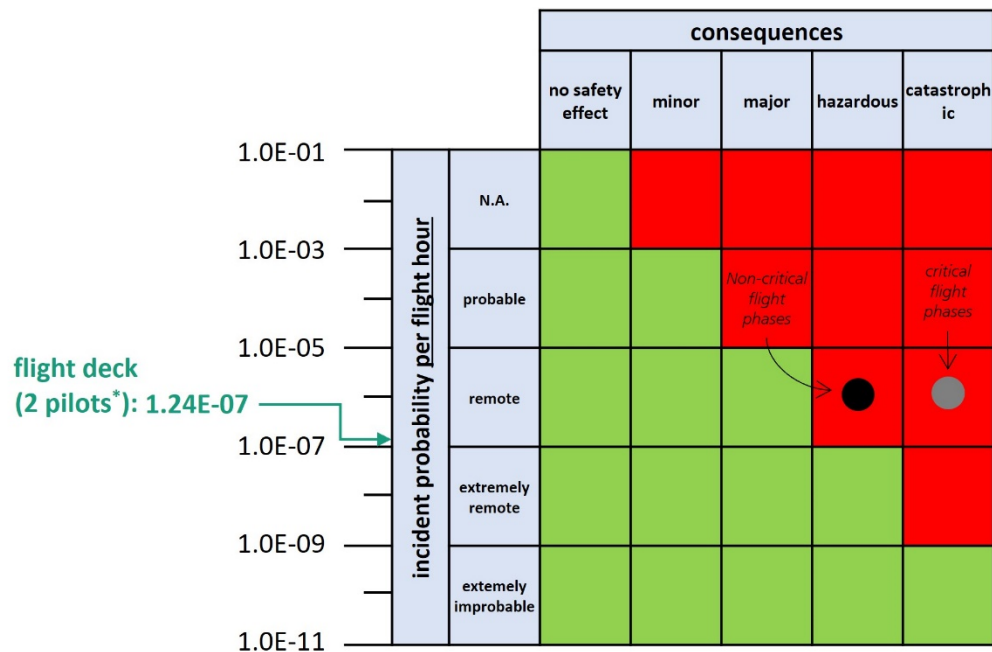


Figure 11: Risk matrix for the flight deck, assuming a two-pilot crew configuration for all aircraft types, illustrating the relative risk associated with lithium battery thermal runaway events in PEDs during critical and non-critical flight phases. The black marker indicates the risk during non-critical phases, while the grey marker represents the risk during critical phases.

7 Sensitivity Analysis

The risk assessment approach and the underlying data presented in the previous chapters permit, within certain limitations, studying the sensitivity of input parameters on the calculated risk. Specifically, this analysis provides an indication of how passenger behavior and/or changing capacities of the lithium batteries in PEDs may influence the overall risk, and it is presented in the following chapter.

7.1 Influence of Passenger Behavior

The following analysis examines how variations in passenger behavior influence the incident's probability, considering that, for the purpose of this assessment, cabin crew members are assumed to behave similarly to passengers. The analysis focuses on the proportion of passengers carrying specific devices containing lithium batteries, namely mobile phones, laptops, tablets, and portable chargers/power banks. Calculations are performed for four scenarios: 0 % (no passenger carries the device, representing a ban on bringing it on board), 100 % (every passenger carries one), 200 % (every passenger carries two), and double the current prevalence. Only one device type varies at a time, while the prevalence of all other PEDs remains as specified in Table 2.

This analysis was conducted for aircraft with different passenger capacities. Cabin crew members are assumed to exhibit the same behavior as passengers with respect to carrying PEDs. Four aircraft types were considered: a narrow-body Airbus A320neo-type aircraft with a capacity of 194 passengers plus 4 cabin crew members (Table 3), a narrow-body Airbus A220-100-type aircraft with a capacity of 135 passengers plus 3 cabin crew members (Table 4), a wide body Airbus A350-type aircraft with a capacity 480 passengers plus 12 cabin crew members (Table 5), and the world's largest passenger aircraft, the double-deck wide-body Airbus A380, with 868 passengers plus 18 cabin crew members approved for evacuation (Table 6).

As can be seen in case of an A320neo-sized aircraft (Table 3), no change in probability level classification occurs for any device type. However, the probability level classification changes when considering portable chargers or power banks. According to the UL survey (see Table 2), currently only about 31 % of passengers carry this item. An increase to 100 % or even 200 % would therefore correspond to a threefold or sixfold rise compared to current figures. On the other hand, banning just any single device type on board likewise does not result in a shift to a lower probability category.

For the smaller narrow-body A220, a shift to a higher probability category would only occur if every passenger and crew member carried at least two power banks or portable chargers (see Table 4).

Since the A350 has more than twice the passenger capacity of the A320, and consequently a proportionally higher number of PEDs on board, the probability of an incident is increased and falls within the **“probable”** category. In the scenarios analyzed, only a reduction of portable chargers and power banks to 0% results in a downward shift to a lower category. Conversely, an increase in the number of any of the device types does not lead to further escalation beyond the **“probable”** category (see Table 5).

In the case of the Airbus A380 (Table 6), the probability of an incident also falls within the **“probable”** category. Even a complete ban on portable chargers and power banks does not reduce the probability sufficiently to reach the next lower category, **“remote”**. Such a reduction would only be achievable by eliminating both power banks and laptops (0 %). In this case, the probability would be 7.68E-06.

Table 3: Sensitivity analysis of PED incident probability as a function of passenger behavior for an aircraft of the size of an Airbus A320neo (i.e. 194 passengers + 4 cabin crew). The table shows overall probabilities when varying the percentage of one device type carried by passengers at a time. Changes in probability categories are highlighted in color. The incident probability with current device prevalence is 4,97E-06.

% of passengers carrying device	Cell phone	Laptop	Tablet	Portable charger or power bank
Double current prevalence	6,42E-06	5,84E-06	5,23E-06	7,34E-06
200 % (2 per passenger)	7,06E-06	8,35E-06	6,17E-06	1,79E-05
100 % (1 per passenger)	5,29E-06	6,22E-06	5,44E-06	1,03E-05
0 % (0 per passenger)	3,51E-06	4,09E-06	4,70E-06	2,59E-06

Table 4: Sensitivity analysis of PED incident probability as a function of passenger behavior for an aircraft of the size of an Airbus A220-100 (i.e. 135 passengers + 3 cabin crew). The table shows overall probabilities when varying the percentage of one device type carried by passengers at a time. Changes in probability categories are highlighted in color. The incident probability with current device prevalence is 3,46E-06.

% of passengers carrying device	Cell phone	Laptop	Tablet	Portable charger or power bank
Double current prevalence	4,47E-06	4,07E-06	3,65E-06	5,12E-06
200 % (2 per passenger)	4,92E-06	5,82E-06	4,30E-06	1,25E-05
100 % (1 per passenger)	3,68E-06	4,34E-06	3,79E-06	7,15E-06
0 % (0 per passenger)	2,45E-06	2,85E-06	3,28E-06	1,80E-06

Table 5: Sensitivity analysis of PED incident probability as a function of passenger behavior for an aircraft of the size of an Airbus A350 (i.e. 480 passengers + 10 cabin crew). The table shows overall probabilities when varying the percentage of one device type carried by passengers at a time. Changes in probability categories are highlighted in color. The incident probability with current device prevalence is 1,23E-05.

% of passengers carrying device	Cell phone	Laptop	Tablet	Portable charger or power bank
Double current prevalence	1,59E-05	1,44E-05	1,29E-05	1,82E-05
200 % (2 per passenger)	1,75E-05	2,07E-05	1,53E-05	4,44E-05
100 % (1 per passenger)	1,31E-05	1,54E-05	1,35E-05	2,54E-05
0 % (0 per passenger)	8,69E-06	1,01E-05	1,16E-05	6,41E-06

Table 6: Sensitivity analysis of PED incident probability as a function of passenger behavior for an aircraft of the size of an Airbus A380 (i.e. 868 passengers + 18 cabin crew). The table shows overall probabilities when varying the percentage of one device type carried by passengers at a time. Changes in probability categories are highlighted in color. The incident probability with current device prevalence is 2,22E-05.

% of passengers carrying device	Cell phone	Laptop	Tablet	Portable charger or power bank
Double current prevalence	2,87E-05	2,61E-05	2,34E-05	3,29E-05
200 % (2 per passenger)	3,16E-05	3,73E-05	2,76E-05	8,02E-05
100 % (1 per passenger)	2,36E-05	2,78E-05	2,43E-05	4,59E-05
0 % (0 per passenger)	1,57E-05	1,83E-05	2,10E-05	1,16E-05

7.2 Influence of Flight Crew Behavior

In chapter 6, a conservative assumption was made that, irrespective of aircraft type, two pilots are present on the flight deck, each carrying one device of all four device types containing lithium batteries: a mobile phone, a laptop, a tablet, and a portable charger or power bank.

By prohibiting power banks and portable chargers on the flight deck (i.e. reducing their prevalence to 0 %), the incident probability per flight can be reduced from 1.24E-07 to 4.68E-08, corresponding to a change from the **"remote"** to the **"extremely remote"** category. Under these conditions, the associated risk during non-critical flight phases falls within the acceptable range; however, this is not yet the case for critical flight phases.

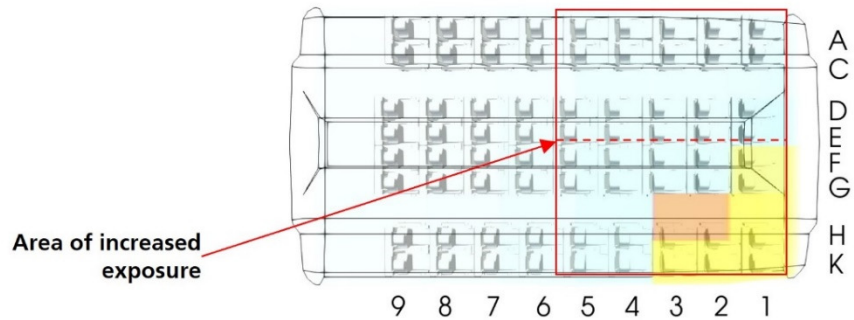
Even with a single tablet present, the calculated incident probability is 3.71E-09, which still does not reach the **"extremely improbable"** category, i.e. the probability required for the risk to be considered acceptable when the consequences are classified as catastrophic.

To minimize the risk during critical flight phases as far as reasonably practicable, in absence of other mitigating measures, it can therefore be recommended to remove all PEDs from the flight deck, allowing at most the use of a tablet (see also Deliverable D2.4) such as an electronic flight bag if authorized at operational level.

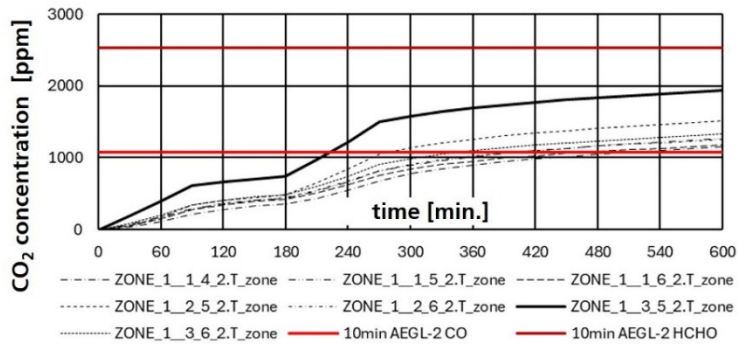
7.3 Influence of Battery Capacity

In addition to varying the prevalence of PEDs among passengers, it is also important to consider how changes in battery capacity might influence the severity of the consequences of a thermal runaway incident. The subsequent analysis addresses this aspect. We consider 2 different scenarios. First, a scenario in which the PED battery capacity is doubled (200 Wh instead of 100 Wh). Under the assumption that the potential volume of toxic gases increases proportionally (D1.7), concentrations and exposures also double. Therefore, the area of short-term exceedance of the 10 min AEGL-2 limit for CO expands accordingly. Already during the first ignition, the margin to the 10 min AEGL-2 level for CO becomes narrow, and short-term exposures exceed the limit for both CO and HCHO (Figure 12).

In a second scenario, the battery capacity is quadrupled (i.e. 400 Wh instead of 100 Wh). In this case, the margin to the 10 min AEGL-2 level for CO becomes exceeded already during the first ignition (Figure 13).



10-min Average Exposure



Concentration evolution

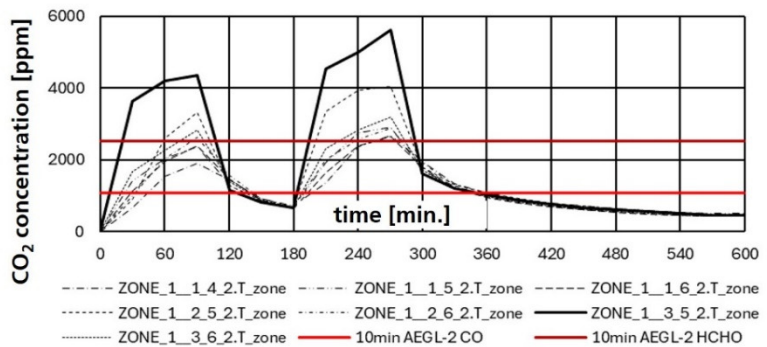


Figure 12: Simulation of exposure in case of an untreated 200Wh laptop fire (compare Figure 7 for simulation with 100Wh laptop). Simulation shows fire in 4H newspaper holder i.e. the rear seat of 3H (top). Simulation of 10-minutes average tracer gas exposure (middle). Tracer gas concentration evolution (bottom).

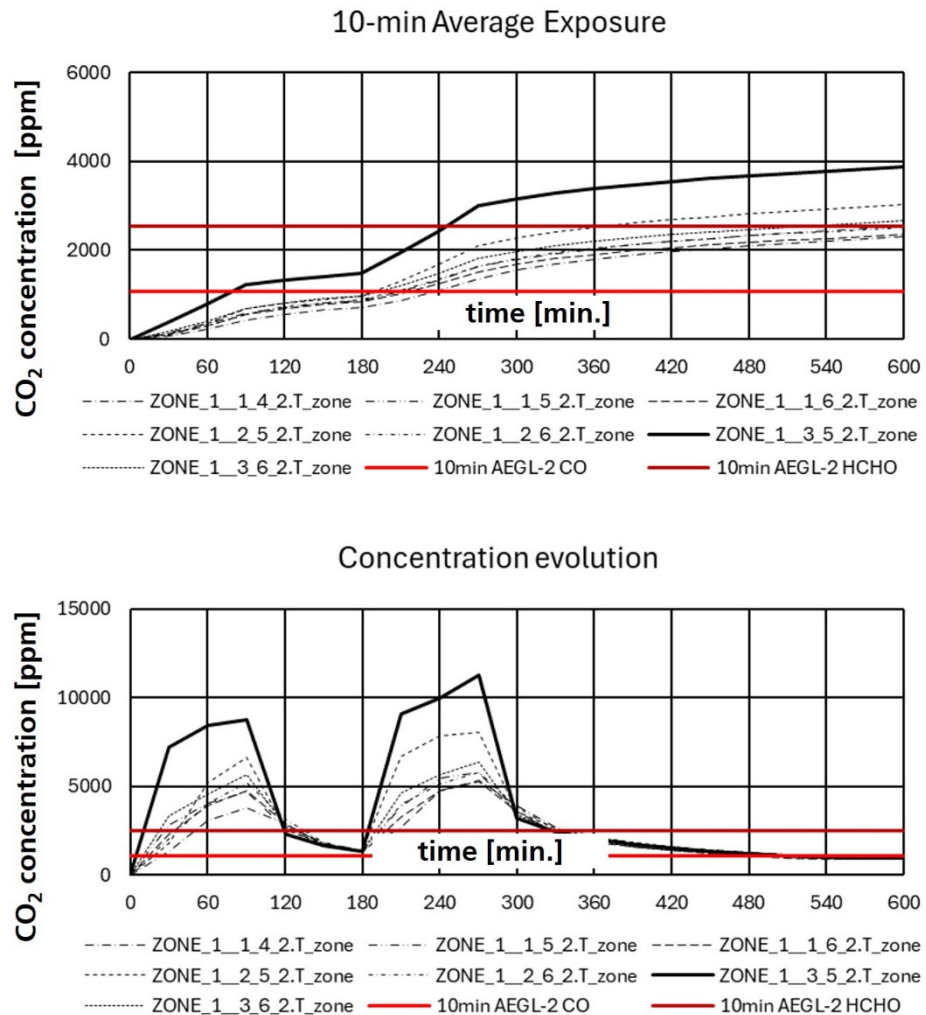


Figure 13: Simulation of exposure in case of an 400 Wh laptop fire. Simulation shows fire in 4H newspaper holder i.e. the rear seat of 3H (top). Simulation of 10-minutes average tracer gas exposure (top). Tracer gas concentration evolution (bottom).

7.4 Concluding Remarks

The sensitivity analysis of the input parameters indicates that variations in passenger behavior (number and type of carried devices) and battery capacity can influence the overall risk of PED-related thermal runaway incidents, albeit to different degrees. Changes in passenger behavior, particularly an increased prevalence of portable chargers and power banks, have the most pronounced effect on incident probability.

For narrow-body aircraft such as the A220 and A320neo, a significant rise leading to a shift in probability classification to **“probable”** occurs only when every passenger carries at least one or two power banks, respectively. This implies that even with mitigation measures (see e.g. Deliverable 6.4) capable of reducing the severity of consequences from **“hazardous”** to **“major”**, the overall risk would remain unacceptable (Figure 14).

For wide-body aircraft (A350 and A380), the baseline probability is already classified as **“probable”** due to the potential larger number of passengers and thus lithium battery devices on board. In these cases, even stringent restrictions, such as banning individual device types, only result in a downward shift in probability classification if power banks, or both power banks and laptops, were not allowed on board. According to the results presented in chapter 5, this represents the only effective means, when combined with mitigation measures, to reduce the overall risk to a level considered acceptable (Figure 15).

In contrast, variations in battery capacity primarily affect the consequences of PED-related incidents (the analysis of the relationship between battery capacity and incident frequency is beyond the scope of the LOKI-PED project). Doubling or quadrupling the battery energy content results in significantly higher gas emissions and a faster exceedance of short-term exposure limits (AEGL-2). This finding suggests that the increasing energy density of lithium-ion cells represents a critical factor in future risk assessments.

Although no change in the classification of consequences (see chapter 5) can be expected based on battery capacity alone, higher energy densities may compromise the effectiveness of existing mitigating measures.

For the flight deck, the probability is classified as **“remote”** in a conservative scenario (cf. chapter 7.2). By restricting the number and type of PEDs permitted on the flight deck, the probability of a thermal runaway can be reduced to **“extremely remote”**. This reduction is sufficient to bring the risk into a range considered acceptable under EASA CS-25 Amendment 28 (AMC 25.1309) [2] during non-critical flight phases, but not during critical flight ones (Figure 16).

To minimize the risk as far as reasonably practicable, it can therefore be recommended to remove all PEDs from the flight deck, allowing at most the use of a certified electronic flight bag (EFB) where operationally required.

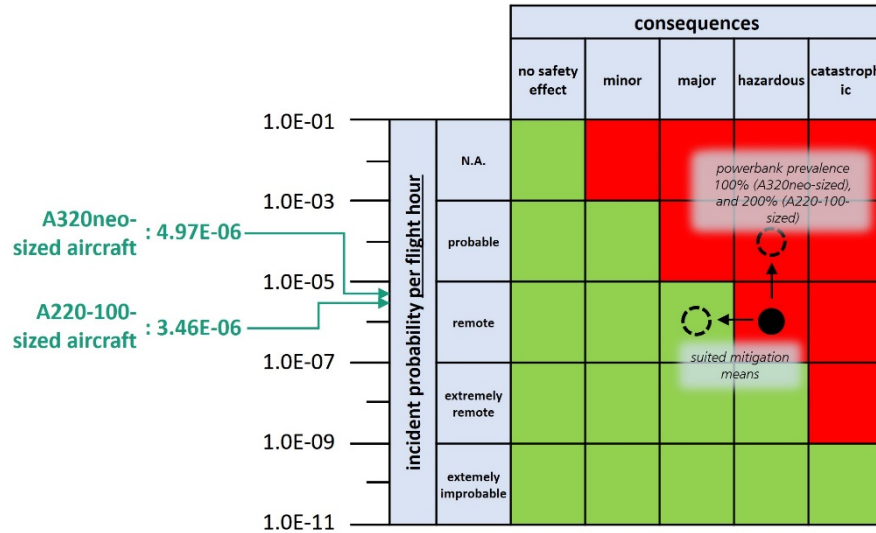


Figure 14: Risk matrix for the passenger cabin of single-aisle aircraft in the capacity range of the A320neo and A220-100. The black marker indicates the risk level as determined in chapter 6 for lithium battery thermal runaway events in PEDs. The dashed marker illustrates how this risk can shift to the next category due to passenger behavior or the implementation of mitigation measures.

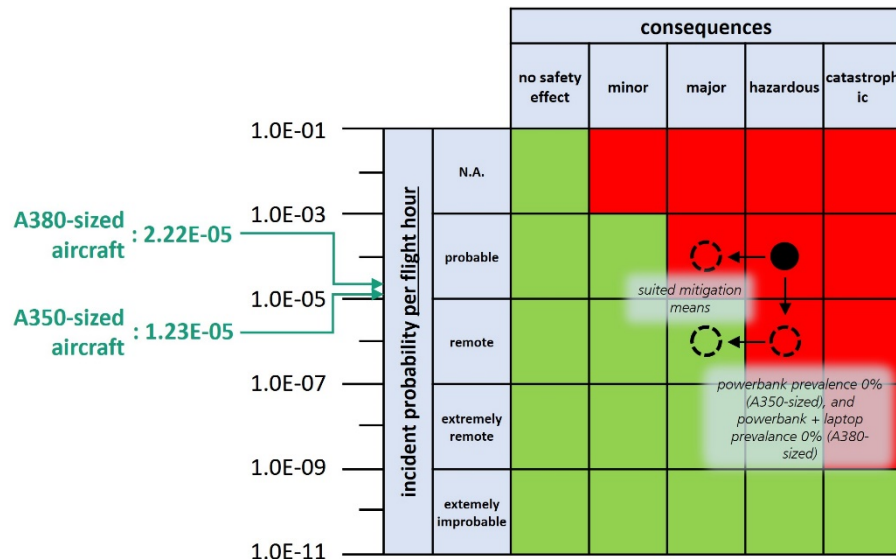


Figure 15: Risk matrix for the passenger cabin of double-aisle aircraft in the capacity range of the A350 and A380. The black marker indicates the risk level as determined in chapter 6 for lithium battery thermal runaway events in PEDs. The dashed marker illustrates how this risk can shift to the next category due to passenger behavior or the implementation of mitigation measures.

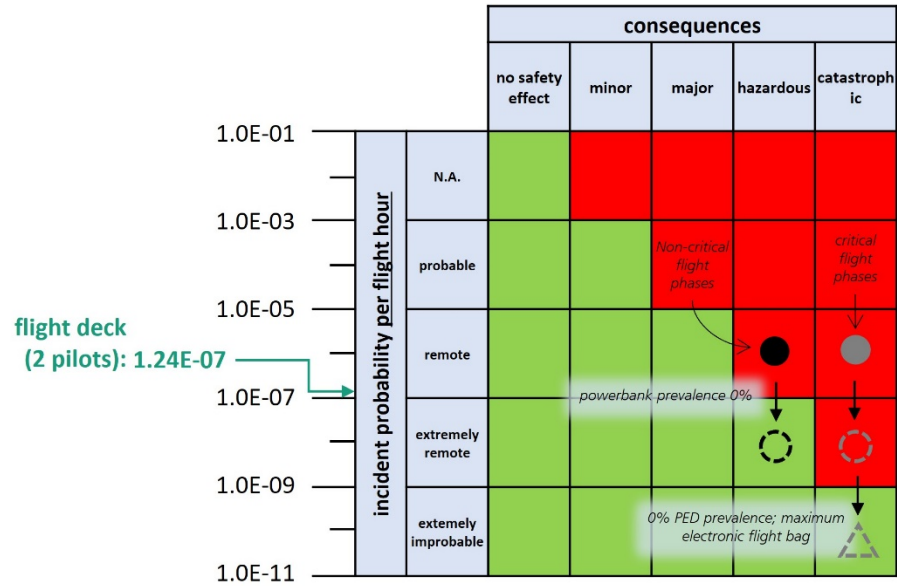


Figure 16: Risk matrix for the flight deck. The black marker indicates the risk level as determined in chapter 6 for lithium battery thermal runaway events in PEDs during non-critical flight phases, and the grey marker for critical flight phases. The dashed marker illustrates how this risk can shift to the next category. Under specific and favorable assumptions, it may be argued that the risk could be further reduced (dashed triangle).

8 Regulations

Operational regulations for Portable Electronic Devices (PEDs) equipped with lithium batteries are primarily focused on mitigating the risk of fire and are governed by international and national aviation authorities. The main organizations that set these standards are the International Civil Aviation Organization (ICAO), the Federal Aviation Administration (FAA) in the United States, and the European Union Aviation Safety Agency (EASA).

Individual airlines may also impose their own, more restrictive, conditions.

This chapter summarizes the key regulations and requirements.

8.1 ICAO (International Civil Aviation Organization)

ICAO's regulations are the foundation for most of the national rules. Transport of dangerous goods falls under the scope of Annex 18 of the Chicago Convention. The detailed provisions can be found in the *Technical Instructions for the Safe Transport of Dangerous Goods by Air (Doc 9284)* [8]. Furthermore, the *IATA Dangerous Goods Regulations (DGR)* [9], which airlines widely adopt, incorporate the requirements of the Technical Instructions.

The Primary Hazard: Lithium batteries are considered “dangerous goods” due to their potential to overheat, short-circuit, and ignite, leading to a fire that is difficult to extinguish. This is known as “thermal runaway”.

Carriage Location: Spare (uninstalled) lithium batteries and power banks are strictly prohibited in checked baggage and must be carried in the passenger cabin (carry-on baggage).

PEDs in Checked Baggage: Portable electronic devices containing lithium batteries can be placed in checked baggage under specific conditions:

- The device must be completely powered off (not in sleep or hibernation mode).
- Measures must be taken to prevent unintentional activation.
- The device and its batteries must be protected from damage.

Watt-Hour (Wh) Limits: The regulations classify batteries by their energy rating (Wh) to determine carriage limits:

- **Less than 100 Wh:** Most common consumer devices (laptops, phones, tablets) fall into this category. They are generally permitted in both carry-on and checked baggage (with the precautions mentioned above).
- **100-160 Wh:** Larger batteries for professional equipment or extended-life laptops. These require airline approval, and a limit of two spare batteries per person is typically allowed in carry-on baggage only.
- **Greater than 160 Wh:** These batteries are generally forbidden from passenger aircraft and must be transported as air cargo under specific dangerous goods regulations.

Safety Information and Training: ICAO emphasizes the importance of providing clear information to passengers and crew. Airlines are required to inform passengers about the regulations through websites, tickets, and airport signage.

8.2 FAA (Federal Aviation Administration – U.S.)

The FAA's regulations are consistent with ICAO standards and are outlined in the *Federal Hazardous Materials Regulations*, which form part of Title 49 of the U.S. **Code of Federal Regulations (CFR)** (*49 CFR 175.10*) [10] and various safety alerts.

- **Carry-on is Preferred:** The FAA strongly recommends that all PEDs with lithium batteries be carried in the passenger cabin. This allows the flight crew to quickly identify and respond to any potential fire.
- **Checked Baggage Rules:** If a PED is in checked baggage, it must be completely turned off and protected from unintentional activation.
- **Spare Batteries and Power Banks:** These are considered batteries and are absolutely prohibited in checked baggage. They must be carried in carry-on bags and protected from short circuits (e.g., by taping the terminals, using original packaging, or placing them in a separate pouch).
- **Damaged or Recalled Devices:** Any damaged, defective, or recalled devices or batteries that are likely to overheat or spark are prohibited from being carried on an aircraft.

In addition, *14 CFR § 91.21 - Portable electronic devices* [11]: This is the foundational regulation for all U.S.-registered civil aircraft. It generally prohibits the operation of any PED on an aircraft, with a few exceptions. Critically, it allows for the use of "any other portable electronic device that the operator of the aircraft has determined will not cause interference with the navigation or communication system of the aircraft on which it is to be used". This places the responsibility of a PED-use policy squarely on the airline or operator.

14 CFR § 121.306 - Portable electronic devices [12]: This regulation applies specifically to air carrier operations (Part 121), which includes most major airlines. It mirrors the language of § 91.21, giving the air carrier certificate holder the responsibility to determine which PEDs can be used without interfering with aircraft systems.

While the CFRs are the regulations themselves, the FAA also publishes **guidance material, as e.g. Advisory Circulars (AC)** to help operators comply. These are not binding rules, but they represent an "acceptable means of compliance."

AC 120-80B, Firefighting of General and High-Energy In-Flight Fires [13]: This is a major reference. It provides information and guidance on the hazards and risks of in-flight fires, including those caused by lithium-ion batteries. It outlines recommended crewmember procedures and training for combating high-energy fires (HEFs). The circular emphasizes the need for a comprehensive response that includes fire suppression, cooling, and containment.

AC 91-21-1D, Use of Portable Electronic Devices Aboard Aircraft [14]: This advisory circular provides guidance to operators on how to determine which PEDs can be used on board their aircraft without interfering with the aircraft's navigation and communication systems. It explains how to comply with the regulations and how to conduct the necessary safety assessments to permit expanded PED use. It references industry standards and test methods for evaluating the potential for electromagnetic interference (EMI).

AC 91-92, Pilot's Guide to a Preflight Briefing [15]: While a general guide, it emphasizes the importance of a thorough preflight brief, which includes checking for potential hazards like undeclared dangerous goods, including lithium batteries.

AC 20-164A - Designing and Demonstrating Aircraft Tolerance to Portable Electronic Devices [16]: This Advisory Circular is more focused on aircraft manufacturers and modifiers. It identifies RTCA, Inc. document DO-307A as an acceptable means for designing and demonstrating that aircraft systems are tolerant to potential EMI from PEDs. This is a crucial step for airlines that want

to allow full use of PEDs, as a “PED-tolerant” aircraft simplifies their operational assessment.

FAA's *PackSafe Website* [17]: The FAA maintains an extensive and accessible public resource on its website under the "PackSafe" section, which details the specific regulations for passengers regarding lithium batteries and other hazardous materials. This serves as a key informational resource for both passengers and airline personnel.

The FAA also publishes information to the operators (InFOs) and Safety Alerts for Operators (SAFOs):

Information for Operators (InFO) 13010, Expanding Use of Passenger Portable Electronic Devices (PED) [18]: This document, and its supplement, were key to the FAA's shift in policy, which allowed airlines to permit the use of PEDs during all phases of flight (including takeoff and landing) as long as the device is in “Airplane Mode” and properly stowed during critical phases. It provided guidance on how to conduct the risk assessment to expand PED use.

Information for Operators (InFO)17008, The Transportation of Portable Electronic Devices (PED) in Checked Baggage [19]: This document was a critical response to security policies that, at one point, considered banning large PEDs from the cabin. The FAA used this InFO to raise awareness of the risks of putting these devices in checked baggage and to recommend that operators conduct safety risk assessments to mitigate the risks. It clearly states that PEDs should preferably be carried in the cabin.

Safety Alerts For Operators (SAFO) 09013, Fighting Fires Caused by Lithium Type Batteries in Portable Electronic Devices [20]: This is one of the earliest and most direct alerts on the topic. It provides guidance on how to fight a lithium battery fire, emphasizing the need for a combination of a fire extinguisher (like Halon) to knock down the flames and then a large amount of water to cool the battery and stop the thermal runaway.

Safety Alert for Operators (SAFO) 15010: Carriage of Spare Lithium Batteries in Carry-on and Checked Baggage [21], It recommends that airlines inform passengers of the requirement to carry spare lithium batteries in carry-on baggage, and inform passengers not to put PEDs in checked luggage if the devices are not completely turned off and protected from accidental activation.

These alerts are not regulations but strongly recommend that airlines take specific actions. Recent SAFOs have emphasized:

- **Crew Training:** The importance of crew training on how to identify and respond to a lithium battery thermal runaway event. This includes recognizing the signs of overheating, smoke, and flames.
- **Firefighting Procedures:** A key recommendation is to revise firefighting procedures. While Halon extinguishers can suppress flames, they do not stop the thermal runaway process. The FAA strongly recommends using large volumes of water to cool the battery and prevent re-ignition.
- **Fire Containment Equipment:** Airlines are urged to equip their aircraft with fire containment products (e.g., fire containment bags) that can safely contain a device in thermal runaway.
- **Passenger and Crew Awareness:** Airlines should proactively educate passengers and crew about the risks of lithium batteries, including where they should and should not be stored. For example, the FAA recommends storing devices in overhead bins where they are not easily accessible for monitoring or fire response.

Additionally, the FAA's William J. Hughes Technical Center has conducted extensive fire safety research on lithium-ion batteries. The results of these tests are frequently **presented at conferences and referenced in FAA guidance documents**, providing the scientific basis for their recommendations on cooling and containment.

These FAA documents are typically "guidance" or "recommendations" rather than legally binding regulations. However, most air carriers and operators follow them closely, and they are considered an acceptable means of compliance for ensuring a high level of safety.

8.3 EASA (European Union Aviation Safety Agency – Europe)

*Commission Regulation (EU) No 965/2012 of 5 October 2012 laying down technical requirements and administrative procedures related to air operations pursuant to Regulation (EC) No 216/2008 of the European Parliament and of the Council [22] (known as the Air OPS Rules) contains a direct reference to ICAO Annex 18 and to the *Technical Instructions for the Safe Transport of Dangerous Goods by Air (Doc 9284)*. Additionally, it refers in its Guidance Material to the *ICAO Emergency Response Guidance for Aircraft Incidents Involving Dangerous Goods (Doc 9481)*.*

The Air OPS rules additionally contain provisions on the use of PEDs on board and establish minimum requirements for occurrence reporting. However, they

do not contain specific provisions for the transport of lithium batteries, as they are already contained in the ICAO provisions referred.

EASA has issued additional guidance through Safety Information Bulletins. The most relevant one is SIB 2025-03 [23], *Passenger and Crew Awareness on the Risks of Lithium Batteries*, applicable to aircraft operators, aerodrome operators, ground handling service providers, and National competent authorities. Key points of this SIB are the following:

- Awareness and risk mitigation: that personnel and passengers are fully aware of the restrictions, including limits in power and number, what can and cannot be in checked baggage, and tailored recommendations for power banks
- Training: personnel are instructed to act, proper equipment is provided, and they report occurrences properly

EASA's "*Dangerous Goods*" **Website** [24]: EASA provides public-facing guidance on dangerous goods, including a dedicated section on lithium batteries, e-cigarettes, and other personal electronic devices. This content aligns with and reinforces the principles found in their SIBs and other regulatory documents.

In the Airworthiness domain, **CS 25 requirements** [2], are only applicable to aircraft installations (and not to the transport of PEDs):

CS 25.1301 - Function and installation: This broad rule requires that all equipment and systems installed on an aircraft perform their intended function without adversely affecting the aircraft's airworthiness. This is the foundational rule that dictates how things like in-seat power outlets and other installations for PEDs must be certified.

CS 25.853 - Compartment interiors: This rule sets fire safety standards for cabin materials. This rule is the basis for ensuring that materials in the cabin can withstand heat and fire.

Guidance Material (GM) & Acceptable Means of Compliance (AMC),

specifically *AMC 20-25A - Airworthiness consideration for Electronic Flight Bags (EFBs)* [25]: While this is primarily for EFBs used by the flight crew, the principles related to battery safety, charging, and thermal runaway are often used as a reference for passenger PED

Special Conditions (SCs). EASA has also issued “Special Conditions” (SCs) to address the specific safety risks posed by lithium-ion batteries in Portable Electronic Devices (PEDs) on board aircraft. These special conditions are a way for EASA to regulate new or unforeseen situations that are not yet fully covered by existing airworthiness codes. The key Special Conditions released by EASA related to PEDs are:

M-TS-0000419 (past reference SC-G25.1585-01): Lithium Battery Fires on the Flight Deck [26]. This is a significant special condition, particularly relevant to aircraft manufacturers (Original Equipment Manufacturers, or OEMs) and operators. It focuses on the risks associated with PEDs carried by flight crew members in the cockpit. The core points of this special condition are:

- **Emergency Procedures:** It mandates that emergency procedures for a lithium battery fire on the flight deck must be clearly defined. These procedures must account for all potential threats, including heat, smoke, flames, and explosion.
- **Training:** Adequate training must be specified for both flight and cabin crew to address these emergency procedures. This ensures that in the event of a thermal runaway, the crew is prepared to handle it effectively.
- **Emergency Equipment:** The special condition requires that the emergency equipment needed to follow the procedures (e.g., fire containment bags, specific gloves for handling hot devices) must be readily accessible to the flight crew.
- **Stowage Assessment:** It requires an assessment of the performance of any stowage compartment on the flight deck where PEDs might be placed. This assessment must be supported by test data simulating a battery thermal runaway event to ensure the compartment can safely contain the fire. The intent is not necessarily to test every single stowage compartment but to have test data that supports the design's effectiveness.

EASA has also issued or consulted on special conditions related to the use and containment of PEDs in aircraft. These include the installation of dedicated stowage and charging trolleys, designed to ensure the safe simultaneous charging of multiple devices while containing potential thermal runaway events within the trolley itself. In addition, EASA has consulted on a special condition for fire containment bags that double as charging stations, reflecting an ongoing effort to integrate fire containment solutions directly into the aircraft design.

In summary, compliance with the ICAO provisions is required by EASA, whose special conditions on PEDs are an additional and proactive measure to address a growing safety concern in aviation. They shift the focus from solely relying on operational procedures to incorporating design requirements (like suitable stowage compartments and emergency equipment) into aircraft certification, especially for areas like the flight deck where a fire could be catastrophic. Other EASA documents are otherwise typically “guidance” or “recommendations” rather than legally binding regulations and are primarily focused on mitigating the risks associated with lithium-ion batteries.

8.4 Existing standards

UN 38.3 [27] and UL 5800 [28] are both important safety standards related to lithium-ion batteries, but they have fundamentally different purposes and apply to different stages of a battery's life cycle.

UL 5800 – in flight fire containment: This is a safety standard for **battery fire containment products** used to mitigate the hazards of lithium-ion battery thermal runaway events, particularly in aircraft. It outlines fire test and performance criteria to ensure that the product can safely contain fires, smoke, and other related effects. UL 5800 applies to a separate product—a fire containment device—not to the battery itself. It is a tool for a “post-incident” scenario, giving trained personnel a way to safely manage a battery fire that has already started. **Test Methods:** UL 5800 provides a standardized, repeatable test methodology to evaluate the containment a product can handle a thermal runaway event. The tests assess the ability to contain flames, smoke, and shrapnel, as well as to keep its exterior surface temperatures below specified thresholds.

- **Performance Levels:** The standard establishes different performance levels for these products. For example, Performance Level 1 requires that all visible smoke is contained within the product, while Performance Level 2 allows for a limited amount of Total Smoke Release (TSR) during test duration (no more than 5 m²).
- **Classification System:** The standard also classifies products based on the size of the portable electronic device (PED) they are designed to contain. This is measured in watt-hours (Wh). For instance, a Class 2 rating is for devices up to 100 Wh (like a laptop), while a Class 3 rating is for devices up to 160 Wh (like a large power bank).
- **Product Requirements:** In addition to performance testing, UL 5800 includes requirements for marking, instructions, and packaging. This ensures that the products are easy and safe to use in an emergency. For example, some products must be packaged with gloves that meet specific safety standards.

To summarize, the objective of the UL 5800 standard is to test the performance of a containment product, such as a fire bag or an enclosure, when a battery inside it goes into thermal runaway. The tests measure the product's ability to:

- **Contain Flames and Shrapnel:** Prevent fire and debris from escaping.
- **Control Smoke and Fumes:** Limit the release of dangerous smoke and gases, while not assessing their flammability and toxicity.
- **Manage Heat:** Keep the external surface temperature below a threshold to prevent burns and damage to surrounding areas.

UN38.3 – safe transport of Lithium battery cells: UN 38.3 applies to all lithium batteries, whether they are shipped on their own or installed in a device. A manufacturer must have a UN 38.3 test report to legally ship their products internationally. This is a mandatory global standard for the safe transport of lithium cells and batteries. Its purpose is to ensure that batteries can withstand the rigors of shipping—whether by air, sea, rail, or road—without posing a safety risk. All lithium cells and batteries must pass a series of rigorous safety tests outlined in the UN Manual of Tests and Criteria, Part III, subsection 38.3 (UN 38.3). This ensures they can withstand typical transport conditions, including altitude, temperature, vibration, and short circuits. If a battery does not pass these tests, it is generally prohibited from air transport.

8.5 Key Regulations Summary

For the specific question of airworthiness requirements for PEDs with lithium batteries carried **in the cabin**, the core references are:

1. **ICAO Doc 9284**, particularly **Table 8-1**.
2. **IATA Dangerous Goods Regulations (DGR)**, specifically **Section 2.3**.
3. **National Aviation Authority Regulations** (e.g., FAA's 49 CFR Part 175) that implement the international standards.

These regulations universally mandate that:

- **Spare batteries and power banks** must be carried in carry-on baggage only.
- The terminals of spare batteries must be **protected from short circuits**.
- **Watt-hour (Wh) limits** must be respected. Batteries over 100 Wh but not exceeding 160 Wh require operator approval, and a limit of two spare batteries per person applies.

- Damaged, defective, or recalled devices and batteries are **forbidden** from carriage.
- The airline has the final authority to deny carriage of any item they deem a safety risk, even if it meets the general regulations.

9 Identification of Potential Gaps and Conclusions

In a scenario involving a 100 Wh laptop, the potential consequences are classified as hazardous. This assessment mainly results from the possibility of burn injuries when touching the affected PED and from inhalation of elevated concentrations of toxic gases within the plume. Concentrations outside the direct plume are numerically still classified as major (if exceedance of the 10-min AEGl-2 exposure is selected as criterion), although very close to the hazardous threshold. If direct inhalation of plume gases and skin contact with burning or overheated PEDs could be effectively prevented, a downgrading of the consequences to major would be justified, especially considering that the event leaves room for mitigation actions and tolerances to clearly reduce exposure risk, namely: (1) relocation of passengers by ± 2 seats from the event, and (2) quick action to avoid cell-to-cell propagation.

Such conditions could be achieved if **sufficiently protective fire gloves were available** on board, if **crew were trained and instructed to don respiratory protection as soon as possible during the intervention**, and if **passengers were explicitly advised never to touch a PED in thermal runaway** and to strictly **avoid inhaling smoke** from the plume (providing breathing protection for each passenger appears unrealistic). To move from advisory to enforceable risk reduction, the following measures should be implemented: (a) crew should don protective breathing equipment as soon as possible during the intervention; (b) availability and use of fire gloves meeting a specified performance standard; until then, it is recommended that operators carry adequate quantities of fire gloves on board; (c) passengers must receive pre-flight briefing to never touch a PED in thermal runaway and to avoid the plume; (d) immediate relocation by ± 2 seats is part of the standard response checklist. It remains to be clarified how point (d) can be implemented when flights are fully booked. Note that there is currently no aircraft design certification standard applicable to fire protective gloves.

In a 200 Wh laptop scenario (see chapter 7.2), however, safety margins would be significantly reduced even if the above mitigation measures were applied, since the 10-min AEGl-2 accumulated exposure is already nearly reached during the first ignition. This leaves minimal time and very limited tolerance for consecutive errors in event management. A hypothetical 400 Wh laptop fire would reach hazardous levels due to toxic gas concentrations already during the first ignition, before any effective mitigation action is likely to take place. Against this background, any exemption for e.g. electric wheelchairs, whose batteries commonly have capacities several times greater than those of laptops,

are difficult to justify from a safety perspective. As this topic falls outside the scope of the LOKI-PED project, a deeper discussion (including associated ethical considerations) is not provided here. The **current regulatory limitation that lithium batteries in PEDs must not exceed 100 Wh therefore appears justified and may already be considered at the limit of acceptability**, given that even a 100 Wh scenario approaches the threshold of hazardous consequences under certain conditions. **However, storage and carriage are currently not limited in terms of total capacity or number of PEDs per passenger (or per flight or seat row), which constitutes a remaining regulatory gap.**

The existing thresholds apply equally to passengers, cabin crew, and flight crew. Given the confined space of the flight deck, leading to a quick accumulation of toxic gases and smoke in case of an incident, the criticality of crew performance, and the limited options for relocation or evacuation, **consideration should be given to introducing more stringent limitations for PEDs on the flight deck compared to the cabin.** In particular, the carriage of PEDs by flight crew could be reduced to the operationally necessary minimum (e.g., company-issued electronic flight bags), and the maximum permitted battery capacity could be set lower than in the passenger cabin (e.g. ≤ 60 Wh). Such a measure would decrease the potential volume of toxic gas release and smoke production in the event of a thermal runaway, thereby mitigating both health and visibility risks in the flight deck (see also chapter 5.4). In this context, the simulation of a tablet runaway in the cockpit (Deliverable 2.2) demonstrated that limiting the allowed battery capacity can significantly reduce the emission of toxic gases, although not below the 10min AEGL-2 limit for all toxic gases (i.e. not for CO). It should be considered to **mandate crew training for immediate flight deck-specific response.**

Burn injury and toxic gas exposure hazards associated with the direct plume are intrinsic to any PED thermal runaway event and should therefore be addressed independently of the device's battery capacity. To ensure the safest possible response, mitigation measures should be implemented at the operator level, emphasizing both passenger awareness and crew preparedness. Accordingly, **binding instructions for the cabin crew** should be envisaged to establish a no-touch/no-plume zone around the affected device and, where feasible, to route the plume away from occupants by controlling cabin airflow. Further measures should include: (a) **recurrent training providing cabin crew with advanced skills to manage unforeseen PED events**, including plume management, rapid isolation, and propagation recognition; (b) **standardized and unambiguous checklists**, validated across all plausible PED-related scenarios; and (c) **pre-flight passenger briefings on PED safety**, covering stowage, charging, and appropriate emergency actions.

Additional studies should be conducted to further substantiate and specify these recommendations.

An important aspect that may warrant further consideration is the **location of the PED** at the onset of a thermal runaway. The detection times and consequences are likely to differ significantly depending on whether the device is within the passengers' line of sight or stored in a compartment containing combustible materials (e.g. coats and bags). While smoke will likely be detected by passengers in any case, the reaction time may be delayed if the PED is stowed remotely. The current **100 Wh limitation therefore appears appropriate for devices kept in view but may require reconsideration for those placed in less accessible or enclosed areas**. To mitigate risks, powered or charging PEDs should not be allowed to be stowed in compartments without smoke detection or direct line of sight. Where such systems are unavailable, PEDs must remain visible to both passengers and cabin crew. The introduction of seat-integrated receptacles could further enhance safety and operational control.

From the regulation standpoint, on EASA side, mitigations are provided by means of supplemental requirements (i.e. special conditions) that are issued for the stowage of PEDs inside the cabin and flight deck. Other measures should be formalized at operational level (e.g. within Acceptable Means of Compliance (AMC) and Guidance Material (GM)) including mandatory elements such as limits on PED capacity and quantity, flight deck-specific restrictions, stowage visibility and detection requirements, and crew training provisions. Additional measures, such as monitored seat-integrated receptacles or restrictions on powered wheelchairs in the cabin, could be considered. Operators should be required to demonstrate compliance through documented procedures, equipment inventories, such as protective breathing equipment, fire gloves, and fire containment devices, and crew training records, and to actively monitor PED usage and charging during flight (Table 7).

Table 7: Summary of gaps in regulations and recommended actions.

Gap in Regulation	Recommended Action / Mitigation Measure
No limitation on total PED battery capacity or number per passenger	Define total capacity and number limits per passenger; include these limits in operator manuals and checklists.
Same PED limits applied to flight deck and cabin despite higher flight deck criticality	Introduce stricter flight deck-specific PED capacity limit (e.g. ≤ 60 Wh) and restrict carriage to essential company-issued devices only.

No clear rules for PED stowage visibility or smoke detection	Require stowage of PED in compartments that facilitate smoke detection; prohibit charging or operating PEDs in enclosed compartments without certified smoke / gas detection.
Insufficient standardization of crew training and checklists	Implement standardized, recurrent training and unambiguous checklists applicable to all PED scenarios.
Lack of flight deck-specific mitigation and monitoring procedures	Mandate flight-deck-specific procedures, equipment (PBEs, gloves), and drills
No mandatory passenger briefings on PED thermal runaways	Mandatory pre-flight briefing of passengers not to touch PEDs in thermal runaway and to stay away from the plume

10 References

- [1] *IEC 31010: Risk management - Risk assessment techniques*, CEI/IEC 31010, International Electrotechnical Commission, Geneva, 2019.
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