ASD PRESSURE FIELD EXTENSION TESTING

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Abstract

Active Soil Depressurization (ASD) systems for residential homes are typically installed without first testing how far a Pressure Field Extension (PFE) can be generated from a single sub-slab suction pit. In commercial buildings requiring radon or vapor intrusion mitigation, the size of the slab needing to be treated, the variation in sub-slab permeability and the possibility of sub-slab barriers makes it necessary to pre-measure the PFE and repeat this measurement in all locations where PFE is not obtained from the previous test or tests. These results are used to optimize the design in regard to the number and location of suction points, determine the appropriate pipe size and overlay fan curves to illustrate lower or higher airflow than the PFE results. This study reviews the original EPA recommended PFE testing method as well as methods currently used on commercial buildings. The results of a commercial PFE testing was compared to the final results when the ASD system was installed.

1.0 Introduction

1.1 Reasons for Understanding and Performing PFE Measurements

Active Soil Depressurization (ASD) is recognized as the primary method of reducing radon or chemical vapors in the soil from moving into a building. A pressure field extension (PFE) test is a measurement of how far and how strong a pressure can be induced under a slab while measuring the suction pit pressure and airflow that the test fan is generating. Residential buildings constructed to modern code requirements often have permeable material under the slab that allow a typical residential ASD radon mitigation system to successful create a sub-slab depressurization that lowers the radon levels below the EPA action level without performing a PFE test. In some residential cases, because there is not a permeable sub-slab material or the slab leakage and or soil permeability is too great, it is necessary or helpful to perform a PFE test. In commercial, multifamily, schools and other large buildings there are often restrictions where piping can be installed or large areas that require an ASD system or the sub-slab material either allows excessive air flow or very limited airflow. These building types, which are all referred to as “commercial buildings” in this paper, could require one to a dozen suction pits and each suction pit could have a minimal airflow requiring very high vacuum fans or very high airflows requiring large size piping and specialized fans. These factors often change dramatically from one area of a building to another. The unpredictability makes it crucial to have reliable information of the sub-slab airflow and PFE characteristics for all areas that require an ASD design and system.

The other often overlooked consequence of poorly designed commercial ASD systems is the installation cost of oversized system fans used to increase PFE and the long-term energy required to operate the ASD system. Three fan laws are important to understand in ASD system design. First fan law is changes in fan RPM equal changes in CFM. Double the fan RPM doubles the fan airflow. Second fan law is the square of the CFM airflow change determines the change in the pressure the fan works against. Double the fan airflow increases the static pressure by a factor of four. The third fan rule is the energy cost or brake horse power to operate the fan changes by the cube of the CFM change. Doubling the fan airflow requires eight times more power.

1.2 AARST/ANSI Requirement to do PFE Testing for Commercial Mitigation

The 2023 version of the ANSI/AARST "Soil Gas Mitigation Standards for existing Multifamily, School, Commercial and Mixed-Use Buildings" (SGM-MFLB-2023) specifies that pressure field extension testing (PFE) shall be done prior to final design and system installation. The following is from the standard.

5.3 Diagnostic investigation

5.3.1 *All mitigation methods*

Diagnostic analysis shall be conducted prior to final design and installation of *mitigation* systems in multifamily, school, commercial or mixed-use buildings and where the purpose of mitigation includes chemical vapor intrusion.

Where such *mitigation* projects include multiple homes, buildings or portions of buildings that are like structures, provisions in Section 5.3.1.1 are permitted after completing *diagnostic analysis* for a representative sample of each like structure associated with the project.

5.3.5 *ASD diagnostic PFE analysis* *(As replicated in ANSI/AARST SGM-SF)*

Diagnostic analysis shall include evaluations required in a), b) and c) of this Section 5.3.5.

a. *PFE* Distance (Qualitative)

With vacuum applied at the chosen suction point, evidence shall be sought to characterize the distance PFE can be achieved across the targeted soil gas collection plenum(s). The pilot hole or test port locations shall be at locations that will best characterize:

1. The full expanse of the targeted soil gas collection plenum(s); or
2. As an alternative or supplement, other locations where evidence suggests that large volumes of soil gas are susceptible to being drawn into the building by air pressure differences between soil and indoor air.

Where *PFE* is not demonstrated across most of the targeted soil gas collection plenum(s), further investigation is required.

b. *PFE* Vacuum (Quantitative)
Once goals for PFE distance are met, measurements shall be made to quantify air pressure differences under the slab or membrane relative to indoor air. Jobsite log records shall include the values measured in this effort to characterize vacuum strength needed for ASD design. The measurements shall be made with a micromanometer or equivalent differential pressure gauge that is capable of reading to 1/1000-inch water column (0.25 Pa).

c. Exhaust Air Volume (Quantitative)
Once goals for both PFE distance and vacuum strength are met, the volume of air exhausted to achieve desired PFE, as measured in cfm (m^3/min), shall be recorded in jobsite logs. Fans chosen and duct pipe configurations, in accordance with Section 6.3, shall be capable of transporting this volume of air.

2.0 Methodology

2.1 EPA Recommended versus WPB - PFE Test Procedures

Although the SGM-MFLB-2023 specifies that a PFE test be done before a mitigation system is designed or installed, it does not specify how to do that test. Specific guidance in how to perform that test was included in the EPA document published in October of 1993, (Henschel, B 1993) "Radon Reduction Techniques for Existing Detached Houses, Technical Guidance (Third Edition) for Active Soil Depressurization Systems" by Bruce Henschel. This document will be referred to in this study as "ASD-TG". Section 3.3 of this guidance "Procedures for Sub-Slab Suction Field extension Measurements" carefully lays out extensive details of how to perform PFE measurements and use the results to design a radon system for residential homes. The ASD-TG recommendations of how to perform a quantitative PFE test are applicable for designing a mitigation system for schools, multifamily and commercial buildings. The recommendations for a PFE test using tracer smoke are more relevant for residential buildings as are the recommendations in the ASD-TG for doing PFE testing during mitigation installation after the suction pit has been excavated.

The following is an overview of the procedures Bruce Henschel detailed in the ASD-TG. Variations or additions to these procedures that are used by the author to perform a commercial PFE test are identified as "WPB".

2.2 Determining HVAC Operation

ASD-TG does not make any reference to recording the operation of the building HVAC system.

WPB always investigates the design and operation of the building HVAC system. Knowing the HVAC operation during the PFE test is important. This often requires gaining access to the mechanical room or the roof top to inspect the roof top units (RTU). Although WPB typically does not have the option to modify intake or exhaust fan usage in a commercial building or control opening and closing of vents, it is important in many cases to discuss changes to the HVAC operation with the building owner to reduce the negative pressure in the building or increase the introduction of outdoor air into the building.

WPB will always measure and record the lowest level inside to outside pressure by running tubing from a micro-monometer input port to under an exterior door. WPB will also make measurements under hallway doors that lead into rooms that may have different room pressures versus the hallway. This is especially needed if the isolated room has an exhaust fan such as a school lab or kitchen.

2.3 PFE Suction Hole Installation

ASD-TG recommends a 1.25" (32mm) suction hole be drilled in a location where a future suction pit would likely be installed. The suction hole should be located away from slab leaks that cannot be easily sealed during the PFE testing. The location of in-slab or sub-slab utilities needs to be taken into consideration. A sump pit that has connection to the sub-slab can also be used if the sump opening or openings can be sealed during the PFE test. A shop vacuum is used during the drilling to minimize the dust and to clean the suction and test holes. The drilling is extended below the slab to help determine if there is sub-slab gravel or dirt. No special effort is recommended to clean out the 1.25" (32mm) suction hole other than using the vacuum.

Vacuum type	0.75" hole	1.0" hole	1.25" hole	1.5" hole
12 Amp Dirt Devil	45 cfm	51 cfm	53 cfm	54 cfm
10.0 amp Craftsman	63 cfm	87 cfm	113 cfm	117 cfm
12.0 amp Rigid	70 cfm	102 cfm	140 cfm	154 cfm

Table (1): Maximum Airflow through a 4-inch slab depending on holes size and vacuum

WPB drills one or more 5/16” test holes first at the PFE suction hole location to determine the thickness of the slab. In commercial buildings the slab can be 12 inches or more thick. The hammer drill used by WPB needs to have a grounding plug because the metal detecting cut off switch used for all holes drilled through the slab requires a ground connection through the drill. See Figure 1. Commercial slab construction typically includes metal re-bar or wire mesh that will activate the cut-off switch and reduce the chance the drill bit will be damaged by trying to drill through metal. If the building was constructed before the mid 1980’s, it is likely but not definite that any sub-slab piping will be constructed with metal that will also activate the cut-off switch. Construction from the mid 1980’s on, often used plastic conduit or plumbing pipes below the slab that may require professional scanning to locate. Inspection of any utility piping routed through the slab may reveal if it is plastic or metal construction. In buildings with critical utilities or structural components like pre-stressed concrete bars in the slab, WPB recommends the slab be professionally scanned to determine their location.

A 2.5-inch (63.5 mm) suction hole is drilled by WPB and a two-foot-long pry bar is used to loosen any material that is below the slab. The standard vacuum 2-inch (50mm) extension tube can be used to clean out the suction hole. Approximately 1.0 to 1.5 gallons (4 to 6 liters) of soil can often be removed from the 2.5-inch suction hole with this method. WPB considers drilling 4” to 5” core holes to perform PFE tests as impractical for commercial ASD design.

Figure (1): Drill cut-off switch and 15-amp speed controller

2.4 Diagnostic Shop Vacuum

ASD-TG recommends a high-capacity shop vacuum be used to perform the PFE test. WPB uses a custom-built high airflow and vacuum that has a 15-amp capacity speed control built in and a maximum static pressure of 56 inches and maximum airflow of 165 CFM with an inline dust filter. See speed controller in Figure 1. Table 1 lists the reduction in airflow using smaller suction holes.

A shop vacuum has greater suction capacity than residential radon fans which can lead to over predicting the final system performance unless the vacuum is adjusted to match existing fan performance.

WPB finds adjusting the vacuum speed to match fan curves onsite not practical because the airflow and sub-slab pressure must also be measured at each vacuum setting and the piping resistance calculated based on the airflow before fan curves can be considered. WPB instead takes three sets of sub-slab vacuum and simultaneous airflow measurements and enters that data into a spreadsheet to display linear sub-slab airflow resistance on a double log graph. Piping airflow resistance is added to the sub-slab airflow resistance to obtain the total airflow resistance. Fan curves are overlaid on the combined soil and piping resistance graph. Where the fan curve passes over the total resistance line is the predicted performance using that fan.

For a fan system with multiple suction holes, WPB uses the soil resistance of the single PFE test and adds the piping resistance of the pipes above the manifold that have combined airflow from multiple test holes. The crossover point of the fan is then divided by the number of suction holes to determine the cavity test hole pressure and test hole pressures at that reduced airflow. This assumes the soil resistance of each of the multiple suction holes is similar.

ASD-TG recommends that the shop vacuum be placed outdoors and a long vacuum hose be used to route to the suction pit. An alternative is to have a long vacuum hose routed from the exhaust to the outside.

WPB does not route the hose to the outside because the long length of vacuum hose will reduce the vacuum performance and the building needs to be in a closed building condition to maintain typical building operation. The shop vacuum is never left on when measurements are not being taken to minimize the on time. After completion of the test, the building is ventilated if this option exists. WPB assumes the vacuum can be discharged into the building because the health risk of radon is based on multi-year exposure not short hourly exposure periods. The exception to this is when volatile harmful chemicals are under the slab. A charcoal type filter is used on the vacuum exhaust to capture a significant portion of the chemicals. An alternative is to route the exhaust to the outside using four inch or larger ducting to minimize back pressure.

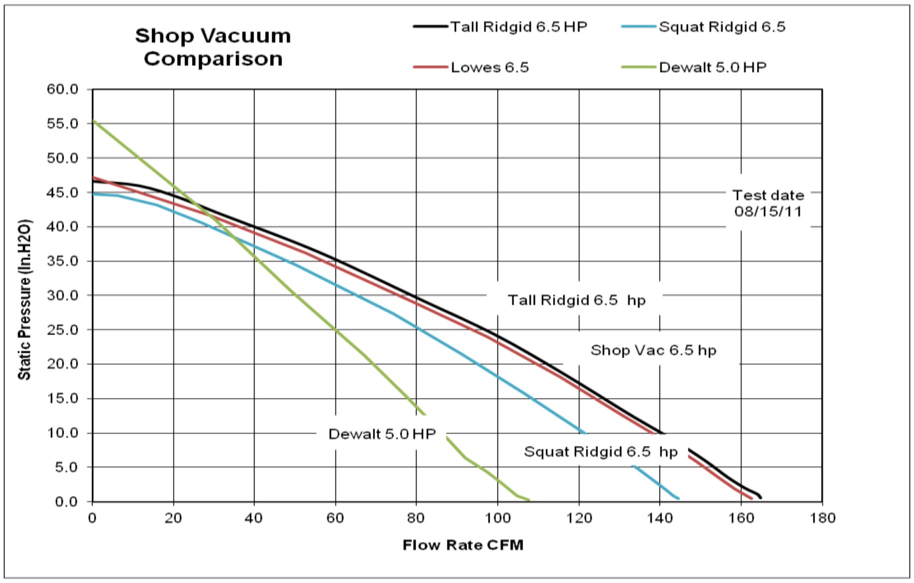


Figure (2): High-capacity shop vacuum comparison

2.5 Cavity Test Hole

ASD-TG recommends installing a cavity test hole about 8” to 12” from the suction hole. See Figure (3). This test location is the approximate typical dug out suction pit radius edge. The future suction pit will be generating sub-slab airflow and vacuum from this edge location. Measuring the static pressure at this sub-slab location while simultaneously measuring the shop vacuum airflow will allow determining a fan that matches these parameters not including the airflow resistance of the piping. If the airflow the fan will generate from the sub-slab is known, the additional resistance of the piping airflow can be determined for different pipe sizes and total equivalent pipe length which includes pipe fittings.

WPB has found that it is best to drill two cavity test holes about 8 inches from the center of the suction hole and averaging the results. If the sub-slab is stone base or very porous the results from different distances from the suction hole varies a small amount. As the soil density increases the cavity distance can produced large differences. In this case a 12-inch cavity test hole distance will have significantly lower pressure than the 8-inch cavity pressure. A 12” cavity test hole low pressure reading taken in dense sub-slab can falsely indicate an installed low vacuum fan will provide the airflow performance of the higher applied vacuum PFE test.

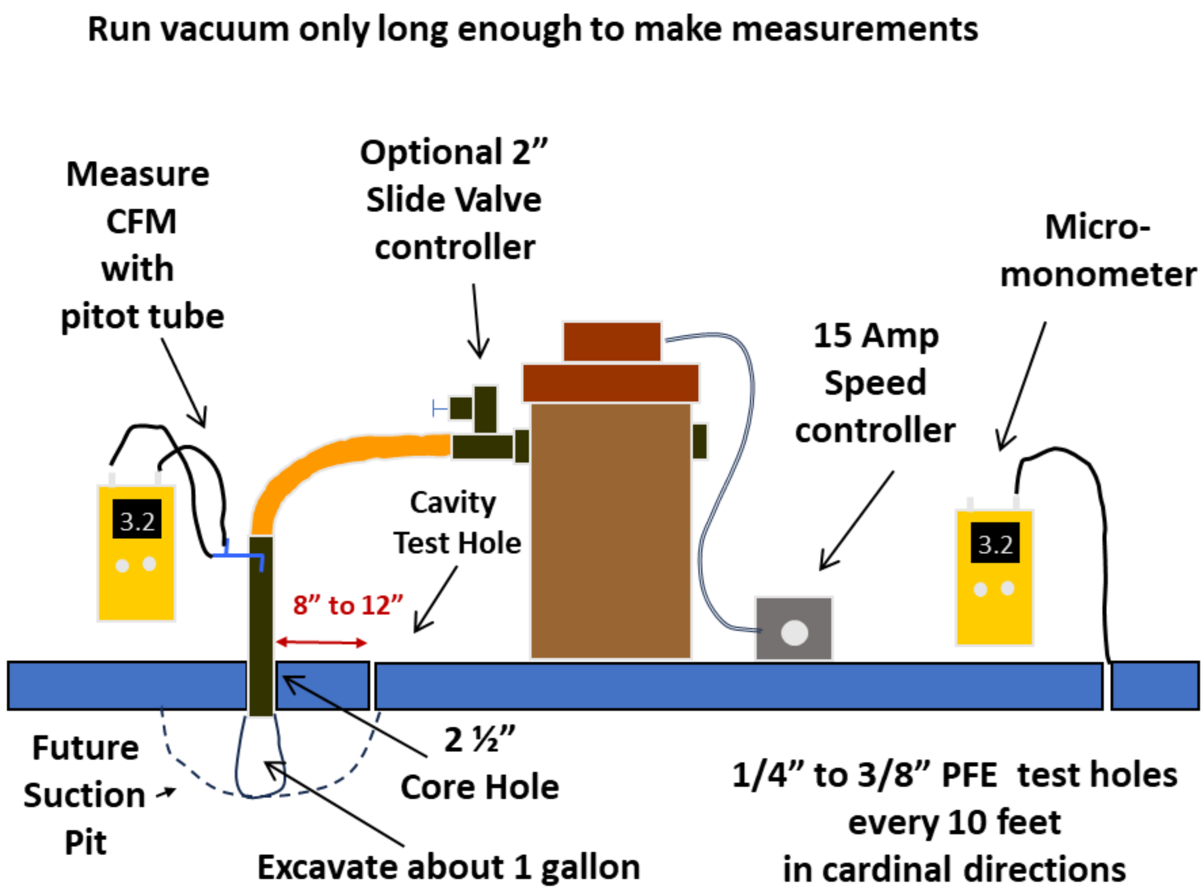


Figure (3): PFE equipment and layout

2.6 Micro-Monometer and Magnehelic Gauge

ASD-TG recommends a digital micro-monometer be used to measure test holes. A caution given is that the micro-monometer must be zeroed before sealing the input tube in the test port. A shop vacuum used in tight soil is likely to have sub-slab pressures greater than five inches (1250 pascals). Most ultra-sensitive micromanometers have a maximum pressure of 4 or 5 inches (1000 to 1250 pascals) of static pressure. A less expensive magnehelic can be used for the cavity test hole that has a static pressure range higher than typical micro-monometer maximum of 5 inches (1250 pascals).

ASD-TG states it is necessary to carefully seal tubing in test holes or the readings will be false low. Plumber's putty can be used to provide the seal.

WPB has found the more expensive digital micro-monometers that have self-zeroing function and sensitivity to 0.1 pascals or 0.0001 inches of static pressure provide easier data collection and the required sensitivity. Rather than a magnehelic, a low-cost digital micro-monometer that reads to 40 inches of static pressure can be used to measure the cavity test hole and provide sufficient sensitivity.

WPB uses a graduated rubber stopper, sized for the test hole diameter with brake line tubing installed through the rubber stopper to provide a faster sub-slab pressure measurement. This concept was developed by Obar Systems.

2.7 Controlling Shop Vacuum Speed

ASD-TD recommends either a speed controller or a relief valve be installed on the suction side of the vacuum to be able to adjust the vacuum performance to match the performance of an available fan. The relief valve needs to be located where it will not cause the pitot tube to be measuring in a significant turbulence. A fan speed controller that can handle at least 15 amps is required. See picture of a speed controller in Figure (1).

WPB prefers the speed controller for ease of set-up and use. The speed controller is also not causing additional airflow turbulence.

2.8 Measuring airflow

The airflow drawn out of the suction hole needs to be measured using a pitot tube. A pitot tube measures the combined air velocity pressure and static pressure inside the tube with one port or ports that face into the moving air. A second separate measurement is made of the static pressure inside the tube. The static pressure port is connected to the reference port of a micro-monometer that reads down to 0.001" or 0.1 pascal. The combined velocity and static ports are connected to the signal port of the micro-monometer. The micro-monometer displays only the velocity pressure of the airflow because the static pressure is automatically subtracted as the reference pressure. The velocity pressure is converted to CFM using the square root function on a smart phone or in a spreadsheet. The formula is the following for a common shop vacuum 2" suction tube or 2" PVC pipe that has the pitot built in.

For two-inch pipe use the fooling formula.
Square Root of Velocity Pressure X 87 = CFM

A hand-held pitot tube SKU#160-8 can be purchased from Dwyer Instruments. A pitot built into a 2-inch PVC pipe is more expedient and reliable onsite. Obar Systems located in NJ has an available flow gauge that can be modified to use in a 2" PVC pipe.

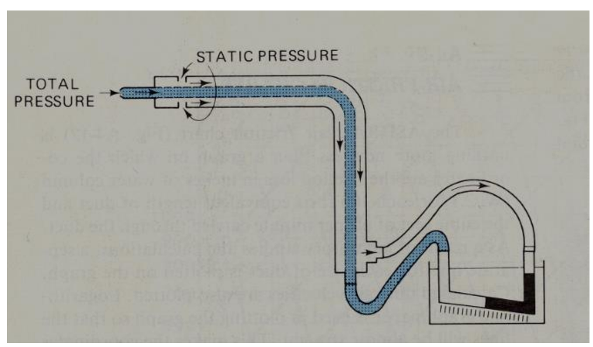


Figure (4): Pitot Total Pressure versus Static Pressure

Figure (5): 2" to 3" to 2" Pitot Tube

Figure 5 displays the parts and tools necessary to build an inline pitot tube. The flow gauge can be obtained from Obar Systems. The 2-inch length of PVC piping is inserted into the 2.5-inch PFE cored hole after subslab material has been cleared out. A shop vacuum with a speed controller is used to adjust the airflow and cavity test hole pressure. A Micro-monometer is used to read the velocity pressure and the results are converted into CFM. Double rubber 2-inch O-rings are used to provide the air seal for the 2-inch pipe.

For flow tube use the fooling formula.
Square Root of Velocity Pressure X 87 = CFM

2.9 Test Hole Installation

ASD-TD recommends installing test holes in each quadrant of the building. After the test hole has penetrated the slab, the drill can be gradually drilled down into the sub-slab and removed to determine if there is stone or dirt below the slab and the condition of any soil that is removed. If the far test holes have adequate negative pressure induced by the shop vacuum that is set to the performance of a typical radon fan, then no more testing is required. If these far test holes show no or inadequate pressure change when the shop vacuum is operated, then additional test holes closer to the suction hole need to be installed to quantify the PFE distance under the slab from the suction hole.

WPB will, if possible, drill test holes every 10 feet in each of the cardinal directions from the suction hole for about 60 feet. Typically, commercial buildings have a ground contact area that will be larger than a single suction hole can induce a PFE. Installing multiple test holes allows a determination of the outer line of PFE. The distance from the suction pit to the outer most pressure change is referred to as the radius of influence (ROI). The area the suction pit creates a measurable pressure change is referred to as Area of Influence (AOI.) In commercial buildings, especially older buildings, the AOI often varies significantly even within the same section of a building. An ROI of 15 feet (4.6 meters) equals a treatment area of 706 ft^2 (66.8 m^2) versus an

ROI of 50 feet (15 m) equals a treatment area of 7,850 ft^2 (730 m^2). This difference would require 11 suction holes in the 15-foot ROI section of the building to equal 1 suction hole in the 50 ft ROI section.

2.10 Recording Pressures with the Shop Vacuum Off

ASD-TD recommends measuring all the test holes first with the shop vacuum off and record that data. The windows and outside doors need to be closed, not only to maintain building competing pressure but to minimize disturbance from outdoor wind. ASD-TD also recommends running house fans that discharge to the outside such as bathroom, dryer or range hood fans.

WPB always brings painters tape and fine tipped magic markers as well as takeoff sheets that are set up to keep the data organized and coherent. See Figure 6. On large buildings there can be 25 or more test holes for a single PFE test. The building may require two to twelve different PFE test suction locations. Each test location is identified by marking the painters tape installed on the slab. Suction holes are identified as S#. Test holes are identified as T#. The cavity test hole is identified with V#. The vacuum off sub-slab pressure at each test hole can be a negative or positive pressure depending on the building pressure and outdoor wind. Small changes induced by the shop vacuum running can only be determined if the vacuum off pressure has been recorded. Sometimes it is necessary to record vacuum off pressure before and after vacuum on measurements have been completed, to determine very small pressure changes.

The building to sub-slab pressure will always be less than the building to outdoor pressure. The amount of this difference is typically related to the air tightness of the slab compared to the density of the soil from the sub-slab to the outdoor air. The difference between the two readings can be an indicator of the slab leakage.

2.11 Recording Pressures with the Shop Vacuum On

ASD-TG recommends to first measure the cavity test hole and other test holes with the vacuum operating at full speed after waiting a few minutes for test hole vacuum to reach maximum pressure. The airflow induced by the vacuum is measured with a pitot tube inside the vacuum suction tube. After the full speed test is completed, the vacuum airspeed is adjusted until the cavity test hole is at a pressure that a typical radon fan can induce. The airflow is re-checked and the airflow versus cavity test hole pressure is compared to typical radon fan performance curves. Further adjustments of the pressure are made to more closely match a chosen fan performance curve or other fan curves. With the vacuum adjusted to match an existing radon fan, the test holes are re-measured. If test hole pressure change is inadequate or non-existent, additional PFE suction holes or test holes need to be installed to identify what is required to depressurize the entire sub-slab. Critical places to measure the sub-slab pressure are at radon entry points and not typically the center of the slab. In residential mitigation installations, a simple PFE test is placing a radon fan on top of a dug-out suction pit to determine if a single suction with this fan is adequate. This method, which only includes soil pressure resistance, has limited applicability for commercial system design prior to system installation.

WPB has a pitot tube built into the shop vacuum riser tube. The tube is inserted into the slab and a pitot velocity pressure to CFM conversion chart is attached to the vacuum. WPB sets the shop vacuum to maximum airflow speed to measure and record all the test hole pressures and shop vacuum airflow after vacuum off measurements have been recorded. If the sub-slab material is extremely tight, there may be a minute delay in the test holes achieving maximum vacuum. WPB will then use the speed controller to turn the vacuum down to its lowest setting. All the test holes and airflows will be measured and recorded on a pre-printed form. See typical takeoff form in Figure (6). The vacuum is then adjusted to half speed between the lowest and highest airflow.

Building:			Page :		Date:	Vac CFM =			
Vac Hole #		In to Out Pres			Test Hole #	Vac off	Highest Vac	Lowest Vac	Distance to Vac
Slab Thickness:		Sub-Slab soil:			T1				
Inches to Center Vac =					T2				
Velocity Pres	High CFM	V1	V2	V3	T3				
					T4				
					T5				
Velocity Pres	Medium CFM	V1	V2	V3	T6				
					T7				
					T8				
Velocity Pres	Low CFM	V1	V2	V3	T9				
					T10				
					T11				

Figure (6) WPB PFE Data Collection Form

2.12 Sub-slab pressure predominately changes as airflow changes

The pressures changes induced at each test hole tend to change the same amount when the PFE airflow is varied. See Figure (8) that demonstrates field measurements of the close linear relationship between airflow and sub-slab pressure changes. If a chosen fan is able to induce twice the airflow that the PFE shop vacuum induced, then it is likely that each of the test holes will have double the sub-slab pressure change achieved by the shop vacuum. If a more powerful commercial fan is chosen, the cost to operate the fan can be considered compared to the pressure change achieved at the far test holes. A more powerful fan may only extend the ROI marginally farther. Additional suction hole installations are typically more cost effective than over sizing the suction fan.

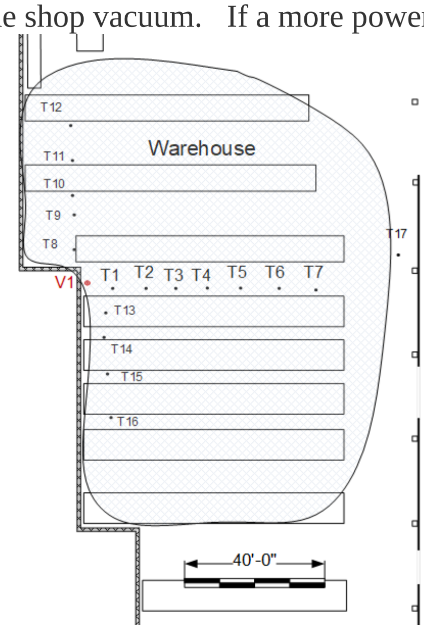


Figure (7): T1 is 10 feet from V1, T7 is 70 feet from V1

Figure 7 and Figure 8 illustrates the amount of change in test hole pressure as airflow and pressure changes. In this case the vacuum airflow was increased 2.3 times from 56 CFM to 128 CFM. All the test holes increased 3.0 to 3.4 times. The cavity test hole pressure increase of 4.2 times is 1.8 times higher change than the airflow change of 2.3 times. In this case, the PFE change in airflow is a closer indicator of pressure change at test holes. The important point is the amount of test hole change was very linear from close to far test holes as the cavity test hole pressure and airflow changed.

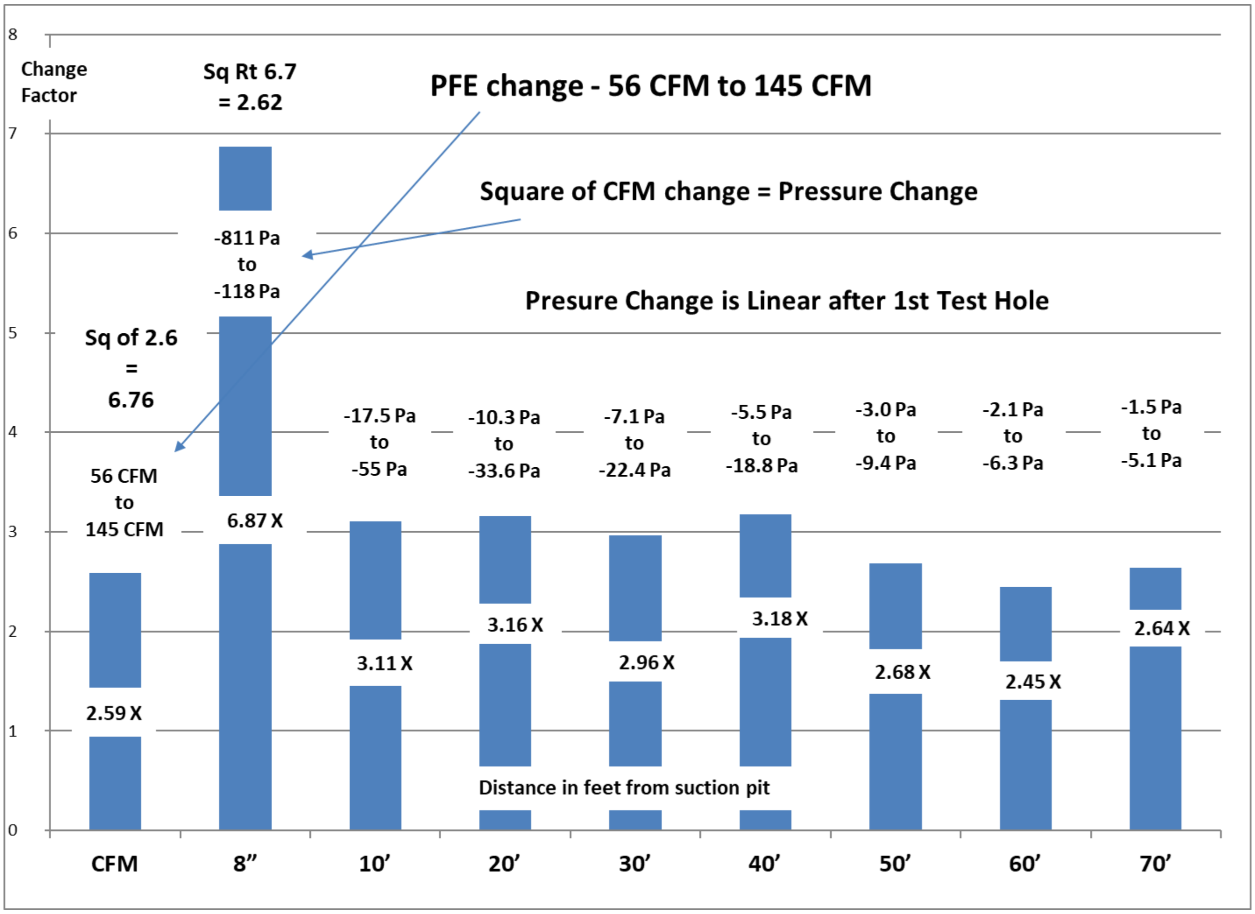


Figure (8): Test hole change from 56 CFM to 128 CFM

An important concept in regards to PFE is the soil gas air being extracted from a suction pit comes from leakage through the slab and the soil permeability. The AOI is actually a hemisphere in the soil and not a one-foot-deep pancake area under the slab. See an illustration in Figure 9. The surface area of a hemisphere illustrated as half an apple is double the area of the slab represented by the pancake. The volume of a hemisphere however is 6 times greater the volume of the one-foot depth below the subslab for a 10-foot ROI. For a 60-foot ROI the hemisphere volume is 40 times greater than the sub-slab volume.

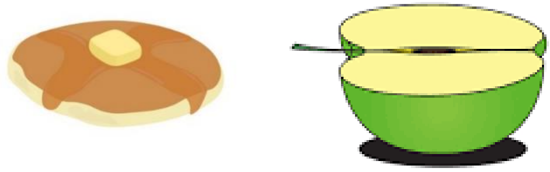


Figure (9): Sub-slab Area of Influence (AOI) is a hemisphere not a pancake

2.13 Changing power versus CFM versus AOI

In the case study PFE suction holes S1 and S4 were compared at the lowest vacuum speed setting and the highest vacuum speed setting. See results in Figure 10.

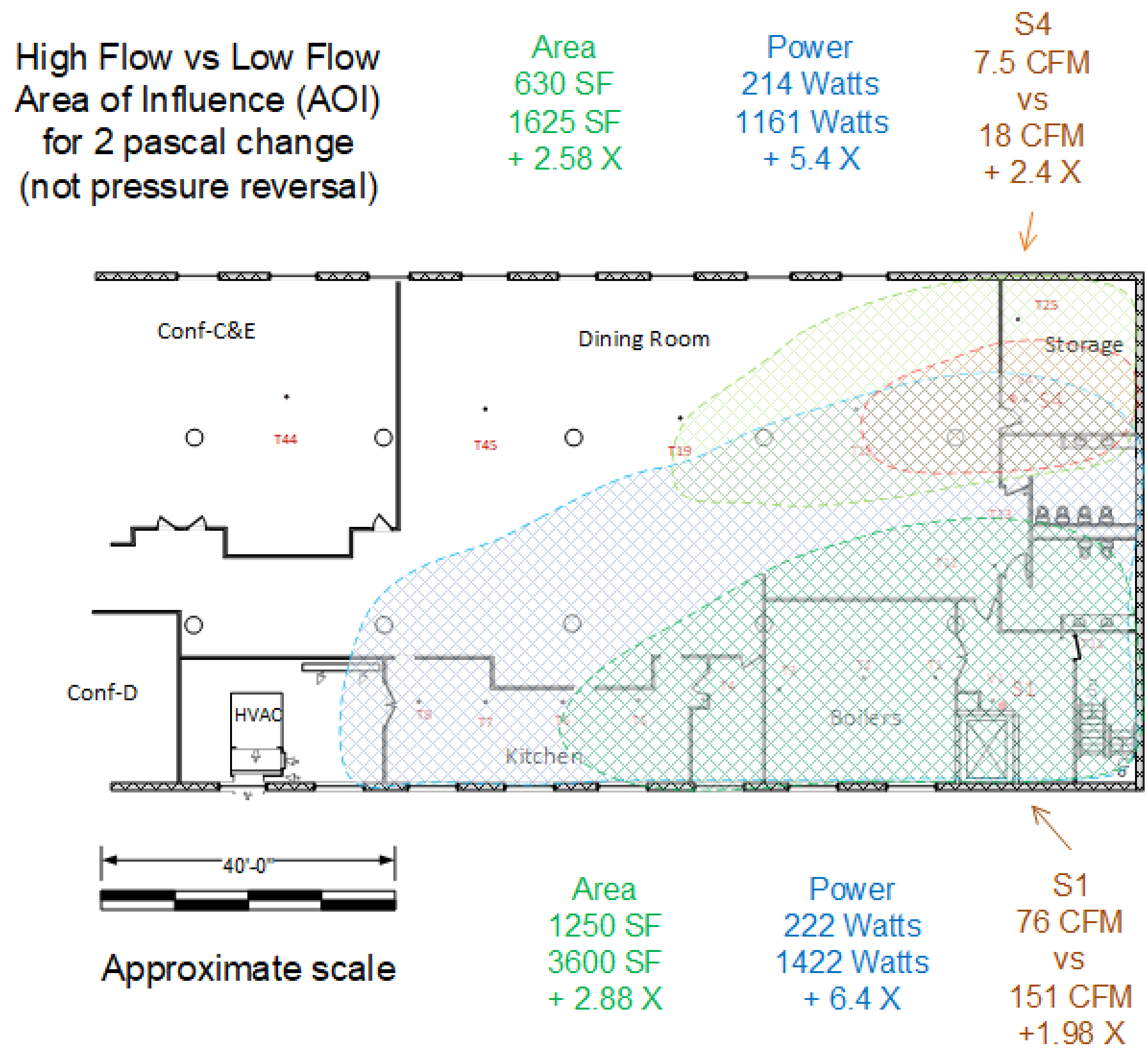


Figure (10): Comparison of low versus high PFE vacuum airflow at S1 & S4

In Figure 10, the airflow for PFE tests for S1 which was high flow and S4, which was low flow, are compared. The change in CFM between the two tests was close, with S1 increasing by a factor of 1.98 while S4 increased by a factor of 2.4. The energy requirement to increase the airflow is calculated as the cube root of the airflow change. At S1 the power increase for a CFM change of 1.98 would be a calculated cube factor of 7.76 while the test fan wattage measured an increase of a factor of 6.4. S4 at a lower flow with a 2.4 factor increase in CFM would be a cube calculation of 13.8 factor increase when the actual measured wattage was a 5.4 factor increase. The 5.4 to 6.4 wattage increase would still be a very significant energy usage that needs to be considered in the design. The power consumption was with a high suction fan. Other commercial fans will have different energy and flow characteristics. The area of influence for both PFE tests increased a similar amount although less than the square of the airflow change. S1 had an AOI increase of 2.88 compared to S4 AOI increase 2.58. The AOI in each case was drawn based on the edge that achieved about a 2 pascal change although in most cases this amount of pressure change did not cause a sub-slab reversal to a negative pressure at the outer areas of the pressure field.

2.13 Determining adequate PFE

ASD-TG discusses how the lowest level of a residential building in the winter can be negative 6 to 9 pascals (0.024” to 0.036”) compared with the outside. If the test is being done in the winter with building exhaust fans on, then even a sub-slab static negative pressure of 0.1 pascal (-0.001 inches would be adequate to stop soil gas entry. When measuring PFE in mild weather, a stronger minimum sub-slab pressure of negative 4 pascals is the suggested ASD-TG goal. Sub-slab pressure readings with the vacuum off in colder periods provides guidance on how much sub-slab vacuum on readings are needed to mitigate the building.

The Canadian “Reducing Radon Levels in Existing Homes, A Canadian Guide for Professional Contractors”, that is listed in the references, provides Table 2 as a guide for determining how much additional negative pressure change from vacuum off to vacuum on needs to be added depending upon the outdoor temperature and what climate zone the test is being done in. For mild to moderate Canadian weather zones, no compensation is needed if temperature is less than14°F or -10°C. For severe winter climate zones, any temperature above -4°F or -20°C needs an adjustment. Note that even in Canadian mild climates, PFE testing when the temperature is above freezing (32 degrees) recommends doubling the pressure change used during the PFE test that obtained a negative sub-slab pressure reading.

Suggested Sub-Slab Pressure Multiplier depending on Outdoor temperature			
	Canadian Climate Zones		
Outdoor Temperature ranges	Mild	Moderate	Severe
>+32°F / > 0°C	2.0	2.2	2.5
+14°F to +32°F / -10°C to 0°C	1.4	1.5	1.6
-04°F to +14°F / -20°C to -10°C	1.0	1.0	1.2
< -04°F / < -20°C	1.0	1.0	1.0

Table (2): Canadian additional sub-slab pressure goal

WPB has found that the sub-slab readings with the shop vacuum off have typically been a fraction of the inside to outside pressure readings. This fraction is determined by the air tightness of the slab compared to the density of the soil surrounding the building. The inside to outside pressures in the lowest level of commercial buildings is often primarily induced by the HVAC system in a commercial building which may or may not be operating the same in different seasons or times of the day. Investigating the operation of the HVAC is critical to understanding how the system may influence PFE measurements and indoor air quality. In general, a minimum negative sub-slab pressure of 1 pascal (0.004" SP) is the goal, however individual states may have different guidance or requirements.

Commercial buildings are often slab-on-grade construction. The perimeter edge of the slab often has high sub-slab airflow characteristics that cannot be easily depressurized. The design team needs to consider if the final few feet (meter) near the outside edge of a slab on grade or above grade construction needs to have measurable sub-slab vacuum when a larger percentage of the slab has been depressurized.

2.14 Graphing PFE results

In order to determine the optimal fan and piping using the collected PFE data, it is necessary to plot the PFE data on a spreadsheet graph and include the piping airflow resistance. If the CFM and cavity test holes pressures from the three vacuum speeds and the pressure drop from an assumed equivalent footage of piping is entered into a double log graph, it will plot a straight line. Fan curves can be overlaid on the graph. Where the fan curve crosses the total resistance line is the CFM the fan would move. The total resistance straight line can be extended to cross a fan curve that outperforms the PFE test fan. This line represents the soil resistance to airflow at the cavity test hole, 8 inches (20cm) from the suction point. If the three measurements are correctly measured, the graph will display a straight line from the lowest recorded airflow and pressure to the maximum airflow and cavity average pressure. Figure 11 (Brodhead, B 2024) provides a formula for determining the piping airflow pressure drop for common pipe sizes based on equivalent feet of pipe and airflow through the pipe. Multiple fan curves can be installed on the graph to allow picking the optimal fan both for its performance, cost and energy usage.

2.15 Determining the pressure loss from system piping and fittings

ASD-TG does not provide guidance on calculating the pressure drop of the piping but does recommend that 4-inch piping be used for the system.

Before choosing the optimal fan, WPB will add in the expected piping airflow resistance by entering into the spreadsheet the equivalent feet of pipe and the pipe size that will be used. The spreadsheet allows changing the pipe size and equivalent feet (EF) of piping to determine what is the optimal pipe size for the system. The equivalent feet (EF) of piping needs to include the EF of all the pipe fittings used to route piping to the exhaust location. Reference #4 lists a paper on how to determine the air flow pressure drop from piping and fittings (Brodhead, B 2024). Figure 11 includes the formula for determining piping pressure drop based on the airflow, pipe size and equivalent feet of piping required from the suction pit to the final exhaust location.

Piping Pressure Drop = ((0.205 * CFM * Pipe inch size ^$^{1.7}$) ^$^{-2.5}$) * (Total EF/100)

Figure (11): Enter CFM, Pipe Size and Equivalent Feet to obtain piping pressure drop

The equivalent feet (EF) of piping in Figure 11, is the total length of piping for that size pipe plus an equivalent feet of pipe for each pipe fitting. Each type of fitting and the initial opening into the system piping has a different amount of equivalent feet for each size of piping and shape of the fitting. Most PVC plumbing fittings have a sweep type radius. Some available PVC fittings have an angled inside radius turn. This angled or hard turn causes additional turbulence and increases the equivalent feet for that style fitting. There is a variation in the equivalent feet depending upon the airflow through the fitting with higher airflow having 25% to 50% greater amount of equivalent feet than at lower airflow rates. The percentage of piping resistance compared to total resistance is greater at higher airflows. The equivalent feet of different fittings is displayed in Table 3 using the higher airflow tested results. Refer to air flow pressure drop from piping and fittings paper (Brodhead, B 2024), for additional information or individual fitting pressure drop formulas.

Pipe Size	CFM airflow	Sweep 45°	Angled Turn 45°	Sweep 90°	Open Pipe Inlet	Transition to smaller pipe
2-inch	60	3’		3.5’	7’	
3-inch	175	2’	4.5’	5’	25’	25’
4-inch	275	2.5	7’	7’	32’	17’
6-inch	450	8‘	12’	16’	44’	60’

Table (3): Equivalent Feet for different pipe fittings and pipe sizes.

2.16 Commercial fan curves

Manufacturer	Fan	Maximum CFM	Maximum vacuum	Maximum Watts
Fantech	RN4EC-4	306	5.2”	164
Obar Sys	GBR76 SOE	235	16”	300
Obar Sys	GBR76 UD	195	30”	1000
Obar Sys	GBR89	529	12”	800

Table (4): Commercial Fan choices

Table 4 lists commonly used commercial ASD fans. All four of these fans are AC to DC motors that can be adjusted down to reduce wattage and extend the fan life. Appendix A is included to provide the actual fan performance data so that it can be entered into a spreadsheet so that fan curves can be overlaid on the graph of the total system resistance line. Where the fan curve intersects the total resistance is the airflow that fan will pull out of the sub-slab. The airflow can then be compared to the original PFE test hole results to predict the pressure change that will happen in each of the test holes. The reduced speed settings of the fans were included in the appendix to allow determination of optimized system to reduce energy cost and extend fan life. The fan wattage at each fan setting and fan speed is included in the appendix to allow calculation of the yearly energy cost. The system installation suction hole digging out may provide additional sub-slab channels that can enhance the final airflow.

2.17 Designing Mitigation System Based on PFE Findings

ASD-TG recommends determining the PFE distance or area of influence (AOI) and over laying AOI circles on a drawing of the building where suction points can be installed. It is important that these circles cover the most likely radon entry locations such as the perimeter slab to foundation joint rather than the center of the slab.

WPB also determines the AOI from each PFE test that is done. The AOI equivalent circle is then drawn on a floor plan of the area requiring an ASD system using the center of the circle to indicate an appropriate suction hole location. Any overlap of AOI induces an additive sub-slab pressure from each suction location. Any commercial building can have multiple different AOIs with large variation in airflows and required base test hole vacuums. Multiple PFE testing of different areas of a commercial building is crucial to determining if the AOI varies from one area of a building to another. The airflow and pressure required to achieve the AOI as well as the available suction pit locations and distances between the suction holes determines if one fan system fan can be used for multiple suction holes.

If multiple suction holes are connected to a single fan, the combined sub-slab resistance of all the holes and the piping resistance of each piping branch needs to be plotted so that the chosen fans curve crosses the combined total system resistance. The airflow of the fan will increase because it will be drawing from two or more suction pits. The PFE test results prediction of final sub-slab pressures must be based on the reduced airflow to each suction pit. The piping size needs to be adjusted to match the different airflows of different legs of the system.

In some cases when the AOI is very limited and or the distance between available suction holes is beyond the connection of overlapping AOI's, it may be necessary to trench or tunnel the sub-slab to enhance the AOI. PFE testing of the AOI is crucial in these restricted sub-slab airflow situations.

3.0 Experimental PFE Results and Discussions

3.1 Garage and House PFE Test Setup

The author replicated the PFE test done in the field at his garage and in his house basement. The garage and house each had a concrete slab poured on top of the dirt with no stone base or vapor barrier. The concept was to measure the sub-slab air flow resistance at four cavity test holes at 8 inches from the center of the suction hole and a second set of four holes at 12" away. See garage test layout in Figure 12. A similar setup was replicated in the authors basement slab. In each case the 2.5" suction hole was drilled in the center of the slab. A long crowbar was wiggle in all directions in the core hole to loosen as much sub-slab dirt and stone as possible and then a shop vacuum wand was used to suck out the loosened subslab material. Approximately 1.5 gallons of dirt was removed with this method. The suction pit was dug about 7" below the bottom of the slab. The airflow was measured at three velocities while measuring all of the eight cavity test holes at 8" and 12" distances from the center of the suction hole. The average of each set of cavity test holes was used with the measured airflow at maximum airflow, mid airflow and lowest airflow. The airflow at full vacuum setting was about 86 CFM. The 8" and 12" PFE data was then plotted as dashed lines on a double log graph. See graph in Figure 15. This is the PFE test measured soil resistance line. The pressure inside the vacuum tube, referred to as the applied vacuum, was also measured and does not correlate with the final dug out test results. In Figure

After completing the garage PFE test, the center garage suction hole was cored to a five-inch diameter hole. An additional 2.5 gallons of dirt was removed for a total empty cavity volume of 4 gallons in the garage and 5 gallons in the house test. The empty cavity radius was about 6 inches. The suction hole was then covered with cardboard and the cavity vacuum and airflow was again measured at three velocities. One difference between the two tests was the highest vacuum airflow was reduced in the garage second test to match the PFE airflow test of about 86 CFM. The two sets of dugout data were entered in the original spreadsheet and graphed as solid lines which in the garage test lined up almost directly with the PFE 8-inch cavity test holes and 12" cavity test hole dashed line.

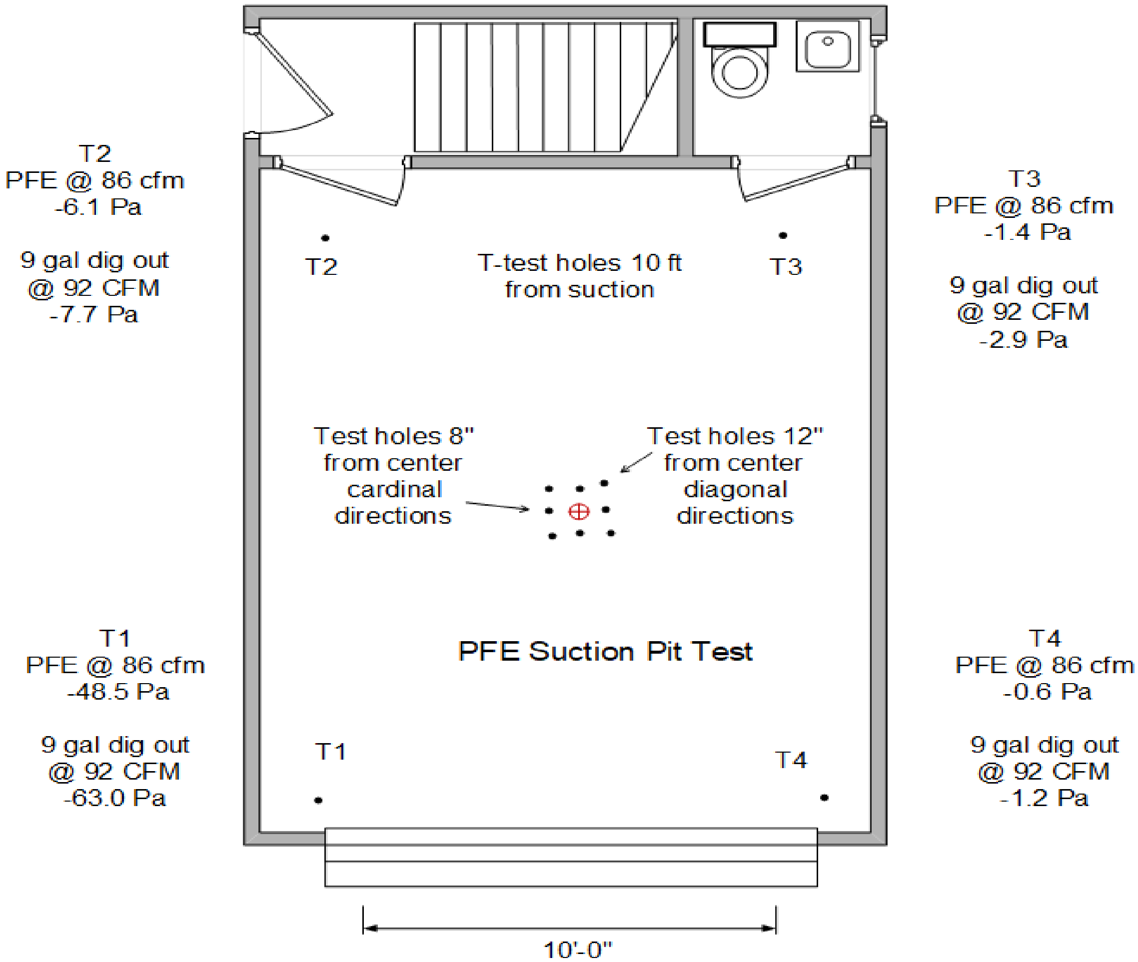


Figure (12): Garage layout and perimeter test hole

Figure (13): 1.5 gallons of dirt

Figure (14): 2.5" core enlarged to 5" core

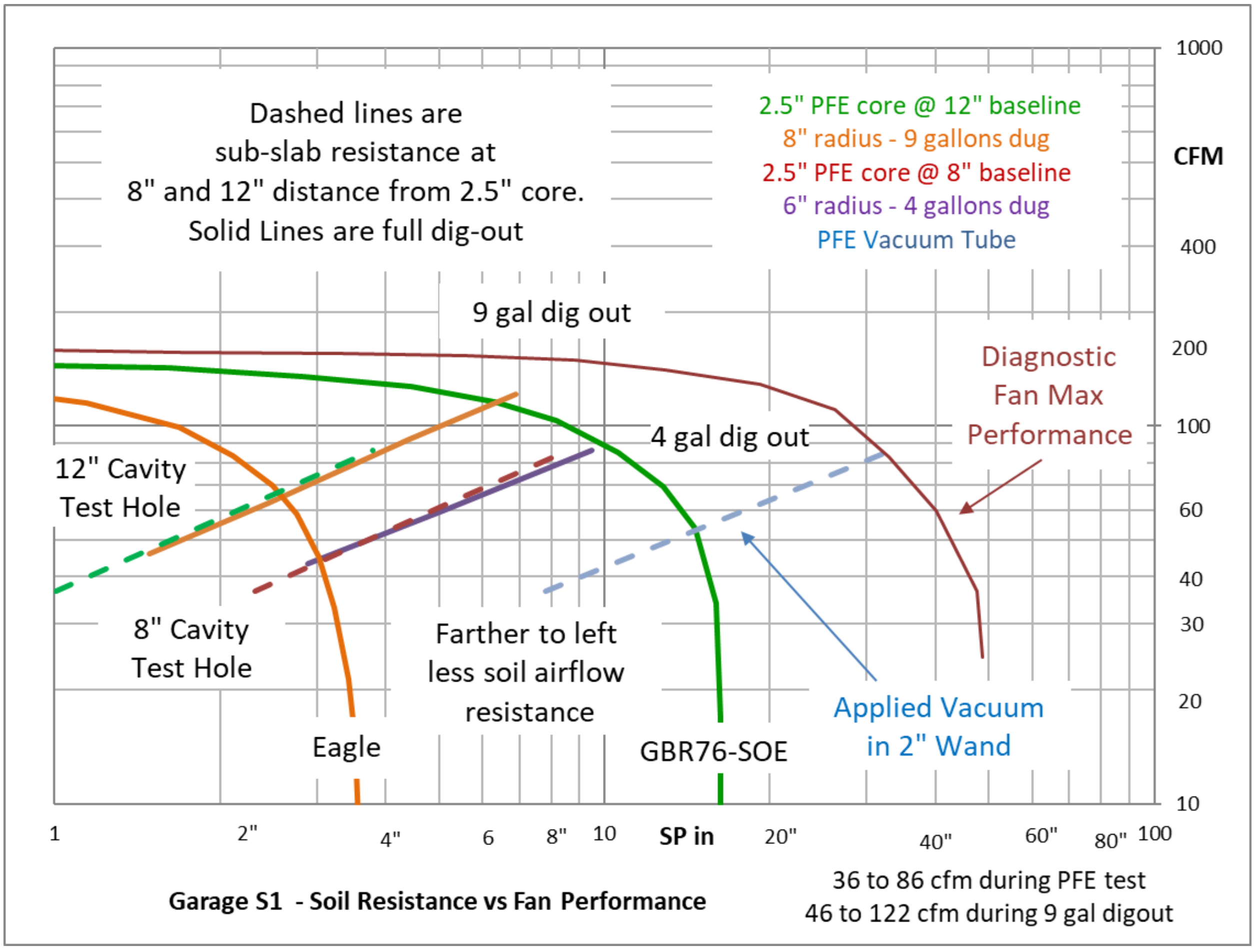


Figure (15): Garage PFE test comparison of 4 gallon versus 9-gallon dig out

3.2 Results of the Garage PFE Test

Five lines appear on the graph in Figure 15. The dashed lines on the graph represent the soil airflow resistance of the PFE test as measure at 8-inches and 12-inches from the center of the suction hole. The solid lines represent the soil airflow resistance after the suction hole is enlarged and a total of 4-gallons is removed to a 6-inch radius and 9-gallons is removed to an 8-inch radius. Although the dugout airflow is higher, the resistance to the airflow as represented by the position and slope of the two sets of lines is almost identical. The cavity 8-inch cavity test hole resistance represents a 4-gallon dig out and the 12-inch cavity test hole resistance equals a 9-gallon dig out. In the garage test the two cavity hole distances almost perfectly matched 4 gallon and 9 gallon dig out performance. The PFE suction fan maximum performance curve was plotted on this graph. The curve intersects the maximum applied vacuum but the applied vacuum resistance does not match the dug-out performance. This illustrates the applied vacuum is not an indicator of the final system performance.

The measurement of the test holes ten feet away was made during the garage initial PFE test at a full vacuum speed of 86 CFM. After nine gallons was dug out the test holes ten feet away were measured at suction flow of 92 cfm which is a 7% increased airflow over the PFE test. The ten foot away test holes increased in sub-slab pressure from 25% to 100%.   Additional airflow pathways were likely created during the dig out that increased the test hole pressures greater than the airflow increased.

Figure (16): PFE test w/8 cavity test hole

Figure (17): 5-inch core w/full dig out

3.3 Analysis of the House PFE Test

A second PFE test was done in the author's house basement. In this case the soil was very compacted. The plotted data in Figure 18 shows there was very little difference between a 5 gallon dig out and a 10 gallon dig out. The two dugout performance results in this case would have been closer to a cavity distance of 10 inches although the 8-inch cavity test hole results would have better predicted the higher final airflow results produced by the GBR76 SOE fan. In the house test the applied vacuum test results also did not predict the final dug out results. The diagnostic fan maximum performance curve matches the applied vacuum maximum results.

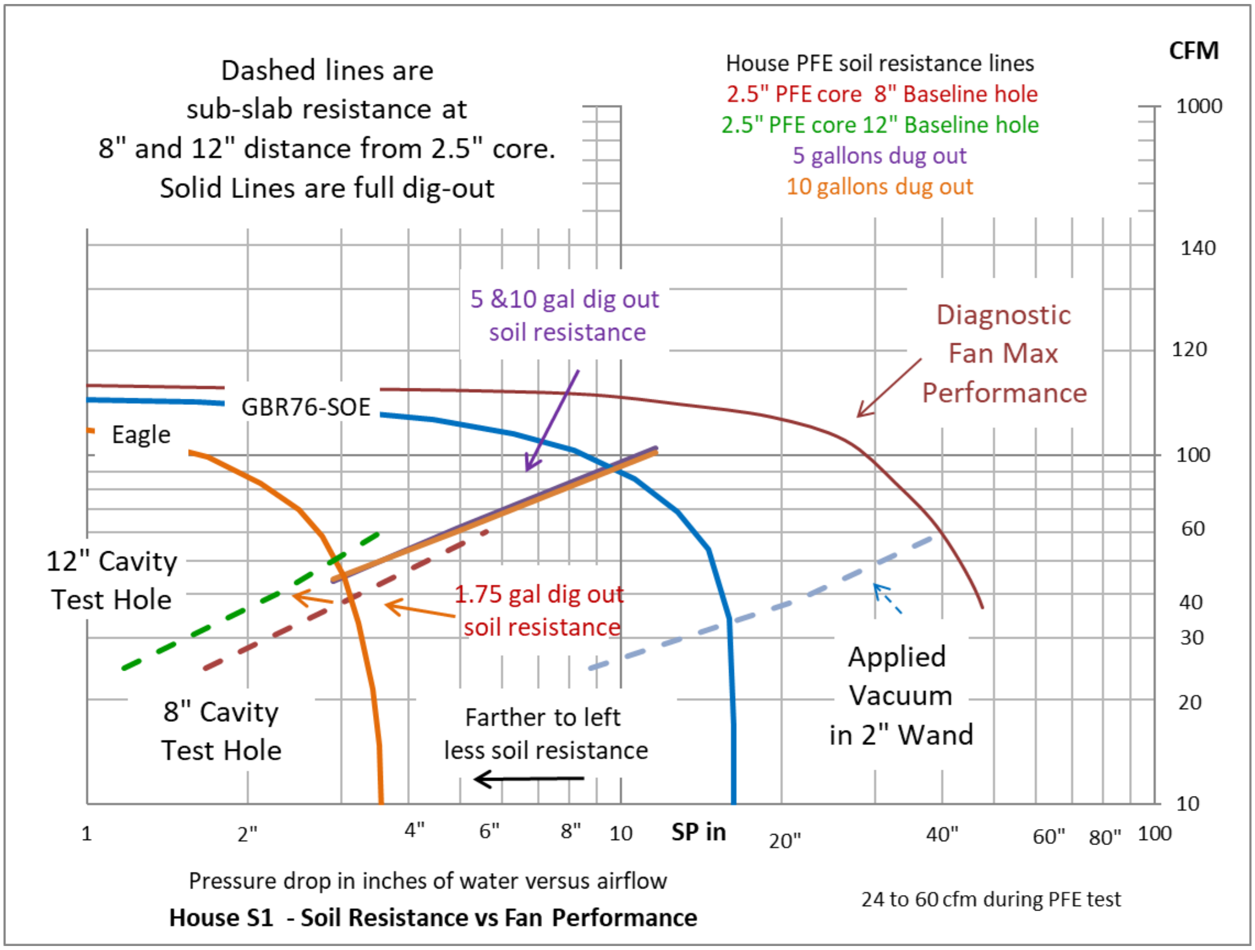


Figure (18): House PFE test with no difference 5 gallon versus 9-gallon dig out

3.4 Analysis of the two PFE Test results

The garage and house PFE results tested the concept of using a cavity test hole at 8” to 12” to predict the final performance of a dug-out suction pit to a similar radius. Installing a 2.5-inch PFE suction test hole with a 1.5 gallon dig out is much quicker and easier to install than a five-inch core and a complete suction pit cavity dig out. Re-sealing the 2.5-inch core, as required in pre-system installation PFE testing, is also quicker and easier. In the garage case, using the cavity test holes that were 8 inches from the center of the suction hole emulated a four-gallon suction pit cavity and using the 12-inch cavity test hole results emulated a 9-gallon cavity dig out. In the house PFE test the results were not as closely match but the 8-inch cavity distance was the more predictive result.

If the sub-slab permeability is high, such as with gravel, then the distance from the suction pit or location of the cavity test hole around the suction pit will not be critical. The soil in this garage study was dry dirt with sandy like consistency. As the sub-slab becomes denser, test holes the same distance from the suction hole tend to have greater measured variation. In the garage test the four cavity test holes at 8” distance from the suction hole had a 2.25 factor maximum variation. The four test holes at 12-inch distance had a maximum variation of 1.85. Measuring two or more cavity test holes in dense sub-slab is therefore recommended. As the distance from the suction hole increases when measuring dense sub-slab, the measured pressure can be dramatically less. A low pressure reading in dense sub-slab material, measured at a greater distance than 8 inches from the suction hole could falsely indicate a low vacuum, low airflow fan would be optimal. In general, from this very small test sampling an 8-inch cavity test hole distance from the suction pit is recommended. This distance is also less likely to provide data that would predict a higher fan performance than is achieved.

4.0 Case Study PFE Results and Discussions

4.1 PFE Case Study Building Description

The case study building was nine stories tall with an additional lower level that is below grade. The building is 235 feet long by 70 feet wide. The building footprint is about 16,450 square feet. The building was constructed around 1940 with major re-construction in 1957. There are no additions added to the original construction foot print. The lower level is fully finished. Radon testing indicated the entire lower level needed a radon mitigation system. The building owner specified no piping could be run up the outside of the building. In order to minimize the piping installed in the finished rooms it was necessary to first determine PFE or suction point AOI.

Figure (19): 10 story building requiring a radon mitigation system design

4.2 Building HVAC Evaluation

The building lower level was negative 34 pascals or - 0.136" of WC compared to the outside. It appeared this was due to the HVAC operation on each floor. The sub-slab test holes with vacuum off varied from positive 2 to 4 pascals to positive 20 pascals. This variation in sub-slab positive pressure was related to the slab leakage, sub-slab density and exhaust fan and HVAC operation.

Each floor of the building had a room that contained the HVAC equipment for that floor. The lowest level HVAC room was an additional 20 pascals or 0.08" of WC negative compared with the rest of the lower-level area. Upon investigation it was determined that the HVAC room was being used as a return air plenum to the HVAC air handler for that floor. The outdoor air duct into the HVAC air handler had no damper installed. The amount of outdoor air entering the system was dependent upon the negative pressure in the mixing chamber. The pressure in the mixing chamber was controlled by the return inlet damper into the mixing chamber. This damper was set wide open. In addition, there was an exhaust fan in the HVAC room that was operating and contributing to the negative pressure in the room.

The outdoor air damper position for each floor above the lowest level was investigated and reported to the building owner. Recommendations were made to the building owner to take steps to reduce the strong negative pressure in the lower level and increase the ventilation in the building but no changes were reported to have been done.

4.3 Building Sub-Slab Pressure Field Testing (PFE)

Building sub-slab pressure field testing was performed over two days in November 2023. The objective was to create a negative pressure under the slab in four locations to characterize how far a single suction pit will extend the negative pressure. Although the building had a single basement style slab with no known footers, it could not be assumed that the AOI from different suction pit locations would be the same. The floor plan in Figure 20 displays the results of the first PFE test at S1.

The building PFE testing involved drilling three separate 2.5-inch suction holes through the slab at holes designated as S1, S3, and S4. The existing sump pit in the facility room was used for the suction pit for S2. Smaller 5/16" test holes designated as T1 through T44 were drilled through the slab at varying distances from the suction pit locations. See test hole locations listed in Figure 20. A vacuum fan was used to draw air out of the suction holes at three different velocities while measuring the airflow and the changes in pressure at the cavity test hole located about 8 inches from the center of the suction hole. The negative pressure generated in the cavity test holes is measured at both the highest vacuum airflow and the lowest to determine the effect of using different radon fans for the final system design. Table 4 lists the typical commercial mitigation fans.

WPB prefers to record the sub-slab readings in Pascals (Pa). One Pascal is equal to 0.004" of static pressure. Generally, negative one Pascal or greater is adequate sub-slab negative pressure.

Some consideration is always given to the need to oversized the system to accommodate changes in the building lower-level pressure.

4.4 Results of Elevator Room PFE Test S1

S1 was the first PFE test. This location was deemed acceptable because piping could be routed outside the elevator, up through all the floors, to the roof. The sub-slab pressures with the vacuum off were around 4.0 pascals positive pressure. With the vacuum at full 141 CFM airflow, 10 feet away the sub-slab vacuum at T1 was reversed to negative 10.7 pascals. At 70 feet away at T7 the sub-slab vacuum was negative 1.8 pascals. The total airflow resistance including 200 equivalent feet of 4-inch piping is the straight solid and extended dashed line in Figure 21. Note that the PFE cavity test hole vacuum at 141 CFM is 0.519 inches while the graph has a total system vacuum of 2.1 inches. The difference is the airflow resistance of 200 equivalent feet of 4-inch pipe at 141 CFM. In Figure 21, the Fury fan performance curve crossover point indicates it would equal the performance of the PFE high flow results. The RN4-EC would be able to increase the airflow from 140 CFM to about 180 CFM. If the GBR89 was used on maximum flow, the airflow would increase from 140 CFM to about 320 CFM. The vacuum to achieve this would increase from 2.1 inches to 10 inches which includes the equivalent feet of piping pressure drop. The far test hole pressures tend to increase closer to the airflow increase rather than the vacuum pressure change. The GBR89 has the benefit of being able to reduce its airflow and wattage to one half and still provide the double the PFE test pressure. Ideally the fan or fans are adjusted to the optimal sub-slab pressure after all the systems are activated.

The second fan law states the square of the CFM change equals the pressure change. The S1 PFE airflow is 141 CFM at 2.04" of static pressure (SP). The predicted GBR89 airflow of 320 CFM is at about 10.3" sp. CFM of 320 divided by 141 CFM equals 2.2695 factor change. The square of that is 5.15 which if multiplied by the PFE 2.04" SP equals 10.5" SP which is very close to the graphed result.

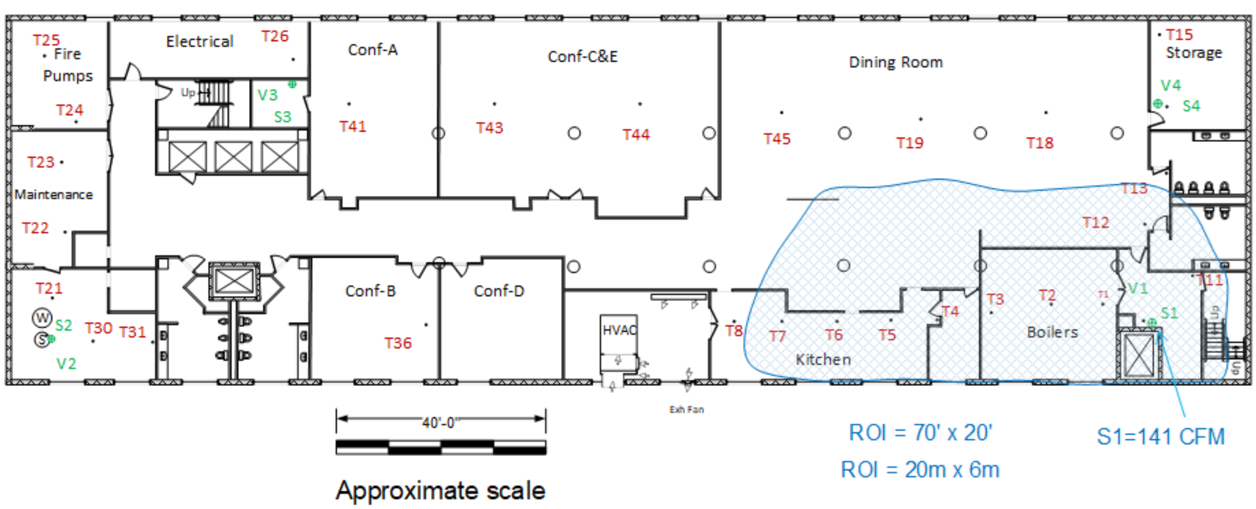


Figure (20): Pressure field extension results for S1

S1 PFE	Elev Rm	Min CFM	Mid CFM	Max CFM
		70	105	141
Distance to S1		Pit Pressure & Pipe Pressure Drop		
V1	6”	-0.161”	-0.315”	-0.62”
Piping EF	200’	-0.46”	-0.89”	-1.21”
S1	Total	-0.62”	-1.21”	-2.04”

Table (5): S1 - 70 to 141 CFM - Piping is 74% of System Airflow Resistance

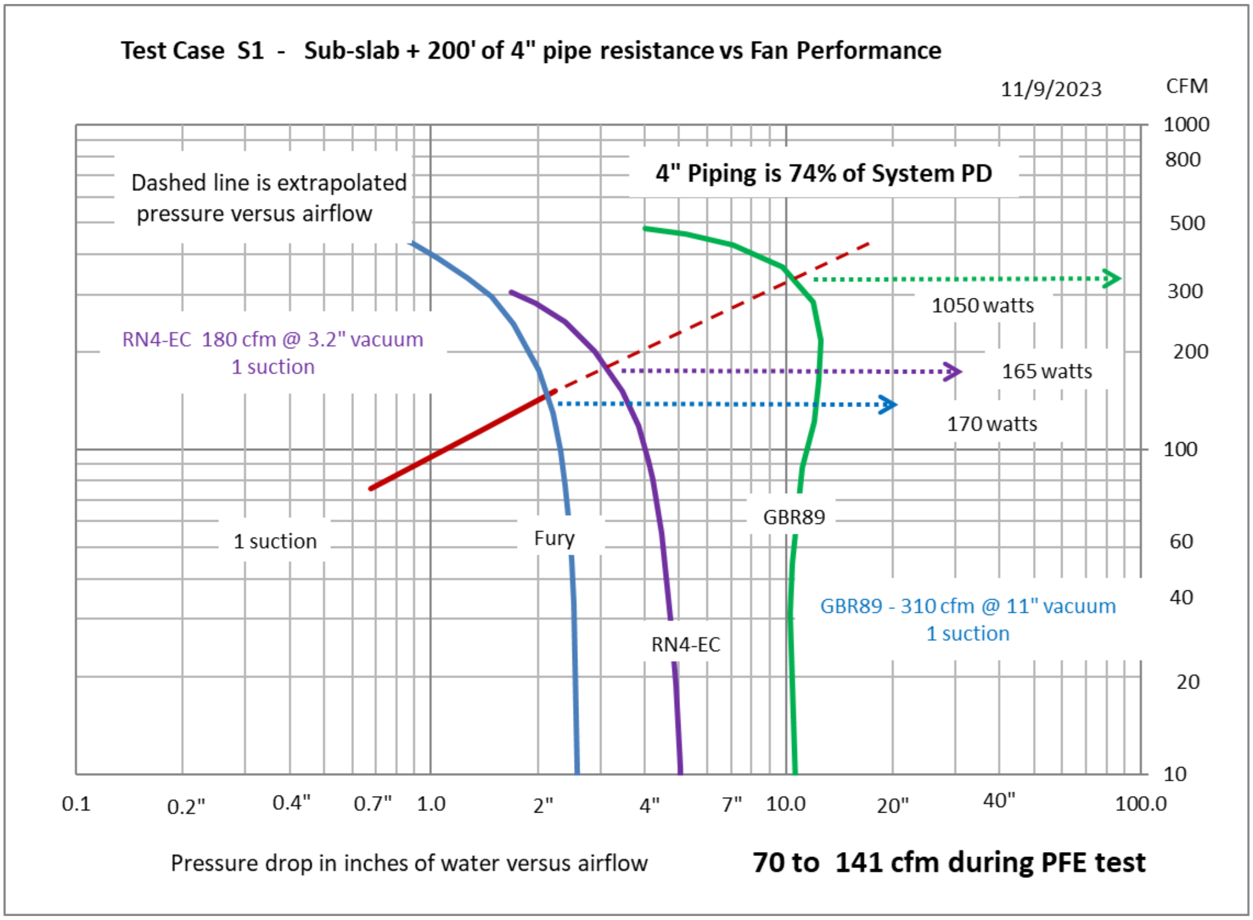


Figure (21): S1 results with three different fan performances

Commercial fans have a significant increased energy cost to operate compared to typical residential radon fans. For S1 the use of a GBR89 at maximum setting is 6 times greater wattage than a RN4-EC. The difference at $0.15/KwHr is $1162 per year. The GBR89 however can be tuned down.

4.5 Results of sump pit pressure field Testing (PFE) S2

S2 was the second PFE test. Although this room was an acceptable place to locate future radon system piping, the room above it was the finished entrance lobby. Pipe routing from this location to the roof had to be figured out prior to performing the PFE test. There was a large sump pit in the maintenance room. Inside the pit was a drainage pipe routed towards the long length of the building. The heavy large sump pit metal cover was slide back and the opening sealed with cardboard and tape. The vacuum tube was inserted through the cardboard into the sump pit. The sub-slab pressures at the test holes in the building with the vacuum off varied from positive 0.4 pascals to positive 7.2 pascals. With the vacuum at full 162 CFM airflow 10 feet away the sub-slab vacuum at T30 was reversed to negative 45 pascals. At 205 feet away, at T12 the sub-slab pressure went from positive 1.5 pascals to negative 5.0 pascals. Figure 23 displays the results with the Fury fan generating less airflow than the PFE test when the 200 feet of 4" piping airflow resistance is included. Note that the S2 PFE cavity test hole was lower vacuum but higher airflow than S1. The total resistance line in the S2 graph has a higher vacuum requirement to achieve the 162 CFM compared to S1 even though the soil resistance was less in S2 because of piping pressure drop at the higher airflow. The RN4-EC would be able to increase the PFE airflow from 162 CFM to about 180 CFM. If the GBR89 was used on full flow, the airflow would increase from 162 CFM to about 340 CFM. The fan suction of 2.2 inches would need to be increased to 10 inches to achieve this airflow. All of the test hole results would correspondingly increase by a factor of 4.7 if this fan was operated at full capacity. The GBR fan could be adjusted to half its capacity and still double the PFE airflow results. It also is apparent that S1 would not be needed if S2 was used and adjusted to optimize its performance.

Negative 1.5 pascals was achieved at T25 in the fire pump room but negative pressure was not obtained at T26 in the electrical room. The electrical room and conference rooms on this side of the lower level needed a separate suction pit. Knowing where the AOI extends is crucial information for deciding on the next PFE test location.

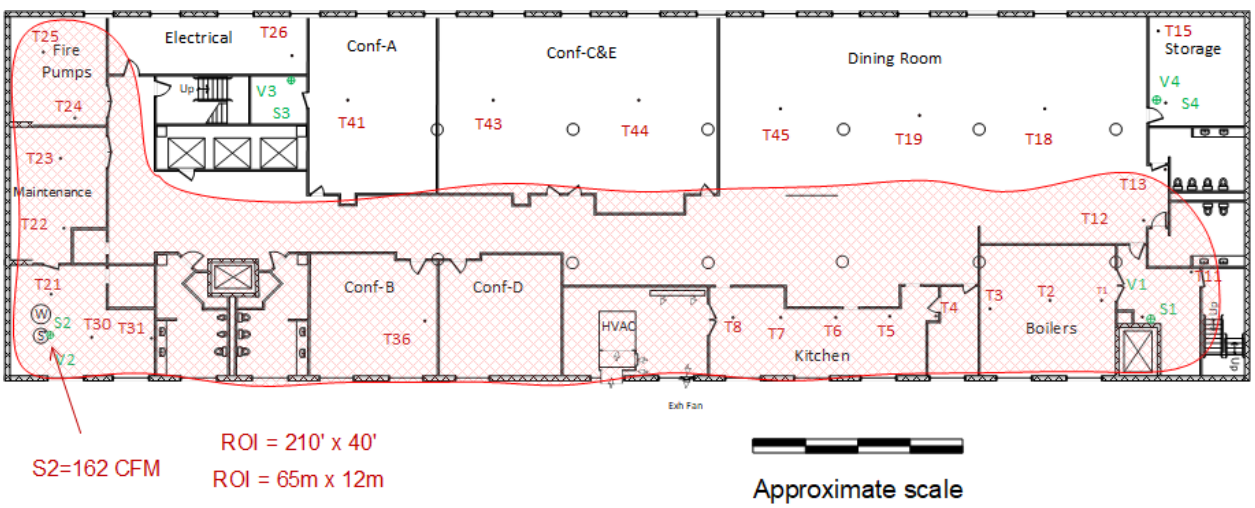


Figure (22): Pressure field extension results for S2.

S2 PFE	Room 121	Min CFM	Mid CFM	Max CFM
		83	120	162
Cavity test hole in sump pit		Pit Pressure & Pipe Pressure Drop		
V2		-0.082”	-0.156”	-0.277”
EF 4” piping	200’	-0.61”	-1.12”	-1.98”
S2	Total	-0.69”	-1.28”	-2.26”

Table (6): S2 - 83 to 162 CFM - Piping is **88%** of System Airflow

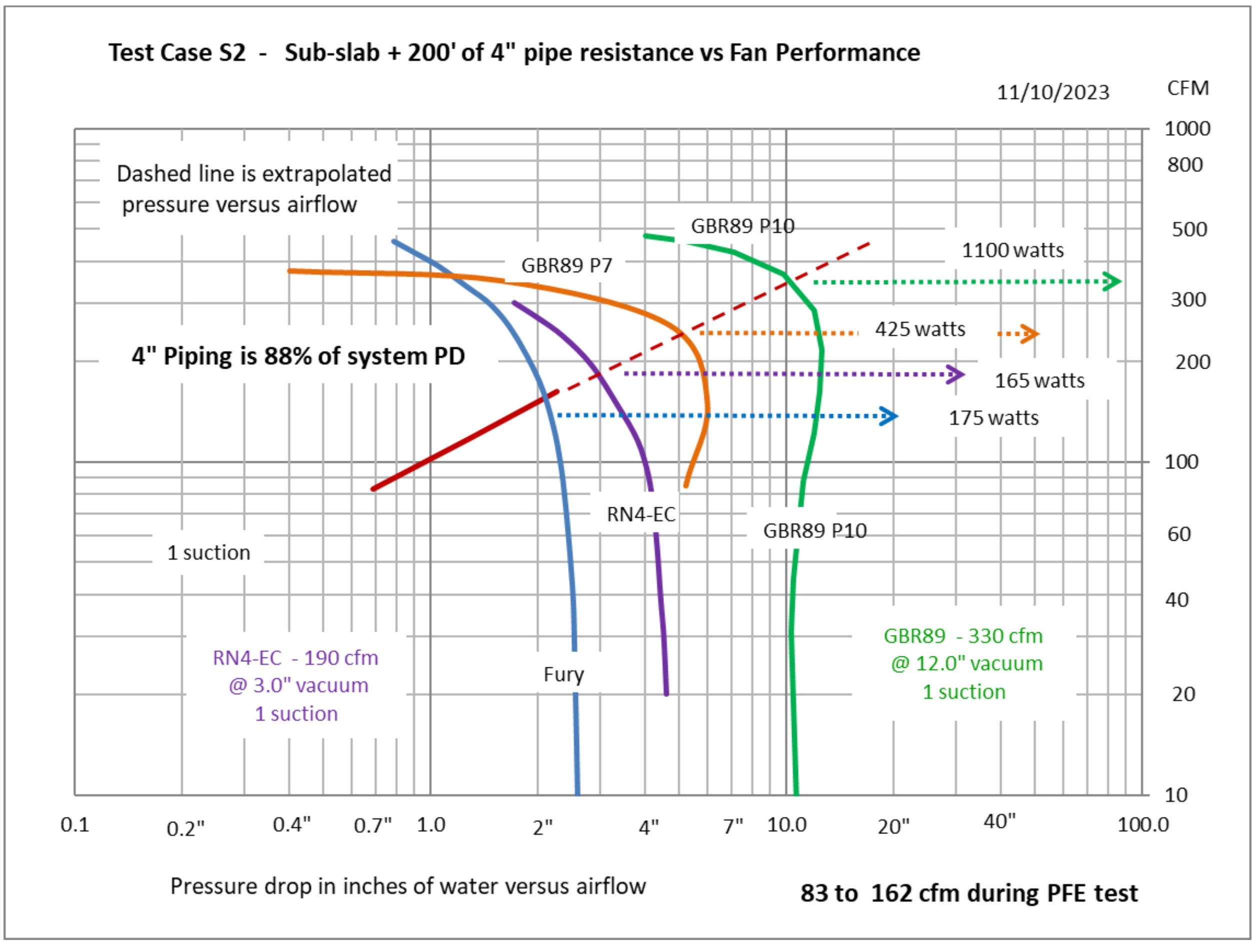


Figure (23): S2 results with three different fan performances

As with S1, the electrical cost to operate the GBR89 versus the RN4-EC is over a thousand dollars per year. Adjusting the GBR89 from P10 to P7 while still meeting the ASD goals would reduce the energy costs from 1100 watts to 425 watts with a ten year savings of $8000.

4.6 Results of Conference A Closet PFE – S3

S3 was the third PFE test. The suction pit location was chosen because future system piping could be easily boxed out inside this closet and there were closets above this location on each floor to route piping to the roof. The sub-slab pressures at the building test holes with the vacuum off varied from positive 1.4 pascals to positive 4.4 pascals. The suction pit revealed the soil was packed dirt with some round river stones. There was no sub-slab stone base. The test vacuum was able to draw 55 CFM out of S3 as compared to the three times higher airflow at S2 sump pit. The PFE extended into the electrical room and back to the fire water pump room T24 and T25 test holes. The PFE also extended about 70 feet towards the dining room but did not extend into the dining room. There was also marginal sub-slab pressure change across the hallway to T36 although the test hole pressure remained positive. This indicates a cross over sub-slab pressure will occur when both S2 and S3 are used for suction points.

Figure 25 indicates either a GBR89 or a GBR76 SOE fan could provide similar performance. The GBR76 SOE is more energy efficient at this airflow and is the better choice. The predicted 70 CFM airflow is 27% higher than the test vacuum airflow which will improve the sub-slab negative pressure readings. The piping to the roof can be three-inch metal pipe because the airflow is only 70 CFM. At 55 CFM, 200 feet of 3" piping caused a pressure drop of 1.09" as compared to S2 4-inch piping pressure drop of 2.0 inches with both using the same EF. See Table 6 as compared to Table 7.

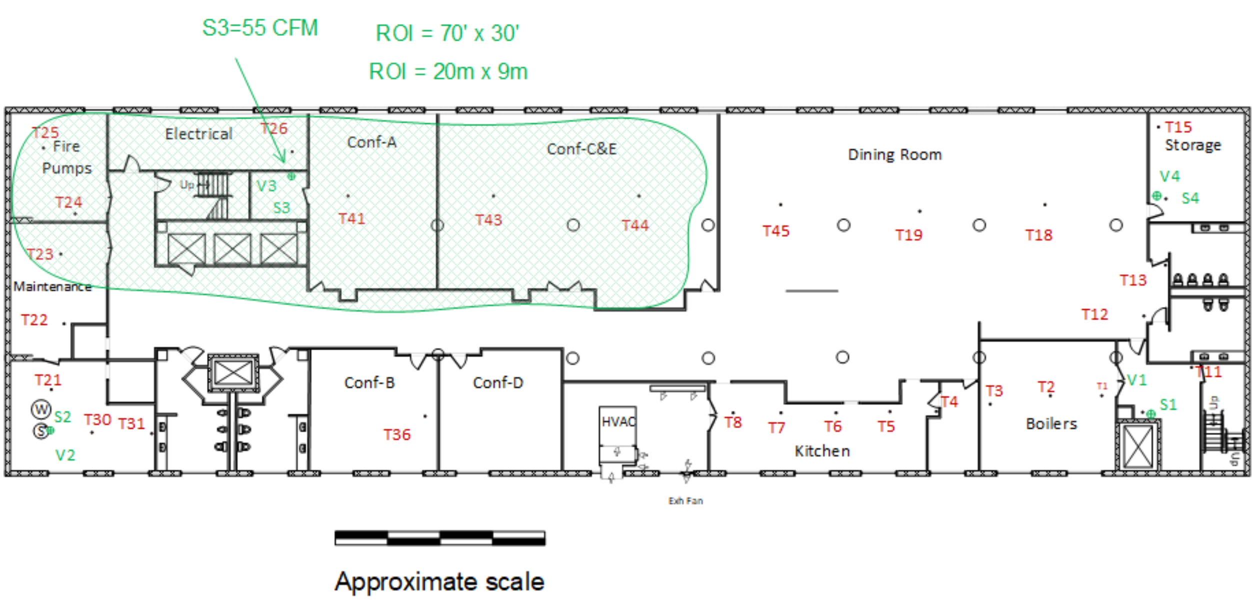


Figure (24): Pressure field extension results for S3

S3 PFE	Rm133 Closet	Min CFM	Mid CFM	Max CFM
		25	41	55
Distance to S3		Pit suction Pressure & Pipe Pressure Drop		
V3	8”	-1.31”	-3.25”	-6.39”
EF 3” piping	200’	-0.27”	-0.63”	-1.09”
S3	Total	-1.58”	-3.88”	-7.48”

Table (7): S3 - 25 to 55 CFM - Piping is **15%** of System Airflow Resistance

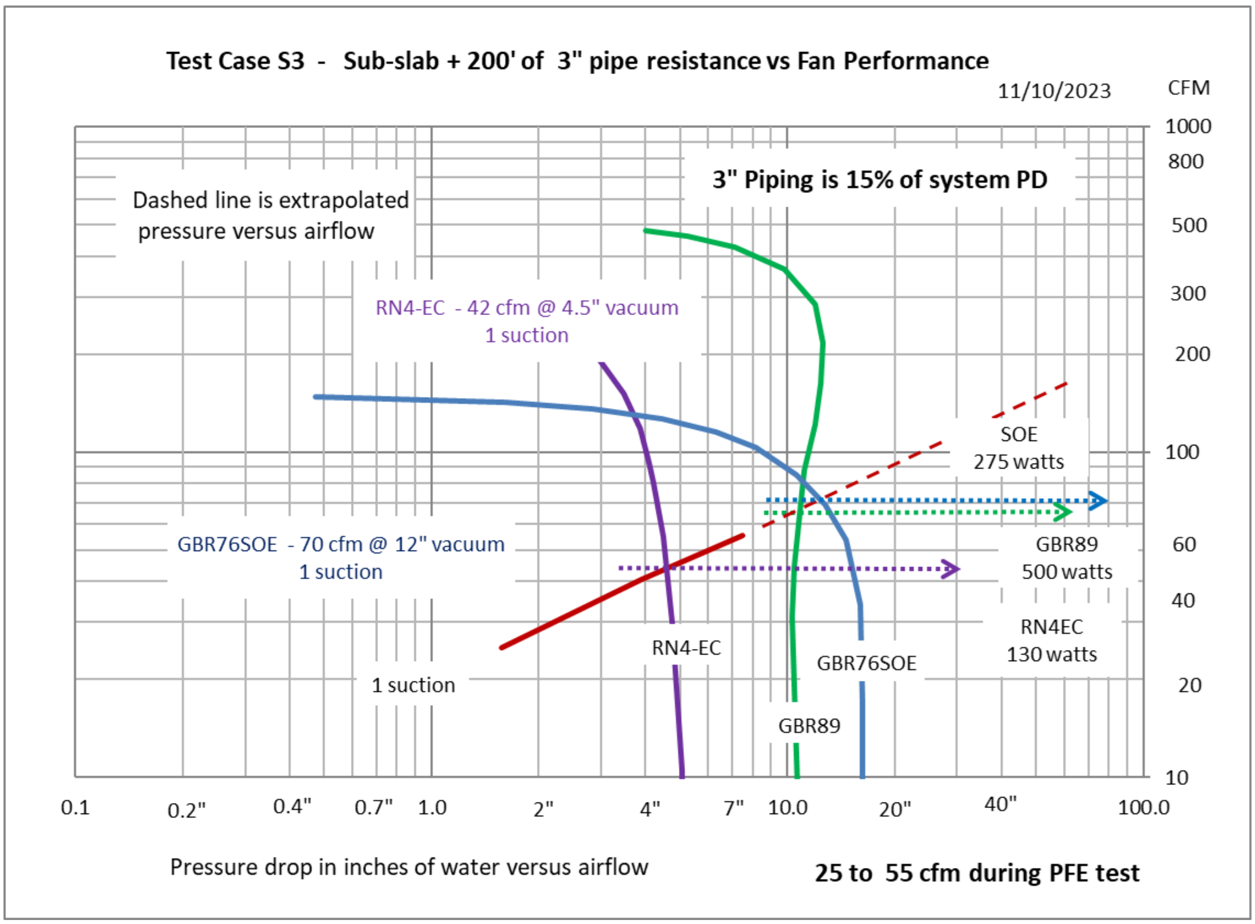


Figure (25): S3 results with fan performances over laid.

The wattage of the SOE is about half the wattage of the GBR89 at this total system resistance. The savings at $0.15/KwHr would be about $300 per year or $3000 over the 10-year life of the fan.

4.7 Results of Kitchen Storage Room PFE S4

S4 was the fourth PFE test. The sub-slab soil under the kitchen storage room was compacted dirt. The vacuum test fan could only obtain a flow of 17 CFM at 11" of static pressure in the cavity test hole test hole 8 inches from the center of the suction test hole. The vacuum off sub-slab pressures varied from – 0.7 pascals to positive 14.3 pascals. Measurable PFE was obtained about a maximum of about 30 feet from the suction hole.

Figure 27 indicates a high vacuum GBR76UD would be the best fit for this tight sub-slab soil. This fan could obtain almost double the airflow of the test vacuum fan and almost three times the cavity test hole suction pressure. To increase the PFE it was specified to trench the slab or install multiple suction pits and connect them together below grade with drilled tunnels created with a long 3/4- or 1-inch drill bit that is angled from suction pit to suction pit. The openings in the slab floor would be filled with gravel and new concrete installed.

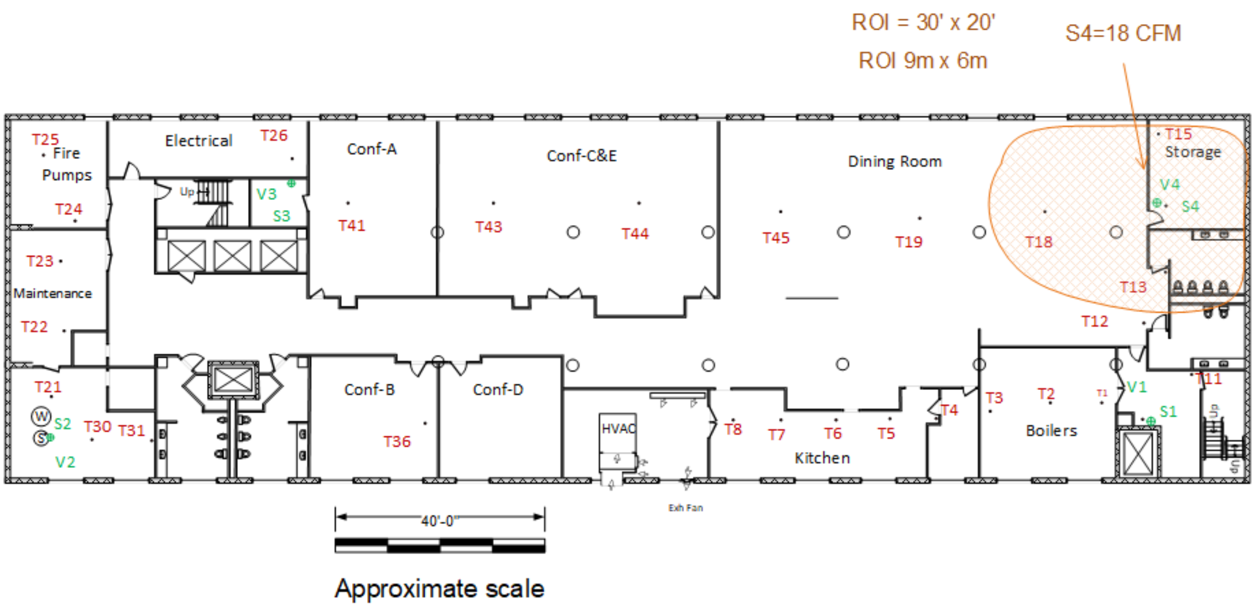


Figure (26): Pressure field extension results for S4

S4 PFE	Kitchen Storage	Min CFM	Mid CFM	Max CFM
		7.5	12	18
Distance to S4		Pit suction Pressure & Pipe Pressure Drop		
V4	8"	-3.51"	-7.50"	-11.6"
EF 2" piping	200'	-0.17"	-0.47"	-0.84"
S4	Total	-3.68"	-7.97"	-12.44"

Table (8): S4 - 7 to 17 CFM - Piping is **7%** of System Airflow Resistance

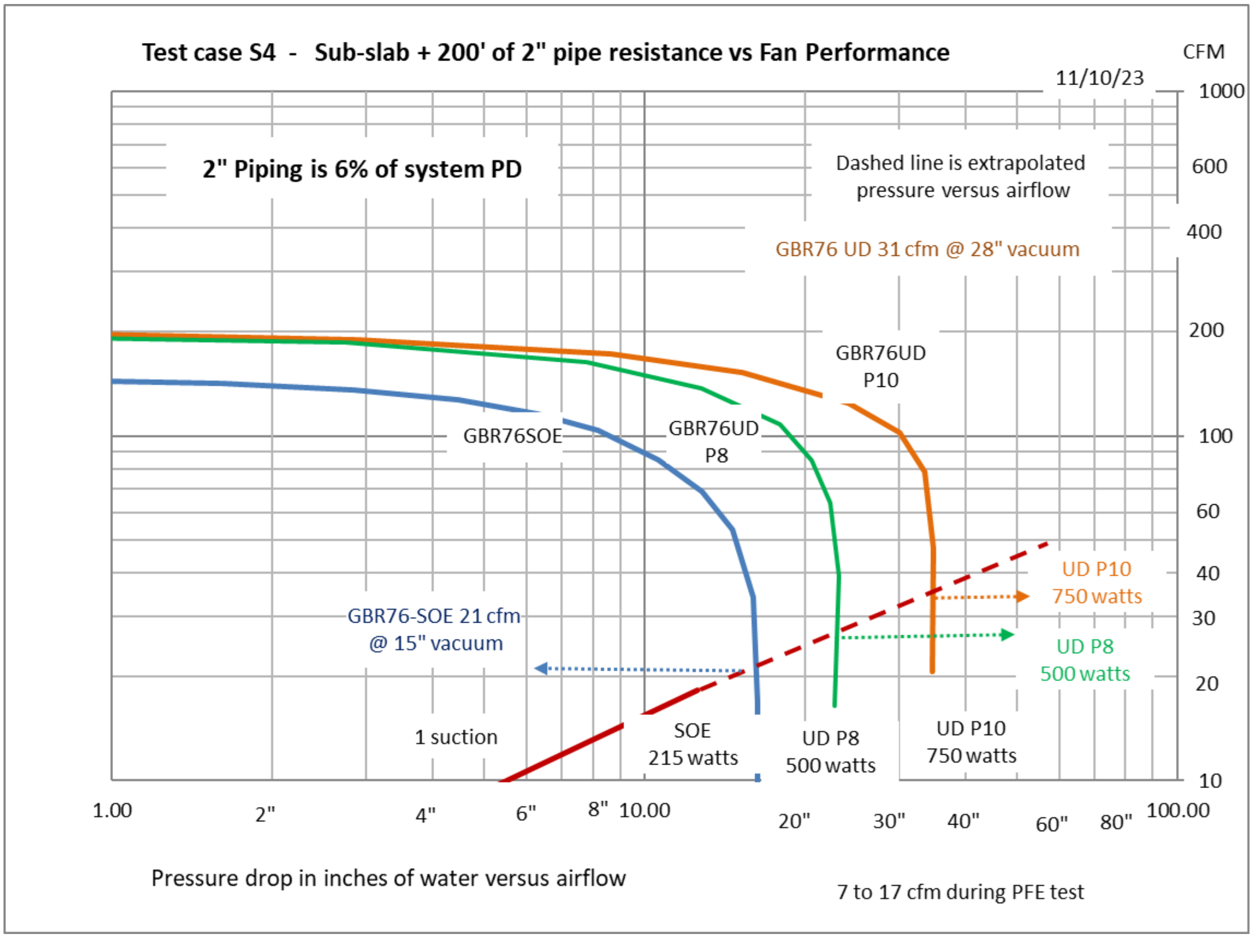


Figure (27): S4 results with high vacuum fan performances over laid

In Test Case study S4 the UD fan uses three times the electrical consumption of an SOE fan but provides a 50% increased air flow over the SOE. In this case the marginal AOI of S4 it would be prudent to use the UD fan because of its higher performance in this limited PFE situation. The UD could be tuned from a P10 setting to a P8 setting for a $3000 electrical savings over 10 years.

4.8 Recommended Radon Mitigation System

The AOI results of all the PFE testing are displayed in Figure 28. Note that in the four different PFE test results using the same vacuum, the airflow varied from 17 CFM to 162 CFM. The corresponding reach of sub-slab pressure field extension (PFE) was similar between S1 and S3 even though S1 airflow of 141 CFM was almost 3 times greater than S3 airflow of 55 CFM. S2 depressurized half of the lower-level sub-slab area including the area generated by S1. The S2 performance was likely due to the sump pit suction that was applied and the perforated pipe in the sump pit that was routed an unknown distance under the slab. S3 had a moderate PFE in comparison to S2 but still covered a large area of the lower level of the building. S4 produced the lowest CFM and smallest PFE. A portion of the dining area lacked PFE coverage. To overcome this lack of coverage during the PFE testing period, the fans chosen for S3 and S4 were capable of generating significantly higher airflow than the PFE test. Additional suction pit excavation was specified at S4 location to enhance the PFE obtained under the dining area. Note that the pressure fields overlap. The over lapping fields will have an additive sub-slab pressure from each suction point. Each of the test suction pit locations was chosen because pipe routing to the roof from each location was possible.

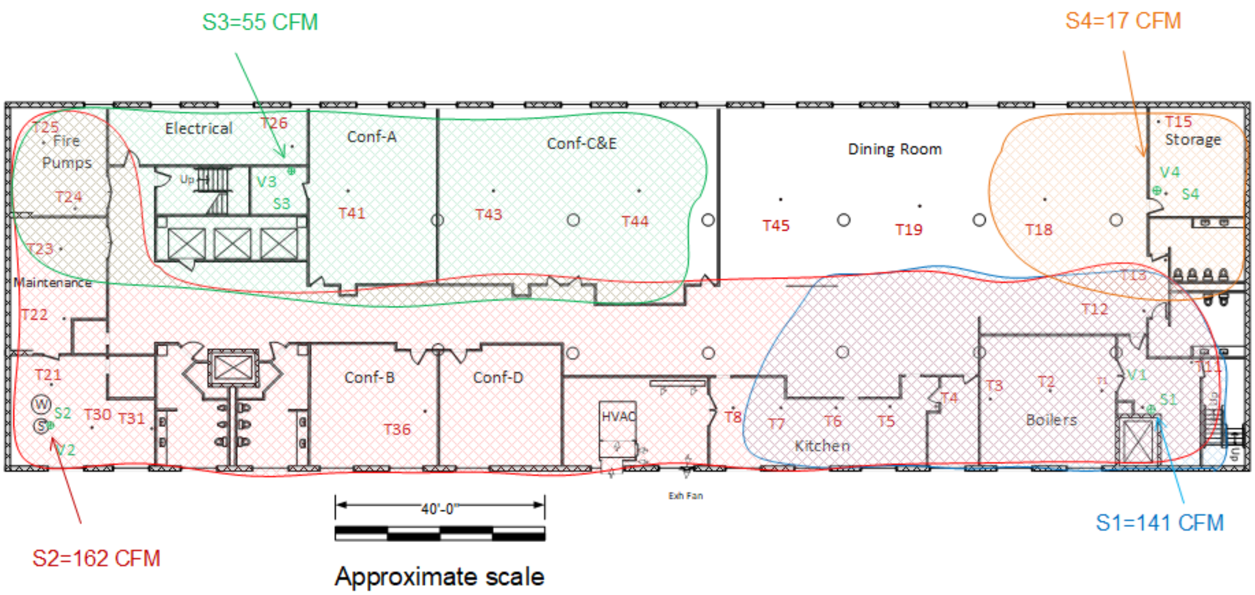


Figure (28): All pressure field extension results for Case Study building

4.9 Radon Mitigation System

The radon mitigation system layout for the lower level is displayed in Figure 29. Figure 30 displays the final fan performance and ASD induced sub-slab vacuum.

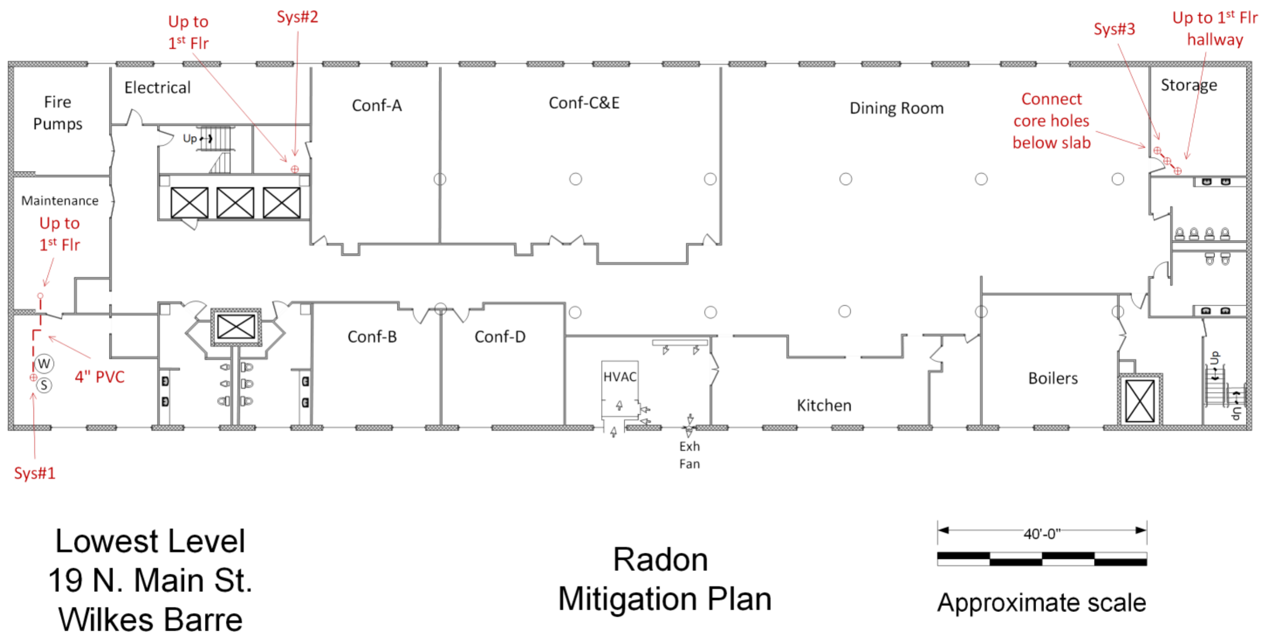


Figure (29): Lower-Level radon mitigation system layout

System #1 was predicted to move a maximum of 330 CFM at 10 inches of pressure. The fan may have been tuned down because the final performance was 300 CFM at 8.7 inches of pressure.

System #2 was predicted to move 70 CFM at 13 inches of pressure. It was moving 60 CFM at 14.5 inches of pressure.

System #3 was predicted to move 32 CFM at 28 inches of pressure. It was moving 65 CFM at 22.0 inches of pressure. The higher airflow is likely because the floor was trenched to obtain better sub-slab communication. During the PFE testing the Dining Room was not within the AOI of any of the suction holes. The extra trenching of System #3 which induced a higher airflow also produced a strong negative 35.3 pascal sub-slab reading at T5 which was about the limit of AOI for the PFE S4 testing. This extra trenching is the likely reason good sub-slab vacuum was obtained in the dining room. All the other test holes had excellent sub-slab vacuum.

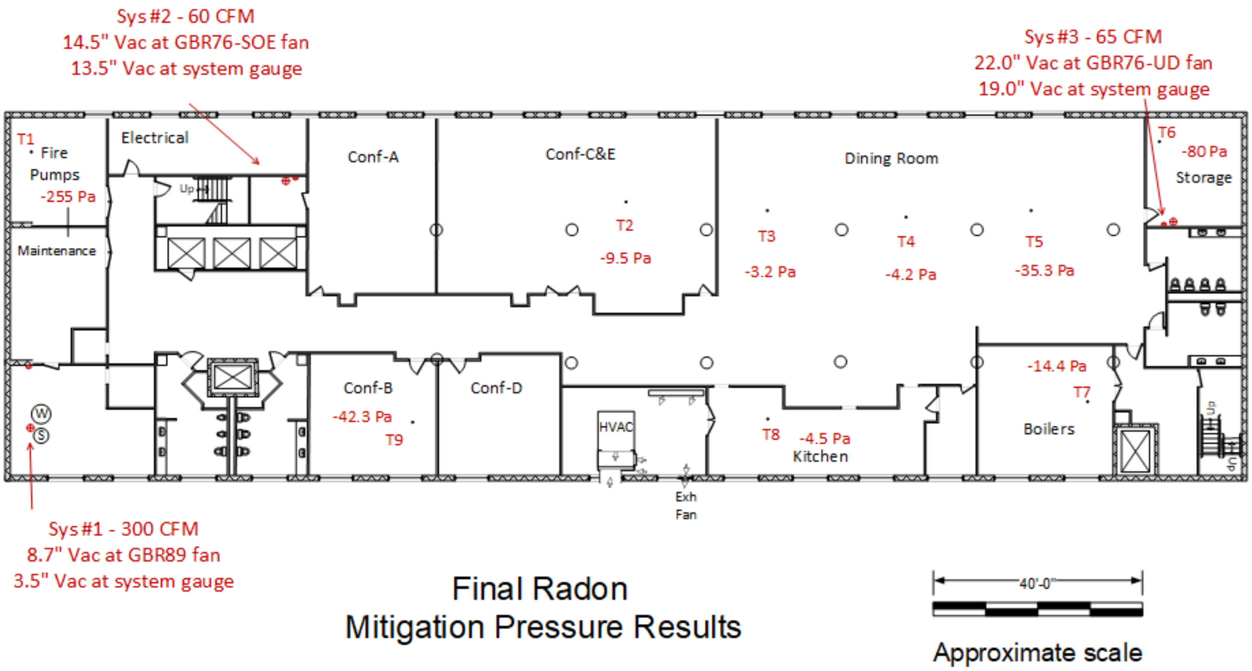


Figure (30): Lower-Level radon mitigation system layout

5.0 Conclusion

Guessing how many suction points will be necessary and how many fans of what size are needed is totally inappropriate for commercial buildings considering their size and complexity. This study depicted the details of performing test to pre-determine how far a single suction hole location will generate a sub-slab pressure field extension (PFE). The determination of the suction pit area of influence (AOI) needs to incorporate the soil resistance to airflow, the required piping pressure drop at changing airflows as compared to available suction fans and the power consumption of the chosen fan. The total system airflow resistance can be plotted against the four commercially available suction fans listed in this study to determine the performance of each fan. Once the AOI is determined it can be overlaid on a drawing of the lowest level of the building to determine how many suction points are required and if a single fan system can draw on more than one suction pit. This information allows precise system design that will succeed in inducing a negative pressure under all portion of the slab requiring minimizing soil gas entry into the building. An accompanying paper can be used to provide additional piping and fitting calculation formulas to determine the appropriate piping size and length as well as the appropriate suction fan. (Brodhead 2024)

6.0 References

1. Henschel D. - Radon Reduction Techniques for Existing Detached Houses, Technical Guidance (Third Edition) for Active Soil Depressurization Systems. EPA/625/R-93/011 October 1993

2. National Standard of Canada "Reducing Radon Levels in Existing Homes: A Canadian Guide for Professional Contractors" CAN/CGSB-149.12-2017

3. ANSI/AARST "*Soil gas Mitigation Standards for existing Multifamily, School, Commercial and Mixed-Use Buildings*" SGM-MFLB 2023

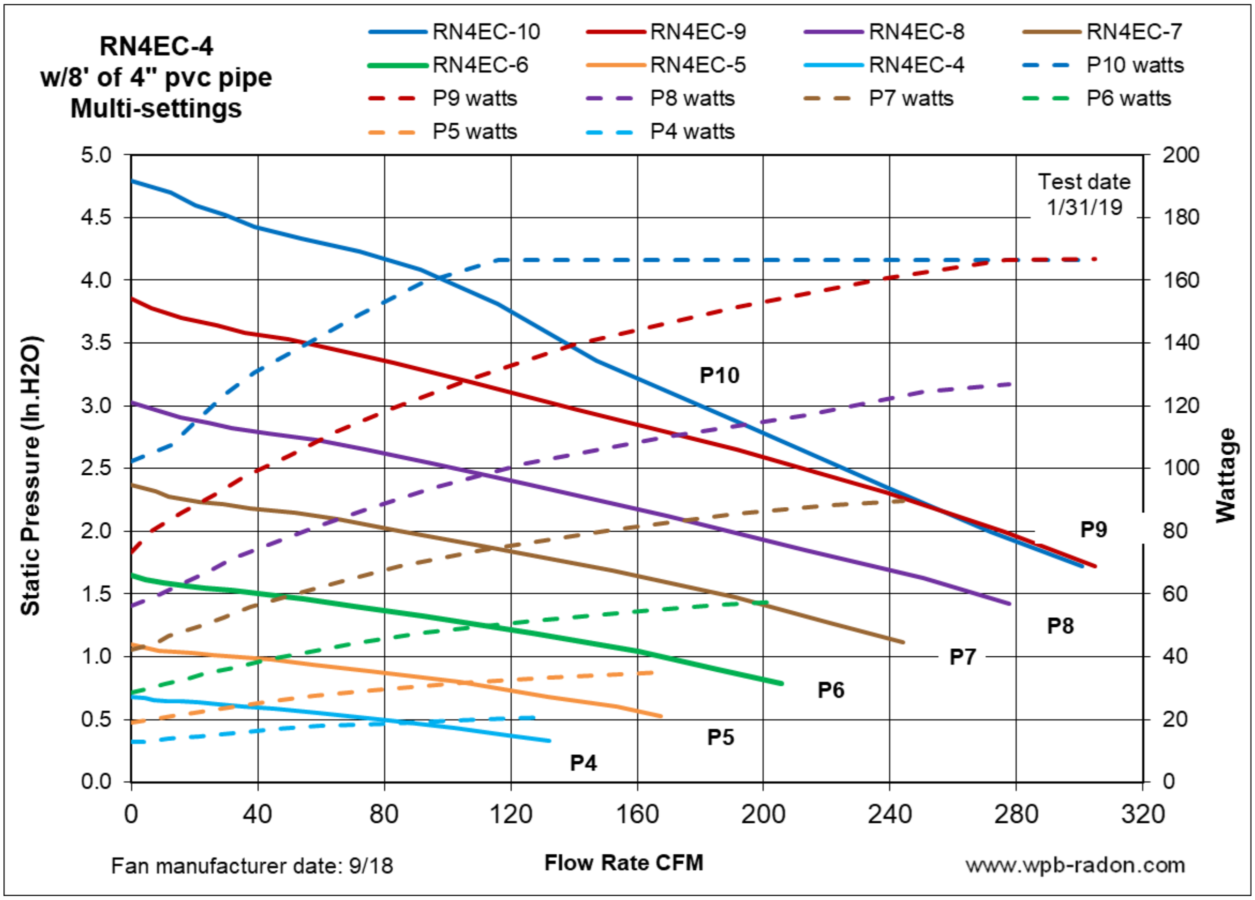
4. Brodhead, B. "*ASD Piping Airflow Pressure Drop*"
IEA Orlando, Fl conference proceedings 2024, WPB Enterprises, Inc. 2844 Slifer Valley Rd., Riegelsville, PA

Appendix A   Commercial Fan Performance Data

The following fan performance data was measured by the author and is included as an appendix. The data for three fan settings can be entered into a spreadsheet to determine the optimal fan, fan setting and wattage. All of the listed fans have potentiality controllers that are labeled from 1 to 10. A setting of ten provides the highest fan speed and electrical cost to operate the fan. Other fan charts are available at www.wpb-radon.com.

RN4EC-4 with 8 feet of 4"										
Setting 10	Stat pres			Setting 8	Stat pres			Setting 6	Stat pres	
CFM	In H2O	watts		CFM	In H2O	watts		CFM	In H2O	watts
0.0	4.807	102.0		0.0	3.026	56.1		0.0	1.644	28.6
7.7	4.695	108.0		7.6	2.964	59.2		4.4	1.615	29.7
20.0	4.595	115.1		15.2	2.905	63.0		10.3	1.589	31.3
30.3	4.500	123.6		24.1	2.862	67.2		17.6	1.561	32.9
41.2	4.420	131.0		31.4	2.823	71.2		23.2	1.546	34.6
51.5	4.328	139.4		42.9	2.775	75.8		31.7	1.526	36.5
72.5	4.214	149.6		57.9	2.724	81.5		42.8	1.497	39.1
91.1	4.073	159.4		73.4	2.647	87.0		54.0	1.460	41.3
117.1	3.795	166.3		94.2	2.536	93.6		69.8	1.401	44.2
148.8	3.348	166.7		123.3	2.375	101.5		91.4	1.320	47.5
198.7	2.814	166.4		167.6	2.120	110.0		125.6	1.188	51.4
241.3	2.345	166.5		211.0	1.850	117.1		158.7	1.039	54.6
277.1	1.985	166.5		247.7	1.625	124.4		183.5	0.893	56.5
304.1	1.714	166.5		274.3	1.425	127.0		203.2	0.790	57.4

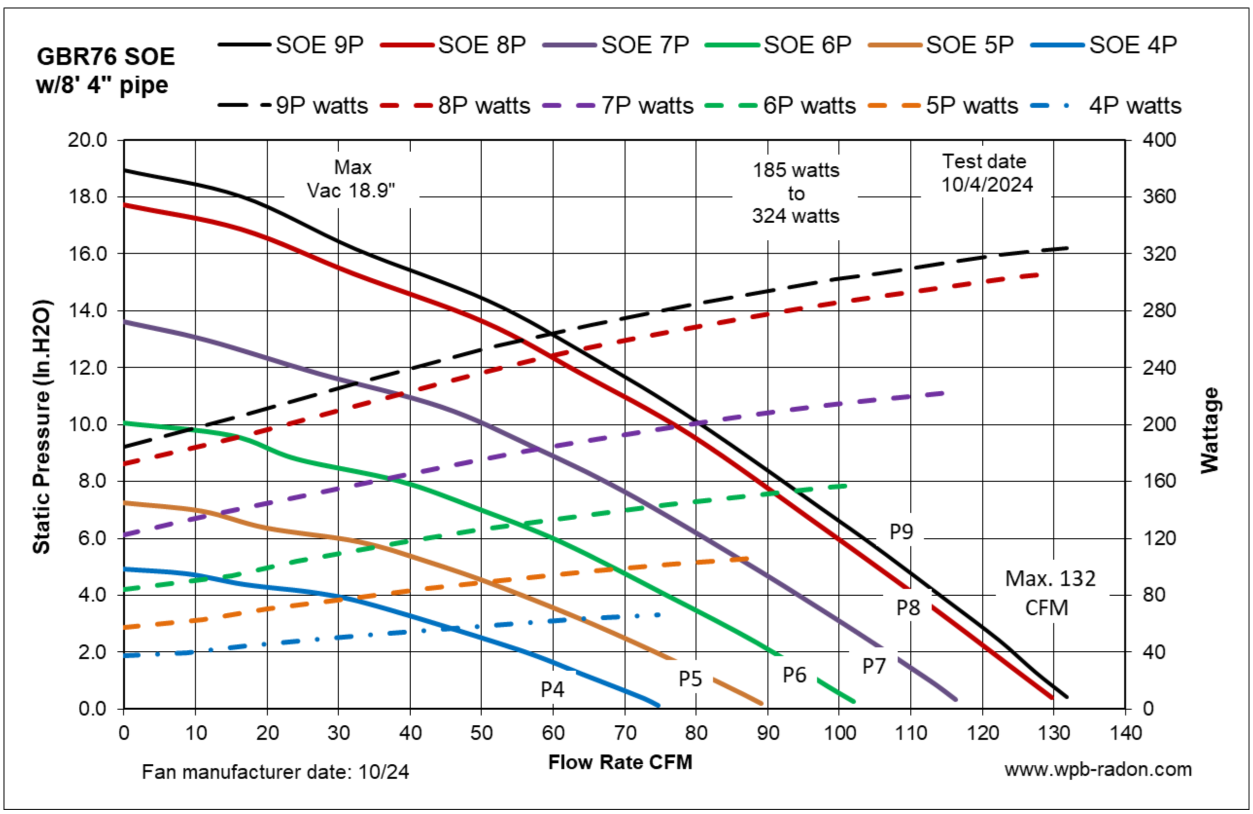
A-Table (1):   RN4-EC Three performance settings



A-Figure (1): RN4-EC performance at each setting

GBR76-SOE with 8 feet of 4” pipe								
Setting 9	Static pres		Setting 7	Static pres		Setting 6	Static pres	
CFM	In H2O	watts	CFM	In H2O	watts	CFM	In H2O	watts
0.0	18.929	184.6	0.0	13.634	122.2	0.0	10.065	84.3
16.4	18.008	206.0	11.7	12.977	135.7	15.0	9.625	93.5
32.4	16.162	229.0	27.3	11.800	152.0	24.2	8.798	104.0
51.1	14.327	254.0	44.4	10.635	169.6	38.5	8.023	116.7
65.2	12.378	270.0	56.8	9.277	181.8	49.3	7.064	125.6
80.0	10.105	285.0	70.0	7.651	192.7	61.3	5.861	134.3
99.4	6.710	302.0	86.9	5.158	206.0	75.9	3.997	143.9
105.6	5.593	306.0	100.8	2.975	215.0	88.6	2.319	150.2
114.9	3.842	314.0	112.6	1.018	221.0	98.4	0.7946	155.8
122.3	2.436	319.0	116.3	0.328	223.0	102.1	0.2578	157.2
127.4	1.310	322.0						
131.8	0.423	324.0						

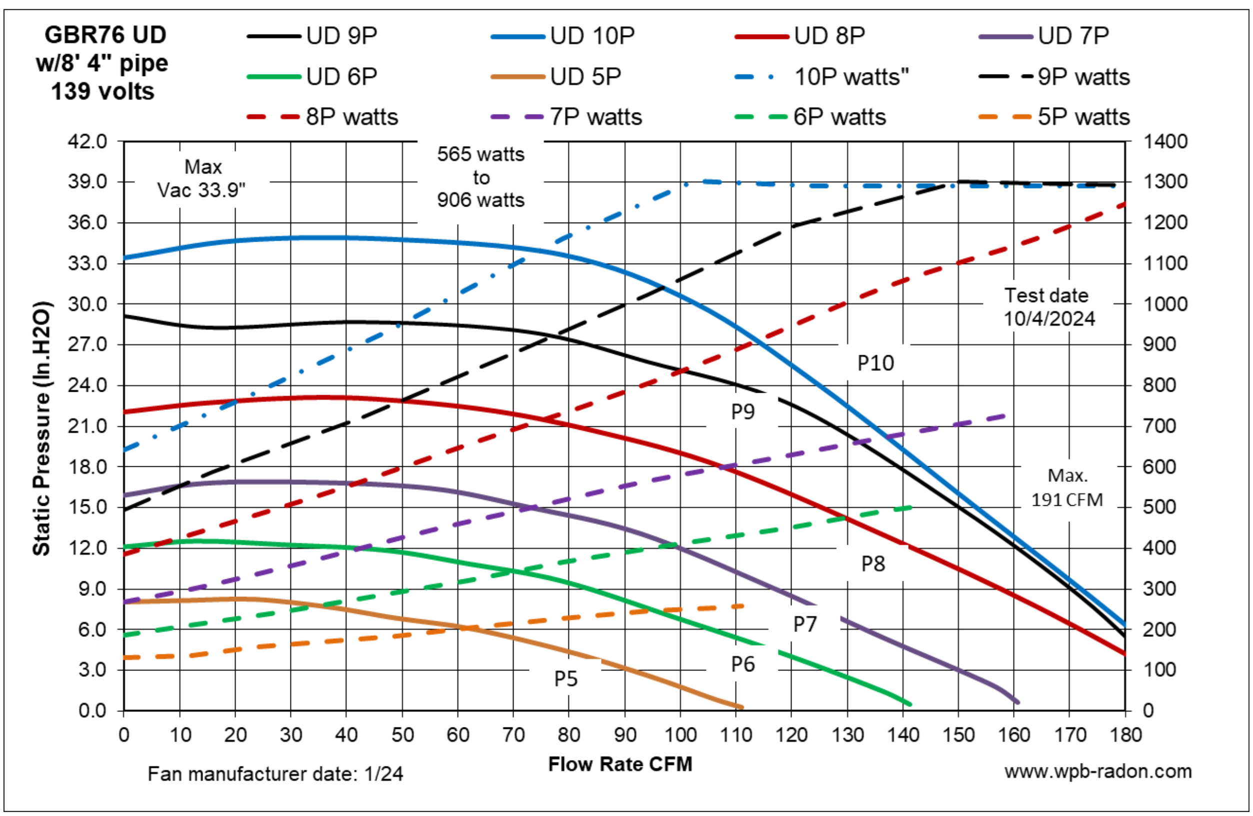
A-Table (2): GBR76-SOE - Three performance settings



A-Figure (2): GBR76-SOE performance at each setting

GBR76 UD with 8 feet of 4” pipe										
P10	Static pres			P8	Static pres			P6	Static pres	
CFM	In H2O	Watts		CFM	In H2O	Watts		CFM	In H2O	Watts
0.0	33.40	640.5		0.0	22.06	384.8		0.0	12.13	186.4
20.7	34.68	764.8		16.5	22.77	451.7		12.9	12.55	213.9
47.1	34.79	932.1		39.1	23.12	547.3		28.6	12.29	245.0
78.8	33.63	1161.5		63.9	22.29	664.4		47.0	11.87	288.0
102.5	30.10	1302.6		84.9	20.63	760.0		61.8	10.89	320.3
124.7	24.11	1290.6		108.0	17.97	877.1		79.0	9.58	366.9
152.4	15.26	1290.6		137.7	12.80	1046.8		99.9	6.79	412.3
173.1	8.64	1290.6		163.9	7.77	1161.5		119.4	4.11	449.3
190.3	2.90	1290.6		186.3	2.76	1278.7		136.3	1.49	491.1
196.4	0.93	1290.6		191.9	0.88	1271.5		141.3	0.48	499.5

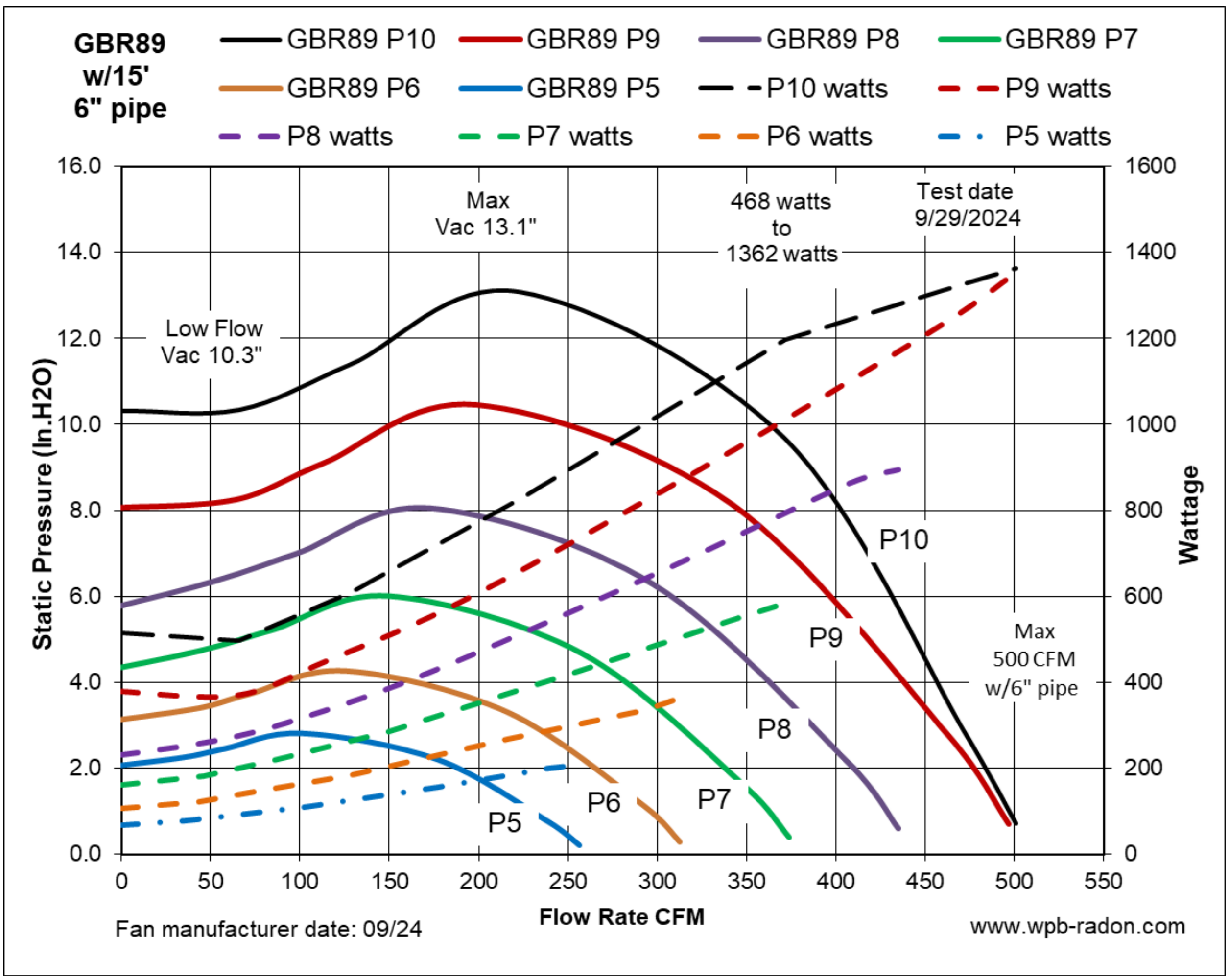
A-Table (3): GBR76-UD - Three performance settings



A-Figure (3): GBR76-UD performance at each setting

GBR89 with 15 feet of 6" pipe										
P10	Static pres			P8	Static pres			P7	Static pres	
CFM	In H2O	Watts		CFM	In H2O	Watts		CFM	In H2O	Watts
0.0	10.32	513.9		0.0	5.78	231.8		0.0	4.35	161.3
65.9	10.34	497.1		53.2	6.37	265.3		46.2	4.76	182.8
128.1	11.40	607.1		98.4	7.00	314.3		84.7	5.22	218.7
222.8	13.09	826.9		172.8	8.06	424.2		149.8	6.00	285.6
371.4	9.67	1196.2		297.5	6.28	650.1		257.7	4.68	427.8
471.6	2.86	1326.5		407.1	2.11	862.8		349.6	1.57	554.5
500.7	0.72	1362.3		434.6	0.59	895.1		373.9	0.40	585.6

A-Table (4): GBR89 - Three performance settings



A-Figure (4): GBR89 performance at each setting