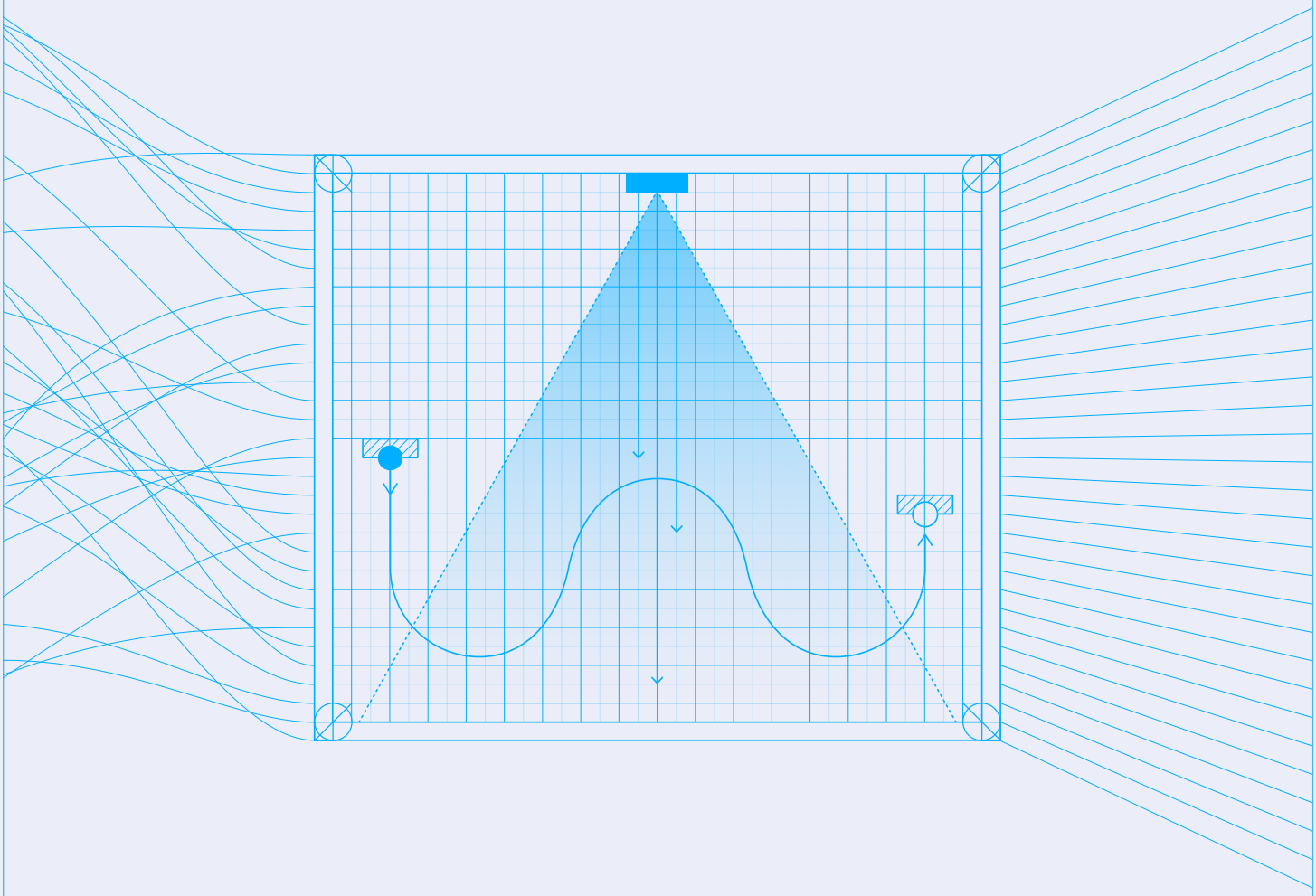
Blueprint Biosecurity



Blueprint for Far-UVC

Executive Summary & Recommendations

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About Blueprint Biosecurity

Blueprint Biosecurity is a nonprofit dedicated to achieving breakthroughs in humanity's ability to prevent pandemics.

Acknowledgements

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The resulting report solely reflects the views of Blueprint Biosecurity, and does not represent the view of any other individual nor represent a consensus among subject matter experts. All opinions provided to us were the individual's own and not those of the organizations with which they are affiliated. Any errors in the report are entirely the responsibility of Blueprint Biosecurity.

In addition to the contributions of individual experts, we also acknowledge essential contributions from the attendees of:

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- Evaluating the Health and Policy Implications of FAR-UV Technology hosted by the Johns Hopkins Center for Health Security, February 27 2024
- Report Development Workshop hosted by Blueprint Biosecurity, St Andrews, June 18 2024
- Recommendations Workshop hosted by Blueprint Biosecurity, Washington DC, October 8 2024

And from presenting our work to the expert community at the following events:

- International Ultraviolet Association Americas Conference 2024, Orlando, May 20-22 2024
- 2nd International Congress of Far-UVC Science and Technology, St Andrews, June 18-21 2024
- Indoor Air 2024, International Association of Indoor Air Quality and Climate, Honolulu, July 7-11 2024
- 42nd American Society for Photobiology Biennial Meeting, Chicago, July 27-30 2024
- American Association of Aerosol Research 42nd Annual Conference, Albuquerque, October 21-25 2024
- 2024 Chemical and Biological Defense Science & Technology Conference, Ft Lauderdale, December 2-5 2024

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Executive summary

Despite the tremendous strides we have made against water-borne, food-borne, and vector-borne diseases, airborne infectious diseases remain one of humanity's biggest challenges: the COVID-19 pandemic has claimed an estimated 27 million lives. Tuberculosis kills 1.6 million people annually. One billion people are infected by influenza every year, leading to millions of serious illnesses and hundreds of thousands of deaths.

Countermeasures to infectious disease are vital, and their champions—Pasteur, Jenner, Fleming, Salk, Karikó—are rightly celebrated. But less celebrated are the interventions that operate in the background of everyday life—sanitation, pest control, food hygiene—which prevent us from encountering pathogens in the first place.

Germicidal ultraviolet light (GUV) has been used in water treatment for over 100 years. Studies in the 1940s showed the promise of treating the air above our heads with GUV—so called 'upper-room UV'—to control the spread of measles in schools and it has been used for decades to control the spread of drug-resistant tuberculosis.

Far-UVC is a new form of GUV. Because it is strongly absorbed by proteins in the outer layer of human skin and eyes, it can inactivate a wide range of pathogens with minimal penetration into and effects on human tissues. This enables higher human exposure limits, unlocking the potential for disinfecting occupied spaces continuously while achieving significantly improved air cleaning over current alternatives. Far-UVC is also silent, energy-efficient, commercially viable at scale, less vulnerable to engendering resistance than pharmaceuticals, and can be deployed in advance of an outbreak to help prevent a pandemic from occurring in the first place.

This report details a comprehensive set of recommendations to accelerate far-UVC's development and prepare it for widespread usage. The four most urgent priorities are:

1. Establish how far-UVC installations need to be designed in order to effectively suppress airborne transmission.
2. Identify different biological effects induced by far-UVC compared to solar UV and conventional GUV.
3. Understand unintended air quality impacts of far-UVC and options for mitigation.
4. Obtain high-quality evidence of real-world effectiveness.

We also identify the key building blocks for facilitating successful adoption and a longer-term research agenda to accompany adoption.

Unfortunately, the drivers of pandemic risk are going in the wrong direction. Climate change, factory farming, and human encroachment into wild habitats more than double the expected risks of pandemic pathogens jumping from animals to humans. Meanwhile, rapid advances in AI and synthetic biology leave us significantly more vulnerable to malicious actors and engineered pandemics. Experts estimate a 1 in 8 chance of a pandemic killing over 90 million people by 2050, three times the death toll of COVID-19. If we want to overcome these immense risks, the time to act is now.

A preview of chapters in the report

This report is based on an extensive review of the published literature and two years of consultation and collaboration with over 100 experts across multiple disciplines, including photobiology, atmospheric chemistry, indoor air quality, building science, environmental engineering, epidemiology, and public health. Its primary purpose is to coordinate the efforts of researchers, policymakers, entrepreneurs, funders, and other stakeholders who can accelerate far-UVC's development. It therefore begins with our *Recommendations*, the specific steps that need to be taken to validate far-UVC's real-world safety and efficacy profile.

In *Germicidal UV: introduction and history*, we cover the history of germicidal ultraviolet light from the 19th century to the present day, placing the development of far-UVC in the context of the shift in understanding of airborne disease transmission caused by the COVID-19 pandemic.

In *Far-UVC primer*, we provide a detailed glossary of important concepts that are referred to throughout the report.

In *Efficacy*, we discuss the evidence for far-UVC's efficacy and effectiveness at disinfecting indoor air. Far-UVC can measurably inactivate airborne pathogens within safe human exposure limits. However, given inconsistencies in estimated susceptibility of pathogens and the impact of dose distribution in practical applications, the degree to which far-UVC will prove superior to existing air cleaning technologies is uncertain.

The following four chapters—*Skin and eye safety*, *Evaluating cancer risk*, *Ozone and indoor air quality*, and *Ozone epidemiology*—examine far-UVC's effects on skin, eyes, and indoor air quality. The evidence indicates that it is appropriate for far-UVC eye and skin exposure limits to be meaningfully higher than the limits for longer UV wavelengths. However, further research is necessary and we expect expert bodies to update their guidance in the coming years. Far-UVC generates small quantities of ozone relative to normal outdoor levels. However, this can be mitigated, and the risks from additional ozone ought to be weighed against the benefits of disinfection.

Emitters and luminaires analyzes commercially available far-UVC lamps. Krypton chloride excimer (KrCl*) lamps are currently the primary emitter source. Fundamental innovation is not necessarily required for widespread commercial adoption, and the cost of KrCl* lamps could decrease significantly in the next 3–5 years. However, solid-state technologies like LEDs or frequency doubled blue lasers could offer several improvements over KrCl* lamps on a 5–10 year timescale.

The *Guidance, standards, and regulations* chapter examines the complex landscape governing far-UVC use and implementation and offers an overview of the consensus standards and guidance provided by a wide array of expert bodies and professional associations.

Finally, *Materials* examines how far-UVC is likely to interact with the built environment and the different materials that comprise it. While relatively little is known about far-UVC's impact specifically, exposure to other forms of UV (such as solar UV and conventional GUV) are known to cause effects on the appearance and performance of some common materials.

Scope

This report evaluates the use of far-UVC to suppress 'long-range' airborne transmission. There are other promising uses of far-UVC, including disinfection of surfaces, prevention and treatment of surgical-site infections, 'near-field' protection (for example through personal protective equipment that incorporates far-UVC), as well as the prevention of 'short-range' airborne transmission. We expect to review the prospects for short-range transmission reduction in a future update.

While there are other air cleaning technologies that play an important role in defending against airborne disease, including ventilation, filtration, and even other types of germicidal UV light, they are not within the scope of this report except insofar as they relate to far-UVC.

Recommendations

The starting point for our recommendations is the mission of Blueprint Biosecurity: achieving breakthroughs in humanity's capability to prevent, mitigate, and suppress pandemics. If far-UVC is to be effective as a pandemic prevention measure, it will need to be widely installed across indoor public spaces before outbreaks occur. That does not mean that there is no value in a more limited adoption, or that widespread adoption is needed for a viable commercial market to exist for far-UVC manufacturers. But we do expect that in order to achieve the goal of pandemic prevention, far-UVC will have to prove highly effective at suppressing the transmission of endemic respiratory illnesses—otherwise, mass adoption before outbreaks won't be justified.

The level of trust that we are asking the public to place in far-UVC is substantial. Far-UVC does not require most individuals to change their behavior to be effective, which is a key reason that it could prove so impactful. But a world in which far-UVC enjoys widespread use in public spaces is one in which only limited personal consent can be given to far-UVC exposure. The corollary of passive collective protection is that great trust is placed in the scientists who develop the technology, the professionals who install it, and most of all the institutions who set safety and efficacy standards.

The thoroughness embodied in our recommendations, in particular with regards to the need for further research, reflects the trust that we believe must be earned through rigorous science in order for far-UVC to have a substantial impact on the world.

The recommendations of this report are specific to advancing far-UVC, with preventing airborne disease transmission as the intended use case. There are other things that could materially advance the cause of airborne infection resilience, including basic research into the aerobiology and epidemiology of pathogen transmission, development of biosensors that can detect infectious aerosols in real time, and better monitoring of respiratory infections acquired in high-risk environments such as healthcare settings. A number of these may be highly impactful, but they have not been evaluated as part of this report.

The recommendations fall into three categories.

First, we offer four **research priorities**, describing the academic and clinical research that urgently needs to be pursued to validate the potential of far-UVC and facilitate adoption.

Second, we offer five **recommendations** for facilitating successful adoption at scale. These are relevant to a wide range of stakeholders, including academia, industry, government, civil society, and early adopters.

Finally, we propose a **long-term research agenda** that ought to be pursued to answer questions that are important, but that we do not believe need to be urgently resolved in order to advance the field.

Research priorities

Recommendation 1: establish how far-UVC installations need to be designed in order to effectively suppress airborne transmission.

The amount of far-UVC power that is needed for air disinfection depends on the dose-response of different pathogens to far-UVC. All of the other challenges highlighted in this report become greater the higher the dose required to be effective, making understanding this the highest priority.

Among the studies that have been conducted so far, there are order-of-magnitude differences in pathogen susceptibility to far-UVC. We need to understand what aspect(s) of experimental procedure or environment cause this variability, and its causes may not be specific to UV inactivation. Standardization of research methods into infectious aerosols may have substantial spillover benefits for other technological approaches to controlling airborne transmission.

The protein absorption that makes far-UVC safer than other forms of UV will also reduce its penetration into the protein-rich human respiratory aerosols in which airborne pathogens are contained. It is not currently known how significant this effect is, nor what additional consequences there could be on the stability of pathogens contained in the aerosol. It is also challenging to synthesize representative human respiratory aerosols in the lab.

Sophisticated modeling, such as computational fluid dynamics combined with lighting simulation, is needed to translate experimental findings into practical guidance for safe and effective deployment in diverse environments. As these research methods can be inaccessible to end users, the goal of this research has to be practical heuristics that can be endorsed by public health agencies and implemented by practitioners at scale (see Recommendation 5).

Finally, we know that environmental factors such as relative humidity affect the susceptibility of pathogens to conventional GUV, and it is reasonable to hypothesize that the efficacy of far-UVC will also be mediated by environmental factors. These must be known in order to provide effective deployment guidance.

Therefore, researchers should:

1.1 Obtain pathogen inactivation data from actual human respiratory aerosols.

1.2 Conduct controlled bioaerosol chamber studies to establish the degree to which environmental variables such as relative humidity affect the susceptibility of relevant pathogens to far-UVC.

1.3 Understand the causes of the variability in experimental results and produce standardized experimental methods.

1.4 Use relevant techniques, such as computational fluid dynamics modeling and lighting simulation, to model UV dose distribution based on different room geometries, ventilation regimes, occupancy, and the location of the infectious source.

Recommendation 2: identify different biological effects induced by far-UVC compared to solar UV and conventional GUV.

Far-UVC is absorbed by proteins in the outer layer of skin and eyes, thus reducing the harms associated with other forms of UV radiation. This is the foundation of far-UVC's promise for whole-room disinfection of occupied spaces.

While there is currently no evidence of significant harm from far-UVC, the impact of protein absorption is not yet fully understood. Protein absorption and other consequences of the higher energies of far-UVC photons will have other effects not traditionally associated with conventional GUV and solar UV exposure. Safe exposure limits for human skin and eyes are based on the propensity of different UV wavelengths to induce harmful biological effects, and therefore we should ensure that the measurable endpoints by which these harms can be detected are fully complete.

Therefore, researchers should:

2.1 Obtain a mechanistic understanding of the effects of protein absorption in the skin and eye.

2.2 Study other pathways through which the higher energies of far-UVC photons may cause relevantly different effects to longer UV wavelengths.

2.3 Use this knowledge to identify biomarkers and create action spectra that can inform the exposure limits recommended by expert bodies such as ICNIRP and ACGIH.

Recommendation 3: understand unintended air quality impacts of far-UVC and options for mitigation.

Far-UVC will generate some ozone. Our knowledge of the amount of potential harm from ozone exposure is based on epidemiological studies of outdoor ozone. In order to use this data to bound the harms of any indoor air quality effects from far-UVC, a number of assumptions need to be made. In particular, we must assume that the complex indoor air chemistry observed with the use of far-UVC is all downstream of the generation of ozone. Establishing whether this assumption is valid, or whether there are byproducts relevant to air quality that are caused by some other effect of far-UVC, should be a high priority.

It is also possible to mitigate indoor ozone generation and any byproducts not only through adequate ventilation but also through the use of catalysts or activated carbon filters. Epidemiological data suggests that reducing the concentrations of ozone and its byproducts in indoor air could have potentially significant public health benefits independent of synergizing with the use of far-UVC, and these technologies are worthy of further development.

Therefore, researchers should:

3.1 Conduct in-depth field measurements of indoor chemistry, in diverse environments representative of the spaces in which far-UVC may be deployed, that compare the effects of far-UVC to introducing the equivalent quantity of ozone. Independently estimating relevant parameters such as fluence rate, ventilation, and background ozone decay is vital to assist with interpretation and modeling of results.

3.2 Replicate lab measurements of ozone generation from different far-UVC devices to establish a robust model for predicting ozone production based on their output power and emission spectrum, and establish a standard test method.

3.3 Build on existing epidemiological research to quantify potential health effects of exposure to ozone and ozone reaction byproducts indoors.

3.4 Investigate the potential for ozone removal with catalysts and activated carbon, and identify the solutions that are most cost-effective without creating unintended consequences.

Recommendation 4: obtain high-quality evidence of real-world effectiveness.

Cluster-randomized trials (CRTs) that demonstrate reductions in infections are considered the gold standard of evidence for infection control.

CRTs have risks and drawbacks for studying transmission suppression technologies like far-UVC. Previous studies of the effectiveness of upper-room UV produced mixed results due to flaws in study design that are challenging to mitigate. It is difficult to ensure that a trial is adequately powered to detect a reduction in transmission, and underpowered studies risk undermining the field. The failure to find statistically significant results can be misinterpreted as evidence that an intervention does not work, when it is often the case that the study is not capable of providing evidence that it *does* work.

It is our judgment that without a paradigm shift in the type of evidence that is expected by public health agencies and experts in infection control, successful CRTs are necessary to catalyze widespread adoption. However, ventilation is an example of an intervention to control airborne transmission that has become widely accepted as effective without such a study. If we are wrong about the importance of CRTs in proving the real-world effectiveness of far-UVC and catalyzing adoption, our other recommendations would still stand.

Therefore, researchers should:

4.1 Ensure that clinical trials are sufficiently powered that plausible effect sizes can be detected with statistical significance.

4.2 Ensure that clinical trials of GUV employ doses that are likely to prove effective based on the experimental evidence, and ensure that building occupants remain within photobiological safety limits.

4.3 Collect data such as temperature, humidity, CO^2 concentrations, ventilation rates, pathogen concentrations and sequencing of confirmed infections, in addition to the primary infection endpoints. This will assist in the interpretation and generalizability of a CRT whether it is successful or not.

Facilitating successful adoption

Recommendation 5: create simple far-UVC deployment guidance, backed by research, that can be clearly communicated by public health agencies and other trusted institutions.

Public health communication, risk communication, and radiation safety communication are mature fields with established principles that can be applied when communicating about far-UVC. It is vital to develop informative guidance that can be implemented by practitioners and educational materials that are comprehensible to a lay audience.

In order to provide this guidance and facilitate clear communication, we need to determine which factors are critical for designing effective far-UVC applications in different spaces (see Recommendation 1).

Therefore, developers of guidance and informational materials should:

5.1 Facilitate dialogue between modelers, experimentalists, public health authorities, communication experts, and the practitioners who will have to follow the guidance.

5.2 Follow established practices in the fields of public health communication, risk communication, and radiation safety communication.

5.3 Produce guidance for far-UVC that accounts for different levels of ventilation. There cannot be a 'one size fits all' approach, and the impact of ozone-initiated secondary chemistry is particularly sensitive to levels of ventilation.

5.4 Bring the institutions trusted by the public into the guidance development process early.

Recommendation 6: improve consensus standards for airborne infection control applications and far-UVC devices.

Some consensus standards are already established, more are needed, and all of these will require future revision. 2023 saw the publication of UL 8802 *Standard for Ultraviolet (UV) Germicidal Equipment and Systems*, as well as ASHRAE 241 *Control of Infectious Aerosols*—the first standard that attempts to provide a technology-neutral framework for preventing long-range airborne transmission in a wide variety of indoor public spaces.

There are other standards that are important to the use of far-UVC, such as UL 2998 *Environmental Claim Validation Procedure (ECVP) for Zero Ozone Emissions from Air Cleaners*, that were not formulated with the properties of germicidal lamps in mind and need to be amended. Another standard that governs far-UVC use in many settings, *IEC 62471 Photobiological safety of lamps and lamp systems*, has not been updated since 2006.

A number of standard test methods exist for quantifying the efficacy of air cleaning devices against bioaerosols, and all of these will likely require revision once we understand the cause of the variability of results on far-UVC efficacy observed in the academic literature (see Recommendation 1).

Developing and revising consensus standards requires input from a wide variety of interested parties, including academic experts, trade associations, government, manufacturers, and end users, to ensure a balanced perspective. If you are reading this document, consider participating in the development of consensus standards.

Therefore, standards-setting bodies should:

6.1 Further develop and refine existing standards, particularly:

- ASHRAE 241 *Control of Infectious Aerosols*.
- ANSI/CAN/UL 8802 *Standard for Ultraviolet (UV) Germicidal Equipment and Systems.*
- ANSI/CAN/UL 8803 *Portable UV Germicidal Equipment With Uncontained UV Sources*.
- IEC/EN 62471 *Photobiological safety of lamps and lamp systems.*
- ISO 15858: *UV-C Devices - Safety information - Permissible human exposure.*
- ANSI/IES RP 27.1-22 *Photobiological Hazards From UV Lamps.*

6.2 Develop new consensus standards for:

- Ozone generation from germicidal applications, using new testing methodologies that account for the particular properties of far-UVC devices.
- Manufacturing and labeling of GUV devices that provide consistent information to consumers on expected lifetime, UV power output and emissions spectrum, and photobiological exposure limits based on the device emissions spectrum.

6.3 Modify standards relevant to particular industries and settings, such as the Facilities Guidelines Institute standards for hospitals and other healthcare settings in the United States, to facilitate the use of GUV in high-infection-risk spaces.

6.4 Develop improved standard testing methodologies for air cleaners that claim to remove infectious aerosols. These can be incorporated into standards such as ASHRAE 241, and can also be used by government agencies such as the US EPA who have the authority to regulate marketing claims.

Recommendation 7: ensure that far-UVC is installed in accordance with consensus standards, as part of a layered approach with other engineering controls such as adequate ventilation and filtration.

Layered interventions with different mechanisms are more resilient to the diversity of potential biological threats, and the use of multiple different approaches is a basic principle of biosecurity. Different technologies have different strengths and weaknesses, and far-UVC is likely to be more effective at mitigating some airborne infection threats than others. Adequate ventilation and the use of mechanical filtration (e.g. HEPA or MERV-13) have other potential health benefits as well as mitigating some of the possible risks of far-UVC use.

Not all far-UVC devices are the same, and emissions of non-far-UVC wavelengths from KrCl* lamps and LEDs pose different photobiological and photochemical risks. Not all use cases are the same either, and the potential risks of far-UVC use are higher in places with longer occupant dwell times and lower standards of ventilation, and without professional facilities management.

We expect some of these recommendations to be superseded by the further development of consensus standards and deployment guidance, but they represent what we believe is prudent today.

Therefore, we recommend to those considering installing far-UVC today:

7.1 Purchase devices that have been certified to appropriate product standards such as IEC/EN 62471 or ANSI/CAN/UL 8802. In some jurisdictions certain standards are mandatory.

7.2 When assessing photobiological exposure limits, either in a test lab or the field, the combined effect of all the emissions of the device—not just the peak 222-nm emissions of a KrCl* lamp—must be factored in.

7.3 Ensure that ventilation is sufficient and working as intended before considering the installation of far-UVC. Far-UVC is not an alternative to minimum acceptable ventilation standards.

7.4 Typically avoid mounting fixtures on walls, and where possible mount devices on the ceiling facing down to provide an additional safety margin for eye exposure. However, the best approach to safe and effective installation does depend on the specifics of room geometry and the behavior of occupants.

7.5 Carefully weigh the benefits and risks of the use of far-UVC in private residences.

Recommendation 8: improve performance and affordability of far-UVC emitters.

Far-UVC emitters are currently expensive and may not be cost-effective outside of high-risk settings, such as healthcare facilities. As disinfection is ultimately a product of dose and the susceptibility of the pathogen (see Recommendation 1), the relevant criteria for cost-effectiveness is the cost per mW of far-UVC output that can be safely installed in a space.

Reducing cost per mW can be achieved through a number of means. Increased production of far-UVC lamps for other applications will help achieve economies of scale, and this additional source of far-UVC emitter production could also be repurposed in a future pandemic. The far-UVC industry is currently very small, and substantial reductions in cost per mW are feasible merely from scale.

There is potential for direct cost reduction of key lamp components, as well as prospects for wholly new emitter technologies based on semiconductor technology such as LEDs or frequency-doubled blue lasers. But there are other strategies for addressing the cost per mW of useful power output that do not require fundamental innovation, and some product features may have the capability of addressing multiple challenges—safety, cost, energy efficiency—simultaneously.

We have seen marked improvements in far-UVC emitters over the last decade, and we believe that the improvements in features and cost necessary for widespread deployment will happen if there is the prospect of a market to sustain the industry and attract investment.

Therefore, industry should:

8.1 Improve diffuser technology, as this has the potential to reduce cost per mW and increase the energy efficiency of fixtures designed for lower ceiling heights.

8.2 Evaluate the use of proximity sensors or cameras, combined with the capability to dim or boost output, allowing for dynamic output regulation based on room occupancy.

8.3 Develop cost-effective filters that are as transparent as possible to far-UVC wavelengths and opaque outside that range. Such filters are useful for multiple different types of far-UVC sources, and filters can be a significant cost component of lamps.

8.4 Extend lamp lifetime to reduce both maintenance and effective cost per mW.

8.5 Develop next generation emitters, such as semiconductor technology. These may outcompete current sources on cost, and also provide different features for different applications.

8.6 Develop markets for far-UVC outside of indoor air disinfection. Examples that we have seen proposed, but we have not evaluated as part of this report, include water treatment, surface disinfection, healthcare tools, agriculture and food production, food processing, pest control, and scientific equipment.

Recommendation 9: create cost-benefit analysis frameworks for deploying far UVC

Far-UVC technology is not meant to be used everywhere or in every situation. Its adoption should be thoughtful and guided by evidence. Many stakeholders, especially institutional decision-makers, will base their investment decisions on a careful cost-benefit analysis.

These decisions, whether made by private businesses, healthcare facilities, or government agencies, require evaluating a complex mix of both tangible (hard) and intangible (soft) costs and benefits. These include costs such as upfront capital, ongoing operational costs, and deployment risks, and expected gains such as fewer infections, reduced absenteeism, increased productivity, and lower healthcare costs.

In situations where achieving airborne infection control is (or becomes) required, and decision-makers use far-UVC to substitute for other methods, then the benefits can take the form of cost and/or energy savings from reducing the use of less efficient methods. Developing frameworks that compare the costs and benefits of different solutions is necessary.

Therefore, to support more informed decision-making, researchers and building design professionals should:

9.1 Develop cost-benefit analysis frameworks and tools tailored to specific deployment settings, starting with high-risk, high-impact environments like healthcare facilities, public gathering spaces, and schools.

9.2 Regularly update these frameworks and tools with the latest research and data on far-UVC technology's benefits, costs, and implementation needs.

9.3 Ensure that these cost-benefit analysis tools are adaptable for use with other disinfection and air-cleaning technologies, enabling fair and consistent comparisons across different solutions.

Long-term research agenda

Recommendation 10: conduct long-term safety studies in diverse populations.

Post-approval studies play an important role in ensuring the long-term safety of pharmaceuticals, and the same principle applies to far-UVC. As with pharmaceuticals, it would be an excessive application of the precautionary principle to require long-term studies of hypothetical side effects before implementing an efficacious innovation that saves lives. However, that does not mean that such studies are unnecessary.

Long-term safety studies for chronic far-UVC exposure will ideally have longer duration and follow-up than a CRT designed to prove effectiveness. The challenges of powering a CRT to detect reductions in infections limits the types of facilities (and therefore people) that can be feasibly studied. To obtain data in diverse populations that may have different sensitivities to far-UVC exposure, long-term safety will likely need to be studied in settings that may not be suitable for studying effectiveness.

Therefore, researchers should:

10.1 Identify practical study designs for assessing the long-term effects of chronic exposure to far-UVC.

10.2 Commence these studies as soon as is practical. This requires a combination of long-term commitment on the part of the participating buildings and occupants in order to justify the set up of the study, as well as knowledge of the relevant biological endpoints that should be included in such a study (see Recommendation 2).

Recommendation 11: study the effects of far-UVC on materials ubiquitous in the built environment.

Far-UVC will interact in some way with materials commonly found in the built environment, and there is a need to prioritize what materials to study. This prioritization exercise should account for both potential mechanisms and the importance, ubiquity, and intended lifespan of the material.

Substantial changes will be necessary to make buildings healthier. We have re-engineered the built environment many times, from the sanitation revolution, to fire safety, to reducing energy usage. Periodic renovations and retrofits are an opportunity to address multiple problems simultaneously. If far-UVC is found to have undesirable effects on common materials, there are potential mitigation strategies.

Therefore, researchers should:

11. 1 Conduct controlled exposure studies in the lab on common materials, cosmetics, clothing, and plants, not just for aesthetics and performance but also for potential off-gassing of harmful compounds.

11.2 Conduct long-term studies in the real-world environment under realistic exposures to quantify whether any hypothesized effects occur in complex products and environments.

11.3 Study potential mitigation strategies including: using coatings or sealants that are far-UVC resistant, identifying sensitive materials, and producing practical guidance for reducing the exposure of materials that prove to be particularly sensitive.

Recommendation 12: obtain a deeper understanding of the mechanisms by which far-UVC inactivates pathogens.

Understanding the mechanisms of pathogen inactivation will help us predict far-UVC's efficacy against a broad range of threats without testing every pathogen individually.

A wider biosecurity goal is facilitating real-time feedback on the effectiveness of interventions that reduce the concentration of infectious aerosols, as proposed in the ARPA-H BREATHE program. However, it is currently not possible to reliably distinguish between infectious and

inactivated pathogens without performing time-consuming bioassays. If we understood mechanisms of inactivation better, this could potentially provide targets for novel biosensors that would be more practical to widely deploy.

Therefore, researchers should:

12.1 Study how far-UVC inactivates microbes, including the likely possibility that this occurs through multiple mechanisms.

12.2 Identify targets that could be used for novel biosensors that would distinguish between infectious and inactivated pathogens.

Why are we interested in accelerating the development of far-UVC?

Even after a global pandemic that spread largely via aerosols, tools to suppress the spread of airborne disease remain deeply neglected. This neglect is particularly concerning given the exceptional efficiency of airborne transmission in the wrong circumstances. The Omicron variant of SARS-CoV-2 demonstrated how rapidly airborne pathogens can spread, doubling cases approximately every 2-3 days and infecting an estimated 125 million people globally within just 10 weeks of its identification. Measles, the most infectious human pathogen, is also airborne.

Existing solutions are critical but insufficient

Current approaches to controlling airborne disease transmission fall broadly into three categories: medical countermeasures like vaccines and therapeutics, personal protective equipment like masks, and engineering controls like ventilation, filtration, and upper-room UV. Each of these technologies plays a critical role in pandemic prevention and mitigation but has significant limitations and vulnerabilities.

Medical countermeasures

Vaccines and therapeutics are vital, but they take time to develop and distribute. Even with record speed, COVID-19 vaccines were not available for a year, and many countries waited significantly longer. Some people, including the immunocompromised, infants, and the elderly, may not be fully protected even when vaccines are available.

Personal protective equipment

High-quality respiratory protection, like N95s and elastomeric respirators, is essential for individual protection against airborne pathogens when properly worn, and we are working on increasing the amount and quality of personal protective equipment that will be available when the next pandemic strikes. However, masks also face significant challenges, including cost, comfort, communication difficulties, and compliance fatigue, so we cannot rely on them alone for population-wide protection during prolonged outbreaks. Masks also pose particular challenges for specific populations, such as young children and individuals with certain medical conditions or disabilities, and in settings where clear communication is essential.

Engineering controls

We are optimistic about the potential for engineering controls to reduce the burden of endemic disease. Once installed, they protect everyone in the space without requiring individual action or compliance. However, existing solutions face severe limitations.

Ventilation and filtration

Ventilation and filtration are proven methods of reducing indoor airborne pathogen concentrations and we are enthusiastic about them being implemented where practical. But they can fall short in specific situations: many HVAC systems cannot meet current air cleaning standards, especially in crowded, aging, or energy-constrained buildings. Portable air cleaners (PACs) with high-efficiency particulate air (HEPA) filters are effective and offer meaningful protection in many spaces, and we are encouraged by recent innovations like the Corsi-Rosenthal box that potentially offer a cheaper, quieter, and more energy-efficient solution. But in many high-risk indoor public spaces and scenarios, these interventions will likely remain insufficient for comprehensive protection. When operated at the high levels needed for substantial protection, they can generate noise and drafts that can make spaces uncomfortable, causing users to turn them down or off.

These limitations become especially apparent when considering the air cleaning levels needed for highly infectious diseases. ASHRAE Standard 241 (Control of Infectious Aerosols, 2023) recommends clean air delivery rates that can far exceed both CDC guidelines and the ventilation capacities of a typical building's systems. A restaurant, for example, would require an additional 60 CFM / person, of clean airflow beyond standard ventilation systems to achieve the protection levels recommended by ASHRAE 241, comparable to the requirements of a modern operating theatre (see *Guidelines, standards, and regulations* section). Achieving this through ventilation or filtration could create disruptive gusts, noise, and unsustainable energy costs.

Upper-room and in-duct UV

Conventional upper-room 254-nm UVC systems have been deployed for decades in tuberculosis wards and operating theatres, and their use is recommended by CDC/NIOSH and WHO. These systems can achieve ASHRAE 241 standards but their key challenge is scalability: in order to be effective, UV intensity in the upper room must be much higher than safe human exposure limits, requiring expert installation and occupant awareness of the overhead hazard. In-duct UV systems disinfect air through HVAC systems but share the same challenges as ventilation and filtration: high energy use, noise, and limited effectiveness in spaces without ducted systems.

The promise of far-UVC

Far-UVC has a number of traits that make it extremely promising as a highly scalable and effective air cleaning technology. It will not be a panacea, however, and the remaining chapters of this report evaluate its safety and efficacy profile in significantly more detail with a critical eye for key gaps and uncertainties. Far-UVC's promising attributes include the following:

- **Far-UVC can inactivate a wide range of pathogens:** studies have shown strong inactivation against viruses like influenza and coronaviruses, bacteria such as *Staphylococcus aureus* and *Pseudomonas aeruginosa*, and even pathogenic fungi like *Candida auris*, suggesting far-UVC may be useful against both familiar and novel threats (see *Efficacy* section).
- **Far-UVC installations can be made safe by design:** far-UVC is absorbed by proteins in the outermost layers of the skin and eyes, allowing for higher safe exposure limits and safe operation in occupied spaces (see *Skin and eye safety* section).
- **Far-UVC is energy-efficient:** modeling shows that far-UVC can be up to 450 times more efficient than ventilation and 40 percent more efficient than air purifiers in delivering clean, disinfected air (see *Efficacy* section).
- **Far-UVC is silent and practical:** far-UVC runs silently, requires far less space than portable air cleaners or ventilation ductwork, and is relatively simple to install.
- **Far-UVC is showing promise for preventing fomite and short-range transmission as well:** while this report focuses on long-range airborne transmission, far-UVC also inactivates pathogens in the concentrated plumes that drive short-range transmission and those on contaminated surfaces.
- **Far-UVC may help combat antimicrobial resistance:** far-UVC has been shown in laboratory studies to inactivate drug-resistant bacteria on surfaces and in air. It holds promise as a supplemental tool to reduce the burden of antimicrobial-resistant pathogens in high-risk settings.

Deployment of far-UVC could be highly cost-effective

The science of far-UVC, and the availability of commercial far-UVC emitters, has rapidly evolved since the onset of the COVID-19 pandemic. Many uncertainties, highlighted in this Blueprint, remain. However, preliminary analyses suggest far-UVC could prove highly cost-effective on a few different dimensions:

1. One analysis of the costs and benefits of implementing ASHRAE 241 air cleaning targets estimated a 10-to-1 return on investment, even when considering only seasonal illnesses.
2. An analysis of the use of far-UVC in indoor public spaces in Switzerland estimated a benefit cost ratio (BCR) of 30–290x in a normal winter respiratory illness season, and higher in pandemic scenarios.
3. Finally, another analysis of the use of conventional UVC in aircraft cabins found a 1,000 percent annual return on investment and a cost of $10,000 per life saved. This analysis focused only on reducing the transmission of endemic influenza and SARS-CoV-2. Far-UVC could offer similar benefits with fewer safety and operational constraints.

Additional rigorous cost-benefit analyses need to be developed and tailored to different contexts and use cases, and updated as both our scientific understanding of far-UVC and the costs of commercially available devices evolve (see Recommendation 9). But these early results are highly encouraging.

Far-UVC technology is at a critical inflection point

There are clear opportunities to rapidly accelerate the development of far-UVC with attainable levels of funding. The Recommendations of this report have been formulated to direct funding and effort towards the most important priorities. They reflect not only the level of trust that the public would be asked to place in this technology, but our ambition to support deployment at the scale necessary to save millions of lives.

We believe that public and philanthropic funding on the order of $100 million will be needed over the next five years to provide the standard of evidence that public health agencies will expect before considering widespread deployment. This is substantial relative to the current investment in the field but achievable. It is an amount routinely invested in promising biomedical research—not a Human Genome Project, Apollo Program or Operation Warp Speed.

Far-UVC represents one of the highest leverage funding opportunities in airborne disease and pandemic prevention that we are aware of. With strategic, coordinated investment, far-UVC technology could transform how we approach preventing airborne disease in the built environment, potentially averting millions of deaths, billions of infections, and trillions in economic costs before the next major pandemic strikes.

Read the full Blueprint for Far-UVC:
blueprintbiosecurity.org/Blueprint-for-Far-UVC