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D5.3 Pre-normative guideline for procedures on appropriate decontamination of the assistive devices

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Vapourised Hydrogen Peroxide (VHP) for Electronics-Safe Decontamination: Reliability and Operational Performance in a Pre-Normative Framework

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Executive Summary

The Vapourised Hydrogen Peroxide (VHP) system provides a safe and effective method for on-site decontamination of sensitive equipment, including electronics and assistive devices. Unlike conventional wet methods, VHP is a dry process in which decontamination occurs through vapour-phase chemistry rather than liquid contact, thereby reducing condensation risk and protecting sensitive electronics while ensuring broad-spectrum antimicrobial activity.

In the absence of an applicable standard, UCLouvain/CTMA generated experimental evidence demonstrating the effectiveness, practicability, robustness, and reproducibility of the process through both controlled laboratory studies and operational field evaluations. Results confirmed that VHP achieves sterilisation-level decontamination, including the inactivation of highly resistant spores (e.g., *Geobacillus stearothermophilus*, a recognised *Bacillus anthracis* surrogate used for validation). Continuous real-time monitoring ensured operator safety and supported condensation avoidance, thereby preserving the functionality of sensitive electronics.

A major societal contribution is the protection of vulnerable populations who rely on assistive technologies (e.g. ventilators, communication aids, mobility devices), which are essential yet difficult to decontaminate by traditional means. VHP provides a practical and electronics-safe alternative that can be applied effectively in real-world operational settings.

In addition, and uniquely among commonly deployed methods, it can preserve forensic evidence such as fingerprints and digital data, making it a valuable tool for both crisis response and post-event investigation. However, VHP may be unsuitable for materials that readily absorb peroxide vapour—such as certain porous polymers, cellulose-based materials, or natural rubber—or in settings where humidity cannot be controlled sufficiently to maintain non-condensing conditions.

This work also supports **pre-normative standardisation** by developing protocols, guidelines, and training to ensure safe, repeatable, and interoperable use of VHP across Europe, strengthening preparedness, interoperability, and inclusive resilience. The results are being integrated into VR/XR training scenarios, supporting cross-border coordination and operational readiness.

Building on European projects such as **ORCHIDS, GIFT, eNOTICE/eNOVATION, TeamUp, MOBVEC, BEHOLDER,** and **Easy2reUSE**, this research creates a continuum of innovation that enhances both responder readiness and community resilience. Beyond healthcare, the method is also relevant to

public health operations (e.g., transport and biocontainment assets) and to military, police, forensic, and mobile laboratory use cases, enabling on-site, electronics-safe, clearance-level biological decontamination consistent with NATO guidance for sensitive equipment.

In conclusion, VHP is a validated, electronics-compatible decontamination method with a favourable environmental profile compared to liquid methods, complementing existing wet decontamination approaches. By addressing a broad range of CBRN biological threats—from spores and bacteria to viruses—it broadens the operational toolkit available to first responders, while ensuring that essential assistive devices and forensic materials can be preserved during incidents.

To our knowledge, this represents the first **pre-normative evaluation** of the operational performance and reliability of an on-site VHP process specifically applied to highly sensitive equipment such as assistive technologies, linking biodecontamination, forensic integrity, and training standardisation. Ongoing work focuses on toxins and on the preservation of DNA traces for forensic profiling.

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1. Introduction

Microbial contamination of electronics-sensitive equipment is a recognised and operationally relevant risk for defence, security, and critical-infrastructure systems, with clear implications for CBRN resilience and hybrid-threat preparedness. Peer-reviewed evidence demonstrates that bacteria and fungi can colonise electronic assemblies through airborne deposition, internal airflow, and humidity cycling—without liquid exposure—forming biofilms that retain moisture, generate corrosive metabolites, and induce microbially influenced corrosion (MIC), signal leakage, and intermittent system failures [Little & Lee, 2007; Flemming & Wingender, 2010]. Such mechanisms have been documented in spacecraft and avionics (Venkateswaran *et al.,* 2014), cleanroom-qualified industrial equipment [Sandle, 2016], and medical and mission-critical devices [Pinholt *et al.,* 2019]), demonstrating that conventional cleanliness or environmental controls do not prevent microbial persistence. From a hybrid-threat perspective, these vulnerabilities may be exploited to degrade availability, reliability, or trust in digital and cyber-physical systems without overt kinetic action, aligning with EU and NATO assessments of sub-threshold, deniable disruption vectors.

Consequently, international standards and authorities now explicitly recognise biological contamination as a reliability and safety hazard for electronics, including NASA planetary-protection and spacecraft hygiene guidance [NASA-STD-8719 series], military environmental resilience requirements [MIL-STD-810], and international electrotechnical frameworks addressing environmental stress and contamination effects on electronic equipment (IEC 60068 series). Collectively, the evidence supports the integration of electronics-compatible, non-liquid microbial decontamination and monitoring into CBRN preparedness, civil-military coordination, and resilience-by-design strategies for defence and critical infrastructures.

Within this context, the present work directly supports the development of a pre-normative guideline for the electronics-safe decontamination of personal assistive devices used by vulnerable persons, as defined for the purposes of this guideline as *individuals whose physical, sensory, cognitive, social, or situational characteristics increase their exposure to, or reduce their capacity to prevent, withstand, respond to, or recover from, biological or chemical hazards, including those who rely on assistive devices or other forms of external support to maintain autonomy and safety* in line with international disaster risk reduction frameworks [UNDRR, n.d.]. This document addresses disabilities in CBRN scenarios by responding to the dual requirement of effective biological risk reduction and the preservation of sensitive, customised electronic components, thereby enabling safe reuse and continuity of assistance.

2. Pre-Normative Expectations for the Current work

The workflow underpinning this work is illustrated in **Figure 1**. The guiding pre-normative principles are as follows:

- Identify gaps in existing standards and regulations.
- Demonstrate the need for future harmonised standards (EU / CEN / ISO).
- Provide strong scientific and technical evidence addressing these gaps.
- Develop methodologies, test protocols, and validation frameworks.
- Ensure relevance through stakeholder engagement (industry, first responders, armed forces, regulators, users with disabilities) and targeted consultations to validate relevance.
- Define measurable outcomes (thresholds, validation) to support interoperability and harmonisation across systems.
- Generate evidence to inform standard-setting bodies.
- Document results in a format suitable for pre-normative use and plan for future standardisation.
- Assess feasibility (resource needs, operational constraints, transition toward formal standards).

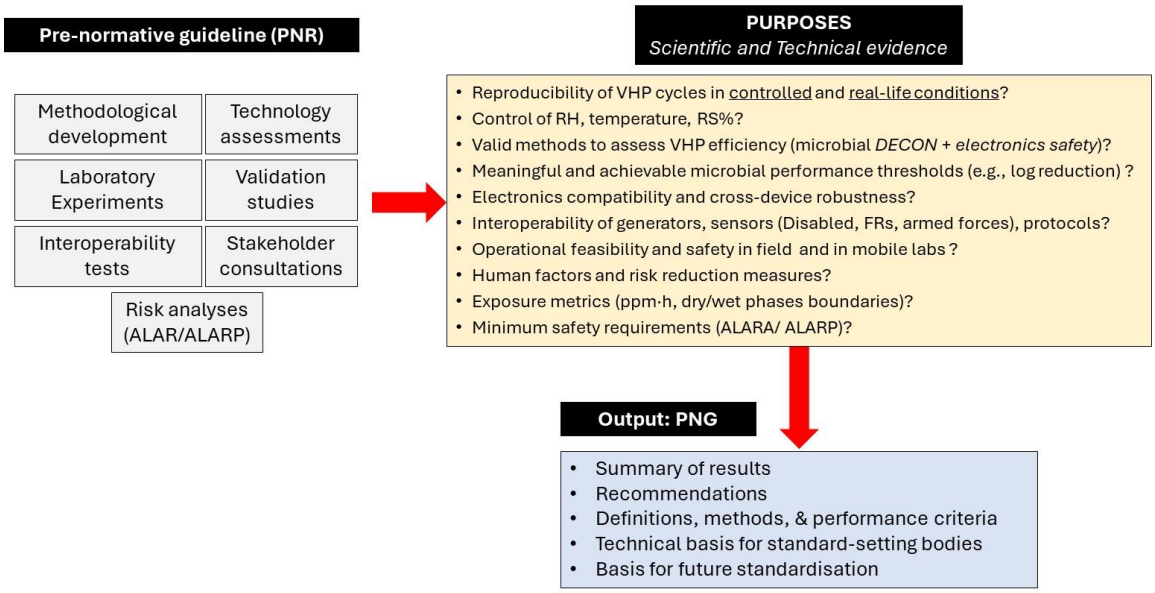

Figure 1. Pre-normative workflow: from evidence generation to guideline output.

3. Microbial and Biological Decontamination

Biological decontamination is the process of inactivating live microorganisms, neutralising toxins, or removing agents of biological origin to an acceptable level using appropriate products or methods. Its complexity exceeds that of chemical decontamination, as biological agents may persist or even proliferate in some environments, thereby posing a significant hazard. Effective and complete destruction may only be accomplished through thorough decontamination. To avoid ambiguity, **Table 1** clarifies how NATO doctrine and international public health guidance distinguish between decontamination, sanitisation, disinfection, and sterilisation. These definitions are important to frame the present work, which focuses on achieving sterilisation-level outcomes for electronics-sensitive equipment using vapourised hydrogen peroxide (VHP).

Table 1. Microbial control: NATO & Public Health definitions.

Term	Definition	Source
Decontamination	Process of removing, neutralising, or making harmless CBRN agents on persons, objects, or areas.	NATO AEP-58 (2014); ATP-3.8.1 (2022); NIH/CDC BMBL (2009)
Sanitisation	Reduction of microbial contamination to levels considered safe by public health standards (commonly used in food/industry).	WHO (2020); CDC, 2008/2019; FDA (2020)
Disinfection	Elimination of most or all pathogenic microorganisms, except bacterial spores, on inanimate objects.	CDC (2008/2019); Rutala & Weber (2016); FDA (2020)
Sterilisation	Complete destruction or removal of all forms of microbial life, including bacterial spores.	Spaulding (1968); Rutala & Weber (2016); NIH/CDC BMBL (2009)

In the event of a deliberate or accidental release of biological or chemical agents, vulnerable and minority groups—including children, the elderly, persons with physical, sensory or cognitive impairments, non-native language speakers, the homeless, tourists, and travelling communities—are likely to be disproportionately affected [Dauvrin *et al*., 2025; De Almeida Tavares, 2025]. Tracking and preserving assistive devices, particularly those with electronic or customized equipment, is challenging [Dauvrin *et al.*, 2025]. Vulnerable persons who depend on such devices face additional challenges when sensitive electronic components risk damage from conventional decontamination methods used after CBRN exposure [Irenge *et al.* 2017].

Assistive devices (as defined by WHO and ISO 9999:2016) are external products designed to maintain or improve function, independence, and well-being. They differ from implantable medical devices, which are surgically placed inside the body (e.g. pacemakers), and from diagnostic tools, which primarily serve to monitor or assess health rather than directly assisting daily activities. The main categories of electronics-sensitive assistive devices that require electronics-safe decontamination after biological contamination are summarised in **Table 2**.

Table 2. Devices requiring thorough decontamination after biological contamination.

Devices Requiring Thorough Decontamination After Biological Contamination		
Category	**Examples of Devices**	**Decontamination Challenge**
1. External / Wearable Medical Devices (high priority)	• Insulin pumps (external units with tubing/infusion sets) • Respiratory assistive devices (portable oxygen concentrators, CPAP[1]/BiPAP[2] masks & tubing) • Hearing aids and cochlear implant externals (sound processors) • Limb prostheses (upper/lower limbs, including myoelectric hands/arms/legs with motors/electronics) • Wheelchairs (manual or powered, large surface area, high-touch device)	• Direct skin/environment contact; • Complex shapes/materials; • Contain sensitive electronics and motors at risk from liquid decontamination.
2. Digital Communication & Interface Devices	• Tablets, smartphones with accessibility apps • Dedicated communication devices (speech-generating devices, eye-tracking AAC[3] systems)	• Essential daily-use electronics; • Small crevices and touch surfaces; • High risk of damage from liquids.
3. Assistive Sensors / Interfaces	• EEG[4]-based brain–computer interface headsets/electrodes (external, non-invasive)	• Precision sensors and electrodes; • Delicate materials requiring dry, non-condensing decontamination.

Notes:

[1] CPAP: Continuous Positive Airway Pressure.

[2] BiPAP: Bilevel Positive Airway Pressure.

[3] Augmentative and Alternative Communication.
[4] Electroencephalography.

Categories are based on WHO terminology for assistive technology (2022) and ISO standards (2016).

Conventional liquid-based decontamination methods—understood here as aqueous, contact-based processes involving spraying, washing, or immersion with liquid disinfectant or decontaminant solutions—may damage the devices listed in **Table 2**. This risk underscores the importance of alternative approaches such as vapourised hydrogen peroxide (VHP), which can achieve high biocidal efficacy while preserving device functionality.

In this work, we reviewed several NATO documents to examine the alignment between doctrine on biological decontamination and the present study on vapourised hydrogen peroxide (VHP) (**Table 3**). AEPs (*Allied Engineering Publications*) provide NATO technical standards and specifications, while ATPs (*Allied Tactical Publications*) define tactical and operational doctrine. Specifically, AEP-58 offers technical and medical guidance on CBRN decontamination, and ATP-3.8.1 establishes the doctrinal framework for CBRN defence operations, including the treatment of sensitive equipment [ATP-3.8.1 Vol I]. NATO guidance highlights the graded levels of decontamination, the need for hazard-specific strategies, and the preference for chemical over physical methods when addressing biological agents [AEP-4784]. These principles are directly reflected in our approach: VHP is a chemical oxidising process capable of achieving clearance-equivalent decontamination while preserving sensitive electronics. Moreover, NATO doctrine defines "sensitive equipment" as items whose performance may be degraded by conventional decontamination methods—corresponding to the assistive devices tested in this study [AEP-58; STO TR-HFM-233]. **Table 3** therefore demonstrates that the operational use of VHP, as validated by UCLouvain-CTMA, is not only scientifically robust but also consistent with NATO doctrinal requirements.

Table 3. Sensitive equipment biodecontamination: NATO doctrine vs. current VHP work.

	NATO Doctrine (AEP-58 / ATP-3.8.1.)	Key Point	Coherence with VHP Work (this report)
AEP-58	Levels of decontamination (Immediate, Operational, Thorough, Clearance)	Clearance is the most technically challenging; may not always be achievable.	VHP is positioned as a high-level decontamination method for sensitive equipment, supporting *clearance*-
AEP-58	Hazard specificity	Clearance must be tailored to the specific biological hazard; persistence, viability, and	UCLouvain-CTMA experiments with VHP assess efficacy under realistic operational conditions (humidity,
AEP-58	Preference for chemical over physical methods	AEP-58 draft notes chemical methods are preferred for biological agents.	VHP is a chemical oxidising agent; this directly supports its use as the method of choice for biological decontamination.
AEP-58	ALARA[1]/ALARP[2] principle	Clearance means reducing residual contamination to a health-protective level; no fixed	VHP validation focuses on achieving sterilisation-level inactivation (endospores, viruses) while protecting
ATP-3.8.1	Scope	Doctrine distinguishes personnel decontamination from materiel decontamination.	Our report excludes human decon and focuses solely on sensitive equipment — aligned with ATP-3.8.1.
ATP-3.8.1	Sensitive equipment	Defined as items whose performance may be degraded by conventional methods,	Table 1 of your report lists electronics-sensitive assistive devices; CTMA

Notes:

[1] ALARA: As Low As Reasonably Achievable — principle used primarily in radiological protection and biological risk management, under which exposures are minimised as far as achievable given available technology and good practice.
[2] ALARP: As Low As Reasonably Practicable — principle widely applied in UK and NATO CBRN risk management, requiring risks to be reduced as far as practicable, considering the balance between risk reduction and the resources (time, money, effort) required.

Other NATO standards, including **AEP-4784** (CBRN decontamination equipment test methods), **STANAG 2352** (general principles of chemical and biological decontamination), and ATP-84 (medical aspects of CBRN defence), were reviewed as part of this work and provide complementary guidance. However, they are less directly applicable to the present focus on vapourised hydrogen peroxide (VHP) decontamination of electronics-sensitive equipment and were therefore not considered further in this comparison.

4. Overview of the VHP Delivery System used in the Current Pre-Normative Work

4.1. Antimicrobial Spectrum and Mechanism of Action of Hydrogen Peroxide (H_2O_2)

Hydrogen peroxide (H_2O_2) is a broad-spectrum antimicrobial and oxidising agent**,** widely used for the decontamination of surfaces and equipment in healthcare environments. It is effective against clinically relevant bacteria, bacterial endospores, and viruses [Abdelshafy *et al*., 2024; CDC 2023]. A key advantage is its spontaneous decomposition into non-toxic by-products, water and oxygen. The antimicrobial mechanism involves oxidative damage to DNA, proteins, and membrane lipids, mediated primarily by reactive oxygen species (ROS) and iron-oxygen species (IOS) (**Figure 2**).

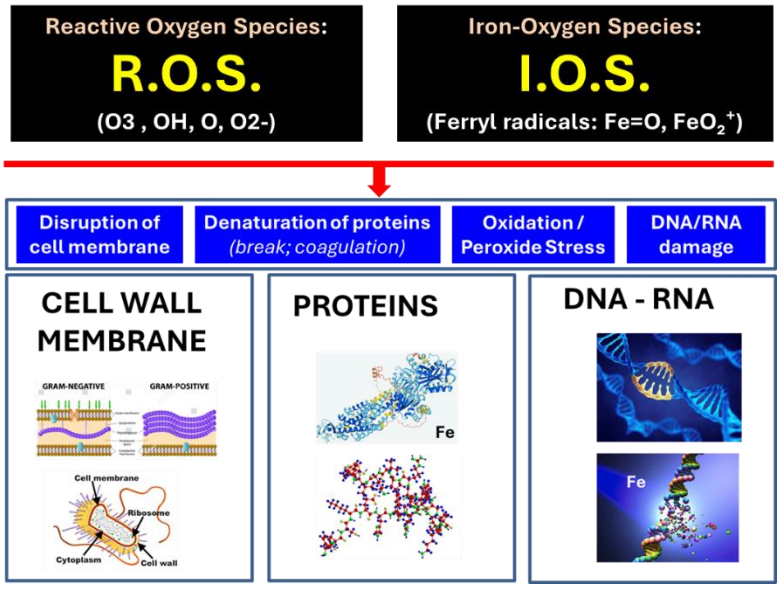

Figure 2. VHP antimicrobial mechanisms.

Notes: Schematic representation of the effects of reactive oxygen species (ROS) and iron–oxygen species (IOS) on microbial cellular targets, including cell membranes, proteins, and DNA/RNA.

4.2. Delivery Systems for Hydrogen Peroxide (H_2O_2)

Two main hydrogen peroxide delivery systems are employed:

- **aerosolised systems**, which disperse fine liquid droplets, commonly referred to as aerosolised hydrogen peroxide (aHP) or dry mist hydrogen peroxide (DMHP),
- **vapourised systems**, which generate hydrogen peroxide in the gaseous phase, usually referred to as vapourised hydrogen peroxide (VHP) or hydrogen peroxide vapour (HPV) [Otter *et al.,* 2013].

VHP decontamination was first developed in the 1980s, commercialized in the early 1990s and originally designed for use in pharmaceutical cleanrooms. VHP decontamination was first developed in the 1980s, commercialised in the early 1990s, and originally designed for use in pharmaceutical cleanrooms. Since then, numerous studies have evaluated its efficacy and application in containment laboratories and healthcare environments.

While aerosolised hydrogen peroxide systems have been deployed in healthcare and emergency settings, their performance has often been less consistent than that of VHP, particularly against bacterial spores and multidrug-resistant organisms [Andersen et al., 2006]. Despite certain operational advantages of aerosolised systems, vapourised hydrogen peroxide has generally demonstrated more consistent efficacy across a broad range of nosocomial pathogens. Importantly, VHP has been shown to achieve reliable inactivation of Bacillus anthracis spores—one of the most resistant biological threat agents—under both laboratory and operational conditions [Wood et al., 2016; Falaise et al., 2022; Oudejans et al., 2023]. Comparative studies further indicate that VHP achieves higher levels of microbial inactivation and more uniform spatial distribution than aerosolised hydrogen peroxide systems [Fu et al., 2012]. Vapour systems typically employ a 30–35% (w/w) liquid H_2O_2 solution, which is vaporised into a controlled air stream and distributed through predefined decontamination cycles [Fu et al., 2012].

Beyond hospital-based applications, no-touch automated disinfection systems—particularly VHP—have consistently been identified among the most effective methods for terminal decontamination of complex environments, with a stronger evidence base than ultraviolet or other no-touch technologies [Boyce, 2016]. Well-documented commercial systems include STERIS VHP®, Bioquell HPV, and Cleamix VCS, with STERIS and Bioquell systems having been used in pharmaceutical, cleanroom, and hospital settings for several decades (**Table 4**). These systems are widely referenced in peer-reviewed studies, GMP guidance, and regulatory documentation as standardised technologies for biodecontamination. Collectively, this body of evidence demonstrates that VHP is highly effective against biological agents and is generally compatible with a wide range of materials, including sensitive electronic equipment, provided that condensation is avoided. VHP has also been investigated for limited applications involving certain chemical agents, although it is not applicable to radiological contamination.

Table 4. Overview of non-liquid biodecontamination methods for sensitive equipment.

Feature	STERIS	CLEAMIX	BIOQUELL	Fumigation (general)
Active principle	Hydrogen peroxide (H_2O_2)	Hydrogen peroxide (H_2O_2)	Hydrogen peroxide (H_2O_2)	Reactive gases/vapours (e.g. formaldehyde, chlorine dioxide)
Physical delivery state	Vapour (gas phase; not aerosol/fog)	Vapour (gas phase; not aerosol/fog)	Vapour (gas phase; not aerosol/fog)	Gas or vapour (non-aerosolised)
Equipment size	Large, fixed or semi-mobile units, typically located outside the enclosure (treatment volume)	Portable, field-deployable units placed inside the enclosure (treatment volume)	Compact or mobile units (e.g., Bioquell Q10, BQ-50); usually placed outside the enclosure but can be placed inside	Variable; may include large industrial systems located outside the enclosure
Coverage	Generally uniform (dependent on mixing/airflow)	Good; dependent on airflow and enclosure characteristics	Generally uniform; widely validated sporicidal performance	Potentially uniform in sealed/controlled spaces (depends on circulation and conditions)
Typical use case	Hospitals, pharma cleanrooms, high-containment laboratories	Field deployments, hospitals, ad hoc deployments*	Hospitals, cleanrooms, BSL laboratories, patient rooms, transport vehicles	Buildings, warehouses, containers
Key Hazards / Limitations	Corrosive potential; condensation must be controlled	Lower condensation risk; process parameters must be controlled	Requires aeration phase; outcomes depend on humidity/saturation control; material compatibility constraints.	Some agents highly toxic or carcinogenic (e.g. formaldehyde, ethylene oxide)

4.3. Selection Rationale for the Cleamix VCS

Modern VHP systems such as the Cleamix VCS-100 generate hydrogen peroxide (H_2O_2) vapour **in situ** within the treated enclosure from a concentrated aqueous H_2O_2 solution using a proprietary vaporising plate/mesh arrangement. Process parameters—typically H_2O_2 concentration (ppm), temperature, and humidity (and, where implemented, relative saturation)—are monitored in real time and used by the control software to maintain vapour conditions below saturation/condensation, maximising antimicrobial efficacy while avoiding liquid deposition that could damage H_2O_2-sensitive materials or equipment. In practice, target concentrations are commonly in the low-hundreds of ppm, with controlled tests reporting maxima up to ~850 ppm, depending on enclosure characteristics and ambient conditions (e.g., volume, leakage, temperature, and relative humidity).

As summarised in **Table 4**, Cleamix's approach differs mainly in **where and how vapour is generated and managed:** Cleamix generates vapour inside the enclosure with feedback control to avoid condensation, whereas Bioquell systems typically generate vapour externally and inject it into the

space (often including saturated conditions to drive micro-condensation), and STERIS VHP systems flash-vaporize H_2O_2 into conditioned air and are generally operated as a non-condensing process to support material compatibility.Independent testing conducted in accordance with EN 17272:2020 confirms that the exposure medium is hydrogen peroxide in the vapour phase, that no surface wetting or liquid deposition step is involved, and that efficacy is achieved through the combined effect of vapour concentration and exposure time (C×t). In this respect, the Cleamix VCS operates in accordance with the same vapour-phase decontamination principles as other validated VHP systems (**Table 4**). The selection of the Cleamix VCS for this work was based on its modular design, portability, and demonstrated technical suitability for electronics-sensitive equipment and a broad spectrum of biological agents.

In addition to its established biocidal performance, VHP as a decontamination process has been shown, under controlled conditions, to contribute to the degradation or detoxification of selected chemical warfare agents and toxic industrial chemicals, although its efficacy is agent-specific and dependent on environmental parameters such as concentration, humidity, and exposure time [Wagner & Yang, 2002; Wood et al., 2010; Wood et al., 2012; U.S. Army Edgewood Chemical Biological Center, 2011].

According to Cleamix technical documentation, the system can be operated in an ammonia-activated VHP mode (VHP with ~1% NH_3) that is intended to support neutralisation of selected chemical warfare agents, including nerve agents (e.g., VX). This manufacturer claim is agent- and condition-dependent and should therefore be interpreted in light of independent data and within validated operating envelopes. In the wider literature (not specific to Cleamix), modified VHP processes using ammonia (VHP + ammonia) have been reported to detoxify agents such as VX (and, under defined test conditions, GD and HD) on surfaces. These findings support the plausibility of the approach, but do not substitute for device- and protocol-specific validation [Talmage et al., 2007]. If the Cleamix ammonia-activated mode can reproduce the critical exposure conditions (e.g., H_2O_2 dose, NH_3 fraction, humidity, contact time, and distribution within the treated volume), comparable detoxification performance may be expected in principle, pending confirmation by Cleamix-specific testing.

Automated, pre-set cycles enable rapid deployment in sealed environments, including personal protective equipment, weapons, optics, electronic devices, and interior spaces. By connecting multiple units, the system can also be scaled to decontaminate larger enclosed areas.

4.4. UCLouvain Operational Performance and Reliability of the Cleamix VCS

In addition to published data, the *CTMA laboratory at UCLouvain has conducted independent Technical and operational validity studies with the Cleamix VCS, particularly focusing on the decontamination of assistive devices used by vulnerable groups*. Our experiments confirmed the system's efficacy across a wide range of electronics-sensitive devices and biological agents under realistic operational conditions.

Chemical agent decontamination was outside the scope of CTMA's experimental protocol; however, the potential applicability of VHP to selected chemical warfare agents and toxic industrial chemicals

has been established in the literature, as discussed in the previous section (Section (c)). Manufacturer data and independent studies further support this process-level capability.

In CBRN scenarios, vapourised hydrogen peroxide (VHP) should be considered **a dry decontamination method**, particularly suited for sealed environments, sensitive materials, and electronics. It complements, rather than replaces, **wet decontamination**, which remains indispensable for exposed individuals and for non-sensitive equipment.

In CBRN scenarios, VHP should be considered a **dry decontamination method**, particularly suited for sealed environments, sensitive materials, and electronics. It complements, rather than replaces, **wet decontamination methods**, which remain indispensable for exposed individuals and for non-sensitive equipment, surfaces, and infrastructure, where aqueous chemical solutions are required to achieve effective agent removal and neutralisation.

5. Cleamix VCS Vapouriser: Functions and Features

- **Automated Operation**: The user specifies the desired H_2O_2 concentration (in ppm) and exposure duration. The vapouriser automatically regulates vaporisation, circulation, and breakdown, with adjustments based on environmental parameters (humidity, temperature, and relative saturation).
- **Smart Monitoring**: Advanced sensors provide real-time feedback on H_2O_2 vapour concentration, preventing condensation and automatically adjusting system parameters to maintain the target ppm. The sensors also monitor key environmental parameters, including local relative humidity (RH), relative saturation (RS), and temperature inside the confined area. A highly sensitive handheld sensor (range 0-20 ppm) is used by operators to ensure the absence of residual H_2O_2 (**Figure 3**).
- **On-site deployment of sealed environments**: CTMA/UCLouvain has used and validated several types of on-site deployable sealed environments, such as containers, inflatable tents, and bubble enclosures. The goal is to rapidly deploy a robust, portable containment system to isolate materials during decontamination, ensuring safety for operators. This setup also helps maintain an optimal temperature and VHP distribution inside the confined area (**Figure 3**).
- **Chemical Indicators**: H_2O_2-sensitive adhesive tape indicators are placed inside the tent, bubble, or container to confirm adequate vapour dispersion. They change colour visibly upon exposure to the vapour (Figure 3).
- **Biological Indicators**: APEX biological assay discs, containing a standardised amount of *Geobacillus stearothermophilus* (~10^6 spores per disk), are strategically positioned within the decontamination zone (**Figure 3**). After the procedure, these discs are tested at the CTMA-UCLouvain laboratory. The absence of microbial growth following incubation confirms microbial inactivation.

Figure 3. Main components of the on-site VHP decontamination system.

Notes: The system comprises: (A) vapouriser unit (Cleamix VCS 100); (B) primary inflatable enclosure; (C) secondary inner enclosure; (D) control tablet; (E) handheld hydrogen peroxide detector (Dräger X-am 5100; 0–20 ppm); (F) biological indicator (spores of *Geobacillus stearothermophilus*); (G) chemical indicator (colourimetric indicator tape for hydrogen peroxide exposure).

6. Pre-Normative Research on VHP Decontamination

Our operational performance activities are conceived as pre-normative contributions to guide future regulatory frameworks and best practices in CBRN bio-decontamination scenarios. They are consistent with international biosafety recommendations, such as those outlined in the WHO Laboratory Biosafety Manual, 4th edition [WHO, 2020], and with relevant CEN and ISO standardisation frameworks on decontamination and assistive technologies [ISO 9999:2016; CEN, 2015]. This ensures that the protocols developed here can support both European standardisation initiatives and global best practices. The system offers a modular and mobile solution that complements wet decontamination procedures for first responders and victims, thereby enhancing responder safety and operational readiness.

The aim of our work on VHP decontamination of biological agents is as follows:

- **Inform and support future standardisation**, regulation, or best practices regarding the on-site decontamination of electronics-sensitive equipment.
- Generate **robust, reproducible data** on VHP performance, including efficacy, ease of use and applicability on-site, and safety.
- **Define** parameters and protocols that could be codified in standards in future normative frameworks.
- **Safety protocol:** A strict safety protocol was followed by all operators. This included continuous remote sensing of H_2O_2 concentrations (ppm) inside and outside the confined space at the end of

the decontamination procedure, as well as the use of appropriate personal protective equipment (gowns, gloves, protective eyewear).

- **Standardisation for operational use:** Given the lack of standardised methods for on-site decontamination of electronic equipment, including assistive devices, all procedures were adapted with the goal of standardisation, allowing operators to repeat them safely and efficiently during on-site interventions.
- **Guideline development:** Data collected from multiple robustness and reproducibility tests have been used to develop a guideline that could serve for future norms in on-site biodecontamination.
- **Dissemination to regulatory bodies:** This information will be shared with relevant regulatory and standardisation bodies such as European Committee for Standardization (CEN) and to the European Committee for Electrotechnical Standardization (CENELEC) following its publication (currently in progress).

7. Pre-Normative Performance of VHP Decontamination

Our operational performance and reliability work consisted of major activities conducted both in the laboratory (in-lab experimental phases) and on-site (operational decontamination).

7.1. Automated, Pre-Set Cycles

Figure 4 shows the typical phases of a VHP decontamination cycle, illustrating the evolution of H_2O_2 vapour concentration, relative humidity (RH), and relative saturation (RS%) throughout the process. While classical cycles begin with a dehumidification step to lower RH and reduce the risk of condensation, this step is not required with the Cleamix VCS. At the start of the procedure, H_2O_2 is released and the concentration gradually increases while sensors continuously monitor RH and RS to ensure levels remain below the condensation point. In the decontamination phase, vapour concentration is maintained within the effective treatment window to achieve microbial inactivation. Finally, in the aeration phase, vapour concentration decreases rapidly—within a few minutes under on-site conditions (by opening the inflatable enclosure), or through controlled ventilation and optional catalytic converter in fixed facilities. RH and RS return to baseline levels. This controlled modulation of vapour and humidity ensures effective sterilisation-level efficacy while avoiding condensation and preserving the integrity of sensitive equipment (**Figure 4**).

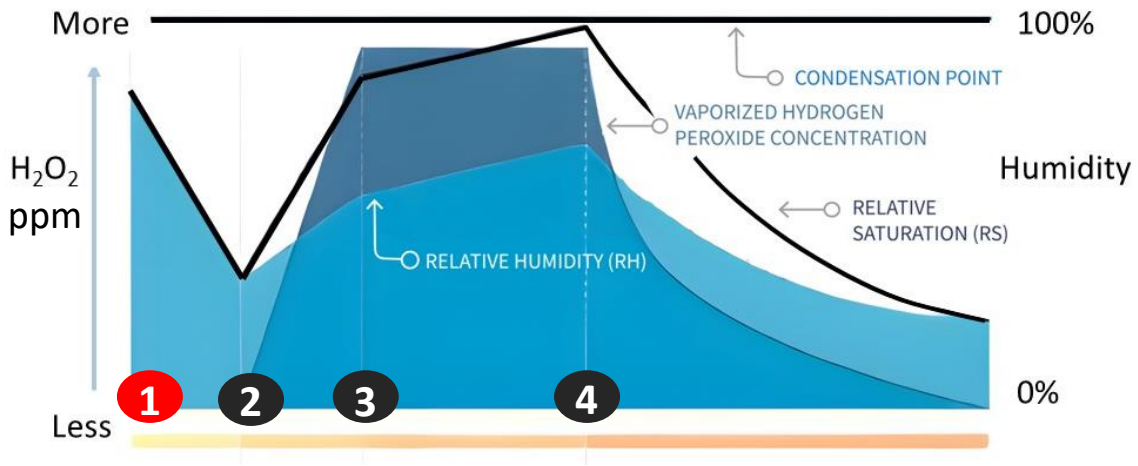

Figure 4. Phases of a VHP decontamination cycle.

Notes: The figure shows the relationship between H_2O_2 concentration, relative humidity (RH), and relative saturation (RS) over time. (1) Dehumidification (not required with Cleamix VCS); (2) Conditioning; (3) Decontamination; (4) Aeration.

As illustrated in **Figure 5**, the vapourised hydrogen peroxide (VHP) process is controlled using a predefined concentration setpoint, while decontamination efficacy is assessed using cumulative exposure (ppm·h) calculated above a targeted threshold concentration. **Figure 5** shows the typical evolution of an automated, controlled release of H_2O_2, displaying VHP concentration (ppm) over time relative to the treatment setpoint and targeted threshold, together with relative saturation (RS%) and cumulative exposure (ppm·h) throughout the decontamination cycle. Horizontal lines indicate the control setpoint and threshold concentration values. In this representative cycle, cumulative exposure reached 600 ppm·h at an average ambient temperature of 32.5 °C. *Geobacillus stearothermophilus* spores were used as the reference biological indicator for both laboratory and on-site decontamination runs. Additional biological agents were included to confirm efficacy across a broader spectrum (see section 7.2.6 for a summary of decontamination parameters and outcomes).

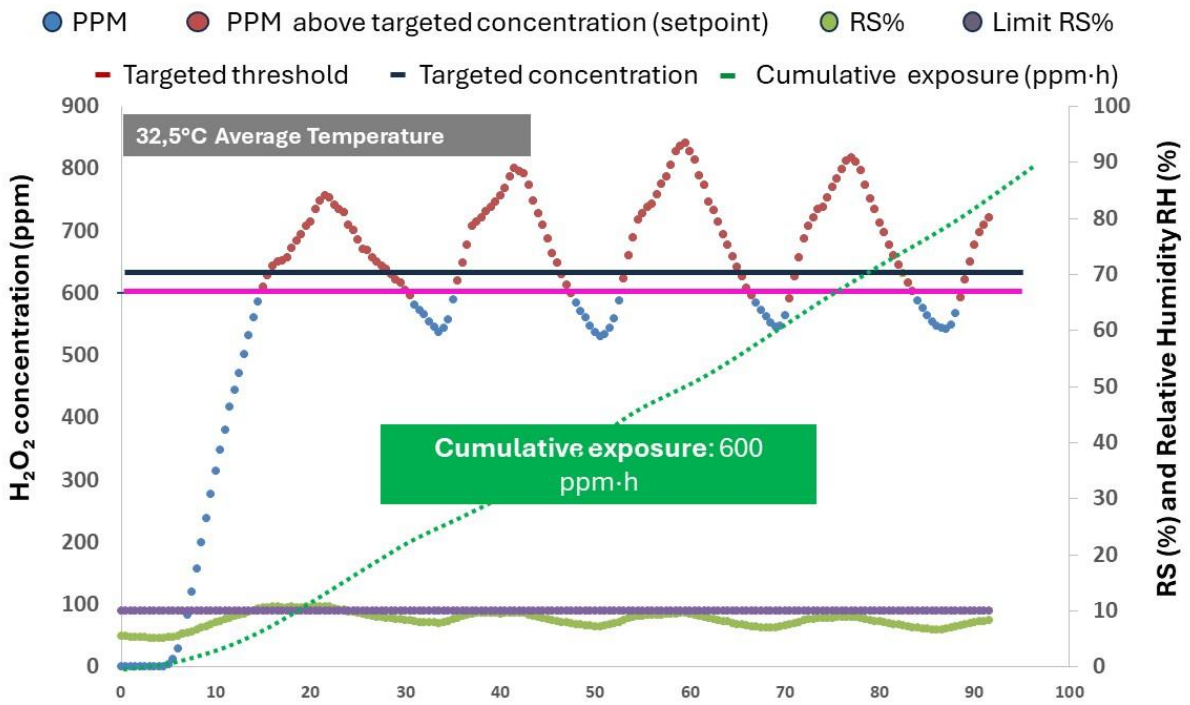

Figure 5. Vapourised hydrogen peroxide (VHP) decontamination cycle.

Notes: This figure shows an automated, on-site vapourised hydrogen peroxide (VHP) decontamination cycle, with hydrogen peroxide vapour concentration (ppm), relative saturation (RS, %), and cumulative exposure (ppm·h) plotted over time. The targeted concentration corresponds to the system control setpoint, while the targeted threshold defines the minimum effective concentration contributing to cumulative exposure, consistent with NATO AEP-58 graded decontamination principles. Relative saturation is monitored to remain below 100% to prevent condensation. Cumulative exposure is calculated as the time-integrated vapour concentration above the targeted threshold, in accordance with EN 17272 airborne disinfection methodology.

7.2. Decontamination

7.2.1. Basic Principles

Hydrogen peroxide is active against a wide range of organisms, but spores remain the most resistant biological form. Consequently, spore-forming bacteria are widely used as biological indicators in decontamination and sterilisation validation, but their characteristics and applications differ significantly.

The rod-shaped, Gram-positive bacterium *Geobacillus stearothermophilus* produces endospores with exceptional resistance to heat, chemical agents (including H_2O_2), desiccation, and radiation — properties that make them a recognised surrogate for *Bacillus anthracis*, the causative agent of anthrax [Setlow, 2006]. *G. stearothermophilus* is the reference organism for sterilisation control because its thermophilic spores are highly resistant, making it a stringent benchmark for validating hydrogen peroxide vapour (VHP) cycles. For the same reasons, *G. stearothermophilus* spores have become the *de facto* biological indicator for validating in-field, electronics-safe VHP decontamination (**Figure 6**).

Figure 6. *Geobacillus stearothermophilus* spores used as biological indicators.

Notes: Left: Representative morphology of *G. stearothermophilus*, highlighting spore structures (red). Right: Biological indicator response following VHP exposure. To assess the efficacy of hydrogen peroxide vapour decontamination on electronic equipment, biological indicator samples were incubated at 55 °C for 7 days in accordance with the manufacturer's recommendations. The untreated control (Tube 1) exhibited a colour change from purple to yellow, indicating bacterial growth, whereas treated samples (Tubes 2–4) showed no colour change. The absence of growth confirms complete inactivation of *Geobacillus stearothermophilus* following VHP exposure.

To illustrate this choice, **Table 5** compares *G. stearothermophilus* with other relevant spore-forming species, including *Bacillus anthracis* and *B. thuringiensis* (used in biopesticides). This comparison highlights why *G. stearothermophilus* is preferred for process validation, while also showing the broader relevance of spore-forming bacteria in biodefence, biotechnology, and biosafety contexts.

Table 5. Key spore-forming bacteria for biodecontamination and sterilisation.

Feature	Bacillus anthracis	*B. subtilis*	*B. cereus*	*B. atropheus*	*B. thuringiensis*	***Geobacilus stearothermophilus***
Genus	Bacillus	Bacillus	*Bacillus*	Bacillus	Bacillus	Geobacillus
Gram Stain	Positive	Positive	Positive	Positive	Positive	Positive
Shape	Rod-shaped	Rod-shaped	Rod-shaped	Rod-shaped	Rod-shaped	Rod-shaped
Spore Formation	Yes	Yes	Yes	Yes	Yes	Yes
Temperature	Mesophilic (~37°C)	Mesophilic (~30–37°C)	Mesophilic (~4–50°C)	Mesophilic (~30–37°C)	Mesophilic (~25–37°C)	**Thermophilic** (~50–65°C)
Habitat	Soil (spores can persist for long periods); often associated with grazing areas	Soil; frequently found on plant surfaces and in decaying matter	Soil, food, dairy products	Soil; commonly found in dust, air, and dry environments	Soil	**Hot environments** (e.g., compost, autoclaves)
Main Function	Pathogenicity (anthrax)	Model organism for research; robust spores assist in survival	Foodborne pathogen; produces diarrheal and emetic toxins	Used as a biological indicator for sterilisation validation	Produces insecticidal toxins	Used in sterilisation control
Application	Vaccine development, biodefence research, and study of anthrax pathology	Industrial enzyme production, probiotics, biotechnological research	Food safety research, microbial contamination control, and toxin studies	Sterilization process validation (e.g., for ethylene oxide and dry heat sterilisation)	Biopesticides, genetically modified crops protected against specifc insect pests	Sterilisation validation

7.2.2. Beyond Spores: Resistance of Other Biological Agents

Research has indicated that organisms which produce superoxidase dismutase, catalase and other peroxidases have increased resistance to VHP thus requiring longer exposure times, as these enzymes can break down the H2O2 [Kahnert *et al.* 2005].Notably, Pottage *et al.* (2012) reported that methicillin-resistant *Staphylococcus aureus* (MRSA) was more resistant to VHP than commercial *G. stearothermophilus* indicators, highlighting that indicator inactivation does not guarantee susceptibility across all pathogens [French *et al*., 2004]. More recent studies, however, confirmed that high-concentration VHP (35%) effectively inactivated both MRSA and spores, within 30 and 20 minutes respectively [Murdoch *et al.*, 2016]. Lemmen *et al.* (2015) further showed ≥6-log reductions of spores and elimination of multidrug-resistant organisms such as MRSA, vancomycin-resistant *Enterococcus* (VRE), and *Acinetobacter baumannii* on both porous and non-porous surfaces. Together with systematic reviews and clinical evaluations [Ahmed & Mulder, 2021; Ayub *et al*., 2024; Maclean *et al.*, 2015; Khandelwal *et al*., 2022; Bioquell, 2017; Courti *et al.,* 2024], these data confirm that VHP at higher H_2O_2 concentrations achieves sterilisation-equivalent decontamination for spores and multidrug-resistant bacteria — and is consistently more effective than aerosol-based systems.

7.2.3. Impact of Organic Load on VHP Efficacy

The factor most influencing VHP efficacy is the presence of organic material ("soil load"), such as dried blood. Organic load reduces the effectiveness of VHP against viruses, vegetative bacteria, and spores [Heckert *et al.*, 1997; Meszaros *et al.*, 2005; Krishnan *et al.*, 2006; Pottage *et al.*, 2010]. This reduced efficacy is partly due to high catalase concentrations in some materials (notably blood), and partly because hydrogen peroxide reacts with any oxidisable compounds present, leaving less available for microbial inactivation [Meszaros *et al.*, 2005; Davies *et al.*, 2010]. These findings underscore the importance of **pre-cleaning surfaces** before VHP application: the cleaner the surfaces, the more consistent and reproducible the decontamination process [Meszaros *et al.*, 2005].

7.2.4. UCLouvain Experimental Evaluation

At least 12 laboratory and 6 on-site VHP decontamination runs were performed, all resulting in complete inactivation of *Geobacillus stearothermophilus* biological indicators. The average cumulative exposure reached 860 ppm·h in laboratory runs (range: 400–1880 ppm·h) and 751 ppm·h in on-site runs (range: 622–921 ppm·h).

To extend evaluation beyond spores, additional agents were included (**Table 6**) to compare their relative resistance. Selection was based on CBRN standards [NATO-AEP-58] and UCLouvain own expertise in biological threats. Another rationale for this inclusion lies in the capacity of certain agents—especially viruses and toxins—to infiltrate or penetrate complex systems and components, such as electronic equipment and assistive devices. This may be facilitated by their smaller physical size, as bacterial spores are among the largest commonly considered CBRN biological agents in terms of particle volume (see **Table 6** for a size comparison across viruses, bacteria, spores, and toxins).

Table 6. Size comparison of selected biological CBRN agents and surrogates.

Agent type	Examples	Typical Size
Viruses	Smallpox, Ebola, Arboviruses	~100–300 nm
Bacteria	*Bacillus anthracis*, *Yersinia pestis*	~0.5–2 µm
Bacterial spores	*B. anthracis*, *G. stearothermophilus*	~0.8–1.5 µm
Fungi	*Candida albicans* (yeast), *Aspergillus fumigatus* (filamentous fungus)	Yeast: 3-10 µm; Hyphae: 2-10 µm width, > 100 µm length
Toxins	Ricin, Botulinum toxin	1-10 nm

7.2.5. Level of Decontamination

The Spaulding classification (1968), reaffirmed in modern guidelines [Rutala & Weber, 2016; CDC, 2008, updated 2019; WHO, 2019], remains central to infection prevention, categorising devices as critical, semi-critical, or non-critical. Only sterilisation ensures complete inactivation of bacterial spores (**Figure 7**). In the CBRN context, assistive devices used by vulnerable groups, though non-invasive in normal healthcare use, must be considered "critical-equivalent" once exposed to contaminating biological agents. Reusing these devices without sterilisation would pose unacceptable risks as they can act as contamination vectors requiring sterilisation-level decontamination (**Figure 7**). Achieving sterilisation-level decontamination is therefore the ultimate objective of VHP — and our results demonstrate that this goal can be achieved for sensitive electronics and assistive technologies.

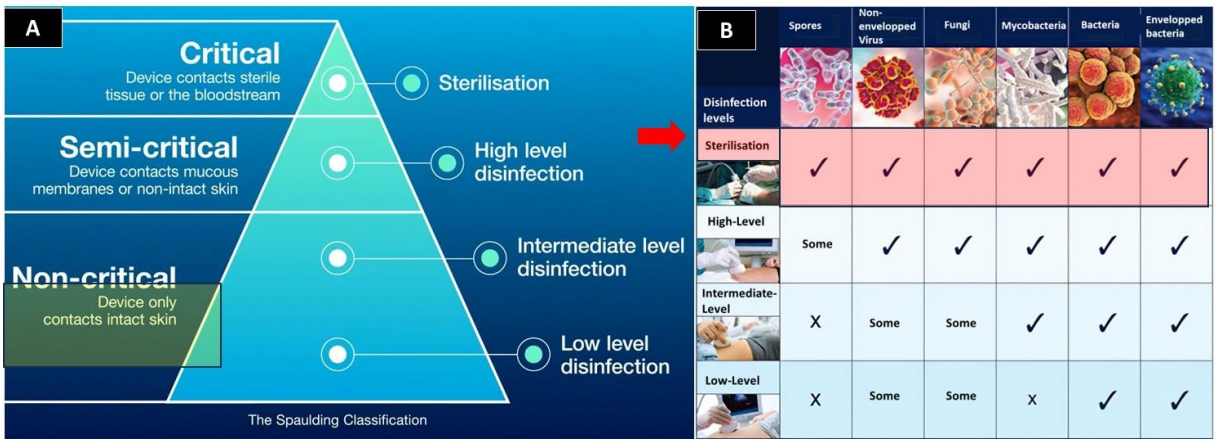

Figure 7. Levels of decontamination.

Notes: (A) Spaulding classification of medical device criticality and the corresponding required level of decontamination. (B) Hierarchy of microbial susceptibility, illustrating that only sterilisation reliably ensures the inactivation of bacterial spores.

7.2.6. VHP Decontamination Parameters and Outcomes

To support pre-normative guidance development, the VHP method was assessed against a representative panel of biological targets (bacteria, viruses, fungi) using duplicate runs under defined enclosure conditions. Outcomes were recorded using target-appropriate post-exposure growth/replication controls, reported as **"No growth"** where no viable organism/replication was detected after the relevant control period. In parallel, material compatibility was screened through post-cycle checks of selected electronic devices, reported as **"Functional"** where operational performance was maintained. Toxin inactivation was not assessed at this stage.

Results in **Table 7** are specific to the stated enclosure configuration and cycle conditions and should be interpreted as performance evidence for this operational setup rather than as a universal efficacy claim.

Table 7. Summary of biological outcomes and VHP cycle parameters.

Targets	Experimental conditions and targets	H2O2 vapors (duplicate runs)
	Hydrogen peroxide solution	H_2O_2 35%
	Sealed Containment Area (m^3)	5 (H= 2 m; footprint: 2.5 m^2)
	Ambient temperature	21-30°C
	Exposure time to VHP (h)	3
	Relative saturation limit	90%
	Target concentration level (ppm)	400 ppm
	Target treatment level	380 ppm
	Cumulative exposure (ppm·h)	1200 ppm·h
Bacteria	*Geobacillus stearothermophilus* (Merck Millipore #1.11499.0001 Solution)	✓ **No growth**
	G. stearothermophilus (Apex disk 106)	✓ **No growth**
	Escherichia coli (MS2 host)	✓ **No growth**
Viruses	MS2 bacteriophage	✓ **No growth**
	Japanese Encephalitis Virus (JEV)	✓ **No growth**
Fungi	*Cladosporium species*	✓ **No growth**
Toxin	Ricin (RTA and RTB)	**To be assessed (perspectives)**
	Purified ricin toxin	**To be assessed (perspectives)**
	Crude ricin toxin	**To be assessed (perspectives)**
Electronic equipment	*Smartphone*	✓ **Functional**
	Telecommunication electronic devices	✓ **Functional**
	Laboratory electronic devices	✓ **Functional**

Notes: Post-exposure growth/replication control periods were applied. These were 21 days for fungi, 7 days for *G. stearothermophilus*, 2 days for JEV virus, 1 day for MS2 virus, and 1 day for *E. coli.*

"To be assessed (perspectives)" indicates targets included as part of the forward-looking assessment described in Section b8.2.7 and not yet evaluated in the present experimental campaign.

7.2.7. Decontamination: Ricin and Functional Assessment

- **Why toxins need specific guidance:** Toxins require dedicated decontamination guidance because they can remain hazardous even in the absence of viable microorganisms, and their neutralisation is harder to demonstrate with routine microbiological endpoints. In operational settings, additional

constraints—sensitive surfaces, electronics, porous materials, and complex equipment—often make conventional liquid disinfectants impractical. This creates a persistent gap between what can be shown to work under controlled laboratory conditions and what can be deployed safely and realistically on site.

- **Rationale for selecting ricin as a model toxin:** Ricin is proposed as a representative model toxin for pre-normative evaluation because of its high intrinsic toxicity and its documented history of malicious use. In real-world criminal or terrorist contexts, the quality of ricin is rarely confirmed publicly; nevertheless, crude preparations are plausibly more likely than highly purified toxin, given the specialised equipment and expertise required for purification. Guidance should therefore cover both crude and purified preparations and explicitly account for matrix effects (e.g., impurities and co-extracted plant material) that can influence persistence, extraction efficiency, and decontamination performance.
- **Limitations of conventional liquid approaches:** Classical ricin decontamination relies on sodium hypochlorite (bleach). Laboratory evidence and existing guidance indicate rapid loss of biological activity under defined conditions (e.g., appropriate hypochlorite concentration and sufficient contact time). However, hypochlorite is corrosive and incompatible with many materials and electronic systems, limiting its applicability where material compatibility is the primary operational constraint. This motivates the evaluation of electronics-safe options, including “dry” and vapour-phase approaches.
- **Evidence gaps for VHP and implications for verification:** For vapourised hydrogen peroxide (VHP), the open literature on ricin is comparatively sparse and the findings are mixed. Available results suggest that short exposures have little effect, intermediate exposures may partially reduce toxicity, and prolonged exposures can show diminishing returns when assessed by functional cytotoxicity endpoints—even when structural degradation is observed by analytical readouts. Ricin may therefore be more challenging to detoxify by VHP than some other biological targets, and alternative gaseous oxidants (e.g., chlorine dioxide) may offer higher efficacy under certain conditions. These uncertainties reinforce a central requirement for pre-normative guidance: efficacy claims must be supported by functional measures of residual toxic activity, not solely by structural or detection assays (e.g., electrophoresis or immunodetection), which may not correlate reliably with intoxication potential after treatment.
- **Pre-normative implications**
  - Efficacy claims should be supported by **functional activity endpoints** (residual toxic activity), not only analytical/structural signals.
  - Validation should address **crude and purified preparations** and relevant **matrices/materials**.
  - Performance should be reported against **defined exposure conditions** (dose, humidity, time, distribution in the treated volume).
- **Proposed functional assay framework:** To enable robust and decision-relevant verification, we propose a genetically encoded translational arrest sensor as the reference functional assay for ricin neutralisation. In parallel, we engineered recombinant versions of ricin’s two subunits—RCA (the catalytic A chain) and RCB (the lectin B chain)—so they can be produced and deployed either independently or reconstituted together for controlled functional testing. This design allows us to (i) quantify the residual translation-inhibitory activity attributable to RCA alone (catalysis-driven ribosome inactivation), (ii) evaluate how RCB alone influences cell binding/uptake-related steps that condition effective intoxication, and (iii) test RCA+RCB together to approximate the holotoxin context and capture any chain–chain interactions that modulate functional toxicity.

Importantly, this engineered “separate vs. combined” strategy makes it possible to dissect and refine the measured inhibitory effect of VHP: distinguishing effects that preferentially impair RCA’s enzymatic function from those that preferentially compromise RCB-mediated delivery, and determining whether VHP acts additively or synergistically when both chains are present. In a pre-normative context, the translational arrest sensor provides a quantitative, mechanism-anchored readout for these comparisons, supporting reproducible thresholds linked to loss of hazardous function rather than loss of detectability.

- **Enhancing VHP via activated formulations:** Building on this, our analysis will also evaluate VHP-based formulations augmented with additional reactive components intended to enhance detoxification performance while preserving operational constraints. As described in the broader decontamination literature, hydrogen peroxide can be blended with alkaline additives (e.g., sodium hydroxide) and/or combined with peroxide activators (e.g., carbonate, bicarbonate, molybdate). When paired with suitable co-solvents (e.g., butanol, ethanol, isopropanol) and, where relevant, surfactants, these formulations are reported to accelerate nucleophilic and oxidative reaction pathways and thereby achieve faster and more robust decontamination. In the present work, such “activated H_2O_2/VHP” variants will be assessed using the same functional, mechanism-linked readouts described above, to determine whether additive or synergistic gains in ricin neutralisation can be demonstrated without relying on structural endpoints alone.

7.2.8. Electronic Equipment Decontamination

While the primary focus of this work is on assistive devices used by vulnerable populations (**Figure 8**)—all of which contain electronic components sensitive to decontamination (**Figure 9**)—, experimental validation was carried out on a representative set of electronics-sensitive equipment — including computers, smartphones, printers, laboratory instruments, and storage devices (**Figure 10**). These items were chosen as surrogates for assistive devices because they share similar electronic components and vulnerabilities to damage from conventional wet methods. This strategy ensured results would be transferable to assistive technologies, while avoiding the ethical and logistical issues of testing directly on patient-owned devices.

Figure 8. Examples of assistive electronic devices potentially vulnerable to decontamination.

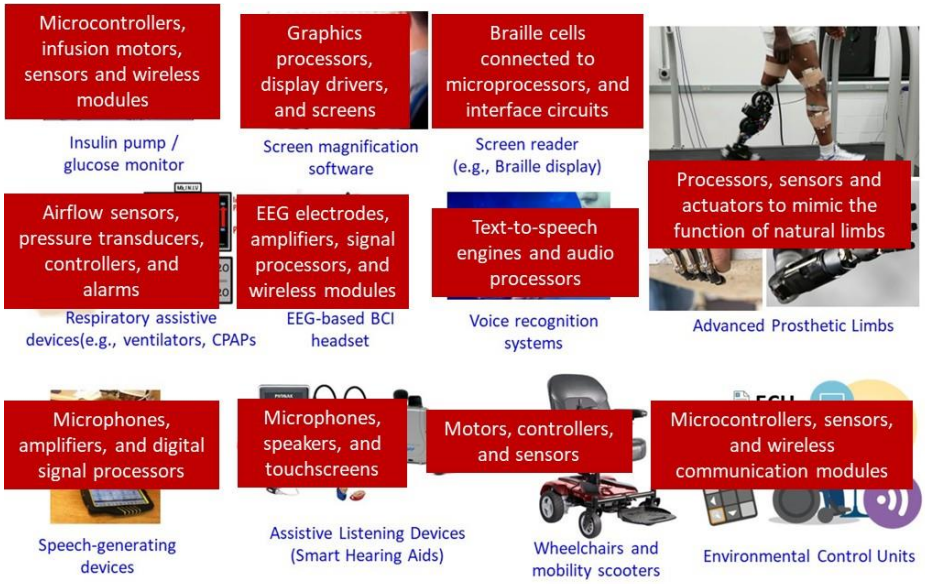

Figure 9. Main electronic components embedded in assistive devices.

Notes: Electronic components include sensors, processors, controllers, and wireless modules, which may be vulnerable to decontamination processes.

Controlled experiments assessed VHP efficacy and compatibility under different operating conditions. Equipment such as fridges, desktop and portable computers (including motherboards), printers and cartridges, smartphones, electronic pipettes, GoPro cameras, and electronic sensors were exposed to varying VHP concentrations (ppm) and exposure durations (**Figure 10**). Across successive laboratory and on-site decontamination runs (n=18), no functional impairment or visible damage was observed in the tested electronic devices.

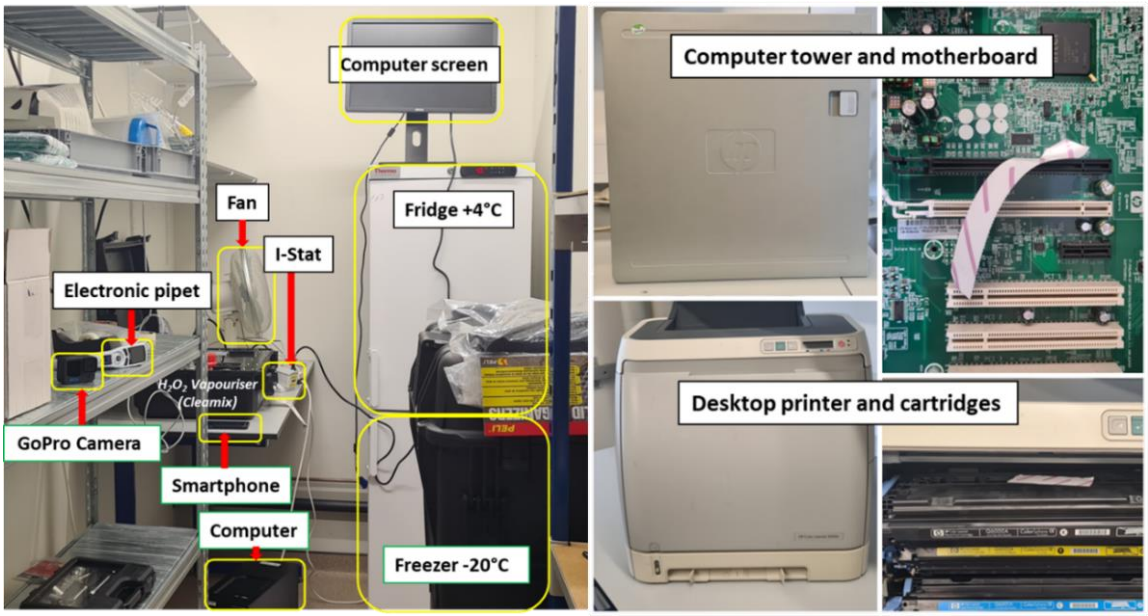

Figure 10. Electronics-sensitive equipment used as surrogates for decontamination testing.

Notes: The equipment shown was selected as representative surrogates for assistive and medical devices in order to assess the compatibility and effectiveness of vapourised hydrogen peroxide (VHP) decontamination

7.2.9. Forensic Analysis

In addition to healthcare and first-responder applications, the non-destructive nature of VHP makes it uniquely suitable for preserving forensic evidence — including fingerprints and electronic data — a capability further detailed in Section 10.

Published data on the impact of VHP on DNA profiling remain contradictory, largely due variations in VHP decontamination setups, VHP concentrations and exposure durations, materials tested, and analytical methods [Wilkinson *et al.*, 2020; Radgen-Morvant *et al.*, 2024]. This variability highlights the need to continue investigations on DNA trace preservation using the current validated protocol.

8. Application of Hydrogen Peroxide (H_2O_2): Safety and Security Considerations

H_2O_2 is toxic to humans, including operating staff, first responders, and potential CBRN victims [Otter *et al.*, 2009; Otter *et al.*, 2013]. Occupational exposure limits reinforce this risk: both the American Conference of Governmental Industrial Hygienists (ACGIH) and the Occupational Safety and Health Administration (OSHA) set an 8-hour time-weighted average of 1 ppm (1.4 mg/m³) as Threshold Limit Value (TLV-TWA) or Permissible Exposure Limit (PEL-TWA) [ACGIH, 2023; OSHA, 2020]. Decontamination must therefore be conducted in a confined area to prevent leakage into the operational environment (**Figure 3**, **Figure 10**, **Figure 11A-C,** and **Figure 12**) [Fu *et al.*, 2012].

Proper staff training is essential to ensure correct use of the vapouriser and placement of equipment—such as the fixed H_2O_2 sensor at the centre of the confined area, chemical/ biological indicators, and

the ventilation and heating units—to ensure even distribution, prevent condensation (i.e., keeping H_2O_2 levels below the dew point), and minimise cycle time, as recommended in the Cleamix manufacturer's guidelines. If needed, a catalyser can be installed inside the confined area to accelerate H_2O_2 breakdown. In field conditions, however, we do not use this device, as simply opening the confined area ensures a rapid decrease of H_2O_2 to safe levels for operators. A hand-held H_2O_2 monitor is required to verify the absence of leakage outside and to confirm that post-treatment levels inside remain within occupational safety limits [[Otter at al., 2013].

Continuous real-time monitoring protects operators and safeguards electronic devices by preventing condensation-related failures — while ensuring simultaneously safe conditions and maximising antimicrobial efficacy through precise control of cumulative exposure.

9. Pre-Normative Assessment of Operational Performance and Reliability (UCLouvain)

UCLouvain's team is now applying a validated VHP methodology during regular missions, including the decontamination of SES TechCom's electronic equipment at the premises of the Grand Ducal Fire and Rescue Corps in Lintgen, Luxembourg (**Figure 11** and **Figure 12**). In addition to using a local container provided by Emergency.lu (**Figure 11A–D**), a double-confined inflatable area was tested, consisting of an external protective inflatable tent (**Figure 12A-B**) and an inner plastic cube constructed from plastic sheets and poles (**Figure 12C-D**).

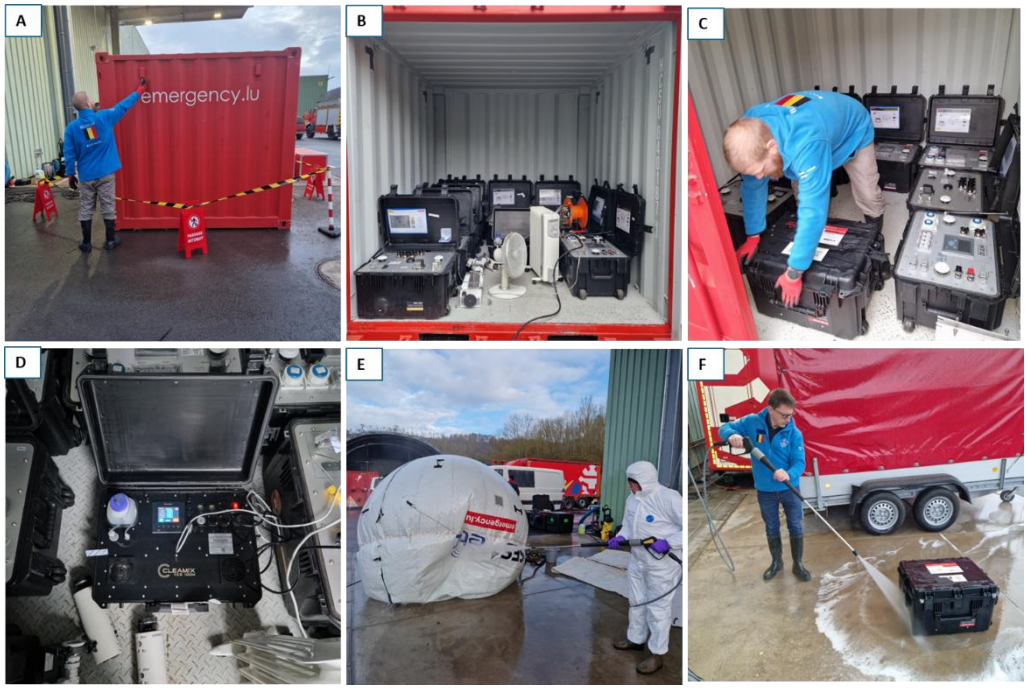

Figure 11. On-site VHP decontamination of SES TechCom electronic equipment.

Notes: Decontamination was conducted at the Grand Ducal Fire and Rescue Corps, Luxembourg. (A–D) Container-based setup. (E–F) Wet decontamination applied to non-sensitive items.

Figure 12. Inflatable primary and secondary enclosures for on-site VHP decontamination.

Notes: (A–B) Inflatable enclosure used as the primary containment volume. (C–D) Secondary confined area within the enclosure, consisting of an inner plastic cube assembled from plastic sheeting and support poles assembled from plastic sheeting and support poles, providing an additional containment barrier.

10. Improving First Responder Training Through Virtual Reality (VR/XR)

10.1. Background

Fondazione SAFE has been developing a Virtual and Extended Reality (VR/XR) training centre to simulate interventions in complex emergency management scenarios, with the aim of significantly enhancing the realism and immersion of WP4 SimEx training activities (**Figure 13**).

Fondazione SAFE has focused in particular on CBRN emergency management training, leveraging the Calvarina training and testing facility as an advanced innovation hub. Within the framework of the eNOTICE-2 project, and with technical advice from UCLouvain (Project Coordinator), SAFE has developed a Virtual Reality training module aimed at enhancing operators' capacity to respond effectively to CBRN emergencies.

Within eNOTICE-2, SAFE is creating a VR/XR scenario focusing on the decontamination of vulnerable individuals. The Calvarina TTX scenario is centred on a Paralympic winter sports gathering involving athletes with disabilities and assistive devices. Particular emphasis is placed on electronics-safe decontamination procedures under operational (on-site) conditions, such as VHP decontamination using automated, closed-loop systems (e.g. Cleamix). The scenario integrates operational procedures

recognised as good practice by Training Centre partners and aims to significantly enhance the realism and immersion of WP4 SimEx training activities.

This VR/XR training work supports the following eNOTICE-2 specific objectives:

- SO-5: Improve cross-border CBRN preparedness and interoperability through innovative VR/XR training.
- SO-6: Test and evaluate the contribution of VR/XR to preparedness and response.

A key milestone (MS7, WP4) was the preparation of an ad hoc VR/XR demonstration scenario addressing harmonised procedures for the decontamination of assistive devices for vulnerable groups. The final SimEx (M24), organised by SAFE in Calvarina, Province of Verona (Italy), tested a harmonised approach informed by the outcomes of previous SimEx events. This work builds on the results of the 3rd SimEx (M18), organised by VESTA (Ranst, Belgium), which featured a demonstration of the VR/XR prototype focusing on decontamination procedures for vulnerable populations.

VR/XR activities also contribute to pre-normative work linked to AFNOR/CEN TC 391 standardisation, particularly regarding safe decontamination procedures for assistive devices. The expected role of VR/XR is to enhance learning of new operational procedures and to serve as a just-in-time training tool in the event of a major cross-border crisis.

To this end, the VR training has been developed around four scenarios of increasing complexity, allowing operators to progressively learn the use of VHP decontamination, from a step-by-step guided tutorial to an advanced operational scenario.

XR-based training tools were demonstrated during a tabletop exercise (TTX) held in Clavarina in November 2026, in the framework of the final eNOTICE conference. Building on this demonstration, VR/XR activities also contribute to pre-normative work linked to AFNOR/CEN TC 391 standardisation.

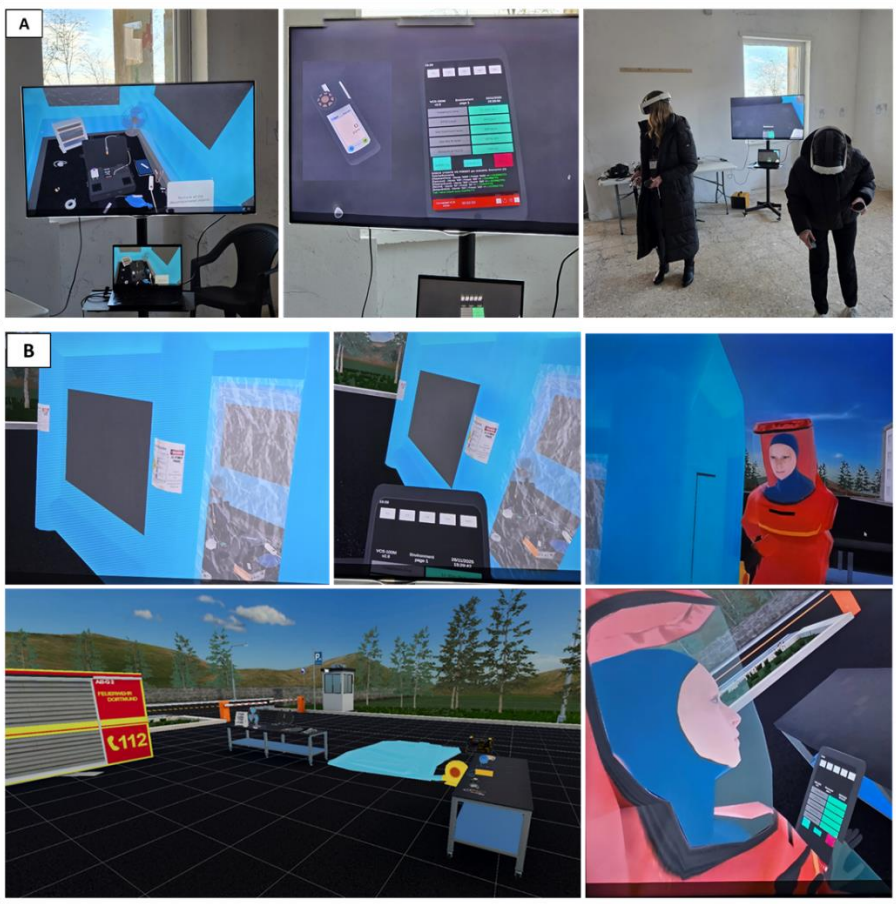

Figure 13. Screenshots from a VR-based training tool and scenario.

Notes: (A) Upper panel: VHP system configuration within the VR environment; (B) Lower panel: external operational set-up represented in the scenario.

10.2. UCLouvain's Contribution to On-Site VHP Decontamination

- The fully developed on-site VHP methodology was first detailed and presented to the German emergency services (Dortmund – Institute for Fire and Rescue Technology) during dedicated training and workshop sessions, in February 2024 and April 2025 (**Figure 14**). The presentation covered achieving a concentration below the saturation point based on relative humidity and temperature, along with the biosafety measures required when working with H_2O_2. Special emphasis was placed on testing and validating electronic-friendly decontamination for assistive devices in an operational environment. This included on-site validation for equipment used by people with disabilities (e.g., hearing aids, mobility scooters, limb prostheses), which often contain sensitive electronic components (**Figure 9**). The key performance indicator was the cumulative exposure to H_2O_2, factoring in concentration, relative humidity, ambient temperature, and exposure time.
- Reviewing and discussing an initial VR prototype applying that applied both standard and new decontamination processes (the latter using VHP), which were presented and evaluated during the 3rd SimEx at VESTA.

- Participating in several online discussions to help SAFE align the VR prototype parameters with on-site decontamination requirements, drawing on UCLouvain's experimental and operational expertise reported herein.
- Co-creating a digital VR-supportive document reproducing the environmental conditions from UCLouvain's real VHP experimental and operational work, with a focus on decontamination procedures for vulnerable populations (see **Table 8** for the experimental and operational values that informed the training design).
- A set of parameters was defined to make the learning process more concrete, based on these environmental conditions (see **Table 9** for the operational decontamination settings used for assistive devices).

Table 8. Environmental conditions in UCLouvain VHP experiments and on-site operations.

Scenario	Column1	Average Temperature	Relative Humidity (RH)	Room Volume	Use of Ventilator	Use of Heater	Threat
1	Sunny Warm	30°C	30%	5 m³	ON	OFF	**Virus:** MS2 Bacteriophage
2	Cloudy	15°C	1-0-1900	5 m³	ON	ON	**Bacillus spores:** *Geobacillus Stearothermophi* lus
3	Rainy /Snowy	5°C	1-0-1900	5 m³	ON	ON	**Bacteria:** *E. coli* MC4001/poX38
Random	Sunny, Rainy, Snowy, Cloudy, Foggy	40°C, 30°C, 20°C, 15°C, 5°C	30 to 95%	5 to 20 m³	ON	ON or OFF	**Random:** • MS2 bacteriophage • *Bacillus* spores • *E. coli* • *Cladosporium*

Table 9. Scenario-based VHP decontamination parameters for assistive devices.

Assistive devices	Cleamix Setup	Scenario 1	2	3
Insuline pump, Tablet, Smartphone , Hearing aids, Respiratory assist device, Pacemaker, Myoelectric prosthesis,	Treatment Time (h)	1,5	3	3
	Target PPM level (ppm)	400	400	400
	Treatment level (ppm)	380	380	380
	H_2O_2 RS limit (%)	90	90	90
	Vol H_2O_2 (ml)	150	250	250
	Cumulative exposure (ppm.h)	600	1200	1200

Figure 14. On-site VHP decontamination demonstration (Dortmund).

Notes: Demonstration conducted at the Institute for Fire and Rescue Technology (FDDO), Dortmund, on 28 February 2025**.**

11. Forensic Decontamination of Sensitive Police Equipment (Belgian Federal Police)

The Belgian Federal Police and the Directorate of Special Units (DSU) have expressed interest in our method for decontaminating sensitive equipment (sensors, onboard electronics, etc.). A demonstration under real-life conditions was requested by both this unit and representatives of the Federal CBRN Crisis Coordination Centre. This outdoor demonstration took place at the UCLouvain site in Brussels on 18 June 2025 (**Figure 15**).

The Belgian Armed Forces' Decontamination Unit also expressed interest and attended the event. On this occasion, a representative of the Fondazione SAFE was invited to put into practice the recommendations made during online meetings between UCLouvain and SAFE. These recommendations were aimed at improving the VR prototype and preparing for the 4th SimEx in Calvarina (see supra).

In addition to the validated "pre-normative" protocol on electronics-safe decontamination conducted during this exercise, a new part of the work specifically focused on the compatibility and suitability of VHP decontamination with the requirements for post-exposure forensic analysis (**Figure 16Figure 17Figure** 18).

Items selected by police experts were exposed to VHP to assess the quality of post-exposure fingermarks and DNA traces. This work continued the work package 4 (WP4) of **GIFT project** (*Generic Integrated Forensic Toolbox, FP7-SEC-2013-1 under grant agreement no. 608100*), which explored methods for cleaning CBRN-contaminated exhibits while preserving DNA, fingermarks and electronic data. The experiments aimed to develop procedures that would allow forensic examination of contaminated items, either through decontamination or containment.

Within GIFT, three commercial decontamination systems were evaluated, two of which can be directly compared to the Cleamix VHP method currently used by UCLouvain's team. They included:

- **Bioquell HPV-AQ** – a high-quality, high-purity 35% H_2O_2, designed for use with Bioquell's VHP decontamination technology. It is primarily used for the disinfection of rooms, equipment and enclosed spaces, particularly in healthcare and research environments. Comparative system details are summarised in **Table 4**.
- **STERIS Corporation** – a sterilisation and biodecontamination technology using VHP to eliminate micro-organisms from environments and equipment, widely applied in the pharmaceutical and medical sectors. Comparative system details are summarised in **Table 4**.

Figure 15. On-site VHP decontamination demonstration (Brussels).

Notes: Demonstration conducted at UCLouvain, Brussels, on 18 June 2025. (A–B) Briefing on the methodology and operational context; (C–D) Setup and operational procedure.

Figure 16. Double-confined inflatable setup for forensic testing.

Notes: (A–B) Inflatable tent and inner bubble configuration, replacing the former plastic cube installation. (C) UCLouvain team during setup. (D) Pre-exposure preparation by a Belgian police forensic expert. (E–F) Close-up views of exposed items.

Figure 17. Electronics-sensitive police equipment tested for VHP decontamination.

Notes: Equipment provided by the Belgian Federal Police, including a secure communication radio and a holographic weapon sight.

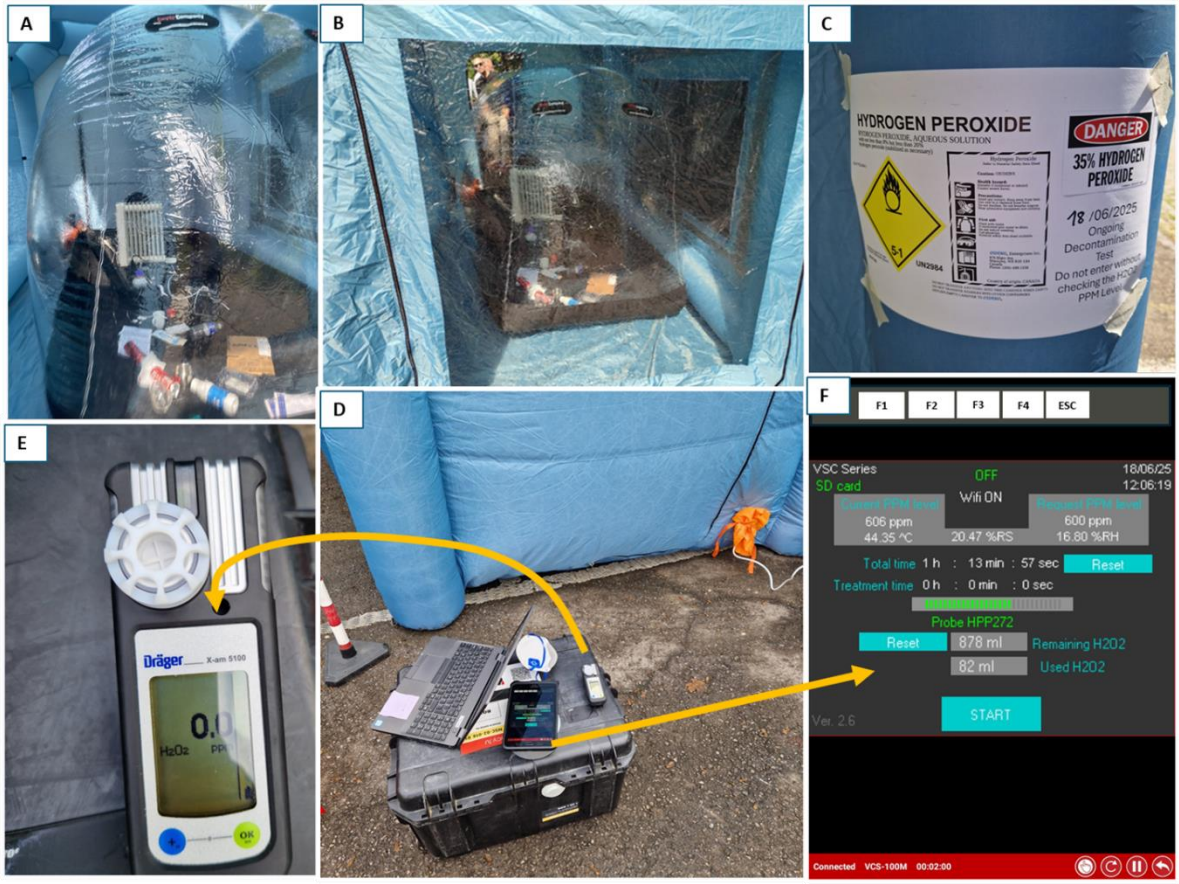

Figure 18. Monitoring of forensic decontamination operations.

Note: (A–B) Observation window. (C) Biosafety signage. (D–F) Remote monitoring using a handheld H_2O_2 sensor and a digital dashboard displaying target and real-time hydrogen peroxide concentration, relative saturation, relative humidity, exposure time, and H_2O_2 container status.

12. Preliminary Conclusions of This Exercise and Comparison with Previous GIFT Results

- **Cleamix system (process control):** Compared with the two VHP-based approaches evaluated in the GIFT project, the Cleamix VCS provides an operational advantage through continuous monitoring and closed-loop control of hydrogen peroxide vapour in the treated enclosure. During the cycle, the system maintains target H_2O_2 vapour concentrations (ppm) by adjusting injection/generation in real time as a function of key physical parameters (e.g., temperature, relative humidity and vapour saturation/condensation margin), thereby supporting efficacy while reducing the risk of condensation on sensitive materials.
- **Fingermarks:** The preliminary observations reported by police forensic experts after VHP exposure are consistent with the GIFT findings. While GIFT assessed fingermarks under fixed H_2O_2 concentration conditions (i.e., without real-time adjustment), both exercises indicate that VHP exposure, under controlled non-condensing conditions, did not show observable degradation in fingermark quality under the tested non-condensing conditions.
- **DNA traces:** It is well established that some decontamination processes can damage biological material and reduce DNA recovery. In GIFT, testing on bodily fluids (saliva and blood) indicated reduced signal intensity in downstream analysis, while still allowing retrieval of usable DNA

profiles. In the present exercise, the focus was on trace DNA deposited on the surfaces of selected items, which represents a different forensic scenario and requires a dedicated sampling and validation approach. At the time of writing, this methodology is being further developed and standardised in collaboration with West Midlands Police, including optimisation of collection, extraction, and interpretation steps following VHP exposure.

- **Electronic devices and digital evidence:** Consistent with earlier observations from both experimental and operational contexts, no detrimental effects of VHP were observed on electronics-sensitive devices used by police, provided condensation was avoided and appropriate aeration was performed. Importantly, device functionality and forensic handling workflows were not impaired under the tested conditions (i.e., devices remained functional and data handling/forensic processing was not impaired). These findings are consistent with and extend the GIFT results, notably by demonstrating on-site operational feasibility under realistic conditions.

Overall conclusion: The combination of (i) electronics compatibility, (ii) preservation of fingermarks and digital forensic evidence, and (iii) demonstrated operational feasibility under controlled VHP conditions provides a strong rationale for police services to retain this approach as an operational option when required (e.g., upon request for service involving contamination risk and evidence preservation constraints).

13. Advantages of Cleamix VHP Decontamination

To our knowledge, this guideline provides a pre-normative, operationally oriented syntheses of on-site, electronics-safe VHP decontamination applied to assistive technologies, linking biodecontamination, forensic integrity, and training standardisation.

- **Efficacy.** VHP efficacy is supported by robust experimental and real-world evidence showing activity against diverse microbial pathogens, including those resistant to conventional decontaminants such as non-enveloped viruses, multidrug-resistant bacteria, and spores. Its ability to diffuse into irregular surfaces and confined areas provides a clear advantage for decontaminating assistive devices, which often have complex geometries.
- **Flexibility and adaptability.** The antimicrobial performance of VHP depends on H_2O_2 concentration, exposure time, and environmental conditions (relative humidity, relative saturation, and temperature). The Cleamix vapouriser allows optimisation of these parameters, enabling treatment levels to be adapted to conditions in the field and achieving cumulative exposures up to 1200 ppm·h while remaining below the condensation point in the tested enclosures and environmental conditions.
- **Safety.** Low-concentration aqueous H_2O_2 (≤3% w/w) has established medical (including topical) use; however, higher concentrations and vapour exposures require strict controls, as they may irritate the skin, eyes, and respiratory mucosa. During decontamination, safety is ensured by real-time remote monitoring of airborne H_2O_2, as applied in the performance and reliability phase of this work, ensuring that occupational exposure limits are never exceeded and that operators and first responders remain protected. After the decontamination step, the Cleamix VCS primarily relies on ventilation for the aeration phase. In fixed facilities, aeration is achieved through mechanical ventilation systems, which may also be complemented by catalytic converters to accelerate H_2O_2 breakdown into water and oxygen. In on-site operations, as carried out in this work, aeration can be

achieved by opening the confined inflatable enclosure and ventilating the space, followed by monitoring to confirm concentrations are below occupational exposure limits before re-entry

- **Minimal environmental impact.** Due to the instability of the peroxide bond, VHP decomposes into water and oxygen, leaving no harmful residues on treated surfaces.
- **Ease of use.** Drawing on our experience with the Rapid Response Mobile Laboratory (RRML) network within the WHO GOARN mechanism, we adapted our mobile laboratory expertise to create a double-contained inflatable facility that can be deployed on-site and operational within 30 minutes. This configuration allows efficient and safe VHP decontamination while reducing workload and labour costs. The process is easily scalable by operating multiple vapourisers simultaneously for large volumes of material or extended surface areas.
- **Stability.** H_2O_2 is stable under recommended storage conditions, but dissociation may occur if stored improperly, reducing its concentration and antimicrobial efficacy.
- **Compatibility with materials.** As a strong oxidising agent, liquid H_2O_2 at high concentrations can damage some plastics and certain metals. In contrast, VHP applied under non-condensing conditions is generally compatible with many materials, including electronics, provided that material compatibility is assessed and process parameters are controlled to avoid condensation. In this work, no adverse effects were observed on the electronics-sensitive devices tested under the validated operating conditions.

14. Limitations and Operational Constraints of Cleamix VHP Decontamination

While VHP provides a valuable dry decontamination option for sensitive equipment, its operational use is subject to several constraints that should be considered in planning and risk assessment:

- **Logistics and transport of consumables**: Hydrogen peroxide solutions, particularly at higher concentrations, are regulated hazardous materials. Air transport may be restricted or require specific dangerous-goods packaging, documentation, and carrier approval, which can affect rapid deployment. Where relevant, planning should include local procurement options, compatible concentration ranges, and secure storage arrangements.

  In addition, hydrogen peroxide is listed as a *restricted explosive precursor* under Regulation (EU) 2019/1148 on the marketing and use of explosives precursors [EU2019/1148]. In practice, procurement of solutions above 12% (w/w) is limited to registered professional users or licensed entities, and its acquisition, possession, and use are subject to reporting and traceability requirements. This regulatory framework should be considered early in mission planning and procurement to ensure legal compliance and timely availability of consumables.

- **Dependence on enclosure integrity and airflow**: Effective VHP decontamination requires a well-sealed, controlled enclosure and adequate mixing/airflow to ensure uniform exposure. Leaks, complex loading patterns, or poor circulation can reduce efficacy and increase operator exposure risk.
- **Environmental sensitivity and condensation risk**: Efficacy depends on concentration × time and environmental parameters (temperature, humidity, saturation margin). If not controlled,

condensation may occur, increasing the risk of material damage and residue formation and potentially reducing uniformity.

- **Safety monitoring and aeration requirements**: VHP requires continuous monitoring, controlled access, and an aeration phase to ensure re-entry only when concentrations are below occupational exposure limits. This may impose time and equipment constraints in field operations.
- **Material compatibility is not universal**: Although generally compatible under non-condensing conditions, VHP can affect certain materials (e.g., some elastomers, adhesives, optical coatings, sensitive polymers, or corrosion-prone metals). A case-by-case compatibility assessment is required for critical items.
- **Not applicable to radiological contamination and limited for chemicals**: VHP is primarily a biological decontamination method. It does not address radiological contamination and has agent-specific, condition-dependent effects on selected chemical contaminants; therefore, it should be integrated within a broader CBRN decontamination concept of operations.
- **Training and procedural discipline**: Successful and safe deployment requires trained personnel, validated cycles, and disciplined procedures (loading, monitoring, aeration, waste handling), especially in mixed-mission environments (forensics, medical support, and response operations).

15. Relevance of This Work for Public Health Applications

To complement the above findings, the dry, vapour-phase nature of VHP is operationally relevant for transport systems and biocontainment units in high-consequence events, where rapid turnaround, material compatibility, and avoidance of liquid residues are critical.

- **Ambulances and patient transport vehicles:** In CBRN and high-consequence infectious disease response, ambulances and transport vans include **electronics, sensors, communication equipment, and porous/complex interior materials**. Wet decontamination can be operationally burdensome (runoff, corrosion risk, material damage) and may conflict with rapid redeployment. VHP, when applied in a sealed/controlled cycle with adequate aeration, can support **terminal decontamination of interior spaces**, complementing (not replacing) standard cleaning procedures.
- **Biocontainment transport units ("Ebola bubble" / isolation pod):** High-level isolation transport systems (e.g., isolation stretchers/pods used for viral haemorrhagic fever response) often combine **polymers, seals, filters, and embedded components**. VHP can be relevant for **non-liquid terminal decontamination** of the enclosure and compatible components, subject to confirmation of material compatibility and validated cycle parameters. VHP-based methods are operationally aligned with field constraints: **rapid, residue-free decontamination** while minimising damage to specialised equipment.
- **WHO / Rapid Response Mobile Laboratory-type deployments** [Storozhenko *et al.*, 2025]**:** For rapid response assets and mobile capabilities, including **WHO-compliant operations**, the ability to decontaminate **equipment and confined spaces** with a dry, vapour-phase method can strengthen continuity of operations, provided that exposure limits, safety monitoring, and aeration requirements are respected [WHO, 2024].

16. Relevance of This Work for Military and Police Applications

Beyond the protection of vulnerable populations, these findings have direct implications for defence and security operations in the control of biological threats.

- **Clearance-level decontamination** – NATO doctrine recognises Clearance decontamination as technically the most demanding level, often unachievable with conventional methods (AEP-4784). Our results indicate that VHP can support clearance-oriented outcomes for sensitive equipment, subject to hazard-specific validation and operational criteria— a challenge NATO explicitly acknowledges, and one that also corresponds to operational requirements for NATO forces, police, and forensic applications. VHP therefore provides an option where other methods fail or are inapplicable.
- **Application of the ALARA/ALARP principle** – NATO emphasises that "zero contamination" is unrealistic; instead, decontamination should aim for "as low as reasonably achievable/practicable." The validated exposures achieved here (600–1200 ppm·h with complete spore inactivation and preservation of electronics) demonstrate a realistic balance between efficacy and equipment protection. These results illustrate a practical ALARA/ALARP trade-off between biocidal efficacy and preservation of sensitive equipment.
- **Sensitive equipment compatibility** – NATO doctrine (STO TR-HFM-233; AEP-58) already identifies sensitive equipment as requiring specialist approaches, since conventional aqueous or solvent-based decontaminants risk permanent degradation. Our in-lab and on-site operational performance and reliability testing confirms that VHP fulfils this role by achieving sterilisation-equivalent efficacy without impairing device function.
- **Rapid on-site deployment** – NATO doctrine stresses that decontamination operations must be initiated quickly, conducted as close to the contamination as possible, and supported by assets that are mobile, flexible, and logistically self-sufficient (ATP-3.8.1, §2.155–2.158). The VHP system validated in this work directly addresses this requirement: unlike large, fixed decontamination facilities, modular units can be rapidly transported and deployed in containers, inflatable tents, or bubble enclosures. This portability allows first responders, military units, and forensic teams to establish a controlled decontamination zone typically within an hour, even in austere environments. In doing so, VHP operationalises NATO's call for mobile and flexible decontamination assets, enabling on-site sterilisation-level cycles while preserving operational tempo and avoiding the risks of transporting contaminated items through unsecured areas.
- **Cost-effective, operationally and logistically preferable** – By preserving sensitive electronics rather than forcing disposal in-theatre, VHP offers a cost-effective and politically acceptable alternative. It mitigates reputational risks, avoids the political sensitivities of abandoning contaminated assets, and helps maintain operational readiness [AEP-4784].

17. Courses, Exercises, and Knowledge Transfer

Knowledge transfer on electronics-safe, on-site VHP decontamination—relevant to military applications, first responders' equipment, and assistive devices for vulnerable populations—was delivered through official courses and eNOTICE-2/eNOVATION-related meetings and exercises:

- **Emerging electronics-safe technologies for decontaminating sensitive assistive devices for people with disabilities: from basic principles to emerging technologies.** eNOTICE-2 & TeamUP joint activity

("Inputs for guidelines for first responders on decontamination of assistive devices"), Institute for Fire and Rescue Technology (FDDO), Dortmund, Germany. *Jean-Luc Gala.* 19 April 2024.

- **First responders to CBRN threats: new methods for assessing, preparing for, and controlling high-consequence biological risks.** Master CBRNe Intensive Defence Course, University of Rome Tor Vergata, Rome, Italy. *Jean-Luc Gala.* 27 June 2024.
- **Emerging electronics-safe decontamination for sensitive devices: principles and technologies for microbial decontamination.** Joint CBRN Defence Centre of Excellence, Brno, Czech Republic. *Jean-Luc Gala.* 25 November 2024.
- **Guidelines and demonstration of on-site use of vapourised hydrogen peroxide (VHP).** Institute for Fire and Rescue Technology (FDDO), Dortmund, Germany. *Jean-Luc Gala.* 28 February 2025.
- **Innovative electronics-safe decontamination: maintaining functionality of sensitive devices while eradicating microbial threats.** International Master Courses in Protection Against CBRNe Events (in collaboration with the Disarmament, Non-Proliferation and Arms Control Office, Italian Ministry of Foreign Affairs and International Cooperation), EU CBRNe CoE Project P100 ("Strengthening Front-Line Biosafety and Biosecurity Measures in Southeast and Eastern Europe"), University of Rome Tor Vergata, Rome, Italy. *Jean-Luc Gala.* 20 March 2025.
- **Emerging on-site electronics-safe decontamination for sensitive devices: principles and technologies for microbial and toxin decontamination.** BIO Consequence Management course, Joint CBRN Defence Centre of Excellence, Vyškov, Czech Republic. *Jean-Luc Gala.* 12–13 June 2025.
- **Guidelines and demonstration of on-site use of vapourised hydrogen peroxide (VHP).** Belgian Federal Police (Special Units) and Belgian Military Decontamination Unit, UCLouvain, Brussels, Belgium. *Jean-Luc Gala.* 18 June 2025.
- **Applications of VHP to decontamination and safe reuse of elastomeric half-mask respirators.** Easy2reUSE project ("Reusable Easy to Breath and Use Masks – Elastomeric half-mask"), EU4H-2024-PJ-01-2 (HERA Action Grants), Kick-off meeting, Helsinki, Finland. *Jean-Luc Gala.* 28 October 2025.
- **Vapourised hydrogen peroxide (VHP) for electronics-safe on-site decontamination: reliability and operational performance in a pre-normative context.** eNOTICE-2 final conference, Soave, Italy. *Jean-Luc Gala.* 27 November 2025.
- **CBRN events: complexities of cross-border cooperation and shared responsibilities in Europe.** "EU preparedness: analysis, planning, reporting and training programmes for health specialists" (EPIC11/CBRN Exchange Visit), DG SANTE, Stockholm, Sweden. *Jean-Luc Gala.* 4 December 2025.
- **Final eNOTICE-2 conference, Soave and Calvarina, 25-26 November 2025.** Vapourised Hydrogen Peroxide (VHP) for Electronics-Safe DECON On-Site: Reliability and Operational Performance in Pre-Normative Context, . *Jean-Luc Gala*. 26 November 2025.
- **Academic outputs addressing vulnerable populations were also disseminated through the following publications:**
    - Dauvrin M, Vybornova O, Gala JL. Inclusive emergency management after CBRN incidents: adapting decontamination for individuals with disabilities and assistive devices. *Front Disaster Emerg Med.* 2025;3:1614121. doi:10.3389/femer.2025.1614121.
    - De Almeida Tavares CA. *Preparedness for large-scale emergencies in Belgium: needs and resources of persons with disabilities* [Master's dissertation]. Louvain-la-Neuve (Belgium): Université catholique de Louvain; 2025.

18. Link with Other Previous and Ongoing European Projects

- **Link with the ORCHIDS project (***Optimisation through Research of Chemical Incident Decontamination Systems*, EU Health Programme, funded by DG SANCO, 2008–2011).

The **ORCHIDS** project, funded by the European Commission (DG SANCO), focused on optimizing mass decontamination procedures in response to chemical incidents. Coordinated by the UK Health Protection Agency with partners from Sweden, the Czech Republic, and France, ORCHIDS provided quantitative evidence and modelling to support improved large-scale decontamination protocols across Europe. ORCHIDS, like eNOTICE-2 later on, also stressed the importance of addressing the needs of vulnerable populations, such as children, the elderly, and persons with disabilities. **eNOTICE-2**—and more specifically our present work—extends this focus by investigating on-site VHP decontamination approaches tailored to assistive devices, which are essential for vulnerable groups yet difficult to decontaminate by conventional means. Our work further develops the foundation laid by ORCHIDS by validating on-site vaporised hydrogen peroxide (VHP) decontamination methods specifically addressing biological contamination of sensitive and complex assistive equipment.

- **Link with the GIFT project** (*Generic Integrated Forensic Toolbox,* FP7-SEC-2013- grant agreement no. 6081001, funded by DG HOME, 2014-2017**).**

The GIFT project focused on developing a forensic toolbox for the effective investigation of CBRN incidents, forming the post-event response foundation. Building on this, the eNOTICE project (2017–2023) and its successor eNOTICE-2 have shifted the emphasis to preparedness — creating EU-wide CBRN training networks, harmonised response protocols, and pre-normative decontamination guidelines, including provisions for vulnerable populations and assistive devices. The eNOTICE-2 research on the decontamination of electronics-sensitive assistive devices and equipment was thus conceptually linked to the groundwork laid by GIFT.

- **Link with other ongoing projects conducted in parallel by UCLouvain:**

Given its high strategic value for different categories of first responders as well as for vulnerable groups dependent on assistive devices, the current work is also grounded in **several other ongoing projects conducted in parallel by UCLouvain** (see **Table 10** for an overview of these complementary initiatives).

- **TeamUp** aims to enhance CBRN-E preparedness and response among first responders, upskilling them with new technologies including electronic-safe decontamination.
- **MOBVEC** supports first response in arbovirus outbreaks by deploying a box-type Rapid Response Mobile Laboratory (RRML). This requires thorough decontamination of workstations used inside the mobile laboratory.
- **eNOVATION**, the natural successor to eNOTICE-2, aims to bring emerging technologies to the forefront of first responders' CBRN preparedness and response, through the support of CBRN Training Centres and Demonstration sites.
- **Easy2reUSE** supports the development of a new type of protective mask that can be cleaned and decontaminated, together with all its components—including a panel of sensors—for safe reuse at least one hundred times.
- **BEHOLDER** operates in the context of urban security by integrating new types of CBRN sensors for real-time monitoring. This equipment also requires regular decontamination that preserves electronic components and thus maintains functionality.

Together, the ORCHIDS, GIFT, and eNOTICE/eNOVATION projects represent a continuum of European efforts, spanning from the optimisation of mass-casualty decontamination (ORCHIDS), through forensic investigation tools for CBRN incidents (GIFT), to preparedness, training, and on-site VHP reliability for sensitive assistive devices (eNOTICE/eNOVATION**). Importantly, eNOTICE-2 distinguishes itself through its original focus** on the specific needs of vulnerable populations and assistive devices, as well as through its performance and reliability of on-site VHP decontamination in real operational contexts. In parallel, complementary projects led by UCLouvain—including TeamUp, MOBVEC, Easy2reUSE, and BEHOLDER—further extend these capabilities, collectively strengthening Europe's preparedness for biological, chemical, and radiological threats while ensuring that innovative solutions are both practical and inclusive.

This work therefore marks the first pre-normative operational performance and reliability of an electronics-safe VHP system tailored to assistive technologies, setting a benchmark that integrates biodecontamination efficacy, forensic compatibility, and standardisation for first responder training.

Table 10. Projects contributing to electronics-safe decontamination.

International Projects	Research Funding	Type of Project	Project Title	Duration (months)	Project number
TeamUp	HORIZON-CL3-2022-DRS-01	IA	HolisTic capability and tEchnology evAluation and co-creation fraMework for Upskilled first responders and enhanced CBRN-E resPonse	36	N°101121167
MOBVEC	HORIZON-EIC-2022-PATHFINDEROPEN-01	EIC	Mobile Bio-Lab to support first response in Arbovirus outbreaks	60	N° 101099283
eNOVATION	HORIZON-CL3-2023-DRS-01-04	IA	Extended Network of CBRN Training Centers for Innovation	48	N°101168349
Easy2reUSE	EU4H-2024-PJ-01-2 HERA Action Grants	EU4H-PJG	Reusable Easy to Breath and Use Masks – Elastomeric half-mask	48	N°101203170
BEHOLDER	HORIZON-CL3-2024-FCT-01-07 HORIZON Action Grant Budget-Based [HORIZON-AG]	IA	Build and Extend CBRN-E related Hazard-Assessment and anOmaLy Detection Capabilties on Urban Environment	36	N° 101226039

19. Perspectives and Integration into an All-Hazards Approach

This pre-normative work establishes an operationally validated, electronics-safe VHP option for sensitive equipment and assistive technologies. The next step is to integrate this capability into an all-hazards decontamination framework—i.e., a decision process that remains valid across CBRN scenarios by selecting the appropriate method(s) based on hazard, exposure pathway, and asset criticality, while applying graded risk-reduction principles (ALARA/ALARP) and ensuring interoperability across services and borders [AEP-58; ATP-3.8.1; UNDRR].

19.1. Role of VHP within an All-Hazards Concept of Operations

Within an all-hazards response, VHP should be positioned as a "dry" module primarily suited to:

- **Sensitive equipment and electronics** (including assistive technologies) where liquid methods risk irreversible damage, provided non-condensing conditions and aeration are assured [STO TR-HFM-233; AEP-58].
- **Confined/contained volumes** (tents, pods, containers, vehicle interiors) where controlled distribution, monitoring, and access control can be maintained [WHO, 2020].

- **VHP should be treated as complementary to, not a replacement for**:
  - Wet decontamination for exposed individuals and for robust infrastructure/surfaces where physical removal and chemical neutralisation with aqueous solutions remain operationally required.
  - Radiological decontamination, which requires survey, containment, physical removal, and contamination control; VHP is not applicable to radionuclide contamination.

19.2. Extension beyond Microbiology: Chemicals and Toxins

From an all-hazards standpoint, the key perspective is to avoid "one method fits all" assumptions:

- **Chemical agents/TICs:** VHP shows agent-specific, condition-dependent effects on selected chemicals, and therefore requires hazard-specific validation and clearly defined endpoints (degradation vs detoxification vs operational acceptability) before being relied upon in chemical scenarios [Wagner & Yang, 2002; Wood et al., 2010; Wood et al., 2012; ECBC, 2011].
- **Toxins:** Ongoing work on toxins (e.g., ricin as a model) is important to close a major gap in current evidence and to define practical validation criteria (assays, sampling, interpretation) that are compatible with field operations.

19.3. Pre-Normative Priorities for Standardisation and Interoperability

To support future harmonisation (EU/CEN/ISO/CENELEC), the following common performance descriptors are recommended as candidates for standardised reporting and acceptance criteria:

- **Process control descriptors**: target concentration (ppm), exposure time, cumulative exposure (ppm·h), and condensation margin (e.g., RS kept <100% throughout), with documented sensor placement and uncertainty.
- **Efficacy endpoints**: biological indicator inactivation (e.g., Geobacillus stearothermophilus) plus a defined panel of representative organisms relevant to intended use.
- **Safety endpoints**: operator exposure monitoring, enclosure leak management, aeration criteria, and re-entry thresholds consistent with applicable occupational limits.
- **Material compatibility checks**: documented pre-assessment for elastomers/adhesives/coatings and evidence of "no functional impairment" for critical electronics under validated non-condensing conditions.
- **Operational endpoints:** deployment time, enclosure integrity verification, loading patterns, mixing/airflow requirements, and minimum documentation package (cycle log + indicators + monitoring record).

19.4. Operational Perspectives (Deployment Readiness)

To mature this capability for routine multi-agency deployment, further work should focus on:

- Logistics and regulatory compliance for H_2O_2 procurement and transport (including restricted-substance constraints where applicable), integrated early into mission planning.
- Field-validated decision aids (checklists/decision trees) that link hazard type, asset type, and operational constraints to the correct combination of methods (VHP + wet + containment + waste handling).
- Training and quality assurance (including VR/XR modules) to ensure consistent loading, monitoring, and aeration practices across teams and countries, and to reduce operator-dependent variability.

19.5. Overall Perspective

In an all-hazards approach, VHP is best framed as a high-value, electronics-compatible biological decontamination capability that can be embedded within a broader CBRN concept of operations—delivering a practical balance between efficacy, safety, and asset preservation—while recognising that chemical and radiological hazards require additional, hazard-specific methods and validation [AEP-58; ATP-3.8.1; WHO, 2020].

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20. Annex A

20.1. Visual handout supporting communication with affected persons during decontamination procedures

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20.1.1. Overview

The visual handout presented in this annex is intended as a **communication aid** to support first responders in explaining the decontamination process to affected persons. Its primary objective is to **reduce anxiety, improve understanding, and facilitate cooperation** during decontamination operations, particularly in high-stress emergency contexts.

The handout has been designed with a strong emphasis on **accessibility and inclusivity**, explicitly including people with visible disabilities and assistive devices. Effective communication is critical to identifying and addressing the specific needs of these individuals during decontamination procedures.

20.1.2. Development process

The handout was developed through several iterative design cycles, incorporating feedback from project partners and operational personnel from the Fire Department of Dortmund. Additional input was obtained from a facility supporting people with disabilities, with particular emphasis on the clarity, sequencing, and visual comprehensibility of each step.

The final design reflects a consensus-driven approach aimed at operational realism, inclusiveness, and ease of use by first responders.

20.1.3. Structure and design principles

The handout consists of **five steps**, each presented on a **separate page**, with printing on one side only to facilitate handling and explanation in operational settings. The number of steps was deliberately reduced to the essentials to enable a **time-efficient explanation** during emergency response.

All pages share a consistent visual structure:

- A simplified **top-view schematic** of the decontamination facility is shown in the upper left corner of each page.
- The sequence of steps corresponds to the **spatial layout** of the facility.
- Step numbers are positioned to reflect the physical progression through the decontamination line.
- A clear visual distinction between **contaminated (red)** and **uncontaminated/clean (green)** zones is maintained.
- A **page register** on the right-hand side supports rapid orientation between steps.

To minimise language barriers, the handout relies exclusively on visual elements and does not include written instructions. The feasibility of including Braille text was assessed and found technically possible;

however, due to space constraints and language limitations, it was concluded that Braille text would offer limited added value compared with direct verbal explanation and support by trained first responders.

20.1.4. Description of illustrated steps

Step 1 (Figure A.1) illustrates the gathering of affected persons near the decontamination facility, depicted here as a combined tent and container solution. A dedicated assembly or transition area may be established for this purpose. At this stage, an initial examination and triage are conducted. During this process, individuals are registered and categorised, for example using triage tags (referred to as "patient tags" in Germany, PAT NRW) [Kühar *et al.*, 2021, p. 123; MIK NRW, 2011, p. 20]. The representation of the assembly/transition area is based on a pictogram commonly used to denote assembly points. To reflect the diversity of affected populations, the illustration includes individuals with different types of assistive devices. Affected persons are visually marked as contaminated, indicated by a light green colour.

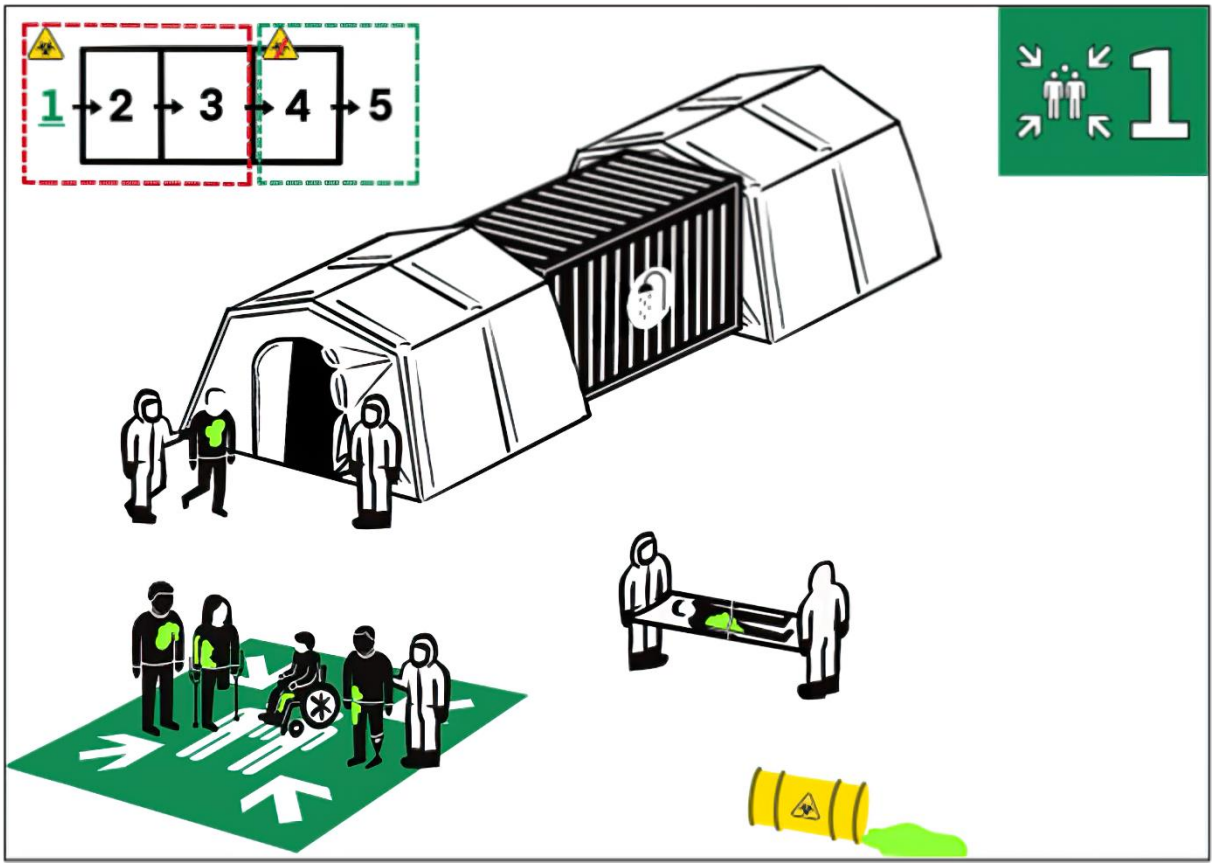

Figure A.1 Handout step 1/5 (Source: FDDO).

Notes: This pictogram shows a first responder wearing protective equipment escorting a contaminated person towards the decontamination tent. The illustration conveys that affected persons are actively supported and not left unattended, and that contaminated individuals remain within the assembly area until they are accompanied into the decontamination facility. Across the handout, particular emphasis is placed on the role of first responders in providing guidance and assistance throughout the process.

Step 2 (Figure A.2) shows the removal of potentially contaminated personal belongings, including clothing. In accordance with the Dekon-V standard procedure, all personal items carried by the affected person are handed over to a first responder wearing protective equipment. These items are packaged in polyethylene bags and labelled to allow traceable reassignment to the individual concerned. Following decontamination, the competent authority determines their subsequent handling or release [Kühar *et al.*, 2021, pp. 126–130]. To illustrate this process, the second step depicts the handover of a wide range of personal items, including assistive devices. The items are represented using pictograms and are received by a first responder wearing protective equipment.

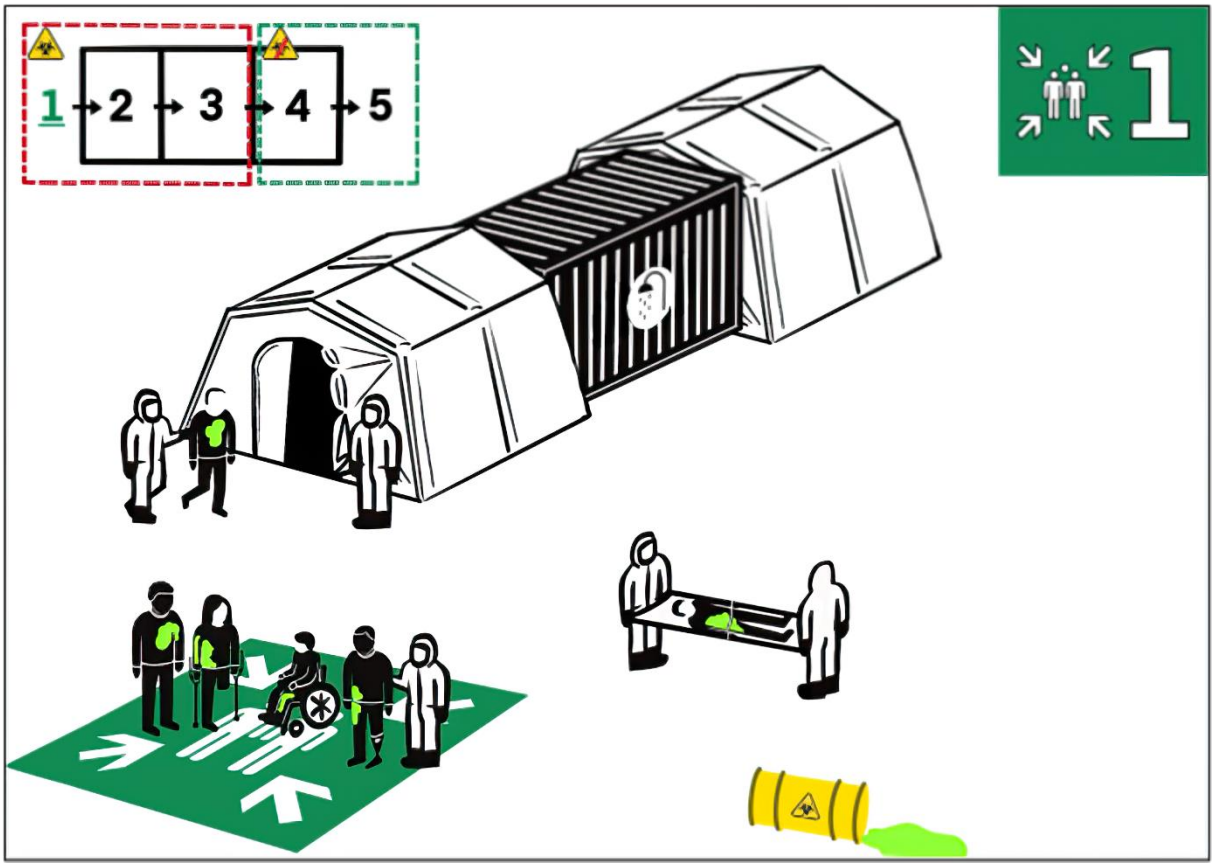

Figure A.2 Handout step 2/5 (Source: FDDO).

Notes: Step 2 also includes undressing of contaminated persons. This is illustrated as being performed using safety scissors, which reduces the risk of secondary contamination, enables rapid execution, and allows the procedure to be carried out on injured or unconscious individuals. The depiction aims to familiarise affected persons with the use of scissors and to minimise anxiety associated with the process. A scissors symbol in the register highlights this action. For clarity and simplicity, the typical cutting direction (from the torso towards the extremities) is not shown [Kühar *et al.*, 2021, p. 130].

Step 3 (Figure A.3) illustrates the cleaning and decontamination of affected persons. This step represents the final operation conducted within the red (contaminated) area. The illustration depicts the standard procedure of washing contaminated individuals using warm water and pH-neutral soap or an appropriate decontamination agent, represented graphically by a cloud of foam. As explained in **Sections 4.4, 6, 19.1, and 20.4.2**, a general distinction is made between decontamination lines for ambulatory and recumbent patients. Both lines are operated in parallel to ensure appropriate care and efficiency.

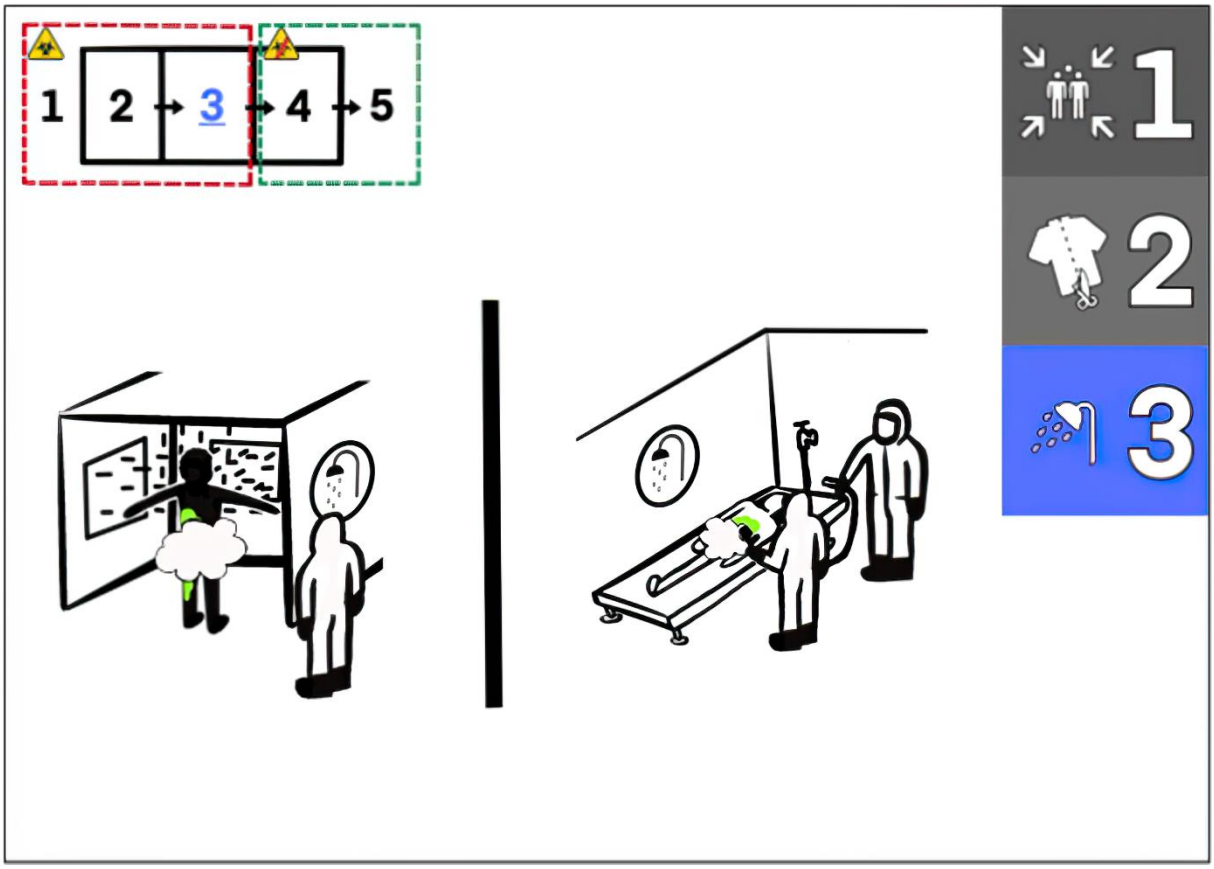

Figure A.3 Handout step 3/5 (Source: FDDO).

Notes: The graphic distinguishes between two situations. On the left, individuals who are able to do so perform cleaning and decontamination themselves under the supervision of a trained first responder, who provides guidance throughout the process. On the right, individuals who are unable to carry out the procedure independently are decontaminated with direct assistance from first responders [Kühar *et al.,* 2021, pp. 122, 131; MIK NRW, 2011, p. 20]. This includes non-ambulatory persons as well as individuals with certain disabilities.

Step 4 (Figure A.4) illustrates the dressing of decontaminated individuals. Following cleaning and decontamination, affected persons enter the green (clean) area, indicated in the top view by a crossed-out biohazard symbol. At this stage, individuals are dried or instructed to dry themselves, as appropriate. Replacement clothing is then provided.

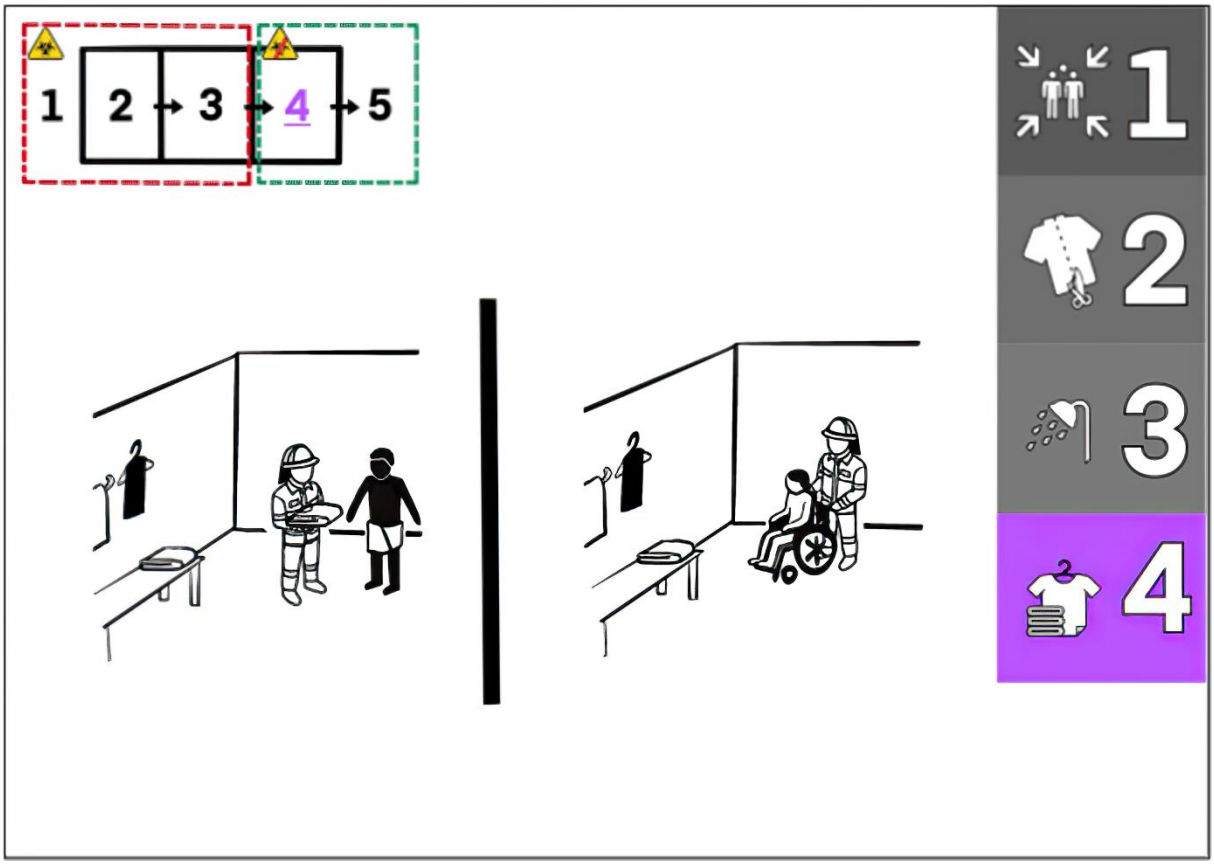

Figure A.4 Handout step 4/5 (Source: FDDO).

Notes: The illustration shows that individuals who are able to do so may dress themselves, while those requiring assistance receive support from first responders. This includes persons with reduced mobility or other specific needs.

Step 5 (Figure A.5) illustrates the completion of the decontamination process. This step involves the transfer of decontaminated individuals to a treatment centre or hospital for further medical care, as required.

Depending on the nature of the hazardous substance involved and the assessed effectiveness of the decontamination procedure (e.g. Dekon-G), the competent authority determines whether personal items and assistive devices may be returned and, if so, under what conditions [Kühar et al., 2021, p. 127, 131; MIK NRW, 2011, p. 26]. As these decisions depend on multiple contextual factors, the return of personal belongings and assistive devices is not depicted in the illustration.

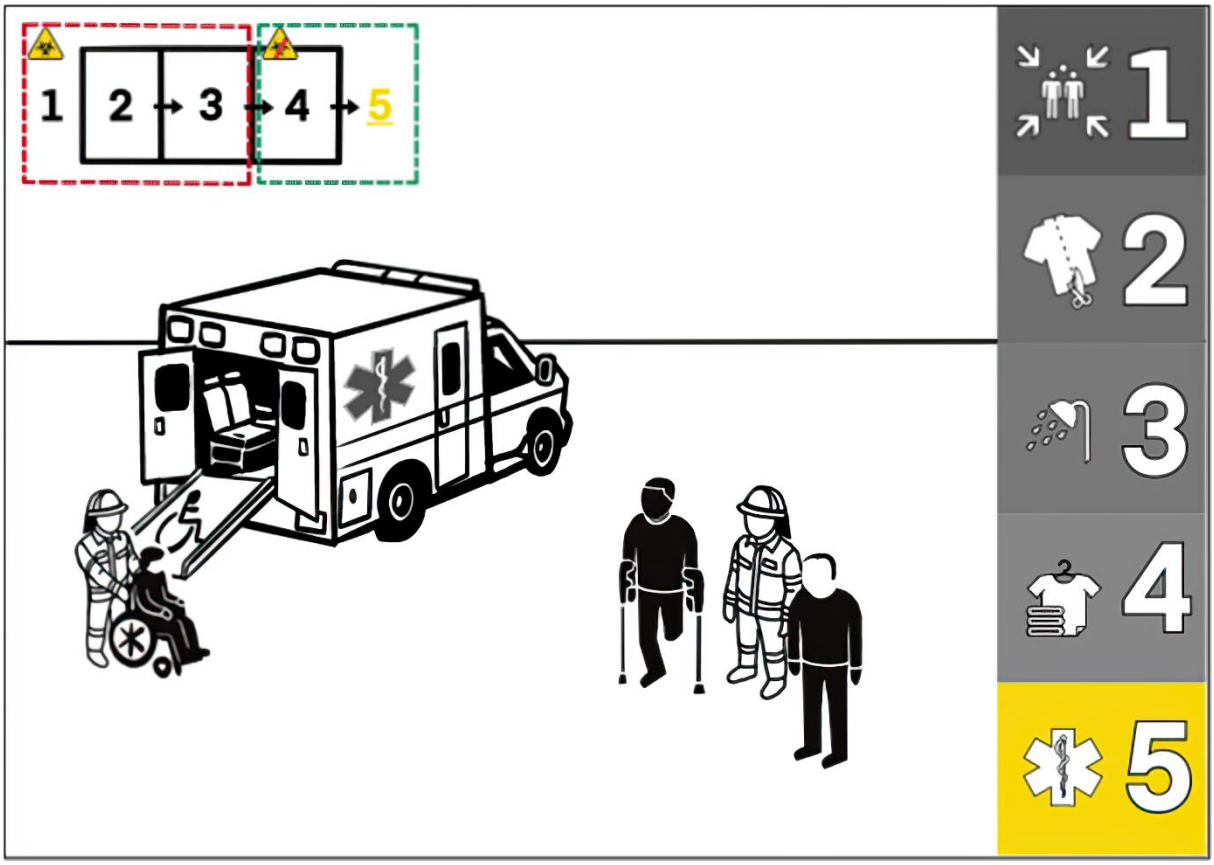

Figure A.5 Handout step 5/5 (Source: FDDO).

Notes: The figure shows first responders assisting a decontaminated person when boarding an ambulance. The vehicle is marked with the Star of Life, a widely recognised symbol for emergency medical services. This symbol was selected as a neutral identifier, as it is not associated with any specific religious community.

Figure A.6 shows two versions of the handout produced using different binding types. The illustrations were printed on polymer foil using UV-curing inks. As a result, the handouts are durable and can be cleaned and reused to a limited extent.

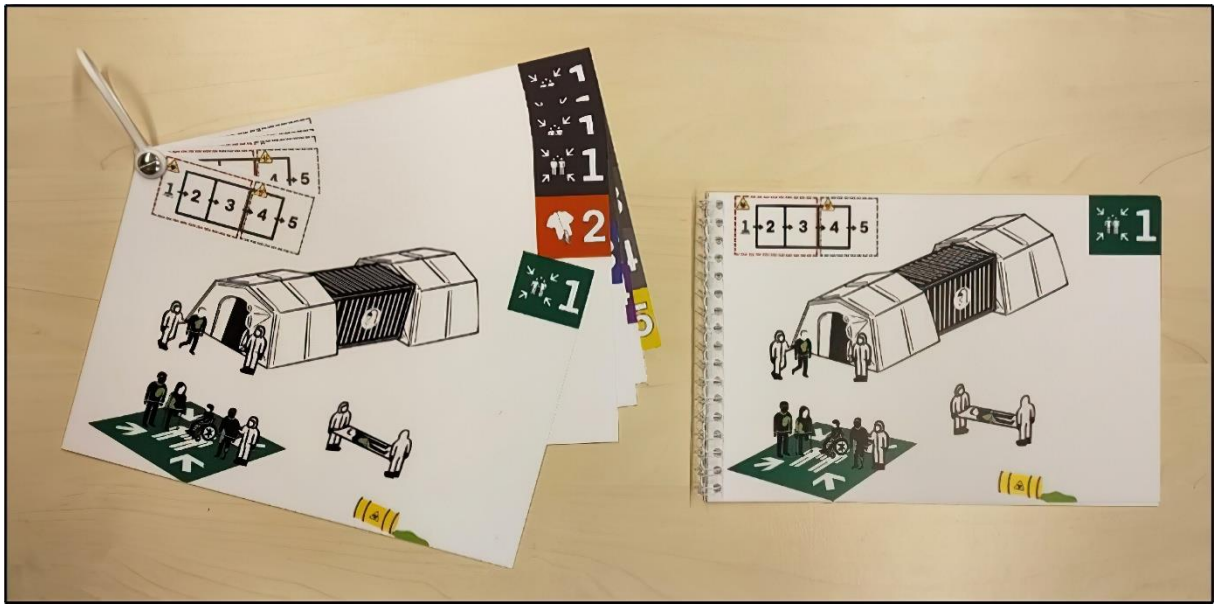

Figure A.6 Handouts (Source: FDDO).

20.2. Relationship to the pre-normative guideline

This handout illustrates a **generic wet decontamination workflow (Dekon-V/G)** for affected persons. It is independent of the specific decontamination technologies used for equipment and sensitive devices, such as vapourised hydrogen peroxide (VHP), which are addressed separately in the main pre-normative guideline.

Historically, assistive devices were often treated as objects rather than as functional extensions of a person's body. In many cases, disposal was considered the safest option, without full consideration of the consequences for the individual concerned. However, for many users, assistive devices are essential to independence, social participation, and overall well-being. Consequently, the decontamination of assistive devices should be assessed on a case-by-case basis, balancing health protection, contamination control, and the functional needs of the user.

Ideally, decontamination of a person and their assistive device(s) would occur in parallel to enable prompt reunification and continued use. In practice, however, assistive devices often require specialised decontamination approaches that differ from those used for people and may involve longer processing times. Parallel decontamination is therefore not always feasible, but it should remain an operational objective where conditions permit. This creates additional requirements for traceability, identification, and logistics, which must be addressed within decontamination workflows.

Regarding traceability: The decontamination process is typically preceded by the removal of clothing and personal items and by the registration of the person to be decontaminated (cf. **Section 20.1.4**). As part of this process, personal items—including assistive devices—may be labelled and assigned to their owner. In many operational contexts, the necessary mechanisms for traceability are already established within standard operating procedures, although they do not always explicitly address assistive devices.

Various triage tagging systems incorporate unique serial or patient numbers that can be used to label a patient's belongings. Examples include the METTAG MT-137 system used in the United States (American Civil Defense Association, n.d.) and the "Cruciform" triage system used in the United Kingdom (CWC Services, n.d.). Similar principles apply to chemical–biological tagging systems such as METTAG CB-100, which is designed for CBRN contexts and may be used to label contaminated items (American Civil Defense Association, n.d.). In most cases, these tags also include fields for additional notes, allowing responders to indicate that an individual depends on assistive devices and that these items have been accepted as personal belongings.

In North Rhine-Westphalia (Germany), a standardised patient triage tag is used in emergency medical services and major incident response (Ministerium des Inneren NRW, 2005). As with other systems, it includes detachable stickers to label a person's belongings. In addition, the fire service doctrine FwDV 500 ("Einheiten im ABC-Einsatz") provides a patient tag template specifically designed for CBRN operations (AFKzV, 2022). This template contains dedicated fields for information such as the type of contaminant and exposure time, but does not provide a specific field for additional notes related to assistive devices.

In the accompanying explanatory guidance on decontamination during hazardous materials incidents, an example of an equipment tag developed by the Fire Department of the City of Düsseldorf is presented (vfdb, 2022). Although primarily intended for contaminated first responder equipment, such tags may also be applied to assistive devices. These tags typically record the type of contaminant and indicate whether basic decontamination has already been performed.

Overall, traceability of assistive devices does not appear to be a fundamental technical limitation. However, explicit reference to assistive devices in guidelines, templates, and training materials would be desirable, not least to raise awareness among responders and to support consistent handling in practice.

Regarding the decontamination of assistive devices: On-site decontamination operations are primarily focused on human decontamination in order to prevent further bodily harm. The decontamination of equipment is generally considered secondary, as it is typically not time-critical, except in mission-specific or tactical contexts. Responsibilities for human decontamination and equipment decontamination may therefore lie with different units or, in some cases, different authorities.

The need for equipment decontamination is also incident-dependent. Not every affected person relies on an assistive device, and not every device will be classified as suitable for decontamination. As a result, operational concepts do not usually provide the same level of capacity for equipment decontamination as for human decontamination.

In Germany, three levels of human decontamination are distinguished (cf. **Section 20.4.1**). Level 1, also referred to as immediate or instant decontamination, involves washing affected individuals with water, with the optional use of simple cleaning agents such as soap. The primary objective at this level is initial care and harm reduction for affected persons; decontamination of equipment, including assistive devices, is not prioritised and no dedicated procedures are applied (Kühar, 2021).

Level 2, commonly termed standard decontamination, also focuses on human decontamination. Contaminated equipment and personal items are collected and packaged, but decisions on subsequent decontamination or disposal are deferred to a later stage (Kühar, 2021; Ministerium des Inneren NRW, 2011).

Level 3 is designed for the decontamination of large numbers of people, for example in mass casualty incidents. At this level, the scale of deployment is significantly increased and specialised decontamination methods may be employed. Nevertheless, across all three levels, the procedures used are predominantly water-based and are therefore generally unsuitable for assistive devices containing electronic components (Kühar, 2021; AFKzV, 2022).

Simultaneous decontamination of personal items and assistive devices alongside human decontamination is not standard operational practice (Ministerium des Inneren NRW, 2011; vfdb, 2022).

Consequently, there is not only a need to introduce suitable decontamination methods for assistive devices on a broader basis, but also to supplement existing standard operating procedures with respect to:

- the number and roles of units or first responders deployed
- additional capacity for parallel decontamination processes suitable for electronic devices and other sensitive equipment, even where only human decontamination is formally indicated
- awareness-raising regarding persons with disabilities and their specific operational needs

20.3. Decision support for handling contaminated assistive devices

Following the accidental or intentional release of CBRN substances, decontamination measures are required to prevent harmful effects on affected persons and to limit secondary spread. Various national concepts exist for the decontamination of people and objects, and the allocation of resources as well as the operational course of action may depend on the nature and scale of the incident. Within

this context, the handling of assistive devices requires structured decision-making that balances health protection, operational feasibility, and the functional needs of the user.

The following decision trees are provided as illustrative decision-support tools to assist competent authorities and first responders in determining appropriate handling options for contaminated assistive devices. They are non-normative and intended to support situational awareness and structured decision-making in operational contexts. These tools do not replace operational decision-making by the competent authority.

Decision tree – chemical contamination (Figure A.7): The decision tree shown in Figure A.7 provides a structured approach to deciding how to handle assistive devices contaminated by chemical substances. The decision-making process is based on four main factors:

1. Identification of the substance
2. Potential health effects
3. Replaceability of the assistive device
4. Removability of the contamination

The first step is the identification of the hazardous substance. The decision path distinguishes between substances that can be identified directly and those requiring analytical identification. Direct identification may be possible, for example, if a labelled container is present at the scene. If identification is not possible, chemical analysis must be carried out by specialised units, which may require additional time.

Where analysis is required, the decision to await results may depend on the type and value of the assistive device. Highly personalised or costly devices may justify delayed decision-making pending analysis, whereas easily replaceable and low-cost devices may be disposed of as a precautionary measure.

Once the substance is identified, potential health effects are assessed. Two broad cases are distinguished:

- substances with significant harmful effects on the human body,
- substances with limited or context-dependent effects (e.g. depending on concentration or volume).

If a substance is classified as highly hazardous, on-site decontamination of the assistive device is generally not recommended; instead, the device may be disposed of or transferred for specialist handling.

If the foreseeable health impact is low, the decision process continues by assessing the replaceability of the assistive device. Devices that are easily replaceable should generally remain within the contaminated area (cf. **Section 20.3**) and be substituted, whereas highly individualised devices may warrant decontamination.

The final decision step assesses whether contamination can be reliably removed. This includes consideration of material properties, device complexity, and the feasibility of verifying successful decontamination. Devices with porous materials, complex geometries, cavities, lubricated joints, or integrated electronics may be difficult to decontaminate effectively on site. Where reliable decontamination cannot be ensured, disposal remains the safest option.

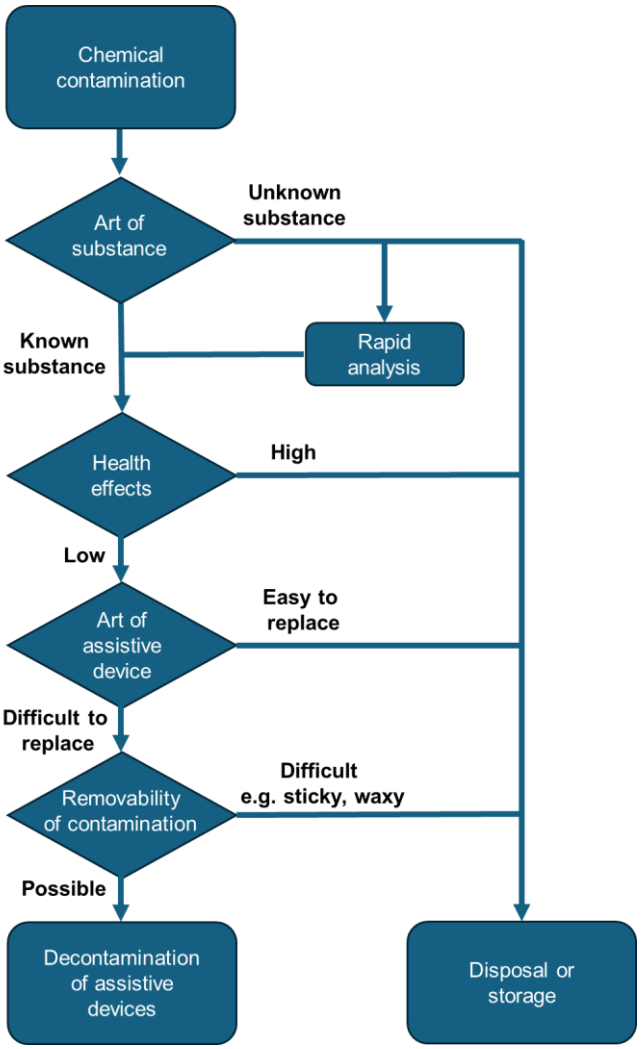

Figure A.7 Decision tree for chemical contamination of assistive devices (Source: FDDO).

Decision tree – biological contamination (Figure A.8): The decision tree for biological contamination, shown in Figure A.8, follows a similar structure but reflects the specific characteristics of biological hazards. Pathogens may pose significant risks even in small residual quantities due to their capacity for replication, whereas the harmfulness of chemical substances often depends on concentration and dose.

In some biological contamination scenarios, removal or dilution with water may be sufficient to reduce risk. However, reliable verification of decontamination success is often more challenging. As with chemical contamination, the availability of a suitable decontamination method on site is a key prerequisite.

In all cases, final decisions regarding the implementation and acceptance of decontamination outcomes remain the responsibility of the competent authority.

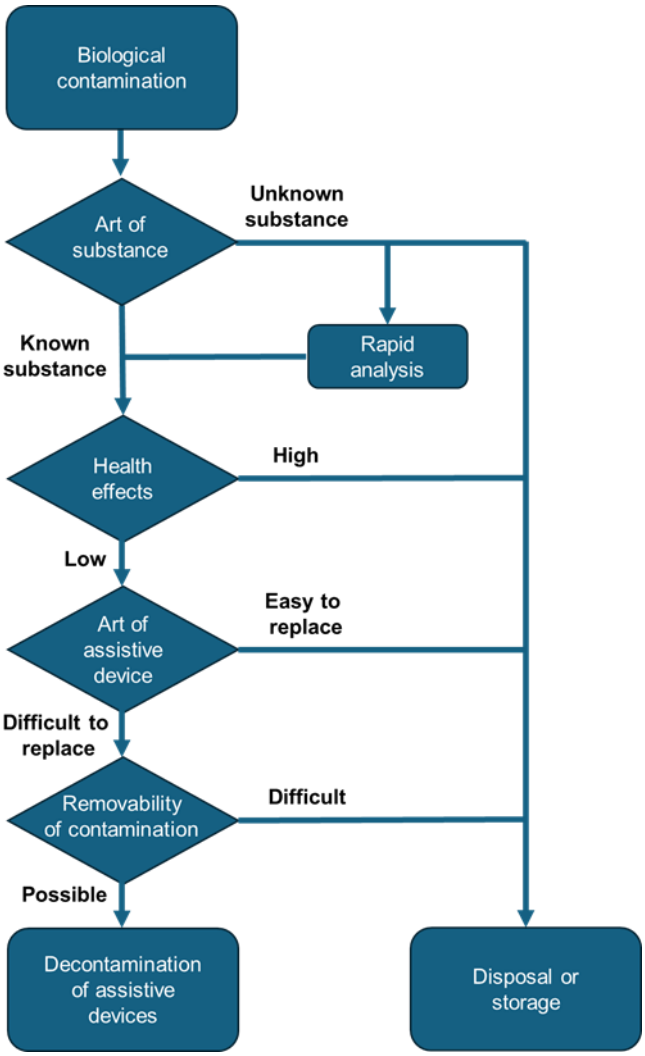

Figure A.8 Decision tree for biological contamination

20.4. Illustrative SOP context: human decontamination procedures in Germany

This section provides an illustrative overview of standard operational procedures (SOPs) for human decontamination as applied in Germany, in order to contextualise the handling of assistive devices within established emergency response frameworks. It does not introduce new requirements and is included for explanatory purposes only.

In Germany, responsibility for civil CBRN emergency response lies primarily with fire departments, which provide the majority of operational forces and are typically the first responders on scene. Nationally standardised procedures govern their deployment in CBRN defence. Comparable principles are applied by other stakeholders involved in decontamination operations.

The deployment of fire departments in CBRN response is regulated by Feuerwehr-Dienstvorschrift 500 (FwDV 500), Einheiten im ABC-Einsatz (AFKzV, 2022). This doctrine is supplemented by additional guidance documents, including the ABC-Schutz-Konzept NRW (Ministerium für Inneres und Kommunales des Landes Nordrhein-Westfalen, 2011–2023). Within FwDV 500, decontamination activities are categorised as follows:

- Dekon P (P = Personal): decontamination of first responders whose protective equipment remained intact.
- Dekon V (V = Verletzte): decontamination of contaminated individuals without life-threatening injuries.
- Dekon G (G = Geräte): decontamination of equipment, such as PPE and vehicles.

Dekon P and Dekon V both relate to human decontamination, while Dekon G applies to objects and equipment. Decontamination operations are conducted under the authority of a designated competent authority, typically an expert responsible for determining appropriate measures and for deciding when an individual is considered decontaminated (AFKzV, 2022). Decontamination is not a conclusive medical measure and is followed by further medical care as required.

20.4.1. Levels of human decontamination

FwDV 500 distinguishes three levels of human decontamination (AFKzV, 2022; Kühar, 2021):

Level 1 – Immediate (instant) decontamination

This level involves rapid washing of affected individuals using water, with the optional addition of simple cleaning agents such as soap. The primary objective is to enable life-saving emergency measures without endangering responders or others. Water serves to remove hazardous substances and, in the case of chemicals, to reduce harmful effects through dilution. Decontamination of equipment, including assistive devices, is not prioritised at this level (Kühar, 2021). Level 1 decontamination can be performed by standard fire engines with their own water supply and is not confined to a dedicated decontamination site. It may precede or complement subsequent decontamination levels.

Level 2 – Standard decontamination

At this level, a dedicated decontamination site is established. Capacities are designed for smaller numbers of individuals, who are decontaminated sequentially. Both ambulatory and recumbent persons can be treated. The procedure remains water-based, using additional cleaning agents as appropriate. Contaminated equipment and personal items are collected and packaged, while decisions regarding decontamination or disposal are deferred to a later stage (Ministerium für Inneres und Kommunales des Landes Nordrhein-Westfalen, 2011; Kühar, 2021).

Level 3 – Extended decontamination

Level 3 is intended for the decontamination of large numbers of individuals, for example during mass casualty incidents. A decontamination line is set up, allowing ambulatory and recumbent individuals to be processed in parallel. Although more resource-intensive, this approach is advantageous in large-scale incidents, adverse weather conditions, and when decontaminating immobile persons, including injured individuals and persons with disabilities. Specialised decontamination methods may be deployed if required (AFKzV, 2022).

Across all three levels, decontamination procedures are predominantly water-based. As a result, they are generally unsuitable for assistive devices containing electronic components (Kühar, 2021; Ehrmann & Kühar, 2020).

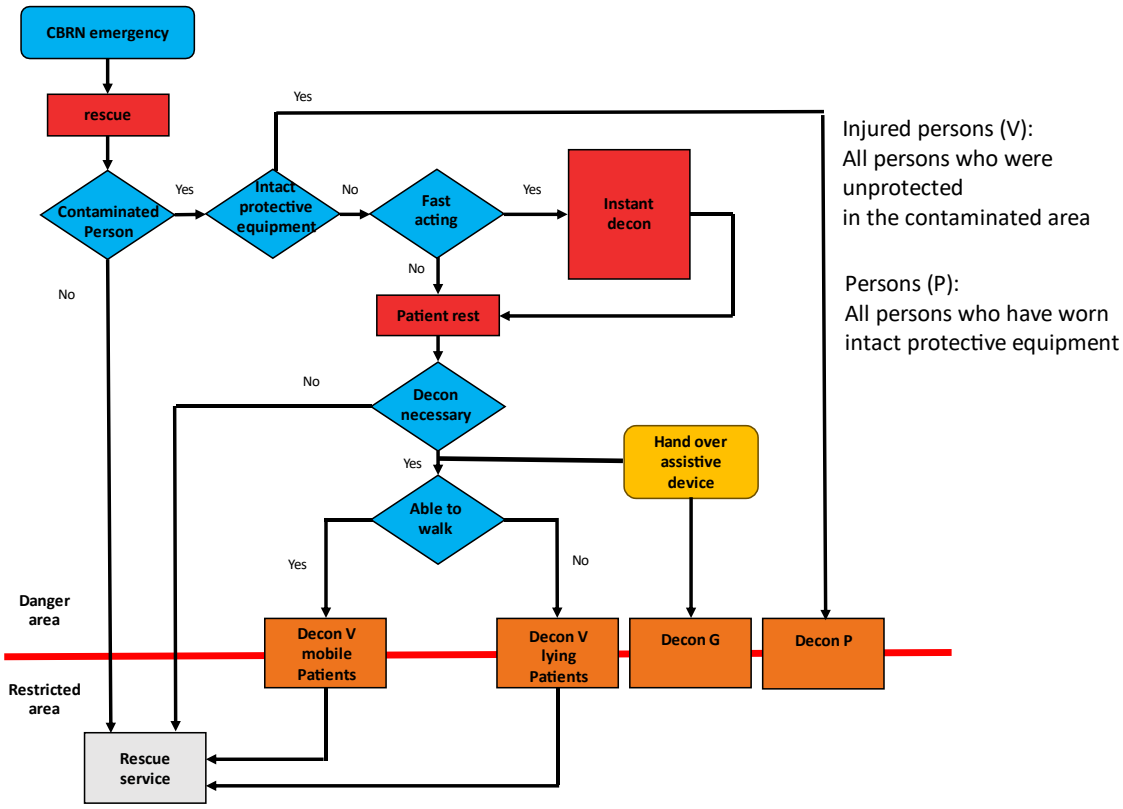

Figure A.9 Human decontamination workflow including assistive devices.

Notes: Modified representation of the human decontamination workflow according to FwDV 500, including procedural adaptations for individuals using assistive devices. Source: Fire Department of Dortmund (FDDO), based on Ehrmann and Kühar (2020).

20.4.2. Integration of assistive devices into human decontamination workflows

The human decontamination workflow is illustrated in **Figure 9**, using FwDV 500 as a reference (AFKzV, 2022). The standard sequence comprises the following steps:

1. Rescue and removal from the hazard area. Affected persons are instructed to leave the hazard area independently where possible or are rescued by first responders if required.
2. Decision-making on the need for decontamination. This includes determining whether immediate decontamination is necessary due to imminent health risks.
3. Gathering, registration, and categorisation. Affected persons are assembled in a transition area, registered, and prioritised according to urgency.
4. Decontamination. Separate sections are provided for ambulatory and recumbent individuals.
5. Handover to medical services. Decontaminated individuals are transferred for further treatment or observation.

In the illustrated workflow, an additional step has been highlighted: the handover of assistive devices, where applicable. Technically, the handover of personal belongings is already part of standard procedures; however, explicit emphasis is placed here on assistive devices due to their functional importance.

For small personal items (e.g. jewellery or watches), handover typically occurs within the decontamination facility during undressing. For assistive devices, handover is positioned earlier in the workflow, immediately before entry into the decontamination line. This placement reflects operational considerations. For example, removal of a leg prosthesis directly affects mobility and reclassifies the

individual as non-ambulatory, with implications for staffing and resource allocation. Delaying handover until this point minimises unnecessary handling and optimises operational efficiency.

Clear communication with the affected person prior to handover is essential, and cooperation should be sought wherever possible. Assistive devices must be labelled to ensure traceability and later reassignment to their owner (Ministerium des Inneren des Landes Nordrhein-Westfalen, 2005; AFKzV, 2022; vfdb, 2022).

Handover may not be feasible in certain cases, notably where:

- the assistive device is life-sustaining (e.g. a respiratory device), or
- the device is not separable from its user.

In such situations, decisions must be made on a case-by-case basis, prioritising preservation of life and health. Where possible, substitution or alternative arrangements may be considered (Kühar, 2021).

20.4.3. Operational limitations of assistive device decontamination

Building on the contextual considerations outlined above, this section summarises structural limitations in current SOPs related to assistive device decontamination. Following handover, the suitability of assistive devices for decontamination must be assessed. FwDV 500 does not explicitly define on-site decontamination procedures for contaminated third-party equipment. Standard practice focuses on packaging and safe storage to prevent further spread of contamination, with contaminated items typically remaining within the hazard zone (AFKzV, 2022).

In Germany, equipment decontamination is further addressed in the ABC-Schutz-Konzept NRW, Part 4 (Geräte-Dekontaminationsplatz NRW), which primarily targets vehicle decontamination and only incidentally addresses smaller equipment (Ministerium für Inneres und Kommunales des Landes Nordrhein-Westfalen, 2011). These procedures are also largely water-based and are therefore not readily applicable to assistive devices containing electronics (Ehrmann & Kühar, 2020).

Consequently, existing SOPs do not adequately address the on-site decontamination of assistive devices. This limitation underlines the need for complementary approaches, as discussed in the main pre-normative guideline in **Section 3**, and for structured decision-making tools to determine whether assistive devices should be decontaminated, transferred for specialist handling, or disposed of.

The decision-support logic illustrated in **Figure A.7** and **Figure A.8** complements this operational context by providing non-normative criteria to guide competent authorities and first responders in handling contaminated assistive devices in both chemical and biological scenarios.

References

All references cited in this annex are included in the consolidated reference list at the end of the document. No separate bibliography is provided for this annex.

Page-level or section-level citations are used selectively where national doctrine, operational manuals, standards, or institutional guidance documents are referenced to support specific procedural steps, definitions, or operational assumptions. This approach ensures traceability, transparency, and precision in a pre-normative context, and enables reviewers and standardisation bodies to verify the exact source passages underpinning technical or operational statements.