COMMISSIONING NR45 CONTAINMENT LABORATORIES ADOPTING LOCAL TEMPERATURE CONTROL WITHIN ACOUSTICALLY UNFAVOURABLE CONSTRUCTIONS

AS Krasnic ASK Acoustics Ltd, London, United Kingdom

1 INTRODUCTION

This paper aims to highlight some of the practical acoustic challenges associated with commissioining an NR45 (Noise Rating) building services room criterion for containment laboratories, specifically where a local temperature control solution is adopted at the design stage and where the internal building constructions are considered acoustically unfavourable.

Localised temperature control, usually by way of in-room mechanical devices, can be adopted for industrial schemes as alternatives to combined in-duct ventilation and temperature control solutions. In such cases, it is prudent at the design stage to consider both the room acoustic conditions within which the localised temperature control devices will be operating, in conjunction with the sound power emissions of each device such that during the commissioining stage, a design criterion of NR45 can be achieved.

The acoustic findings of a recently completed containment category, research laboratory scheme in the United Kingdom[1], have been used as an illustration of the practical challenges outlined above. Therefore, this paper initially considers the room acoustic challenges relating to the illustrative scheme, followed by an assessment of the acoustic characteristics of the proposed temperature control devices and concluding with a summary of the acoustic commissioining outcomes.

The remit of this study does not extend to the contribution from other sources of internal noise such as; fume cupboards, Micro-Biological Safety Cabinets (MBSC), other noise-generating table-top equipment, portable Uninterruptible Power Supplies (UPS) which it is assumed for the purposes of this study, that noise generated from such sources are not required to comply with room acoustic criteria nor demonstrate compliance against these during the commissioining stage. In the case of building services ventilation systems and associated airflow device performance (for both supply and extract air movement), it is assumed that the noise contribution of these is controlled via other means (eg. in-duct attenuation) not detailed in this paper and typically to within 10 dB less than that of the temperature control devices, as a discrete measured internal noise component.

2 NOISE DESIGN CRITERIA FOR LABORATORIES

Both in the UK and internationally, there are a few guidance documents and technical publications which provide indicative recommendations regarding suitable criteria, either as a Noise Rating (NR), Noise Criteria (NC) or Room Criterion (RC, now revised to the Room Criteria Mk. II), which can be adopted for the design of research laboratory schemes, a selection of which are summarised in Table 1 overleaf.

Guidance Document or Publication	Country of Origin	Building Description	Recommended Criterion
ASHRAE Handbook, HVAC Applications (SI edition)[2]	United States of America	Laboratories, Testing/research with minimal speech communication	NC/RC50
		Laboratories, Extensive phone use and speech communication	NC/RC45
		Laboratories, Group teaching	NC/RC35
Handbook of Facilities Planning, Vol. 1: Laboratory Facilities[3]	United States of America	Laboratories	NC45
National Institutes of Health, Office of Research Facilities[4]	United States of America	Biomedical Research Laboratories	NC40-45*
Health Technical Memorandum, HTM 08.01[5]	United Kingdom	Hospital laboratories	NR40**
Chartered Institute of Building Services Engineers, CIBSE Guide A1[6]	United Kingdom	Hospitals and healthcare laboratories	NR35-40
Noise and Vibration Control Engineering, Principles and Applications (Ver and Beranek)[7]	United States of America	Hospitals and clinics	NC35-45

Table 1 Summary of laboratory design noise criteria recommended in International guidance documents

* For reasonable speech communication in these spaces, a maximum noise level of NC45 shall be maintained.

** Excluding contribution from fume cupboards.

3 LABORATORY CONTAINMENT PROTOCOLS

In the United Kingdom, pathogen containment protocols for research laboratories are governed by two primary regulatory frameworks; the *Advisory Committee on Dangerous Pathogens* (ACDP) and the *Specified Animal Pathogens Order* (SAPO)[8]. As a Committee of Experts working under the auspices of the *Department of Health* (UK) and comprising up to seventeen members, the ACDP's work translates across a number of organisations, including the *Health and Safety Executive* (HSE), *Public Health England* (PHE) and the *Department for Environment, Food and Rural Affairs* (DEFRA). The ACDP's role is primarily to advise on all aspects of hazards and risks regarding human exposure to pathogens. Conversely, licenses issued by the HSE to laboratory facilities under the SAPO, stipulate the way in which specified animal pathogens must be handled, to ensure their safe containment and disposal, the areas of the laboratory in which various types of work may be conducted and the person(s) responsible for supervising such work.

The ACDP can approve up to four levels of containment for laboratory facilities; Containment Level 1 (CL1) constituting the least risk and up to Containment Level 4 (CL4) constituting the greatest risk. Similarly, licenses issued under the SAPO are in respect of up to four pathogen categories; SAPO1 constituting the least risk and SAPO4 constituting the greatest risk.

4 LABORATORY CONSTRUCTION AND TEMPERATURE CONTROL SOLUTION

Much of the initial construction planning and design for containment laboratories will be dependent on the need for building compliance with often critically demanding regulatory protocols, such as ACDP and SAPO performance criteria, combined with the end-user's operational requirements. Due to the onerous nature of ACDP and SAPO requirements on laboratory building performances, notably with regards to air movement and handling of pathogenic (or otherwise toxic) substances, internal building elements must be as inert and mechanically sealed as possible. This includes every design element from the external glazing, floor, wall and soffit finishes, through to the design of negative air pressure ventilation systems comprising complex High Efficiency Particulate Air (HEPA) filtration systems.

4.1 Laboratory Construction and Types

Typical internal constructions within laboratory buildings can vary from masonry (eg. blockwork) or pre-cast concrete internal walls for laboratories required to achieve a higher containment category to simpler drywall (eg. plasterboard studwork) constructions suitable for the lowest risk containment categories. To achieve the highest containment categories, walls in particular are required to be seamless, free from joints and leak-resistant to fumigant substances (either by gas or liquid fumigation methods). In addition, they must be smooth and resistant to various air pressure regimes with any building services penetrations effectively sealed. For the purpose of this study, the building elements were pre-cast concrete, the floor finishes comprised a non-porous, non-slip surface and the walls, soffit and junctions were finished and sealed with a proprietary epoxy-coated, multi-laminate coating. Furniture, Fittings & Equipment (FFE) specifications were individual to each laboratory type but generally comprised of high-level shelving, low-level work benches and cabinets with typical equipment comprising various numbers of MBSCs electrically connected to portable UPS systems dependent on the size and functionality of the laboratory space. There were three laboratory room types assessed in the acoustic study, each with varying volumes as detailed in Table 2. It should be noted that the Half-Bay laboratory represented is the lobbied variety which comprises a bio-security back-to-back door arrangement resulting in a slightly smaller volume than the un-lobbied equivalent.

Laboratory Type	**Assumed Design Dimensions (m)**			**Equivalent**	**Approximate**
	Width	**Length**	**Height**	**Floor Area (m^2)**	**Volume (m^3)**
Half-Bay (Lobbied)	3.1	4.8	3.0	14.9	45
Full Bay	6.2	6.2	3.0	38.4	115
Open Lab	6.2	13.1	3.0	81.2	244

Table 2 Summary of laboratory types assessed in acoustic study

4.2 Temperature Control Solution

With regards to room temperature control, a localised mechanical services solution comprising Fan Coil Unit (FCU) devices were located at the wall-soffit interfaces of laboratory rooms and remotely monitored and operated by a Building Management System (BMS). The scheduled number and mechanical performance of each type of FCU varied dependent on room type and ambient temperature requirements. Essentially, these FCUs were the wall-mounted variety and supplied with manufacturer's own derived test data relative to the sound power emissions of each type, as measured in accordance with the test procedures contained in *BS EN ISO 3746: 2010 Acoustics. Determination of sound power levels and sound energy levels of noise sources using sound pressure. Survey method using an enveloping measurement surface over a reflecting plane*.

Generally, Half-Bay laboratories contained 1 no. FCU, Full-Bay laboratories contained 2 no. FCUs and Open Laboratories contained 4 no. FCUs and arranged in a row at high-level of one side of each laboratory (Figs. 1 and 2 by kind permission from The Pirbright Institute). From this, a sound power assessment relative to the predicted design room acoustic characteristics for each laboratory type was derived and initially presented in Section 5.2 of this paper.

Fig. 1 End of Open Laboratory with one of 4 no. FCUs shown

Fig. 2 Full Bay Laboratory with 2 no. FCUs

5 INITIAL ROOM ACOUSTIC ASSESSMENT

During the early design stage of the project, an initial room acoustic assessment was conducted to determine if the potential for increased reverberation time due to the acoustically unfavourable constructions (described in Section 4.1) combined with the sound power emissions relative to the FCU specification schedule, could pose a significant challenge in achieving the NR45 room criterion. To assist in this initial assessment, a series of full-range (63 Hz to 8 kHz) Reverberation Time (T60) tests were conducted in a static and unfurnished R&D Mock-up laboratory facility, constructed in advance of the construction stage, to simulate the design internal visual and operational characteristics of a finished Half-Bay laboratory. The key observation to note is that the Mock-up facility underwent a series of constructional modifications, each time a new set of T60 tests were conducted to progressively evaluate the room acoustic performance. Generally, the final iteration of a Dynamic (ie. operationally simulated) Mock-up facility was constructed to mimic the dimensional and operational characteristics of an actual Half-Bay laboratory. Hence, the T60(63Hz-8kHz) results from both an initial Mock-up and a final Mock-up were assessed separately. Table 3 details the RT test results obtained from the initial iteration of Mock-up tests as conducted in accordance with the Survey Grade method contained in *BS EN ISO 3382-2:2008 Acoustics. Measurement of room acoustic parameters. Reverberation time in ordinary rooms*, as follows.

5.1 First iteration Mock-up RT test results

Due to time, security and Mock-up limitations preventing the use of both AC mains powered equipment and blank-firing pistols, an impulse-response method was instead adopted by bursting large air-filled balloons, the decays of which measured using a field-calibrated Brüel & Kjær Type 2250 Sound Level Analyser (microphone set to random incidence response). By variation of T60 measurement at 4 no. microphone positions diametrically opposed to 4 no. source positions in the Mock-up (ie. a total of 4 no. decays), the characteristic room response could be obtained albeit limited to the frequency characteristics of the impulse signal source (particularly at the 63 Hz and 125 Hz 1/1-Octave Bands) and volume of the test space (58.3 m^3). Further, due to the dimensional limitations of the test space, the microphone at each measurement position could only be positioned at least 1.5 metres from any of the vertical surfaces. From the results presented in Table 3, it can be seen that the arithmetic mean of the 4 no. full-range decays is around 4.78 seconds (to 2 d.p.) compared with the predicted (Sabine) calculation of 2.79 seconds for the same Mock-up test room.

It was determined that this variation was likely to be due to a combination of the test procedure limitations (see test signal description) and the influence of both pronounced Room Modes (seemingly manifested in the 63 Hz to 500 Hz 1/1-Octave Band measurements) and audible propagation of Flutter Echoes in the space. To note; based on the predicted (Sabine) $T60_{(63Hz-8kHz)}$, the Schroeder Frequency of the Mock-Up was determined to be around 437 Hz (to 3 s.f.). Subsequently, to predict a probable $T60_{(63Hz-8kHz)}$ for an actual constructed Half-Bay (Lobbied) Laboratory space, a heavily approximated correlation method was derived by firstly determining the Sabine ratio between the Half-Bay and Mock-up T60 predictions and multiplying this ratio by the arithmetic difference between the Mock-up measured and predicted T60 and finally summing this correction factor to the predicted Half-Bay T60.

Calculation Step	**1/1-Octave Band Centre Frequency (Hz)**								
	63	**125**	**250**	**500**	**1 k**	**2 k**	**4 k**	**8 k**	**Mean** (63Hz-8kHz)
Arithmetic mean of 4 no. decays	7.13*	5.50*	6.80*	6.31**	4.97**	3.23**	2.59**	1.67**	4.78
Half-Bay T60 prediction***	3.18	2.74	3.79	3.01	2.81	2.57	1.72	0.99	2.60
Mock-up T60 prediction***	3.48	2.97	4.07	3.26	3.01	2.69	1.81	1.02	2.79
Sabine ratio	x1.09	x1.08	x1.07	x1.08	x1.07	x1.05	x1.05	x1.03	-
Mock-up Meas. T60-Pred. T60	3.65	2.53	2.73	3.05	1.96	0.54	0.78	0.65	-
Correction Factor (Sabine ratio * Mock-up diff.)	+3.98	+2.73	+2.92	+3.29	+2.10	+0.57	+0.82	+0.67	-
Probable T60 Half-Bay	7.16	5.47	6.71	6.30	4.91	3.14	2.54	1.66	4.73

Table 3 Measured versus predicted initial Mock-Up Reverberation Times, T60 (seconds)

* Numerically extrapolated from T10 measurement (T10x6)
** Derived from T30 measurements
*** Predicted by standard Sabine method

From this correlation, it could be determined that the probable RT for an actual Half-Bay (Lobbied) laboratory could be of the order of $T60_{(63Hz-8kHz)}$ 4.74 seconds (which is numerically 0.04 seconds less than that of the measured Mock-up T60) and in the un-furnished condition (ie. excluding any FF&E). Similarly-correlated probable RT assessments were also conducted for both the Full Bay and Open Laboratory spaces, the results of which whilst not detailed in this paper, were approximately $T60_{(63Hz-8kHz)}$ 6.5 seconds and 7.0 seconds respectively.

5.2 Initial FCU sound power assessment

To conclude the initial room acoustic assessment, sound power data based on the specified FCU schedule for each Laboratory space was then obtained from the manufacturer and assessed in a global room acoustic analysis. Each FCU was set to a specific speed tapping (which ultimately influences the sound power emissions) but usually the lowest speed tapping was selected (Speed 1). To do this, elementary room acoustic formulae (reproduced in several acoustical texts notably; *Noise Control in Building Services*[9]) which can be derived from room acoustic first principles, were used to determine both the reverberant ($L_{p(rev)}$) and direct ($L_{p(dir)}$) sound pressure level components from the sound power level of the device(s) (L_W), as follows;

Equ. 1 $L_{p(rev)} = L_W + 10.Log_{10}T - 10.Log_{10}V + 14$ (dB)

Equ. 2 $L_{p(dir)} = L_W + 10.Log_{10}[Q/(4.\pi.r^2)]$ (dB)

Q - Surface Directivity Factor
r - Distance from source to a nominal receiver position in the room, nominally taken to be 1.5 metres for Half-Bay laboratories

Considering initially a Half-Bay laboratory containing 1 no. FCU and applying the manufacturer's sound power spectrum for the scheduled FCU device and the test-corrected $T60_{(63Hz-8kHz)}$ 4.74 seconds from Section 5.1, Table 4 presents the results of the initial assessment against the NR45 criterion.

Data	Calculation Step	1/1-Octave Band Centre Frequency (Hz)								
		63	125	250	500	1 k	2 k	4 k	8 k	NR
Input Data	FCU Lw spectrum* (dB)	34.1*	34.1	38.0	44.0	42.3	41.0	38.0	34.0*	-
	Corrected T60 prediction (s)	7.16	5.47	6.71	6.30	4.91	3.14	2.54	1.66	-
Predicted Result	$L_{p(rev)} + L_{p(dir)}$ (dB)	40.3	39.1	43.9	48.5	45.5	42.5	39.9	34.2	47
	NR45	71.0	61.2	53.9	48.5	45.0	42.2	40.0	38.4	45
	Compliance	**-30.7**	**-22.1**	**-10.0**	**+1.1**	**+1.9**	**+1.5**	**-0.1**	**-4.2**	-

Table 4 Initial room acoustic assessment for Half-Bay laboratory

* dB re: 10^{-12} W
** Estimated linear L_W at 63 Hz and 8 kHz

The results of this initial room acoustic assessment for a Half-Bay laboratory, shows that based on RT tests conducted in the first Mock-up and applying the manufacturer's sound power data, initial observations suggest that an NR45 criterion would not be achievable. Furthermore, it can be concluded that in order for the Half-Bay laboratory to become capable of achieving an NR45 criterion, either/or the T60 or the FCU sound power levels must be reduced. Upon further deliberation, it was deemed that reduction of the FCU sound power could not be achieved because the devices were already operating at the lowest speed tappings (Speed 1), therefore an interim contingency assessment was adopted to investigate practical methods of reducing the room RT, the findings of which are summarised in the following section.

6 CONTINGENCY ROOM ACOUSTIC STUDY

Based on the less-than-favourable initial findings, a subsequent contingency design study was embarked, the purpose of which was to investigate practical methods of reducing the laboratory RT performances, should it not be demonstrable through subsequent RT tests following constructive iterations of the Mock-up facility and well in advance of the commissioning stage. This sub-study aimed to identify the acoustic and mechanical properties which additional absorption materials (eg. wall/ceiling panels) would be required to achieve, should their incorporation into the room design specifications be necessitated. To note, the optimal RT performance for a Half-Bay laboratory based on the initial room acoustic assessment to achieve NR45, would limit the 1/1-Octave Band times to approximately 4.8 seconds at 500 Hz, 3.5 seconds at 1 kHz and 2.3 seconds at 2 kHz. The following list summarises typical acoustical and mechanical properties of additional absorption materials.

- Fumigation resistance to Hydrogen Peroxide and Formaldehyde substances.
- Specified ISO clean room class performance (minimum ISO performance stated in Employer's Requirements).
- Non-mechanical and inert bonding agent to be used to bond panels to the Laboratory substrate (eg. walls) with no mechanical penetrations or fixings permitted through the proprietary wall coatings.
- Non-hygroscopic and inert product surface to inhibit growth of organisms.
- Perimeter and edge details to be suitable to achieve fixing details under the Employer's Requirements.
- All mastics and sealants to be inert and non-hygroscopic.
- Installation and product dimensions to be suitable for the appropriate site application.
- Minimum acoustic performance to achieve Class C as a direct-fix solution (in accordance with *BS EN ISO 11654:1997. Acoustics. Sound absorbers for use in buildings - Rating of sound Absorption*.).

7 FINAL ROOM ACOUSTIC ASSESSMENT

During the early phase of the construction stage, a final room acoustic assessment was conducted and adopting a similar approach to that conducted for the initial assessment (described in Section 5.0). The basis of this assessment was to conduct further RT tests in a final Dynamic Mock-up facility which evolved as an iterative construction of the initial Mock-up. The Dynamic Mock-up (DMU) differed to the first iteration in that appropriate building services equipment including a working ventilation/HEPA supply and extract system and furnished with specified FF&E elements were installed. The volume of the DMU was 45.6 m^3 and included all the high-level shelving and low-level furniture and MBSC which would be expected in a specified Half-Bay laboratory (Fig. 3).

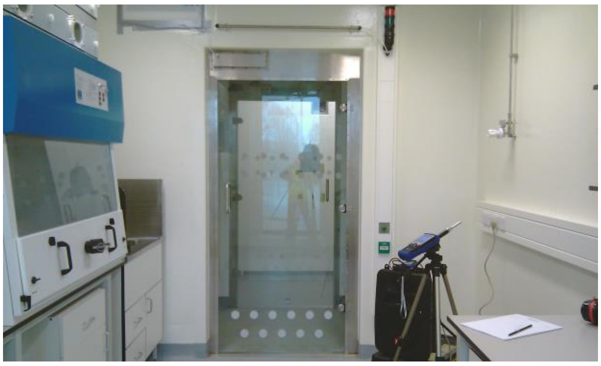

Fig. 3 RT tests underway in the DMU

Table 5 presents the results of these RT re-tests, including a revised iteration of the original room acoustic assessment presented in Section 5.2 previously. It should be noted that unlike the first RT tests, the Engineering Grade method was adopted and AC mains powered equipment could be used in the test facility, thereby permitting an interrupted noise test signal method. In total there were 3 no. microphone positions and 2 no. source positions. 2 no. decays were measured at each of the 6 no. microphone positions in total using a field-calibrated NTi-Audio XL-2 instrument.

Data	Calculation Step	1/1-Octave Band Centre Frequency (Hz)								
		63	125	250	500	1 k	2 k	4 k	8 k	NR
Input Data	FCU Lw spectrum (dB)	34.1	34.1	38.0	44.0	42.3	41.0	38.0	34.0	-
	DMU measured T60	1.33	1.19	1.11	1.25	1.13	1.20	1.08	0.81	-
Predicted Result	$L_{p(rev)} + L_{p(dir)}$ (dB)	33.5	33.1	36.7	43.2	41.1	40.0	36.6	31.6	**43**
	NR45	71.0	61.2	53.9	48.5	45.0	42.2	40.0	38.4	45
	Compliance	**-37.5**	**-28.1**	**-17.2**	**-5.3**	**-3.9**	**-2.2**	**-3.4**	**-6.8**	-

Table 5 Final room acoustic assessment for Half-Bay laboratory

Furthermore, unlike the first RT tests, no additional correction factor was applied to the DMU RT test results, since the facility very closely simulated all dimensional and operational characteristics of a design Half-Bay laboratory.The results of the final iterative RT tests demonstrated that whilst there was a significant reduction in the measured RT results to $T60_{(63Hz\text{-}8kHz)}$ 1.14 seconds, which represented a reduction of approximately $\Delta T60_{(63Hz\text{-}8kHz}$ 3.6 seconds but also the specified FCU sound power emission was now capable of achieving the NR45 room criterion due to the reduction of the reverberant sound pressure level component.

It was further inferred from these test results that the presence of Room Modes and audible Flutter Echoes which had originally influenced the room response in the first Mock-up were no longer significantly affecting the measured room response in the DMU. This could be put down to a combination of improved test methodology (adopting an interrupted noise test signal and Engineering Grade method) and inclusion of the FF&E which resulted in the beneficial effects of diffusing the propagation of Room Modes at the microphone positions and also minimising the influence of Flutter Echoes, which were audibly much less apparent than in the first Mock-up.

Given the added confidence provided by the final room acoustic assessment, it was deemed that by application of a similar test-corrected methodology proposed in Section 5.1, the room responses for both the Full Bay and Open Laboratories could eventually demonstrate reductions in final T60 performance, based on the observed effects of introducing the FF&E and other services into the DMU, without the need to introduce additional remedial absorption measures into the room specifications and therefore the contingency room acoustic intervention was not called into action. For information, the test-corrected RT predictions for both the Full-Bay and Open Laboratories were subsequently calculated to be $T60_{(63Hz\text{-}8kHz)}$ 2.79 and 3.34 seconds respectively. Furthermore, these test-corrected T60 predictions were also within the maximum optimal design values of $T60_{(63Hz\text{-}8kHz)}$ 3.14 and 4.15 seconds respectively, theoretically permitting an NR45 criterion to be achievable in the larger laboratories.

8 PRE-COMMISSIONING ACOUSTIC TESTING

Following the conclusion of the RT tests and room acoustic assessments conducted to date, it was necessary to conduct both pre-commissioining RT tests and installed FCU sound pressure level tests in a selection of Laboratory spaces, to identify the likelihood of the NR45 criterion being achievable on site and just prior to the commissioning stage.

8.1 Final laboratory RT tests results

Adopting the same instrumentation and test methodology as for the final Mock-up test described in Section 7 except for 3 no. decays per microphone position, the following results were obtained and summarised in Table 6.

Pre-commissioning Laboratory space	**1/1-Octave Band Centre Frequency (Hz)**								
	63	**125**	**250**	**500**	**1 k**	**2 k**	**4 k**	**8 k**	**Mean** (63Hz-8kHz)
Half-Bay (lobbied) laboratory	2.43	1.63	1.60	1.87	1.75	1.50	1.25	0.99	1.63
Full Bay laboratory	1.85	1.50	1.62	1.88	1.88	1.66	1.47	1.11	1.62
Open Laboratory	2.31	1.94	1.95	2.28	2.25	2.01	1.69	1.24	1.96

Table 6 Pre-Commissioining Reverberation Time results, T60 (seconds)

It can be seen from these final RT test results obtained during a pre-commissioining exercise, in a selection of the three operational Laboratory types, that the pre-construction concerns regarding unfavourable constructions which could have caused a significant hindrance to the achievement of an NR45 criterion, could now be allayed. Furthermore, it can be seen that the final tests results measured in both the Full and Open Laboratories were of the order $\Delta T60_{(63Hz-8kHz}$ 1.17 and 1.38 seconds less, respectively than the final test-corrected predicted $T60_{(63Hz-8kHz}$ values. Following on from this, the second part of the pre-commissioining exercise was to evaluate the acoustical performance of installed FCU devices in a number of laboratory spaces.

8.2 Pre-Commissioining FCU room SPL test results

For the purpose of this study, the pre-commissioining FCU noise emission evaluation focuses on site tests conducted on a single FCU located in a lobbied Half-Bay laboratory. As for all lobbied Half-Bay laboratories, the FCU under test was installed above the internal bio-security door which leads to the Laboratory from the internal pressurised lobby. The acoustic tests comprised of a sequence of SPL measurements, each taken at the same nominal measurement position and under modified FCU operational characteristics, as identified. The microphone measurement position was taken to be in the vertical centerline axis of the room (ie. equidistant between the internal partitions) and at 1.5 metres distance at a 45-degree angle from the centrepoint of the FCU under test.

Early tests indicated that the stock FCU devices supplied by the manufacturer might struggle to achieve the NR45 criterion in a selection of Laboratory spaces, in part due to the directivity effects imparted by the close proximity of room boundaries to the FCU location. Whilst both directivity corrections and manufacturer’s sound power data provided a reasonably accurate design indication of the likely noise propagation of each device, it was deemed that further pre-commissioining tests were required to allow any operational modifications to be carried out, thereby allowing FCU devices to achieve the NR45 criterion at the commissioining stage. Table 8 summarises the sequential FCU room SPL measurements and the corresponding operational condition and modifications made at each test.

Test No.	**Test Condition**	**1/1-Octave Band Centre Frequency (Hz)**							
		63	**125**	**250**	**500**	**1k**	**2k**	**4k**	**8k**
-	NR45 criterion	71.0	61.2	53.9	48.5	45.0	42.2	40.0	38.4
1	Baseline test (stock FCU - no modifications)	**55.0**	**57.0**	**53.0**	**52.0**	**49.0**	**40.0**	**29.0**	**22.0**
2	FCU with “top” variable vanes re-aligned and internal filter pads removed	**55.0**	**56.0**	**52.0**	**50.0**	**46.0**	**38.0**	**28.0**	**21.0**
3	FCU with all “top” variable vanes and internal filter pads removed	**57.0**	**56.0**	**51.0**	**48.0**	**44.0**	**35.0**	**27.0**	**21.0**
4	FCU with all “top” and “Bottom” vanes and internal filter pads removed plus minor casing installation modifications	**56.0**	**56.0**	**51.0**	**47.0**	**42.0**	**34.0**	**26.0**	**21.0**

Table 7 Results of pre-commissioining FCU room sound pressure level tests dB L_{Zeq} (re: $2x10^{-5}$ Pa)

From these pre-commissioining results, it was determined that the final FCU modification (Test 4) comprising the removal of both the “top” and “bottom” row of vanes and the redundant internal filter pads (due to the HEPA-controlled atmosphere), yielded the best improvements in terms of reduction of FCU room sound pressure levels.

However, early on during this pre-commissioining exercise, FCUs under acoustic test were observed to not be operating at the design voltage (230 Volts) because not all building services and low-voltage systems were yet fully operational. This prevented the site-wide electrical load from stabilising to result in the design voltage supply from being achieved. The actual building supply voltage to Laboratories varied approximately between 244 Volts to around 238 Volts at the lowest pre-commissioining levels. This phenomenon resulted in significant increases in measured FCU room SPLs (due to elevated rotational fan speed) thereby necessitating a 'voltage-to-noise' (VNA) analysis to be conducted. The purpose of which was to determine the likely FCU room noise levels, once the building was operating at the design electrical load, resulting in a supply voltage closer to 230 V and simulated on site by wiring a potentiometer directly to the electrical terminals of an un-modified FCU. Table 7 summarises the results of the VNA analysis conducted on one FCU located in a representative Half-Bay (Lobbied) laboratory.

Voltage	**1/1-Octave Band Centre Frequency (Hz)**								**NR**
Condition	**63**	**125**	**250**	**500**	**1k**	**2k**	**4k**	**8k**	**Level**
@240 V	57.8	59.0	54.7	50.1	44.5	38.1	29.7	21.6	**46**
@230 V	55.6	55.8	50.8	46.9	42.0	34.4	25.8	21.0	**44**
Difference	**-2.2**	**-3.4**	**-3.9**	**-3.2**	**-2.5**	**-3.7**	**-3.9**	**-0.6**	-

Table 7 Results of pre-commissioining un-modified FCU room sound pressure level tests, dB L_{Zeq} (re: $2x10^{-5}$ Pa)

From these results, it is clear that the effect of the unmodified FCU operating at the elevated voltage condition (240V) results in the NR45 criterion not being achievable in the Half-Bay laboratory. However, by simulating a reduction of the supply voltage down to 230V (design voltage), this results in the NR45 being achieved with significant reductions in 1/1-Octave Band sound pressure levels of between Δ0.6 and 3.9 dB. From this, it was deemed that by the eventual reduction of the site-wide voltage down due to the design load being achieved, in conjunction with the minor operational modifications to the FCU devices, that the NR45 criterion could be achieved satisfactorily in all Laboratory spaces commissioned, without the need to introduce contingent room acoustic absorption.

9 CONCLUSIONS

The following conclusions can be gleaned from this study which are summarised below:

- There are only a limited number of UK and International standards and guidance documents which recommend room noise criteria for Laboratories.
- Laboratories required to achieve the highest levels of containment category will usually be constructed using acoustically unfavourable constructions.
- Early assessment of room acoustic conditions and sound power data of manufacturers of temperature control devices is highly recommended.
- With careful design and planning of laboratory spaces, the introduction of FF&E providing secondary diffusing effects can assist in significantly improving measured RT performance.
- Careful attention should be given to the positioning and subsequent directivity effects of installing temperature control devices, particularly in tighter Laboratory spaces.
- A "rule-of-thumb" suggests that an NR45 criterion is achievable in unfavourably-constructed Laboratory spaces when there is up to 1 no. temperature control device per 60 m^3 of room volume.

10 REFERENCES

1. *Institute for Animal Health, Development Project 1, IAH-DP1*. The Pirbright Institute, Surrey, United Kingdom.
2. American Society of Heating, Refrigerating and Air-Conditioning Engineers, *ASHRAE Handbook: HVAC Applications (SI edition)*. United States of America (2011).
3. T. Rhys, AIA, *Handbook of Facilities Planning*, Vol. 1, Laboratory Facilities. Van Nostrand Reinhold, New York. (1990).
4. National Institutes of Health, Office of Research Facilities (Development and Operations), *Noise in Biomedical Research Laboratories and Animal Facilities*, Vol. 1, No. 12. United States of America (March 2011).
5. Department of Health, Specialist Services, *Health Technical Memorandum (HTM) 08-01: Acoustics*. United Kingdom (March 2013).
6. Chartered Institute of Building Services Engineers, *CIBSE Guide A: Environmental Design*, Section 1.9.4, 1-28, Table 1.16. United Kingdom (2007).
7. I.L. Ver and L.L. Beranek, *Noise and Vibration Control Engineering, Principles and Applications*, 2nd ed John Wiley & Sons, Inc., 890-891. (2006).
8. *Specified Animal Pathogens Order* (Statutory Instrument, no. 944), United Kingdom (2008).
9. Sound Research Laboratories, *Noise Control in Building Services*, Pergamon Press. (1988).