Cooling Equipment Sound Measurements: Test Code Comparisons And Recommendations

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Introduction

The Cooling Technology Institute first published CTI ATC-128, Test Code for Measurement of Sound from Water-Cooling Towers [CTI1], in 1981. Before that, there was no generally-accepted standard available for cooling tower sound measurements in the United States. This meant manufacturers and operators had to either rely on their own internal testing protocols, or follow one of a number of international standards. With ATC-128, CTI began the process of unifying the format and reliability of sound data published by manufacturers in the US.

For context, ATC-128 has a two-part goal:

- To standardize a method for consistently measuring sound emissions from cooling towers.
- To use these measurements to demonstrate compliance with noise safety ordinances and guarantees.
- This standard has changed considerably since its first publication, especially in its 2005 revision, but general feedback indicates that it has arguably delivered on the first goal: its methods are simple and easy to reproduce, and clearly measures the real sound levels at certain locations. However concerns about the code are surfacing, like those posed by the CTI Technical Paper TP16-11[CTI2], which questions how useful that data is to extrapolate to other distances.

TP16-11 asks whether or not ATC-128 does enough to guide users on which data set in the code provides the most accurate predictions. It additionally suggests several instances of problems using published sound levels to sufficiently estimate a cooling tower's contribution at distance.

While ATC-128 strictly avoids addressing how to use its published data for predictions, instead leaving that process in the hands of experienced sound consultants, it does leave itself open to questions on accuracy. If there are flaws in the standard's methods or calculations, there will be errors in any predictions resulting from that data.

ATC-128 does not share any measuring locations with any of the other codes we want to compare; however, there is a common thread in all of these standards: each of them provides a method of estimating the total sound emission power from tested equipment.

It is by using this calculation that allows us to compare the sound power levels between methods. And as differences between the methods surface, it allows us to find ways to bring their results closer together.

Important Definitions

Before proceeding, a basic understanding of the following definitions is needed.

Sound Spectrum: Any sound is a composite of multiple simultaneous wavelengths of disturbance moving through a medium (generally air). These wavelengths can be measured, and are typically expressed in frequency bands, known as octaves.

Audible sound generally spans about 8 octaves, and is represented by the frequencies of 63, 125, 250, 500, 1,000, 2,000, 4,000, and 8,000 Hertz (Hz). Higher frequencies will result in high pitch tones, while lower frequencies result in low rumbles.

The total sound at any instant in time is related to the logarithmic sum of all combined frequencies.

Sound Pressure Level: Sound waves moving through the air typically cause small pressure fluctuations. These pressure waves create the sound that can be audibly heard and recorded by a microphone or other measuring equipment. The sound pressure is essentially the audible sound that is present at a given distance from an emitting source. This is measured in Decibels (dB).

Sound Power Level: This is the sound emitting power of an object or source. Since sound radiates outward in expanding waves, often taking paths through multiple surfaces and openings, capturing all the sound emissions from a source is nearly impossible, so this value cannot typically be measured directly. But it can be estimated by taking enough pressure level readings around the sound emitting unit and triangulating the power back to the source. This power level is also reported in Decibels (dB).

Sound Weighting: While recording equipment captures the real sound pressure level and the corresponding sound spectrum within it, ears are more sensitive to certain tones, making certain sounds seem louder (or softer) than recording devices indicate. This can be accounted for by weighting certain frequencies in the sound spectrum. The unweighted measured sound is expressed as dB, or sometimes dB(L) (L for linear). The weighted value for human hearing is often expressed as dB(A). To convert from dB(L) to dB(A), add the correction constants for each of the corresponding frequencies from Table 1.

dB(L) to dB(A) Conversion							
63	125	250	500	1K	2K	4K	8K
-26.2	-16.1	-8.6	-3.2	0	1.2	1	-1.1

Table 1: Sound conversion from unweighted dB(L) to weighted dB(A).

For simplicity, all sound pressure and power values in this paper will use the dB(A) weighting when applicable.

Unit Origin: This is the midpoint of the unit, as located on the bottom plane (elevation = 0).

Free-Field: A free-field exists when a sound emitting source is isolated in a location where there is no surrounding objects for sound to reflect back (other than the ground). This is extremely difficult to achieve in practice, as most locations are crowded with additional structures and equipment.

Nearfield: The nearfield is the area around the tower where it's difficult to group the sound emitting surfaces together as a single point. Instead, sound can be audibly-located to different areas of the unit. At this distance, sound seems to come from multiple paths and positions. Thus, back-calculating the total power level can be extremely difficult.

Far-Field: The far-field is located far enough away from the emitting source that all the sound from the unit appears to come from a single, pin-point location. This makes it easier to calculate the sound emission of the unit, as the emitted sound appears homogenous. However, the further away from the unit the sound measurement is taken, the greater the risk of interference from other noise sources affecting the results.

While it's difficult to determine exactly when nearfield becomes far-field, it can be approximated by using a characteristic dimension, Do, which is based on the sound emitting source's length, width and height. It's generally safe to say that far-field has been reached at distances of 2 times the characteristic dimension from the unit. Note: for most definitions, this distance is measured from the unit origin. For ATC-128, it is from the face of the unit.

$$D_o = \sqrt{\left(\frac{UnitLength}{2}\right)^2 + \left(\frac{UnitWidth}{2}\right)^2 + (UnitHeight)^2} \quad \text{Eq. (1)}$$

Test Codes and Standards

There are a number of sound test codes and standards across industries and world regions. Each have their own, unique methodology and level of complexity that distinguishes them. The following were chosen for their prevalence and suitability for cooling equipment.

ATC-128

First published in 1981, it was significantly re-written in 2005 by the Cooling Technology Institute. Lightly revised in 2014.

Scope and Purpose: To provide standard test procedures for measuring near-field sound from water-cooling towers. Applies to any evaporative cooling tower or cooler.

Methods of Measurement: ATC-128 contains multiple methods; however, this paper will focus on small cooling equipment in a free-field (Procedure 1, Section 8 of test code). This section consists of 2 sets of measurements, one in the near-field, and the other in far-field. Note: for this paper, Procedure 2, Section 9, sound measurements on large towers will not be addressed, only Section 8.

To complete a full set of measurements, the sound pressure levels need to be recorded at the center of each cooling tower face, first in the nearfield at 1.5m (5ft), then again in the far-field. Though the recommended distance to ensure far-field is typically 2·Do (Characteristic Dimension – Equation 1), most of the industry is used to measuring at a more distant 15m (50ft), regardless of unit dimensions. This has been a generally accepted practice. Note: the effect of this distance will be addressed in Section 8.1.1.

Since most small cooling towers are box-shaped, these measurements are fairly simple. The only nuances are as follows:

- For each of the 4 sidewalls, the elevation of the recorder is at 1.5m (5ft) regardless of the height of the tower.
- If there is a fan near a measuring location, then the measuring point will be moved to 1.5m above and 1.5m to the side of the fan discharge. This is to limit the air velocity across the microphone to below 4.5 m/s (10 mph). (For velocities greater than that, the moving air can artificially inflate the sound measurement – like blowing on a microphone).

These measurement locations can be seen in Figure 1.

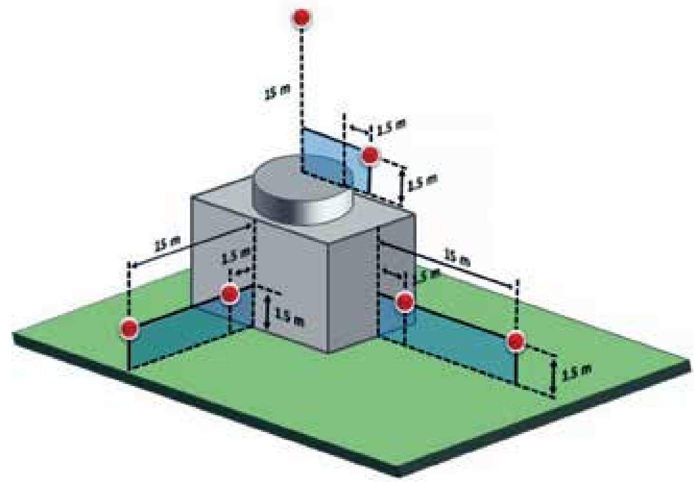

Figure 1: Sound Measurement Points According to ATC-128. (4) Points mirrored on back faces.

Note: It's important to remember that the measurements, as defined in the test code, are taken at distance from the cooling tower face, rather than the center of the unit. This will be discussed in detail in Section 8, as it likely leads to many of the differences in calculations when compared to other standards.

ISO 3744

ISO 3744 [ISO2] is one of a series of standards which specify methods for determining the sound levels of noise sources, including machinery, equipment and their sub-assemblies. This standard began as ISO 4872, published in 1978, focusing on the measurements of construction equipment intended for outdoor use. It was expanded into ISO 3744 in 1994, and revised again in 2010.

Scope and Purpose: The purpose of this code is to specify methods for determining sound power or sound energy levels of a noise source. This is accomplished by gathering sound pressure levels on a surface enveloping the source. This code is the most widely applied method mentioned in this paper, as it is meant for a robust range of different machinery; however, it can be tough to apply to equipment with moving air.

Methods of Measurement: Several methods are given in this standard, but all revolve around the concept of wrapping the sound emitting source in an array of recording locations, in order to capture the total sound emissions. There are several different geometric arrays available to be used:

Hemispherical: One method measures along the surface of a hemisphere that surrounds the emitting source. This captures the sound at a far-field location. The code specifies two hemispherical patterns, one symmetrical, the other not. Since the symmetrical measurement can sometimes exaggerate sound when certain tones are present, this paper will focus on the non-symmetrical hemisphere. This can be seen graphically in Figure 2, with the coordinates of each point given in Table 2.

The hemisphere is centered at the midpoint of the unit's base. The radius of the hemisphere is recommended to be a minimum of 2 times the characteristic dimension 2·Do. The radius cannot exceed 16m.

Parallelepiped: Another method measures a boxed enclosure around the emitting source. This method is often referred to as a parallelepiped method. A parallelepiped is just an ornate way to explain the shape of the measurement surface, which is a box encapsulating the unit. This box is shown in Figure 3. Note: The easiest way to remember this: a parallelogram is to a rectangle, what a parallelepiped is to a 3-dimensional box.

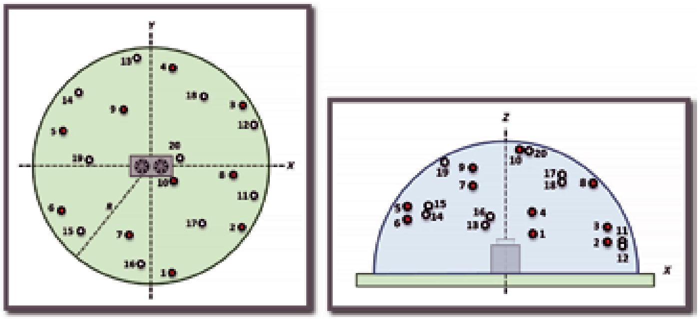

Figure 2: Sound Measurement Points According to ISO 3744 Annex B. Shows locations of 10 primary measurement points (Red 1-10) and 10 secondary measurements (White 11-20).

Position	X/R	Y/R	Z/R	Position	X/R	Y/R	Z/R
1	-0.99	0	0.15	11	0.99	0	0.15
2	0.5	-0.86	0.15	12	-0.5	0.86	0.15
3	0.5	0.86	0.15	13	-0.5	-0.86	0.15
4	-0.45	0.77	0.45	14	0.45	-0.77	0.45
5	-0.45	-0.77	0.45	15	0.45	0.77	0.45
6	0.89	0	0.45	16	-0.89	0	0.45
7	0.33	0.57	0.75	17	-0.33	-0.57	0.75
8	-0.66	0	0.75	18	0.66	0	0.75
9	0.33	-0.57	0.75	19	-0.33	0.57	0.75
10	0	0	1	20	0	0	1

Table 2: Sound Measurement Points According to ISO 3744 Annex B. Shows locations of 10 primary measurement points and 10 secondary measurements.

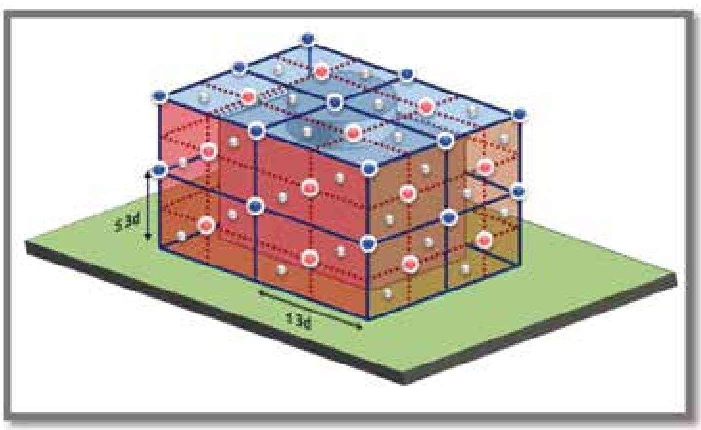

Figure 3: Sound Measurement Points According to ISO 3744 Annex C. Shows parallelepiped array for primary measurement points (dark blue and pink) and optional localized measurements (small gray).

For this method, points are measured along an invisible face at distance, d, from each surface of the emitting source. Typically, d is 1 m, though it could be greater depending on unit dimensions.

Each measurement face is broken into a grid, where the primary points are spaced no more than 3·d lengths apart. Both the grid corners (dark blue) and mid-points (pink) are required measurements. The number of grids per face depends on the unit dimensions. This grid can be seen in Figure 3.

Note: If certain conditions are present, such as a large sound gradient, or if directionality is detected, additional measurements (small gray) are required.

AHRI 370

AHRI 370[AHR1] is a comparable sound test code created by the Air-Conditioning, Heating and Refrigeration Institute. First published in 1986, it was updated in 2001 and 2011. In 2015, it was approved by the American National Standards Institute (ANSI).

Scope and Purpose: To establish methods of determining the outdoor sound emissions of commercial and industrial refrigerating and air-conditioning equipment with heat loads greater than 40kW.

Methods of Measurement: There are several methods presented in the standard, but again, this paper will focus on measuring pressure levels in a free-field. This is covered in the appendix of AHRI 370. Unlike ATC-128, this method has a variable number of measurements, based on the unit's size. In essence, this method tries to capture the sound power level by wrapping the unit with 2 rings of sound measurements, one at an elevation of 1.5 m from the base of the unit, and one at 1 m above the top of the unit. The ring of measurements consists of a single point measured at the midpoint of each cardinal direction, then extends outward in a rectangular pattern using 1 m increments. This is shown in Figure 4.

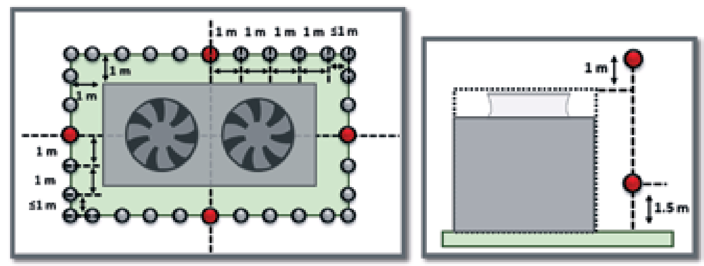

Figure 4: Sound Measurement Points According to AHRI 370. Left: Represents single elevation. Right: Shows locations of 2 elevations. The left pattern is repeated for each of these elevations.

Some nuances with this method are as follows:

- While the spacing of the rectangular ring is at 1 m intervals, there may be points at each of the corners where the distance will be less than 1 m as the two sides meet.
- If the top measurement elevation is 3 m or less (which means the unit is 2 m tall or under), then only the 1.5 m elevation is needed
- The top measurement elevation cannot exceed 6 m.

DIN 45635: Part 46

DIN 45635 is a set of codes published by the German Institute for Standardization that define methods for measurements of noise emitted by machines. Part 1 of DIN 45635 [DIN1] is an introductory standard that has become obsolete, replaced by ISO 3740 [ISO1]. Part 46 [DIN2], last updated in 1985, is still active and focuses specifically on the enveloping surface method of cooling towers.

Scope and Purpose: This standard provides the basis of determining noise emitted by cooling towers to the surrounding air. The standard is short and provides a method of measurement for both natural and mechanical draft towers.

Methods of Measurement: While the other standards mentioned in this paper all specify methods that completely enclose the sound source in a virtual measurement volume, this DIN standard is different, attempting to capture the sound in volumes only surrounding the primary sound emitting points. A diagram of this can be seen in Figure 5.

For the mechanical draft portion of this standard, there are four different volumes to consider:

- **Outlet:** A hemispherical volume above the fan cylinder. 4 points are measured radially along the circumference of the hemisphere in 90° increments. While the base of the hemisphere extends out from the fan stack edge by 1m, the measurements are taken on the hemisphere at an angle above that base, as shown in Figure 5.

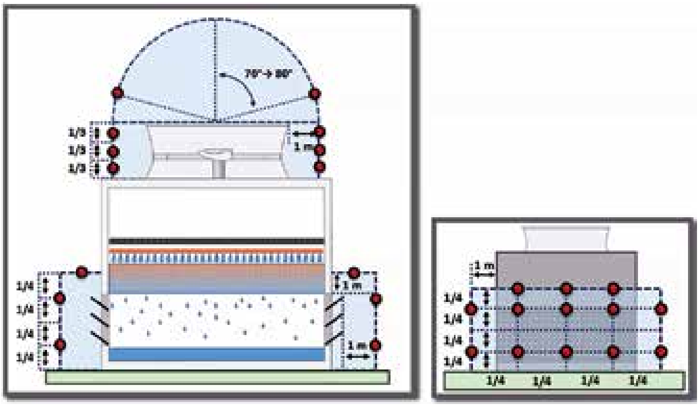

Figure 5: Sound Measurement Points for DIN 45635: Part 46. First image shows elevations for air inlet, fan cylinder and exhaust locations. Second image shows longitudinal dimensions for the air inlet.

- **Fan Stack:** A cylindrical volume surrounding the fan cylinder. 4 points are measured radially along the fan (in 90° increments), in 3 different elevations. For short fan cylinders, the vertical elevations become so close that a single elevation would suffice.
- **Motor:** A cuboid surrounding an exterior motor. The measurement surface is only detailed in DIN 45635 Part 1, not Part 46. Because of this, and since the units tested primarily have internal motors, this area is not shown in Figure 5.
- **Inlet:** A cuboid surrounding each of the air intake faces. These points are measured at 3 elevations:
  - At a height h, which is the top of the air inlet + 1m
  - At a height of 0.75·h
  - At a height of 0.25·h.

Additionally, points are taken in intervals along the length of the air intake according to Figure 5.

EN 13487

EN 13487 is a standard from the European Committee for Standardization, focusing mainly on the sound measurements of air cooled condensers and coolers. This standard is currently under review and may soon be updated, though the details of the proposed changes are not publicly known.

Scope and Purpose: To calculate the sound power level and spectrum of forced convection air-cooled refrigerant condensers and dry coolers.

Methods of Measurement: This standard is similar to the other parallelepiped methods, with the exception that it acknowledges the fact that there's moving air from fans that make capturing sound at certain points all but impossible.

For equipment with fans in a horizontal plane, the required data points are subsequently fewer, and the collection points are extended from unit corners, rather than midpoints. For units with multiple fans, this pattern is extended for each of the mid-points between fans. This is shown in Figure 6

For units with fans in a vertical plane, the measurement points alter slightly, as the code tries to capture as much fan noise as possible while avoiding the air streams. Two locations that were on the top plane in Figure 6 have now moved to the side with the fans, and are located 30 cm from the ground. On the back-side of the unit, instead of measuring from the corners, the points are now offset 0.5m. It's not intuitive, but Figure 7 tries to represent this as best as possible. The light gray points are identical to Figure 6. The red points have been re-located.

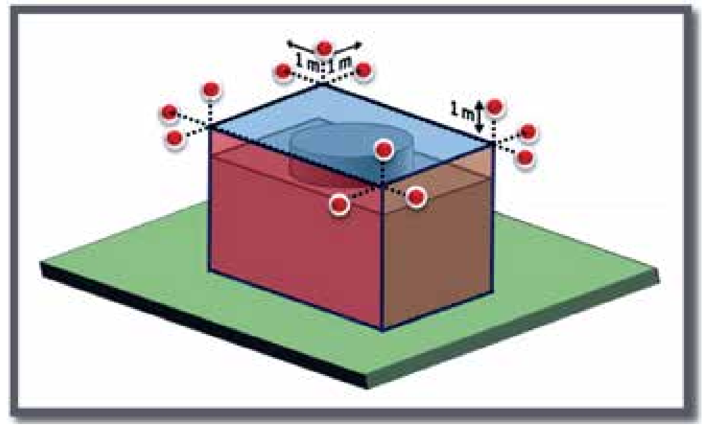

Figure 6: Sound Measurement Points for EN 13487. Measurement points are taken 1m from the exterior corner dimensions of the unit. Fans in horizontal plane.

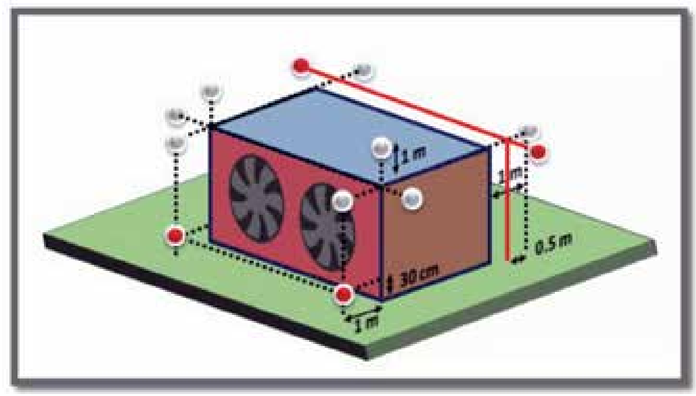

Figure 7: Sound Measurement Points for EN 13487. Fans in vertical plane.

Additional Standards

Other standards were briefly considered for inclusion in this paper. Of note, Chinese Standard GB/T 7190.1-2008, which is a code on fiberglass cooling towers. It has a small section (Appendix C) which refers to measurements of sound. This standard was excluded since it does not calculate sound power levels from the measured data, thus it could not be directly compared to other codes.

Test Setup

Test Location

The tests for each unit were conducted between September and December 2017 at the Evapco Research and Development Center, located in Maryland.

While not completely free of obstructions, the facility has a concrete test pad, which offers enough space to execute each free-field method in a real-world environment. Figure 8 shows the condition of the site during Unit 1 testing. The location has enough open space to measure 50ft in each cardinal direction from the unit without significant reflection.

Figure 8: Picture of test site. Condition during Unit 1 test.

Sound Measurement

The measurement devices used to record data were 1) a Larson Davis model 824 type 1, and 2) a Larson Davis SoundTrack LxT1 (The use of the second device was limited to tests on Unit 3, and was only required due to time constraints). Each recording was taken according to the test method being conducted, using measurements of at least 20 seconds (until stable).

Measurements at high elevations were taken using a boom lift (Figure 9), where distances were measured via laser.

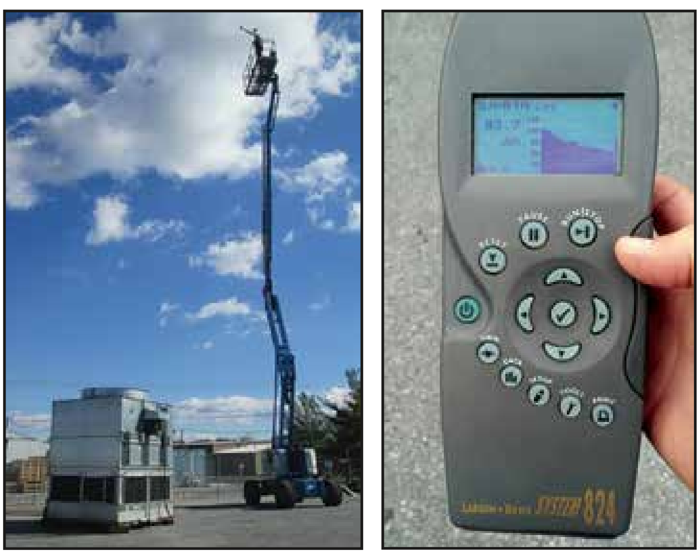

Figure 9: Pictures of sound collection.
Left: measurement at elevation using boom lift. Right: meter.

Test Units

To adequately compare the test codes mentioned in section 3, each method must be followed precisely for a variety of applications. Since cooling equipment comes in a number of sizes and configurations, multiple units were selected for this comparison (See Figure 10). A unit summary can be found in Table 3.

Throughout the duration of each unit's test, the same conditions were run, meaning no heat load, full fan speed, and full water flow (if applicable). The only variant was the atmospheric conditions.

Unit	Draft	Flow	Class	W x L x H (ft)	W x L x H (m)
1	Induced	Counter	Tower	8.5 x 9 x 12.5	2.59 x 2.74 x 3.81
2	Forced	Counter	Tower	12 x 12 x 16.51	3.66 x 3.66 x 5.03
3	Induced	Cross	Dry	7.75 x 29.33 x 9	2.36 x 8.94 x 2.74

Table 3: List of cooling equipment units that were tested.

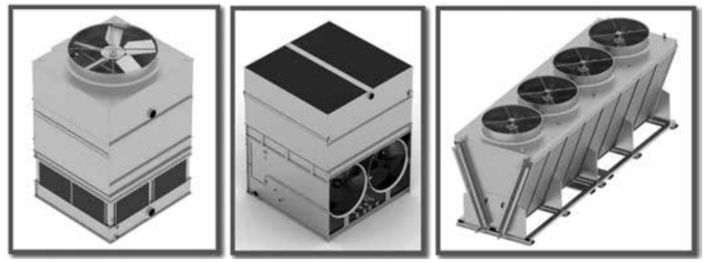

Figure 10: Renders of units tested.

Note: This paper had intended to address more unit configurations; however, cold weather prevented the collection of data from more evaporative equipment, as the test units kept freezing.

Code Comparisons (Single Unit Type)

All the test codes presented in Section 3 share the same approach of calculating sound power from the measured pressure levels. To avoid overloading the main body of this paper with data, this section will focus more on the comparison of results, rather than the calculations behind them. These computations will be briefly presented here, though more detail is available in Appendix A.

The methods from Section 3 can be categorized into two groups, those that calculate sound power from nearfield measurements, and those that calculate the power from far-field points. Since these categories are distinctly different in both measurement locations and surface areas, they will each receive their own unique section. A summary of each method type can be found in Table 4.

	Nearfield	Far-Field
ATC-128	5ft Points*	50ft Points
AHRI 370	Parallelepiped	-
ISO 3744	Parallelepiped	Hemisphere
DIN 45635	Enclosure	-
EN 13487	Parallelepiped	-

Table 4: Test code measurement methods by type.
Used for sound power calculations.

**Note: ATC-128 does not use nearfield 5ft points to calculate sound power.*

In order to best express the information from this study, the standards will first be compared for a single unit, Unit 1. This will be helpful in explaining the nuances of each code without adding in the complexity of multiple units. The additional data for Units 2 and 3 will be given in Section 6.

Sound Power Calculation

Before diving into the details, a basic understanding of the sound power calculation is needed. At its core, the power calculation is simple (as shown in Equation 2): the average measured sound pressure is taken and corrected for background noise and other attenuating factors. A geometric term is then applied, which accounts for the measurement surface area.

$$SoundPower = SoundPressure_{Avg} + Corrections + GeometricTerm \qquad \text{Eq. (2)}$$

- Corrections can include background noise, reflections, directivity, and atmospheric absorption.
- Geometric Term depends on measurement method. Typically hemispherical for far-field measurements, cuboid (parallelepiped) for nearfield.

Average Sound Pressure: A critical part of any sound power calculation is making sure the sound pressure levels are averaged correctly. The most thorough way to average the sound pressure readings is specified by ISO 3744's equation 14. (Shown simplified in Equation 3 below). This sums each point based on the surface area associated to it, before finally dividing by the overall measurement surface. This provides an area-weighted average. All surface areas are expressed in square meters in the subsequent equations.

$$SoundPressure_{Avg*} = 10 \cdot \log_{10}\left[\frac{1}{SA_T} \cdot \sum_{Point=1}^{n} \left(SA_{Point} \cdot 10^{(0.1 \cdot SP_{Point})}\right)\right] \qquad \text{Eq. (3)}$$

* For data points with **non-equal surface area of measurement**
SA_T = The total geometric surface area of the measurement plane or hemisphere.
SA_{Point} = The surface area of the measurement that is allocated to the data point.
SP_{Point} = The measured sound pressure at the data point.
n = Number of measurement points

When Equation 3 is evaluated for a surface that is divided into equal area points, then the surface area portion of the calculation can be dropped. For these data sets, Equation 3 can be simplified into Equation 4.

$$SoundPressure_{Avg*} = 10 \cdot \log_{10}\left[\frac{1}{n} \cdot \sum_{Point=1}^{n} \left(10^{(0.1 \cdot SP_{Point})}\right)\right] \qquad \text{Eq. (4)}$$

* For data points that have **equal surface area**

Corrections: The corrections portion of Equation 2 can be broken down into multiple components, though the primary correction is for background sound, shown in Equation 5.

$$Correction_{Background} = -10 \cdot \log_{10}\left[1 - 10^{\left(-0.1 \cdot (SP_{Avg} - SP_{Background})\right)}\right] \qquad \text{Eq. (5)}$$

The background correction is common through all test codes, and is only applied if the measured background is within 10-15 dB of the average measured sound pressure. If the difference is less than 6 dB, then the test becomes indeterminate, as there is no discernable difference between the test unit and background. For this paper, the background was always measured to be insignificant.

There are a few other corrections defined in some of the standards, each based on the influence of the test environment. For the basis of this paper, since all the methods were followed using the same ambient environment, all comparisons will be made assuming no ambient corrections.

Geometric Term: This is the portion of the sound power equation that differs the most from method to method. While the main correction, shown in Equation 6, is the same for each standard, the measurement surface area used is not.

$$GeometricTerm = 10 \cdot \log_{10}[SA] \qquad \text{Eq. (6)}$$

SA = The geometric surface area of the measurement planes or hemisphere.

The surface area calculations can be broken into both nearfield and far-field measurement types. The far-field is simple, and employs a hemispherical surface based on the distance. The nearfield is more complex, with deviations in the parallelepiped areas and enclosure surfaces. Table 5 shows the breakdown of calculations per code.

	Nearfield	Far-Field
ISO 3744	$SA = 4 \cdot (ab + bc + ca)$ $a = 0.5 \cdot L + d$ $b = 0.5 \cdot W + d$ $c = H + d$	$SA = 2\pi \cdot distance^2$
ATC-128	SA = Not Defined = Assumed Same As ISO	$SA = 2\pi \cdot distance^2$
AHRI 370	$SA = Same\ as\ ISO\ 3744$ Or $SA = \pi \cdot \left(\frac{L + 2m}{2}\right) \cdot \left(\frac{W + 2m}{2} + (H + 1m)\right)$	-
DIN 45635	$SA_{AirOutlet} = 2\pi \cdot (FanRadius + 1m)^2$ $SA_{Stack} = 2\pi \cdot (FanRadius + 1m) \cdot StackHeight$ $SA_{Inlet} = a \cdot b + (2a + b) \cdot c$ $a = H_{TopOfLouver} + 1m$ $b = AirInletWidth + 2m$ $c = LouverExtensionFromFace + 1m$	-
EN 13487	SA = Not Defined = Assumed Same As ISO	-

Table 5: Measurement surface area calculations by code and type.

Some of the equations in Table 5 are straightforward, while others are not. Most notably, AHRI 370 has two equations for nearfield. The first (same as ISO 3744) is the calculation of 5 sides of the measured parallelepiped. This is not defined in the AHRI code, though it is the intuitive surface area. The second equation is a hemispherical equivalency calculation derived by AHRI with little explanation other than it's based on empirical data to give equivalency between the survey and reverberation room methods.

When reaching out to AHRI for clarification, we received a response that explained the correction was essentially derived to correct for discrepancies found when testing equipment that was long and narrow. Additionally, this may also be tied to correcting a difference found between nearfield and far-field methods. The effect of this correction is clear, as it reduces the sound power levels by 2-3 dB(A). How this compares to other standards will be investigated later.

Unit 1 Data: Near-Field

In order to compare the results of each method, a baseline must first be selected. As ISO 3744 is often regarded as the most complete means of measuring sound, and its methods most likely offer the best chance of capturing representative (and repetitive) data, this standard will be used in this paper as the baseline against which all the other standards will be compared.

ISO 3744 (Parallelepiped)

The data for this method was measured using the grid pattern outlined in Figure 3 of Section 3.2.

Calculating the power levels using this method is complicated because the code could arguably be applied several ways to average the measurements. Section 8.2.2.1 of the standard applies to uniform distribution across the whole surface, and although the length and width of the unit are slightly different (creating marginally different grid patterns on the sides vs. the top and ends), the sound power can be calculated using this simplification.

If all the points on the parallelepiped are assumed to have the same equal area, then the power can be calculated by averaging all the points first, and then applying the geometric correction over the whole cuboid (using the SA equation in Table A.1) as shown in Table 6.

ISO 3744 (Parallelepiped): Sound Power (Equal Area)				
Position	SP_{Avg}	SA (m2)	Geo. Term	SoundPower
Average	77.9	111.6	20.5 dB(A)	98.4 dB(A)

Table 6: ISO 3744 Parallelepiped Method. Sound power calculation for Unit 1, assuming equal area.

However, the standard also addresses unequal areas in Section 8.2.2.2. This unequal area section weights each measurement point by the surface area associated to each point. In essence, the points can be averaged on each of the 5 faces first (assuming equal area on each face), and then the surface area correction can be applied based on each of the individual face areas. This result is shown in Table 7.

ISO 3744 (Parallelepiped): Sound Power (By Face)				
Position	SP_{Avg}	SA (m2)	Geo. Term	SoundPower
Side 1	75.4	22.8	13.6 dB(A)	89.0 dB(A)
Side 2	77.5	22.8	13.6 dB(A)	91.1 dB(A)
End 1	75.7	22.1	13.4 dB(A)	89.1 dB(A)
End 2	75.4	22.1	13.4 dB(A)	88.9 dB(A)
Top	80.1	21.8	13.4 dB(A)	93.5 dB(A)
Total	84.3	111.6	13.5 dB(A)	97.7 dB(A)

Table 7: ISO 3744 Parallelepiped Method. Sound power calculation for Unit 1, averaging per face.

The differences between the two averaging methods are subtle for Unit 1, but shows that there is still a level of judgement needed to interpret a code as complete as ISO 3744.

For the purpose of this paper, the 'By Face' (Table 7) averaging method will be used as the baseline, as it likely represents the best application of the code. This means that the baseline sound power for Unit 1 is 97.7 dB(A).

ATC-128 (Procedure 1, 5FT)

It is important to note, that per ATC-128 Procedure 1, the nearfield 5ft points are not used to calculate sound power. But if we were to use this data to calculate power, we can assume the same parallelepiped measurement surface area equations (for 5ft) as ISO 3744. The result can be seen in Table 8.

ATC 128 (5ft): Sound Power (By Face)				
Position	SP_{Avg}	SA (m2)	Geo. Term	SoundPower
Side 1	76.4	30.9	14.9 dB(A)	91.3 dB(A)
Side 2	77.9	30.9	14.9 dB(A)	92.8 dB(A)
End 1	76.2	30.1	14.8 dB(A)	91.0 dB(A)
End 2	76.5	30.1	14.8 dB(A)	91.3 dB(A)
Top	76.5	32.7	15.1 dB(A)	91.6 dB(A)
Total	83.7	154.6	14.9 dB(A)	98.6 dB(A)

Table 8: ATC-128: Procedure 1, 5ft. Near-field sound power calculation for Unit 1.

Interestingly, the sound power level is only 0.9 dB(A) higher than the ISO baseline. While this is a single unit configuration, it appears this method may be a viable way of estimating the sound power. However, it's unclear if it will hold up for other unit types. This congruity will be evaluated in Section 6.

AHRI 370

As outlined in Section 3.3, this nearfield method is simple, though perhaps a tad tedious. Data is collected in rings 1m away from the unit at 2 elevations.

To calculate the sound power using this method, the standard assumes each point has an equal share of the measurement surface. This is not exactly true (the corner measurements can be located at a variable distance), so it's a simplification that might add marginal error.

Additionally, AHRI specifies a different surface area calculation than ISO 3744, and is not sufficiently explained other than it offers equivalency between the AHRI survey method and reverberation room method. The surface area calculated from this equivalency equation equates to about half the expected measurement surface. The results for this method can be seen in Table 9.

AHRI 370 (Parallelepiped): Sound Power (Equivalency)				
Position	SP_{Avg}	SA (m2)	Geo. Term	SoundPower
Total	77.1	52.9	17.2 dB(A)	94.4 dB(A)

Table 9: AHRI 370 Nearfield Method. Sound power calculations for Unit 1 using equivalency area.

It's important to note that this method (as written) provides a sound power calculation that is significantly lower than the baseline by 3.3 dB(A). The impact of this will be explored in Section 7.2.

DIN 45635

DIN 45635 offers perhaps the most complex of all the nearfield methods, as the measurement surfaces are focused around sound emitting parts of the unit, rather than the unit as a whole. It's worth noting that ATC-128 Procedure 2 is comparable to this standard, even though that is not a focus for this paper.

Although this standard doesn't specifically apply to units with air inlets on all four faces, the inlet sound can be captured by duplicating the enclosures on each of the 4 intake faces. However, doing so can result in some significant overlap of enclosure spaces. The calculation of the sound power using this assumption can be shown in Table 10.

DIN 45635: Sound Power (Overlapping Inlets)				
Position	SP_{Avg}	SA (m2)	Geo. Term	SoundPower
Side 1	75.3	20.6	13.1 dB(A)	88.5 dB(A)
Side 2	80.4	20.6	13.1 dB(A)	93.5 dB(A)
End 1	75.9	20.1	13.0 dB(A)	88.9 dB(A)
End 2	75.6	20.1	13.0 dB(A)	88.6 dB(A)
Cylinder	76.9	4.2	6.2 dB(A)	83.1 dB(A)
Top	79.9	25.5	14.1 dB(A)	94.0 dB(A)
Total	85.6	111.0	12.9 dB(A)	98.5 dB(A)

Table 10: DIN 45635: Sound power calculation with overlapping inlet enclosures for Unit 1.

While the motor was not specifically included in this analysis despite being mounted externally, this unit is so small, some of the motor enclosure space is captured with the air inlet measurements. This is why there is an elevated sound pressure average for one of the sides (Side 2), which reflects a tone in the motor. The overall difference from baseline is 0.8 dB(A).

EN 13487

The nearfield method in EN 13487 mirrors that of the ISO parallelepiped and AHRI 370, only with fewer points, which come off the corner of the unit (rather than midpoints). This adjusts the measurement grid to account for regions that have fans moving air, thus relocating data points out of the air stream. The measurement surface area and sound power calculation are the same as the ISO. These results are shown in Table 11.

EN 13487 (Parallelepiped): Sound Power (By Face)				
Position	SP_{Avg}	SA (m2)	Geo. Term	SoundPower
Side 1	74.1	22.8	13.6 dB(A)	87.7 dB(A)
Side 2	74.9	22.8	13.6 dB(A)	88.5 dB(A)
End 1	74.3	22.1	13.4 dB(A)	87.7 dB(A)
End 2	74.3	22.1	13.4 dB(A)	87.7 dB(A)
Top	80.4	21.8	13.4 dB(A)	93.8 dB(A)
Total	83.4	111.6	13.4 dB(A)	96.9 dB(A)

Table 11: EN 13487: Nearfield. Sound power calculations for Unit 1.

What's interesting here is that while the EN standard is simple, requiring only 12 easily located points, it calculates very close to the ISO baseline, only 0.8 dB(A) less.

Unit 1 Data: Far-Field

There are only two far-field methods evaluated in this paper. ISO 3744 will again be the baseline against which the ATC-128 will be compared. Note: Now that the far-field is being evaluated, the subsequent data will be re-baselined against the ISO 3744 (Hemispherical) data, rather than the near-field equivalent.

ISO 3744 (Hemispherical)

This standard was followed according to Section 3.3, with measurements taken at a radius of 15 m (50 ft) from the unit's center. ISO 3744 calls out 10 primary points, and 10 secondary points. Only the 10 primary points are needed unless one of the measurement points is more than 5 dB off from the average. For this study, we did not need to collect the secondary points, as the data was consistent, but the measurement points were taken anyway to evaluate their effect.

Table 12 shows the results for the first 10 points separately from secondary points (11-20). It also shows the results for all 20 points averaged together.

ISO 3744 (Hemispherical): Sound Power				
Position	SP_{Avg}	SA (m2)	Geo. Term	SoundPower
Points 1-10	65.6	1459.3*	31.6 dB(A)	97.2 dB(A)
Points 11-20	65.0	1459.3*	31.6 dB(A)	96.6 dB(A)
Total	65.3	1459.3	31.6 dB(A)	96.9 dB(A)

Table 12: ISO 3744 Hemispherical sound power calculation for Unit 1, broken into averages of the first 10 points, second 10 points and all points.
**The surface area for the points 1-10 and 11-20 cases assume the full hemisphere, as if they were the only points measured.*

There are some interesting points to note from Table 12:

- This data was analyzed so that each row in the table covers the whole hemisphere. In this case, there is little difference between only taking the first 10 points, only taking the second set of 10 points, or taking all 20. This may change for other unit configurations.
- The sound power level is slightly less than ISO parallelepiped method (by 0.8 dB). This may be within the margin of error for the test, or it could reflect the suggestion from AHRI that the near field methods calculate higher than the far field methods. It's impossible to discern any correlation from one unit, so more data is needed.

ATC-128 (Hemispherical)

The only other far-field method to compare in this paper is ATC-128. The results of this method for Unit 1 can be seen in Table 13.

ATC 128 (Hemispherical): Sound Power (By Face)				
Position	SP_{Avg}	SA (m2)	Geo. Term	SoundPower
Side 1	62.2	291.9	24.7 dB(A)	86.9 dB(A)
Side 2	64.9	291.9	24.7 dB(A)	89.5 dB(A)
End 1	61.3	291.9	24.7 dB(A)	85.9 dB(A)
End 2	62.2	291.9	24.7 dB(A)	86.8 dB(A)
Top	64.2	291.9	24.7 dB(A)	88.9 dB(A)
Total	70.2	1459.3	24.7 dB(A)	94.8 dB(A)

Table 13: ATC-128 Sound power calculations for Unit 1 at 50ft from face.

Comparing this to the ISO result, ATC-128 comes in 2.1 dB(A) below the baseline for the unit. It's important to note that while the measurements were taken 50ft from the face, the calculation per the code assumes that all the points reside on the same hemisphere. This means the calculation under-predicts the surface area, and subsequently the sound pressure. This is likely the main source of discrepancy and will be evaluated in detail in Section 8.

Code Comparison (Multiple Unit Types)

While Section 5 evaluated the sound power for each of the different standard's methods, this section will expand that comparison to add multiple unit types and geometries.

Each of the three units shown in Table 3 were tested using the same methods as Unit 1, as discussed in the previous section. The results, shown in Table 14, indicate some interesting trends.

Sound Power in dB(A) for Multiple Unit Types						
	Unit 1		Unit 2		Unit 3	
Brief Description	Square Induced Counterflow		Square Forced Counterflow		Long Dry Cooler	
ISO 3744 (Hemisphere)	96.9		96.3		111.7	
ATC-128 (Hemisphere)	94.8	-2.1	94.5	-1.8	107.5	-4.2
ISO 3744 (Parallelepiped)	97.7	+0.8	97.1	+0.8	113.0	+1.3
ATC-128 (Parallelepiped)	98.6	+1.7	101.1	+4.8	112.9	+1.2
AHRI 370	94.4	-2.6	94.4	-1.9	109.6	-2.1
DIN 45635	98.5	+1.6	97.4	+1.1	114.9	+3.2
EN 13487	96.9	-0.1	97.2	+0.8	111.9	+0.2

Table 14: All sound power calculations for each of the 3 units tested. Results calculated per each code. The ± value next to each result is the delta between that result and the ISO 3744 (hemi) baseline.

Table 14 contains a lot of information, so we'll break it down by parts.

The first thing to understand is that the ISO 3744 (Hemisphere) method was chosen as the baseline against which each of the other methods are compared. Based on the uniformity and consistency of data collected using this method, it is likely this represents the most accurate indication of sound power emission (Even more-so than the ISO near-field). Each of the other methods are then compared back to this baseline for each of the units. The difference is reported next to the result.

Knowing that difference allows us to see clearly which methods seem to calculate consistently high, and which calculates low. The ATC-128 hemispherical method calculates consistently low, especially since the calculations do not account for the fact that the measurements are taken from the unit's face, not origin.

It's also interesting that the AHRI 370 method also calculates consistently low. Based on the standard and feedback from AHRI, we were expecting that the square units would have resulted in lower than baseline results; however, the long dry cooler should have tested much closer to baseline, since the correction AHRI applies is meant for such an oblong unit.

Among those methods that produced results that are consistently high, are the ISO 3744 (Parallelepiped), the ATC-128 (Parallelepiped/Nearfield), and the DIN 45635. In fact, other than the AHRI 370 method, which is corrected aggressively, all of the nearfield methods result in higher than baseline sound pressure levels. It's not clear what causes this, other than perhaps a slight over-weighting of some of the loudest emission points, but the trend here is clear.

Lastly, note that the EN 13487 performed the best, consistently matching the baseline for each test.

Considered Code Clarifications and Corrections (Excluding ATC-128)

During the course of collecting and analyzing data for this paper, avenues for improving some of the test methods presented themselves. This section will focus on exploring the effect these issues have on the sound power results.

ISO 3744 Parallelepiped: Measurement Points in Air Stream

The ISO standard is already ambiguous on which data averaging method should be used, which has been discussed in Section 5.2.1. But since this standard was not written for moving air applications, it's possible that some of the measurement locations are poorly located inside high-velocity air-streams. This was the case for several of the units tested, as shown in Figure 11.

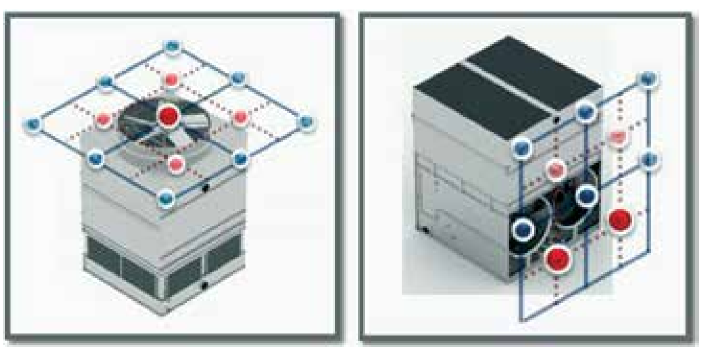

Figure 11: ISO 3744 Parallelepiped.
Measurement locations in air stream.

As ISO 3744 does not provide guidance on how to correct for this scenario, we're left to determine this on our own. There are a few means to do so, but the most straightforward is to just simply drop the biased data points and recalculate the average pressure per face with one or two fewer points. The effect of this correction can be seen in Table 15.

ISO 3744: Corrected Sound Power in dB(A)						
	Unit 1		Unit 2		Unit 3	
Brief Description	Square Induced Counterflow		Square Forced Counterflow		Long Dry Cooler	
ISO 3744 (Hemisphere)	96.9		96.3		111.7	
ISO 3744 (Parallelepiped)	97.7	+0.8	97.1	+0.8	113.0	+1.3
ISO 3744 (Corrected)	97.4	+0.4	96.2	-0.2	112.5	+0.8

Table 15: ISO 3744 Parallelepiped Method.
Sound power calculation corrected for points near fan.

The effect is subtle, but does bring the results closer to the baseline.

AHRI 370 Parallelepiped: ISO 3744 Surface Area

Already discussed in the paper is the AHRI 370 surface area calculation, which is different than the ISO parallelepiped area (by about half). If we were to ignore the standard's equivalency equation, and instead use the ISO 3744 area, then the sound power results become much more in line with the baseline. This can be seen in Table 16.

AHRI 370 Corrected Sound Power in dB(A)						
	Unit 1		Unit 2		Unit 3	
Brief Description	Square Induced Counterflow		Square Forced Counterflow		Long Dry Cooler	
ISO 3744 (Hemisphere)	96.9		96.3		111.7	
AHRI 370	94.4	-2.6	94.4	-1.9	109.6	-2.1
AHRI 370 (ISO Surface)	97.6	+0.7	97.7	+1.4	111.6	-0.1

Table 16: AHRI 370 Parallelepiped. Sound power corrections based on ISO measurement surface.

DIN 45635: Overlapping Inlet Measurement Area

As discussed in Section 5.2.4, the DIN typically applies to large towers with only two (non-adjacent) air inlets. For small towers with multiple inlets, the DIN enclosures can include overlap. This is roughly shown in Figure 12, where the adjacent air inlet measurement surfaces is first shown separately, and then together.

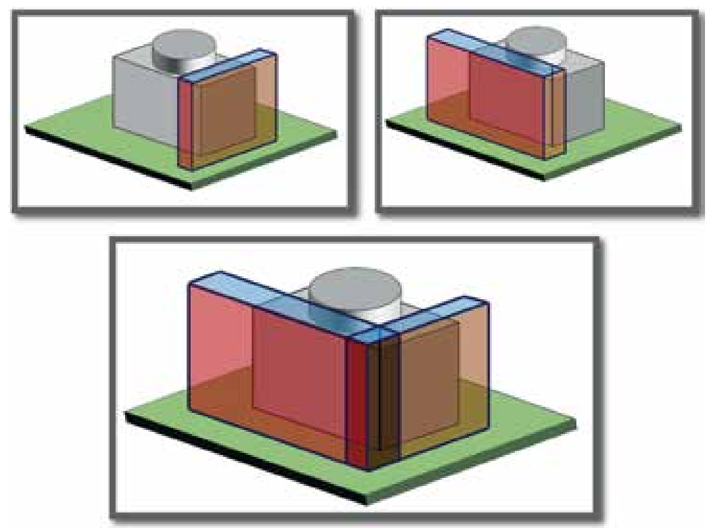

Figure 12: DIN 45635. Overlapping air inlet surfaces.

For large units, this may not be much of a problem, but for small units, like Unit 1, this overlap artificially inflates the measurement surface area (by nearly 40 percent). By adjusting the surface area of each of these enclosures by splitting the corners as in Figure 13, the calculated sound power levels are reduced slightly to better match the baseline.

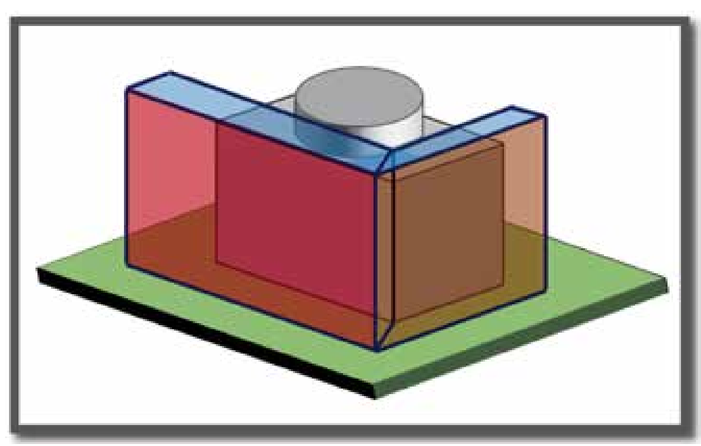

Figure 13: DIN 45635. Corrected air inlet surfaces.

Additionally, for small, multi-fan equipment like Unit 3, measuring 1m away from the fan cylinder edge also results in significant overlap. This can also be corrected by removing the overlapping spherical cap surface area between fans. This is shown in Figure 14.

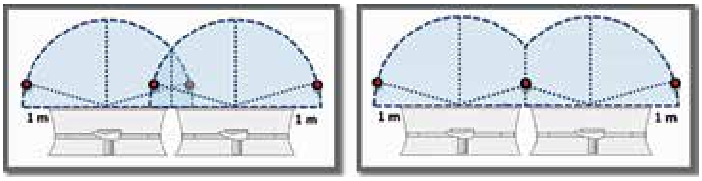

Figure 14: DIN 45635. Corrected air exhaust surfaces.

Table 17 shows the new DIN sound power results using both these adjustments.

DIN 45635 Corrected Sound Power in dB(A)						
	Unit 1		Unit 2		Unit 3	
Brief Description	Square Induced Counterflow		Square Forced Counterflow		Long Dry Cooler	
ISO 3744 (Hemisphere)	96.9		96.3		111.7	
DIN 45635	98.5	+1.6	97.4	+1.1	114.9	+3.2
DIN 45635 (No Overlap)	97.7	+0.8	97.4	+1.1	112.8	+1.1

Table 17: DIN 45635. Corrected sound power calculation with non-overlapping enclosures.

ATC-128 Considered Code Clarifications and Corrections

In the previous section, we suggested corrections to some of the codes that ended up bringing their results closer to the baseline. The results of ATC-128 still fall outside that tight grouping of data. This section will offer suggestions for modifying ATC-128, in order to bring its results more in-line with the other standards (without sacrificing its simplicity).

These corrections will be broken down into two categories, location-based, and calculation-based.

Location-Based Corrections

This section will explore what would happen if the points in ATC-128 were re-located.

Location: 2x Characteristic Dimension from Face

All the measurement locations for the ATC-128 far-field method were taken at 50ft (15m). This is called out as acceptable in ATC-128, though it more clearly defines measurements to be taken at a minimum of 2·Do (characteristic dimension, defined in Equation 1). This is shown in Figure 15.

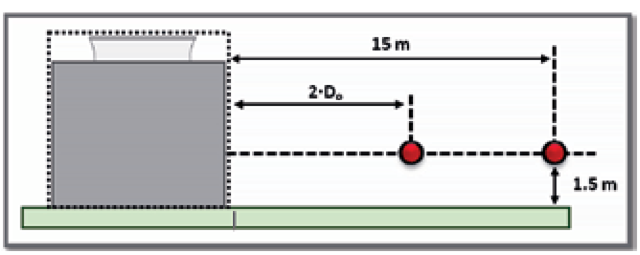

Figure 15: Using ATC-128 at 2·Do vs. 15m.

ATC 128: Sound Power (2Do From Face)				
Position	SP_{Avg}	SA (m2)	Geo. Term	SoundPower
Side 1	66.0	90.9	19.6 dB(A)	85.6 dB(A)
Side 2	65.3	90.9	19.6 dB(A)	84.9 dB(A)
End 1	65.0	90.9	19.6 dB(A)	84.6 dB(A)
End 2	65.7	90.9	19.6 dB(A)	85.3 dB(A)
Top	68.6	90.9	19.6 dB(A)	88.2 dB(A)
Total	73.3	454.4	19.6 dB(A)	92.9 dB(A)

Table 18: ATC-128 Sound power for Unit 1 at measurements locations of 2·Do = (27.9 ft) from Face.

For Unit 1, 2·Do = 27.9 ft (8.5 m). Measuring this distance from each of the faces yields the sound power shown in Table 18.

Measuring at 2·Do for Unit 1 resulted in a sound power of 92.9 dB(A), -4 from baseline, further out of the scatter of the rest of the methods. As a reference, measuring at 50ft resulted in a sound power of 94.8 dB(A), -2.1 from baseline.

Since the 2·Do sound power calculation deviated further than the original ATC-128 points, it's possible that the location still may not be truly in far-field, but in the transition region between near and far. This likely indicates that measuring further away from the unit is preferable to ensure far-field has been reached, so long as the background remains insignificant.

As the 2·Do measurement locations did not bring the results any closer to the baseline ISO 3744 on Unit 1, this correction was not repeated for any of the other units.

Location: 50ft from Origin

After several months collecting data for this paper, it seemed the likeliest source of discrepancy between ATC-128 and other sound codes lies in the fact that the measurements are taken from the unit face, rather than the internal midpoint. While this simplifies marking off measurement locations, it creates a discrepancy because it is not accounted for in the sound power calculations.

Each of the points (as measured by ATC-128) are treated as though they reside on the same hemisphere, which as Figure 16a shows, is clearly not the case. By relocating the points closer to the unit so that the locations are based on 50ft from the midpoint of the unit's base, they will essentially reside on the same hemisphere. This can be seen in Figure 16b.

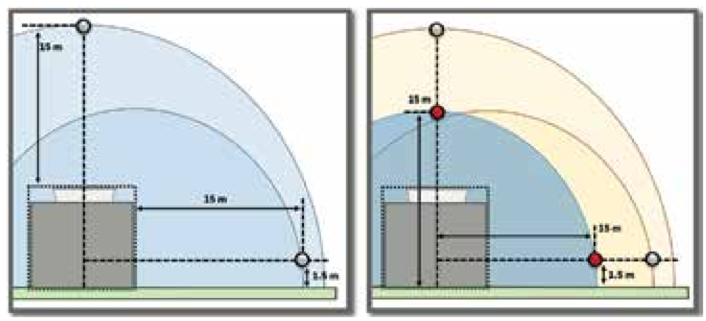

Figure 16: 16a (left) shows the previous measurement locations from face, resulting in distinct hemispheres for each measurement location. 16b (right) shows measurement locations 15m from the unit origin, which results in all the points residing on the same hemisphere.

Note: Since the measurement for the 4 sides are elevated 1.5m above the ground, there is a slight offset even in this orientation, though they are much closer to the same hemisphere than in the previous measurement locations.

By measuring from the unit's origin, the results improve against the baseline, shown in Table 19.

ATC-128 Corrected Sound Power in dB(A)						
	Unit 1		Unit 2		Unit 3	
Brief Description	Square Induced Counterflow		Square Forced Counterflow		Long Dry Cooler	
ISO 3744 (Hemisphere)	96.9		96.3		111.7	
ATC 128	94.8	-2.1	94.5	-1.8	107.5	-4.2
ATC-128 (Origin Measured)	95.9	-1.0	96.3	-0.0	108.9	-2.8

Table 19: ATC-128 Sound power for multiple units at measurements locations of 50ft from origin.

As Table 25 suggests, measuring from the unit's origin rather than the face brings the sound power results much closer to the baseline.

For more information on this correction, please see Appendix C.5.

Calculation-Based Corrections

There are several methods to alter the calculation of sound power within the bounds and measurement locations of the existing ATC-128 code to make it better match the ISO 3744 results.

Calculation: Common Origin

As noted in Section 8.1.2, measuring sound data based on distance from the origin, rather than the face improves the sound power results from those data points. What if, instead of changing the measuring location, the calculation accounts for the points residing on different hemispheres? Each point taken can be represented by a hemisphere with a common origin at the center of the base of the unit. A diagram of this can be seen in Figure 17.

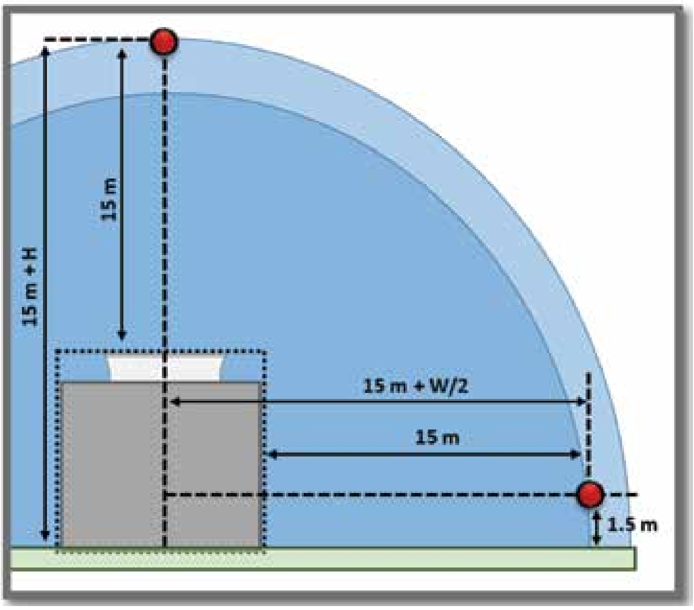

Figure 17: ATC-128 measurements 15m from face, with hemisphere of common origin.

The easiest way to calculate this correction is to adjust the surface area for each measurement location based on its distance from the origin. To do this, calculate the hemispherical surface area for each point based on the distance to the origin, and then take 1/5 of that new surface. (Each point represents 1/5 of the sound power). The result of this calculation can be seen in Table 20.

ATC-128 Corrected Sound Power in dB(A)						
	Unit 1		Unit 2		Unit 3	
Brief Description	Square Induced Counterflow		Square Forced Counterflow		Long Dry Cooler	
ISO 3744 (Hemisphere)	96.9		96.3		111.7	
ATC 128	94.8	-2.1	94.5	-1.8	107.5	-4.2
ATC-128 (Origin Measured)	95.9	-1.0	96.3	-0.0	108.9	-2.8
ATC-128 (Origin Corr.)	95.9	-1.1	96.0	-0.3	109.1	-2.6

Table 20: ATC-128 Sound power for multiple units, corrected for differing location hemispheres.

Interestingly, this gives us very comparable values as if the points were measured at those locations (Section 8.1.2), and is even identical for Unit 1.

Calculation: Common Hemisphere

Another method of adjusting the calculation is to use sound equations to mathematically relocate the data's measurement points. In figure 18, if we were able to predict what the sound would be on a common hemisphere (gray points), we would then accurately be able to use the 15m to calculate sound power levels.

This prediction of pressure levels at alternate distances can be accomplished using Equation 7.

$$SoundPressure_{P2} = SoundPressure_{P1} + 20 \cdot \log_{10}\left[\frac{Distance_{P1}}{Distance_{P2}}\right] \quad \text{Eq. (7)}$$

This power law works well, assuming both points are located in the far-field. Thus, measuring the red points in Figure 18, the sound pressure can be estimated at the gray points. Using those gray locations on a common hemisphere can then result in a corrected sound power level.

Interestingly, the math behind this yields an identical geometric term as the common origin correction in Section 8.2.1. As such, the Table 20 also represents this method as well.

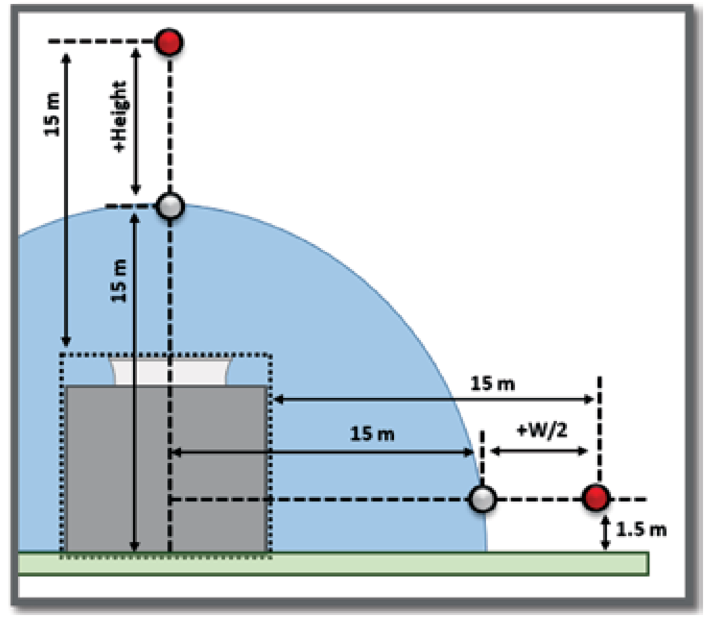

Figure 18: ATC-128 measurements 15m from face, adjusting data points to common hemisphere.

Calculation: Common Origin & Triple Fan Weighting

This correction takes the approach already discussed in Section 8.2.1, which corrects for the actual hemispherical surface areas of each measurement point, but this takes it one step further and weights the result based on observations in the field.

The sound at distance for cooling equipment is generally driven by fan and mechanical noise, (low frequencies are attenuated less than high frequencies). In the base ATC-128 method, the point measured 50ft from the fan-face only accounts for an equal share of 1/5 of the hemisphere, despite possibly being the dominant measurable sound at that distance. To explore the effect of this, the fan data point can be weighted accordingly with a correction that is simple to apply.

Using this, the hemispherical areas can be calculated according to Section 8.2.1, but instead of applying an equal 1/5 to each point's hemisphere, the fan would be adjusted to 3/7, while the other points would each account for 1/7. This adds 2 identical points in the top location, so the result would be the average of 7 points instead of 5. Note: the 3x factor is an arbitrary weighting and can be adjusted if a better number suites. The results of this correction can be seen in Table 21.

ATC-128 Corrected Sound Power in dB(A)						
	Unit 1		Unit 2		Unit 3	
Brief Description	Square Induced Counterflow		Square Forced Counterflow		Long Dry Cooler	
ISO 3744 (Hemisphere)	96.9		96.3		111.7	
ATC 128	94.8	-2.1	94.5	-1.8	107.5	-4.2
ATC-128 (Origin Measured)	95.9	-1.0	96.3	-0.0	108.9	-2.8
ATC-128 (Origin Corr.)	95.9	-1.1	96.0	-0.3	109.1	-2.6
ATC-128 (Fan Weighted)	96.5	-0.4	97.2	+0.9	110.3	-1.4

Table 21: ATC-128 Sound power for multiple units, corrected for common origin and fan weighting.

Recommendations

As noted throughout the paper, the results for the units tested yielded interesting trends between sound test codes. Though there was considerable scatter in the results when the tests were conducted to the letter of the standards, several corrections and interpretations can be applied to clump these results closer together.

While Table 14 shows the uncorrected results for all the methods on each unit, Table 22 (below) shows what this would be if the corrections discussed in this paper were applied.

Corrected Sound Power in dB(A) for Multiple Unit Types						
	Unit 1		Unit 2		Unit 3	
Brief Description	Square Induced Counterflow		Square Forced Counterflow		Long Dry Cooler	
ISO 3744 (Hemisphere)	96.9		96.3		111.7	
ATC-128 (Origin Measured)	95.9	-1.0	96.3	-0.0	108.9	-2.8
ATC-128 (Origin Corr.)	95.9	-1.1	96.0	-0.3	109.1	-2.6
ATC-128 (Fan Weighted)	96.5	-0.4	97.2	+0.9	110.3	-1.4
ISO 3744 (Parallelepiped)	97.4	+0.4	96.2	-0.2	112.5	+0.8
AHRI 370 (ISO Surface)	97.6	+0.7	97.7	+1.4	111.6	-0.1
DIN 45635 (No Overlap)	97.7	+0.8	97.4	+1.1	112.8	+1.1
EN 13487 (No Correction)	96.9	-0.1	97.2	+0.8	111.9	+0.2

Table 22: All sound power calculations for each of the 3 units tested. Results are corrected. The ± value next to each result is the delta between that result and the ISO 3744 (hemi) baseline.

Of the 3 proposed corrections to ATC-128, the fan weighting discussed in Section 8.2.3 shows the most promise. Looking at this correction and (those below it) in Table 22, the scatter of each of the methods falls within ±1.5 dB(A).

Looking ahead, additional steps would include continuing to test additional unit configurations to make sure that these trends and corrections still hold true across the full spectrum of cooling equipment.

Additionally, since EN 13487 appears to consistently offer the best relation to the ISO 3744 hemispherical calculation at a fraction of the difficulty, it is recommended to see if the EN 13487 approach could be adapted to use in future ATC-128 revisions.

References:

[AHR1] ANSI/AHRI Standard 370: 2015 Standard for Sound Performance Rating of Large Air-Cooled Outdoor Refrigerating and Air-Conditioning Equipment. (November 6, 2015) Air-Conditioning, Heating and Refrigeration Institute.

[CTI1] ATC-128: Test Code for Measurement of Sound from Water-Cooling Towers. (February 2014). Cooling Technology Institute.

[CTI2] TP16-11: Using ATC-128 for Sound Testing & Verification in the Field. (February 2016). Erik Miller-Klein, SSA Acoustics, LLP. Cooling Technology Institute.

[DIN1] DIN 45635: Part 1: Measurement of noise emitted by machines; airborne noise emission; enveloping surface method; basic method, divided into 3 grades of accuracy. (April 1984). German Institute for Standardization.

[DIN2] DIN 45635: Part 46: Measurement of noise emitted by machines: Airborne noise emission: Enveloping surface method: Cooling towers. (June 1985). German Institute for Standardization.

[EN1] EN 13487:2003: Heat exchangers - Forced convection air cooled refrigerant condensers and dry coolers - Sound measurement. (December 2003). European Committee for Standardization.

[ISO1] ISO 3740: Acoustics – Determination of sound power levels of noise sources -- Guidelines for the use of basic standards. (2000). International Organization for Standardization.

[ISO2] ISO 3744: Acoustics – Determination of Sound Power Levels and Sound Energy Levels of Noise Sources Using Sound Pressure – Engineering Methods for an Essentially Free Field Over a Reflecting Plane. (2010). International Organization for Standardization.