March 2023

Air Source Heat Pump Noise Control

iKoustic

Creating Quieter Spaces Together

University of Salford MANCHESTER

In partnership with

ROCKWOOL

Noistop® Essential

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ATK2i Project Summary

03/2023

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Abstract:

Noise control plays a significant factor in the acceptance of existing and proposed Air Source Heat Pump (ASHP) permitted developments. Throughout this report, ASHP noise reduction at a typical receiver position has been observed as a result of various Noistop Essential® acoustic barrier configurations. All reductions were observed under normal operation, not defrost. Additional results have been obtained from simulations developed in the sound modelling software, CadnaA. To quantify the effects of acoustic barrier configurations tested in terms of noise rating reductions as defined by BS4142, the Joint Nordic Method has been implemented to objectively assess the tonality of the measured sound before and after each installation. From these results, expected decibel reductions associated with different configurations are presented alongside recommended installation 'guidelines'.

Introduction:

Heat pumps are a viable solution to decarbonising air-conditioning and are part of the UK government's plan to reach carbon zero by 2050 [1, 2]. Despite this, acceptance is still obstructed by concerns regarding noise disturbance [1]. Where an installation fails UK noise regulation standards, post-installation treatment can be used for noise control. Depending on the design, full enclosures reduce the sound pressure level (SPL) by between 6 - 20 dB(A) [3-5], however, they are expensive, often aesthetically suited to more industrial environments and can impede airflow over the heat exchanger, reducing the efficiency [6]. As such, there is an incentive for a more versatile acoustic solution which; can control ASHP air-borne noise; is aesthetically suited for residential settings and does not compromise efficiency. Noistop Essential acoustic fence modules are acoustic barriers packed with ROCKWOOL® stone wool. Due to the range of different sizes available, these barriers can be assembled and tested in different configurations, offering insight into important design characteristics. With the use of simulation and measurement, this report quantifies the success of several Noistop Essential configurations as post-installation solutions to ASHP noise.

Case Study Methodology:

Measurement:

Measurements have been taken at an "Outdoor" location (rural Uk residence) and in a "Laboratory" at the University of Salford (EnergyHouse2.0, https://energyhouse2.salford.ac.uk/). These measurements aimed to observe the ASHP noise control capabilities of various Noistop Essential configurations. Each test site was subject to the same methodology. Four class 1 measurement microphones were positioned surrounding the ASHPs to record time-averaged SPL over 1-minute intervals. Ideally, a longer time average would have been used to obtain a more general measure of the ASHP acoustic signature, however, given the limited time available at each test site and the relatively stable acoustic output, 1-minute averages were deemed sufficient. One microphone positioned within each enclosure acted as a control signal, ensuring significant changes to the ASHP operating conditions could be observed and suitably reported. All remaining microphones were distributed in typical receiver positions or such places where interesting observations regarding ASHP noise reduction could be made, see Figures A.1 - A.2. Sound levels were corrected for the background level following methods in BS4142. Initial Sound levels were obtained before the installation of Noistop Essential. Sound levels were then obtained for the following configurations at heights of 1m and 2m, see Figures 1 - 2:

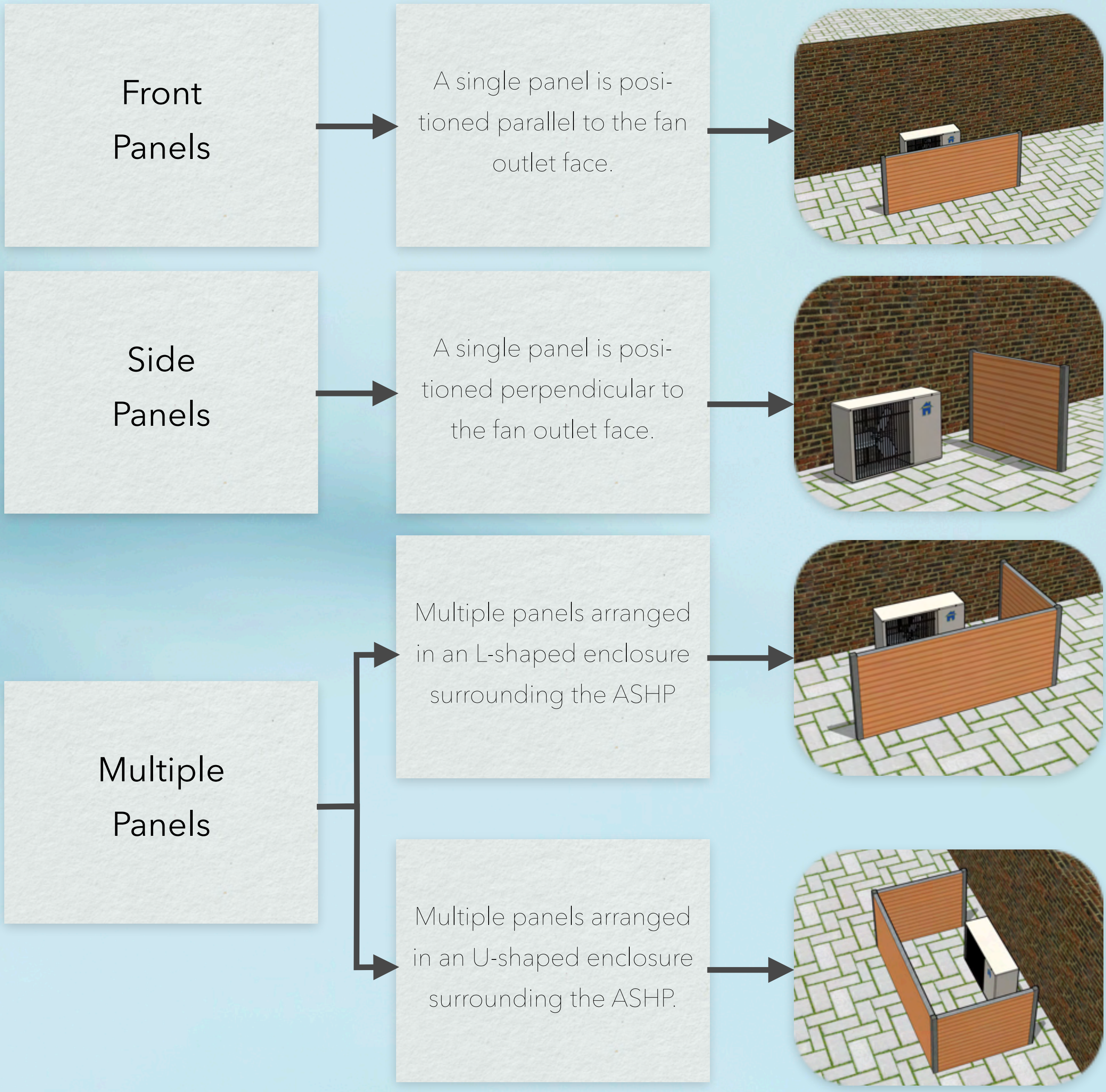


Figure 1 - Explanations of the different test configuration categories used throughout measurement and simulation.
Throughout measurement: Front panel length = **2.40m**, Side panel length = **1.2m.**
N.B presented diagrams show configurations at 1m height.

The heat pumps used were a Mitsubishi Electric Ecodan PUHZ-HW140VHA2 *(Outdoor test site)* and a Panasonic Aquarea MDC - J *(Laboratory test site)*. Care was taken to ensure configurations did not breach manufacturers' installation guidelines on minimum distances to nearby walls and objects [7, 8], thus minimising adverse effects on efficiency. Consequently, front panels were centred on the middle of the heat pump, 1m from the fan outlet. Front and side panel locations remained constant with each configuration, see Figures A.3 - A.4

Figure 2 - *Left* - U-shape (2m) configuration laboratory. *Left Center* - L-shape (1m) configuration outdoor. *Right Centre* - Side Panel (2m) configuration laboratory. *Right* - Front Panel (1m) configuration outdoor.

Corrections:

Laboratory measurements were corrected for long reverberation times in agreement with BS ISO16032:2004. Reverberation times were derived in third octaves using the interrupted noise method following BS ISO345. Level corrections were applied to individual third-octave bands.

The Joint Nordic Method (BS4142 Annex D) was implemented to quantify tonality changes. The method assesses the audibility of tones in agreement with established criteria, namely, peak −3dB bandwidth < 10% encompassing critical bandwidth. All measured signals were analysed using this approach, with respective tonal corrections applied in line with BS4142 recommendations.

Simulations:

To simulate acoustic behaviour at the aforementioned test sites, the Z-weighted sound power level was required so the emission and propagation of ASHP noise could be modelled. This was obtained following methods in BS ISO3746, section 8. Microphones were positioned in agreement with Annex C (*Microphone arrays on a parallelepiped measurement surface)* with the measurement distance set to 1m, see Figure 3

ASHP modelling was approached using a combination of vertical and horizontal area sources in CadnaA. Source dimensions and sound power levels matched the reference box component areas and corresponding microphone third-octave sound power levels respectively. All Noistop data was obtained from the Noistop Essential data-sheet in third-octaves [9]. Transmission loss was modelled following the recommended method in the CadnaA reference manual [10]. All simulated results were obtained with reflections up to the 4th order.

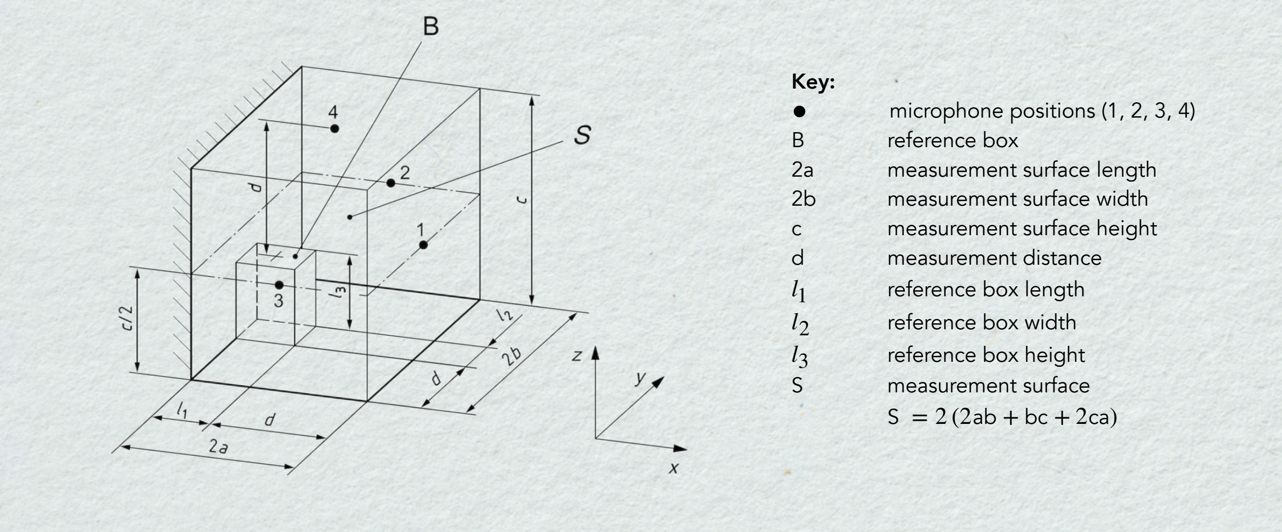


Figure 3 - Parallelepiped measurement surface with four microphone positions for floor-standing noise sources adjacent to two reflecting planes.

Sound levels & Calculations:

A sound level reduction was computed at each microphone location across both test sites by comparing the level before and after the installation of the respective Noistop Essential configuration:

$$\text{Level Reduction}_{\text{conf,i}} = L_{\text{eq,NoNoistop,i}} - L_{\text{eq,conf,i}} \tag{1}$$

where, $L_{\text{eq,NoNoistop,i}} =$ time-averaged specific level obtained from microphone i with no Noistop installed, $L_{\text{eq,config,i}} =$ time-averaged specific level obtained from microphone i with a given Noistop configuration installed.

As defined in BS4142, the rating level is the specific noise level (i.e., $L_{\text{eq,NoNoistop,i}}$ & $L_{\text{eq,config,i}}$) plus character correction for tonality according to Annex-D *(among others)*. The impact level is the difference between the rating level and the L_{90} background level. Impact level reduction results presented indicate the average difference between impact levels obtained with and without Noistop Essential installed. Since the L_{90} background level is taken as constant, this result reveals how changes to the tonal properties of the ASHP noise, arising from respective enclosure designs, may impact a BS4142 assessment. That is:

$$\begin{aligned}\text{Impact Level Difference} &= \left(L_{\text{r,NoNoistop,i}} - L_{90}\right) - \left(L_{\text{r,conf,i}} - L_{90}\right) \\ &= L_{\text{r,NoNoistop,i}} - L_{\text{r,conf,i}}\end{aligned} \tag{2}$$

where, $L_{\text{r,NoNoistop,i}} =$ the rating level obtained from microphone i with no Noistop installed, $L_{\text{r,config,i}} =$ the rating level obtained from microphone i with a given Noistop configuration installed and $L_{90} =$ the background level as defined in BS4142.

Level reduction results presented were averaged across both test sites (and simulations) for "Side Panel", "Front Panel" and "Multiple Panel" installations. **Only** data from microphones with a panel impeding the direct sound were considered, see Figure 3. Upper-frequency limits were introduced to limit the adverse impacts of background noise and, since ASHP noise is primarily low-mid frequency with no significant emission above 8000Hz, see Figure 4. Sound levels were measured between 50 - 3150Hz and 50 - 5000Hz for the outdoor and laboratory measurements respectively.

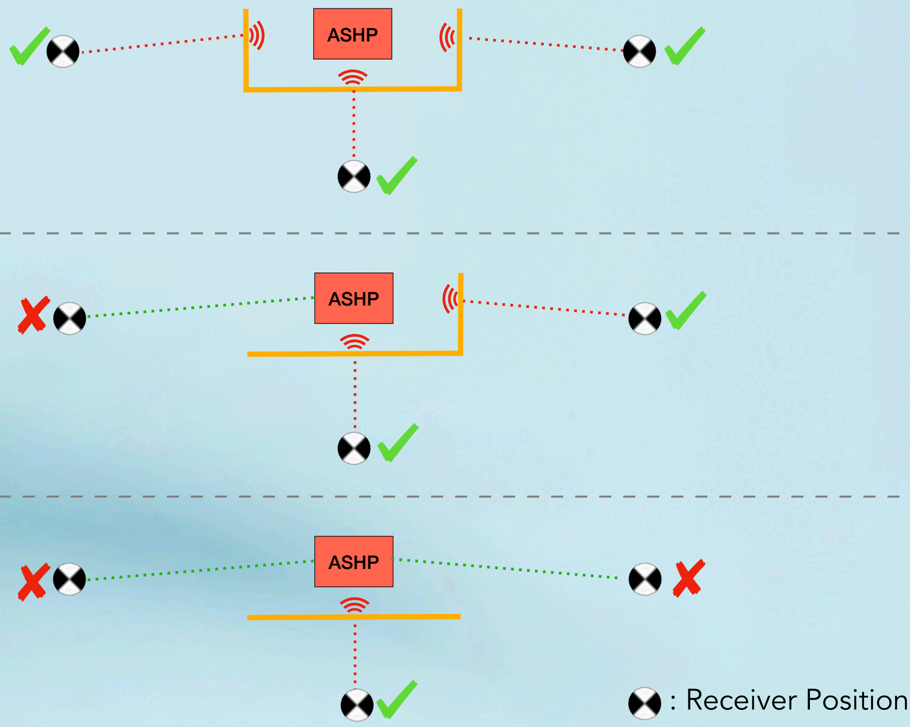


Figure 3 - Diagrams demonstrating line of site criteria.

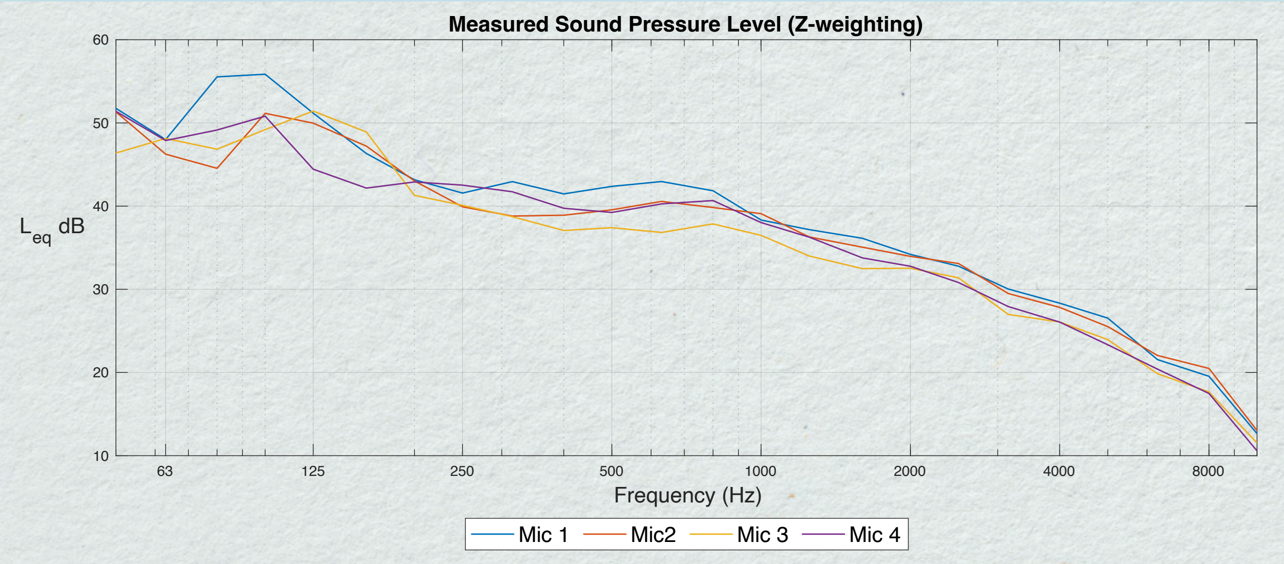


Figure 4 - Third-octave SPLs used to obtain the sound power of the laboratory ASHP.

Case Study Results: Case Study: Side Panel. Height: 1m

Maximum Measured Reduction:

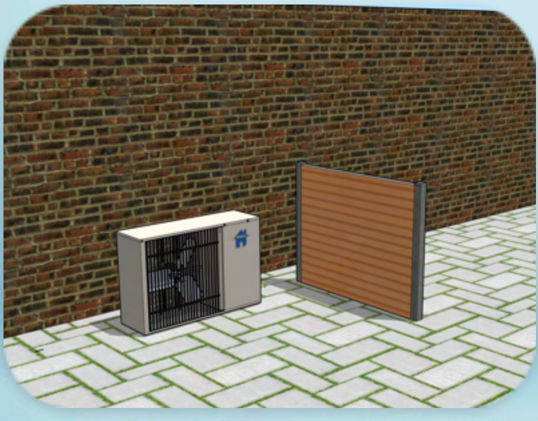
Following the installation of a 1m Noistop Essential panel positioned to the side of the HP, the maximum observed reduction to the measured sound pressure level was:

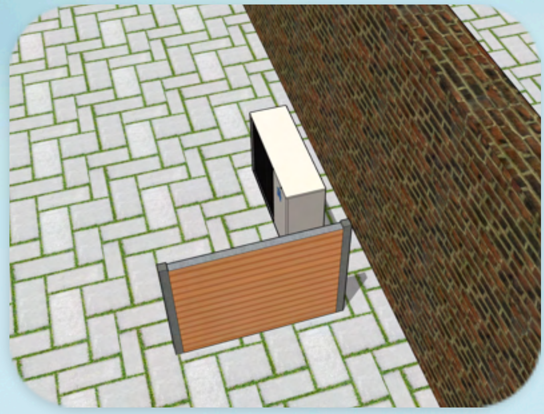
3.7 dB

Average Measured Reduction:

A microphone average from both test sites suggests the expected decibel reduction from installing a 1m Noistop Essential Panel at the side of the HP to be:

2.0 dB





Average BS4142 Impact Reduction:

Considering the level of tonality on the measured signals, a microphone average from both test sites suggests the installation of a 1m Noistop Essential panel at the side could reduce a BS4142 Impact assessment by:

2.0 dB

Max Panel Area:

The amount of Noistop Essential used was:

$1m^2$

Average Simulation Reduction:

Average results from simulations suggest the expected decibel reduction following the installation of a 1m Noistop Essential panel at the side to be:

2.1 dB

Case Study: Side Panel. Height: 2m

Maximum Measured Reduction:

Following the installation of a 2m Noistop Essential panel positioned to the side of the HP, the maximum observed reduction to the measured sound pressure level was:

1.5 dB

Average Measured Reduction:

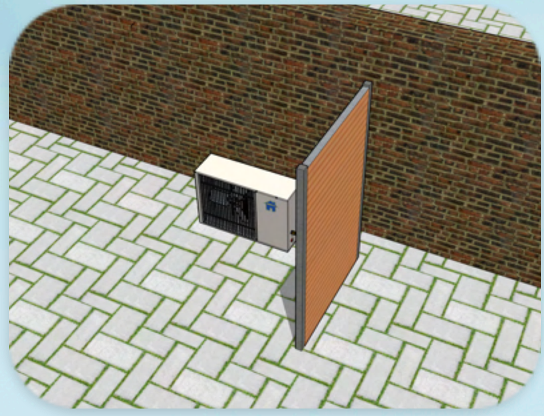
A microphone average from the laboratory test site suggests the expected decibel reduction from installing a 2m Noistop Essential Panel at the side of the HP to be:

1.5 dB

Average BS4142 Impact Reduction:

Considering the level of tonality on the measured signals, a microphone average the laboratory test site suggests the installation of a 2m Noistop Essential panel at the side could reduce a BS4142 Impact assessment by:

1.5 dB



Average Simulation Reduction:

Average results from simulation suggest the expected decibel reduction following the installation of a 2m Noistop Essential panel at the side to be:

3.4 dB

Max Panel Area:

The amount of Noistop Essential used was:

$2m^2$

*NB: Discrepancies between simulated and measured values arise due to lack of test data from the outdoor test site. See discussion.

Case Study: Front Panel. Height: 1m

Maximum Measured Reduction:

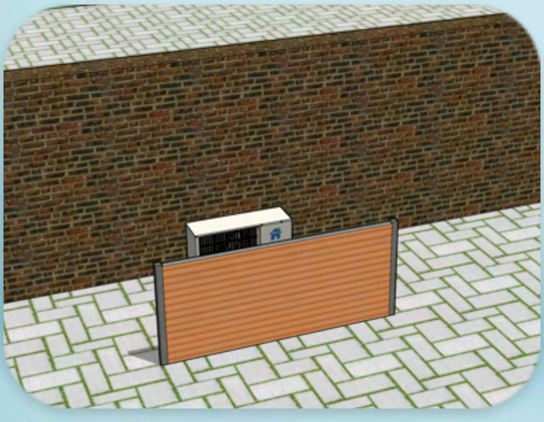
Following the installation of a 1m Noistop Essential panel positioned in-front of the HP, the maximum observed reduction to the measured sound pressure level was:

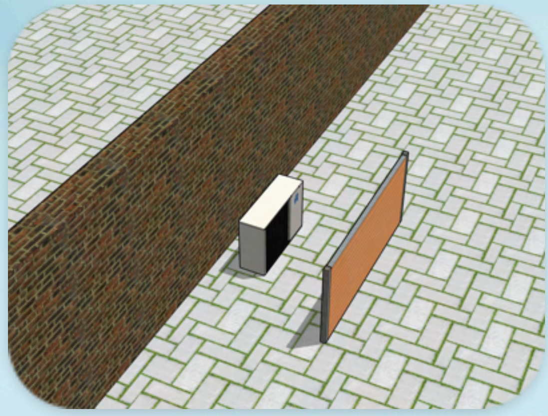
3.2 dB

Average Measured Reduction:

A microphone average from both test sites suggests the expected decibel reduction from installing a 1m Noistop Essential Panel in-front of the HP to be:

2.1 dB





Average BS4142 Impact Reduction:

Considering the level of tonality on the measured signals, a microphone average from both test sites suggests the installation of a 1m Noistop Essential panel in-front of the HP could reduce a BS4142 Impact assessment by:

2.5 dB

Max Panel Area:

The amount of Noistop Essential used was:

2.4m^2

Average Simulation Reduction:

Average results from simulation suggest the expected decibel reduction following the installation of a 1m Noistop Essential panel in-front of the HP to be:

3.3 dB

*NB: Differences between simulated and measured sound levels attributed to diffraction effects. See discussion.

Case Study: Front Panel. Height: 2m

Maximum Measured Reduction:

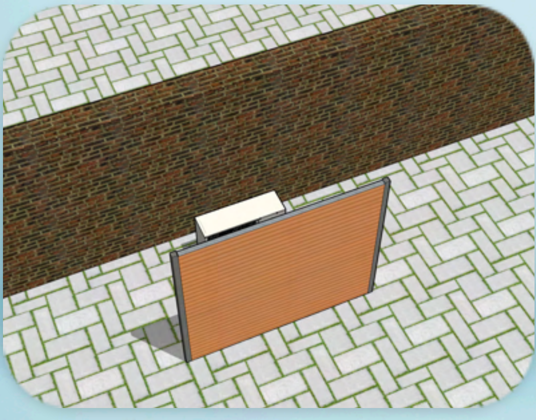
Following the installation of a 2m Noistop Essential panel positioned in-front of the HP, the maximum observed reduction to the measured sound pressure level was:

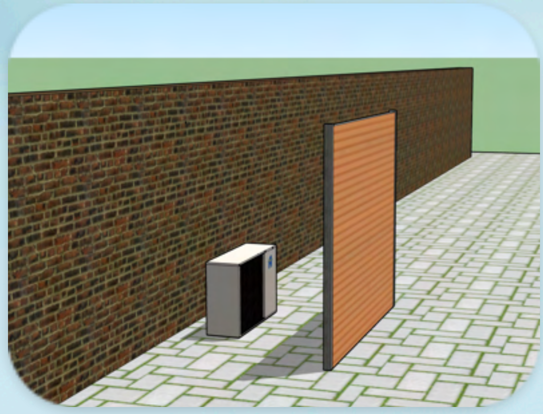
5.1 dB

Average Measured Reduction:

A microphone average from both test sites suggests the expected decibel reduction from installing a 2m Noistop Essential Panel in-front of the HP to be:

3.3 dB





Average BS4142 Impact Reduction:

Considering the level of tonality on the measured signals, a microphone average from both test sites suggests the installation of a 2m Noistop Essential panel in-front of the HP could reduce a BS4142 Impact assessment by:

4.3 dB

Max Panel Area:

The amount of Noistop Essential used was:

$4.8m^2$

Average Simulation Reduction:

Average results from simulation suggest the expected decibel reduction following the installation of a 2m Noistop Essential panel in-front of the HP to be:

4.3 dB

Case Study: Multiple Panels. Height: 1m

Maximum Measured Reduction:

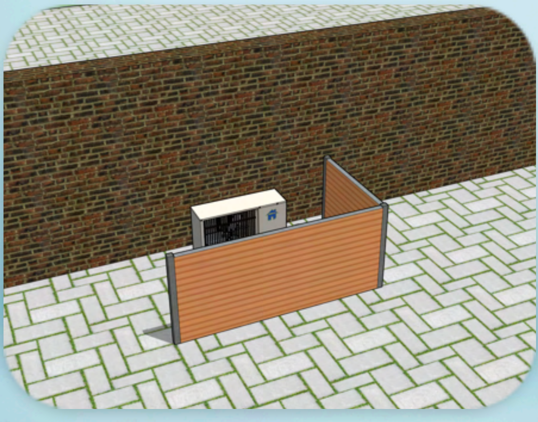
Following the installation of multiple 1m Noistop Essential panels surrounding the HP, the maximum observed reduction to the measured sound pressure level was:

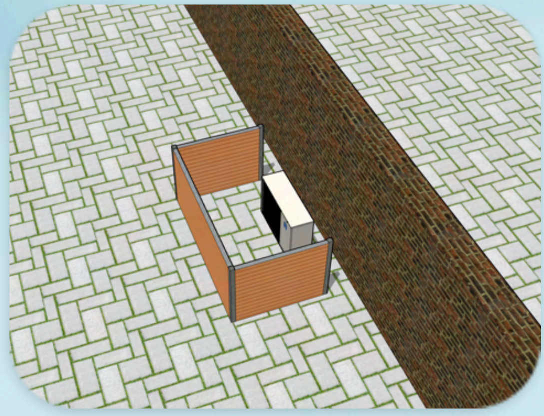
6.6 dB

Average Measured Reduction:

A microphone average from both test sites suggests the expected decibel reduction from installing multiple 1m Noistop Essential panels around the HP to be:

4.1 dB





Average BS4142 Impact Reduction:

Considering the level of tonality on the measured signals, a microphone average from both test sites suggests the installation of multiple 1m Noistop Essential panels surrounding the HP could reduce a BS4142 Impact assessment by:

5.3 dB

Max Panel Area:

The amount of Noistop Essential used was:

4.8m^2

Average Simulation Reduction:

Average results from simulation suggest the expected decibel reduction following the installation of multiple 1m Noistop Essential panels surrounding of the HP to be:

5.7 dB

Case Study: Multiple Panels. Height: 2m

Maximum Measured Reduction:

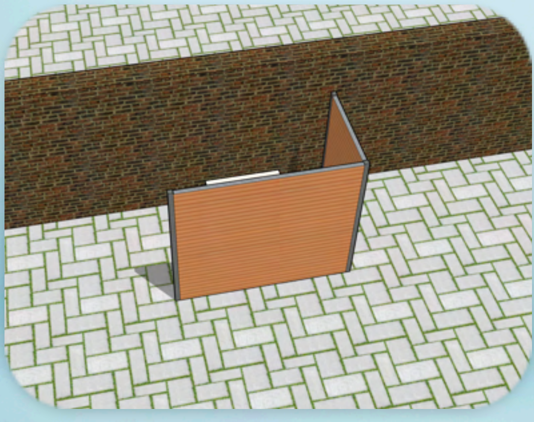
Following the installation of multiple 2m Noistop Essential panels surrounding the HP, the maximum observed reduction to the measured sound pressure level was:

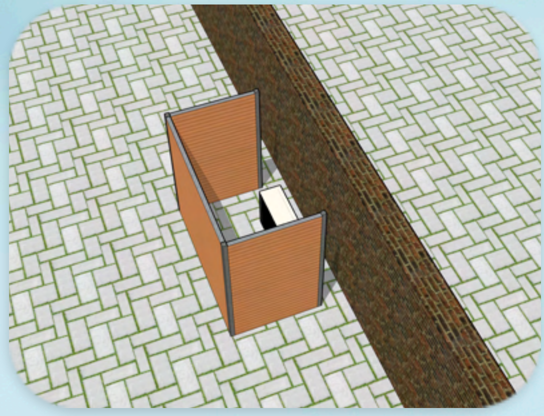
9.1 dB

Average Measured Reduction:

A microphone average from both test sites suggests the expected decibel reduction from installing multiple 2m Noistop Essential panels around the HP to be:

6.2 dB





Average BS4142 Impact Reduction:

Considering the level of tonality on the measured signals, a microphone average from both test sites suggests the installation of multiple 2m Noistop Essential panels surrounding the HP could reduce a BS4142 Impact assessment by:

7.8 dB

Max Panel Area:

The amount of Noistop Essential used was:

9.6m^2

Average Simulation Reduction:

Average results from simulation suggest the expected decibel reduction following the installation of multiple 2m Noistop Essential panels surrounding of the HP to be:

7.9 dB

Case Study: Results Figures

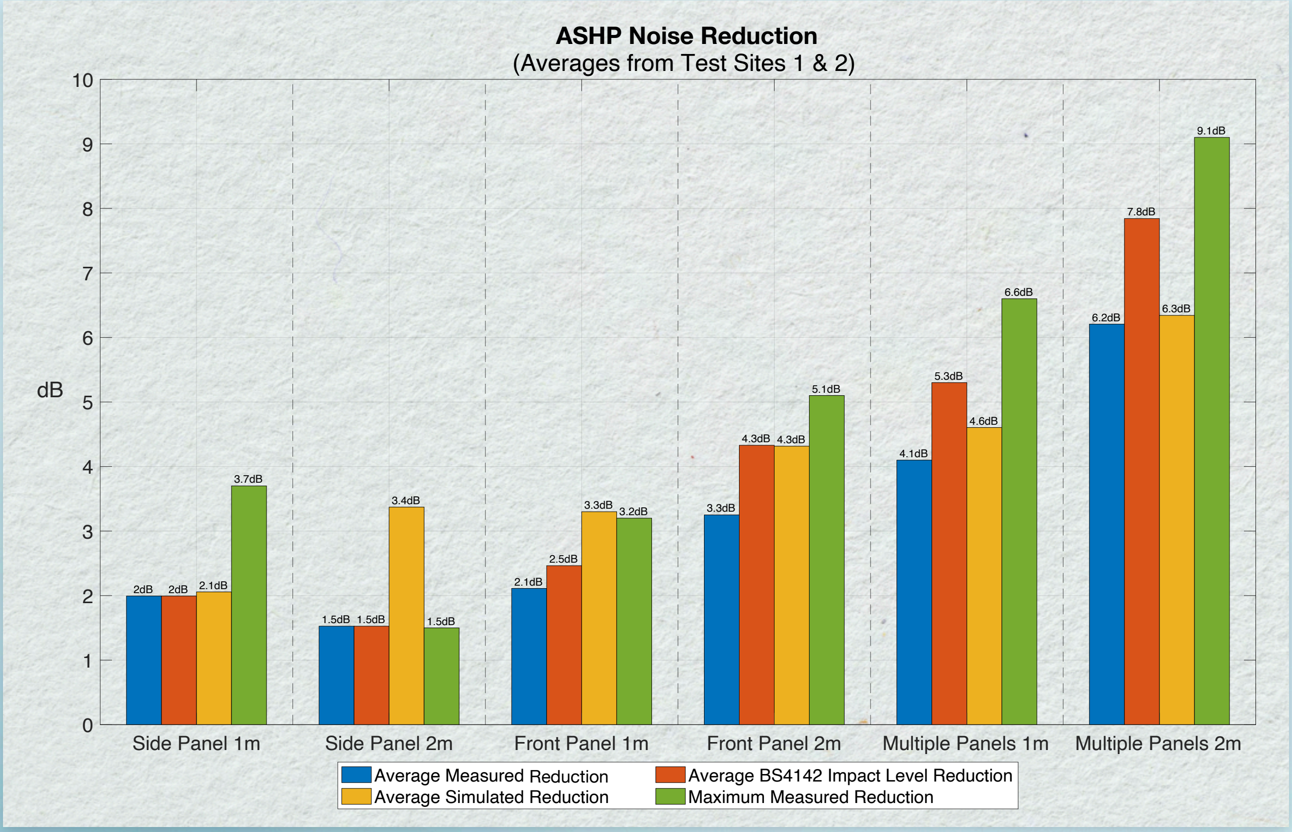


Figure 5 - Case study ASHP Noise reduction results obtained from both test sites

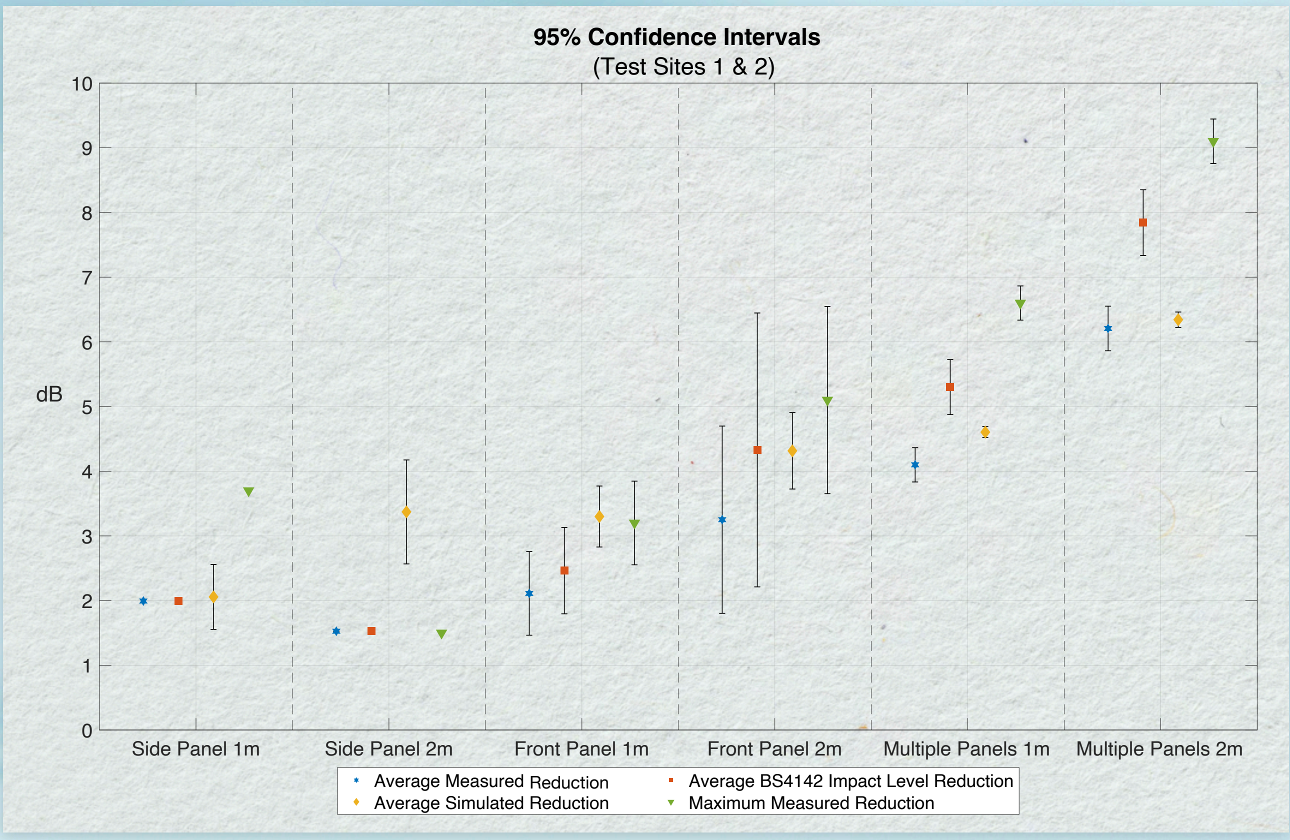


Figure 6 - Case study ASHP Noise reduction results obtained from both test sites with 95% confidence intervals presented.

Case Study Discussion:

Results obtained from the two case studies highlight how an increase in panel area leads to a greater reduction in ASHP Noise. Results for the "Side 2m" trials deviate from this trend due to the lack of measured data available from the outdoor test site. Consequently, the results seen only represent the laboratory sound levels. As this was an indoor reverberant sound field, results were influenced by long reverberation times $\left(1s < R_{T15} < 3s \text{ , see Figure A.11}\right)$. Despite corrections being applied independently for each configuration and microphone position, responses with and without Noistop will have been subjected to similar corrections. In effect, this improves the accuracy of the measured level in contrast to a free field measurement but does not completely "undo" the effects of the reverberation on the perceived ASHP noise reduction. Had results from test site 1 been obtained, the "Side 2m" result would likely lie between the average measured result and the simulation: i.e 1.5dB < Side 2m < 3.4dB.

Even when excluding these results, simulations suggest a higher ASHP noise reduction than the average measured results. The analytical method used in CadnaA is based on BS ISO 9613-2, where it is acknowledged that "a barrier may be less effective than calculated … as a result of reflections from other acoustically hard surfaces near the sound path from the source to the receiver or by multiple reflections between an acoustically hard barrier and the source" [11]. Although reverberation effects from the laboratory conditions have been accounted for, their effects on the calculated sound levels have not been accurately considered by the simulations (due to the limitations of BS ISO 9613-2). Consequently, barriers appear more effective in simulation than physical measurements suggest.

This effect is most significant for the Front panel results *(excluding Side 2m results)*, whereby differences of 1.2dB and 1dB are observed for the 1m and 2m trials respectively. Measured results obtained for the Front panels have been most affected by reverberation in the laboratory as these responses were obtained from a microphone located approximately mid-way between two acoustically reflecting surfaces, see Figure 7. Reflections beyond those simulated (4th order) will have contributed significantly to measured sound levels at this position, reducing the effectiveness of the Noistop Essential barrier. When compiling these results with those from the outdoor location, a large distribution of data is obtained, leading to the long error bars seen in Figure 6. While a reverberant environment is unrepresentative of many outdoor locations, it does provide insight into how these enclosure designs may perform when located in between two neighbouring houses or down a small alleyway. In such locations, reflections affect the perceived sound [12], hence it is useful to have an averaged assessment of acoustic performance in non-reverberant and reverberant settings.

The largest measured ASHP noise reductions were 6.6dB and 9.1dB from the 1m and 2m Multiple panel results respectively. Average results show 4.1dB and 6.2dB respectively. As sound is radiated in 360^o from the ASHPs, sound energy is reflected off the wall [2] and escaping through openings in the side of the enclosure. Attenuation could likely be increased by extending the side panels to the wall. The effectiveness of this is explored in the "additional enclosures" section of the report.

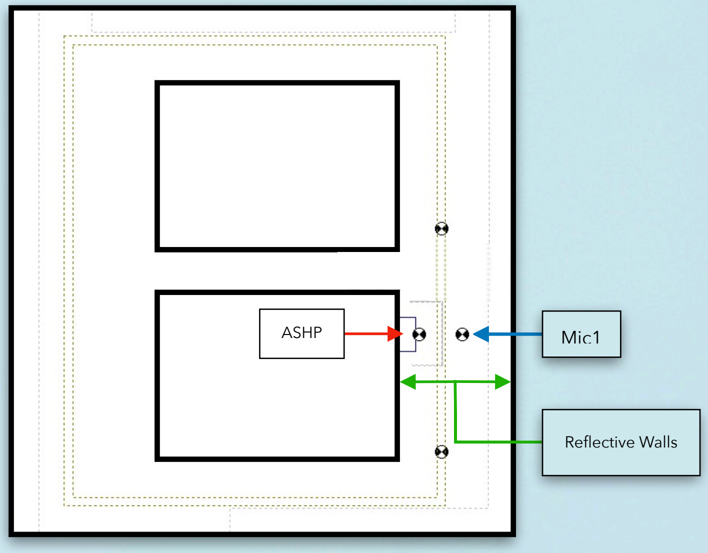


Figure 7 - Reflecting surfaces affecting results for Front panel at the laboratory test site.

Both Multiple panel results show good agreement with simulation, likely due to a large portion of sound at the receiver locations being comprised of sound transmitted through the barrier. If most reflections remain within the enclosure, limitations in the analytical barrier calculations (BS ISO 9613-2) are minimised due to screening effects being reduced.

It is worth reiterating that **only** microphones/receiver locations with a barrier impeding the direct sound were considered in the results, see Figure 4. Where a direct sound path was possible, measured and simulated results showed a little reduction in the ASHP noise. As such, it is advised to assess locational requirements for sound attenuation and use these as a guide for optimal barrier installation.

Average BS4142 Impact reduction results demonstrate how the different acoustic barrier installations can alter the tonal properties of the measured sound. Results suggest that an increase in panel area leads to a greater impact reduction, implying a reduction in the tonal content of the measured sound. Low-frequency tones are a topic of discussion within heat pump noise control [13], and this result suggests that the acoustic barrier enclosures could be used as a post-installation tool to mitigate certain reported issues.

Additional Enclosures:

Designs:

Agreement between simulated and measured results from both case studies suggests reliability in the modelling methods used. From this, additional simulations have been conducted to further understand the effects differing panel areas/enclosure designs have on the ASHP noise attenuation. Excluding enclosure design, all other simulation parameters were the same as those used to obtain results from the original case studies i.e ASHP sound power, ASHP geometry, test site geometry, Noistop acoustic characteristics and receiver locations. The CAD drawings below present examples of the additional design groups tested. Detailed diagrams can be found in the appendix, see Figures A.5 - A10

Original Configuration Group: Front Panel: **2.4m** | Side Panel: **1.2m**

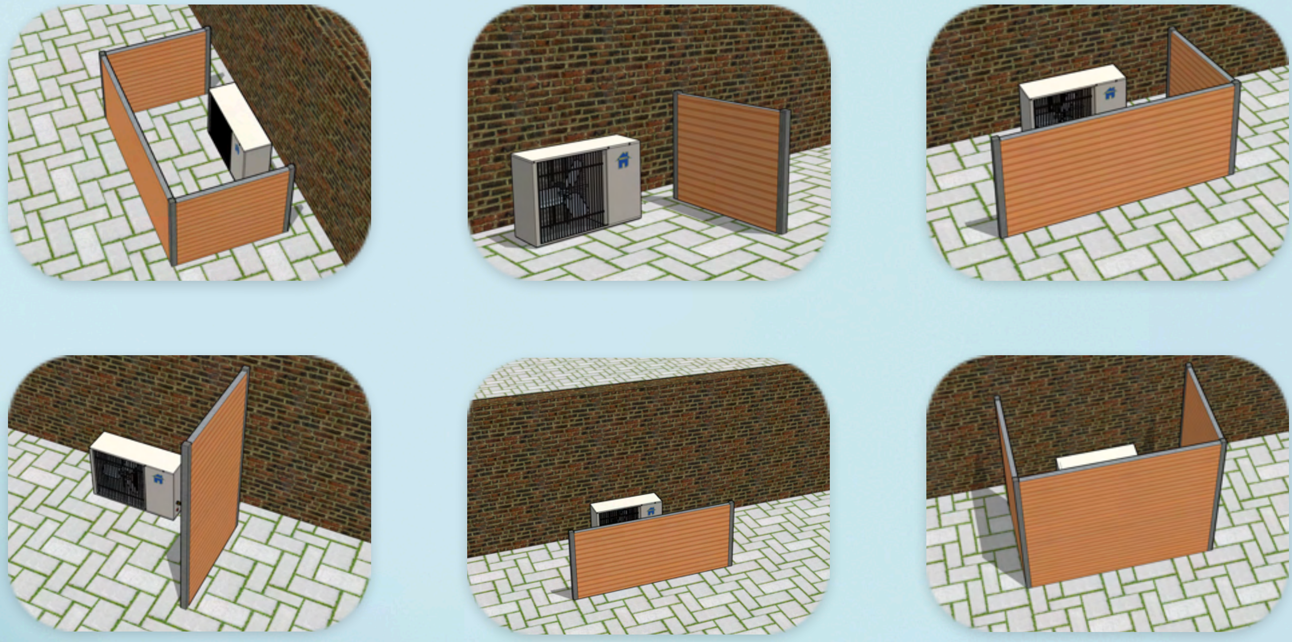


Figure 8 - Original Configuration examples. *Top Left* - 1m U-shape (Multiple Panel). *Top Middle* - 1m Side. *Top Right* - 1m L-Shape (Multiple Panel). *Bottom left* - 2m Side. *Bottom Middle* - 1m Front. *Bottom Right* - 2m U-shape (Multiple Panel)

Configuration Group A: Front Panel: **1.8m** | Side Panel: **1.2m**

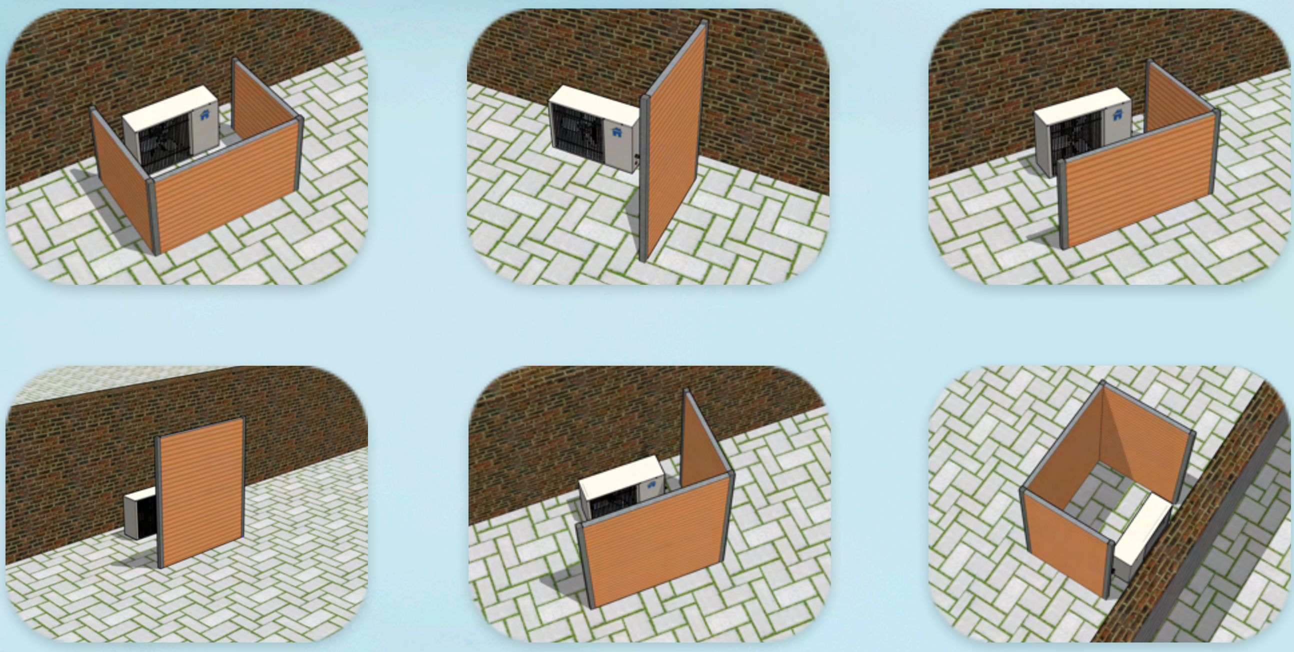


Figure 9 - Configuration Group A examples. *Top Left* - 1m L-shape (Multiple Panel). *Top Middle* - 2m Side. *Top Right* - 1m L-shape (Multiple Panel). *Bottom left* - 2m Front. *Bottom Middle* - 2m L-shape (Multiple Panel). *Bottom Right* - 2m U-shape (Multiple Panel)

<u>Configuration Group B:</u> Front Panel: **1.8m** | Side Panel: **0.6m**

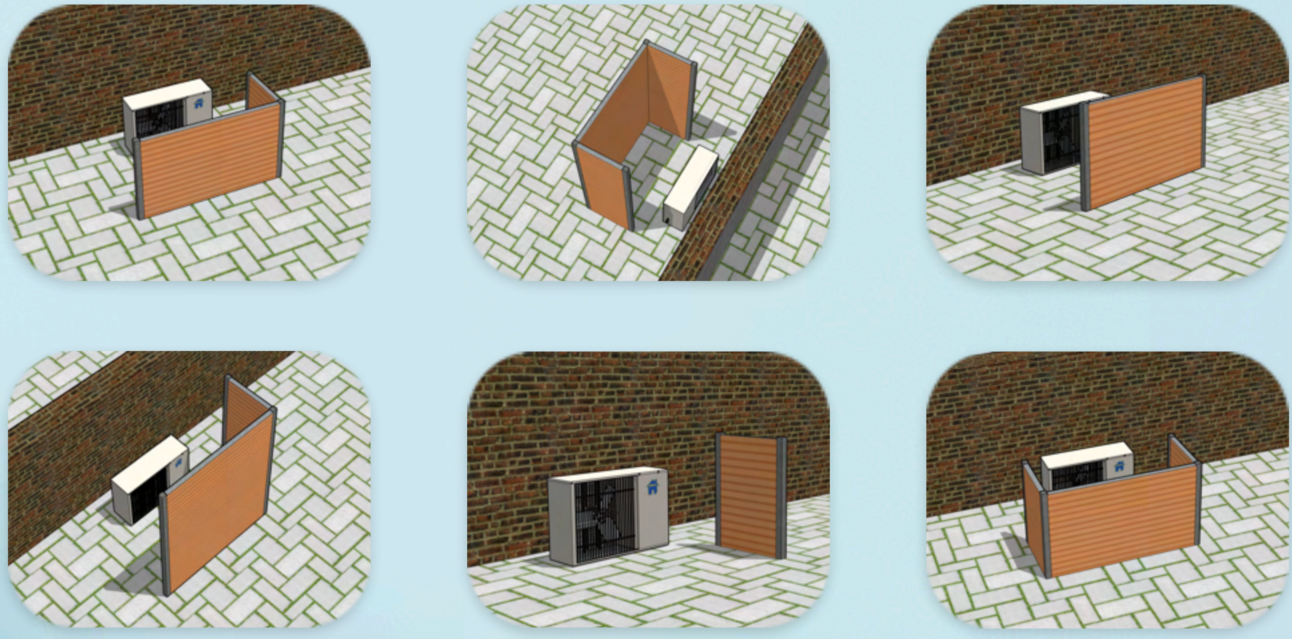


Figure 10 - Configuration Group B examples. *Top Left* - 1m L-shape (Multiple Panel). *Top Middle* - 2m U-shape (Multiple Panel). *Top Right* - 1m Front. *Bottom left* - 2m L-shape (Multiple Panel). *Bottom Middle* - 1m Side. *Bottom Right* - 1m U-shape (Multiple Panel)

<u>Configuration Group C:</u> Front Panel: **1.8m** | Side Panel: **1.8m**

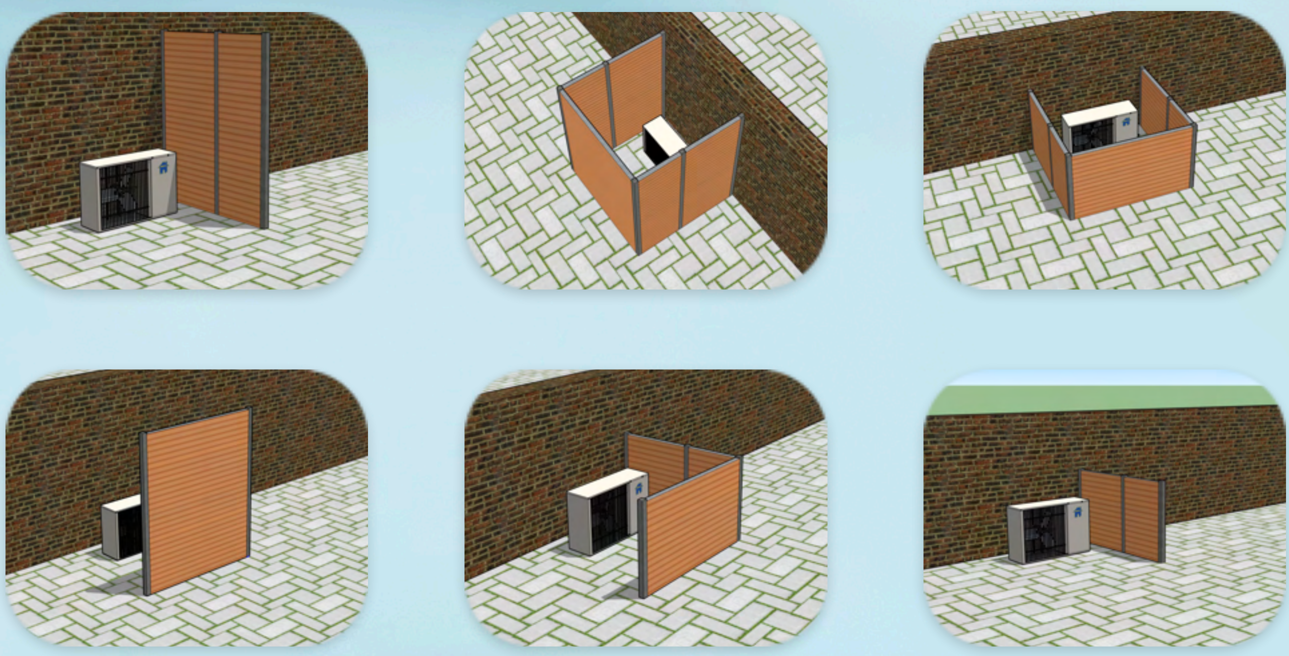


Figure 11 - Configuration Group C examples. *Top Left* - 2m Side. *Top Middle* - 2m U-shape (Multiple Panel). *Top Right* - 1m U-shape (Multiple Panel) . *Bottom left* - 2m Front. *Bottom Middle* - 1m L-shape (Multiple Panel). *Bottom Right* - 1m Side.

Results: Figures

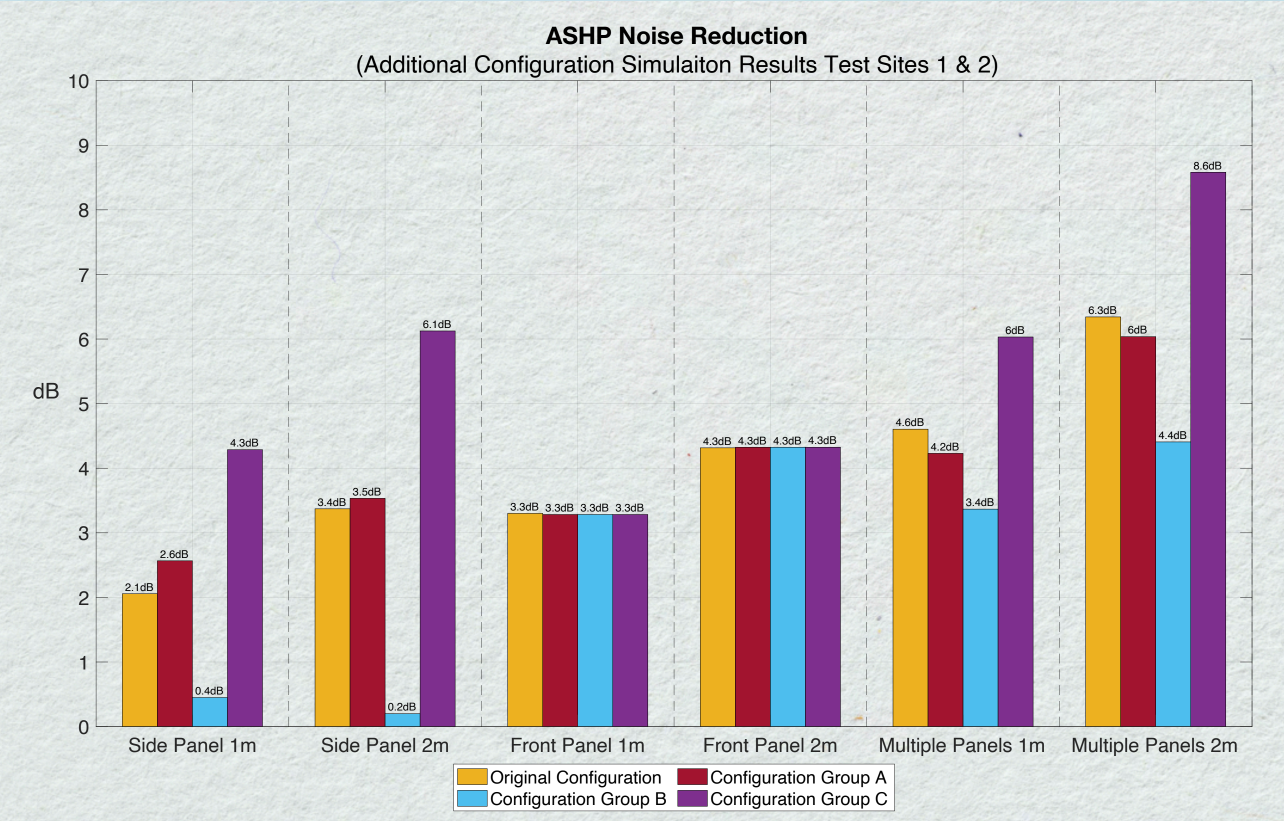


Figure 12 - Simulated ASHP Noise reduction results obtained for different configuration groups.

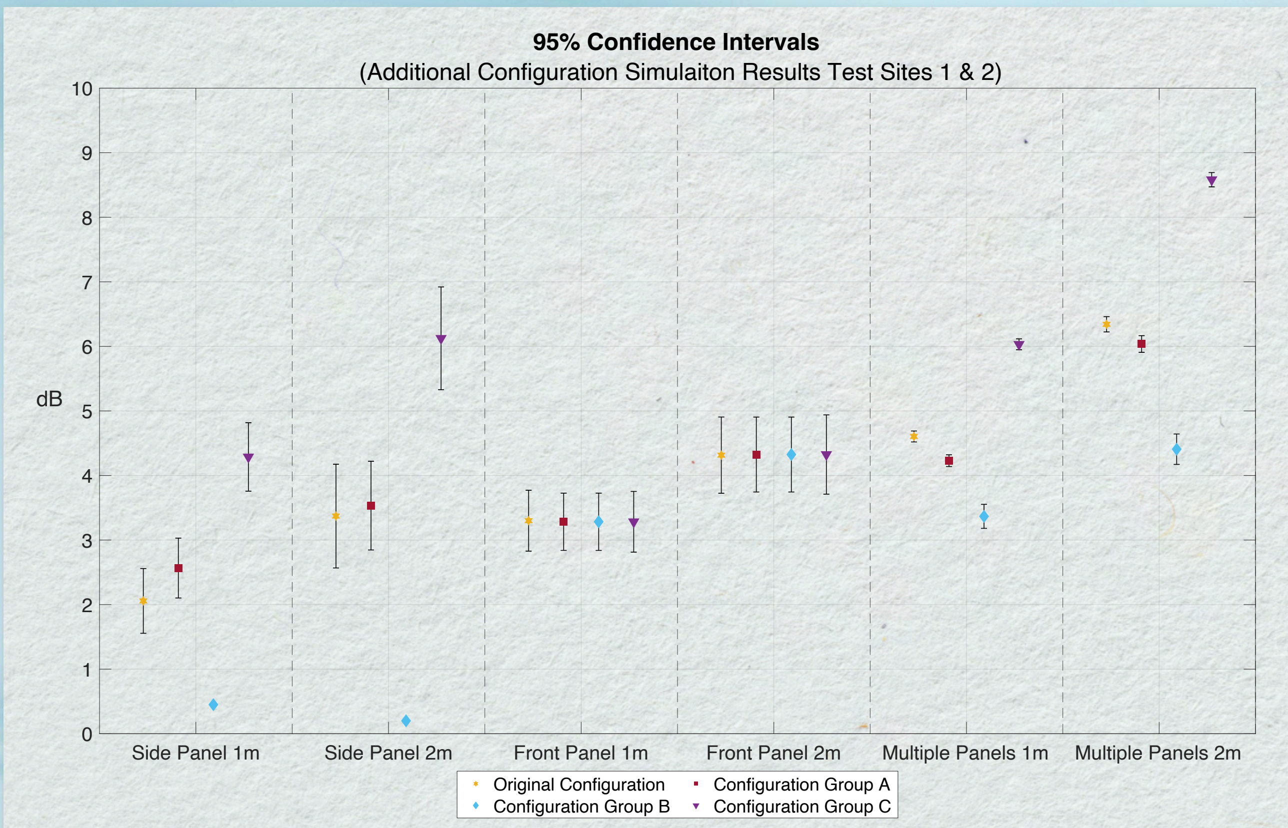


Figure 13 - Simulated ASHP Noise reduction confidence intervals obtained for different configuration groups.

Discussion:

Additional simulation results help expose how the length of the side panels affects the overall ASHP noise attenuation. Results from configuration Group A share the most similarities to results obtained using the original configuration. Explanations for this are the equal-sized openings shared between the wall and the end of the Noistop barrier since both are comprised of 1.2m sides. The marginally lower reductions are likely observed for configuration Group A due to smaller panel surface areas resulting in less absorption.

Results obtained for Group B show the poorest response. Again, the reasons for this can be attributed to the large opening between the end of the Noistop panel and the wall (0.6m side panels). Contrastingly, the opposite is observed when analysing Group C results, where the enclosure extends up to the wall. Excluding all Front panel results *(where Group A, B & C all share the same configuration)*, Group C exhibits the largest ASHP noise reduction out of all simulated results. Where installations would not compromise manufacturers' installation guidelines, it does appear that there is a significant value to be gained (2.3dB) from installing acoustic barriers up to the wall. Due to access requirements, it is not advised to permanently install an enclosure restricting access to the heat pump. Future products available from iKoustic may include a hinged acoustic barrier which could alleviate this issue.

It is worth noting similarities between the Front panel results in Figures 12 - 13. Despite the original configuration having a 2.4m front panel vs all subsequent simulations having 1.8m, these results show the same decibel reduction. Physical measurements would likely not exhibit the same behaviour due to the effects of diffraction. Furthermore, only receiver positions free from direct sound have been considered. For smaller panel designs, this results in fewer receivers which abide by this criteria. As such, despite responses showing similar decibel reductions, the effective area in which this reduction may expect to be measured reduces with smaller panel designs, see Figures 14 - 16. With this in mind, the following installation guidelines are suggested.

Installation Guidelines:

Based on the findings of this study, the following recommendations are suggested for those seeking to install acoustic barriers to control ASHP air-borne noise. Discussions before installation should focus on establishing clear objectives regarding areas where noise reduction is required. Once clarified, a better understanding of enclosure design can be gained. While these recommendations can provide guidance, individual factors such as the ASHP model, local climate and background noise level will alter how any given installation may perform.

<u>Consider Assessment Location:</u>

The location of the required ASHP noise reduction has a significant influence on the enclosure design. Since this is likely to be an area versus a specific point, the extremities of this area should be located. Similar to the MCS standard [14], a line of sight between the back of the ASHP and the assessment area extremities should be established. If located next to a wall, the line of sight between the wall and the assessment area should be established, see Figures 14 - 16.

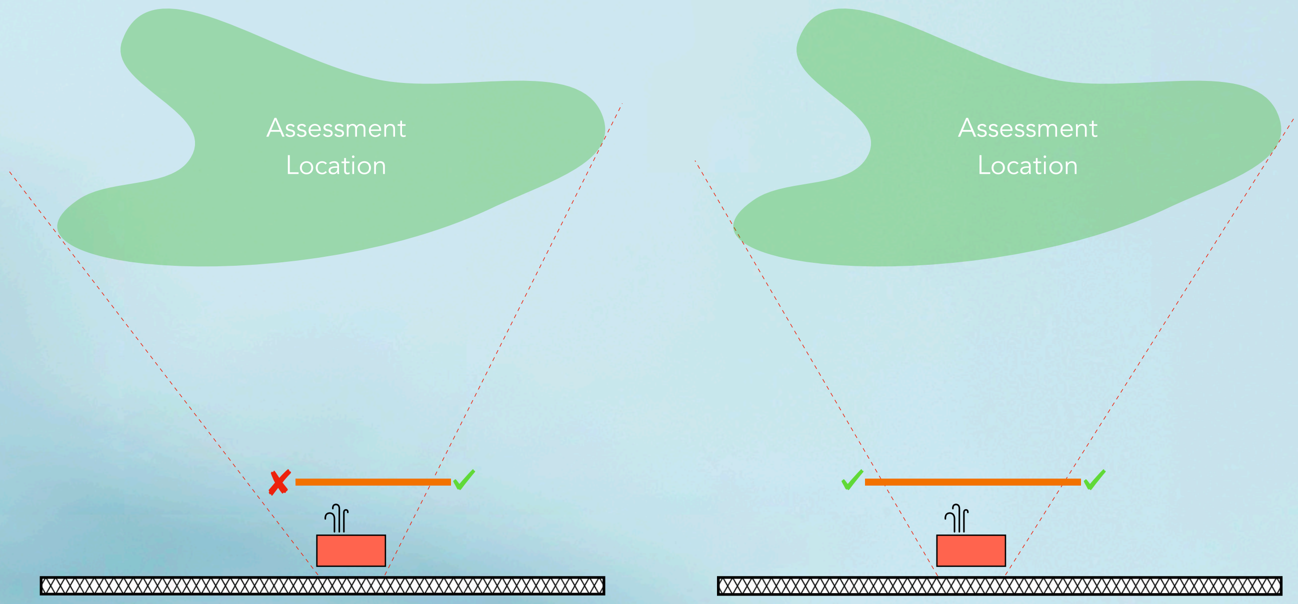


Figure 14 - *Left* - Iinitial panel design fails to meet requirements. *Right* - Iinitial panel design meets requirements.

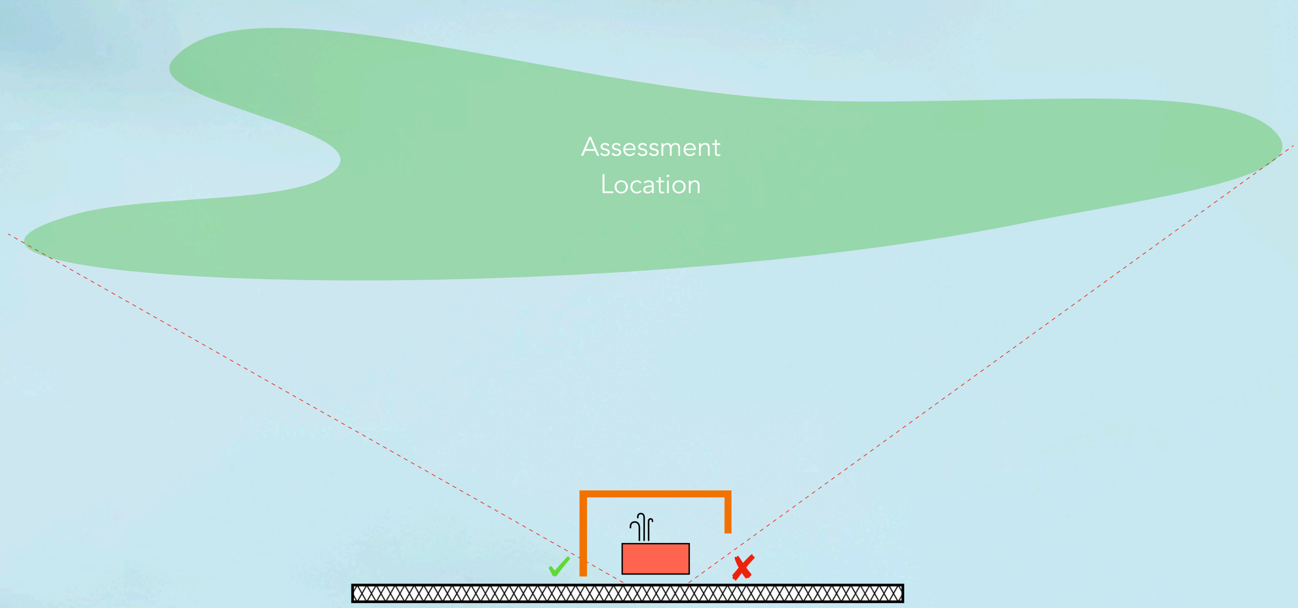


Figure 15 - Due to the wide angle, a multiple-panel (U-shape) enclosure may be the most practical solution to meet the initial panel requirements. The left-hand side meets requirements, however, the right-hand side fails to obstruct a direct line of sight, as such this side should be extended.

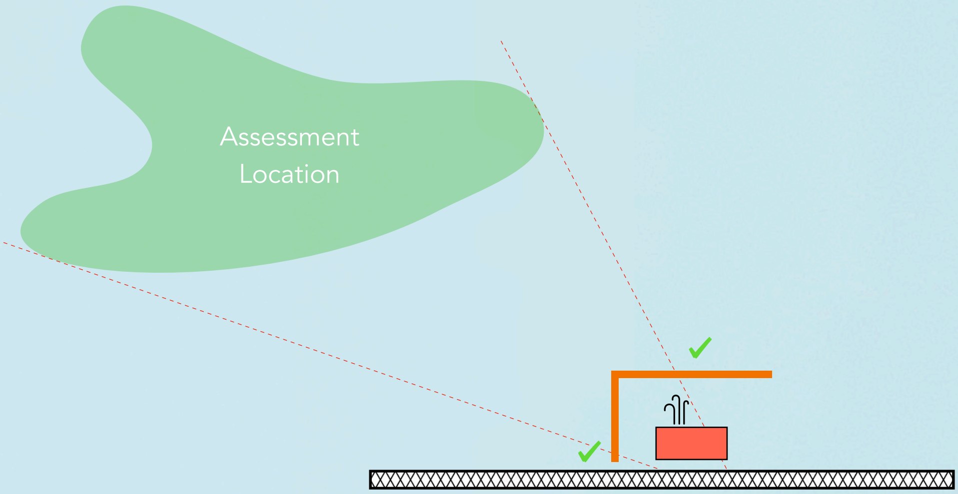


Figure 16 - Due to the assessment area being off centre to the HP installation, a Multiple panel (L-shape) enclosure may be the most practical solution to meet the initial panel requirements.

Consider ASHP Location & Size:

Depending on the size and location of the ASHP, the acoustic barrier requirements may vary. Enclosure designs installed near two reflective planes *(such as those tested i.e the floor & the wall)* will likely exhibit similar acoustic responses to those seen throughout this report. Installations next to three reflective planes may require additional panels to reduce any reflective effects, see Figure 17.

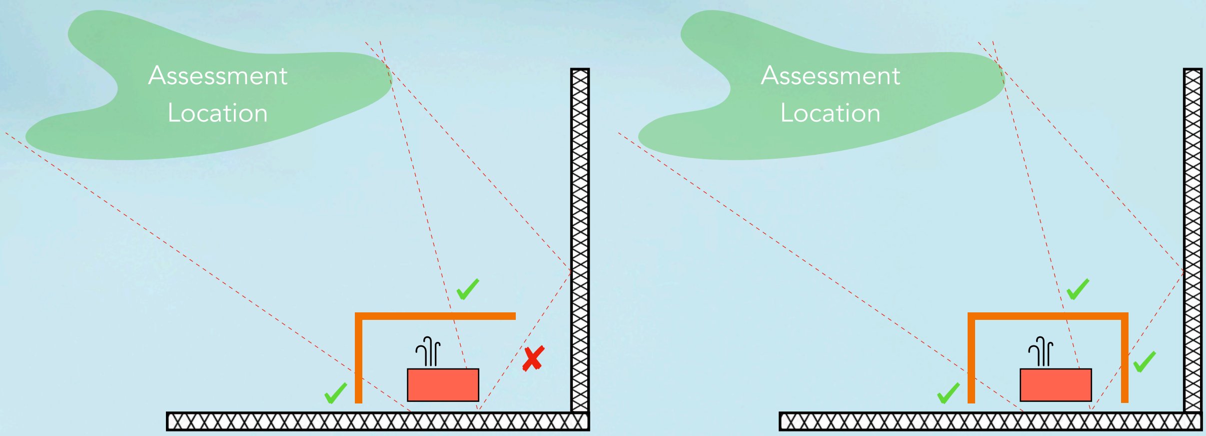


Figure 17 - Suggested enclosure design for three reflective planes. Left - Reflective effects from the wall remain untreated, SPL reduction may be compromised. Right - Absorbing, acoustic barrier installed in front of the reflecting plane, potentially minimising SPL doubling effect.

Where the ASHP is installed away from buildings, reflections will only be induced by the ground. In such cases, the line-of-sight method should be implemented to establish suitable panel designs. ASHP installations exceeding 1m in height should seek to install 2m enclosures, thus eliminating any vertically elevated line of sight.

Consider Required Magnitude Reduction:

Once the assessment location is established, the magnitude of the desired attenuation should be discussed. While the line of site is useful in understanding the minimum enclosure requirements, ASHP noise reduction results presented throughout this report should then be consulted. Due to reflection and diffraction effects, single-panel designs adhering to the line of site guidelines may exhibit lower ASHP noise reductions than required. In such cases, multiple panel designs will likely be required. Simulation results suggest ASHP noise attenuation can be maximised when designs extend to the wall, as such, this enclosure design is recommended where cost and space permit. Additionally, all results obtained from 2m high enclosures surpass their 1m counterparts, hence where large ASHP noise reductions are desired, 2m high enclosures are likely necessary.

Conclusions & Further Work:

Findings from this report reveal how Noistop Essential performs as a post-installation passive acoustic solution to air-borne ASHP noise. Measurements and simulations both highlight the effects of increased panel area on the magnitude of ASHP noise attenuation. Furthermore, additional simulation results suggest that attenuation may be improved by extending enclosure designs to the wall, however, this has not been validated with measurement.

Certain permitted developments which fail current UK noise regulations may benefit from tailored acoustic barrier designs. Installation guidelines presented primarily utilise the "line of sight" method to establish initial barrier requirements due to research findings. An additional consequence of this is that MCS assessments will receive more favourable outcomes due to the contractor's view of the assessment location being obstructed by the acoustic barrier. Furthermore, BS4142 impact assessment results highlight how the tested enclosures reduced the penalty weighting when following the Joint Nordic Method, potentially increasing the likelihood of positive BS4142 assessment outcomes.

Heat pumps are part of the UK Government's strategy to reach net zero carbon emissions by 2050 [1, 2]. Having an adaptable, residentially suited post-installation noise control solution may provide more opportunity for the continued use and new approval of permitted developments. Results suggest that when configured optimally, Noistop Essential may lead to similar attenuation as custom-manufactured acoustic enclosures, however, without breaching manufacturers' guidelines on nearby reflecting surfaces. Further research should seek to better understand the influence *(if any)* these enclosures have on the Coefficient of performance (COP). Additionally, measurements should be repeated at more sites to further understand how nearby reflecting surfaces, heat pump designs, heat pump operating cycle (defrost vs normal) and climatic conditions affect the performance of the suggested enclosure designs. Simulations could also be developed using Finite Element / Boundary Element software to capture the effects of diffraction and improve the agreement between measured and simulated values.

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Appendix:

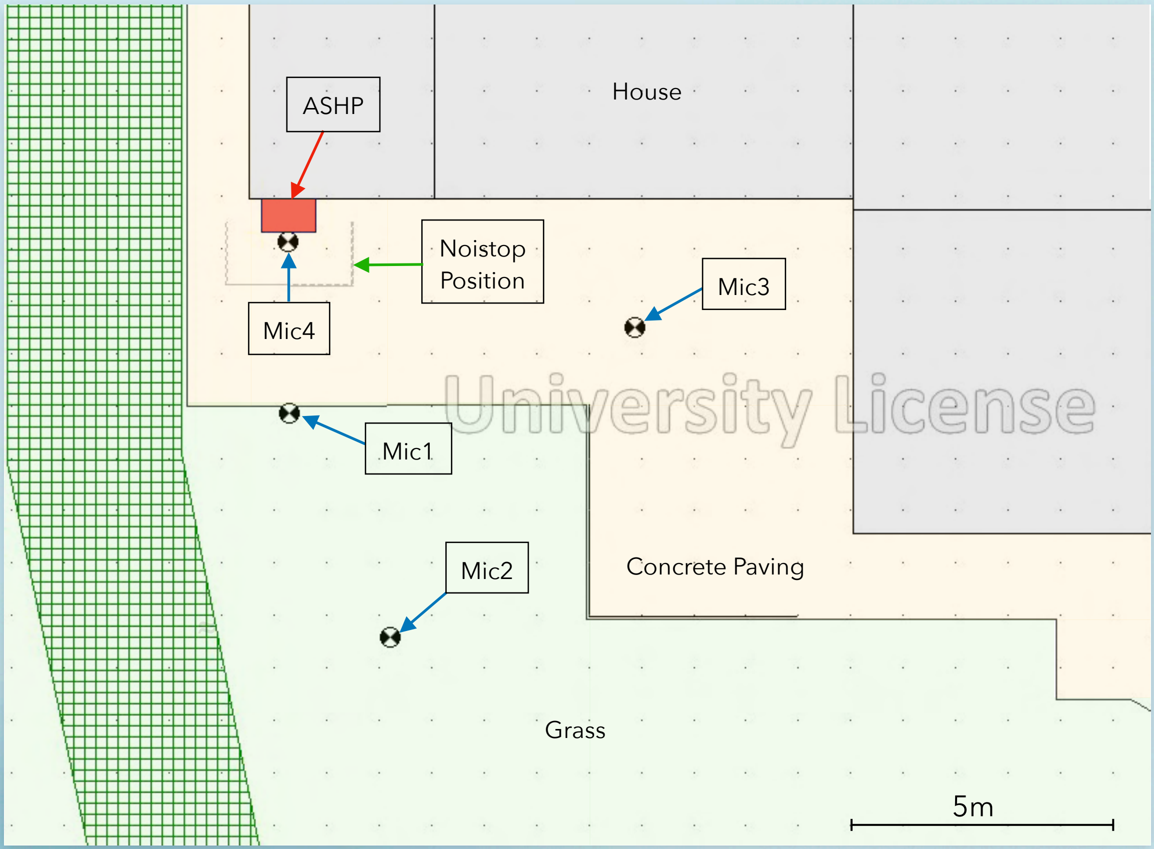


Figure A.1 - Export from CadnaA demonstrating an arial view of the outdoor test location.

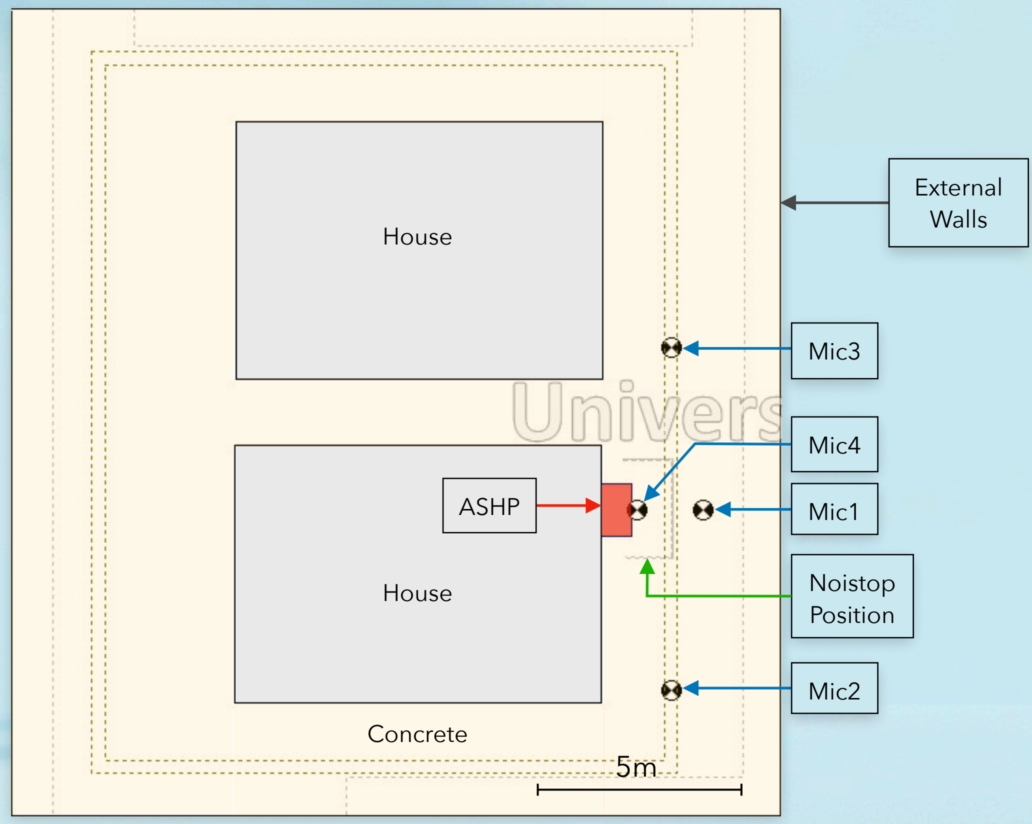


Figure A.2 - Export from CadnaA demonstrating an arial view of the laboratory test location.

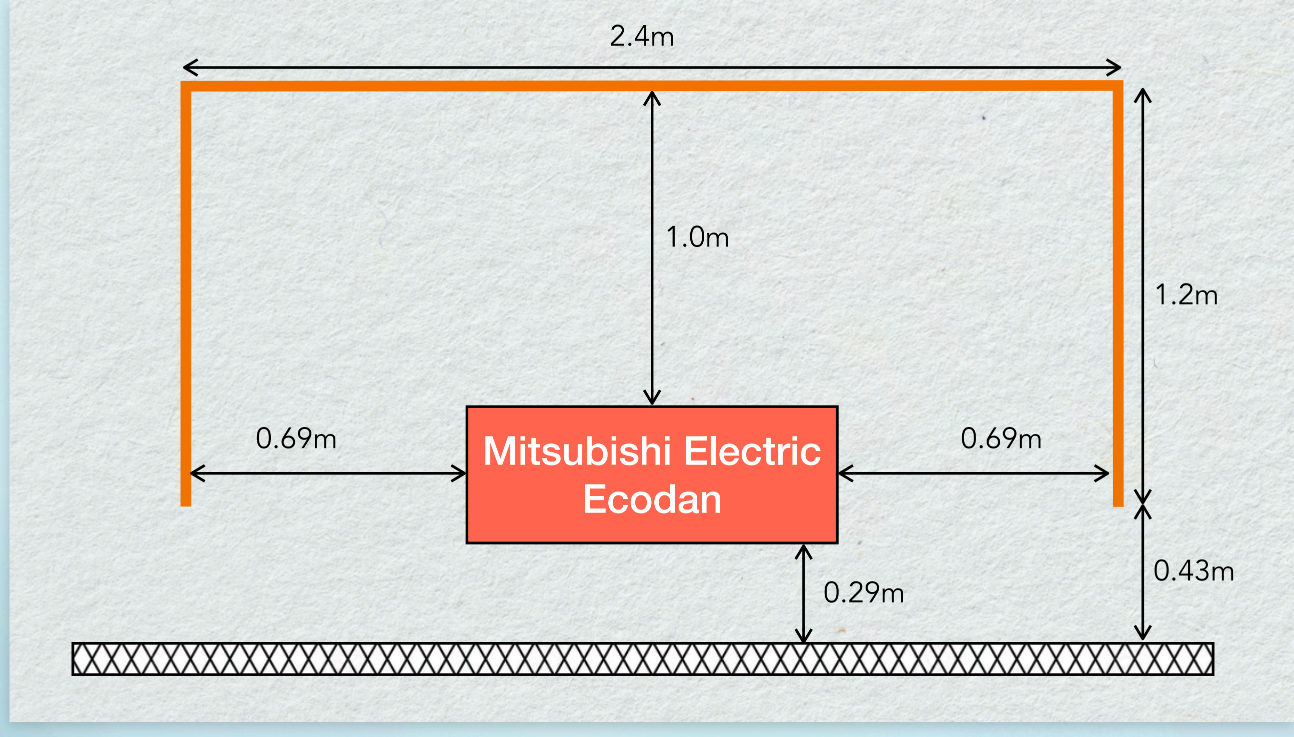


Figure A.3 - ASHP / Noistop original configuration at the outdoor test site, arial view *(Physical Tests).*

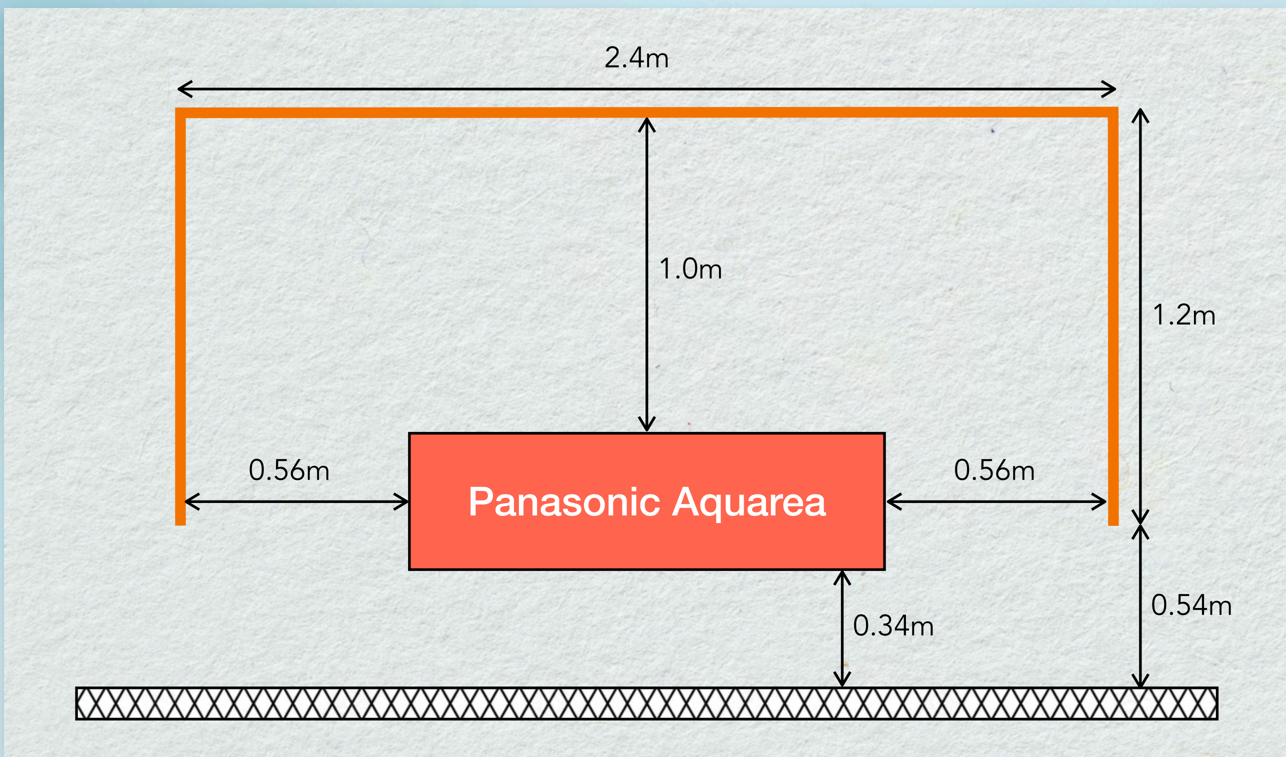


Figure A.4 - ASHP / Noistop original configuration at the laboratory test site, arial view *(Physical Tests).*

Key:

: Wall

: Heat Pump

: Noistop

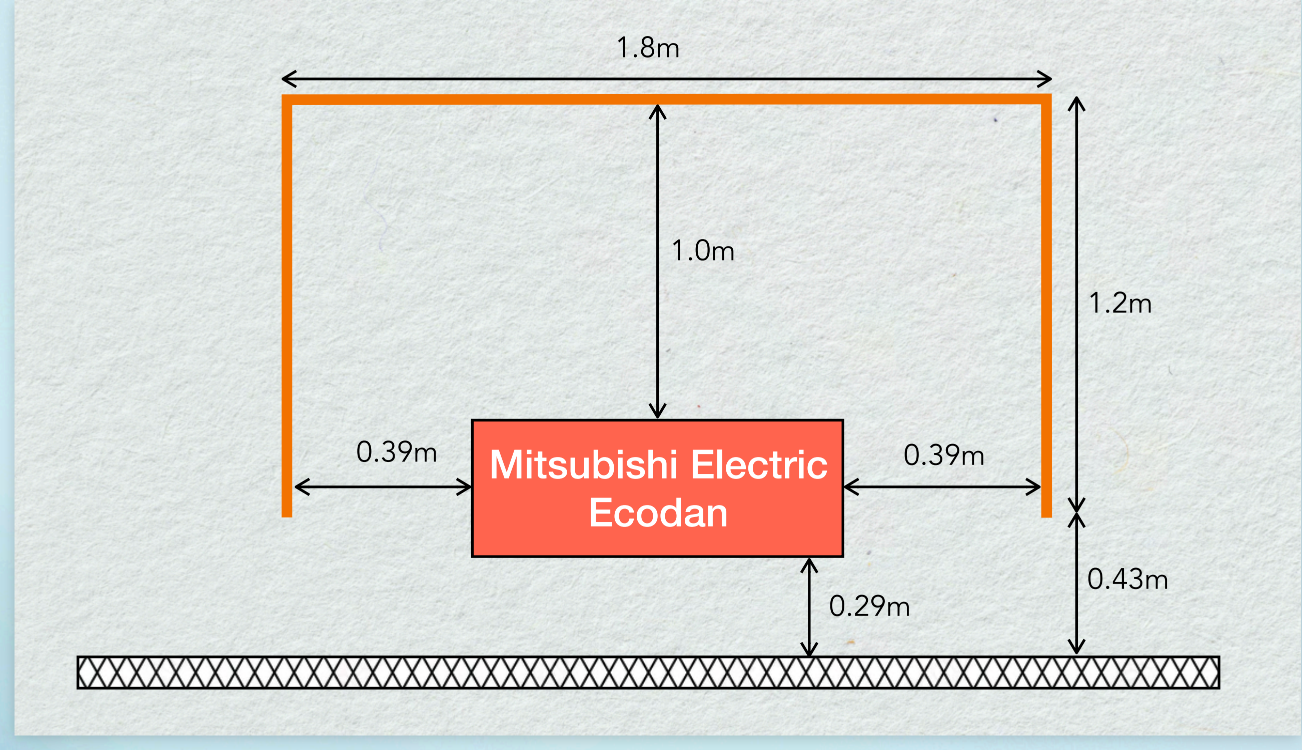


Figure A.5 - ASHP / Noistop configuration A, outdoor test site, arial view (*Additional Simulations)*

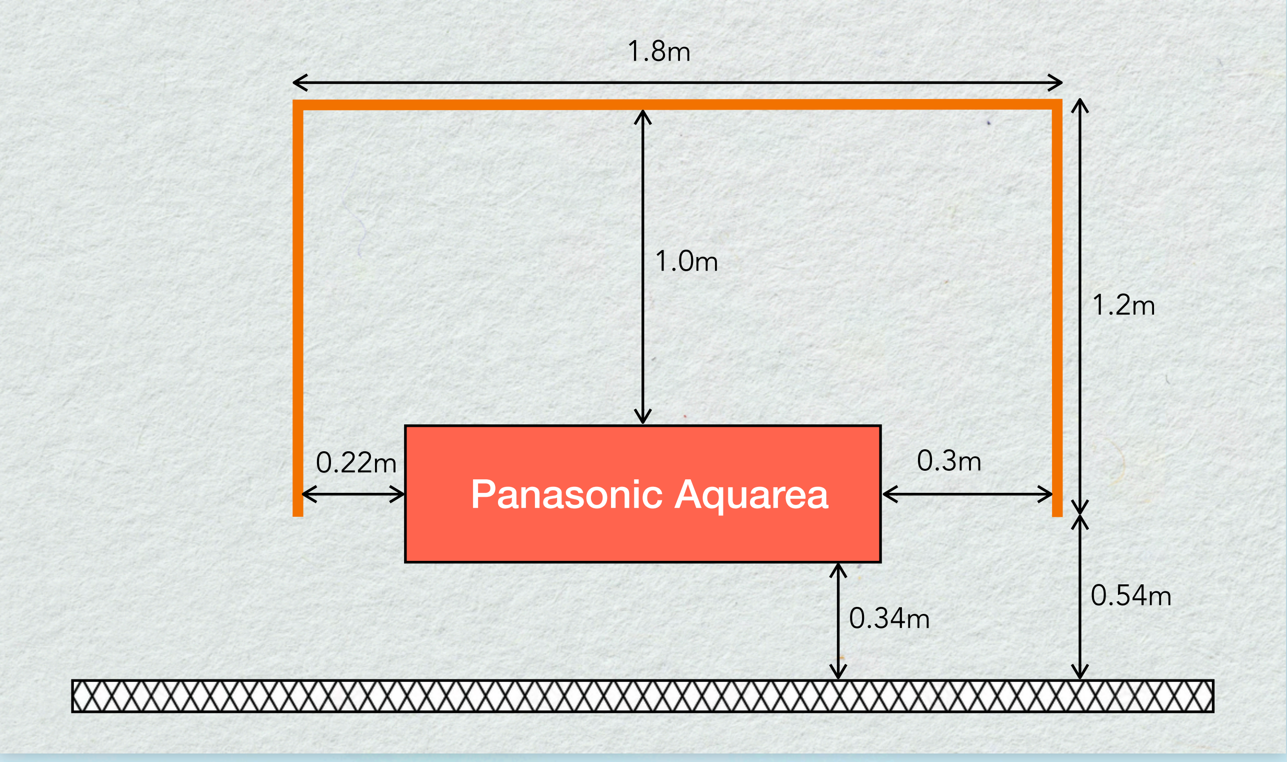
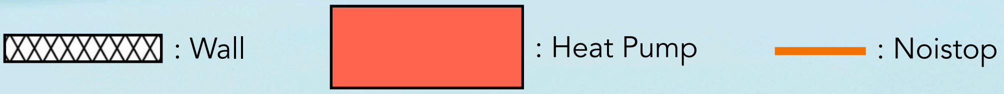


Figure A.6 - ASHP / Noistop configuration A, indoor test site, arial view (*Additional Simulations)*

Key:



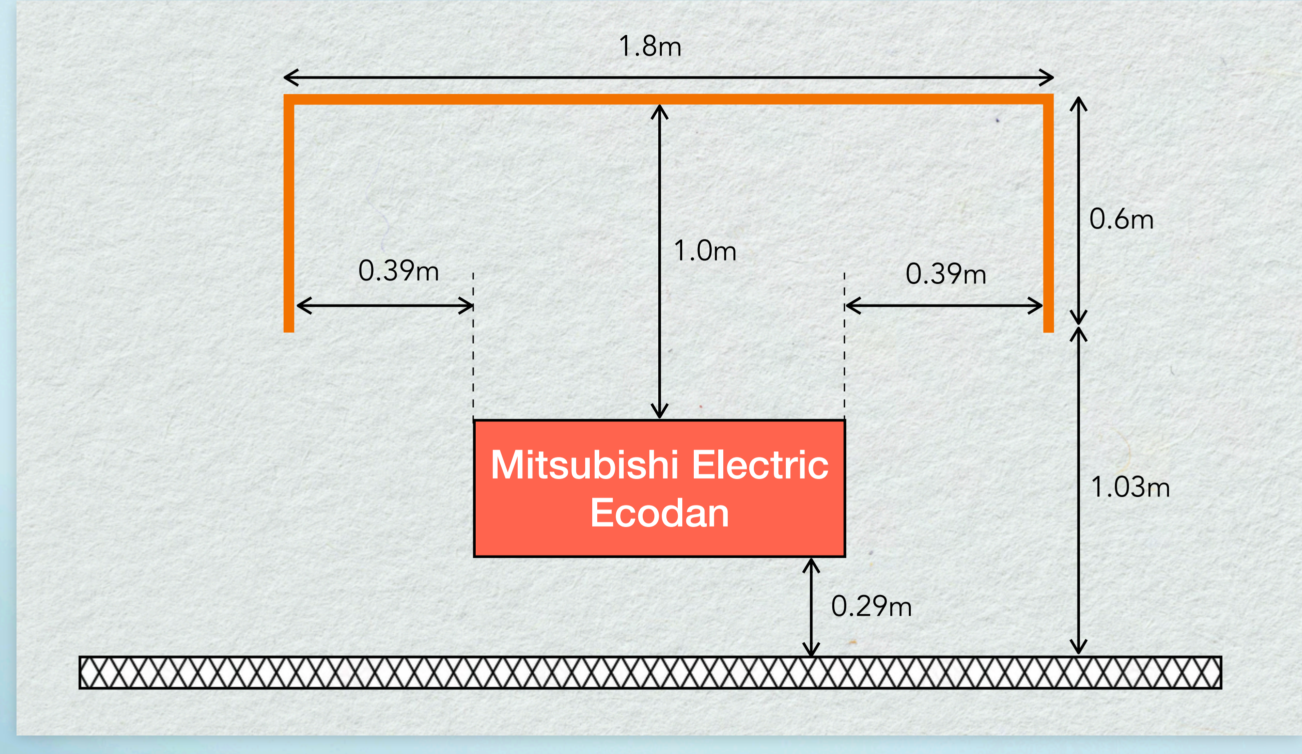


Figure A.7 - ASHP / Noistop configuration B, outdoor test site, arial view (*Additional Simulations)*

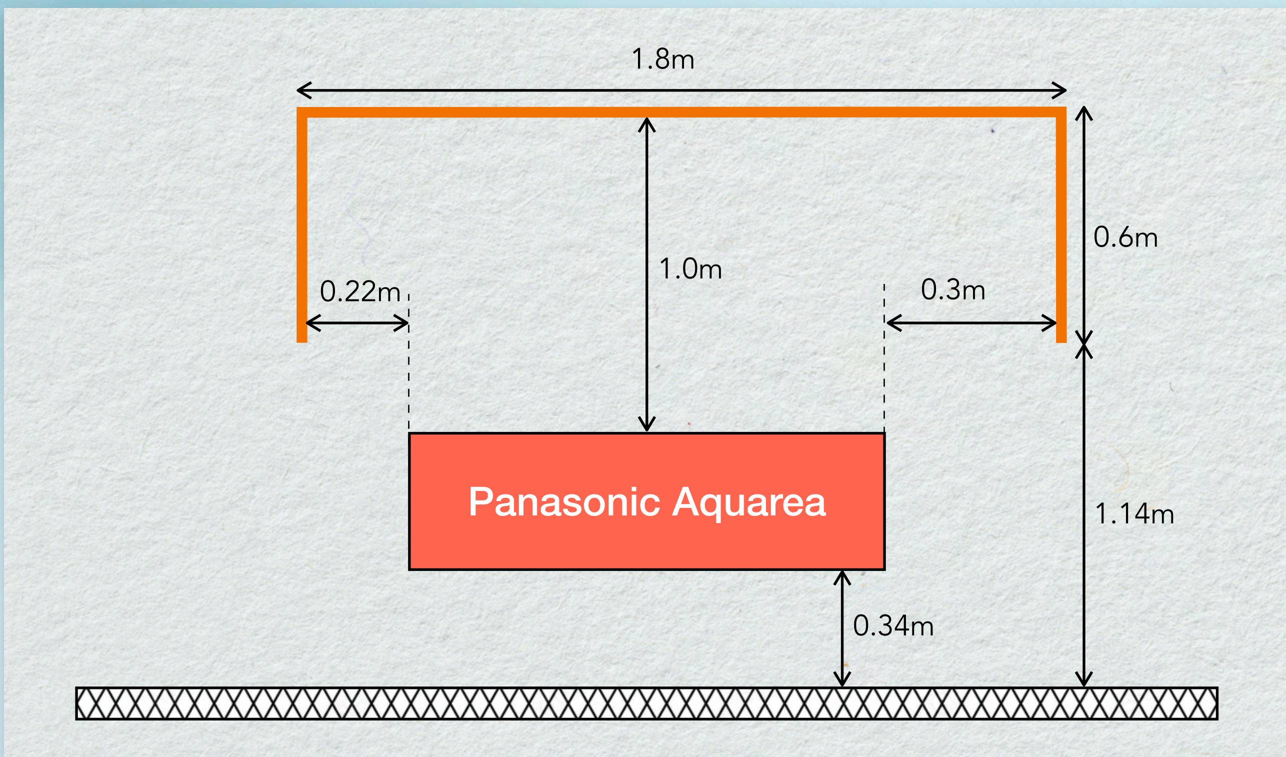


Figure A.8 - ASHP / Noistop configuration B, indoor test site, arial view (*Additional Simulations)*

Key:

: Wall

: Heat Pump

: Noistop

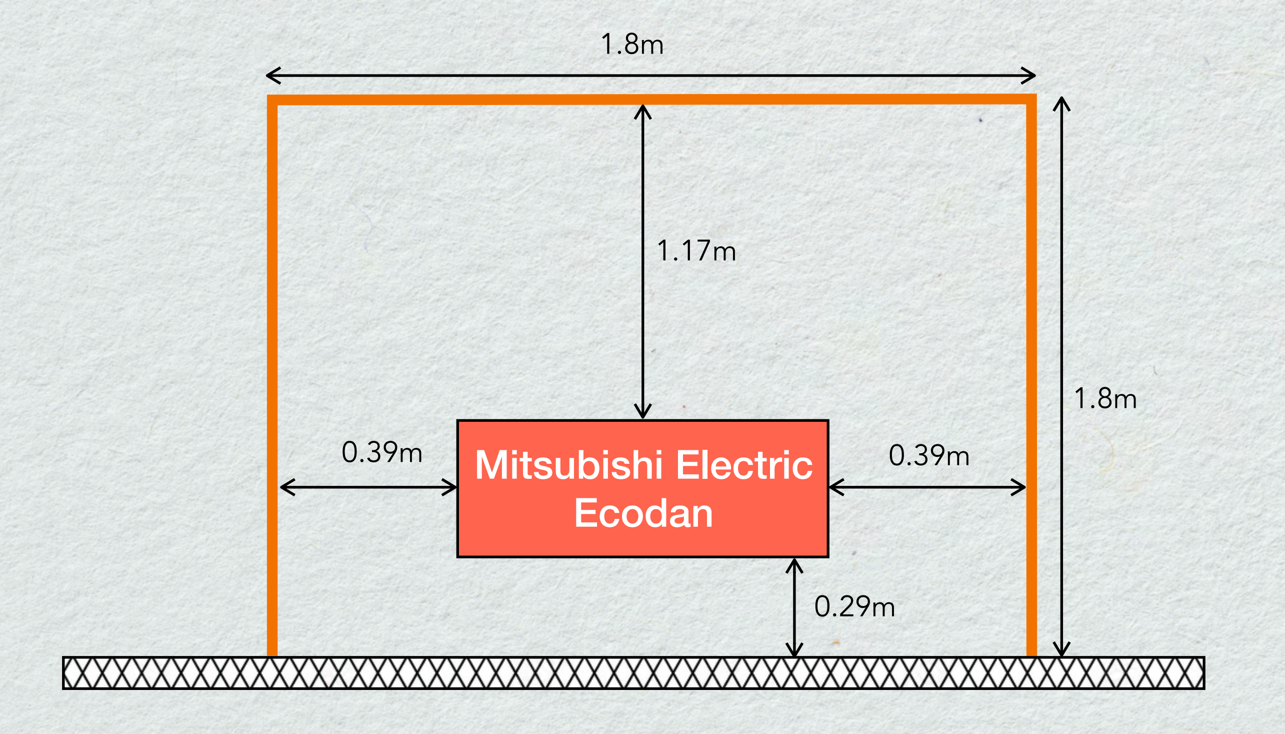


Figure A.9 - ASHP / Noistop configuration C, outdoor test site, arial view (*Additional Simulations)*

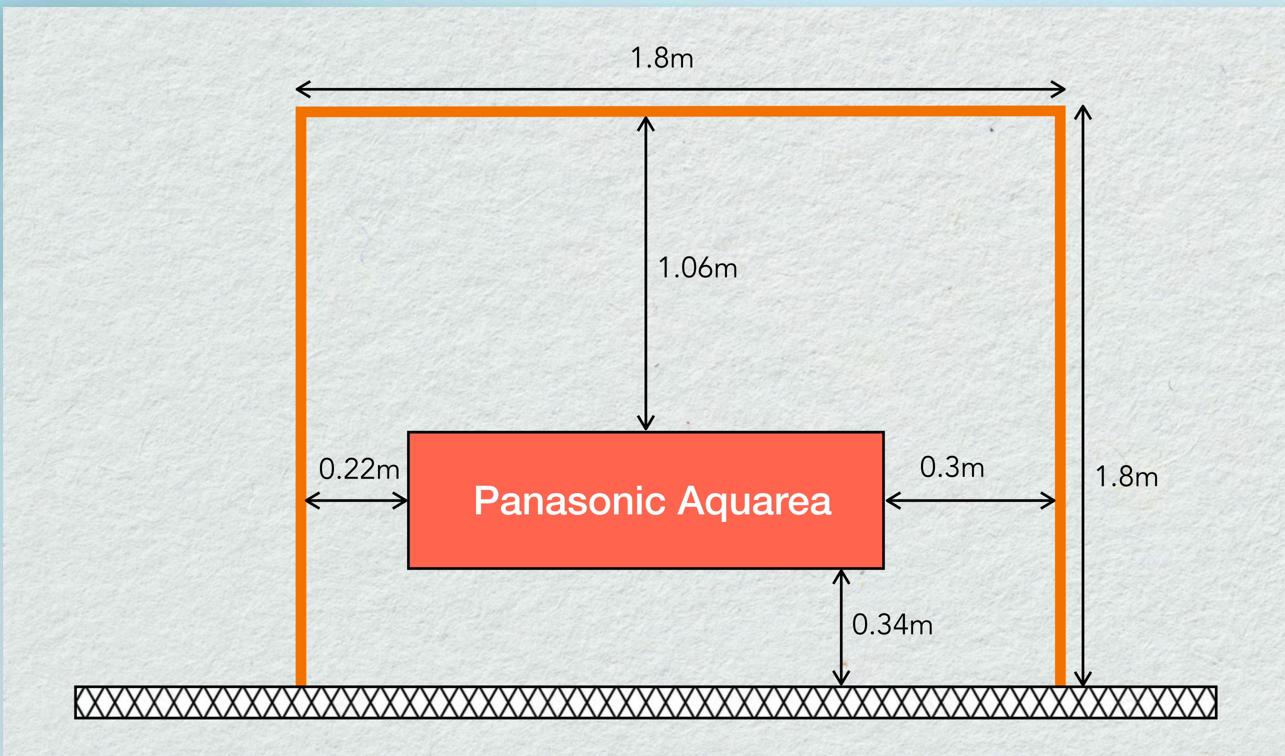


Figure A.10 - ASHP / Noistop configuration C, indoor test site, arial view (*Additional Simulations)*

Key:

: Wall

: Heat Pump

: Noistop

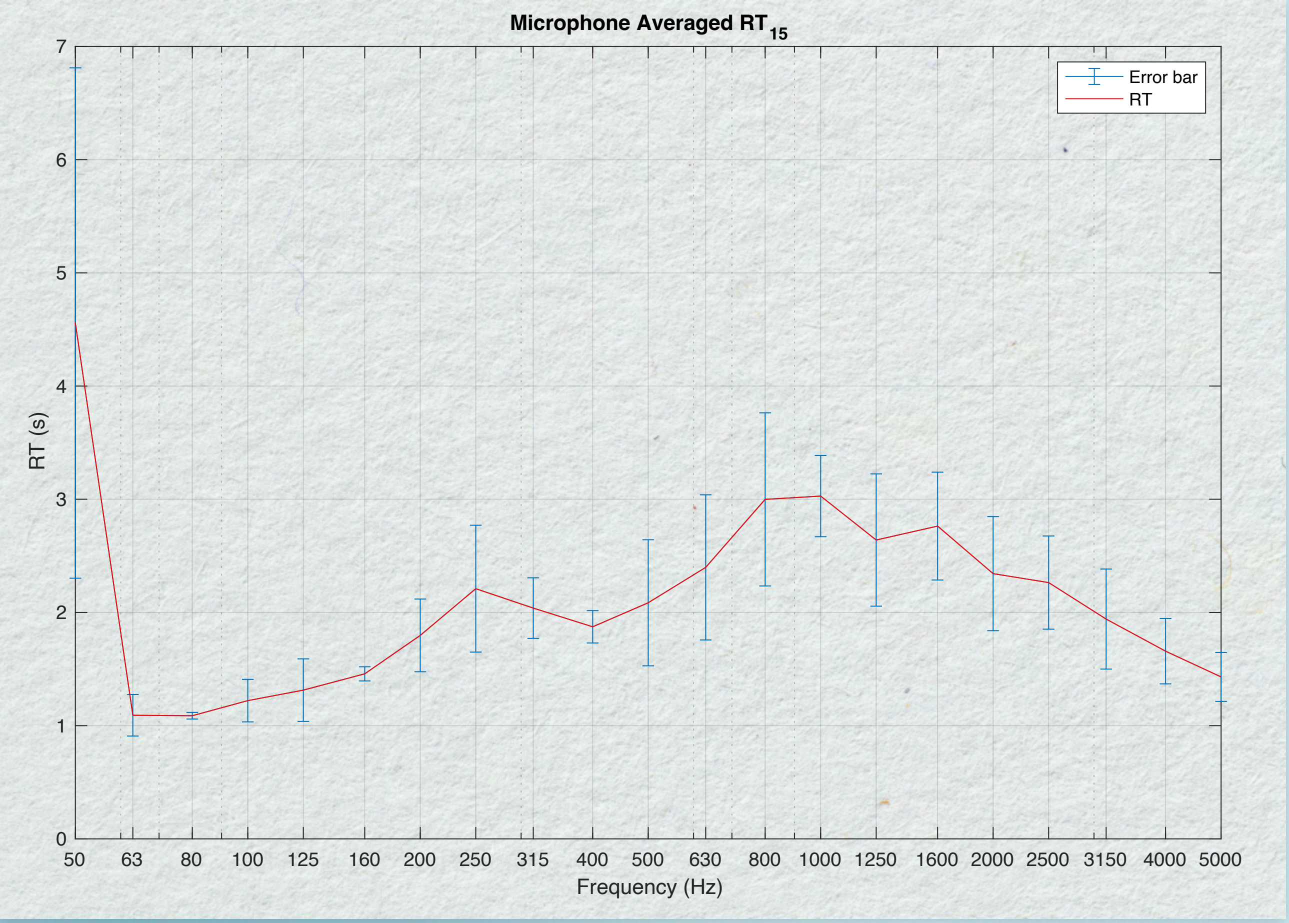


Figure A.11 - Third-octave microphone averaged reverberation times obtained from the laboratory test site (U1m configuration installed).