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Sizing Exhaust System for Refrigerating Machinery Rooms

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Section 8.11.5 of ASHRAE Standard 15-2001[1] requires that refrigeration machinery rooms have exhaust systems with the following exhaust air capacity:

Equation 1

$$Q = 100\sqrt{G}$$

The purpose of the exhaust is to provide operator safety by preventing a buildup of refrigerant in the room caused by a leak to a concentration that would be flammable, toxic, or cause oxygen deprivation. The maximum concentrations for each major refrigerant with respect to these limits are listed in Table 1 of Standard 15.

According to the Standard 15 User's Manual, Equation 1 may date back to 1930 and the engineering basis for it has never been found. Given that the exhaust rate is based on limiting refrigerant concentration, the equation has several fundamental flaws since it does not account for:

1. The maximum refrigerant concentration listed in Table 1, which varies among refrigerants by as much as 3 orders of magnitude
2. Refrigerant specific volume, and
3. Room volume

Accordingly, for some refrigerants the exhaust rate required by Equation 1 is not sufficient to maintain safe refrigerant concentrations caused by a major leak; it could potentially lead to operators being exposed to many times the allowable concentrations listed in Table 1. For other refrigerants, Equation 1 can result in excessive exhaust rates even for major leaks.

To address this issue, a revised exhaust rate calculation procedure was developed. This new procedure has been proposed to replace the current procedure in Standard 15. The procedure is intended to:

1. Reflect the fundamentals of dilution
2. Account for the concentration limits of each refrigerant
3. Be simple enough to use in a building code for determining refrigerating machinery room exhaust requirements

Method

A refrigerant leak, followed by a purge cycle can be described as follows:

- A refrigerant leak occurs.

- The refrigerant concentration rises until the refrigerant detector setpoint is reached. After a time delay, the detector turns on refrigeration room emergency exhaust ventilation. Per Standard 15, the detector setpoint must be the TLV-TWA concentration for the refrigerant. This value is typically found in refrigerant manufacturer Material Safety Data Sheets (MSDS) forms.
- The rise of concentration is slowed down by the ventilation. However, depending on the leakage rate, the concentration within the room can rise further until the end of the leak when the entire refrigerant charge has been expelled (refrigerant concentration in the vessel and room are the same).
- Once the refrigerant has completely leaked out, the exhaust ventilation produces exponential dilution of refrigerant in the room.

To calculate the exhaust rate required to provide a safe environment, the following steps are required:

1. Define the formula that describes the rise of refrigerant concentration during the leak. This results in a non-linear curve that rises until the leak ends.
2. Find the exhaust ventilation rate that prevents the curve found above from exceeding the maximum allowable concentration set forth in Table 1 of Standard 15.

The premise of this approach is to ensure that the refrigerant concentration never exceeds the Table 1 limit. Other less conservative scenarios are possible, such as allowing the concentration to rise above the limit, but not until x amount of time from the alarm initiation point to allow any occupants to escape from the room. We propose the more conservative approach because:

- Safe concentrations are maintained even if operators are unable to leave the room immediately, e.g. if disabled by an injury related to the cause for the leak.
- Many simplifying assumptions have been made in the determination of the exhaust rate, some of which are not conservative, so making even more non-conservative assumptions in the accident scenario would result in higher risk to operators.

Assumptions

The following assumptions are made to allow for reasonable simplicity of exhaust rate calculation:

1. Leak rate declines linearly over time. Actual leak rate will begin by declining exponentially, as pressure in the refrigerant vessel decreases. Then, as refrigerant is released, temperature in the vessel will change, causing the leak rate to vary non-exponentially. This relation is too complex to model. Since the basic leak rate, which is based on an assumption of leak size, is not precise, a linear decline of leak rate over time is a sufficiently accurate simplification.
2. The effectiveness of the ventilation system is 1.0, meaning the concentration of refrigerant in the occupied zone of the room is the same as that at the exhaust outlet. In other words, the make-up air induced into the room is assumed to fully mix with the room air. In reality, some inefficiency can occur if inlet velocity is low and inlets are

located near outlets, causing short circuiting of make-up air. On the other hand, real systems can have an effectiveness greater than unity if the exhaust inlets are located sufficiently near the leak to capture refrigerant before it mixes with room air. (The User's Manual to Standard 15 offers some design advice on maintaining good ventilation effectiveness, but this appears to be based on common sense, not rigorous research. Research is recommended to investigate the ventilation effectiveness of various ventilation system designs.)

3. The refrigerant will immediately disperse throughout the room and create equal concentrations of refrigerant in all areas. In reality, the concentration near the leak will initially be higher, particularly before the exhaust system starts. However, our analysis indicates that the performance of the system after the ventilation system is on is much more significant in determining final room concentration than how the system responds before the fans come on. Once the system is on, the room is assumed to be well mixed per assumption 2.
4. The specific volume of the refrigerant is based on atmospheric conditions, at 75°F. This assumes that, once escaped, the refrigerant reaches these conditions immediately. In reality, refrigerant may be liquid (leak at evaporator), evaporating into the machinery room and cooling surrounding air. Or, refrigerant may be at high temperature (leak at condenser) and will heat surrounding air. Again, in practice, the activation of exhaust systems and subsequent mixing of air should quickly minimize thermal effects on refrigerant volume.

Exhaust Rate Calculation

With the refrigerant leaking at a linear declining rate, all refrigerant will have entered the room at time $t = t_L$ so the leakage volume over time equals

Equation 2

$$Q_L = Q_0 * \frac{(t_L - t)}{t_L}$$

Before ventilation starts, the refrigerant concentration in the room rises:

Equation 3

$$dC_t = \frac{10^6 Q_L dt}{V_R}$$

Once the refrigerant concentration reaches C_{TLV}, the ventilation system starts after a time delay t_a and the refrigerant concentration in the room is:

Equation 4

$$dC_t = \frac{(V_R - Q_e dt) * C_t + 10^6 Q_L dt}{V_R}$$

assuming a zero concentration of refrigerant in the make-up air. The concentration over time becomes on an iterative basis with time step Δt

Equation 5

$$C_t = \left(\frac{V_R - Q_e \Delta t}{V_R} \right)^n C_{TLV} + \sum_{a=1}^{n} \frac{10^6 Q_L \Delta t * (V_R - Q_e \Delta t)^{a-1}}{V_R^a}$$

or expressed as a an integral

$$C_{\max} = C_{TLV} \int_{t=0}^{t_L} \left(\frac{V_R - Q_e dt}{V_R} \right)^t + \int_{t=0}^{t_L} \left(\frac{10^6 Q_L dt * (V_R - Q_e dt)^t}{V_R^t} \right)$$

Equation 6

Using a time-step model based on Equation 5, Figure 1 was developed for R22 and a leakage rate of 10 lbs/minute.

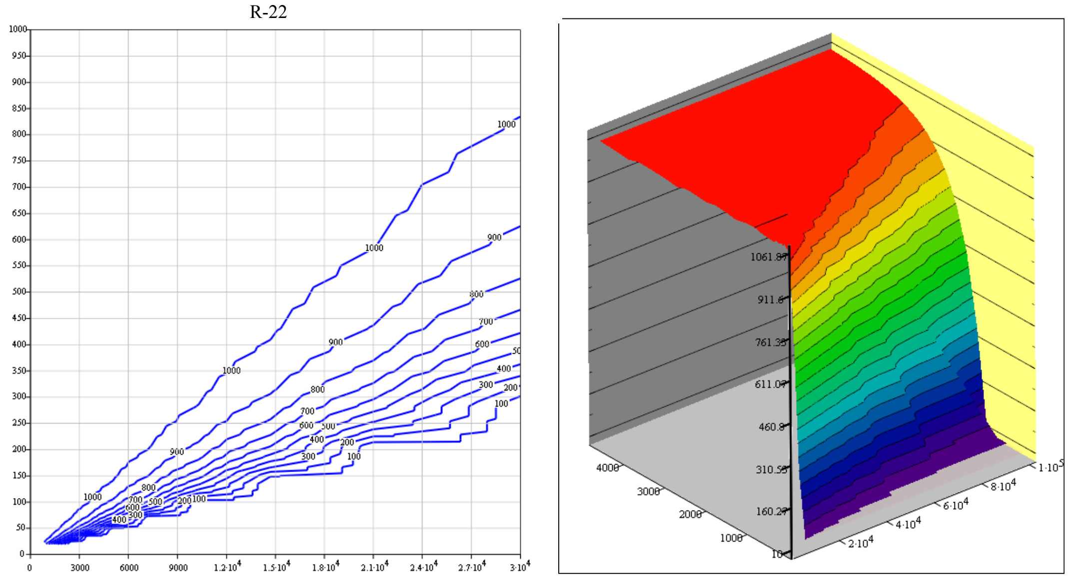

Figure 1. Exhaust rate (cfm) as a function of refrigerant charge (lbs) and room volume (ft^3)

The graph shows some “cragged” curves. They are the result of the numerical inaccuracy because of the mesh size chosen. A finer mesh results in smooth curves.

Figure 1 shows that for refrigerant charges that are small relative to the volume of the room, the required exhaust rate varies with the charge and room size because as refrigerant leaks, the ventilation rate will not prevent the concentration in the room from rising.

Figure 1 also shows that for refrigerant charges that are large relative to the room volume, there is a maximum exhaust rate which is never exceeded (red plateau). Instead, enough air has to be exhausted (fresh air introduced) to keep the refrigerant concentration below the allowed maximum concentration regardless of how long the leak continues. For an infinitely large charge, the leak would in fact continue indefinitely.

In other words, the air exhausted has to transport as much refrigerant out of the room as is introduced by the leak. The air exhausted will be at the maximum allowable concentration C_{max}:

Equation 7

$$Q_{\max} C_{\max} = \frac{Q_0 10^6}{V_R}$$

Equation 7 can be expressed using only values tabulated in standard 15 (specific volume is not one of these):

Equation 8

$$Q_{\max} = \frac{Q_0 10^6}{V_R C_{\max}} = \frac{1{,}000 m_0}{M_{\max}}$$

Since the maximum exhaust rate depends only on refrigerant properties and leak size, a graph can be produced, valid for every refrigerant, that shows the relationship between required exhaust rate (*Q*), refrigerant charge (*M*), and room volume (*V*) using dimensionless variables:

Equation 9

$$f = \frac{Q}{Q_{\max}}$$

Equation 10

$$M^* = \frac{1{,}000}{V_R} \frac{M}{M_{\max}}$$

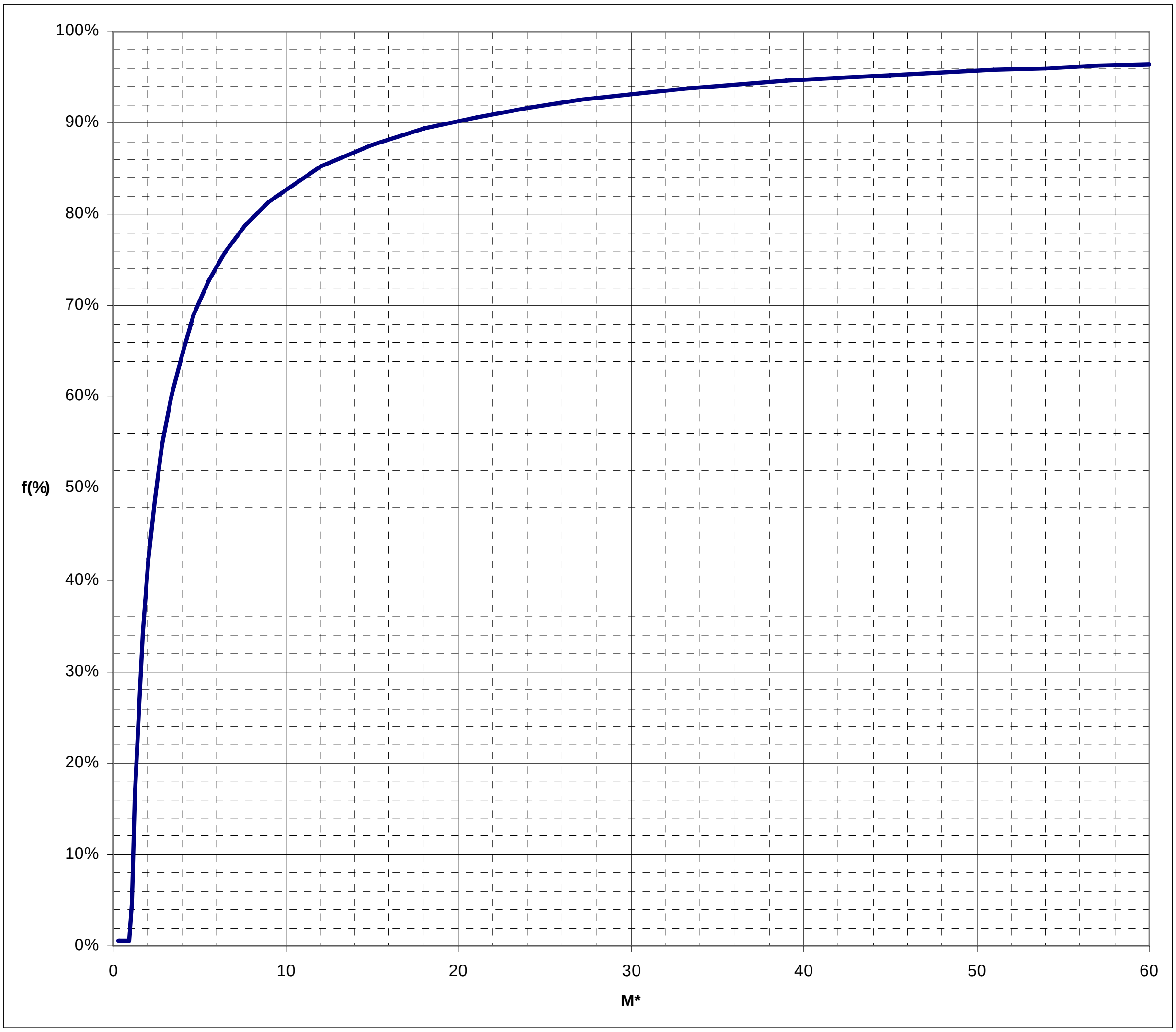

Figure 2. Fraction of maximum exhaust rate (f) as a function of refrigerant mass ratio (M*)

Figure 2 shows that the amount of exhaust required depends on the multiple of allowed refrigerant per 1,000 cfm tabulated value in standard 15. For refrigerant mass below 1x the allowed amount (M*=1), no exhaust is needed (f=0). For 8 times the allowed refrigerant mass (M*=8), approximately 80% of the maximum exhaust rate (f=80%) is needed.

Leak Rate Assumption

The required exhaust rate, Q, depends on the maximum rate, Q_{max}, which in turn depends on the initial mass leakage rate, m_0. The question then is what is a realistic leakage rate?

To see how sensitive the results are to the leakage rate assumption, assume a 2000 ft^3 refrigeration room houses a chiller with one circuit containing 60 lbs of R-22. The refrigerant mass is 60/(9.4 *2) = 3.2 times the allowable limit, so exhaust fraction, f, is 58% per Figure 2. If the leakage rate is assumed to be 10 lbs/min, the maximum exhaust rate Q_{max} would be 1,063 cfm, resulting in a required exhaust rate, Q, of 617 cfm or 19 air changes per hour.

Now assume the actual leakage rate is 20 lbs/min. As shown in Figure 3, the concentrations in the room would reach a maximum of 63,000 ppm. The concentration would exceed allowable limits from 82 seconds to 366 seconds after the leak, or 4.7 minutes. This might be enough to cause serious oxygen deprivation and even death for an operator who is unable to evacuate the room when the detector goes into alarm.

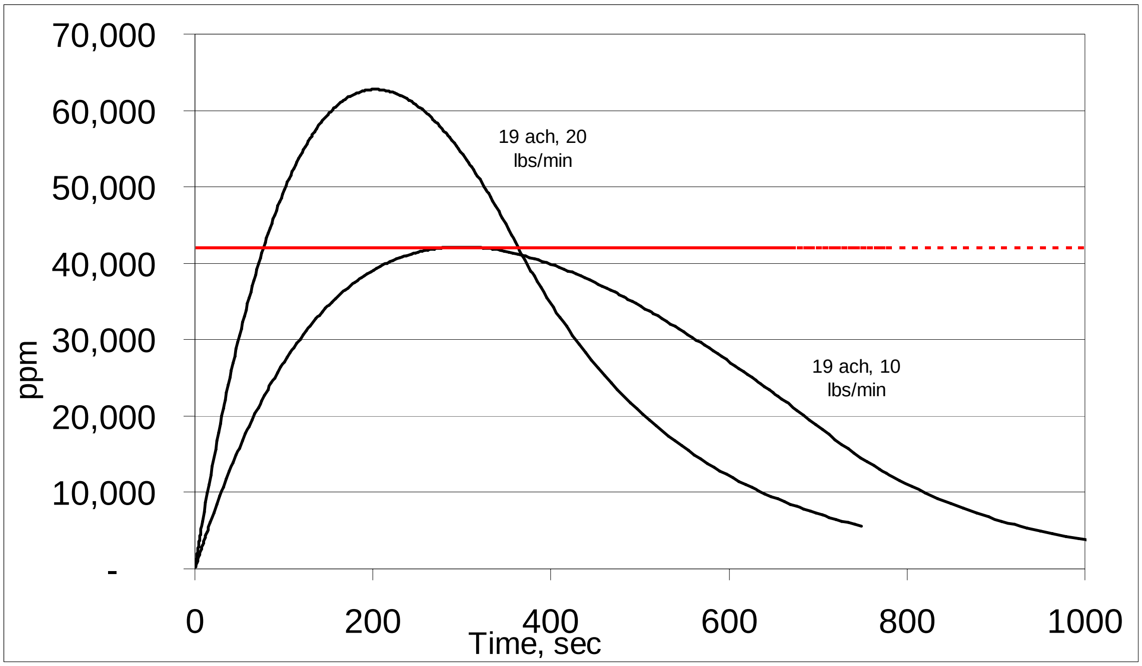

Figure 3. R-22 concentration over time

It is clear from this example that the ability of the exhaust system to maintain acceptable concentrations is strongly a function of the assumed leakage rate.

The most conservative approach is to assume an instantaneous leak (the entire charge is leaked into the room instantaneously), but no amount of exhaust would provide protection in this case. On the other hand, the leak rate could be assumed to be very small, typical of a slow leak at gasket of an open-drive chiller, but this would result in a trivially small required exhaust rate. To limit exhaust systems to practical sizes while still providing reasonable protection of operators, an assumed leakage rate between these extremes must be selected.

To guide the discussion, assume that the leak is caused by a hole on the refrigerant vessel or piping. A common cause of such a hole is accidentally drilling through a coil or air handler housing into a coil u-bend.

One equation used to determine leak rate over small leaks is the Moss equation, often used to determine leaks in pneumatic air systems[2].

Equation 11

$$m_{moss} = \frac{0.5303 * a * c * \Delta P * 60}{\sqrt{T}}$$

Note this equation is mass-based and does not depend on refrigerant specific volume.

Another equation is used by the EPA to determine leakage rates of toxic gases from tanks[3]:

Equation 12

$$m_{EPA} = HA * P_t * \frac{1}{\sqrt{T_t}} * GF$$

Gas factors (GF) for listed gases are approximately in the range 15-35, with ammonia as the lowest at 14, and Boron trichloride as the highest at 36.

There are many more approximations of leakage rate gas flows. Most of them result in the same order of magnitude results. Since our considerations will be a rough estimate of leak size at best, a comparison of the above two commonly used equations should suffice.

The comparison in Figure 4 shows that the formulas are approximately equal for GF=20.

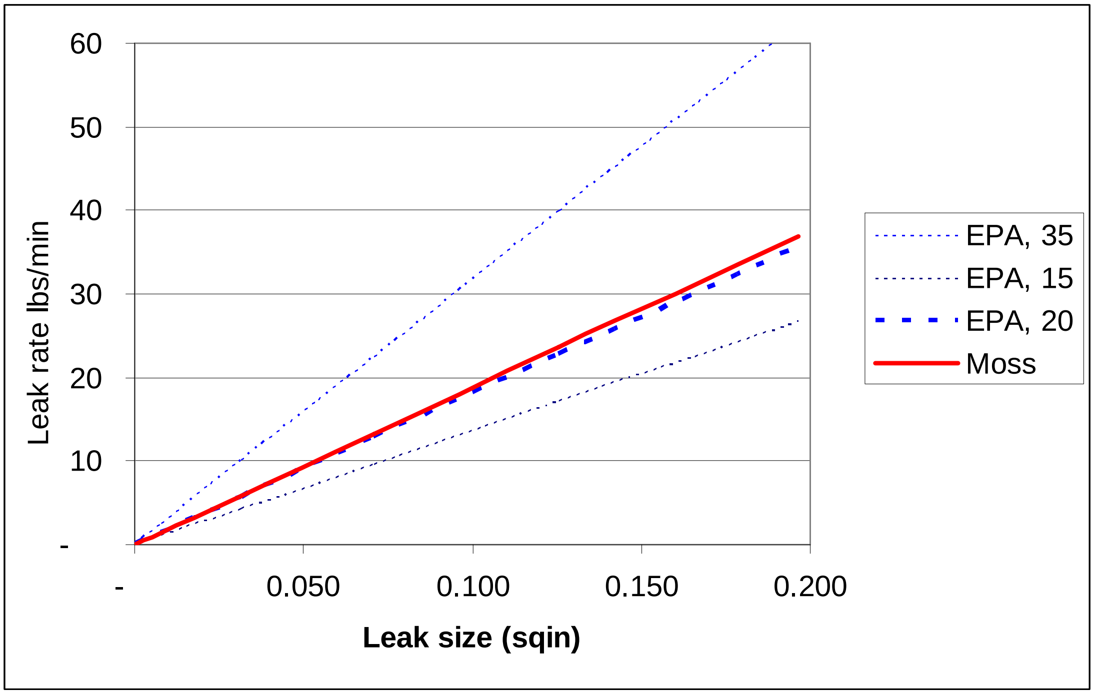

Figure 4. Comparison of leak rate equations

For a temperature of 40°F, pressure 83 psia, the leakage rate for a 0.25” hole is 3.52 lbs/min. This would be representative of a leak at the evaporator in an R22 system.

For a temperature of 100°F, pressure 210 psia, the leakage rate for a 0.25” hole is 8.5 lbs/min. This would be representative of a leak at the condenser in an R22 system. For a 0.5” hole, this becomes 34 lbs/min.

Based on these considerations, an average leak rate of 10 lbs/min -30 lbs/min range appears reasonable for a typical accidental refrigerant leak from a hole in piping or vessel.

The authors recommend stipulating a 15 lbs/min initial leak rate for the purpose of sizing exhaust systems for Standard 15 because:

1. Exhaust rates for common non-toxic refrigerants (e.g. R-22, R-134a) will be on the same order of magnitude as required by the existing Standard 15 equation for typical room volumes. The existing rates, while apparently not based on valid engineering principals, have resulted in reasonably safe refrigerating machinery rooms given the industry track record.
2. This rate corresponds to a leak from a quarter inch diameter hole for systems operating at about 200 psia, which is a conservative but not unreasonable leak that might occur with an accidental drilling or puncturing of a vessel or pipe or breaking of a gauge.
3. Larger leak rates will result in excessively large exhaust systems for toxic refrigerants (e.g. R-123, R-717). Even at this rate, exhaust rates are significantly larger than currently required by Standard 15 (see examples below).
4. To SSPC 15 reviewers–– please provide additional rationale for this or any other assumption

Detector Alarm Period

To enable the exhaust system, the refrigerant leak detector must sense that the refrigerant concentration has exceeded setpoint, C_{TLV}, and energize a contact to start the exhaust fan. Some refrigerant detectors, particularly those using multiple sampling tubes to a single detector, can have very long response times. If the delay between the refrigerant concentration reaching setpoint and the start of exhaust ventilation is too long, the room concentration will rise above the allowable level C_{max}. Figure 2 is based on zero time delay.

By iteratively solving Equation 5, it was found that with no ventilation is present and with a 15 lb/min initial leak rate, the room will reach the allowable concentration C_{max} after time t_s:

Equation 13

$$t_s(\text{sec}) = \frac{4.36 M_{\max} V_R}{10^3} = 4.36 \frac{M}{M^*}$$

Figure 5 shows the refrigerant concentration as percent of C_{max} that is attained for slower actual detector activation times, t_a, expressed as a percentage of t_s.

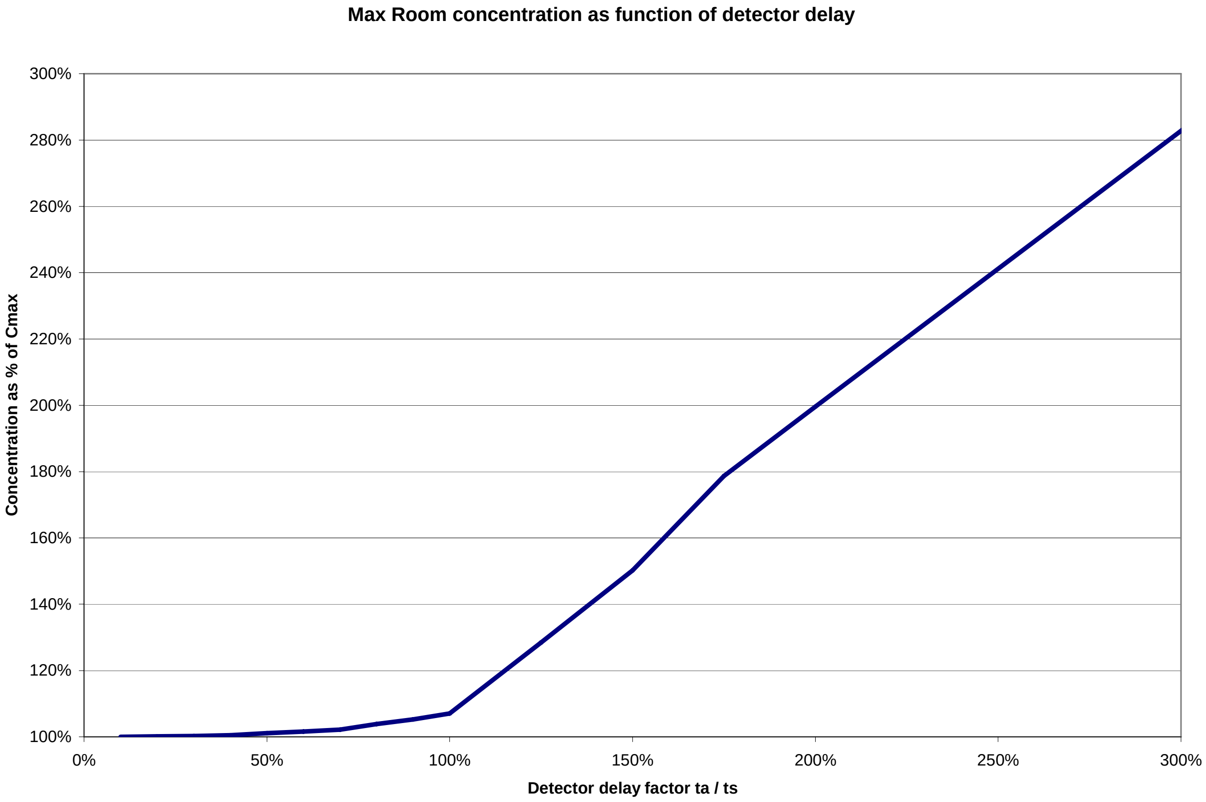

Figure 5. Refrigerant concentration as function of detector delay factor

If the detection time delay t_a is less than 10% ors alarm of t_s, then refrigerant concentrations will not exceed C_{max} if the exhaust rate is chosen using Figure 2. For t_a at 1/4.36 = 23% of t_s, refrigerant concentrations will only exceed C_{max} by a few percent. This value is proposed to be the minimum response time for detectors for Standard 15 for simplicity:

Equation 14

$$t_a(\text{sec}) \le \frac{M}{M*}$$

Revised Rate Calculation Procedure

The proposed new procedure for calculating refrigerating machinery room exhaust rate is:

Equation 15

$$Q = f * Q_{\max}$$

where

Q = the required exhaust airflow in cubic feet per minute (liters per second)

f = fraction of Q_{max} determined from Figure 2 as a function of refrigerant mass ratio, M*

Q_{max} = $\frac{1{,}000 m_0}{M_{\max}}$ from Equation 8

m_0 = initial mass leak rate, which is assumed to be 15 lb/min (0.11 kg/sec) unless approved otherwise by the authority having jurisdiction

M_{max} = quantity of refrigerant per occupied space as listed in Table 1 of Standard 15, lb per 1,000 ft^3 (kg/liter)

$M^* = \dfrac{1{,}000}{V_R}\dfrac{M}{M_{\max}}$ from Equation 10

V_R = Volume of the machinery room, ft^3 (liter)

M = the mass of refrigerant in pounds (kilograms) in the largest system, any part of which is located in the machinery room.

Table 1 shows an example chiller room. The room is 33 ft x 30 ft x 13.5 ft high (13,365 ft^3 total volume) and has two chillers, each 325 tons. Per Standard 15, the charge of the largest refrigerant circuit is used to determine *M*, in this case the charge of one chiller. The required exhaust volume and refrigerant detector response times are shown for the three currently most common refrigerants used in chillers today.

	Reference	Units	Refrigerant		
			R-22	R-123	R-134a
Approximate mass/ton	Typical	lb/ton	2	2.2	2.7
M	@ 325 tons	lbs	650	715	877.5
M_{max}	Table 1 of Standard 15	lb/1000 ft^3	9.4	0.4	16
Q_{max}	Equation 8	cfm	1,596	37,500	938
M^*	Equation 10	–	5.2	133.7	4.1
f	Figure 2	%	70%	98%	65%
Q	Equation 15	cfm	1,117	36,750	609
Q (15-2001 equation)	Equation 1	cfm	2,550	2,674	2,962
% of 15-2001 equation			44%	1,374%	21%
t_a	Equation 14	seconds	126	5	214

Table 1: Example Exhaust Rates and Response Time Requirements

The exhaust rates for R-22 and R-134a are smaller than the exhaust rate required by Standard 15-2001, while the exhaust rate for R-123 is substantially larger and the detector response time is very small. The latter is typical of refrigerants that have very low maximum concentrations in Table 1 of Standard 15. Because these requirements may not be practical for every refrigerating machinery room, an exception should be provided in Standard 15 for those rooms where operators must don self-contained breathing apparatus before entering the room. The SCBA would protect operator health and safety so the exhaust rate could be reduced to a nominal amount required to keep the refrigerating machinery room at a negative pressure to limit migration of refrigerant outside the room.

Conclusions

The existing refrigerating machine room exhaust rate formula in Standard 15-2001 does not take into account refrigerant maximum concentration limits and room size, possibly exposing operators to unsafe concentrations of refrigerants in the case of a large leak. The exhaust rates required by the new procedure presented here are designed to ensure that maximum concentrations required by Standard 15 are not exceeded after a large, but limited, leak. This new procedure results in rates that are on the same order of magnitude as the current requirements for non-toxic and non-flammable (A1) refrigerants but larger rates for other refrigerants. The rates are significantly larger for those refrigerants with very low concentration limits. For these rooms, it may be more practical to protect operators using self-contained breathing apparatus rather than via exhaust dilution.

The new procedure also points out the importance of refrigerant detector response time. Standard 15 should require adequate response time based on the maximum refrigerant concentration.

It is recommended that additional research be performed to verify the accuracy of the methods and procedures proposed in this paper, including issues such as the ventilation effectiveness of various exhaust system designs, realistic refrigerant leakage rates, and response times of various refrigerant detector designs.

Variables

C_t = concentration at time, ppm
C_{max} = maximum concentration allowed per Table 1 of Standard 15, ppm
C_{TLV} = threshold limit value concentration, triggers refrigerant exhaust, ppm
M = mass of refrigerant in largest system, lbs
M_{max} = allowed mass of refrigerant per Table 1 of Standard 15, lbs/1000 ft^3
t = time, sec
t_L = end time for leakage, sec
t_a = activation time of exhaust system; detector response time, sec
v = specific volume of refrigerant, ft^3/lb
Q_L = Refrigerant volumetric leak rate, ft^3/sec
Q_0 = Initial volumetric refrigerant leak rate, ft^3/sec
m_0 = Initial mass refrigerant leak rate, lb/min or lb/sec
Q = Required exhaust airflow, ft^3/min or ft^3/sec
Q_e = Exhaust rate, ft^3/sec
V_R = Refrigerating machinery room volume, ft^3
f = ratio of Q to fraction of Q_{max}
Q_{max} = maximum exhaust rate, cfm

M^* = ratio of actual refrigerant mass to maximum refrigerant mass per Table 1 of Standard 15

m_{moss} = gas leakage rate per the Moss equation, lbs/min

a = orifice, or leak, area, in^2

c = flow coefficient (0.65 for sharp edge)

ΔP = pressure differential over opening, psia

T = absolute temperature, R

m_{EPA} = gas leakage rate per EPA equation, lbs/min

HA = orifice or leak area, in^2

P_t = tank pressure, psia

T_t = absolute tank temperature, R

GF = Gas factor (EPA equation)

References

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[1] ASHRAE Standard 15 Safety Standard for Refrigeration Systems

[2] See example at www.cleandryair.com/system_leaks.htm

[3] See http://www.epa.gov/ceppo/pubs/oca/oca-all.pdf