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B3 Sustainable Solutions for Pandemic and Bushfire Resilience in Healthcare Facilities

Progress Report I

Progress Report I

RACE for Business

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Project partners

Project team

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- Prof Ke Xing
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Plasma Shield Ltd

- Saeid Vossoughi
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Litmas

- Dr. Claire Bird

What is RACE for 2030?

Reliable, Affordable Clean Energy for 2030 (RACE for 2030) is an innovative cooperative research centre for energy and carbon transition. We were funded with $68.5 million of Commonwealth funds and commitments of $280 million of cash and in-kind contributions from our partners. Our aim is to deliver $3.8 billion of cumulative energy productivity benefits and 20 megatons of cumulative carbon emission savings by 2030. racefor2030.com.au

Contents

1 Introduction

This report outlines the current project status together with the research progress made in the RACE for 2030 project "Sustainable Solutions for Pandemic and Bushfire Resilience in Healthcare Facilities". This report is divided into three sections:

1) Section 1: Introduction (i.e. this section), which provides a short background of the project and summarises the current status of the project;
2) Section 2: Project Progress, which provides an update on the research activities, while also presenting preliminary results; and
3) Section 3: Industry Reference Group , which provides an update on stakeholder engagement and the Industry Reference Group, IRG).

Appendices featuring further detail on energy, indoor air quality, IRG members and IRG minutes are provided for further reading.

1.1 Project background

In healthcare facilities across Australia, HVAC systems are required to provide a minimum amount of outdoor air (OA) flow to ensure sufficient indoor air quality (IAQ), with the minimum flow rate depending on local regulations and the type of space being conditioned. In Victoria, patient spaces are usually required to have 6 air changes per hour (ach) of supply air, and 2 ach of outdoor air (i.e. 33% OA fraction), while in specific high-risk rooms (e.g. isolation rooms and pandemic spaces), the HVAC system may be required to operate in with 100% OA. In some healthcare facilities, such as Echuca Regional Hospital (VIC), HVAC systems are designed to operate with 100% OA even for non high-risk areas (i.e. where the minimum required outdoor air fraction is 33%) to provide further improved indoor air quality (IAQ). However, utilising 100% OA increases energy consumption, peak electrical demand and plant sizes. While some of these drawbacks can be offset through the use of heat recovery systems, these add cost and introduce additional pressure drop within the HVAC system, which in turn increases fan energy consumption and size.

The aim of this project is to demonstrate a pathway for HVAC systems to provide similar (or improved) IAQ as 100% OA systems while reducing energy consumption and peak demand through the use of a multi-modal air treatment system (featuring electron beam irradiation). More specifically, the aim of the project is to demonstrate and monitor the performance of a multi-modal air treatment system which has been retrofitted into a HVAC system at Echuca Regional Hospital.

These aims will be met through detailed measurements of energy and thermal performance, together with measurements of a broad range of IAQ metrics, including particle counts, CO_2, volatile organic compounds (VOCs) including formaldehyde, ozone and microbial levels. These measurements will be conducted across multiple seasons, with the thermal and energy measurements conducted continually across a continuous span of 9 months (encompassing summer, winter and one shoulder season). The measurements will be conducted across two separate air handling units (AHUs), each serving two separate zones, namely:

1) Intervention unit (AHU-02), serving the medical ward, with a design flow rate of Q = 6140 L/s. This unit is retrofitted with the Plasma Shield bioHEPA air filtration system (see also Section 2 for retrofit details)
2) Reference unit (AHU-03), serving the surgical ward, with a design flow rate of Q = 4255 L/s. This unit will remain unchanged during the duration of the project.

Both units operate similarly, i.e., they both utilise a dual-zone (North and South) variable air volume (VAV) system serviced by central chilled/heated water systems. Both also utilise heat recovery units, and are designed to nominally operate under full outdoor air mode, 24 hours per day, 7 days per week. A schematic of the

intervention air handling unit (AHU-02) is shown in Appendix A, while a full list of measurements is shown in Appendix B and C.

One of the key questions of this research project is the following: What is the difference in energy consumption and IAQ under two different scenarios:

- Scenario A: Full (100%) outdoor air with heat recovery
- Scenario B: Minimum 2 air changes per hour (ach) outdoor air (equivalent to 33% outdoor air fraction) as per relevant regulations, with bioHEPA air treatment system and no heat recovery

A comparison of these scenarios based on preliminary results is discussed in Section 2.

1.2 Project Timeline & Key Dates

- Project duration: 7 July 2025 to 4 September 2026
- Progress Report I:
    - Draft due to IRG: 30 Jan 2026 | Final version to RACE: 17 Feb 2026
- Final Report
    - Draft due to IRG: 10 July 2026 | Final version due to RACE: 4 September 2026

1.3 Project status

Overall, the project is running smoothly, with the only major departure from original research proposal being the timeline, with the start of the measurement period being delayed, as summarised in Table 1 below.

Table 1. Summary of project status.

	Status	Comment
Timelines	🟡	Due to protracted procurement timelines (particularly for sensors) and challenges associated with securing tradespeople on site (noting that Echuca is in regional Victoria), there has been a delay of approximately 3 months to the start of the measurement period. As such, the project will not be able to achieve a continuous 12 months of measurements as part of this project. However, the project team will still be able to achieve the aims of the project as there will be continuous measurements across the three key seasons: summer, winter and shoulder.
Budget	🟡	The project team had to resort to utilising some of the contingency budget, due to escalating prices of sensors and of the retrofit works. However, there is some contingency remaining in the budget, and considering that most of the financially risky activities (i.e. purchasing of sensors and retrofit works) have now been completed, the budget outlook looks good.
Milestones & Deliverables	🟡	The project team is on track at completing all the project deliverables, although there has been a delay in completing Progress Report I (i.e. this report, which was originally due in December), due to the holiday season.
Technical	🟢	The project team have completed sensor installation, BMS updates and all retrofit works.
Personnel	🟡	The project team have been working well together, with regular meetings (at least weekly) held between members. All project team members are committed to the project. The main risk stems from the fact that the research associate (RA) working on the project (who bears the bulk of the research work) is currently only partially funded through the project, and therefore may depart the project if a more secure position arises. The lead CI is currently attempting to secure further funding (outside the present project) for the RA to enable him to transition to full-time employment.
Knowledge Sharing	🟢	The project team have a clear knowledge sharing plan, with a range of knowledge sharing activities planned for the remaining duration of the project (see also Section 3).

2 Project Progress

2.1 Update on research activities

The project involves a range of measurements (for both the intervention and reference AHUs), which can be divided into two categories:

1) Continuous measurements, typically comprising of thermal and energy measurements (e.g. fan energy, air temperature, air flow rate, chilled/heated water temperatures and flow rates), particle counts down to 0.3 micron, and CO_2 levels.
    a. All sensors required for these continuous measurements have been procured, installed and commissioned, and were fully online (and producing data) as of 27th October 2025;
    b. These are measured continuously every 5 minutes and are logged by the building management system (BMS). These measurements will be recorded throughout the duration of the project.
2) Spot measurements, comprising of microbiological sampling (both within the AHU and on the AHU coils), together with measurements of VOCs including formaldehyde, ozone and ultra-fine particles (between 20 nanometres and 100 nanometres)
    a. The first phase of these measurements were successfully conducted across multiple days during each of the three different stages (see Table 2 below);
    b. Additional spot measurements will be conducted every 3 months, with the next set of spot measurements planned for March 2026.

A full list of continuous measurements is provided in Appendix B, while a full schedule of spot measurements is listed in Appendix C.

The research activities are divided into two main phases, with phase 1 comprising of three separate stages. A summary of the stages (including their durations) and the completion status is summarised in Table 2 below.

Table 2. Summary of project phases. Note that the reference AHU (i.e. AHU-03) remain unchanged throughout the project. Continuous and spot measurements were conducted both in AHU-02 (intervention unit) and AHU-03.

		Date	Description	Continuous Measurements	Spot Measurements
Pre-phase		27/10/2025	All required sensors for both AHUs have been installed, commissioned and tested.	-	-
Phase 1	Stage I	28/10/2025 to 4/11/2025	AHU-02 set at 100% OA. HRU and existing porous media filters remained in place.	Complete	Complete
	Stage II	8/11/2025 to 25/11/2025	AHU-02 remained at 100% OA. HRU removed from AHU-02. Existing supply air porous media filter remained.	Complete	Complete
	Stage III	28/11/2025 to 12/12/2025	AHU-02 changed to 2 ach of OA. BioHEPA system integrated into AHU-02, and porous media filters removed.	Complete	Complete
Phase 2	-	13/12/2025 – 4/9/2026 (project completion)	Similar to Phase 1: Stage III.	Ongoing	Every 3 months

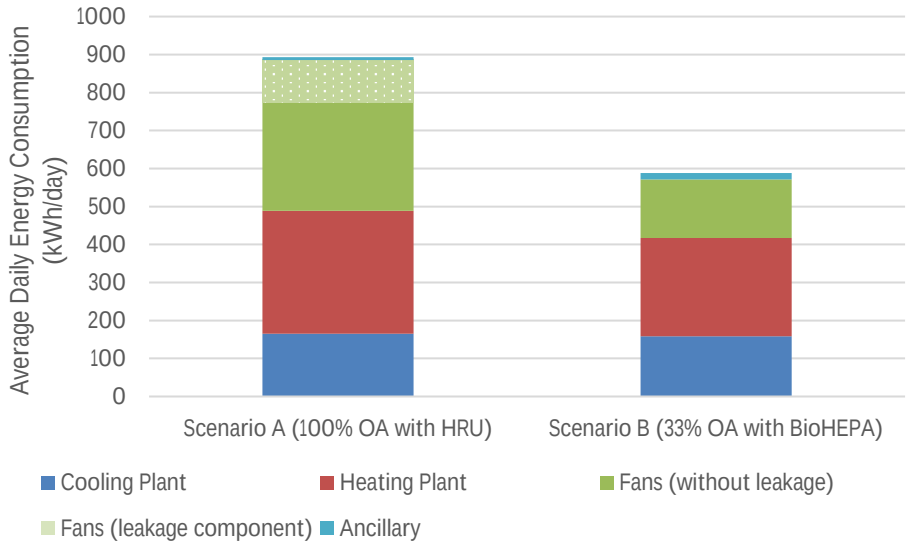
2.2 Preliminary findings

In this section, we provide a brief summary of the preliminary findings, noting that these findings are based on a limited range of measurements (and analysis) conducted thus far. These findings may change once data is collected over a longer period of time.

2.2.1 Final energy assessment

Firstly, we compare the average total energy consumption of AHU-02 (intervention AHU) under the two scenarios of interest in the present study, i.e. Scenario A (100% OA with heat recovery unit and porous media filters installed) and Scenario B (33 % OA without heat recovery, but with bioHEPA air treatment system installed) – see also Appendix D. The results are summarised in Figure 1 below. Full results, together with assumptions used in the calculation of energy consumption are shown in Appendix F.

Figure 1. Estimated average daily energy consumption of AHU-02 (intervention AHU) under Scenario A (100% OA with HRU) and Scenario B (33% OA with Plasma Shield bioHEPA system).



The results show that under Scenario B, the heating and cooling plant consume slightly less energy than in Scenario A. This is expected, because the average thermal efficiency of the HRU is estimated to be ≈ 57% (see Appendix D), which is less than 67% (the latter being the heating/cooling energy saved due to recycling 67% of the return air back into the supply air stream). In systems where a more efficient HRU is used, it is conceivable that the heating/cooling plant energy would be higher in Scenario B than in Scenario A.

Nevertheless, in Scenario A, the single largest consumer of energy are the fans, consuming approximately 397 kWh of energy per day, of which 111 kWh (or 28% of the fan's energy consumption) is due to leakage. The degree of leakage here is higher than first anticipated, given anecdotal evidence suggesting typical leakage rates of about 10%. The results here therefore suggests that there may be an opportunity for energy efficiency gains by reducing the levels of leakage, however, it should be noted that a reduction of the leakage rate to zero is unrealistic in the present wheel-type heat recovery units, and that a materially significant fraction of leakage should be expected in these systems. Nevertheless, the leakage rates found here may not necessarily be representative of other AHUs employing HRUs.

In any case, in the present system, the fan energy is significantly reduced in Scenario B, due to the removal of the pressure drop associated with the heat recovery unit and the supply/return porous media filters, together with the removal of the source of leakage. As a result, and noting that the energy consumption of other

components within the AHU (e.g. the heat recovery wheel motor, and bioHEPA units themselves) are small, the total energy consumption of Scenario B is 34% lower than in Scenario A, of which 22% is due to the reduction in pressure drop and 12% is due to leakage through the heat recovery unit.

2.2.2 Indoor Air Quality (IAQ)

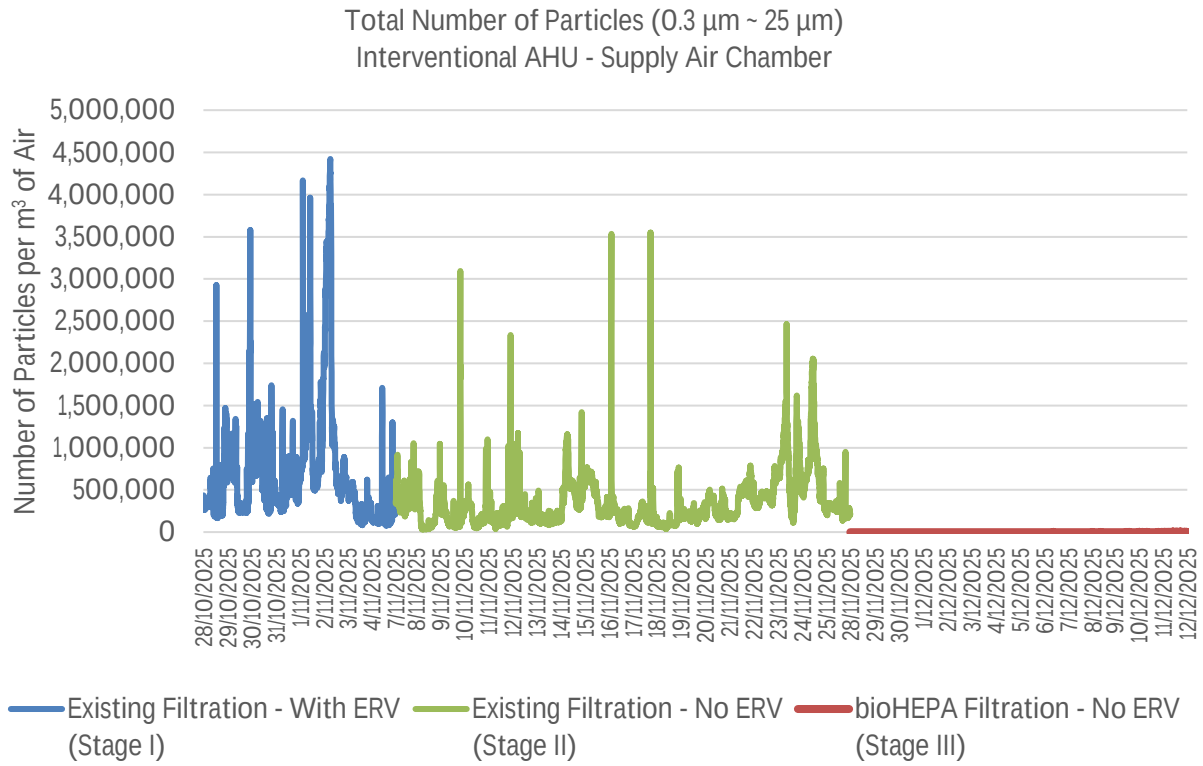
Next, we compare the difference in IAQ between the different stages. As the measurements and subsequent analysis of the IAQ data is extensive, comprising of measurements of particle count, ultra-fine particles, VOCs, and fungi, only a brief snapshot of the results are shown here. For readers who would like more information, the authors have attached two appendices to this report so readers can choose their preferred depth:

- Appendix G, *recommended reading* comprising a two-page narrative summary of all indoor air conclusions; and
- Appendix H, optional reading of the 29-page report, more fully detailing the breadth of the study and data.

Perhaps the two most pertinent conclusions are demonstrated by Figure 2 and Figure 3 below.

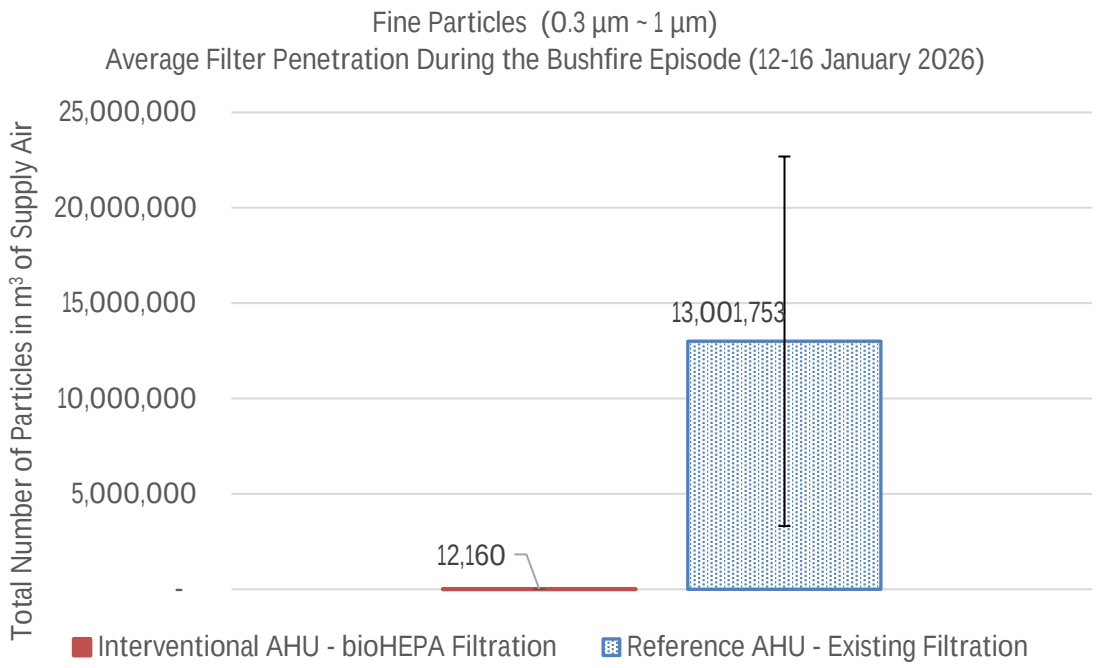
Figure 2 shows the total number of particles measured in the supply air stream of AHU-02 (the intervention AHU) across the three different stages. As can be seen, in Stage I and II, the particle counts are significant, on the order of millions of total particles (per cubic meter of air), notwithstanding some hour-to-hour variation, as can be expected. Importantly, in Stage III, the particle counts reduce significantly, providing evidence of the efficacy of the bioHEPA filtration system.

Figure 2. Concentration of fine and coarse particles downstream of the interventional AHU filter across all stages.



The results in Figure 3 show the average number of particles in the supply air during a bushfire event that occurred between the 12-16 January, 2026. The results show that during the bushfire event, the number of particles in the supply air of the reference AHU (without the bioHEPA filtration) exceeded 13 million particles per m^3, while during the same period the number of particles in the supply air of the intervention AHU was only approximately 12 thousand, indicating a 1,000 fold decrease in the number of particles.

Figure 3. Supply air submicron particle number concentration during the bushfire episode (12–16 January 2026).



2.3 Project challenges, and actions taken to address challenges

The project team encountered a number of challenges during the project, some of which were difficult to completely resolve. The main challenges encountered, and the actions the team tried to take to address these challenges are summarised in Table 3 below.

Table 3. Summary of key challenges encountered during the project, and actions undertaken to address these challenges.

	Description of Challenge Encountered	Action Taken
Procurement of sensors	This project involved the procurement of 25 separate sensors, comprising of measurements of temperature and flow rates (for both water and air), particle count (down to 0.3 µm), relative humidity and electrical energy. These sensors were selected based their accuracy and on their ability to readily integrate into the existing BMS. This narrowed down the range of suitable sensors and vendors. As a result, in many instances procurement timelines exceed what was originally planned.	The project team had in fact begun selecting sensors and obtaining quotes prior to the official start of the project. However, despite this, the project team experienced long delays in sensor delivery times. Our recommendation for future projects is to factor in an extended procurement phase.

Integration of sensors	The project team also encountered difficulties in incorporating the particle counters with the BMS, with the different native communication protocols between the particle counter and the BMS resulting either in no data recorded, or worse, incorrect data being recorded. The project team required additional support from the BMS contractor to resolve this issue.	The project team did not foresee this issue, as all prior communications with the sensor provider indicated that it would be straightforward to integrate the particle counters into the existing BMS. The project team had to engage a BMS contractor, who assisted the building manager resolve this issue.
Availability of sub-contractors	The project team also found it challenging to engage suitable sub-contractors and tradespeople reliably within short timeframes, due to Echuca being in regional VIC.	The project team initially tried to address this issue by booking in tradespeople weeks beforehand. However, delays due to challenges listed above meant that the team could not work to a fixed timeline, which in turn exposed the project to variable availability of tradespeople.
Reliability of existing sensors	Some sensors were producing results that were unlikely or implausible (these sensors are listed in Appendix B).	The team are currently in the process of analysing the data from these sensors, and are corroborating the results to spot measurements conducted on site.

In many instances, these challenges could not be addressed in parallel, which resulted in further delays. For example, the difficulty in integrating the sensors were only encountered after the prolonged procurement period, and was only resolved once a suitable BMS contractor was available to be on site.

Due to these compounding factors, the start to the measurement phase of the project was delayed by two and a half months, which has shortened the total monitoring period from the initial 12 months to 9 months.

3 Industry Reference Group

The Industry Reference Group for this project is a collection of outstandingly well qualified individuals.

Across the IRG, project members and researchers, we have:

- 7 members with a PhD
- 4 Associate Professors or above
- 9 Engineering Professionals
- 6 members with hospital expertise
- 2 from relevant industry associations
- 2 from sustainability backgrounds
- 2 health economists
- 1 Surgeon
- 5 members who are involved in writing or administering engineering standards across Australia.

The full membership list and biographies can be found in Appendix D.

3.1 Initial IRG

IRG #1 was completed on 23 September 2025. The project summary, desired outcomes and test plan were reviewed. Member feedback included:

- Clear sector appetite for credible, real-world evidence on Equivalent Clean Air
- Strong alignment with current pressures on hospital energy use and resilience
- Strongly supportive, described it as a well-designed study
- Encouraged external data sources on bushfire smoke from EPA or similar
- Consider additional data sources from de-identified hospital stays and infections
- Value of independent academic leadership in maintaining credibility
- Need for careful, standards-aware communication of results

3.2 Future IRG Meetings

IRG meetings are conducted for 90 minutes each, spaced evenly throughout the project.

IRG #2 was conducted on 5 February 2026 where the findings of this report was disseminated for discussion.

IRG #3 is planned for August and will review a draft final report.

IRG #4 is planned for September to discuss knowledge sharing and industry communication.

Knowledge Sharing is current planned via:

- IHEA National Conference – March 2026
- AIRAH Innovation Conference – March 2026
- ARBS – May 2026
- AIRAH Reshaping Existing Buildings – June 2026
- Singapore Indoor Air – June 2026
- AIRAH IAQ – September 2026
- AIRAH Technical Paper – undated
- Publication to peer-reviewed Journal "Buildings and the Environment" – submission targeted September 2026

APPENDICES

A. Schematic of Monitored Air Handling Units (AHUs)

Figure 4. Schematic diagram of the intervention AHU (AHU-02). Continuous measurements are indicated in blue text.

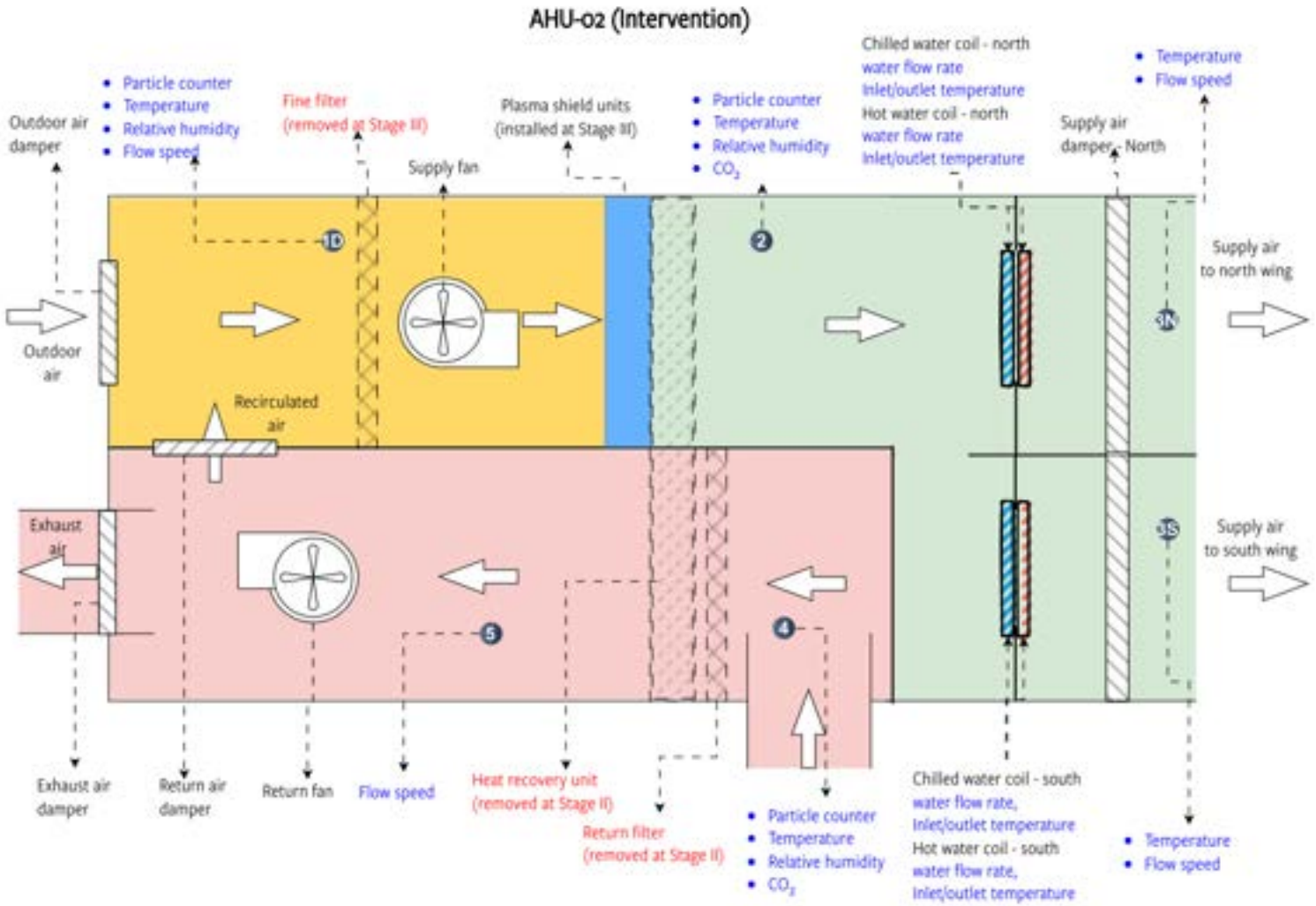
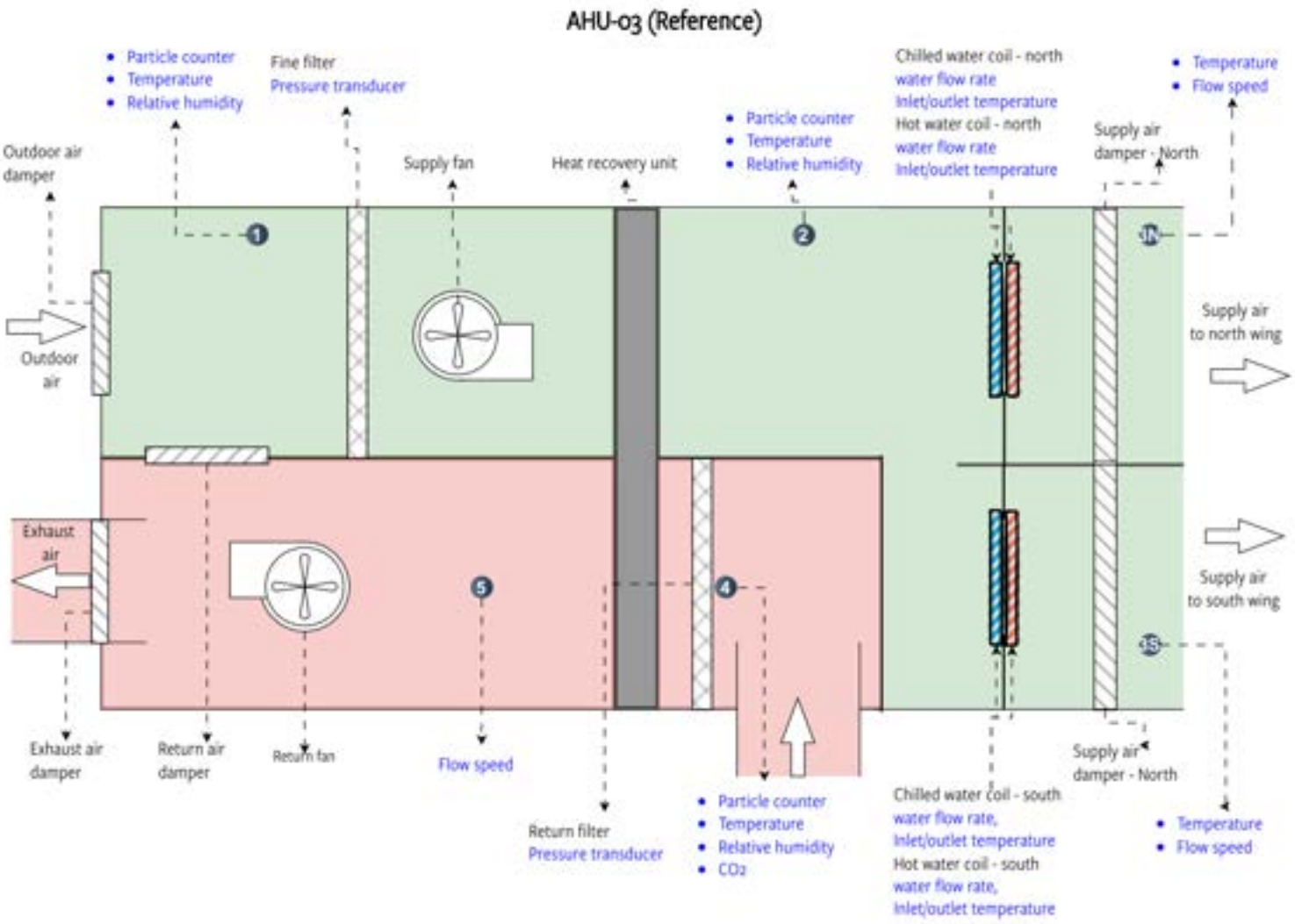


Figure 5. Schematic diagram of the reference AHU (AHU-03). Continuous measurements are indicated in blue text.



B. List of Continuous Measurements

Table 4. List of continuous measurements (recorded by the building management system) for both the intervention AHU (AHU-02) and the reference AHU (AHU-03). Ticks (✓) indicate that sensors are producing valid data, while crosses (×) indicate that sensors are producing results which require further investigation. Dashes (-) denote that no continuous measurements are being conducted. *Note that particle counts are measured across 6 different particle size ranges, i.e. 0.3-1 **µ**m, 1-3 **µ**m, 3-5 **µ**m, 5-10 **µ**m, 10-25 **µ**m and >25 **µ**m.

Measurements	Units	AHU-02 (Intervention)	AHU-03 (Reference)
Temperature of mixed air	°C	☑	☑
Temperature of supply air upstream of coils	°C	☑	☑
Temperature of supply air downstream of coils (N)	°C	☑	☒
Temperature of supply air downstream of coils (S)	°C	☑	☒
Temperature of return air	°C	☑	☑
Relative humidity of mixed air	%	☑	☑
Relative humidity of supply air upstream of coils	%	☑	☑
Relative humidity of return air	%	☑	☑
Flow speed of mixed air	m/s	☑	-
Flow speed of supply air (N)	m/s	☑	☑
Flow speed of supply air (S)	m/s	☑	☑
Flow speed of return air	m/s	☑	☑
CO_2 concentration in mixed air	ppm	☑	-
CO_2 concentration in return air	ppm	☑	☑
Power of supply fan	W	☑	☑
Power of return fan	W	☑	☑
RPM of supply fan	rpm	☑	☑
RPM of return fan	rpm	☑	☑
Pressure difference across supply fan	Pa	☑	-
Pressure difference across return fan	Pa	☑	-
Pressure difference across supply filter	Pa	☑	☑
Pressure difference across return filter	Pa	☑	☑
Chilled water flow rate (N)	L/s	☑	☒
Chilled water inlet temperature (N)	°C	☑	☑
Chilled water outlet temperature (N)	°C	☑	☑
Heated water flow rate (N)	L/s	☑	☑
Heated water inlet temperature (N)	°C	☑	☑
Heated water outlet temperature (N)	°C	☑	☑
Chilled water flow rate (S)	L/s	☑	☑
Chilled water inlet temperature (S)	°C	☑	☑
Chilled water outlet temperature (S)	°C	☑	☑
Heated water flow rate (S)	L/s	☑	☑
Heated water inlet temperature (S)	°C	☑	☑
Heated water outlet temperature (S)	°C	☑	☑
Particle count* of mixed air	counts	☑	☑
Particle count* of supply air	counts	☑	☑
Particle count* of return air	counts	☑	☑
		Outside of building	
Ambient temperature	°C	☑	
Ambient relative humidity	%	☑	

C. List of Spot Measurements

Table 5. List of spot measurements conducted in Stage I, II and III. Ticks (✓) indicate successfully completed measurements, while crosses (×) denote that the measurements were performed, but yielded no usable data.

Measurements	Duration	Stage I	Stage II	Stage III
AHU-02 (intervention): Mixing chamber				
Microbial load (bacteria)	4 hours for 3 days	☒	☒	☒
Microbial load (mould)	4 hours for 3 days	☑	☑	☑
Ultra-fine particle counter	72 hours	☑	☒	☑
AHU-02 (intervention): Supply chamber				
Microbial load (bacteria)	4 hours for 3 days	☒	☒	☒
Microbial load (mould)	4 hours for 3 days	☑	☑	☑
Ultra-fine particle counter	72 hours	☑	☒	☑
Ozone	72 hours	☑	☑	☑
VOCs	7 hours for 3 days	☑	☑	☑
Formaldehyde	7 hours for 3 days	☑	☑	☑
AHU-02 (intervention): Return chamber				
Microbial load (bacteria)	4 hours for 3 days	☒	☒	☒
Microbial load (mould)	4 hours for 3 days	☑	☑	☑
VOCs	7 hours for 3 days	☑	☑	☑
Formaldehyde	7 hours for 3 days	☑	☑	☑
AHU-02 (intervention): Cooling coils				
Microbial load (surface)	Once	-	-	☑
North wing room (serviced by AHU-02)				
Particle counter	72 hours	☑	☒	☑
Agar plate (Bacteria + Mould)	3 hours for 3 days	☑	☑	☑
South wing room (serviced by AHU-02)				
Particle counter	72 hours	☑	☑	☑
Agar plate (Bacteria + Mould)	3 hours for 3 days	☑	☑	☑
AHU-03 (reference): Mixing chamber				
Microbial load (bacteria)	4 hours for 1 days	-	☑	☑
Microbial load (mould)	4 hours for 1 days	-	☑	☑
AHU-03 (reference): Supply chamber				
Microbial load (bacteria)	4 hours for 1 days	-	☑	☑
Microbial load (mould)	4 hours for 1 days	-	☑	☑
AHU-03 (reference): Return chamber				
Microbial load (bacteria)	4 hours for 1 days	-	☑	☑
Microbial load (mould)	4 hours for 1 days	-	☑	☑

D. List of IRG Members

Table 6: List of Industry Reference Group (IRG) members

Name	Organisation	Role	Domain Expertise	Description
John Mihalinac	VIDA Health	Senior Technical Specialist	Hospital Design and Operations	Exec Sponsor, engineering background coming up to 10 years with VHBA
Michael Hamilton / Ben Fogerty	Aus Mechanical Contractors Assoc.	Executive Manager - Partnerships	Link to Contractors	Exec Manager of Technical Services, former Westfield
Mark Vender	AIRAH	Advocacy & Policy Manager	Link to Mechanical Consultants	Advocacy & Policy, comms background, rely heavily for our knowledge sharing
Plum Stone / Amy Lewis	Safer Air Project	CEO & Founder	Patient Advocate and IAQ Advocate	Amy & Plum are the co-founders for the Safer Air Project, design background
Professor Christina Candido	University of Melbourne	Professor Environmental & Sustainable Design	IEQ & Sustainable Design	Director of the SHE lab, Architecture, Civil Engineer and a PhD in environmental science
Assoc. Prof. Stephane Bouchoucha	Australian College of Infection Control Professionals	President | Associate Head of School, Deakin University	Infection Control	Associate Professor and Associate Head of School, Deakin University, also the president of the Australian College of Infection Prevention and Control
Loukas Tsigaras	University of Melbourne	Research Engineer	BioMedical & Mechanical Engineering	Bio-Medical Engineer and currently running the implementation of the Burnett Institute Pathway to Clean Air. He's also a Tottenham supporter.
Patrick Chambers	Stantec Engineering | AIRAH STG	Director. Member of AIRAH Operating Theatre STG	Mechanical & Hospital Engineering & IAQ	Pat sits on the AIRAH Operating Theatre STG, He's the Director for Stantec and is their discipline leader for Building Engineering. Pat was also the supervising engineer for a recent Queensland Health project that concentrated on air-decontamination.
Matt Sykes	VIDA Health	Manager. Environmental Sustainability	Engineering & Sustainability	Matt is the Manager for Environmental Sustainability for the VHBA and comes with an architectural engineering background.
Tosh Szatow	RACE 2030	Business Innovation & Policy Lead	Economics and Sustainable Engineering	Tosh is the RACE for 2030 Business theme lead, and has a background in consumer advocacy in the energy sector.
Melissa Muller	RACE 2030	SA Node Manager	Low Carbon Policy & Research Funding	Mel is the SA Node Manager for RACE 2030 and comes from a low carbon policy background with the SA Govt.
Dr. Abe Chandra	Calvary, Wakefield and Ashford Hospitals	Consultant Surgeon, Professor with Uni SA	Vascular Surgery, Clinical Research	Abe is a Consultant Surgeon, specialising in vascular surgery. He's also an Adjunct Professor with UniSA and a founder of a company that creates mobile operating theatres.

Dr Rhonda Kerr	Guidelines & Economists International (Health Services)	Executive Director, Economics & Health Planning	Health Planning, Health Economics	Rhonda has worked on 42 hospital projects, translating guidelines into the capital required for effective clinical spaces. Dr Kerr is also networked into the Australasian College of Health Services Management and Australian Council on Health Care Standards.
Ron Pulido	NABERS	Sector Lead	Rating Schemes, Australian Std Development	Ron is the sector lead for NABERS IEQ and is a leading voice amongst those pushing for a NABERS Indoor Air rating.
Matilde Martin	NABERS	Senior Project Officer - Hospitals	Rating Schemes, Sustainable Finance	Matilde has held diverse roles in design and sustainability. She is now acting lead for the Hospital sector for NABERS.
Dr. Chris McGowan	Formerly SA Health, now Non-Exec Director of Plasma Shield	Former Chief Executive of SA Health	Health Planning, Health Economics	Chris is a health economist by trade and led SA Health throughout the pandemic. He sits on the Plasma Shield board as a valued advisor.

E. Scenario Modelling (Energy)

One of the key aims of this report is to compare the energy consumption and peak demand of an air handling unit operating under two different scenarios, i.e.,

- Scenario A: AHU operating with 100% outdoor air and with heat recovery. The AHU also contains conventional porous media filters on both the supply air stream and the return air stream. This scenario represents the current operating paradigm for most of the AHUs at Echuca Regional Hospital, and for AHUs serving specific high risk zones in healthcare facilities more broadly across Australia;
- Scenario B: AHU operating with 2 air changes per hour (ach) of outdoor air and 4 ach of recycled air (i.e. 33% outdoor air), with Plasma Shield bioHEPA air treatment system unit installed and no heat recovery. In this scenario, the AHU does not use porous media filters (other than the ones installed within the bioHEPA units).

In both scenarios, the nominal minimum supply air flow rate is 6 ach (in accordance with relevant standards). Additionally, the AHUs in both scenarios operate 24 hours a day, 7 days a week.

It should be noted that neither Scenario A nor Scenario B represent the most common HVAC operating paradigm in healthcare facilities in Australia. The most common operating mode in healthcare buildings is to operate with the minimum allowable outside air flow rate (typically 33%, but may vary depending on local regulations and depending on the space that is being conditioned), without heat recovery and without the use of the bioHEPA air treatment system. This scenario has currently not been modelled, but will be included in future reporting.

In any case, as summarised in Table 2, the project includes measurements of Scenario A (conducted in Stage I) and Scenario B (conducted in Stage III). However, a like-for-like comparison of energy between Stage I and II could not be performed because the ambient conditions, building occupancy and internal heat gains/losses within the conditioned space were not the same between the stages.

To allow the two scenarios to be compared on an equitable basis, a simple thermal model was developed of the monitored AHUs, which was then used to estimate the energy consumption of the AHUs under the two different scenarios given a pre-determined set of ambient conditions and internal heat load.

The modelling of the different scenarios is outlined in more detail below.

Estimation of internal (non-outside air) load

To obtain an estimate of how the internal (non-outside air) load within the space, L_{int}, varies with conditions and time, we first assume that this load is most influenced by the ambient dry-bulb temperature, T_{amb}.

Then, we calculate the actual internal load in the space from measurements of supply air flow rate, Q_{sa}, supply air temperature, T_{sa}, and return air temperature, T_{ra}, using

$$L_{int} = \rho Q_{sa} C_p \left(T_{ra} - T_{sa}\right) \quad (1)$$

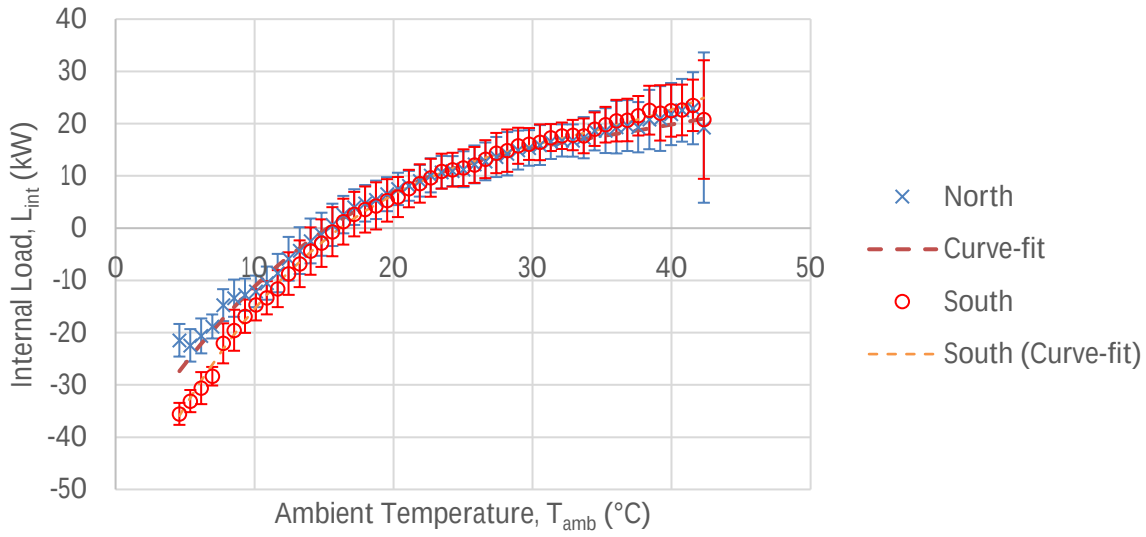
where ρ and C_p is the density and specific heat capacity of air, respectively.

We then plot the relationship between L_{int} and T_{amb}, which is shown in Figure 6 (with separate loads shown for the north and south zones). As can be seen, the internal (non-outside air) loads are strongly influenced by the ambient temperature. Therefore, we can now curve fit the data using a 3rd order polynomial of the form,

$$L_{int} = a_1 T_{amb}^3 + a_2 T_{amb}^2 + a_3 T_{amb} + a_4 \quad (2)$$

where a_1 = 0.001039, a_2 = -0.1121, a_3 = 4.456 and a_4 = -45.57 for the north zone, and a_1 = 0.001622, a_2 = -0.1593, a_3 = 5.831 and a_4 = -59.47 for the south zone. Here T_{amb} is in Celcius.

Figure 6. Correlation between the measured internal (i.e. non-outside air) load and the ambient temperature for AHU-02 (intervention unit). Note that positive values of L_{int} indicate that the space is gaining heat, while negative values of L_{int} indicate that the space is losing heat.

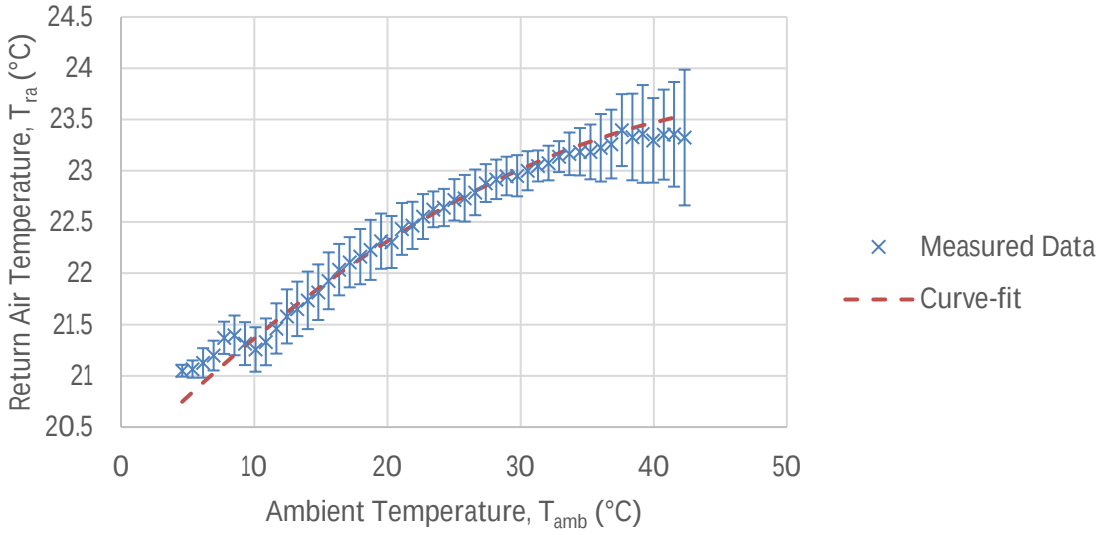


Estimation of return air temperature

The monitored AHUs in the present project have a complex control protocol, whereby the supply air flow rate to each room is modulated via individual VAV units so that the room temperatures meet the setpoint temperature. Each room may have a different setpoint temperature, which may change according to the outdoor conditions. Additionally, the supply air temperature is controlled by comparing the temperatures of selected rooms against their setpoints – if multiple rooms are not meeting their setpoints then the supply air temperature either reduces or increases according to demand.

The above control cannot be modelled in any simple way. Therefore, in the present analysis, we use the return air temperature as a proxy for the indoor temperature, and assume that the measured return air temperature is always tracking to within acceptable indoor comfort conditions. That is, we assume that the measured return air temperature represents the indoor setpoint temperature.

Figure 7. Correlation between return air temperature and ambient temperature



To determine how this proxy setpoint temperature varies with ambient conditions, we plot the return air temperature against the ambient dry-bulb temperature, as shown in Figure 7. As can be seen, the return air temperature is also strongly correlated to ambient conditions, with the return air temperature increasing slightly as the ambient conditions become hot, as expected. Additionally, the measured return air temperatures are within the range 20.5 °C < T_{ra} < 24 °C, which is within the range typically associated with comfortable indoor conditions.

In any case, the data can be fitted with a 2nd order polynomial of the form

$$T_{ra} = b_1 T_{amb}^2 + b_2 T_{amb} + b_3 \tag{3}$$

where b_1 = -0.001233, b_2 = 0.1319 and b_3 = 20.17. Here both T_{ra} and T_{amb} are in Celcius.

Model of heat recovery unit

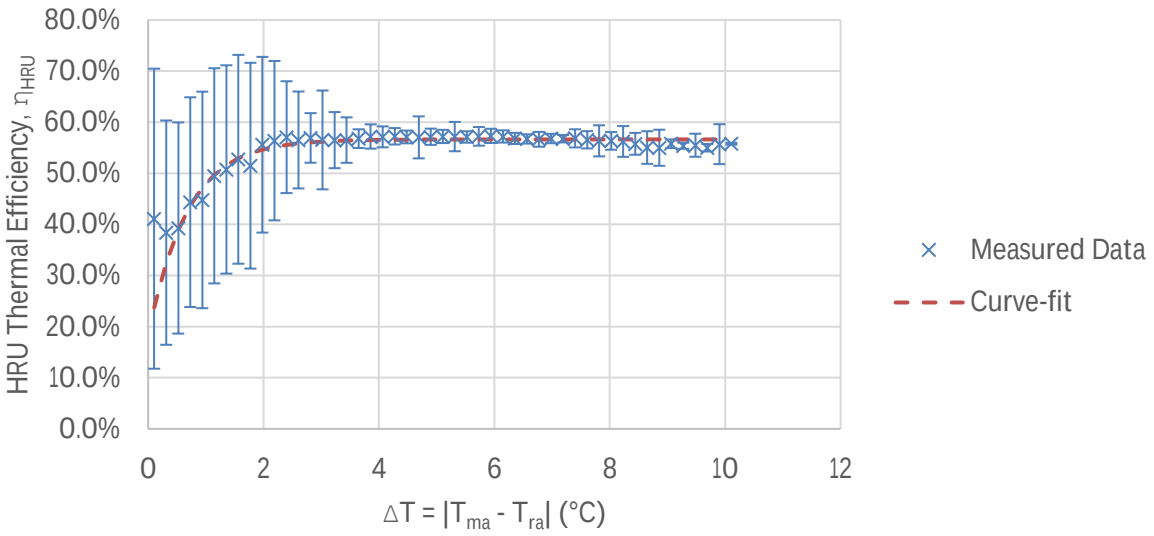
In the present analysis, the thermal efficiency of the heat recovery unit (HRU) is defined as

$$\eta_{HRU} = \frac{Q_{sa}\left(T_{on,coil} - T_{ma}\right)}{Q_{ra}\left(T_{ra} - T_{ma}\right)} \tag{4}$$

where Q_{ra} is the return air flow rate, $T_{on,coil}$ is the temperature of the air approaching the cooling/heating coils, and T_{ma} is the mixed air temperature. Here it should be noted that the above definition does not take into account the latent heat transfer between the return and supply air streams. This is because the present measurements do not provide sufficient data to calculate the latent heat transfer. Nevertheless, the latent heat transfer is expected to be small given that both the ambient air and the return air have typically low humidities.

It is well-established that the thermal efficiency of heat recovery units are dependent upon the temperature difference across the unit. To determine what this relationship is, we plot the measured HRU thermal efficiency against the difference in temperature between the mixed air (which is the flow entering the HRU on the supply side) and the return air (which is the flow entering the HRU on the return side). The results are shown in Figure 8.

Figure 8. The influence of temperature difference across the HRU on its thermal efficiency



The results show that the thermal efficiency increases as ΔT increases, as expected. However, this increase in thermal efficiency asymptotes to a near constant value of 57 % for $\Delta T > 2$°C. That is, as long as the temperature difference across the HRU is above 2 °C, the HRU is shown to perform near its maximum thermal efficiency.

It is also noteworthy that the thermal efficiencies measured here are close to the manufacturer's specified thermal efficiency of 58%, providing further confidence in the measurements.

In any case, the HRU thermal efficiency can be modelled using the following equation

$$\eta_{HRU} = -0.3847 \exp(-1.494 \Delta T) + 0.5663 . \quad (5)$$

Calculation of thermal loads

Based on the results and empirical equations obtained above, the process for determining the cooling/heating thermal loads is as follows:

1) Obtain a time-series of ambient dry-bulb temperature, T_{amb}. Presently, this is based on measurements of ambient conditions at Echuca Regional Hospital between 28th October 2025 and 14th January 2026;
2) Use the ambient temperature to calculate the internal (non-outside air) loads within the conditioned space, L_{int}, as well as the target return air temperature, T_{ra}, using equation (2) and equation (3);
3) Calculate the required supply air temperature using equation (1);
4) Then, calculate the on-coil temperature, $T_{on,coil}$:
    a. For Scenario A:
        i. Since the AHU operates at 100% outdoor air, therefore the mixed air temperature equals to the ambient temperature, $T_{ma} = T_{amb}$;
        ii. Calculate the thermal efficiency of the HRU using equation (5);
        iii. Calculate the on-coil temperature using equation (4).
    b. For Scenario B:
        i. Calculate the mixed air temperature as $T_{ma} = (2T_{amb} + 4T_{ra})/6$, noting that the system operates with 6 ach of supply air and 2 ach of outdoor air;
        ii. Given there is no heat recovery unit, therefore the on-coil temperature equals to the mixed air temperature, $T_{on,coil} = T_{ma}$.

5) Finally, calculate the thermal load on the coils using the supply air flow rate (which is constant at 6 ach) and the difference between the on-coil temperature and the supply air temperature.

It should be noted that the above calculations are highly simplified, and rely on a number of assumptions. Nevertheless, we consider that this simplified analysis is adequate for the purposes of comparing loads (and energy) across different scenarios, given the comparison was done on an equitable basis.

However, the project team will also be improving upon this analysis over the duration of the project. In particular, over the next few months the project team may implement the following:

- Incorporating economy cycle to the scenarios
- Applying a deadband to the return air setpoint temperature
- Calculating two separate HRU thermal efficiencies for heating and cooling modes.

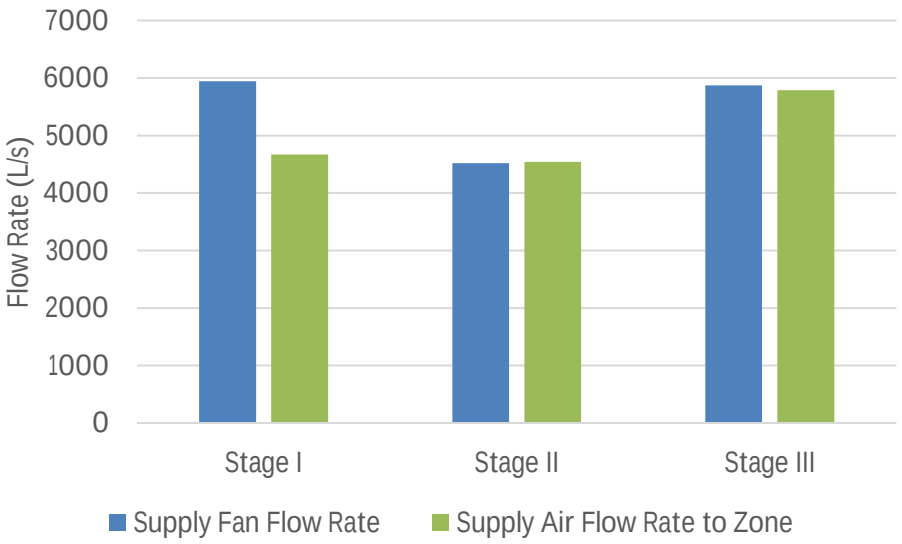
F. Preliminary Results (Energy)

This section presents a selected of key preliminary findings based on the measurements conducted so far for both energy and IAQ. Note that these results are only based on measurements across a limited time, and that the findings here may change once the project team obtain more complete results.

Air flow and leakage

One of the drawbacks of using a heat recover unit, particularly the rotary-wheel HRU used in the monitored AHUs, is that there is potential for leakage of air between the supply and return air streams through the HRU. To estimate the scale of leakage, we first estimate the flow rate through the supply air fan using the measurements of fan power, fan static pressure and speed (i.e. rpm) using the fan curve, and then compare this with the measured supply air flow rate. The results are shown in Figure 9 below (for the intervention AHU only).

Figure 9. Air flow rates through supply air fan and to the conditioned zone for AHU-02 (intervention AHU) for all three stages (see also Table 2).



The results show that in Stage I, where no changes were made to the AHU (i.e. the HRU was operating normally), there is a significant difference between the flow rate though the fan, and the flow rate to the zones, with this difference being approximately 25% of the flow through the fan (i.e. 1,250 L/s). However in Stages II and III, after the HRU was removed (and the opening between the supply and return ducts where the HRU was previously located was sealed), the flow rate through the fan is approximately equal to the measured flow to the zones. These results strongly indicate that in Stage I, there was significant leakage of flow between the supply and return ducts through the HRU. This finding has implications for the energy consumption of both the supply and return air fans.

It should be noted that the leakage rates found here are higher than typical leakage rates of around 8-10% anecdotally reported for wheel-type heat recovery units. This may be due to the age of the heat recovery units, noting that prolonged use can result in misalignment of the heat recovery wheel (as the supply and return air flow pushes against the wheel asymmetrically), and can result in wear-and-tear of the HRU seals. Therefore, the relatively high leakage rates found here may not be representative of the typical leakage rates found in other AHUs using heat recovery units, especially those which do not use rotary-type HRUs. In any case, even in new

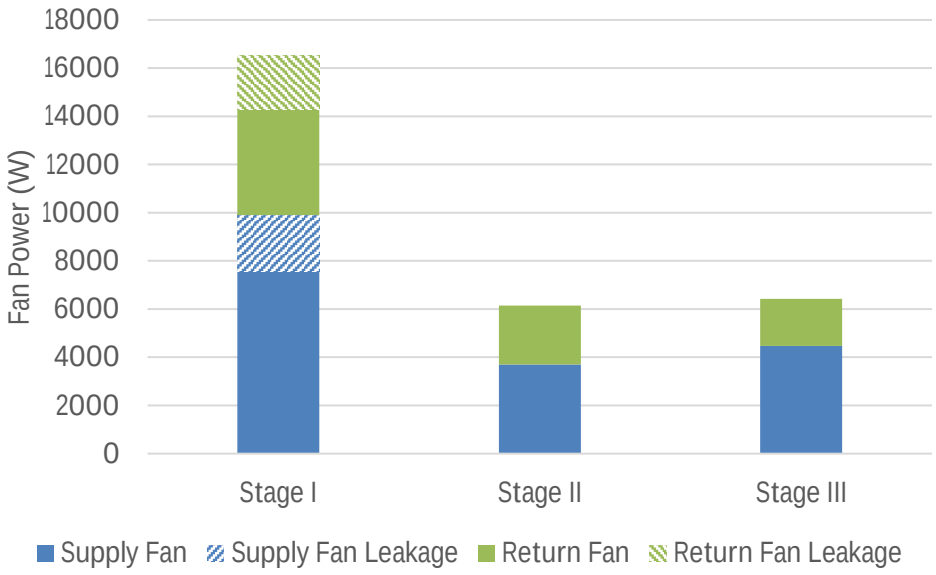
or fully-refurbished systems, or where non-rotary wheel HRUs are used, the leakage rates are unlikely to be zero.

Fan power

A major component of HVAC energy consumption is due to the fans within the air handling units. In the monitored system, the AHU contains two separate fans, one for the supply stream and the other for the return air stream (see also Appendix A). One goal of the current study is to compare the fan energy consumption between the different stages, noting that the HRU, together with the conventional porous media filters on the supply and return air streams are expected to add significantly more pressure drop (and hence use more fan energy) than the Plasma Shield bioHEPA unit.

The results of the fan energy across the three different stages are presented in Figure 10. To allow the fan energy to be compared equitably across the three stages, the fan energy was normalised (using fan affinity laws) such that the energy is based on the supply and return air flow rates measured in Stage III. That is, the values in Figure 10 assume that each fan has the same flow rate as that measured in Stage III.

Figure 10. The change in supply and return fan power across the three stages for AHU-02 (intervention AHU). Note that the fan power was normalised such that the supply and return air fans have the same air flow rate as those measured in Stage III.



The results show that in Stage I, the energy consumption of both the supply and return air fans is significantly higher than the other stages. This is partially due to leakage of air from the supply air stream to the return air stream, as previously discussed, which accounts for approximately 24% of the supply air fan's energy consumption, and 34% of the return air fan's energy consumption. The energy efficiency of the AHUs can therefore be increased by either improving sealing of the heat recovery units, or in the case of new builds, selecting heat recovery units that are less prone to leakage (noting that the wheel-type heat recovery units utilised in the present AHUs are anecdotally known to be prone to leakage, as previously noted). However, as previously discussed, in AHUs employing wheel-type HRUs, the leakage rates are unlikely to be reduced to near-zero, and therefore the fan energy will always be greater than in systems where leakage is not present.

In any case, the results show between Stage I and Stage II, there is a reduction in total fan energy of 63% (combined for both supply and return air fans). This is because in Stage II, the HRU and the porous media filter on the return air was removed, which in turn significantly reduced the pressure drop within the AHU.

Additionally, with the heat recovery units removed, the source of leakage between the supply and return streams was removed, thereby decreasing leakage (and the fan energy associated with the leakage) to zero. Between Stage II and III, the supply fan energy increases, while the return air energy slightly decreases (such that the total fan energy increases slightly). This is because in Stage III, the Plasma Shield bioHEPA system was installed, and at the same time the AHU was re-configured to deliver 33% outdoor air flow rate (as opposed to 100% OA in Stage I and II). This rebalancing changed the relative static pressures between the supply and return air fans, which in turn resulted in the return air fan delivering significantly lower pressure in Stage III than in Stage II (not directly shown here). As a result, in Stage III the return air fan was operating at a point where its efficiency was lower than in was in Stage II. Therefore, the total fan energy in Stage III is approximately 4% higher compared to Stage II, despite the Plasma Shield BioHEPA air treatment system having a lower pressure drop than the supply air filter (see following page).

Nevertheless, comparing Stage I and III, we measure a total reduction in fan energy of approximately 61%, of which 28% is due to leakage, and 33% is due to the reduction in pressure drop.

From the analysis above, we can also estimate the pressure drop of major component within the AHU as follows (based on the flow rates measured in Stage III):

- Supply air filter = 150 Pa
- Return air filter = 107 Pa
- HRU = 360 Pa (each side)
- Plasma Shield bioHEPA air treatment system = 116 Pa

HVAC thermal loads and energy consumption

Based on the scenario modelling described in Appendix D, we can now calculate the thermal loads expected for the intervention AHU (i.e. AHU-02) at Echuca Regional Hospital, based on the ambient conditions measured at the site between 28th October 2025 and 14th January 2026. The results are summarised in Table 7.

Table 7. Summary of thermal loads and peak thermal demand for the intervention AHU (AHU-02) for both Scenario A and Scenario B.

	Scenario A (100% OA with HRU)	Scenario B (33% OA with bioHEPA)
Average daily cooling load (kWh_t/day)	496.9	476.5
Average daily heating load (MJ/day)	1047	837
Peak cooling demand (kW)	108.7	94.9
Peak heating demand (kW)	104.2	92.1

The results show that there is a reduction of 5% to 20% in the thermal loads and peak thermal demand experienced by AHU-02. This is primarily due to the reduction in outside air load, given that in Scenario A the peak efficiency of the heat recovery unit, which is approximately 57%, is insufficient to make up for the fact that in Scenario B, 67% of the return air is recycled back to the return air stream. Additionally, the increased fan power in Scenario A (see Figure 10) also adds heat to the supply air stream, which in turn increases the cooling load. In other words, for the two Scenarios to have similar thermal loads, the average HRU efficiency will need to be in excess of 67%, which is not the case for the present monitored systems.

Next, we use the fan power shown in Figure 10, together with the thermal loads calculated above, to determine the total AHU energy consumption for both Scenario A and B. To convert the thermal loads to energy, we use the following assumptions

- Average chiller plant coefficient of performance (COP) = 3
- Average heating plant efficiency = 90%

It should be noted that the above assumptions are not a true representation of Echuca's plant performance (which is challenging to measure), but rather an indicative value used to allow a reasonable comparison to be made between Scenario A and B. In any case, the results are summarised in Table 8 below.

Table 8. Summary of AHU energy consumption for Scenario A and Scenario B for the intervention AHU (AHU-02).

	Average Daily Energy Consumption (kWh/day)	
	Scenario A (100% OA with HRU)	Scenario B (33% OA with BioHEPA)
Cooling Plant	165.6	158.8
Heating Plant	323.3	258.2
Supply and Return Air Fans (without leakage component)	285.7	154.1
Supply and Return Air Fans (leakage component)	111.2	0.0
Heat Recovery Wheel	7.6	0.0
Plasma Shield BioHEPA System	0.0	17.3
Total	893.5	588.4

As can be seen, there is a significant decrease in energy consumption in Scenario B, mainly due to the decrease in fan energy. These results are discussed in more detail in Section 2.2.1.

G. Summary of Indoor Air Quality (IAQ) Findings

This interventional field trial demonstrated that the quality of indoor air in healthcare ventilation systems is strongly influenced by both ventilation strategy and filtration performance. Across Phase I, reductions in outdoor air intake alone lowered exposure to outdoor-derived particulates and biological aerosols but did not fully address variability or transient contamination events.

Removal of the heat recovery wheel reduced particle carryover and leakage-related variability; however, this system configuration was associated with increased energy demand and is not practical for routine healthcare operation.

Installation of the bioHEPA filtration system resulted in consistently high and stable removal of fine, ultrafine, and biological particles, including mould (fungal) spores and structures, independent of fluctuations in outdoor air quality, environmental conditions, or prolonged bushfire smoke exposure.

Most notably, filtration performance remained stable during extended high-load events, with particle removal efficiencies approaching 99.98% even during multi-day bushfire episodes and total removal of detectable mould structures under light microscopy.

Importantly, the installation of the bioHEPA filter displayed a 92.7% drop in mould settling onto surfaces in the operational ward, reducing its rate of settling from greater than 1,000 colony forming units (CFU) per square metre per hour to 44 CFU/m^2/h significantly reducing potential risk to hospital surfaces, equipment, staff and patients.

Assessment of gas-phase contaminants demonstrated a range of outcomes across pollutant classes. Ambient ozone present in outdoor air was substantially reduced downstream of the interventional AHU following installation of the bioHEPA system, with mean concentrations decreasing from approximately 12–13 ppb to ~1 ppb, corresponding to an ~90–92% reduction.

This reduction is operationally important given the role of ozone as a respiratory irritant and driver of secondary indoor chemistry and aldehyde production, particularly during periods of elevated outdoor ozone.

Formaldehyde and VOC concentrations remained low across all stages and well below relevant guideline values, with no change in VOC profiles observed, indicating stable gas-phase behaviour and no evidence of chemical transformation associated with the intervention.

Conventional mechanical filtration alone showed no meaningful impact on these gas-phase contaminants.

From a resilience perspective, the findings support a pathway for maintaining infection control and environmental protection without reliance on continuous 100% outdoor air operation.

While full outdoor air ventilation is a well-established strategy to reduce airborne infection risk during pandemics, it introduces energy, emissions, and pollutant-ingress penalties.

The results align with the ASHRAE 241 framework, which recognises Equivalent Clean Air (ECAi) as a substitute for outdoor air when achieved through effective air cleaning.

This study showed that operation of the HVAC system using approximately one-third outdoor air and two-thirds equivalent clean air delivered by bioHEPA filtration provided conditions functionally equivalent to full outdoor air.

The strategy simultaneously offers greater control over external pollutants and avoids the energy and emissions penalties typically associated with using 100% outdoor air operation to reduce respiratory infection transmission risk, especially during periods of extreme temperatures.

It further provides tighter control on ambient humidity, avoiding high humidity which generates a greater risk of mould and biofilm development in the HVAC system and low humidity in winter which makes patients more prone to infection.

Reducing external air intake further prevents unwanted ingress of external pollutants during vegetation fire smoke episodes.

Carbon dioxide monitoring confirmed that, due to mandated high ventilation rates and lower occupancy densities in healthcare facilities, CO_2 concentrations remained low under all operating conditions.

Collectively, the Phase I findings indicate that the combined ventilation and bioHEPA filtration strategy improves resilience to environmental pollution events, maintains biological and chemical air quality under real-world operating conditions, and provides a robust foundation for long-term evaluation in Phase II.

Further discussion and full results can be found in the full IAQ report attached in Appendix H.

H. Detailed Indoor Air Quality Report

In the following section we attach the detailed indoor air quality (IAQ) report, which outlines the full details of the analysis of IAQ metrics for the project. The following section was produced as a separate standalone report written with support from Dr Claire Bird (LITMAS), and is attached here verbatim.

RACE 2030 Interim Report - Echuca Regional Hospital

Detailed Indoor Air Quality Report

January 2026

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Contents

Introduction

This interventional field trial was conducted at Echuca Regional Hospital in Victoria to assess sustainable solutions for pandemic and bushfire smoke resilience in healthcare facilities. The study was designed as a two-phase interventional investigation involving one interventional air handling unit (AHU-02) and a comparable reference air handling unit (AHU-03).

Phase I comprised three stages, as outlined below:

- **Stage I:** Existing HVAC filtration system with the heat recovery system in place in two air handling units, AHU-02 and AHU-03. During this stage, both air handling units operated in full outdoor air intake and full exhaust mode, consistent with their original design.
- **Stage II:** The heat recovery system was removed from the interventional AHU (AHU-02), while the HVAC operational configuration for both AHUs remained in full outdoor air/full exhaust mode. No changes were made to the reference AHU, AHU-03.
- **Stage III:** The pre-existing fine filters in the interventional AHU were replaced with the bioHEPA filtration system. The HVAC configuration of this AHU was also modified to operate with a mixture of one-third outdoor air and two-thirds return air, as prescribed by the Victorian Health Building Authority (VHBA) for patient wards in healthcare facilities. No changes were made to the reference AHU.

Phase II consists of a further ten months of monitoring to assess long-term performance of the intervention and to account for weather variability and seasonal effects.

This interim report presents air quality findings from Phase I of the project. It also summarises observations from several bushfire incidents that occurred within a 100 km radius of the test site during the first and second weeks of January 2026. A more comprehensive analysis on bushfire smoke will be provided in later project stages if additional data become available.

During Phase I, a total of approximately 1.8 million data points were collected from the interventional and reference AHUs, and within the Medical Ward which is served by the interventional AHU over a 46-day monitoring period from 28 October 2025 to 12 December 2025. This high-resolution dataset underpins the analyses presented in this report and enables robust comparison across system configurations and operating conditions.

Air Quality Assessment

The inhalable and respirable contaminants and pollutants responsible for deteriorating indoor air quality can be broadly categorised into three main sources:

1. Non-biological airborne particulate matter including aerosols such as dust, asbestos fibres, respirable crystalline silica;
2. Biological airborne particulate matter including pollen, viruses, bacteria, and fungi); and
3. Gas-phase contaminants of human origin (e.g. body odour) and non-human origin including volatile organic compounds (VOCs), ozone, formaldehyde, carbon monoxide and oxides of

nitrogen. Carbon Dioxide (CO_2) measurement was also included as part of this study to assess its relevance as a proxy for ventilation effectiveness in healthcare settings.

Detailed descriptions of the assessment methods used in this study are available upon request and will be included in the final report.

1) Undifferentiated airborne particles

a. Particle Concentration

Figure 1 shows the total particle number concentration (0.3–25 µm) measured in the mixing chamber of the interventional AHU upstream of the filtration system across all three project stages.

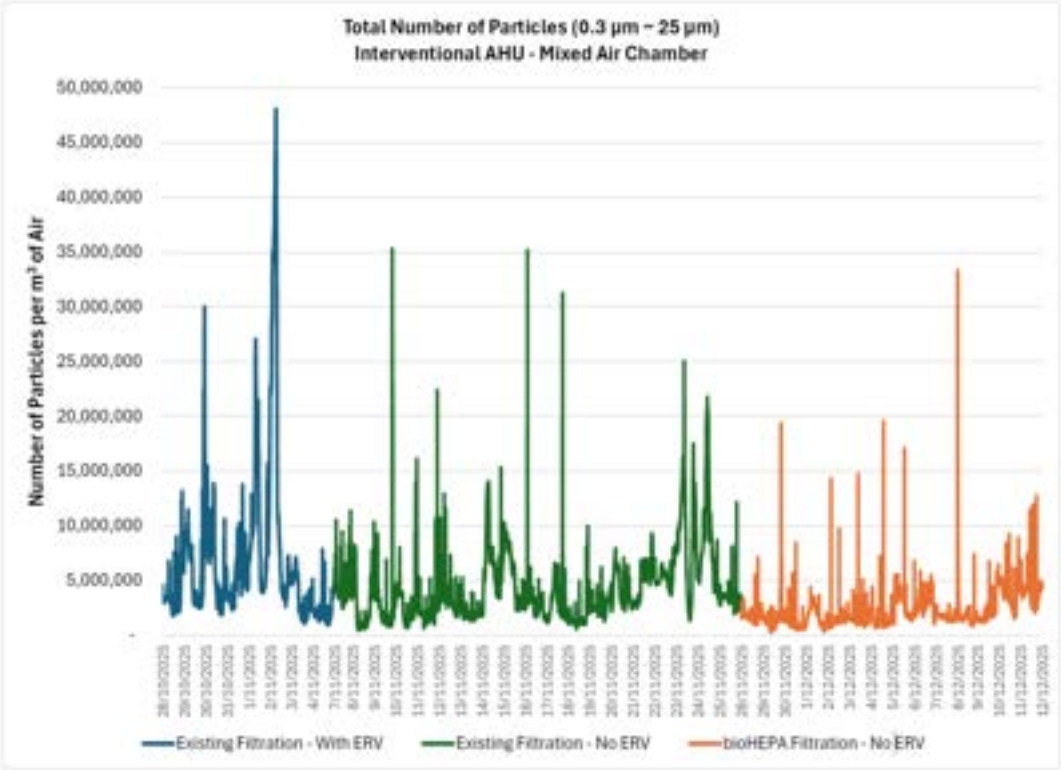

Figure 1: Number Concentration of Fine and Coarse Particles Upstream of the Interventional AHU Filter Across All Stages

Particle concentrations exhibited substantial temporal variability in all stages, reflecting fluctuations in outdoor airborne loads and in return air contributions.
Higher peak concentrations were observed during Stage I with the existing filtration with heat recovery wheel in place and during Stage II when just the heat recovery wheel was removed. Intermittent spikes were noted reaching several tens of millions of particles per cubic metre.

During Stage III comprising bioHEPA filtration without the heat recovery wheel, the upstream particle number concentration was slightly lower on average and exhibited reduced peak magnitudes. Given that only one-third of the mixed air in Stage III was outdoor air and the remaining two-thirds was return air, and considering that the supply air was highly filtered, a

larger reduction in particle concentration in the mixing chamber may have been expected as the majority of particles typically originate from outdoor air. These observations may be explained by system-specific factors, including the location of a return air grille in a common area outside the Medical Ward and the presence of negative pressure within the ward during the study period, as supported by air volume measurements, which may have increased particle ingress through infiltration.

Figure 2 shows the data trace from rea ltime devices located downstream of the filtration system.

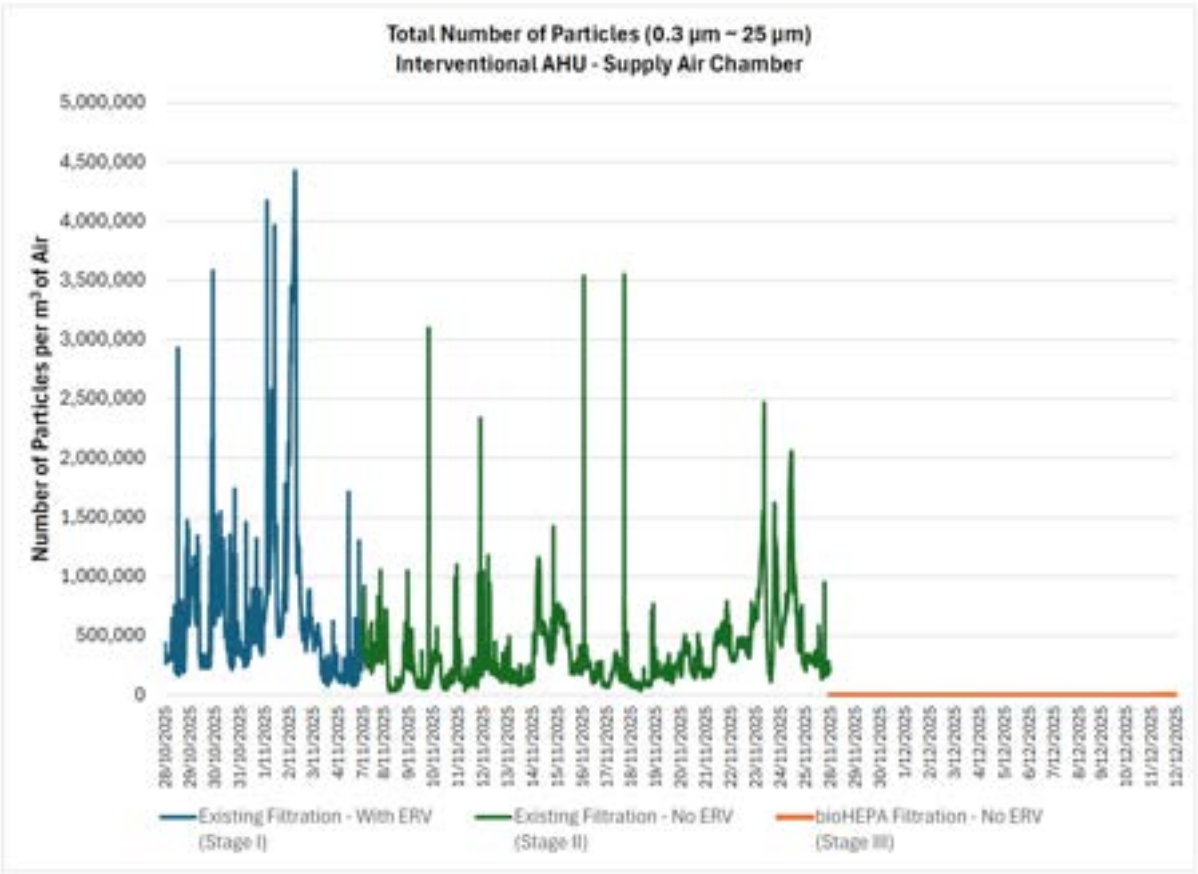

Figure 2: Number Concentration of Fine and Coarse Particles Downstream of the Interventional AHU Filter Across All Stages

Particle number concentrations in the supply air chamber continued to exhibit temporal fluctuations during Stage I and Stage II (blue and green link respectively in Figure 2). However, the average particle number concentration in Stage II was slightly lower than in Stage I (Figure 2). This reduction was potentially attributable to removal of the heat recovery wheel and the associated elimination of particle carryover and infiltration pathways around the wheel assembly.

Particle number concentration downstream of the filter were consistently close to zero (average of 118, median of zero) with minimal temporal variation (orange line in Figure 2), despite changes in environmental conditions and upstream contamination loads which may be expected to lead to increased levels. These observations indicate that downstream particle number

concentrations in Stage III were effectively independent of upstream variability under real-world operating conditions.

b. Filtration Efficiency

During **Stage I** (existing filtration with HRW), filtration efficiency for particles relevant to inhalation exposure (in the 0.3–25 µm diameter range) exhibited significant temporal variability, with frequent and substantial transient reductions from baseline efficiency levels of approximately 85% (Figure 3).

Figure 3: Filtration Efficiency

Occasionally efficiency dropped to the order of 65%. Importantly, these performance reductions were not limited to short-duration events and, in several instances, persisted for extended periods (on the order of hours).

Such sustained efficiency losses are operationally relevant. In systems with borderline filtration performance, such drops in efficiency have potential to effectively downgrade filtration performance criteria by one or two classification levels. This can lead to under-performance compared with the anticipated outcomes of installing a particular filtration

system, but most importantly can result in non-compliance with applicable healthcare ventilation and filtration guidelines.

During **Stage II** (existing filtration with the HRW removed), filtration efficiency increased and variability was reduced, consistent with the elimination of particle carryover and elimination of considerable leakage around the HRW assembly. However, HRWs are standard practice and commonly a compliance requirement for HVAC systems operating with 100% outdoor air to meet energy efficiency requirements. Consequently, the filtration performance improvements as a result of removing the HRW are not practically achievable in real-world hospital HVAC systems where energy is be managed.

During **Stage III** (bioHEPA filtration with the heat recovery wheel removed), filtration efficiency remained consistently around >99.99% across the full measurement period, with minimal temporal variation and no spikes in efficiency losses. Compared with Stages I and II, this stage demonstrated both higher mean efficiency and improved stability.

Collectively, the results indicate that while removal of the heat recovery wheel reduced particle carryover and leakage effects, replacement of the existing fine filters with bioHEPA filtration produced the most substantial improvement in both the magnitude and consistency of particle removal under the studied conditions.

c. Filter Penetration Rate

Figure 4 shows the average filter penetration rate for particles in the 0.3–25 µm range for the interventional AHU (AHU-02 – serving the Medical Ward) and a reference AHU (AHU-03 – serving the Surgical Ward) located in the same plant room.

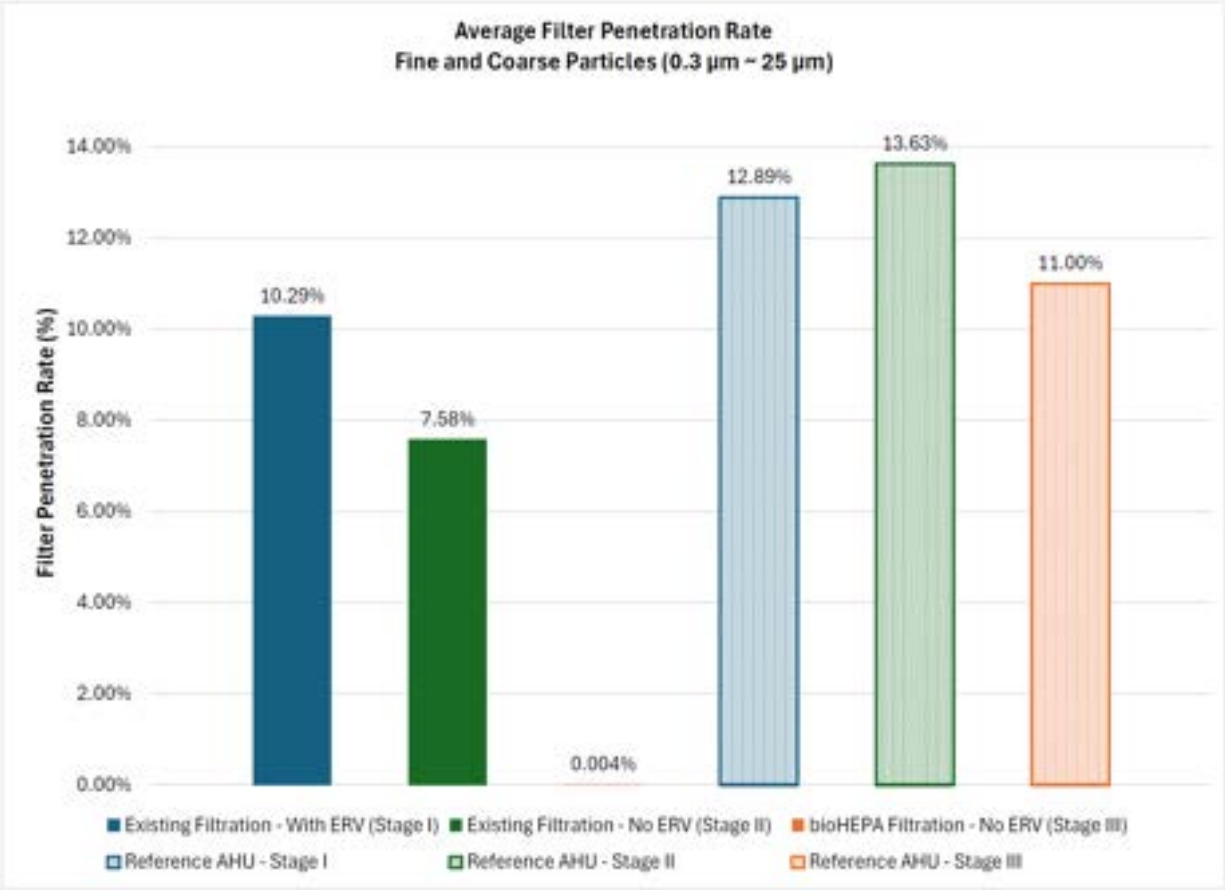

Figure 4: Average Filter Penetration Rate for particles in the 0.3–25 µm range in AHU-02 and AHU-03

Observations from the reference system, AHU-03

AHU-03 had comparable operational capacity and operated with a filter type and HVAC configuration equivalent to Stage I of AHU-02. However, this configuration was not changed throughout Stages I–III in AHU-03.

As shown in Figure 4, penetration rates for AHU-03 remained broadly stable across all intervention stages, indicating the presence of consistent background conditions, suggesting that fluxes arising from plant room influences, environmental source strength variability, and particle size distribution did not influence findings.

Observations from the intervention system, AHU-02

In contrast to observations of minimal change during stages I through to III in AHU-03, AHU-02, showed reduced particle penetration in Stage II following removal of the heat recovery wheel (Figure 4). This reduction was further pronounced in Stage III after replacement of the existing fine filters with bioHEPA filtration (Figure 4).

The divergence in particle penetration rates between the interventional AHU and the reference AHU in Stage III supports attribution of the observed reduction in particle penetration to the filtration intervention rather than to external or site-wide factors.

Size-resolved filtration performance data for both AHUs are presented in Table 1.

Filtration Efficiency - Stage I

Intervention - AHU02 (Medical Ward)								
	HVAC Configuration	# of Samples	0.3 µm	0.5 µm	1 µm	5 µm	10 µm	25 µm
Average	100% Outdoor Air	2289	89.71%	94.88%	96.86%	97.70%	99.91%	100.00%

Reference - AHU03 (Surgical Ward)								
	HVAC Configuration	# of Samples	0.3 µm	0.5 µm	1 µm	5 µm	10 µm	25 µm
Average	100% Outdoor Air	930	87.11%	91.54%	93.81%	96.76%	99.89%	100.00%

Filtration Efficiency - Stage II

Intervention - AHU02 (Medical Ward)								
	HVAC Configuration	# of Samples	0.3 µm	0.5 µm	1 µm	5 µm	10 µm	25 µm
Average	100% Outdoor Air	5391	92.42%	96.18%	97.29%	98.36%	99.53%	100.00%

Reference - AHU03 (Surgical Ward)								
	HVAC Configuration	# of Samples	0.3 µm	0.5 µm	1 µm	5 µm	10 µm	25 µm
Average	100% Outdoor Air	2450	86.37%	90.88%	93.37%	96.52%	99.51%	100.00%

Filtration Efficiency - Stage III

Intervention - AHU02 (Medical Ward)								
	HVAC Configuration	# of Samples	0.3 µm	0.5 µm	1 µm	5 µm	10 µm	25 µm
Average	2 ACH Outdoor Air 4 ACH Return Air	3989	99.996%	99.998%	100.00%	100.00%	100.00%	100.00%

Reference - AHU03 (Surgical Ward)								
	HVAC Configuration	# of Samples	0.3 µm	0.5 µm	1 µm	5 µm	10 µm	25 µm
Average	100% Outdoor Air	2103	89.00%	92.59%	94.67%	97.54%	100.00%	100.00%

Table 1: Size-resolved Filtration Performance for the Interventional and Reference AHUs when operated under identical 100% outdoor air configurations

d. Ultrafine Particles

Ultrafine particles (UFPs; 20–100 nm) are a sensitive indicator of certain outdoor pollution events, including bushfires, traffic emissions, and other combustion-related sources. From a health perspective, UFPs are of particular concern as they can translocate into the bloodstream across the lungs, and where exposure has been heavily documented to increase rates of cardiovascular and inflammatory diseases. Despite their medical importance, UFPs are rarely monitored in hospital ventilation studies, which typically focus on coarse or fine particulate matter which contains respiratory pathogens, and agents which can cause diseases such as asthma. The link between long term UFP exposure and increased vulnerability to poor outcomes from infection makes them particularly pertinent to this study.

Inclusion of UFP measurements in this study therefore strengthens the assessment by capturing particle classes most relevant to acute environmental events and potential health impacts, as well as providing a more sensitive evaluation of filtration system performance.

Figure 5 shows the average filter penetration rate for ultrafine particles across all stages for the interventional AHU.

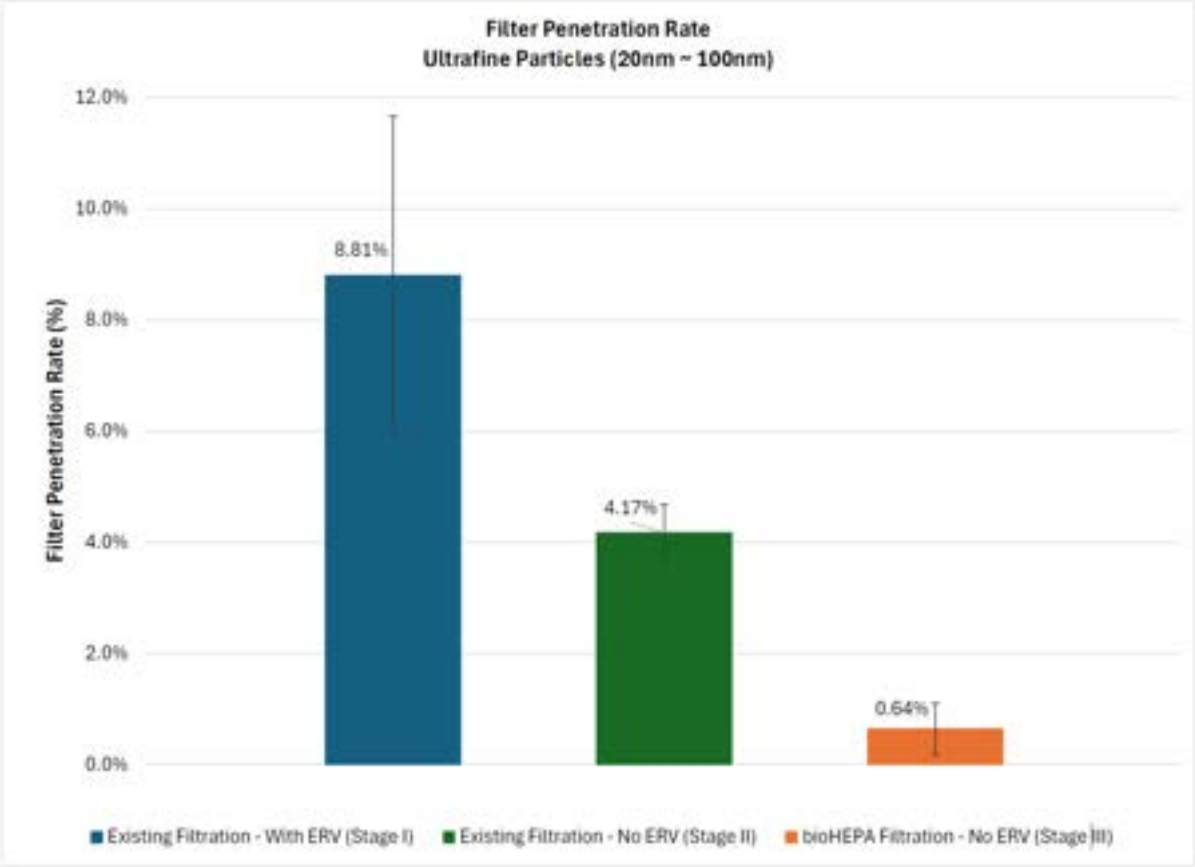

Figure 5: Filter Penetration Rate – Ultrafine Particles

Removal of the HRW in Stage II resulted in an intermediate reduction of over 52% in UFP penetration.

However, Stage III (bioHEPA filtration without HRW) achieved an approximately 12-fold (over 92%) reduction in ultrafine particle penetration compared to Stage I (existing filtration

with HRW) and an over 84% reduction compared to Stage II. Stage III data further demonstrated substantially reduced temporal variability in UFP levels. (refer to the size of error bars in Figure 5).

The context of operational practice

Notably, Stage I represented a baseline filtration performance that already exceeded minimum filtration grades recommended by relevant authorities, meaning Stage III is compared against a high-performance benchmark rather than a minimally compliant system.

2) Biological Aerosols

a. Total Airborne Mould in the Intervention AHU

Figure 6 shows total airborne mould (fungal structure) concentrations detected in AHU-02 across the study stages and sampled directly onto filters that were directly examined under a light microscope. This means that it was possible to consider whether spores were present as discrete spores or in chains or clusters which point to filter effectiveness and can reveal findings around mould spore penetration.

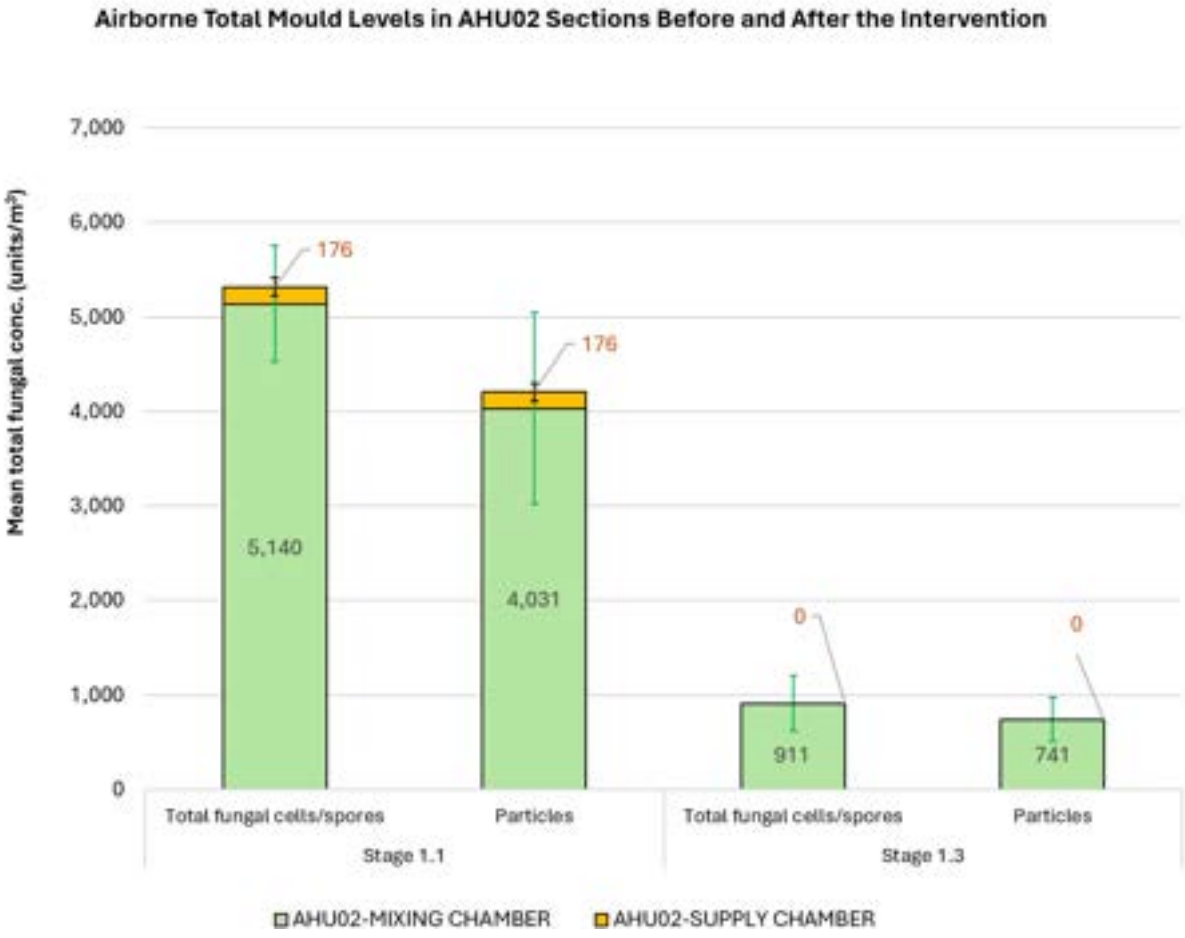

Figure 6: Total Mould Levels in the interventional AHU before and after the intervention.

Particle concentrations refer to the number of airborne particles observed down a microscope which contained at least one spore, whilst the total spore count included counting of the total individual spores present whether as discrete entities or aggregated to each other.

Most notably, there was a significant reduction in mould concentration in the mixing chamber between Stages I and III. Given that mixed air comprises a combination of return and outdoor air, understanding the contribution of mould associated with environmental sources may help to elucidate the cause of this observation.

The only notable change that would affect the mixing chamber was the difference in the mixing ratio between outdoor and return air. The working hypothesis ahead of that

discussion was that by reducing the outdoor air fraction from 100% to 2 ACH (out of a total 6 ACH), mould concentrations in the mixing chamber were lower because mould concentrations were much higher the outdoor environment than were being recirculated from the building. This would indicate that outdoor air was a primary fungal source under full outdoor air operation which may be anticipated to increase fungal load on filters, and increase risks from biofouling of coils as well as energy loads.

The impact of the bioHEPA filtration system on mould in supply air

There was clear evidence that prior to the installation of the bioHEPA filter, during Stage I, mould spores were penetrating the filtration system. The presence of aggregated spores in the mixing chamber (particle concentrations were lower than spore concentrations), but only single spores in the post-filter sections is commensurate with an efficient system for removing aggregated spores, but indicating that some spores were sufficiently small to escape capture.

Following installation of the bioHEPA filtration system, airborne mould concentrations downstream of the filter were reduced to below the detection limit, demonstrating effective removal of biological aerosols under mixed-air operation. Further, the proportion of spores passing through the filters during Stage I was between 3.4 and 4.4%. At this ratio, we would expect to see around 30 – 40 spores escaping the bioHEPA filter if removal efficiencies were the same during Stage III. In contrast, there was a 100% removal efficiency of fungal particulate matter from the sampled air when using the bioHEPA filter.

Understanding mould sources and types in relation to system *effectiveness*

The composition of mould assemblages collected from air changes depending on their sources. An understanding of this coupled to mould spore aggregation behaviour, the importance of resuspension on concentrations which is picked up debris levels, and other factors allow us to better understand the contribution of outdoor air to the mixing chamber.

For the purpose of this exercise, the following factors were included in interpretation:

1. *Aspergillus, Penicillium* and *Chaetomium* species are often observed where building dampness, high humidity and condensation are present, although it can also be derived from outdoor air.
2. *Cladosporium* and *Aureobasidium* are strong markers or dampness in HVAC systems.
3. Varied spores with wide-ranging appearance arising from Ascomycetes and Basidiomycetes are commonly associated with outdoor air.
4. The aggregation of spores is important, with aggregates of *Cladosporium* frequently arising outdoors, yet aggregates of *Aspergillus* and *Penicillium* more frequently the result of internal damp materials.

As shown in figure 7, the taxonomic analysis available using direct microscopy can help to differentiate outdoor-derived fungi from moulds typically associated with indoor moisture conditions.

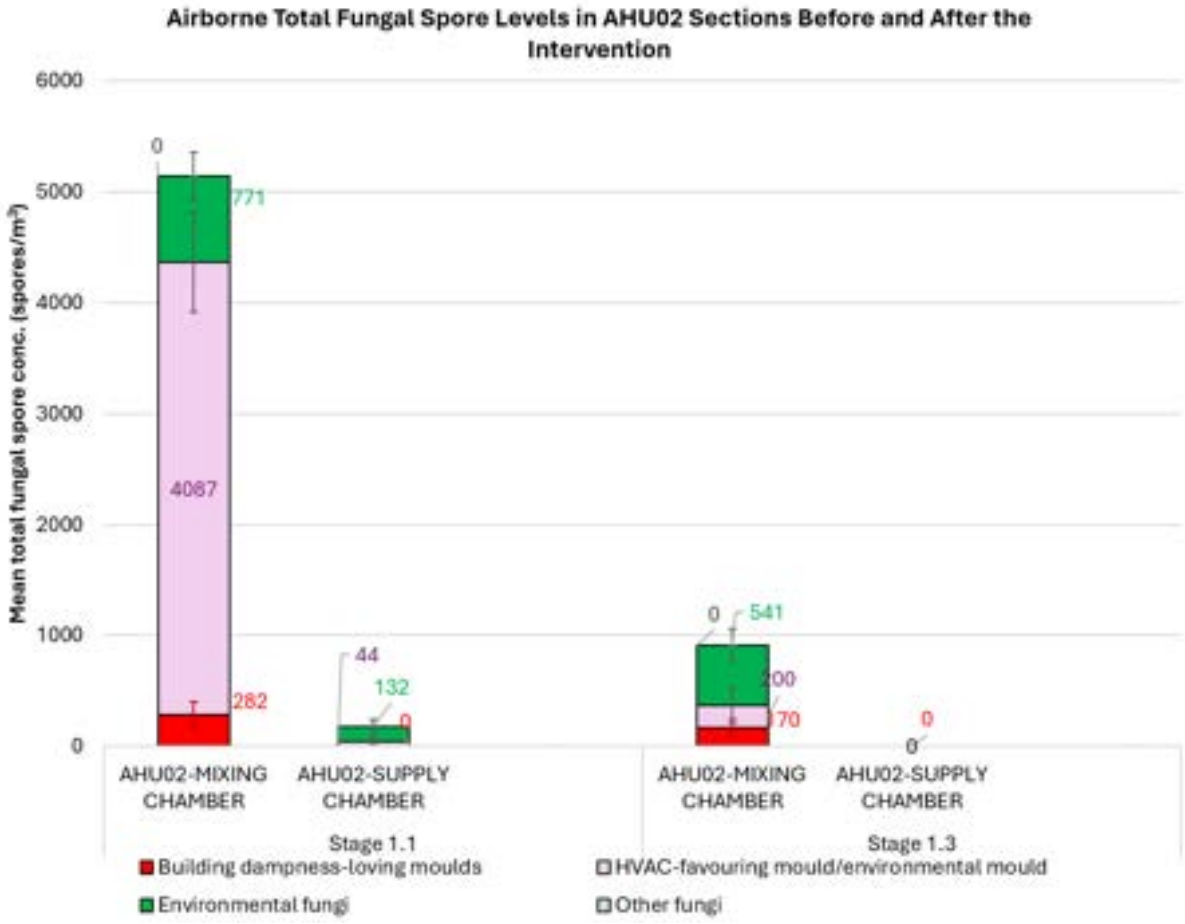

Figure 7: Total Fungal Spore Levels in the interventional AHU before and after the intervention

Microbial risks to HVAC

Prior to the intervention (Stage 1.1 in Figure 7) *Cladosporium* was the dominant species detected. *Cladosporium* is a ubiquitous environmental fungus but rapidly amplifies in surfaces subject to high humidity and condensation, making it the primary indicator of a contaminated HVAC system. This means that it served two roles during this investigation. The first was to determine if our hypothesis was correct in stating that the decreased mixing chambers levels were the result of lower mixing ratios of outdoor air in Stage III and the second was to determine whether there was mould growth occurring on the coils of chilled surfaces that was impacting the air in the supply chamber.

The presence of consistent spore chains mixed with single spores in the mixing chamber sample (Figure 6 spore v particle concentration) suggested that the *Cladosporium* was characteristic of that frequently observed in outdoor air despite the fact that a similar reduction was not seen in other environmental moulds. It was noted that the wind direction was different on the two days, which may further account for not only the difference in concentration, but also the difference in taxonomy.

Most notably, some *Cladosporium*-like spores were detected in the supply air chamber during Stage 1. Stage III showed that no *Cladosporium*-like spores were detected in air after it had passed the bioHEPA filtration. Most notably the laboratory reported that no spores were

detected anywhere on the filter, not just absent from the representative area that their methods require them to count.

This means that the system was providing 100% protection of the cooling coils, ducts and registers from mould being brought in from outdoor air whilst prior to its installation, microorganisms (mould in this case) may be able to grow or become part of a biofilm with knock-on effects of energy efficiency and maintenance costs of the filtration system.

Overall outdoor mould levels

Based on the observations above, external mould levels potentially comprised the sum of both the pink and green bars in Figure 8.

Prior to the intervention, operation with 100% outdoor air resulted in significant ingress of outdoor-derived fungal spores, potentially consistent with high intake of environmental bioaerosols.

Stage III was operated with a reduced outdoor air fraction (approximately one-third outdoor air) and was associated with an 8-fold reduction in concentrations of total fungi in the mixing chamber, but only a 1.5-fold reduction in non-*Cladosporium* environmental markers and of *Aspergillus/Penicillium.* This pointed to the difference being due to both a reduction in outdoor air intake rates and a different mould profile in the external air due to a difference in its source.

In addition, installation of the bioHEPA filtration system eliminated detectable fungi downstream of the filter, demonstrating effective removal of biological aerosols and confirming that the intervention did not promote conditions conducive to indoor mould growth.

Microbial risks to health

Aspergillus and *Penicillium* species are commonly associated with building dampness and moisture-related conditions. Of great importance in healthcare settings are those species of these genera (especially of *Aspergillus fumigatus*) that are highly documented as health risks in hospital settings.

Significantly, the pre-existing filtration system in Stage I was resulting in removal of *Aspergillus/Penicillium* from the air stream in the Supply chamber. However, total mould loads in the mixing chamber were very low on the date of testing for Stage III compared to Stage I, and the significant change in *Cladosporium* levels and abundance which cannot be accounted for purely based on rates of outdoor air intake suggest that under different meteorological conditions total mould levels and abundance of *Aspergillus/Penicillium* may be substantially higher in the mixing chamber even with operating under lower outdoor air intake ratios.

The most notable finding was that no fungal particulate matter was detected in the Supply Chamber during Stage III. This included *Aspergillus/Penicillium*. The characteristics of *Cladosporium* and its susceptibility to bioHEPA filtration may reasonably be expected to align with that of *Aspergillus/Penicillium,* whilst specific testing has not yet been conducted to confirm this.

b. Culturable Settled Mould in the Environment (Medical Ward)

Of major concern in wards is the settling of microbial particulate matter onto surfaces, equipment and wounds. The greatest risk to patients is from infection in this scenario. For this reason, the rate of settling of mould spores from the air based on culture-based analysis (whereby many viable organisms will grow) was performed to examine the impact of the installation on those organisms that can grow on agar.

Figure 8 presents the results of the settled fungal assessment conducted within the interventional environment (Medical Ward) served by the interventional AHU, using three culture media: Sabouraud dextrose agar (SDA), DG18 agar, and nutrient agar (NA). These media were selected to capture a broad range of fungal growth characteristics. Results are reported as mean culturable fungal settling rates averaged across triplicate samples and across Rooms 12.16 and 13.06, which are located at opposite ends of the Medical Ward.

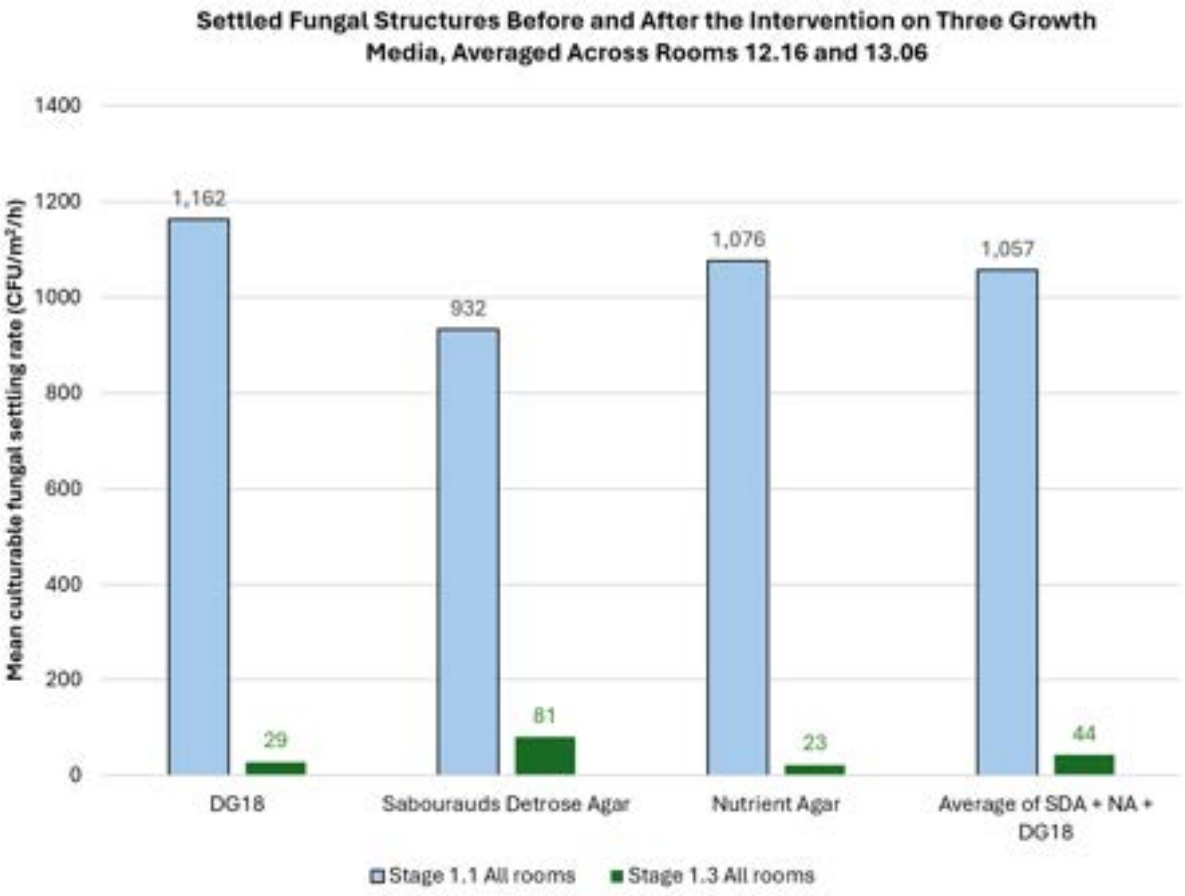

Figure 8: Settling Rate of Culturable Mould Before and After the Intervention

During project Stage I, prior to intervention (Stage 1.1 in Figure 8), high fungal settling rates were observed based on counts across all media, with mean values ranging from approximately 932 +/- 115 to 1,162 +/- 138 CFU/m²/h. This means that in each hour, around 1,000 fungal spores that were shown to be viable on agar settled onto a square metre of surface. Even with a wound size of 20 cm^2 this equates to approximately 20 spores per hour. Most notably, these rates of settling may allow biofilm-generated bioaerosols if they exist in

an HVAC system to colonise hospital surfaces and equipment which has potential to cause infection in vulnerable individuals.

During project Stage III, following intervention (Figure 8, Stage 1.3), the rate of settling of culturable fungi decreased substantially across all growth media, in all replicate samples and in each location. This resulted in not only large differences in the concentration of settled fungi in Stage III but in no overlap between error bars that would otherwise suggest a level of statistical uncertainty in these findings.

Based on the averaged results across SDA, NA, and DG18, the intervention corresponded to an approximate 95–96% reduction in settled fungal deposition within the ward environment, indicating a marked decrease in culturable fungal presence consistent with improved control of airborne biological aerosols.

Even when put in the light of the slightly lower concentrations of *Aspergillus/Penicillium* in the mixing chamber during Stage III, such a large proportional reduction would be unlikely to arise from day-to-day variability in air entering the chamber unless the bioHEPA was removing culturable fungi from the airstream.

The relevance of this finding to potential infection reduction in a hospital environment cannot be overstated, and repetition of this test may be recommended given that there was suspected variance in external airborne conditions on the days of testing should greater detail be required.

3) Gas-phase contaminants

a. Ozone

Ozone (O_3) is a major outdoor air pollutant formed by photochemical reactions involving sunlight and stagnant air coupled to high levels of NO_x and VOCs. Ozone is monitored as part of regulatory ambient air quality programs because of its known respiratory irritant effects. Ambient ground-level ozone concentrations in Melbourne and surrounding regions frequently vary with meteorology and sunlight. Historical data shows that 8-hour averaged ozone levels in the city can exceed health guideline levels set as the Australian National Environment Protection Measure (NEPM) (65 ppb) and the World Health Organization (50 ppb) on numerous occasions.

Standards bodies recognise outdoor ozone as a contaminant of concern and advise reducing its entry into occupied spaces when feasible; ASHRAE guidance notes that ozone should be removed from outdoor air at the intake or as early as possible in the ventilation process when concentrations are elevated, as ozone and its reaction products can impact indoor chemistry and occupant health. Normal mechanical filtration media are generally ineffective at removing ozone, as ozone is a gas and is not readily captured by particle filters.

Figure 9 presents the average ozone concentration measured downstream of the filters in the interventional AHU supply air across all stages. In Stage I (existing filtration with HRW) and Stage II (existing filtration without HRW), mean downstream ozone levels were 12.7 ppb and 11.0 ppb, respectively, with observed variability around these means reflecting ambient outdoor air conditions and pointing to negligible statistically significant concentration differences.

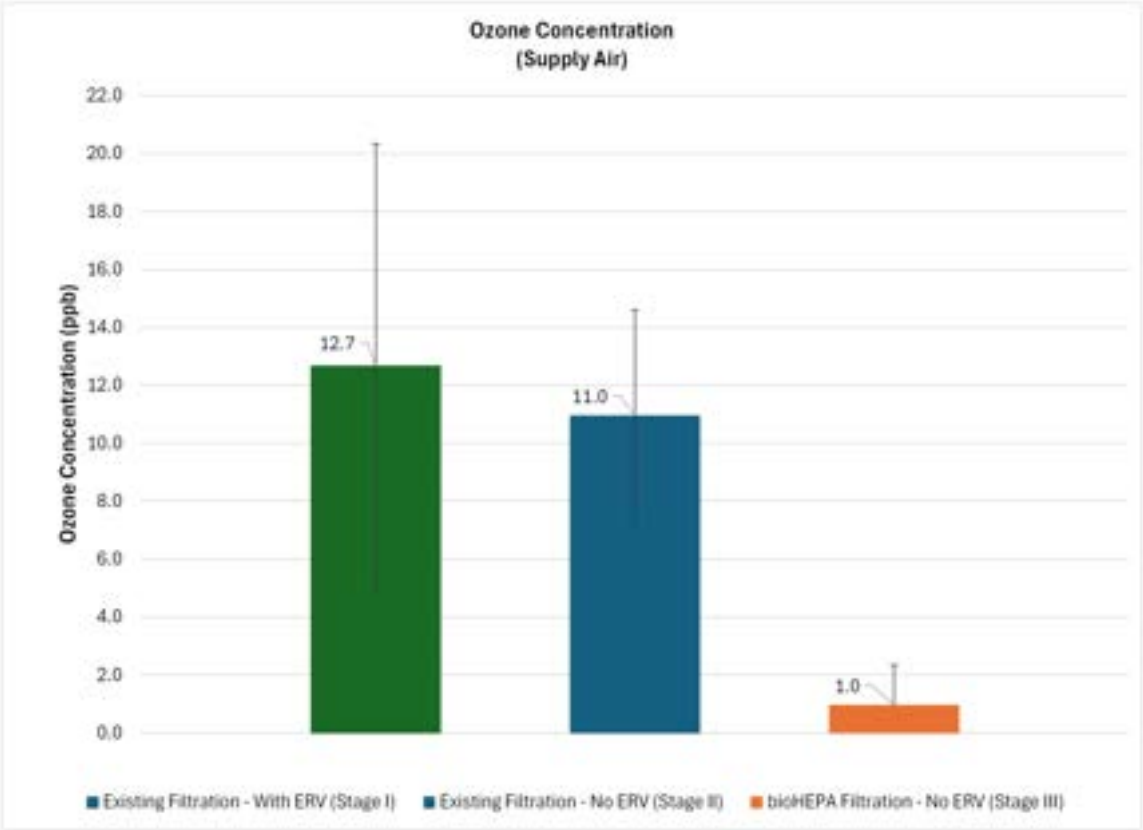

Figure 9: Ozone concentration downstream of filters

However, during Stage III (bioHEPA filtration without HRW), mean downstream ozone concentration was reduced to approximately 1.0 ppb with much lower variability, demonstrating that the intervention corresponded with substantial ozone removal or reduction relative to the upstream outdoor air loads. Given the ambient presence of ozone in outdoor air and its typical concentrations in the region during spring–early summer, these results indicate effective downstream reduction beyond what would occur with particle filtration alone.

The ozone test methodology was informed by the procedures outlined in UL 867, Section 40.

For context in HVAC system specification, recognised international standards such as UL 2998 define zero ozone emissions for air-cleaning systems as ozone output below 5 ppb, providing a benchmark for ozone safety performance in electronic air cleaners.

b. Formaldehyde

Formaldehyde is a common indoor air pollutant emitted from building materials, furnishings, cleaning products, and some clinical consumables, and is of concern due to its irritant properties and classification as a potential human carcinogen at elevated or prolonged exposure levels. In healthcare environments, formaldehyde is monitored because even low concentrations can contribute to mucosal irritation, and its presence is often used as an indicator of indoor emission sources rather than outdoor pollution. For context, the World Health Organization (WHO) indoor air quality guideline for formaldehyde is 100 µg/m³ for short-term exposure.

Formaldehyde concentrations were measured using sample collection and laboratory analysis.

Concentrations during the trial were low in all stages, remaining below 4 µg/m³, well below the WHO guideline value.

During Stage I and Stage II, low levels of formaldehyde were detected in the return air, while concentrations in the supply air were below the detection limit, consistent with operation in 100% outdoor air mode and the absence of significant outdoor formaldehyde sources in the vicinity of the test site.
During Stage III, similar low concentrations were observed in the return air to Stages I and II; however, despite approximately two-thirds of the air upstream of the filter being return air in Stage III, the bioHEPA filtration system reduced formaldehyde concentrations downstream of the filter were below the detection limit, resulting in supply air levels comparable to those observed in Stages I and II when full outdoor air was supplied to the AHU.

c. Volatile Organic Compounds (VOCs)

The term VOC refers to a very wide range of organic compounds that are generally gases or low boiling point liquids at room temperature. As air contaminants, their toxicity, odour thresholds, and impact on health and amenity vary widely. TVOC refers to the totality of individual VOCs and has its origins in gas chromatographic methods. Whilst real-time monitoring provides data on trends in VOC levels it is generally insufficient to characterise individual compounds which may come from a wide range of sources. For this reason, in this study air samples were collected onto a sorbent matrix and analysed using gas chromatography-mass spectrometry (GC-MS).

Sources of VOCs in healthcare environments include cleaning agents, disinfectants, offgassing from building materials, and clinical activities, and can influence overall indoor air quality and occupant comfort. In ventilation studies, VOC monitoring is also used to identify any changes in chemical composition associated with system configuration or air-cleaning interventions, as the appearance of new compounds or altered VOC profiles may indicate secondary reactions or transformation processes within the air-handling system.

While no formal indoor air quality standard exists for total VOCs, the NCC Indoor Air Quality Handbook references a TVOC guideline value of 500 µg/m³, adopted from earlier NHMRC guidance, providing context for the measured concentrations.

Key findings showed that:

- No VOCs other than ethyl alcohol and isopropyl alcohol were detected across all stages of the study.
- These compounds are commonly associated with disinfectant wipes disposed of in open bins, a pattern observed in other healthcare facilities and verified onsite at Echuca Regional Hospital using a photo-ionisation detector (PID), a real-time monitor suitable for detecting these two compounds.

- The types of VOCs detected remained unchanged across Stages I, II, and III, indicating no observable conversion, transformation, or formation of additional VOC species associated with changes in HVAC configuration.
- Total VOC concentrations in the supply air were generally below 500 µg/m³ in all stages.

d. Odours

Odours were not directly or specifically assessed as part of this study. However, among the 75 volatile organic compounds (VOCs) monitored, several can be considered odorous gases; none of these were detected in the return air during the study period. In addition, an occupational hygiene screening was conducted in the Medical Ward (interventional ward) using a photo-ionisation detector (PID) to assess the general presence of gaseous contaminants rather than to identify specific compounds. Detectable gas levels were observed only in close proximity to waste bins containing alcohol wipes, which was expected, and no unusual or elevated gas levels were detected elsewhere in the ward.

The removal efficiency of the applied technology for a range of body odour–related chemical compounds has been assessed separately under controlled conditions, with the findings currently under review for publication.

e. Indoor Carbon Dioxide (CO_2) Levels

Carbon dioxide (CO_2) profiles differs in healthcare facilities to that in commercial buildings due to differences in mandated ventilation requirements and operational characteristics. National and state healthcare guidelines require higher outdoor air rates than those prescribed in Australian Standard AS 1668.2 for commercial buildings, and typical occupancy densities in hospital wards are lower than in offices or other commercial spaces. As a result, CO_2 concentrations in healthcare environments generally remain low regardless of filtration configuration or other indoor air quality parameters. Consequently, CO_2 is a limited proxy for overall indoor air quality and instead should be viewed as a measure of ventilation effectiveness. Through this lens, it can be utilised to identify increased risks of long-range airborne infection transmission in healthcare settings aiming to prevent this, where supplemental infection reduction technologies are absent. Where these are present, ASHRAE 241 Infection Control standard may be referenced to understand how such technologies may deliver quantifiable effective clean air.
At present, CO_2 is seeing widespread use as a “gold standard” metric in commercial buildings.

In this study, CO_2 concentrations in return air were monitored as average indoor CO_2 levels across all three stages of the study for both the interventional and reference AHUs.

As shown in Figure 10, average return-air CO_2 concentrations for the interventional AHU remained low across all stages, with a slight increase observed in Stage III relative to Stages I and II.

This increase is attributable to the reduced outdoor air fraction in Stage III (approximately one-third outdoor air compared to 100% outdoor air in Stages I and II), rather than any change in filtration performance. It is noted that the Stage III configuration of one-third

outdoor air and two-thirds return air is compliant with Victorian Health Building Authority (VHBA) requirements for healthcare facilities.

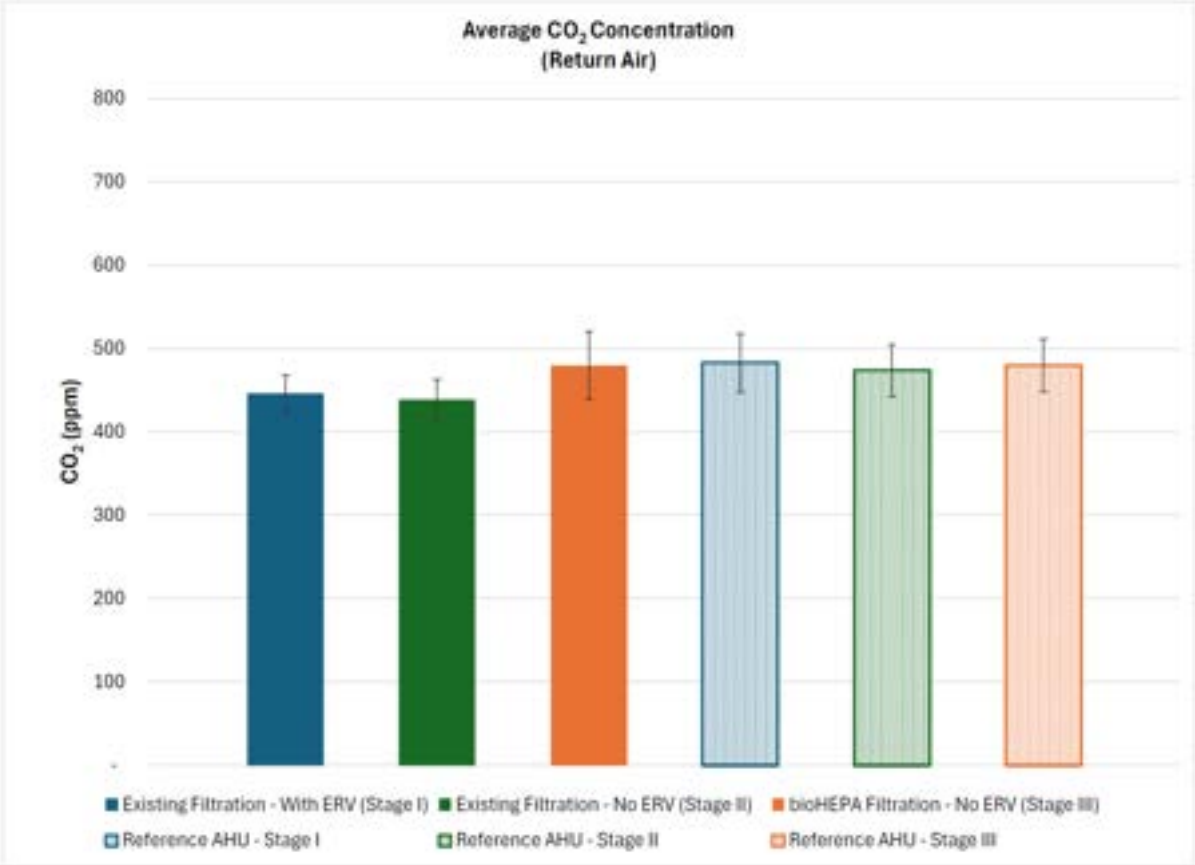

Figure 10: Average CO_2 concentration – Medical Ward (Interventional AHU - Return Air)

Average CO_2 concentrations measured in return air are presented for comparative assessment across stages and are not intended to represent CO_2 levels within individual rooms.

Bushfire Smoke

a. Bushfire-Related Air Pollutants

Bushfire smoke is a complex and highly variable mixture of particulate and gas-phase pollutants, with composition dependent on fire type, fuel load, combustion conditions, and proximity to the source. In regional Victoria, including the Echuca area, smoke exposure can arise from both controlled (prescribed) burns and uncontrolled bushfires, each contributing overlapping but distinct contaminant profiles. As illustrated in the Table 2, both burn types generate fine and ultrafine particles, semi-volatile organic compounds (semi-VOCs), polycyclic aromatic hydrocarbons (PAHs), and carbon monoxide. Uncontrolled bushfires additionally produce a broader range of hazardous pollutants, including acid gases (e.g. hydrogen cyanide), heavy metals, dioxins, flame retardants, phthalates, and microplastics, reflecting higher combustion temperatures, structural burn, and incomplete combustion.

From a resilience perspective, this complexity is particularly relevant for healthcare facilities in regional settings such as Echuca, which may be exposed to smoke plumes from distant large-scale fires as well as nearby planned burns. Ultrafine particles and semi-volatile compounds can readily penetrate building envelopes and conventional ventilation systems, while many gas-phase contaminants are not addressed by standard mechanical filtration.

Contaminant	Controlled Burn	Uncontrolled Burn
Fine particulates <1um	✓	✓
Ultra Fine Particles <0.1um	✓	✓
Semi-VOCs	✓	✓
PAHs	✓	✓
Carbon Monoxide	✓	✓
Acid Gases and HCN		✓
Heavy Metals		✓
Dioxins, flame retardants, phthalates		✓
Microplastics etc		✓

Table 2: Summary of Air Pollutants Associated with Controlled and Uncontrolled Burns

b. Bushfire Location

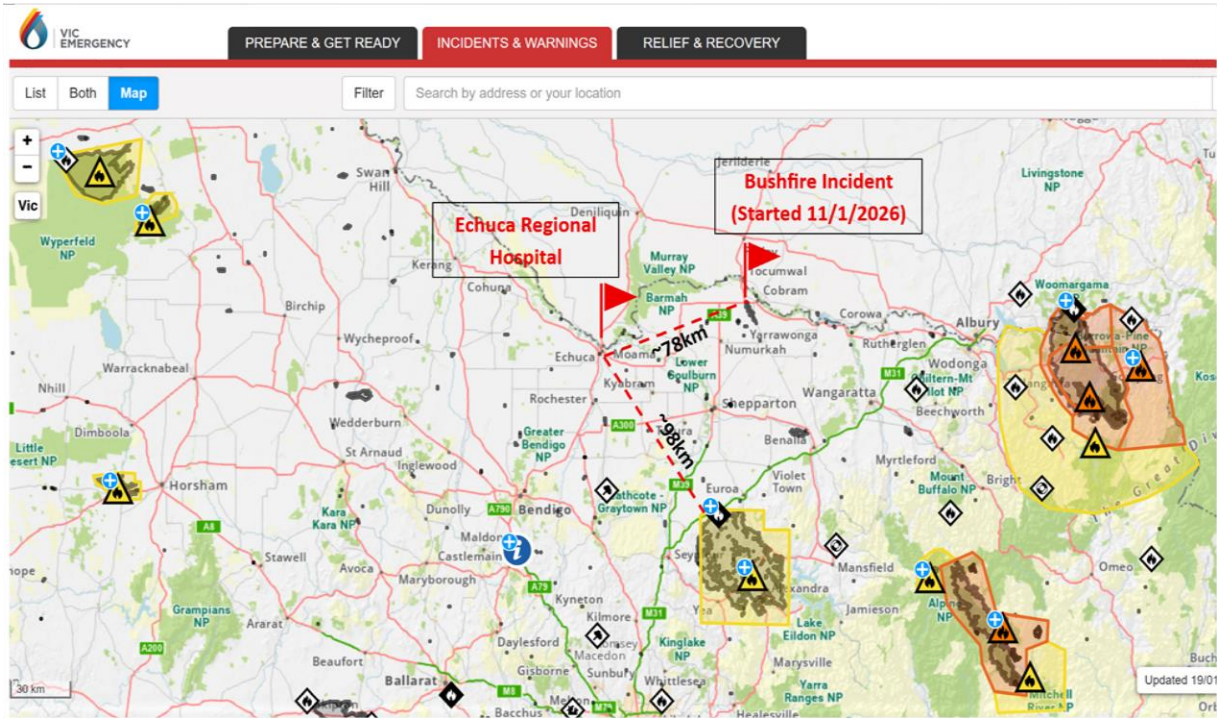

Figure 11: Bushfire map - CFA

The Country Fire Authority (CFA) reported several bushfire incidents within a 100 km radius of Echuca Regional Hospital between 12 and 15 January 2026, including a fire near Yarrawonga (approximately 78 km from the test site) and a large bushfire near Seymour (approximately 98 km from the test site).

c. Bushfire Impact on Air Quality at the Test Site

These bushfires resulted in up to a 30-fold increase in particle number concentration upstream of the AHU filters. The magnitude of the increase depended on the distance to the bushfires and environmental conditions such as wind speed and wind direction.

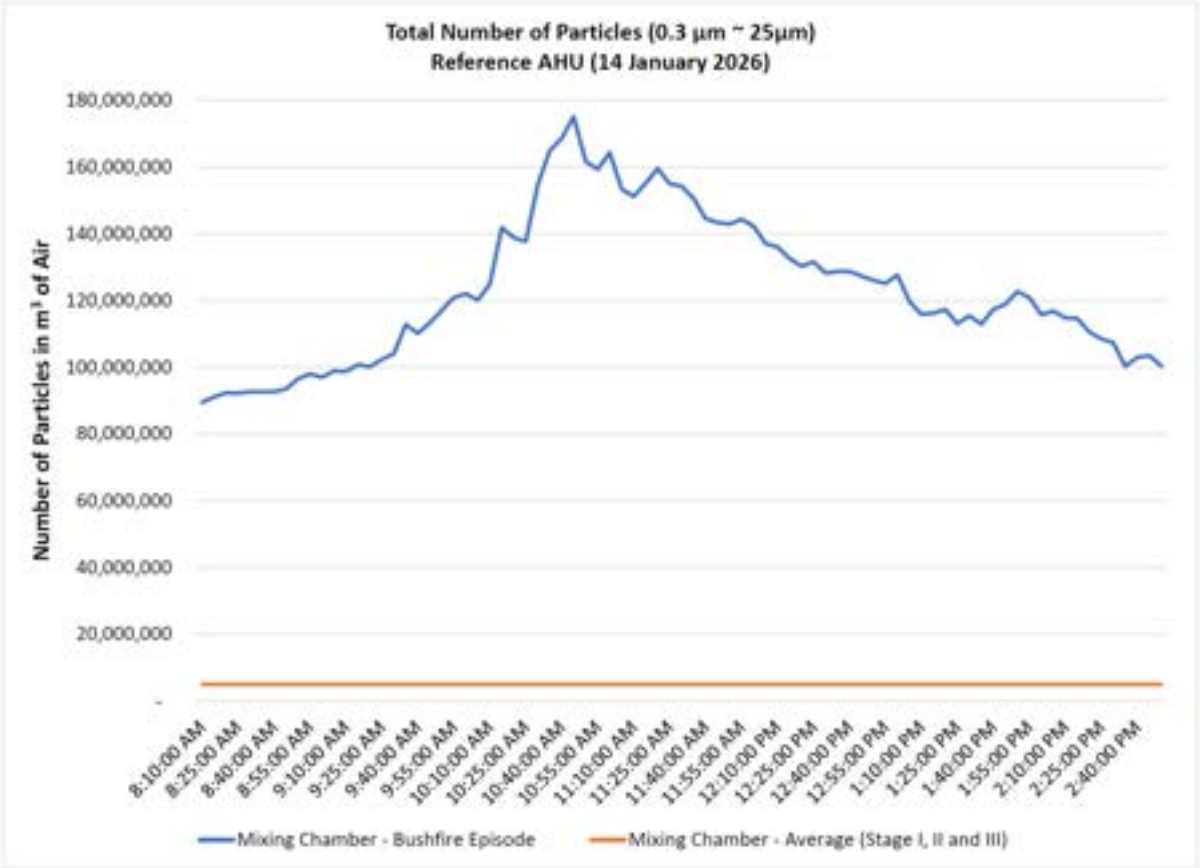

Figure 12: Particle concentration in the reference AHU: average across the three stages compared with concentrations measured during the bushfire episode on 14 January 2026.

As shown in Figure 13, the number concentration of submicron particles in the supply air downstream of the filter in the interventional AHU was approximately 1,000 times lower than the upstream particle concentration measured in the reference AHU for the duration of the bushfire episode from 12 to 15 January 2026.

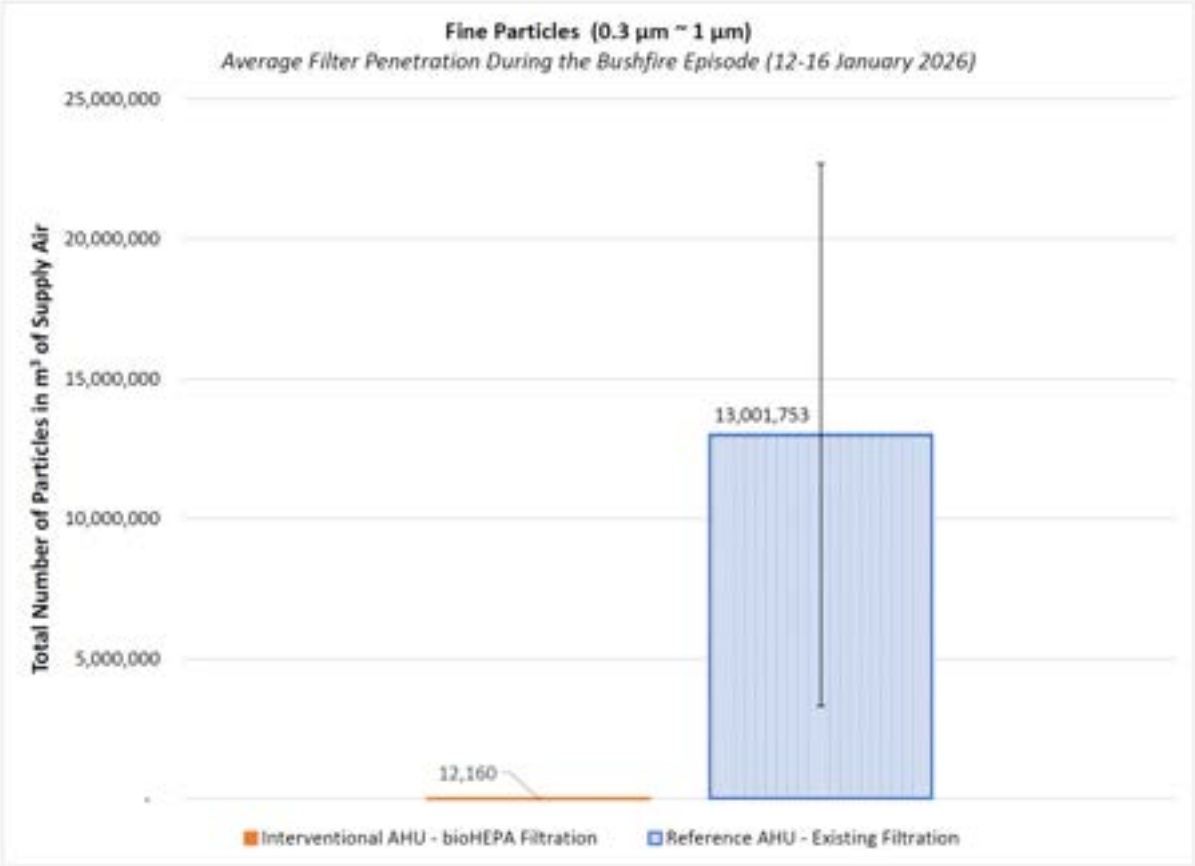

Figure 13: Supply Air Submicron Particle Number Concentration During the Bushfire Episode (12–16 January 2026)

d. Duration analysis

Figure 14 presents the duration (time series) analysis of particle number concentration during the bushfire episode. Elevated particle concentrations in the mixing chamber persisted for multiple consecutive days, exceeding three days in duration, reflecting prolonged exposure to bushfire smoke rather than short-term transient events. Despite these extended periods of highly polluted outdoor air, particle concentrations in the supply air downstream of the filter remained consistently low. Across the entire bushfire period, the bioHEPA filtration system maintained stable performance with an average removal efficiency of approximately 99.98%, demonstrating consistent filtration effectiveness under prolonged high-load conditions.

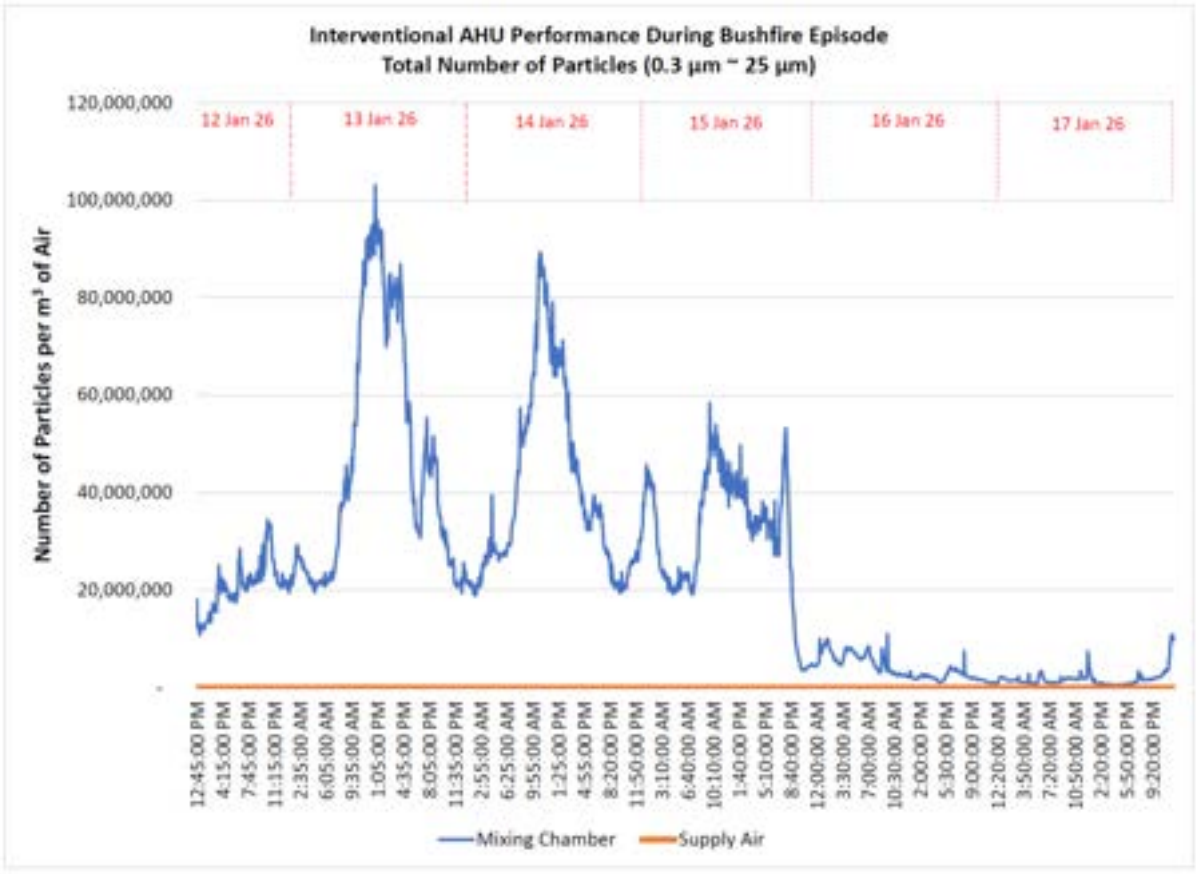

Figure 14: Duration Analysis of the Bushfire Episode

e. Key Points

- Bushfire incidents can significantly degrade air quality at significant distances
- Highly polluted outdoor air may persist for extended periods.
- Toxic gases and vapours may attach to particles, be inhaled and then released into lung tissue by metabolic processes (one known aspect of cigarette smoking risk)
- Particle count measurements provide the most sensitive measure of smoke, but doesn't identify the specific substances
- The bioHEPA filtration addresses smoke risk primarily by efficient particle removal, but then also by VOC and SVOC adsorption onto the catalyst filter, thereby increasing resilience of the air cleaning system

Results Requiring Further Investigation

The following areas require further investigation and may necessitate additional data types or sensor hardware for comprehensive assessment. Findings will be reported in subsequent interim reports as additional data become available.

- Broader Impacts on Air Quality in the Interventional Space
- Impacts of Bushfire Periods

Conclusion

This interventional field trial demonstrated that air quality in healthcare ventilation systems are strongly influenced by both ventilation strategy and filtration performance. Across Phase I, reductions in outdoor air intake alone lowered exposure to outdoor-derived particulates and biological aerosols but did not fully address variability or transient contamination events.

Removal of the heat recovery wheel reduced particle carryover and leakage-related variability; however, this system configuration was associated with increased energy demand and is not practical for routine healthcare operation.

Installation of the bioHEPA filtration system resulted in consistently high and stable removal of fine, ultrafine, and biological particles, including mould (fungal) spores and structures, independent of fluctuations in outdoor air quality, environmental conditions, or prolonged bushfire smoke exposure. Importantly, filtration performance remained stable during extended high-load events, with particle removal efficiencies approaching 99.98% even during multi-day bushfire episodes and total removal of detectable mould structures under light microscopy.

Most notably, the installation of the bioHEPA filter displayed a 92.7% drop in mould settling onto surfaces in the operational ward, reducing its rate of settling from greater than 1,000 colony forming units per square metre per hour to 44 CFU/m^2/h significantly reducing potential risk to hospital surfaces, equipment, staff and patients.

Assessment of gas-phase contaminants demonstrated a range of outcomes across pollutant classes. Ambient ozone present in outdoor air was substantially reduced downstream of the interventional AHU following installation of the bioHEPA system, with mean concentrations decreasing from approximately 12–13 ppb to ~1 ppb, corresponding to an ~90–92% reduction. This reduction is operationally important given the role of ozone as a respiratory irritant and driver of secondary indoor chemistry and aldehyde production, particularly during periods of elevated outdoor ozone.

Formaldehyde and VOC concentrations remained low across all stages and well below relevant guideline values, with no change in VOC profiles observed, indicating stable gas-phase behaviour and no evidence of chemical transformation associated with the intervention.

Conventional mechanical filtration alone showed no meaningful impact on these gas-phase contaminants.

From a resilience perspective, the findings support a pathway for maintaining infection control and environmental protection without reliance on continuous 100% outdoor air operation. While full outdoor air ventilation is a well-established strategy to reduce airborne infection risk during

pandemics, it introduces energy, emissions, and pollutant-ingress penalties. The results align with the ASHRAE 241 framework, which recognises Equivalent Clean Air (ECAi) as a substitute for outdoor air when achieved through effective air cleaning.

This study showed that operation of the HVAC system using approximately one-third outdoor air and two-thirds equivalent clean air delivered by bioHEPA filtration provided conditions functionally equivalent to full outdoor air. It simultaneously offers greater control over external pollutants and avoids the energy and emissions penalties typically associated with using 100% outdoor air operation to reduce respiratory infection transmission risk, especially during periods of extreme temperatures. It further provides tighter control on ambient humidity, avoiding high humidity which generates a greater risk of mould and biofilm development in the HVAC system and low humidity in winter which makes patients more prone to infection. Reducing external air intake further prevents unwanted ingress of external pollutants during vegetation fire smoke episodes.

Carbon dioxide monitoring confirmed that, due to mandated high ventilation rates and lower occupancy densities in healthcare facilities, CO_2 concentrations remained low under all operating conditions.

Collectively, the Phase I findings indicate that the combined ventilation and bioHEPA filtration strategy improves resilience to environmental pollution events, maintains biological and chemical air quality under real-world operating conditions, and provides a robust foundation for long-term evaluation in Phase II.

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