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Precautionary Approach to Reduce Occupational Exposures among Airport Apron Workers in the Context of Many Unknowns—A Methodological Position Paper

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Abstract: Airport apron workers are exposed to complex mixtures of volatile and particulate substances generated by jet fuel, exhaust from aircraft main engine and auxiliary power units (APU), and ground-service equipment. Evidence from both commercial and military airport settings indicates potentially serious health risks associated with acute and chronic exposure to these heterogeneous emissions. Emissions include CO, NO_x, SO_2, PAHs, UFPs, and larger particulates. In addition, there is chronic low-dose exposure to volatile organic compounds (VOCs) and organophosphates (OPs). The limited number of epidemiological studies specifically targeting apron workers report chronic respiratory symptoms. Evidence for cardiovascular effects is inconsistent, and potential neurological impacts are insufficiently explored. Some studies suggest genotoxic effects or elevated cancer risks but are insufficient to support unequivocal conclusions regarding the necessity of stringent risk management measures. Especially combined acute and chronic exposure to the mentioned volatile and airborne substances may represent a substantial but underrecognized risk, particularly with respect to neurotoxic health effects. This emphasizes the need for prospective cohort studies incorporating detailed exposure assessment, biomonitoring critical toxicological endpoints. At the same time, significant uncertainties and the limited availability of up-to-date, well-characterized exposure data, hinder effective risk assessment and management on the apron. This urges for a precautionary approach with priority for kerosene combustion-derived UFPs, due to their potential toxicity at low concentrations and their role as carriers of carcinogenic particle-bound PAHs (pb-PAHs). However, no widely accepted health-based occupational exposure limit (hb-OEL) currently exists for this nanoscale fraction, while UFPs represent a practical indicator for exposure and a useful tool for risk management. Based on existing risk assessment approaches, a combined number-based and mass-based precautionary health-considered OEL for kerosene exhaust emissions (phc-OEL_{KEE}) has been proposed. Field measurements indicate that this precautionary threshold is frequently exceeded on the airport apron.

Keywords: aircraft emissions; airport air quality; ultrafine particles; kerosene exhaust emission; occupational exposure limits; precautionary approach

1. Introduction

Risk management in occupational settings requires balancing worker protection with practical feasibility, particularly when essential information such as health-based occupational exposure limits (hb-OELs) is lacking or incomplete [1]. This challenge is especially pronounced for exposure to complex mixtures, where both hazard characterization and exposure assessment are difficult [2,3]. For the airport apron, the area where workers are active in aircraft parking, loading, unloading, refueling, and boarding of passengers, this is an urgent issue. Worldwide, civil and military airports employ more than two million apron workers [4,5]. At Amsterdam Schiphol Airport alone, nearly 500,000 annual flight movements and more than 66 million passengers are handled by approximately 2000 baggage handlers [6–8].

Apron workers are routinely exposed to aircraft kerosene exhaust emissions (KEE), a combustion-derived heterogeneous mixture containing numerous gaseous and particulate toxic components [4,9–21]. Auxiliary power units (APUs), small on-board engines that operate primarily during ground activities, are major contributors to local apron air pollution [22,23]. KEE contains soot (carbonaceous particles including elemental carbon (EC)), polycyclic aromatic hydrocarbons (PAHs), metals, SO_2, NO_x, and many other constituents, and is generally characterized by high concentrations of ultrafine combustion-generated particles [16,24]. In addition, apron workers may be simultaneously exposed to diesel engine emissions (DEE) from ground service vehicles, refuelers, and supply trucks [25]. Other particulate sources include tyre wear, road wear, and brake wear particles [26]. Particulate matter in this heterogeneous mixture, especially the nano-sized fraction, the ultrafine particles (UFPs), may act as carriers for hazardous semi-volatile and non-volatile substances such as black carbon (soot) and PAHs [27].

Growing awareness of the potential health risks associated with these heterogeneous airborne emissions has increased public and regulatory pressure to reduce emissions and worker exposures on the apron [28,29]. Although the aviation industry recognizes the importance of effective risk management [7,30,31], implementation of mitigation measures is often constrained by operational and economic considerations. Consequently, proposed interventions have been perceived as progressing slowly, with implementation relying more on technological innovation than on health-based urgency [32]. A major obstacle is the lack of unambiguous exposure and health data, which complicates risk assessment and hampers consensus on appropriate risk management measures. However, using scientific uncertainty as a justification for delaying action will only lead to more unacceptable adverse health effects.

A key limitation is the absence of a hb-OEL for KEE. While deriving hb-OELs for manufactured nanomaterials (MNMs) is already a complex and slow process [33–35], establishing such limits for combustion-generated UFPs and complex emission mixtures such as KEE is even more challenging. Recently, the Dutch Health Council and the Nordic Expert Group (DECOS/NEG) published recommendations concerning occupational exposure to KEE [36]. They concluded that a hb-OEL for KEE cannot currently be derived because of insufficient human data and the absence of a suitable selective and measurable exposure indicator that adequately represents the airborne mixture. Nevertheless, DECOS/NEG recommend classifying KEE, by analogy with DEE, as a category 1B carcinogen (“presumed to be carcinogenic to humans”) [37]. In the absence of a specific hb-OEL, they advise applying existing OELs for relevant KEE constituents such as PAHs and metals, while emphasizing that it remains uncertain whether these limits provide adequate protection for workers exposed to kerosene-fueled aircraft emissions [36]. Furthermore, classification as carcinogen-1B under the European Carcinogens Directive, obliges employers to prevent exposure wherever possible and otherwise reduce exposure to the lowest level reasonably achievable [38].

The absence of a hb-OEL, combined with evidence suggesting potential carcinogenicity and uncertainty regarding other health risks, argues for the application of a precautionary approach. To address comparable situations involving occupational exposure to nanoparticles and UFPs, precaution-based Nano Reference Values (NRVs) were introduced as provisional exposure benchmarks [39]. NRVs provide an operational risk-management tool when toxicological and epidemiological data are insufficient to derive health-based limits. Furthermore, they are relatively easy to apply across workplaces and do not require extensive physicochemical characterization or toxicity testing of airborne nanoparticles.

Nevertheless, NRVs have been subject to criticism. The non-health-based nature of NRVs has led to reluctance among policymakers and occupational hygienists to adopt these values, partly due to concerns that they may not provide sufficient protection against certain highly toxic particles [40]. Efforts to move beyond precaution-based values have recently resulted in proposals for Health-based Nanomaterial Guidance Values (HNGVs) for specific classes of nanomaterials [34,35]. However, for KEE and related combustion-generated UFP mixtures, a health-based limit remains unavailable.

Against this background, there is a need to examine how occupational risks associated with KEE can be managed under conditions of substantial scientific uncertainty. This methodological position paper discusses these uncertainties surrounding exposure to hazardous aircraft emissions and summarizes the epidemiological evidence regarding health effects among apron workers. Finally, we explore the conditions required to operationalize a precautionary approach and propose a route towards deriving a precautionary occupational exposure limit value for KEE.

2. Conceptual Framework

The DECOS/NEG advice [36] urges to reconsider a precautionary approach for risk evaluation and management of KEE exposures. The context of this reconsideration can be the European Commissions' communication [41], which determines the precautionary principle applies under defined conditions (Box 1).

Box 1. Application of the precautionary principle according to the European Commission [41].

> The precautionary principle applies where scientific evidence is insufficient, inconclusive or uncertain and preliminary scientific evaluation indicates that there are reasonable grounds for concern that the potentially dangerous effects on the environment, human, animal or plant health may be inconsistent with the high level of protection chosen by the EU.

Discussions on the philosophy behind the precautionary principle [41–43], its interpretations and its non-binding character are still ongoing, but despite this, there still is an ethical responsibility to translate the principle into an operational precautionary approach for industrial practice. Especially, the more operationalized format of the definition, as developed by von Schomberg [44] (Box 2), is useful for the occupational situation at the airport apron, where the uncertainties of the hazards of process generated nanoparticles (PGNPs), i.e., KEE and other aircraft and airport emissions are at stake.

Box 2. Policy definition of the precautionary principle [44].

> Where, following an assessment of available scientific information, there are reasonable grounds for concern for the possibility of adverse effects but scientific uncertainty persists, provisional risk management measures based on a broad cost/benefit analysis whereby priority will be given to human health and the environment, necessary to ensure the chosen high level of protection in the Community and proportionate to this level of protection, may be adopted, pending further scientific information for a more comprehensive risk assessment, without having to wait until the reality and seriousness of those adverse effects become fully apparent.

As practice demonstrates, a key point of debate concerns the normative qualifier "reasonable grounds" within this definition. Nevertheless, the current lack of knowledge regarding hazards, the presumed category 1B carcinogenic advice and exposures among apron workers, appears to justify the invocation and further development of a precautionary approach. These considerations include issues such as the unquantifiability of risks with potentially severe health effects.

It should be noted that precaution is not identical to prevention. Precautionary action differs from prevention: precaution is warranted when risks are plausible but not yet fully characterized, whereas preventive measures are based on risks that can be qualified and quantified.

3. Methods

3.1. Literature Review and Precautionary Approach

Via PubMed (MEDLINE) and ScienceDirect, original articles as well as technical reports from regulatory and occupational health & safety agencies, up to April 15, 2026, were identified, addressing:

- apron worker exposure to aircraft exhaust during real-world airport operations,
- epidemiological evidence of acute or chronic health effects,
- KEE composition details.

Both reports from civil and military airports were considered. Key pollutants included CO, CO_2, NO_2, SO_2, VOCs, PAHs, OPs, and NPs/UFPs (diameter <100 nm). The designations NP and UFP are equivalent terms; in this publication UFP is used.

To retrieve literature on occupational exposure, epidemiology and health effects search key words were: airport workers, aircraft, Air Force, air quality, APU, apron, emission, engine exhaust, baggage handlers, maintenance technicians, carbon monoxide, nitrogen oxides, PAHs, black carbon, combustion, ultrafine particles, nanoparticles. Data extraction of >500 initially identified publications included: airport location, study design, exposed worker populations, control groups, exposure metrics, and health outcomes. Studies were excluded if they addressed cruise-altitude emissions, populations residing in the vicinity of airports, aircraft manufacturing workers, simulated aircraft turbine testing, methodologies for measuring airport air quality, the contribution of airport emissions to climate change, in vitro cell culture experiments, animal studies and helicopter emissions. Ultimately less than 100 publications were included.

The development of a precautionary approach focused on occupational health risks associated with exposure to manufactured nanomaterials (MNMs) and UFPs, the uncertainties arising from insufficient or absent hazard data, and the strategies developed to address these uncertainties while complying with existing European legislation. A key foundation was provided by the Nano Matters study [45–47], which introduced the concept of generic Nano Reference Values (NRVs) as a risk management tool for occupational exposure to nanomaterials. Additional insights were obtained from European research initiatives within the 7th Framework Programme and the Horizon 2020 Research and Innovation Actions in the period 2013–2023 [1,48,49], as well as from more recent discussions on the further development of NRVs and the transition towards health-based nanomaterials guidance values [33–35]. Furthermore, this publication draws on the ongoing scientific and regulatory debate regarding the assessment of combined exposures [50–52] and, more specifically, the management of occupational exposure to KEE [36].

NRVs represent pragmatic benchmark levels intended to reduce workers' exposure to manufactured nanomaterials (MNMs) in the absence of substance-specific OELs [39,45,46]. Their underlying rationale is that these generic reference values serve as provisional exposure limits until legally established or health-based OELs for nanoparticles become available. The NRV is expressed as an 8-h time-weighted average (TWA) and is based on a reference mass concentration of 100 µg/m^3. Four classes of NRVs have been defined, reflecting differences in particle characteristics and associated hazard potential (Table 1).

Table 1. Nano Reference Values (NRVs) for 4 classes of manufactured nanomaterials [45].

Class	Description	Density kg/m^3	NRV (8-hr TWA)	Examples
1	Rigid, biopersistent nanofibers for which effects similar to those of asbestos are not excluded	-	0.01 fibers/cm^3 (=10,000 fibers/m^3)	SWCNT or MWCNT* or metal oxide fibers for which asbestos-like effects are not excluded
2	Biopersistent granular nanomaterial in the range of 1 and 100 nm	>6000	20,000 #/cm^3	Ag, Au, CeO_2, CoO, Fe, Fe_xO_y, La, Pb, Sb_2O_5, SnO_2,
3	Biopersistent granular and fiber form nanomaterials in the range of 1 and 100 nm	<6000	40,000 #/cm^3	Al_2O_3, SiO_2, TiN, TiO_2, ZnO, nanoclay Carbon Black, C_{60}, dendrimers, polystyrene Nanofibers with excluded asbestos-like effects
4	Non-biopersistent granular nanomaterial in the range of 1 and 100 nm	-	Applicable OEL	e.g., fats, NaCl

* SWCNT = single wall carbon nanotube; MWCNT = multi wall carbon nano tube.

The NRV is developed for MNMs, but also applicable for heterogeneous PGNPs [53]. NRV class 3 applies to low-density, non-biodegradable granular nanomaterials (<6000 g/L) established at a level of 40,000 #/cm^3; UFPs generated by KEE fall within this category 3.

3.2. Derivation of the phc-OEL

The recently proposed Health-based Nanomaterial Guidance Value (HNGV) for the specific subset of low-toxic spheroidal biodurable engineered nanomaterials (ENMs) uses the dissolution rate in physiologically relevant media and the absence of substance-specific toxicity as a benchmark [35]. The scientific panel selected pulmonary inflammation as the critical effect. Persistent inflammation is considered as an important driver for chronic adverse effects. Furthermore, they postulate that exposures below levels causing neutrophil influx, will protect against effects such as ENM-induced lung fibrosis and lung cancer. Subsequently, no-observed-adverse-effect-concentrations or lowest-observed-adverse-effect-concentrations were derived from in vivo studies to provide a range of derived no-effect levels (DNELs). Based on these DNELs, the panel recommended a HNGV of 4 μg/m^3 (8-hr TWA) for this specific subset of ENMs [35].

In operationalizing a precautionary approach for KEE exposures, this HNGV provides a useful point of departure. The hazardous nature of the KEE mixture—including UFPs as a vector, carrying genotoxic, carcinogenic PAHs, together with other toxic combustion-derived pollutants—can be considered a relevant exposure metric for assessing increased, and presumably additive, health risks.

At the same time, in the specific context of apron workers, where exposure concentrations are highly variable, it may be considered technically, practically, and economically infeasible to continuously monitor, characterize, and quantify KEE exposures. To address this issue, we applied an approach analogous to the environmental risk-based use of a mixture allocation factor (MAF) for cocktail exposures [50–52]. The introduction of a MAF has been proposed to mitigate environmental risks occurring from the daily co-existence of complex mixtures of chemicals that are inherently unknown and variable. For KEE exposures, the MAF-approach enables to address the uncharacterized and unquantified components that are undebatable hazardous and are known to be present within the exposure mixture. Introduction of such an additional safety factor enables risk assessment without necessarily requiring measurement of all individual constituent components. A range of MAF values has been proposed in the scientific literature, varying from 2 to 1000, values of 10 or 100 most commonly being suggested [50–52].

Subsequently, a precautionary health-considered OEL for KEE (phc-OEL_{KEE}) can be derived by starting from the HNGV and, analogues to the environmental MAF, applying an assessment factor (AF). (see Equation (1)).

$$\frac{\mathrm{HNGV}}{\mathrm{AF}} = \mathrm{phcOEL_{KEE}} \tag{1}$$

Besides the mass-based phc-OEL, and depending on the median particle diameter of the KEE UFP-fraction, a corresponding precautionary number-based, health-considered OEL can be derived.

Conversion of mass-based concentrations to particle number concentrations (PNCs) is required for comparative purposes and to enable the use of recent emission and exposure data on UFP from KEE. As an approximation, this conversion can be performed using the relation weight = volume × density, assuming KEE-UFPs are spherical and a known particle size distribution:

$$W = \frac{\pi d^3 \rho_p}{6.10^{15}} \tag{2}$$

W = particle weight (μg/particle)
d = particle diameter (nm)
ρ_p = particle density (g/cm^3)

Airborne particulate matter is commonly classified by size into inhalable, respirable, and ultrafine fractions. The first two are typically assessed using mass-based metrics, whereas ultrafine particles (UFPs) are more appropriately quantified by number concentrations using direct-reading instruments [54]. Importantly, UFP number concentrations show little to no correlation with $PM_{2.5}$ mass concentrations, reflecting their distinct origins—local combustion processes for UFPs versus mechanical processes and secondary aerosol formation for $PM_{2.5}$—and differing atmospheric behavior. Consequently, these metrics are not interchangeable [55].

4. Results

4.1. Airports Apron Generated Emissions and Exposures

Many studies report harmful airborne emissions (KEE) at airports, generated by incomplete combustion in aircraft kerosene engines and auxiliary power units. Upon exposure, these emissions may be mixed with pollutants from ground service equipment (DEE), and tyre, road and brake wear particles.

Exposure concentrations of major toxic compounds at airports compared to occupational exposure limits are summarized in Table 2. High concentrations exceeding OELs or NRVs are observed of CO, NO_2, PAHs and NPs/UFPs.

Table 2. Summary of measured peak concentrations of toxic compounds at airports, and inventory of related established occupational exposure limits (OELs) [39,54–83].

Compound	Highest Measured Exposure conc.	OELs (ppm)	OELs (mg/m³)	↑ or ↓ OEL	References
CO	150–320 ppm	NIOSH: 200 ($TWA_{\text{-15 min}}$) WHO: 85.8 ($TWA_{\text{-15 min}}$) EU: 20 ($TWA_{\text{-8 hr}}$) EU: 100 ($TWA_{\text{-15 min}}$)	NIOSH: 233 ($TWA_{\text{-15 min}}$) WHO: 100 ($TWA_{\text{-15 min}}$) EU: 23 ($TWA_{\text{-8 hr}}$) EU: 117 ($TWA_{\text{-15 min}}$)	↑	[56–58]
CO_2	660 ppm	EU: 5000 $TWA_{\text{8 hr}}$	EU: 9000 $TWA_{\text{8 hr}}$	↓	[59,60]
NO_2	1 ppm	EU, NL 0.5 ($TWA_{\text{-8 hr}}$) 1 ($TWA_{\text{-15 min}}$)	EU, NL 0.96 ($TWA_{\text{-8 hr}}$) 1.91 ($TWA_{\text{-15 min}}$)	↓↑	[59,61–63]
SO_2	0.09 ppm	0.5 ($TWA_{\text{-8 hr}}$) 1 ($TWA_{\text{-15 min}}$)	1.3 ($TWA_{\text{-8 hr}}$) 2.7 ($TWA_{\text{-15 min}}$)	↓	[59]
PAHs (coal derived)	4–27.7 μg/m³		PAH mix 0,55 μg/m³ ($TWA_{\text{-8 hr}}$)	↑	[64–66]
Naphthalene	0.00008-0.485 mg/m³	Germany: 0,4 ($TWA_{\text{-8 hr}}$) 1,6 ($TWA_{\text{-15 min}}$)	Germany: 2 ($TWA_{\text{-8 hr}}$) 8 ($TWA_{\text{-15 min}}$)	↓	[66–69]
Formaldehyde	0.028 ppm 4.5 μg/m³	EU (BOEL): 0,3 ($TWA_{\text{-8 hr}}$) 0,6 ($TWA_{\text{-15 min}}$)	EU (BOEL): 0,37 ($TWA_{\text{-8 hr}}$) 0,74 ($TWA_{\text{-15 min}}$)	↓	[66,70,71]
Acetaldehyde	0.062 ppm 4.6 μg/m³	NL: 20 ($TWA_{\text{-8 hr}}$) 50 ($TWA_{\text{-15 min}}$)	NL: 37 ($TWA_{\text{-8 hr}}$) 92 ($TWA_{\text{-15 min}}$)	↓	[66,68,70,71]
Benzene	0.005–0.013 ppm; 0.25 mg/m³	NL: 0,2 ($TWA_{\text{-8 hr}}$) EU: 1 ($TWA_{\text{-8 hr}}$)	NL: 0,7 ($TWA_{\text{-8 hr}}$) EU: 3,25 ($TWA_{\text{-8 hr}}$)	↓	[66,69,72]
Toluene	0.001–0.056 ppm	EU: 50 ($TWA_{\text{-8 hr}}$) 100 ($TWA_{\text{-15 min}}$)	EU: 192 ($TWA_{\text{-8 hr}}$) 384 ($TWA_{\text{-15 min}}$)	↓	[66,68,72]
Xylene	0.012 ppm	EU: 50 ($TWA_{\text{-8 hr}}$) 100 ($TWA_{\text{-15 min}}$)	EU: 221 ($TWA_{\text{-8 hr}}$) 442 ($TWA_{\text{-15 min}}$)	↓	[66,68,72]
N-Hexane	0.016 ppm	EU: 20 ($TWA_{\text{-8 hr}}$) 40 ($TWA_{\text{-15 min}}$)	EU: 72 ($TWA_{\text{-8 hr}}$) 144 ($TWA_{\text{-15 min}}$)	↓	[66,68,72]
Nanoparticles /UFP	**Particle Number Concentration**	**Background Particle Number Concentration**	**Occupational Reference Level**		**References**
NP/UFP <100 nm	10^5–10^8 #/cm³	Rural area: 5 × 10³ #/cm³ Urban: 1–2 × 10⁴ #/cm³;	NRV: 4 × 10⁴ #/cm³ ($TWA_{\text{-8 hr}}$)	↑	[54,66,73–76]
Toxic Compounds Adhered to NPs	**Concentrations at the Airport**	**Particle Control Values**	**Urban Concentrations, Diesel Exhaust**		**References**
Black carbon	0.03–30 μg/m³	3 mg/m³ $TWA_{\text{8 hr}}$ (40-hr working week)	0.01–6.8 μg/m³	↓	[65,68,73,77–79]
pb-PAHs	0.12–4 μg/m³	EU standard for particle-bound benzo(a)pyrene: 0.001 μg/m³	0.025–1.70 μg/m³	↑	[73,80–83]

Explanation: ACGIH = American Conference of Governmental Industrial Hygienists; NIOSH= National Institute of Occupational Safety and Health; WHO = World Health Organization; BOEL= Binding occupational exposure level; ↑, ↓↑, ↓ = resp. substance exceeds, equals, meets OEL-levels. Mass-based measured values are generally time-weighted average values, PNC are generally measured with direct reading instruments.

- Particulates

At airport aprons, measured inhalable and respirable dust levels are generally low and do not exceed OELs, whereas concentrations of the dominant hazardous particulate fraction, UFPs, regularly exceed provisional NRVs substantially. The highest daily-average exposures (>10^5 particles/cm³) are reported for workers involved in baggage handling, pushback / tower operations, and aircraft servicing at parking spaces [54,84,85].

UFP concentrations within the breathing zone of apron workers at civil and military airports range from 2 × 10^5 to 2 × 10^8 #/cm³ [61,75,76,86–92], with background levels during periods without flight activity typically a factor 100 lower [82,93]. The highest emissions occur near taxiways and runway holding points, where aircraft queue, characterized by short peaks of 45–55 s [94]. Mean exposures for apron workers often exceed 10^5 #/cm^3 over much of the workday; baggage handlers spend approximately 76% of their time on the apron [54]. Personal monitoring of UFP exposure showed multiple short peaks of 10^5–10^7 #/cm^3 in workers operating in an airport taxiway during take-off, landing or pre-flight operations [84,95].

Aircraft particulate emissions comprise both soluble and insoluble fractions. The soluble fraction includes sulfuric acid and hydrophilic hydrocarbons [1,94], while the insoluble fraction consists mainly of black carbon (soot) with adsorbed PAHs, nitro-PAHs, and trace metals formed during incomplete combustion—even in modern engines with combustion efficiencies up to 98% [96]. Compared to background conditions, aircraft departures can increase nano-sized black carbon concentrations by up to two orders of magnitude (reaching ~30 μg/m^3) [65,73,79]. UFPs rich in black carbon are considered particularly hazardous [14]. Metal wear emissions, including aluminum, iron, and zinc, vary with engine type and age [11,54]. UFP-bound organics may include lubricating oil constituents such as OPs and PAHs [81,97–99]. Soot emissions increase with engine thrust, accompanied by a compositional shift from organic carbon-rich at idle to EC-rich at higher thrust [36]. Additional contributions to UFP concentrations may arise from nano- and microscale tyre, road and brake wear particles generated during landing [16,20,100,101].

A notable feature of KEE is their bimodal particle size distribution, consisting of a nucleation mode (~3–40 nm) and an accumulation mode (~80–100 nm), with most particle mass residing within the ultrafine fraction. In contrast, DEE exhibit a similar nucleation mode but a broader and larger accumulation mode (~30–500 nm), with only 1–20% of particle mass in the ultrafine range and the majority in the accumulation fraction [36].

Laboratory studies further indicate that, despite particle growth through agglomeration, KEEs predominantly remain within the ultrafine size range (<100 nm) [102]. These findings support earlier observations that aviation-related particles largely fall within the UFP fraction in urban air [103,104] and suggest that secondary organic aerosol formation from aircraft emissions constitutes an important source of ultrafine particulate matter.

UFP concentrations are strongly influenced by meteorological conditions and flight activity. Low wind speeds, limited dispersion, and high humidity or fog can lead to sustained local increases in PNC [54,105,106]. Smaller airports generally exhibit lower PNCs (8×10^5–2.7×10^6 #/cm^3) than larger hubs [73,93,107]. Particle size distributions also shift during aircraft operations, with peak diameters decreasing from ~70 nm to <20 nm during take-off and landing [93].

Background UFP concentrations require a key consideration in exposure assessment due to their spatial and temporal variability [108,109]. Mean ambient levels range from approximately 0.26×10^4 #/cm^3 in rural areas to 4.8×10^4 #/cm^3 near roadsides, with typical urban backgrounds around 1×10^4 #/cm^3 [110,111]. In clean environments, concentrations are generally below 0.1×10^4 #/cm^3, while urban hourly averages are typically below 2×10^4 #/cm^3 [55]. At Schiphol Airport, 24-h background concentrations measured 6 km from the apron ranged between 1.2–2.8×10^4 #/cm^3, with a long-term mean of 1.6×10^4 #/cm^3 [54].

The WHO air quality guideline [57] distinguishes between low and high PNC, to guide decisions on the priorities of UFP source emission control. Low PNC can be considered $<0.1 \times 10^4$ #/cm^3 (24-h mean). High PNC can be considered $>1 \times 10^4$ #/cm^3 (24-h mean) or 2×10^4 #/cm^3 (1-h mean), while a NRV of 4×10^4 #/cm^3 has been proposed (see Table 1). Measured apron concentrations however, frequently reach 10^5–10^7 #/cm^3 [67,92,107,112].

- PAHs and transport

PAHs originate from incomplete combustion. Lower molecular weight PAHs (2–3 rings) remain predominantly in the gas phase, whereas heavier (>3- rings), more carcinogenic PAHs (e.g., benzo[a]pyrene [BaP)) are largely particle-bound [61,81,113]. On airport aprons, vapor-phase PAH concentrations range between 4–27.7 μg/m^3 and are dominated by naphthalene's (60–85%) [16,64,65,67]. Biomonitoring studies in fuel system maintenance workers have demonstrated substantial occupational exposure, with exhaled breath concentrations of volatile compounds increasing up to 100-fold compared to controls, and approximately 15% exceeding OELs [69,114].

For pb-PAHs, approximately 85% is associated with submicron particles (peak range 0.27–0.54 μm), while 15–20% is bound to UFPs [113]. Concentrations vary from baseline levels below 0.02 μg/m^3 to peaks exceeding 4 μg/m^3 during aircraft operations, representing increases of 10–25 times above ambient background levels and exceeding the OEL significantly [64,73,81,82].

- Gasses and volatiles

Mean CO concentrations at airports range from 7.5–42 ppm (8 h TWA) [56,115–117]. Idling and taxiing aircraft are major sources, with levels near gates reaching 150–320 ppm, up to 40 times background concentrations [56,59,72,118]. In case of delays and older engines even higher emissions occur [118,119]. Exhaled CO in airport workers (5–27 ppm) exceed control levels (3–17 ppm) [120–122]. Short-term exposure near gates has been associated with increased inflammatory markers such as IL-6 [19]. Chronic low-level exposure may cause neurological symptoms, including headache and impaired cognition, while physical workload aggravates these symptoms [123–125]. OELs vary; DECOS recommends 6.4 ppm [125].

NO_2 levels of 0.5–1 ppm have been reported at major airports, approaching or exceeding OELs [16,59,61,63,126]. Additional emissions arise from ground-support vehicles [72]. Acute exposure leads to irritation of eyes and the respiratory tract, while chronic exposure increases cardiovascular and respiratory morbidity [127,128]. Other pollutants, including VOCs, CO_2 (400–660 ppm), and SO_2 (median 0.003–0.005 ppm; peaks up to 0.09 ppm), are generally below ambient standards [59,118,129–131]. However, in the absence of established European maximum limits, the sulfur content in kerosene varies widely (3–3000 ppm), potentially resulting in substantial variability in SO_2 emissions [132].

- The ground-service equipment and APUs

Ground-support equipment often fueled with gasoline, some with diesel, are additional emission sources, contributing almost 3% of the total airports' emissions [29,133]. This equipment comprises a large number of service vehicles: passenger buses, baggage and food carriers, container loaders, refilling trucks, anti-icing vehicles, cleaning and lavatory services. Tugs move any equipment or push the aircraft between gates and taxiways [16]. Pushback tractors and diesel vans can emit high PNCs of 10^6–10^7#/cm^3 [76].

APU emissions include CO (0.5–31 g/kg fuel), NOx, VOCs, and UFPs (10^{15} #/kg fuel), with black carbon emissions potentially exceeding those of main engines [22,87,118]. Electrification and ground power units are expected to reduce emissions [134,135].

4.2. Health Effects among Airport Workers

Potential health effects of exposure to the respective mentioned KEE components are well known and extensively reported. A summary of these effects is presented in Table 3.

Table 3. Potential health effects of toxic compounds after chronic occupational exposure in apron workers.

Exposures	Representative Health Effects	References
NO_2	Irritation of eyes and airways, cardiovascular and respiratory effects, asthma exacerbation	[127,128,136]
CO	Dizziness, headache, confusion, impaired concentration	[137,138]
UFPs	Oxidative stress, inflammation, cardiovascular and respiratory effects, exacerbation of asthma and COPD, lung fibrosis, carcinogenicity	[139–141]
PAH	Increased cancer risks of breast, lung, bladder. Reduced lung function, exacerbation of asthma, cardiovascular effects, infertility	[142–146]
Solvents/VOC	Memory and concentration impairment, irritability, depression, personality changes, fatigue, headache, peripheral neuropathy, carcinogenicity	[147–149]
(Low dose) OP	Apathy, fatigue, insomnia, confusion, memory deficits, anxiety, depression	[150,151]
SO_2	Cardiovascular and respiratory effects, airway irritation	[152]

- Epidemiological studies

The identified 17 epidemiological studies on health effects among 85,797 airport workers exposed to jet fuel and aircraft exhaust at civil and military airports are summarized in respectively Tables 4 and 5. Study populations include baggage handlers [18,85,153], aircraft maintenance workers [154–157], painters [159], and technical personnel. Most studies are cross-sectional or retrospective cohorts and focus on jet fuel, exhaust, hydrocarbons, or solvents (e.g., trichloroethylene, benzene, naphthalene). Increased incidences of cardiovascular, pulmonary, and cancer outcomes have been reported, particularly among baggage handlers [18,85,153], while cancer risks were evaluated in maintenance workers at Hill Air Force Base [154–157].

Benzene exposure during fuel tank repair is notable due to high temperatures and permeable clothing [65]. Chronic exposure to benzene and PAHs via inhalation and dermal routes is associated with increased risks of multiple cancers and non-malignant diseases, including impaired lung function, asthma, cardiovascular disease, and infertility [69,142–146,158].

Table 4. Reported health effects after exposure to aircraft exhaust and other pollution sources at civil airports: epidemiological studies.

Airport, Year, Ref	Study Design	Exposed Group/Control Group	Exposure, Health Outcome	Remarks
Birmingham, International airport, UK 1999 [121]	Cross-sectional survey, questionnaire, lung function, (spirometry), exhaled CO concentration	222 full time airport workers, mean age 38.6 years, 63% male, 28% current smokers, mean duration of employment: 7.6 yrs Control High (n = 53) vs medium (n = 83) vs low (n = 86) exposure group; high exposure: median time in aircraft taxiing area: 8 h/day	Respiratory symptoms, lung function Health outcome Prevalence of 7 respiratory symptoms: In male workers, high exposure significantly associated with runny nose and cough, adjusted for age and smoking. No significant differences in lung function	Exhaled CO conc. in high exposure group: 5.1–27.1 ppm; higher, but not significant compared to less exposure groups
Barcelona airport, Spain 1999 [159]	Prospective controlled study to evaluate genetic damage in blood lymphocytes due to hydro-carbons and jet fuel exp.	39 male apron workers, mean age 47.9 yrs, mean duration of employment 9.7 yrs Control 11 healthy not exposed men, mean age 34.9 yrs	SCE, MN- frequency and Comet assay; personal dosimeters for vapour samples Health outcome Slight but significant differences in the mean comet length and genetic damage index. SCE and MN: no significant differences	Airport air benzene, toluene and xylene levels were similar to those found in intense traffic streets of Barcelona
Kaohsiung international airport Taiwan 2003 [160]	Cross-sectional study, self-reported symptoms, questionnaire	106 full time apron- workers, high exposure group, working > 0.5 yrs. Duration of exposure> 10 yrs: 69% Control 305 terminal or office workers	Prevalence rates for acute irritative and chronic respiratory symptoms Health outcome Chronic respiratory symptoms (cough, dyspnoea) significantly more common among the exposed group, adjusted for age, smoking and previous exposure	Differences in acute irritative effects: not significant
Rome airport, Italy 2006 [65]	Cross sectional study, questionnaire, environmental monitoring of 23 PAHs in air samples, urinary 1-h-pyrene levels after 5 working days	41 high (n = 24) and medium (n = 17) exposed groups, mean age 43 yrs, baggage handlers, fitters. Mean duration of employment 8.3 yrs Control 31 healthy subjects, airport office workers, mean age 43.6 yrs. Mean duration of employment 10.6 yrs	Genotoxic effects and early direct-oxidative DNA damage of lymfocytes and exfoliated buccal cells Health outcome Oxidative DNA damage of buccal cells in 9.7% and in lymphocytes in 14.6% of exposed personnel, compared to absent in controls	Highest PAH levels in airport apron. No differences in urinary 1-h-pyrene between exposed and controls
Copenhagen airport, Denmark 2014, 2017 and 2020 [18,85,153]	Cohort study in the period 1990–2012; linkage to nationwide health and population registers and correlation with life style data (smoking, BMI)	69175 baggage handlers or other outdoor airport workers, of which 6515 exposed Control: 61,617 workers in different occupations (drivers, postal workers, factory workers	1st hospital contact or death due to ischemic heart or cerebrovascular disease vs cumulated apron years Health outcome 983,754 person years at risk; mean follow-up: 14.4 years. No association between cumulative apron years and ischemic heart or cerebrovascular diseases	Mean NP-exposure baggage handlers, catering drivers and cleaning staff, at the apron: 2.3–4.3 × 10^4 #/cm^3. Peak exposure: mainly baggage handlers
Local airport, Italy 2021 [161]	Observational, cross-sectional study; personal monitoring of combined noise and NP-exposure	34 operators, mean age 43 years Control No controls	Heart rate variability, Holter ECG, noise and NP-exposure Health outcome Mean PNC 6 × 10^4, peak noise 130 dB, mean < 80 dB. Significant association between NP exposure and decrease in heart rate variability	Noise peak level: no effect on heart rate variability
Paris and Marseille airport, France 2025 [120]	Longitudinal study, 6.6 years follow-up, spirometry and exposure to aerosols, NPs	68 office workers, 83 mechanics, 29 terminal workers and 35 apron workers Control Terminal and apron workers vs office workers and mechanics	Lung function, exhaled CO, organic carbon levels Health outcome Excessive decline in lung function, overall, in 24.75% of airport workers, and in 35.3% of apron workers; exhaled CO 16.7 ppm	Mechanics: higher exposure to elemental carbon

Table 5. Reported health effects after exposure to jet fighter exhaust and other pollution sources at military air force bases: epidemiological studies.

Airport, Year, Ref	Study Design	Exposed Group/Control Group	Exposure, Health Outcome	Remarks
Hill air force base, Utah 1991 [154,155]	Retrospective cohort study, excess of mortality due to trichloroethylene exposure?	14,457 (10,730 male) civilian aircraft maintenance workers, of which 6929 exposed to solvents, working > 1 year at air force base between 1952–1956 Control Mortality exposed group compared to expected number of deaths, adjusted for age, sex, calendar period	Excess risk of mortality due to solvents exposure (trichloroethylene), follow-up until 1983 Health outcome Detailed analysis of the 6929 exposed employees: no significant relation between exposure to trichloroethylene and excess of cancer	Other solvents involved: acetone, toluene, MEK, methylene chloride, styrene, xylene, dichlorobenzene, alcohols and trichloroethane
Hill air force base, Utah 1998 [162]	Pilot study, longitudinal, at 3, 6 and 12 months, personal air sampling pump, computer neurocognitive tests	17 workers exposed to jet fuel Control 13 non-exposed individuals	Kidney/ liver function, neuro-cognitive tests, symptoms Health outcome No significant differences between exposed and non-exposed subjects in liver, kidney, neurocogn function and symptoms	Insufficient power to detect differences
Hill air force base, Utah 1998 and 2008 [156,157]	Retrospective cohort study, excess of mortality due to trichloroethylene and other chemicals exposure?	14,457 civilian aircraft maintenance workers; 5727 workers had died by 31-12-1990, and 8580 subjects had died by 31-12-2000 Control Mortality exposed group compared to expected number of deaths, adjusted for age, sex, calendar period	Excess risk of mortality due to solvents exposure (trichloroethylene), extended follow-up from 1952–2000 Health outcome Significant excesses for ischemic heart disease, asthma and cancer of the bone in 1990. Relative excesses for cancers of bone, esophagus, and cervix, not statistically significant in 2000. Significant relative excess of death for overall exposure from respiratory disease	Workers exposed to solvents other than TCE had slightly increased mortality from asthma, non-Hodgkin's lymphoma, multiple myeloma and breast cancer
US air force 1997 [163]	Prospective, repeated measures design study, sampling prior to exposure, and after 15 and 30 weeks while exposed	50 men, 18–50 years, sheet metal workers or aircraft painters, with low-level exposure to a mixture of fuel and solvents Control (1) Each subject serving at his own control (2) 8 unexposed men	SCE, MN-frequency, air quality sampling, expired breath analysis for jet fuel and solvents Health outcome Genotoxicity; 2711 air samples, 670 breath analysis samples. Small but statistically significant increase in frequency of SCE after 30 weeks of exposure for sheet metal workers and painters. Air concentrations and breath samples were low	Sheet metal workers: exposure to solvents, adhesives, sealants, jet fuel, purging fluid; aircraft painters: exposure to solvents and paints
Royal Australian Air Force 2008 [164]	Retrospective cohort study, level and duration of exposure: exposure-questionnaire	873 fuel tank maintenance workers, 14,526 person years, exposed to jet fuel, (ethyl) benzene, white spirit Control 2 Air Force non-exposed control groups, n = 7577 and 9408	Any cancer incidence Health outcome Unspecified cancer risk higher in the exposed group, incidence ratio range 1.45–1.62	Study period 1975–2000
2 Turkey air force bases 2012 [165]	Prospective, controlled study of genotoxic and oxidative effects of hydrocarbons in jet fuel	43 exposed men, mean age 31.7 yrs, > 2 yrs of exposure, mean duration of exposure 11 yrs; aircraft fuel system maintenance workers, mechanics Control 38 men, mean age 33.3 yrs, not exposed	SCE, MN-frequency, serum antioxidant enzymes and urinary 1- and 2- naphthol excretion Health outcome Urinary naphthol (metabolite of naphthalene) levels higher in exposed workers. Statistically significant increase in frequency of SCE in exposed workers, compared to controls. No differences in oxidative stress parameters	Aircraft fuel system workers: mainly exposed in the hangar, mechanics more at the platform
6 air force bases, US 2012 [166]	Prospective, repeated measures before and after 4 h work shift	324 active duty personnel, mean months in current job: 53.3 (1–352); high (fuel tank maintenance), moderate (fuel handling) and low exposure Control Comparison between exposure groups	Breathing zone air, and exhaled breath measurements of benzene and naphthalene; urinary MEAA, Comet assay Health outcome Prior to 4 h shift: DNA damage, correlated with exhaled breath benzene. No differences in comet assay measurements between low, moderate and high exposure groups.	High exposure group: use of respirators and gloves
3 air force bases, US 2017 [167]	Consecutive 6-day study, daily air samples day 2–5; cognitive tests day 1,2,4 and 6	38 fuel cell repair and maintenance workers: high exposure Control 36 technicians, administration: low exposure	Neurocognitive performance (battery of tests). Exposure levels: personal air monitoring, urinary biomarkers and exp. Questionnaire Health outcome No association between average exposure levels, duration of exposure and neurocognitive performance	15 of high and low exposed subjects (20 %): > 10 years of air force service. Increased 1-naphthol levels in the high exposed group

Table 5. *Cont.*

Airport, Year, Ref	Study Design	Exposed Group/Control Group	Exposure, Health Outcome	Remarks
Air force military base, Denmark 2021 [168]	Cross-sectional study, effects of dermal or inhalation exposure to PAHs and OPs	42 workers, mean age 46.9 yrs (25–61 yrs), 87% males, > 10 yrs employment: 48%; crew chiefs, engineers, fuel operators, munition specialists Control 37 other military staff, office workers, avionics	PAH and OP air concentrations and skin wipes, urinary excretion of PAH metabolites; PNCs in breathing zone air. Lung function, plasma levels of CRP, and genetic damage levels of blood cells Health outcome High levels of fluorene (PAH) and TPP (OP) in exposed group. No significant effects of systemic inflammation, genetic damage, or lung function	Crew chiefs: high NP levels
Air force base, Poland 2025 [169]	Observational, cross-sectional study	121 technicians, 112 male, 9 female, aged 19–56 years, responsible for maintenance of aviation equipment and aircraft Control Compared with military personnel, not exposed to aviation fuels, exhaust emissions and lubricants	Cardiometabolic biomarkers and cardiovascular risk Health outcome Elevated apolipoprotein B, non-high-density lipoprotein cholesterol, and alanine aminotransferase	Increased cardiovascular risk

Explanation: SCE = Sister-chromatid exchanges; MN = micronuclei; TPP = triphenyl phosphate; MEAA = 2-(methoxy ethoxy) acetic acid, a metabolite of a de-icing agent, added to fuel.

- Neurotoxic effects

Aircraft exhaust contains neurotoxicants, irritants, and carcinogens [11,16,89,134,170]. Exposure risks as summarized in Tables 4 and 5, show neurotoxic effects in relation to exposure to CO, solvents/VOCs and OPs. Evidence for neurotoxic effects in apron workers is limited; only two studies exist, one underpowered [162]. Biomonitoring indicates increased urinary 1-naphthol in highly exposed workers, without clear neurocognitive effects [167]. However, cumulative exposure to OPs and solvents has been linked in other occupations to neurodegenerative diseases, including Parkinson's disease and Alzheimer's disease [171–179]. No cohort studies specifically address neurodegenerative risks in apron workers. Particulate matter and UFP exposure are associated with adverse neurological effects [180].

- Respiratory effects

Exposure to airport aerosols is associated with chronic respiratory symptoms, reduced lung function, and airway inflammation. Three studies show chronic, rather than acute respiratory symptoms [120,121,160], while two studies show reduced lung function and airway inflammation in individuals with asthma (19,156). An exploratory exposure assessment to airport aerosols and NPs was performed in a cohort of airport workers in France. Using personal monitoring devices, several spirometric variables were documented for office workers, mechanics, terminal and apron workers, over a 6.6-year period. A decline in lung function was found in almost 25% of the overall cohort of the airport workers, with terminal (45%) and apron workers (35%) more often affected, as compared to office workers and mechanics [120]. Experimental studies confirm pulmonary toxicity mediated by oxidative stress and inflammation [2,181–186].

- Cardiovascular effects

Cardiovascular findings are mixed. An Italian study investigated the association between exposure to fine and ultrafine particles, and heart rate variability in airport personnel (n = 34), operating nearby taxiways with mean PNCs of 6×10^4 #/cm^3 [161]. Holter ECG devices showed that NP exposure was significantly associated with a decrease in heart rate variability, an early indicator of failing cardiovascular autonomic response [161]. The Copenhagen cohort found no association between cumulative apron years, exposure to NPs and ischemic heart or cerebrovascular diseases [18,85,153]. In contrast, the Hill Air Force cohort demonstrated a significant excess of ischemic heart disease due to exposure to trichloroethylene, which is used as a small parts cleaner or as a vapor degreaser for oils and other contaminants [156,157]. Recent biomarker studies indicate altered cardiometabolic profiles in exposed Polish aircraft maintenance workers [169].

Although one large cohort study reported no association between PNC exposure and cardiovascular outcomes, other evidence indicates that traffic-related UFP exposure independently increases cardiovascular risk [139,187]. Occupational exposures at airports are likely orders of magnitude higher than environmental levels. Cohort studies among construction workers and systematic reviews have shown clear associations between UFP exposure and ischemic heart disease morbidity and mortality [188,189].

- Genotoxicity

Genotoxicity was assessed in 8 of 17 studies (see Tables 4 and 5), with modest but significant effects in 4 of them. Increased cancer incidence was observed in fuel tank maintenance workers [164], while other studies were negative or inconclusive [157,166]. Biomarkers such as sister chromatid exchange, micronuclei frequency, and Comet assay, indicate DNA damage following exposure to jet fuel or aircraft exhaust [159,163,165,166]. Genotoxic effects were also present in lymphocytes of a group of baggage handlers and fitters, and in buccal cells of marshallers [65].

UFP exposure as a carrier of carcinogenic PAHs is associated with increased lung and bladder cancer risk [142,190]; black carbon exposure is linked to glioblastoma and lung cancer [191,192]. Jet fuel emissions resemble diesel exhaust [16,20,193], which is classified as carcinogenic [194].

4.3. Analogy of KEE with DEE and PAHs as Critical Exposure

As fraction with a lower boiling point in the petroleum distillation aircraft, kerosene is chemically, in terms of composition, comparable to diesel fuel [16,20]. This analogy between KEE and DEE has been recognized by the expert committees DECOS/NEG and is recommended as a basis for KEE hazard assessment [36].

Diesel exhaust has been classified as carcinogenic to humans (Group 1) by the IARC [194], as have certain aircraft combustion products, including PAHs and black carbon (Group 1 and 2A) [194]. Accordingly, KEE combustion products should be regarded as carcinogenic to humans [142,157,163,165,168,195]. Based on the available, albeit limited, epidemiological and toxicological evidence, DECOS/NEG [36] recommends classification of KEE as carcinogenic category 1B and germ cell mutagenicity category 2.

As argued by DECOS/NEG [36], the analogy between DEE and KEE with respect to toxicity is insufficient to identify a suitable, selective, and measurable exposure indicator. A key limitation is that the OEL for DEE, expressed as mg EC/m^3, relies on EC (elementary carbon) formation and concentrations that differ substantially from those in KEE. (Consequently, another indicator is required for KEE exposure assessment. As an alternative DECOS/NEG advise applying existing OELs to relevant hazardous KEE-components.

Although individual exposures may comply with standards, cumulative low-dose exposure is associated with respiratory disease, neurotoxicity, and cancer. Mixture toxicity is likely additive and not adequately addressed by single-substance risk assessment [3,68,196–200]. This would imply using the existing addition rule for substances with comparable effects, by adding the different components divided by their respective OELs, as shown in Equation (3):

$$\sum_{i} \frac{c_i}{OEL_i} < 1 \qquad (3)$$

c_i = exposure concentration of component i

OEL_i = OEL of component i

As such, the sum of the mixed exposures divided by their respective OELs should remain smaller than 1. A complicating factor is that all relevant exposures have to be characterized and quantified.

For PAHs the Dutch Health Council calculated an occupational cancer risk value of 550 ng BaP/m^3 (cancer risk 4 per 1000) and a value of 5.7 ng BaP/m^3 (cancer risk 4 per 100,000), both for 40 years working life exposure [201]. Based on this advice, and taking into account the practical feasibility, the hb-OEL for PAH in The Netherlands is established at 550 ng BaP/m^3. The long-term goal is to lower this hb-OEL, according to the technical state-of-the-art, to the preferred low value of 5.7 ng BaP/m^3 [208]. The European SCOEL follows the Dutch approach in this matter [202]. Accordingly, in their communication the European Chemical Agency states that in fact all PAH-mixtures should be considered non-threshold carcinogens [203].

With the measured PAH levels of 15–850 ng/m^3 the European target value for the PM_{10} fraction of 1 ng BaP/m^3 [204] is frequently exceeded [73,82].

4.4. Summary of Evidence Relevant for Risk Assessment

The reviewed evidence indicates that airport apron workers are chronically exposed to complex KEE and lubrication derived mixtures of UFPs, combustion compounds, PAHs, VOCs and OPs. UFP concentrations frequently exceed provisional Nano Reference Values, while PAH-, CO- and possibly NO_x concentrations may exceed hb-OELs. Epidemiological studies suggest associations with respiratory, neurotoxic, cardiovascular and carcinogenic outcomes. Together, these findings support the conclusion that KEE constitutes a relevant occupational health concern, irrespective of remaining uncertainties regarding exposure characterization and dose-response relationships.

5. Discussion

Implications for precautionary risk management. Following the policy definition of the precautionary principle (see Box 2) [44], the available evidence provides reasonable grounds for concern regarding adverse health effects among airport apron workers, notwithstanding persisting scientific uncertainty. Although causal relationships and quantitative exposure-response functions remain incompletely characterized, the combination of substantial exposure levels, carcinogenic constituents, and suggestive epidemiological evidence justifies precautionary risk management. From a precautionary perspective, prioritizing human health and environmental protection, the establishment of an acceptable and measurable OEL is essential to support effective risk governance. Meanwhile the implementation of interim risk management measures is warranted. For this a guidance for the assessment of KEE exposure remains urgently needed.

Selection of an exposure indicator for KEE. Precautionary risk management requires the identification of a reliable exposure indicator for KEE, as the EC–based approach used for DEE cannot yet be applied. The hb-OEL for DEE is quantified based on the generated EC-concentration, but for KEE, this analogy cannot be applied without further consideration due to insufficient data regarding the differences in EC-formation.

In this context, the UFP fraction represents a strong candidate as exposure indicator. The majority of KEE particle emissions fall within the nanoscale range [102–104], making UFPs the dominant hazardous particulate fraction. In addition, the very low and frequently exceeded health-based OELs for pb-PAHs at the apron, indicate that pb-PAHs constitute critical combustion-derived components of KEE. These considerations support complementing conventional mass-based risk assessment approaches with particle number–based metrics for nanoscale particles.

Derivation of a precautionary health-considered OEL (phc-OEL_{KEE}). In the absence of a hb-OEL for KEE, and building on the precautionary framework described above, a precautionary health-considered OEL (phc-OEL_{KEE}) was derived. This proposed value should be regarded as a methodological output intended to support interim risk management until sufficient evidence becomes available to establish a formal hb-OEL.

The NRV provides a useful reference. However, as already argued, as a non-health-based benchmark, its adequacy for highly hazardous substances has been questioned [34,40]. As indicated in the introduction and methods section, the recently proposed HNGV of 4 $\mu g/m^3$ (8 h TWA) for low-toxicity, bio durable ENMs [35] can serve as a basis for deriving a phc-OEL for the heterogeneous UFP fraction of KEE.

For the derivation of an OEL for the KEE mixture, we introduce an assessment factor (AF), analogous to the aforementioned MAF approach and corresponding to Equation (1) in the Methods section, to adapt the HNGV to the occupational health context. This AF is introduced to take into account the simultaneous exposure to a large number of substances with similar toxicological effects (e.g., neurotoxicity, carcinogenicity, cardiovascular effects, various airway effects). Application of an AF effectively reduces the probability that apron workers will experience adverse health effects as a result of combined exposures to multiple components within the KEE mixture.

Analogous to the commonly proposed MAF range of 10 to 100 [50–52], and taking into account the hazards of chemicals typically reported in relation to KEE-related exposures and the carrier-function of the UFPs, we propose here that for KEE-related exposures an assessment factor of 10 is appropriate. This value reasonably reflects the likelihood that apron workers are exposed to many more than ten combustion-derived substances, some of which (at least PAHs, CO, and NO_2) may be present at levels close to, at, or exceeding their respective individual OELs. Table 2 summarizes these data: CO exceeds regularly the EU-OEL with a factor of >10, PAH regularly with a factor >20, while UFP with pb-PAH may exceed the NRV with a factor of >1000. Accordingly, the assessment can be limited to KEE-UFP exposure as a representative proxy for the airborne mixture, thereby eliminating the need for continuous monitoring of all combustion-related pollutants.

Applying Equation (1) for a mass-based approach a phc-OEL_{KEE} of 0.4 $\mu g/m^3$ (8-hr TWA, background-corrected) is derived.

For practical application, and given that UFPs may be underestimated or overlooked in a mass-based approach, the phc-OEL_{KEE} for UFPs should also be expressed as a number-based metric. Conversion from a mass concentration to a particle number concentration requires assumptions regarding particle density and size (see Equation (2)). The density of exhaust-derived black carbon (BC), used as a proxy, varies widely, approximately <1.5–2.1 g/cm^3 depending on source characteristics, particle morphology, and atmospheric aging [205]. Based on this a mean density of 1.8 g/cm^3 is assumed. A representative particle diameter of 30 nm for the lower mode of the bimodal UFP distribution is selected, motivated by the fact that this is the dominating UFP-fraction in the particle size distribution. Approximately 60–70% of the particles belong to the non-aged nucleation mode [206]. Furthermore, it has been hypothesized [205] that the reactivity of black carbon is not solely determined by its oxidative capacity. Rather, reactivity may more generally reflect the availability of reactive atoms on both the particle surface and within the particle bulk. This availability is expected to be greatest for particles in the 30 nm size fraction due to their high surface-to-mass ratio. In addition, particles of approximately 30 nm exhibit a higher deposition efficiency in the alveolar region than particles belonging to the larger mode of the bimodal distribution [102].

Applying these assumptions, a phc-OEL for KEE of 1.5×10^4 #/cm^3 (8-h TWA, background-corrected) is derived.

In occupational hygiene practice, both the number-based and a mass-based approach may be applied, either independently or in combination. For the purpose of KEE risk assessment, neither the number-based (phc-OEL_{KEE}) nor the mass-based limit value (HNGV/10) should be exceeded.

Practical implications. A major advantage of using the phc-OEL_{KEE} is that it relieves those responsible for risk assessment and management of the need to carry out the highly complex and laborious measurement strategy for the heterogeneous KEE mix. Restriction to determining the UFP exposure and the local background concentrations, is sufficient to assess the relevant occupational risks and to advise on adequate risk management measures. This also prevents the postponement of risk management measures due to the absence of essential hazard data.

This phc-OEL_{KEE} is slightly more stringent than the currently applied NRV. To put this in context, taking Schiphol Airport as the example we already mentioned; 24-h background concentrations measured 6 km from the apron ranged between 1.2×10^4 and 2.8×10^4 #/cm^3, with a long-term mean of 1.6×10^4 #/cm^3 [54].

The commonly measured PNCs at airports, varying between 2×10^5 and 2×10^8 #/cm^3 show the likeliness of exceeding this phc-OEL_{KEE} on airport aprons. It highlights the urgency of implementing effective exposure control measures. Since stakeholders in the aviation sector increasingly recognize these risks, remaining scientific uncertainties and anticipated technological developments should not delay the adoption of precautionary risk management strategies. The regular exceedance of the phc-OEL_{KEE} on the apron underscores the urgency of drastic exposure-limiting measures.

The relevant cited and calculated UFP concentrations and limit values are summarized in Table 6.

Table 6. Overview of the different calculated and cited UFP concentrations and limit values.

	Number-Based Concentration (#/cm^3)	**Mass-Based Concentration (µg/m^3)**
phc-OEL KEE (background corrected)	1.5×10^4	0,4
hb-OEL non-toxic ENM		4
NRV (ρ < 6.000 kg/m^3) (background corrected)	4×10^4	
OEL-DEE (NL) (based on EC)		10
Binding OEL-DEE (EU) (based on EC)		50
OEL-PAH (NL) (µg BaP/m^3)		0.55
PAH target value (NL) (µg BaP/m^3)		0.0057
pb-PAH at apron		0.02–> 4
Apron UFP concentrations	20×10^4–2×10^8	
Background UFP rural	0.26×10^4	
Background UFP typical urban	1×10^4	
Background UFP near roadsides	4.8×10^4	
Clean environment	$< 0.1 \times 10^4$	

The availability of a phc-OEL_{KEE} is expected to stimulate the further development and adoption of source-oriented mitigation measures. Effective emission reduction will inevitably require reduced engine operation, particularly during idling and taxiing. Additional exposure reductions may be achieved by limiting APU use during ground operations [135], promoting single-engine taxiing [96], expanding the use of electric tugs [16], further electrifying ground-service equipment [133], and applying lower thrust settings during take-off and climb [92]. However, the successful implementation of these measures—including the use of sustainable aviation fuel (SAF) [207,208]—depends on the full commitment of the aviation industry, transparent communication regarding occupational KEE exposure and associated health risks, and the provision of effective personal protective measures.

The practical implementation of a phc-OEL_{KEE} requires acceptance not only by airport management but also by regulatory authorities. This is particularly important because regulators and their scientific advisors will need to recognize the inherent uncertainties underlying the phc-OEL framework in order to address—and, where necessary, enforce—the urgent issue of risk governance for KEE exposure on the apron in the short term.

Without strong and sustained regulatory pressure, the widespread adoption of these interventions may take considerable time [32].

6. Limitations

The number of peer-reviewed epidemiological studies (n = 17) investigating health effects associated with exposure to aircraft exhaust and other pollution sources at airports remains limited, despite the inclusion of both civil and military airport activities. Recent reports in the grey literature may offer valuable additional information; however, the absence of peer review raises concerns regarding potential bias and the influence of stakeholder interests. Furthermore, the available evidence is dominated by cross-sectional study designs, which provide limited insight into long-term health effects. Consequently, the identification of indications of adverse health outcomes, including carcinogenic and neurotoxic effects, largely remains beyond the scope of the current evidence base.

Nevertheless, it can be argued that the development of responsible risk governance is strongly supported by the proposed precautionary approach, given the substantial variation in job-specific activities, the uncertainties surrounding actual occupational exposures, and the associated potential health effects. This applies to both civil and military apron workers.

The low phc-OEL_{KEE} may present challenges for the development and implementation of a robust occupational hygiene strategy based on the hierarchical STOP framework (Substitution, Technical measures, Organizational measures, and Personal protective Equipment). Consequently, the proposed precautionary approach should be explicitly recognized and effectively communicated to relevant stakeholders in order to secure the commitment of responsible management and the support of the appropriate regulatory authorities.

7. Conclusions

Current evidence convincingly indicates that both acute and chronic exposure to exhaust emissions at airport aprons pose significant health risks. In addition to particulate exposure, apron workers are chronically exposed to volatile components of jet fuel and exhaust, comprising complex mixtures of respiratory irritants, neurotoxic and carcinogenic substances. Although ambient concentrations of VOCs are generally considered low, cumulative low-dose exposure may still be clinically relevant. Risk assessments based on acute or single-compound exposures are likely to underestimate the long-term toxicity of such mixtures [3,68,196]. Among these, UFPs generated by KEE represent a critical exposure. Yet no hb-OEL is currently available for this heterogeneous nanoscale fraction. UFPs appear to be a suitable indicator for KEE exposure.

The phc-OEL_{KEE} based on the HNGV for non-toxic engineered nanomaterials, incorporates an assessment factor to account for the exposure to hazardous nature of the multiple KEE constituents.

Both, a mass-based phc-OEL_{KEE} of 0.4 µg/m^3 (8-hr TWA, background-corrected) and simultaneously a number-based phc-OEL_{KEE} of 1.5×10^4 #/cm^3, (8-hr TWA, background-corrected) have been derived, assuming a dominating size fraction of the exhaust UFP of 30 nm.

The frequent exceedance of this phc-OEL_{KEE} highlights the urgent need for efficient risk management measures. Neither the number-based nor the mass-based phc-OEL_{KEE} should be exceeded. Implementation requires acceptance by airport management and regulators. To address and, where necessary, enforce urgent risk governance for apron-related KEE exposure, regulators and their scientific advisors must acknowledge the inherent uncertainties of the phc-OEL_{KEE} framework.

The combined exposure to CO, NO_2, PAHs, UFPs, VOCs, and OPs make neurotoxic risks among apron workers plausible. However limited attention has been given to neurological effects in the 17 available epidemiological studies that focused on genotoxic, cardiovascular, and respiratory outcomes,

There is a clear need for prospective longitudinal cohort studies incorporating detailed exposure assessment, biomonitoring, and systematic evaluation of neurotoxicological endpoints. Such studies should examine exposure–response relationships and include long-term follow-up, particularly to assess delayed neurological outcomes that may manifest after cessation of exposure.

Author Contributions

P.J.C.v.B.: conceptualization, methodology, writing—original draft preparation; G.H.: conceptualization, methodology, writing—original draft preparation; J.N.: conceptualization, writing. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

No AI tools were used for this paper.

Abbreviations

#/cm^3	number of particles per cm^3
AF	assessment factor
APU	auxiliary power unit
BaP	benzo(a)pyrene
BC	black carbon
CLP	Classification, Labelling and Packaging
CO	carbon monoxide
CO_2	carbon dioxide
DECOS	Dutch Expert Committee on Occupational Safety
DEE	diesel engine exhaust
EC	elemental carbon
EC	(in references) European Commission
ENM	engineered nanomaterial
hb-OEL	health-based OEL
HC	hydrocarbons
HNGV	health-based nanomaterial *guidance* value
IARC	International Agency for Research on Cancer
IATA	International Air Transport Association
MNM	manufactured nanomaterial
NEG	Nordic Expert Group for Criteria Documentation of Health Risks from Chemicals
MAF	mixture allocation factor
NO_2	nitrogen dioxide
NO_x	nitrogen oxides
NP	nano particle
NRV	nano reference value
OEL	occupational exposure limit
OP	organophosphates
PAH	polycyclic aromatic hydrocarbon
pb-PAH	particle-bound PAH
phc-OEL	precautionary health-considered OEL
PM	particulate matter
PNC	particle number concentration
SO_2	sulfur dioxide
TNO	Dutch Organization for Applied Scientific Research
TWA	Time Weighted Average
UFP	ultrafine particles
VOC	volatile organic compounds
WHO	World Health Organization
KEE	kerosene engine exhaust

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