NEBRASKA
DEPT. OF ENVIRONMENT AND ENERGY

Wet Scrubber Operational Parameter Monitoring and Variability at Ethanol Plants

March 2021

Summary

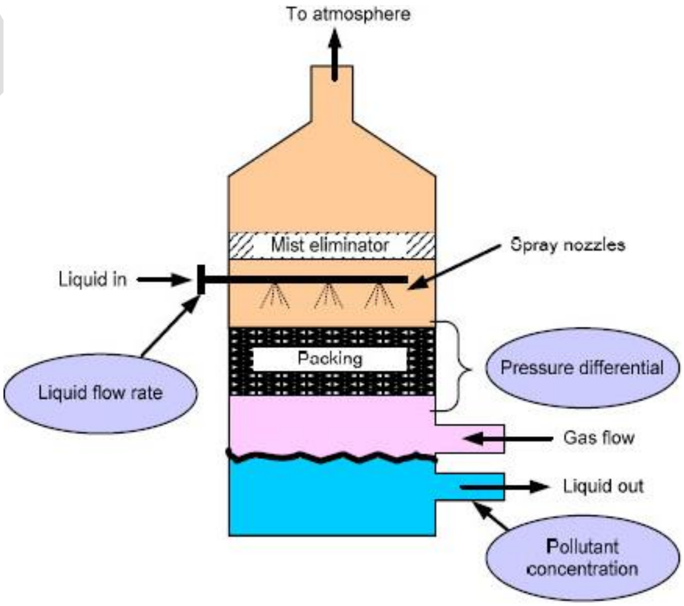
This guidance discusses the review process the Nebraska Department of Environment and Energy (NDEE or the Department) used to determine the operational parameter monitoring requirements for packed-bed wet scrubbers controlling gaseous pollutants. There is a specific focus on emission rate variations observed during emissions testing events at dry mill batch fermentation plants.

Background

Wet scrubbers use a liquid to remove pollutants from an exhaust stream via absorption to transfer components from the gas phase to the liquid phase. Wet scrubbers rely on the creation of large surface areas of scrubbing liquid that allow contact between the liquid and gas. This can be accomplished by passing the liquid over a variety of media (packing, meshing, grids, trays) or by creating a spray of droplets. There are several types of wet scrubber designs, including spray tower, tray-type, and packed-bed wet scrubbers.[1] This document focuses on operational parameter requirements for packed-bed wet scrubbers controlling gaseous pollutants utilizing water as an absorbent or water which contains added chemicals to react with the gas being absorbed and reduce the concentration.

Packed-bed wet scrubbers consist of a chamber containing layers of variously-shaped packing material, such as raschig rings, spiral rings, or berl saddles, that provide a large surface area for liquid-particle contact. The packing is held in place by wire mesh retainers and supported by a plate near the bottom of the scrubber. Scrubbing liquid is evenly introduced above the packing and flows down through the bed. The liquid coats the packing and establishes a thin film. The pollutant to be absorbed must be soluble in the scrubbing fluid. Physical absorption depends on properties of the gas stream and liquid solvent, such as density and viscosity, as well as specific characteristics of the pollutant(s) in the gas and the liquid stream (e.g., diffusivity, equilibrium solubility).[2]

Typical Packed-bed Wet Scrubber



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[1] U.S. EPA, Office of Air Quality Planning and Standards, “Compliance Assurance Monitoring Technical Guidance Document, Appendix B: CAM Illustrations, Revision 1, Review Draft” (January, 2005)

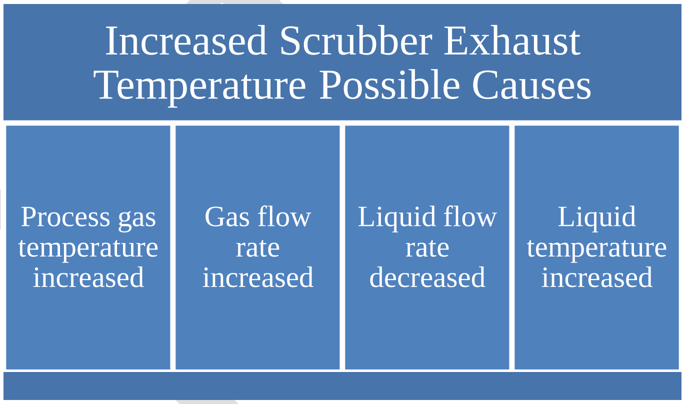
[2] U.S. EPA, Office of Air Quality Planning and Standards, “Air Pollution Control Technology Fact Sheet, Packed-Bed/Packed-Tower Wet Scrubber” EPA-452/F-03-015 (July 2003)

Operational Parameter Requirements for Packed-Bed Wet Scrubbers Utilized for Gaseous Control

The Environmental Protection Agency’s (EPA) Compliance Assurance Monitoring (CAM) Technical Guidance Document, Appendix B.5 Guidance Document (CAM B.5) identifies several parameters to be used as indicators of wet scrubber performance. The guidance identifies the most appropriate indicators to monitor depend upon a number of factors, including type of pollutant (whether particulate matter [PM] is also present), scrubber design, and exhaust gas characteristics. In addition to the factors described in the CAM guidance, data which indicates variability of inlet gas, absorbent liquid, and chemical additive characteristics at biological processes are included in this document which have also been utilized for the determination of appropriate operational parameter monitoring requirements for packed-bed wet scrubbers in NDEE issued permits.

The CAM B.5 guidance identifies the key indicators of wet scrubber performance for the control of gaseous pollutants (Volatile Organic Compounds [VOC] and acid gases) to be pressure differential, liquid flow rate, and scrubber liquid outlet concentration with the other less significant indicators being gas flow rate, neutralizing chemical feed rate, and scrubber outlet gas temperature. As an alternative to monitoring scrubber liquid outlet concentration, the guidance lists scrubbing liquid pH, scrubbing liquid specific gravity, and scrubber makeup/blowdown rates. For systems that control thermal processes, the guidance identifies scrubber outlet gas temperature monitoring as a surrogate for scrubber liquid flow rate as increases in the outlet or exhaust temperature of the gas stream are an indication of a change in operation where either the process exhaust temperature has increased, the gas flow rate has increased, or the liquid flow rate has decreased.

Relatedly, in the CAM rule[3], it is identified that scrubber exhaust gas temperature is indicative of adequate water flow (as a result of heat exchange between the gas stream and scrubber water), but also that since the inlet scrubber water temperature (in the rule’s hypothetical example) is affected by ambient temperature, the resulting scrubber outlet temperature will be affected by ambient conditions. This example in the CAM rule provides support that, as expected, an increase in exhaust temperature of the gas stream could also be an indication of a change in scrubber water temperature along with the other listed possibilities in the CAM guidance of a change in operation where the process exhaust temperature has increased, the gas flow rate has increased, or the liquid flow rate has decreased.



Mass transfer governs the rate at which pollutants are transferred to the scrubbing liquid via absorption and is driven by vapor-liquid equilibrium. Vapor-liquid equilibrium is temperature dependent. Therefore, because vapor-liquid equilibrium is temperature dependent, the rate of mass transfer is temperature dependent. The CAM B.5 guidance identifies exhaust temperature as an indicator of heat transfer in order to infer mass transfer and as an indication of adequate liquid flow. Rather than requiring monitoring of outlet exhaust temperature, the NDEE requires monitoring of the scrubbing liquid temperature as they are interdependent. Liquid temperature monitoring is required in addition to liquid flow monitoring due to the temperature dependency of mass transfer.

The NDEE has determined that, especially for processes where there is potential for variable inlet gas and/or inlet liquid characteristics, liquid flow monitoring on its own does not yield reliable data to account for temperature variations which have the potential to be caused by increases in process exhaust gas temperature, increases in gas flow, decreases in liquid flow, or changes in liquid temperature and which may have an impact on the liquid flow rate necessary for adequate mass transfer.

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[3] Compliance Assurance Monitoring (CAM) Rule; Vol. 62 Fed. Reg. No. 36 (February 24, 1997) (40 CFR Parts 51, 52, 60 and 61)

Based on the above criteria, the NDEE has determined monitoring of the following operational parameters for packed-bed wet scrubbers utilized for gaseous control to be adequate to demonstrate compliance with the underlying requirements:

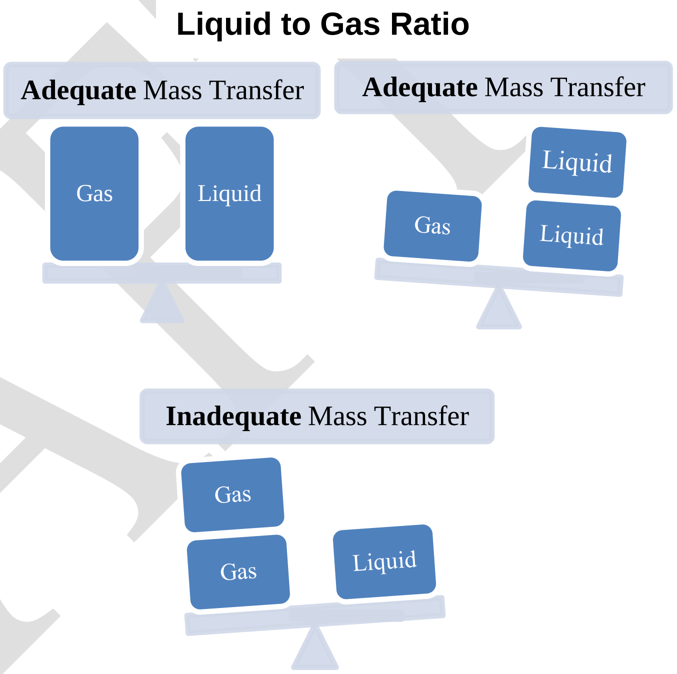
- Liquid Flow
- Pressure Differential
- Liquid Temperature
- Chemical Addition Rate and Type

Liquid Flow

In EPA's CAM Technical Guidance Document, Appendix A for example CAM approach submittals, it is indicated that to comply with the applicable emission limit, a minimum water flow rate must be supplied to the scrubber to absorb a given amount of VOC in the gas stream, given the size of the tower and height of the packed bed. The liquid to gas (L/G) ratio is a key operating parameter of the scrubber. If the L/G ratio decreases below the minimum, sufficient mass transfer of the pollutant from the gas phase to the liquid phase will not occur. The minimum liquid flow required to maintain the proper L/G ratio at the maximum gas flow and vapor loading through the scrubber can be determined. Maintaining this minimum liquid flow, even during periods of reduced gas flow, will help ensure that the required L/G ratio is achieved at all times.[4]

Relatedly, EPA's CAM B.5 Guidance indicates that gas flow rate is often a constant based on process conditions and is the major design consideration of the scrubber; the L/G ratio is determined and maintained by the scrubber liquid flow rate. Scrubber liquid flow rate is a key indicator of performance provided the liquid is being properly distributed, and the liquid-gas interface is maintained. Under these conditions, higher liquid flow rates are indicative of higher levels of control. However, for packed-bed scrubbers, there is a critical flow rate above which flooding occurs.

In order to ensure the L/G ratio, which is identified as a key operating parameter in EPA guidance, is maintained and adequate mass transfer is occurring, the NDEE requires continuous monitoring of the scrubber liquid flow rate. This monitoring determination is supported by performance test and operation parameter data.



Pressure Differential

EPA CAM B.5 Guidance indicates that for the control of gaseous pollutants (VOC and acid gases), the key indicators of wet scrubber performance generally are the same as the critical performance indicators for PM emission control with a few exceptions. Pressure differential, liquid flow rate, and scrubber liquid outlet concentration are the key indicators of performance. Pressure differential is one of the most critical indicators of performance for most wet scrubber designs. Pressure differential remains fairly constant and reflects normal operation of the liquid flow and gas flow through the system. For packed-bed scrubbers, plugging of the bed can result in increased pressure differential; the increase in pressure differential would likely be observed as a

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[4] U.S. EPA, Office of Air Quality Planning and Standards, "Compliance Assurance Monitoring Technical Guidance Document, Appendix A: Example Monitoring Approach Submittals" (August, 1998; June, 2002)

gradual increase over time. In such cases, an increase in pressure differential can correspond to a decrease in performance.

As discussed above, mass transfer is the driving force for absorption of gaseous pollutants. Scrubber plugging or channeling which causes a change in pressure differential can lead to a decrease in mass transfer efficiency as there is less surface area for absorption to occur, resulting in a decrease in scrubber performance.

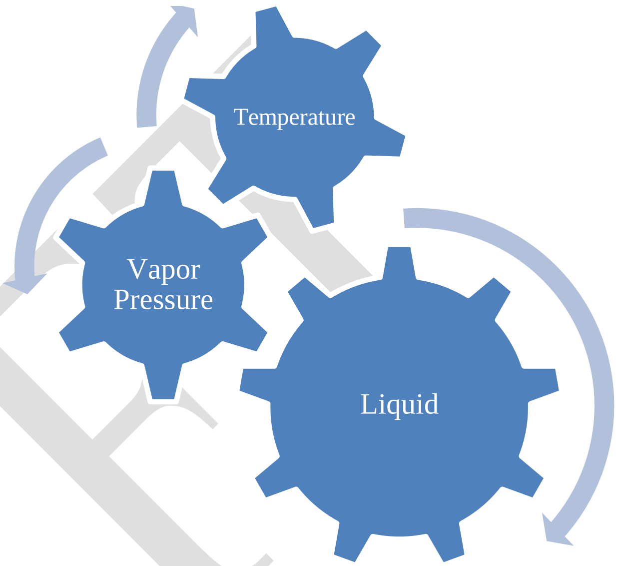
The NDEE requires pressure differential monitoring in order to identify plugging or channeling issues within the scrubber which could lead to a decrease in scrubber performance and a direct impact on emissions.

Liquid Temperature

As discussed above**,** mass transfer of pollutants into an absorbent is a temperature dependent process governed by vapor-liquid equilibrium. EPA's CAM B.5 Guidance identifies one potential indicator of performance to monitor to be scrubber exhaust temperature as a surrogate to liquid flow monitoring in order to infer mass transfer by measurement of heat transfer. The CAM B.5 Guidance identifies an increase in scrubber exhaust temperature as an indicator of a change in operation where either the process exhaust temperature has increased, the gas flow rate has increased, or the liquid flow rate has decreased. The CAM rule also indicates that scrubber outlet temperature has the potential to be affected, expectedly, by inlet scrubber water temperature.

The NDEE requires monitoring of inlet scrubber water temperature as a surrogate to scrubber outlet exhaust temperature for processes which have consistent (expected) process exhaust temperatures. It is expected that monitoring of inlet scrubber water temperature is sufficient to yield data for potential temperature variations which would impact mass transfer. EPA's Air Pollution Control Technology Fact Sheet (APCTFS) indicates that the higher the gas temperature, the lower the absorption rate, and vice-versa. Excessively high gas temperatures can also lead to significant solvent or scrubbing liquid loss through evaporation. Additionally, the APCTFS indicates that the properties of physical absorption depend on properties of the gas stream and liquid solvent, such as density and viscosity, as well as specific characteristics of the pollutant(s) in the gas and the liquid stream (e.g., diffusivity, equilibrium solubility). These properties are temperature dependent, and lower temperatures generally favor absorption of gases by the solvent. Absorption is also enhanced by greater contacting surface, higher liquid-gas ratios, and higher concentrations in the gas stream.

Mass Transfer Components



Supporting the exhaust temperature discussions in the CAM rule, CAM B.5 Guidance, and APCTFS which identify that increases in exhaust temperature can be indicators of changes in operations as well as can lead to significant solvent or scrubbing liquid loss through evaporation and decreased resulting absorption, the NDEE obtained performance testing and operational parameter data at an ethanol facility in Nebraska and modeled ethanol volatility as temperature increases. The dataset utilized for the model included 80 separate temperature data points from a range of 33.8° F to 176° F, utilizing the Antoine equation. The complete dataset and equation used for the model can be found in Appendix A of this document. For Table 1b, the data temperature ranges selected were for the average operating temperature range of 50° to ~133° F. The model graphed in Tables 1a and 1b indicate that ethanol is much more likely to evaporate at higher temperatures.

The model supports the discussions from the CAM guidance and APCTFS that a reduction in scrubber efficacy may occur as operating temperature or inlet liquid temperature increase. The model indicates that temperature plays an important factor in ethanol's volatility, which has a direct impact on vapor-liquid equilibrium and subsequently mass transfer.

The dataset and equations utilized for Tables 1a and 1b can be found at the end of this document beginning on Page 18

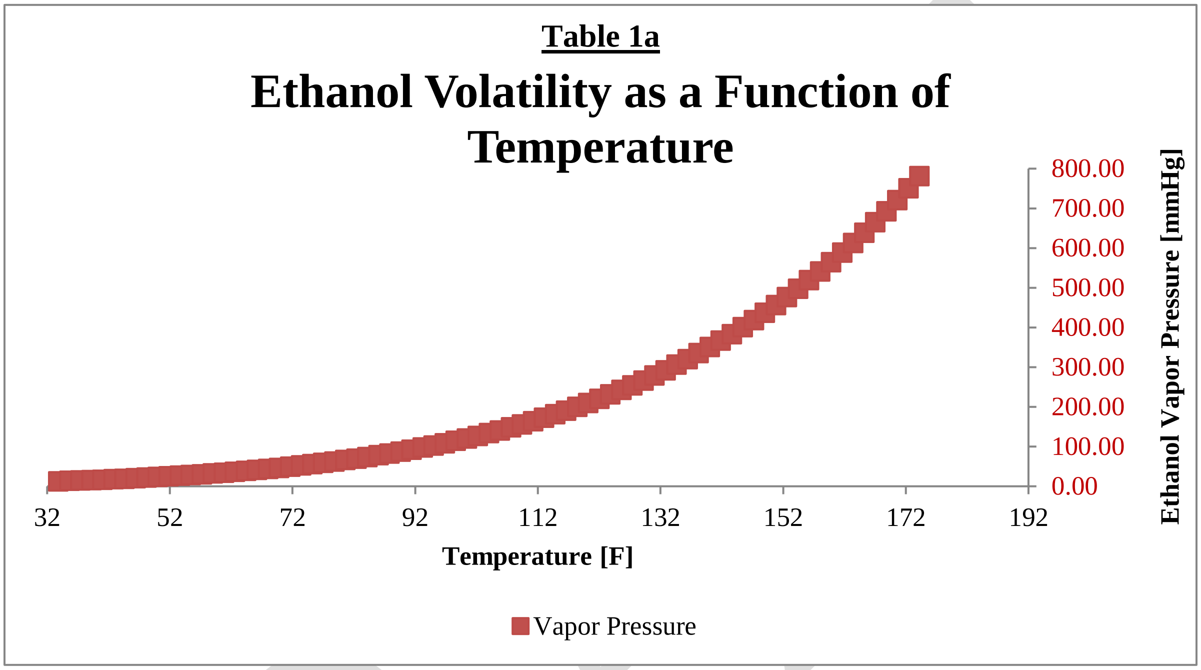


Table 1a

Ethanol Volatility as a Function of Temperature

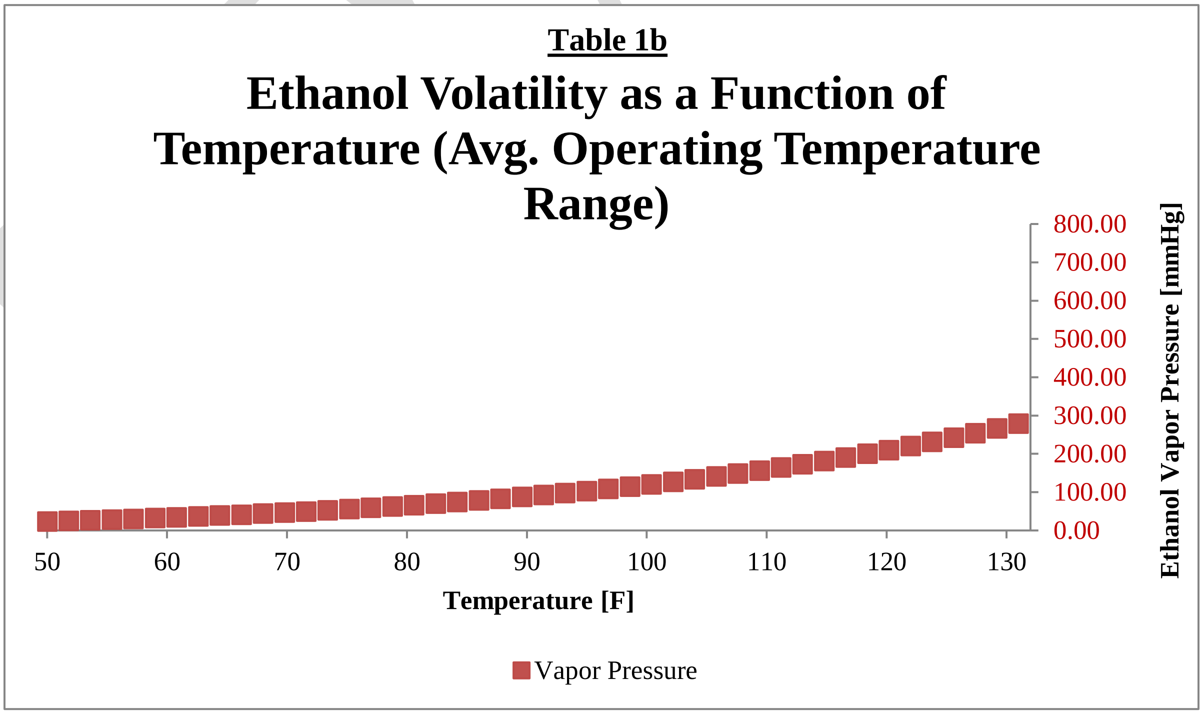


Table 1b

Ethanol Volatility as a Function of Temperature (Avg. Operating Temperature Range)

Example A below shows two temperatures used in the model and the differences in percent change of ethanol evaporation (99% increase).

Example A:

Ethanol Vapor Pressure		
Temperature		**Percent Change**
50° F	**69.8° F**	
Vapor Pressure: **23.30 mmHg**	Vapor Pressure: **46.41 mmHg**	**+ 99%**

In addition to the temperature modeling included in Tables 1a and 1b above, the NDEE has evaluated stack test data from a continuous ethanol plant which appears to demonstrate the temperature dependency of packed-bed wet scrubbers controlling gaseous pollutants. Figures/Tables 2, 3, 4, and 5 below are from four testing events completed on a packed-bed wet scrubber controlling VOC/HAPs from a fermentation process on separate dates from 2013 to 2019 and include test runs at normal operation and alternate operating conditions including high temperature scrubber water and reduced chemical addition rate.

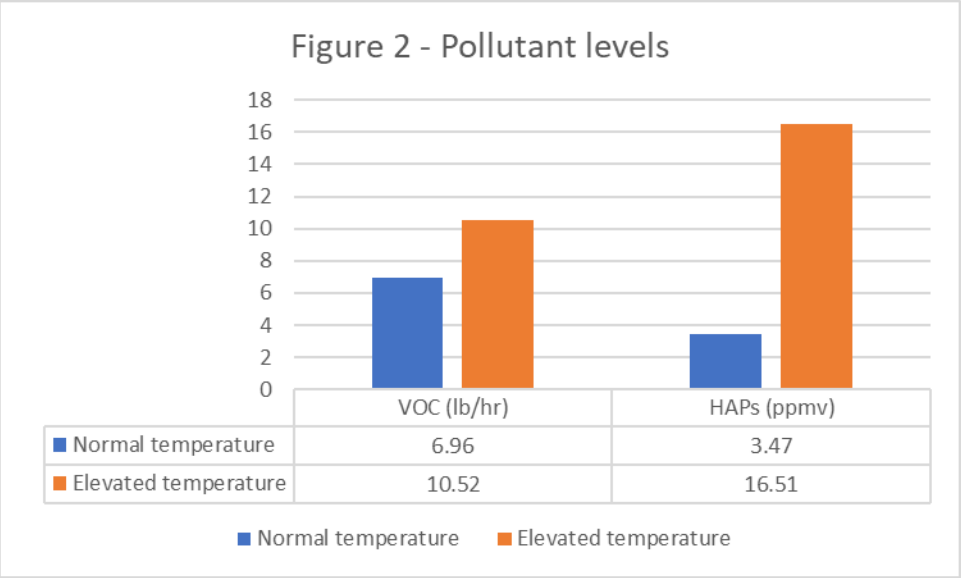


Figure 2 - Pollutant levels

Table 2 - Plant and control parameters – 9/24-9/25/13				
Scrubber Water Temperature Parameter	**Average Scrubber Water Temp**	**Average Scrubber Water Flow**	**Average SBS Flow**	**Fermentation Dextrose Pull**
Normal	58.6°F	70.0 gpm	92.4 lbs/hr	2761.9 lbs/min
Elevated	90°F	70.0 gpm	92.1 lbs/hr	2845.1 lbs/min

In Figure and Table 2, water flow rate was not increased in this elevated scrubber water temperature test. Results show an increase in outgoing HAP concentration and VOC emission rate.

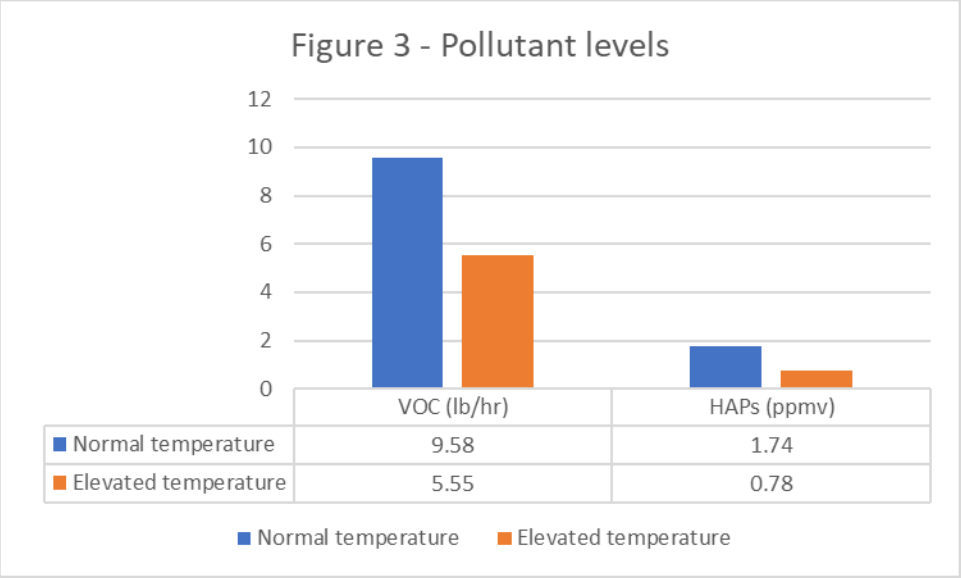


Table 3 - Plant and control parameters – 11/20-11/21/19				
Scrubber Water Temperature Parameter	**Average Scrubber Water Temp**	**Average Scrubber Water Flow**	**Average ABS Flow**	**Fermentation Dextrose Pull**
Normal	63°F	60.0 gpm	65.5 lbs/hr	3303.63 lbs/min
Elevated	89.7°F	78.0 gpm	65.0 lbs/hr	3275.49 lbs/min

In Figure and Table 3, during the test runs with elevated scrubber water temperatures, the scrubber water flow rate was increased. Additional data would be necessary to determine if the increase in water flow rate was necessary to maintain scrubber efficiency at elevated temperatures.

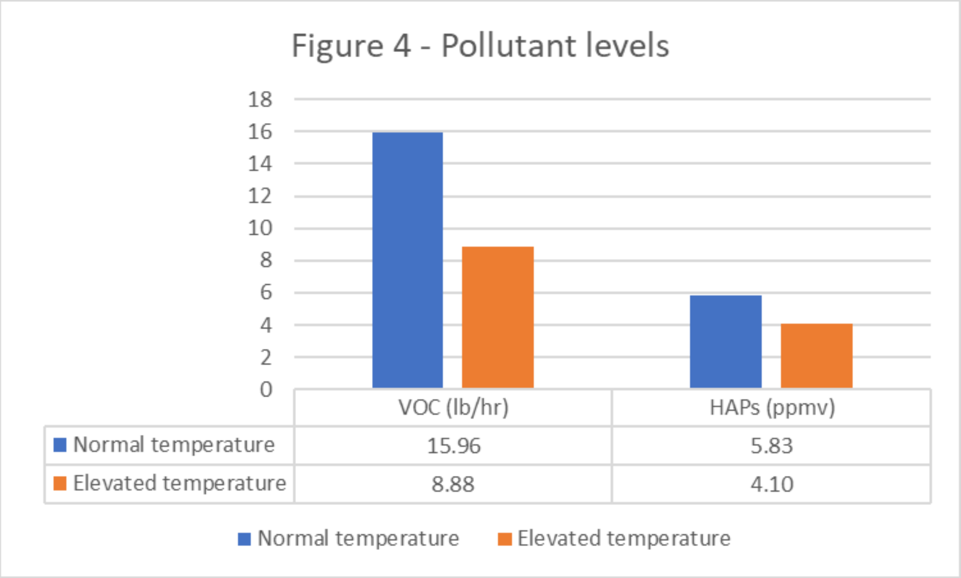


Table 4 - Plant and control parameters – 8/22-8/24/17				
Scrubber Water Temperature Parameter	**Average Scrubber Water Temp**	**Average Scrubber Water Flow**	**Average ABS Flow**	**Fermentation Dextrose Pull**
Normal	62.5°F	59.7 gpm	50.0 lbs/hr	3110.35 lbs/min
Elevated	95°F	78.0 gpm	50.0 lbs/hr	3109.90 lbs/min

In Figure and Table 4, during the test runs with elevated scrubber water temperatures, the scrubber water flow rate was increased. Additional data would be necessary to determine if the increase in water flow rate was necessary to maintain scrubber efficiency at elevated temperatures.

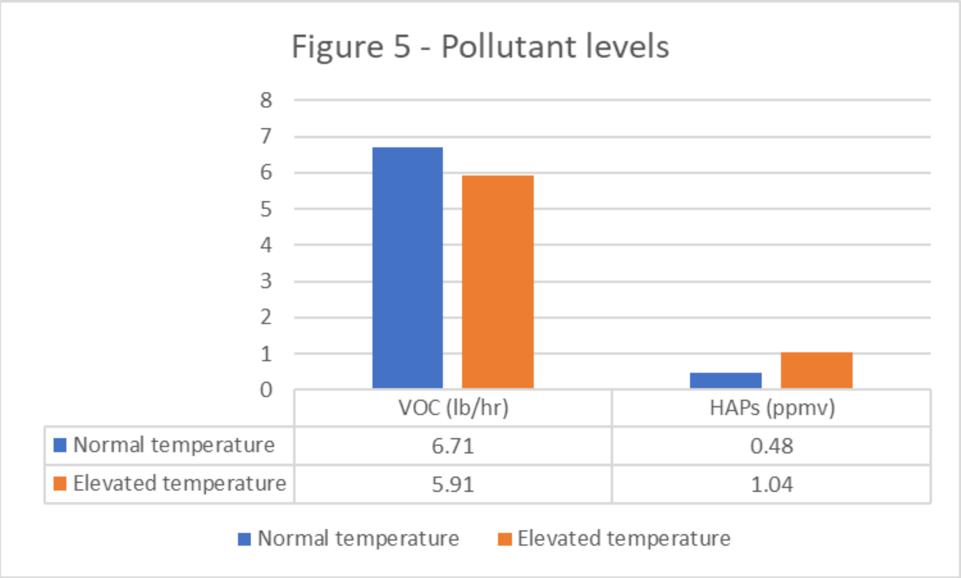


Figure 5 - Pollutant levels

	VOC (lb/hr)	HAPs (ppmv)
■ Normal temperature	6.71	0.48
■ Elevated temperature	5.91	1.04

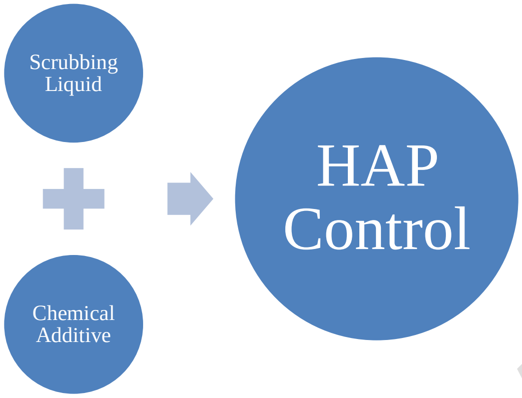
Table 5 - Plant and control parameters – 12/2-12/4/14				
Scrubber Water Temperature Parameter	**Average Scrubber Water Temp**	**Average Scrubber Water Flow**	**Average SBS Flow**	**Fermentation Dextrose Pull**
Normal	56.2°F	52.0 gpm	122.5 lbs/hr	3096.1 lbs/min
Elevated	92.6°F	70.0 gpm	126.1 lbs/hr	3163.2 lbs/min

In Figure and Table 5, during the test runs with elevated scrubber water temperatures, the scrubber water flow rate was increased. Additional data would be necessary to determine if the increase in water flow rate was necessary to maintain scrubber efficiency at elevated temperatures.

Figures and associated Tables 2, 3, 4, and 5 appear to show a temperature dependency with scrubber efficiency, however additional data is necessary to be sure. Consistent with EPA CAM Guidance, the EPA CAM rule, and EPA's APCTFS which describe the temperature dependency of mass transfer through absorption, in addition to the evaluated performance test and operation parameter data discussed above, the NDEE requires liquid temperature monitoring in packed-bed wet scrubbers controlling gaseous pollutants in order to ensure that changes in liquid temperature are not reducing the efficiency of mass transfer and scrubber efficiency.

Chemical Addition Rate and Type

CAM B.5 guidance indicates that if a neutralizing chemical is used, the chemical feed rate is an indicator of wet scrubber operation. Chemical addition to scrubber water acts as a means of Hazardous Air Pollutant (HAP) emissions control and thus monitoring of the chemical addition rate is required in order to ensure appropriate scrubber efficiency is being achieved for HAPs.



In addition to the chemical addition rate, a related parameter which is an indicator of wet scrubber operation is the chemical addition type. Performance testing data has indicated that chemical type appears to have the potential for a direct impact on HAP control. Two of the most common chemicals used in wet scrubbers, sodium bisulfite (SBS) and ammonium bisulfite (ABS) as shown in Figure 6 and Figure 7 of Section 2, have the potential for different HAP control effects.

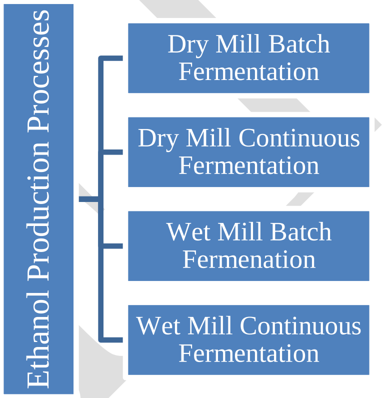
Overview

After review of EPA guidance and available performance test and operational parameter data presented above and in Appendix A, the NDEE has determined monitoring of the operational parameters liquid flow, pressure differential, liquid temperature, and chemical addition rate and type for packed-bed wet scrubbers utilized for gaseous control to be adequate to demonstrate compliance with the underlying requirements, however these requirements are subject to change if additional data becomes available which indicates a change is necessary. The NDEE regularly reviews requirements for efficacy and is open to reviewing all related data which becomes available.

Variability in Practice

Historical Emissions Testing at Dry Mill Batch Fermentation Ethanol Plants

Over the last 20 years, the the Department has developed an evolving understanding of ethanol production processes and their variable pollutant emission rate contributions of VOCs and HAPs. Ethanol plant production processes can be broken down into four general categories:



For the purposes of this document, the Department is focusing solely on emission rate variations observed during emissions testing events at dry mill batch fermentation plants, all of which utilize well water of consistent temperature for scrubber control. The reasoning for this focus is primarily due to an abundance of consistent historical stack testing data for this category, compared to a relative scarcity of stack test data for the other three categories. Where dry mill batch plants across the state have had at times multiple testing events per year, continuous and wet mill plants have experienced gaps between testing events of 3-10 years, and often with varying testing parameters. Additionally, the majority of ethanol plants operating in the state fall into the first category.

This document presents the variability in emission rates observed during past emissions testing events from various vantage points. Emissions and plant operational data is provided in graph form to best depict observed trends, with some narrative provided for context.

Production & Process Variability

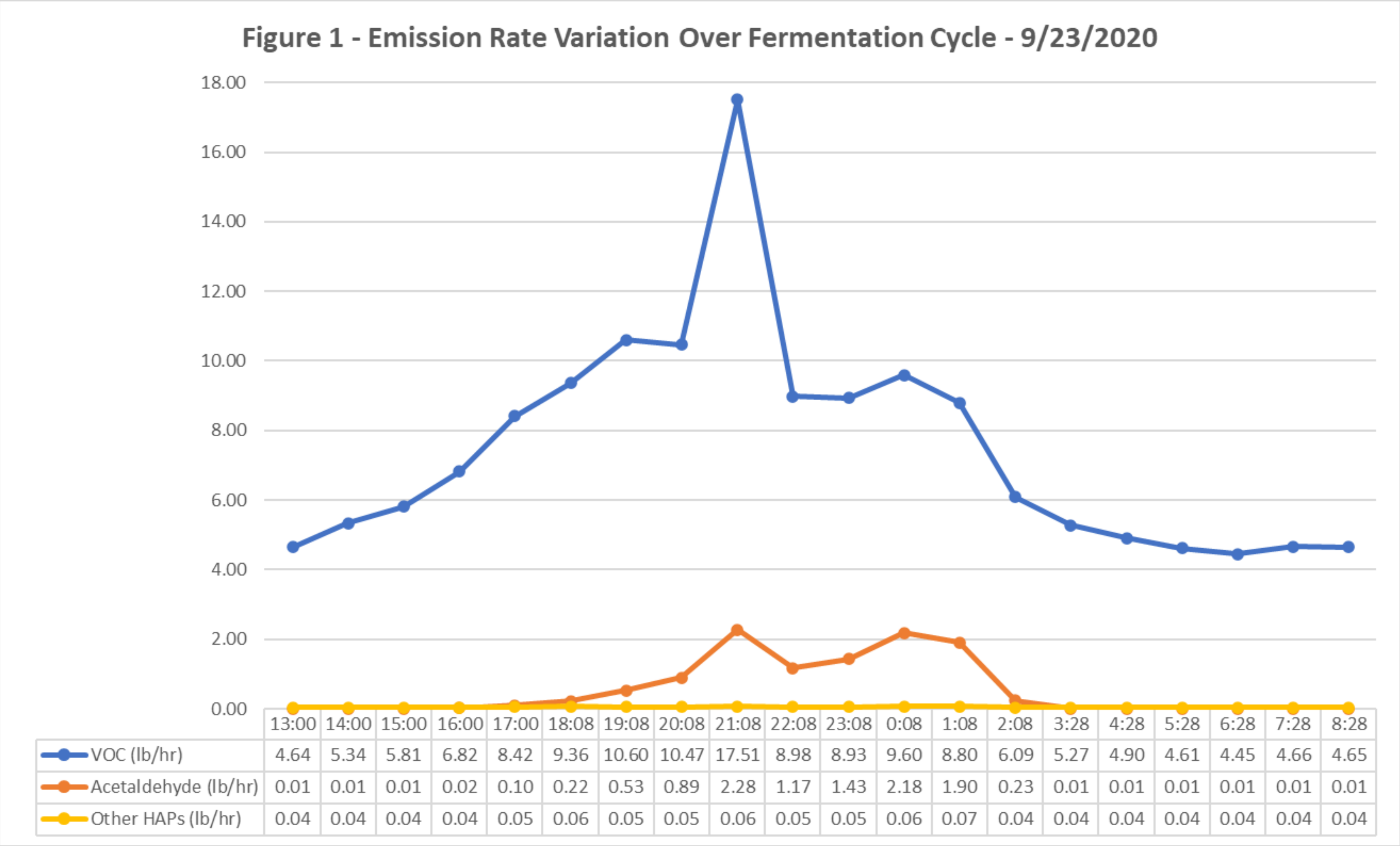


Figure 1 - Emission Rate Variation Over Fermentation Cycle - 9/23/2020

	13:00	14:00	15:00	16:00	17:00	18:08	19:08	20:08	21:08	22:08	23:08	0:08	1:08	2:08	3:28	4:28	5:28	6:28	7:28	8:28
VOC (lb/hr)	4.64	5.34	5.81	6.82	8.42	9.36	10.60	10.47	17.51	8.98	8.93	9.60	8.80	6.09	5.27	4.90	4.61	4.45	4.66	4.65
Acetaldehyde (lb/hr)	0.01	0.01	0.01	0.02	0.10	0.22	0.53	0.89	2.28	1.17	1.43	2.18	1.90	0.23	0.01	0.01	0.01	0.01	0.01	0.01
Other HAPs (lb/hr)	0.04	0.04	0.04	0.04	0.05	0.06	0.05	0.05	0.06	0.05	0.05	0.06	0.07	0.04	0.04	0.04	0.04	0.04	0.04	0.04

Above is an example of emission rate variations observed at a dry mill batch process ethanol plant over the course of a fermentation cycle, typically occurring between 12 to 20 hours. Historically, standard testing requirements for emission rate testing call for three 1-hour test runs. As shown in the figure above, limiting test periods to a three hour block could drastically underestimate or overestimate emission rates, depending on what point within the fermentation cycle that testing period took place. This appears to be endemic to dry mill batch process plants. While the availability of consistent test data is comparatively scarce, this emissions "peak" has generally not been observed at continuous process ethanol plants; rather, VOC and HAP emission rates at these plants have maintained a more steady-state.

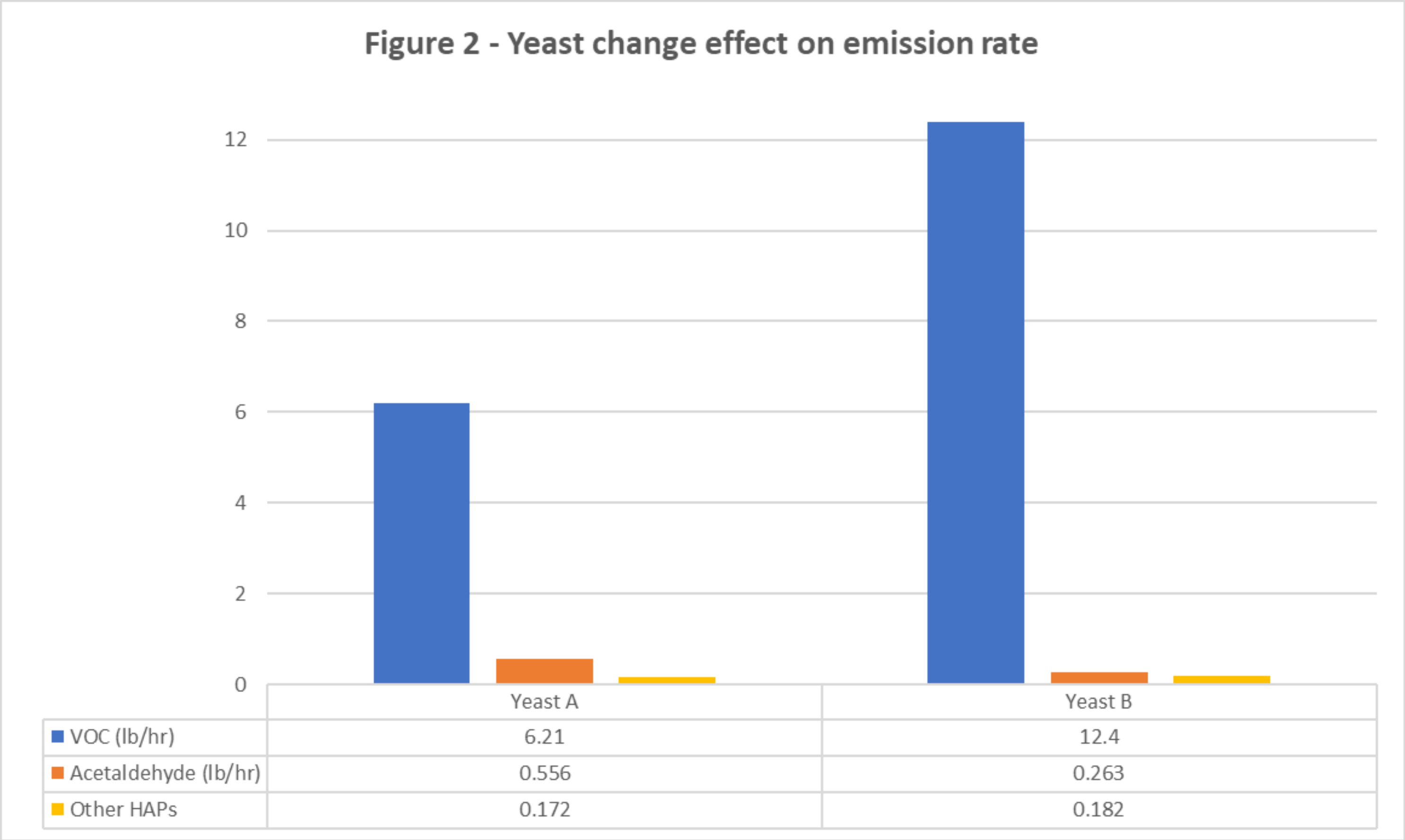


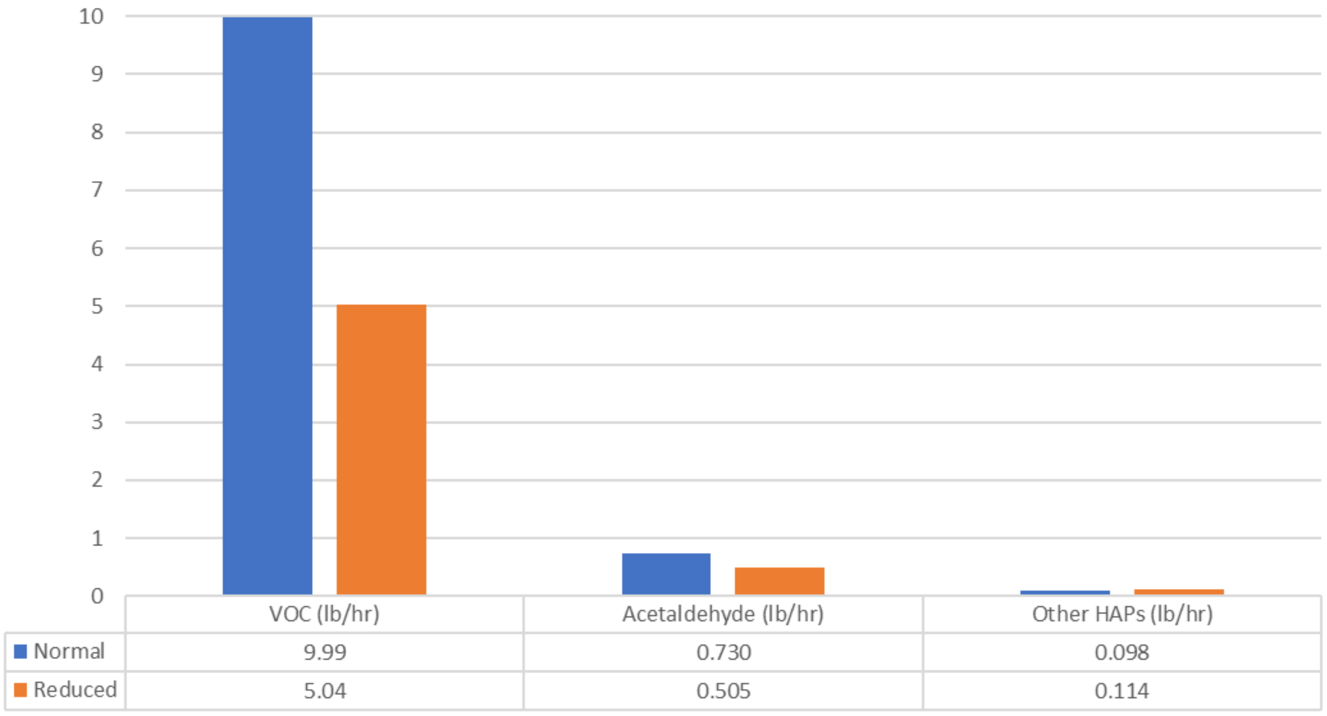
Figure 2 - Yeast change effect on emission rate

	Yeast A	Yeast B
🟦 VOC (lb/hr)	6.21	12.4
🟧 Acetaldehyde (lb/hr)	0.556	0.263
🟨 Other HAPs	0.172	0.182

Plant and control parameters				
Yeast	**Scrubber Water Flow Rate**	**SBS addition rate**	**Scrubber pressure differential**	**Beer feed rate**
A	120 gpm	*630 mL/min*	5.0 in H_2O	*1628 gpm*
B	119 gpm	*349 mL/min*	6.3 in H_2O	*1549 gpm*

Above is an example of emission rate variations seen at an ethanol plant where the only noted process change was a change in yeast. As a result of the raw material change, average acetaldehyde emissions were more than halved, despite substantially lower application rates of HAP-controlling sodium bisulfite (SBS). However, despite a slight decline in overall plant production (reflected in the beer feed rate), VOC emissions roughly doubled.

Figure 3 - Production level effect on emission rates



	VOC (lb/hr)	Acetaldehyde (lb/hr)	Other HAPs (lb/hr)
🟦 Normal	9.99	0.730	0.098
🟧 Reduced	5.04	0.505	0.114

Production Level	Scrubber Water Flow Rate	ABS addition rate	Scrubber pressure differential	Beer feed rate	200 Proof production
Normal	130 gpm	425 mL/min	11.6 in H_2O	1738 gpm	273 gpm
Reduced	85 gpm	350 mL/min	5.35 in H_2O	1144 gpm	186 gpm

Above is an example of emission rate variations seen at an ethanol plant at different production levels. This plant projected decreased demand and tested to establish lower control equipment set points such as minimum scrubber water flow rates and chemical addition rates. Testing events were approximately one month apart. Predictably, there is a correlation between increased ethanol throughput and greater VOC emission rate potential.

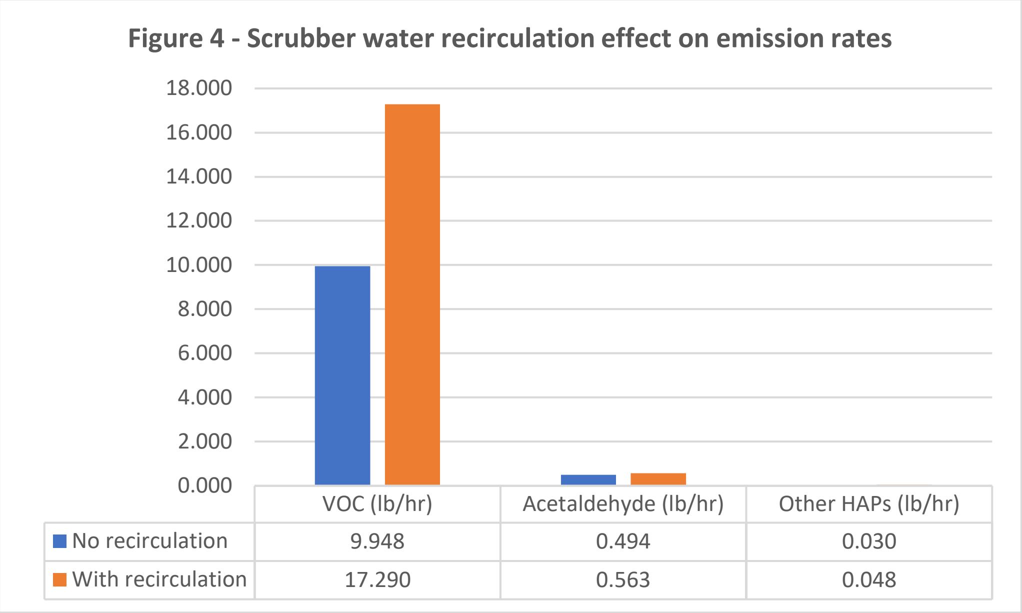


Figure 4 - Scrubber water recirculation effect on emission rates

	VOC (lb/hr)	Acetaldehyde (lb/hr)	Other HAPs (lb/hr)
■ No recirculation	9.948	0.494	0.030
■ With recirculation	17.290	0.563	0.048

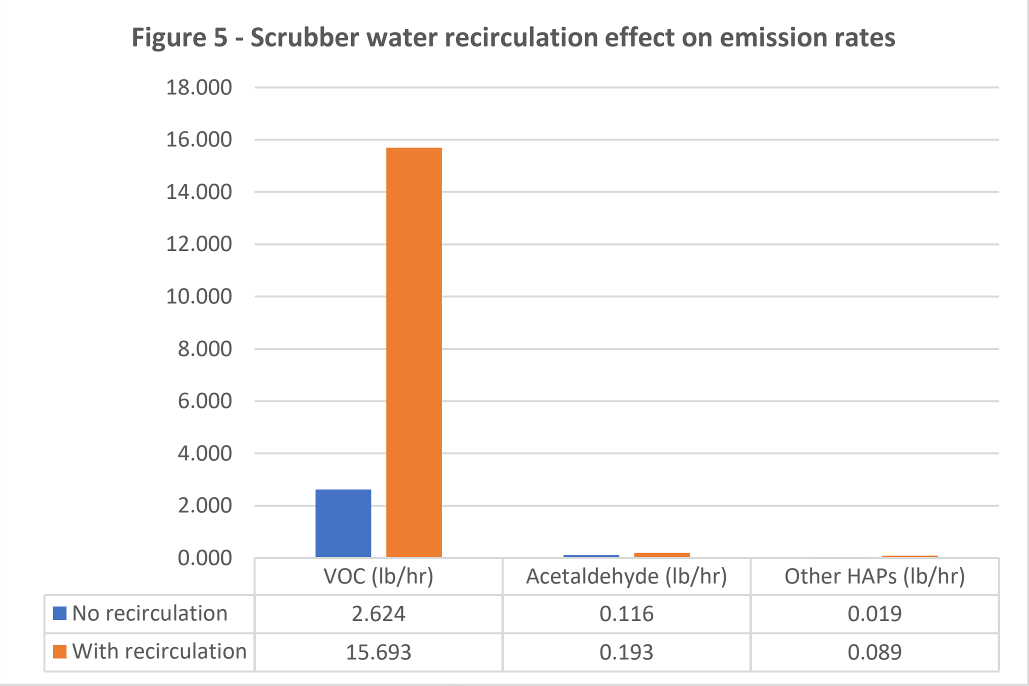


Figure 5 - Scrubber water recirculation effect on emission rates

	VOC (lb/hr)	Acetaldehyde (lb/hr)	Other HAPs (lb/hr)
■ No recirculation	2.624	0.116	0.019
■ With recirculation	15.693	0.193	0.089

Here are examples of two ethanol plants utilizing a process device known as a recirculating loop. This device captures ethanol absorbed by scrubber water and reintroduces this alcohol-infused water back into the process. At both plants, testing took place under two operating scenarios: without the device operating (“no recirculation”) and with the device operating (“with recirculation”). Other operating parameters, with the exception of scrubber water flow rate, were approximately the same in each testing scenario.

These devices benefit ethanol plants by increasing overall ethanol production capacity, and by requiring less overall scrubber water use thereby lowering operating costs. However, as seen here, these benefits come with the consequence of higher VOC and HAP emission rates.

Control equipment operational variability

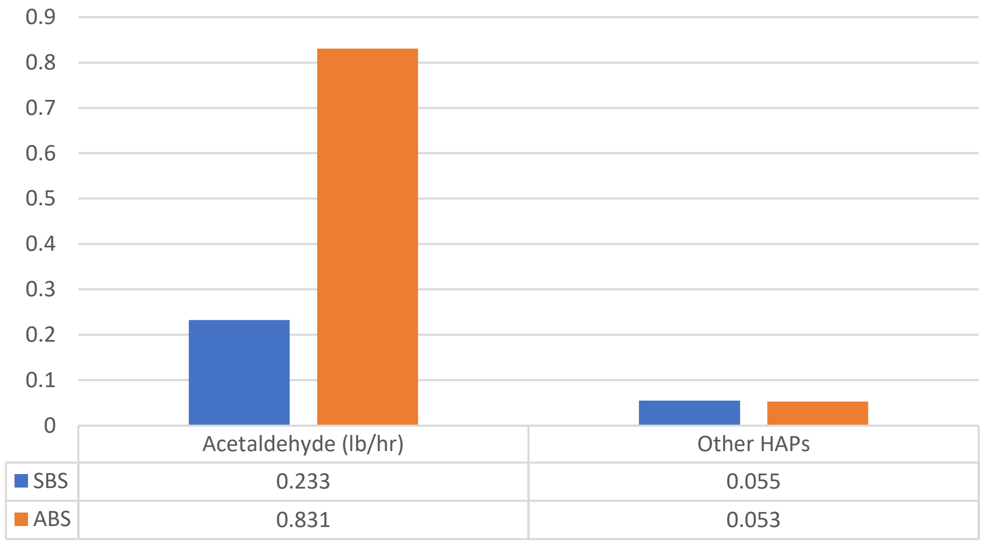


Figure 6 - Chemical type effect on HAP control

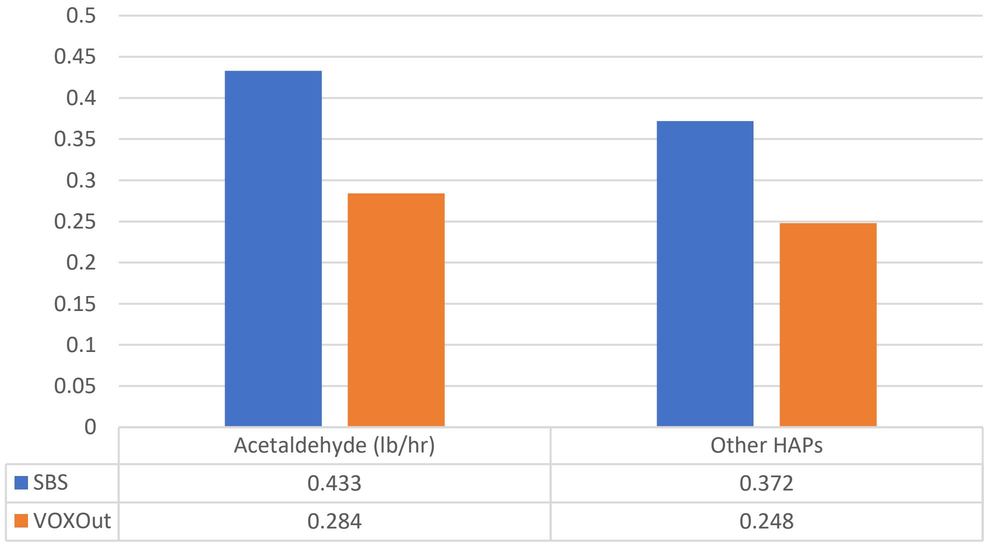


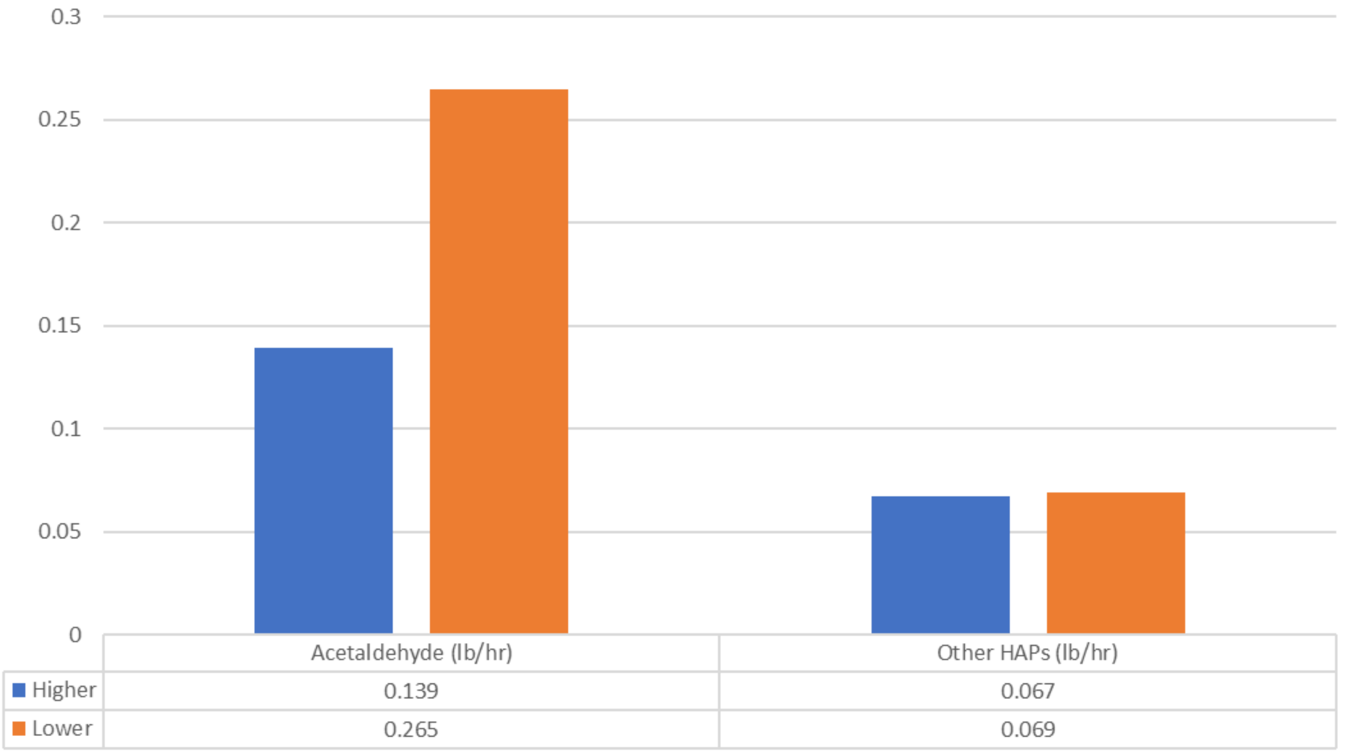
Figure 7 - Chemical type effect on HAP control

Chemical addition to scrubber water acts as means of additional HAP emissions control. Acetaldehyde, in particular, is the primary HAP seen in ethanol industry emissions. These charts illustrate the variation in HAP emissions observed during testing events where plants utilized different types of chemical additive.

In the case of Figure 6, sodium bisulfite (SBS) and ammonium bisulfite (ABS) were the chemicals of choice, with both testing events occurring on the same date. All operating parameters, with the exception of chemical type, were relatively similar, but use of ABS yielded substantially higher emissions of acetaldehyde.

Figure 7's plant tested with SBS and VOXout, a chemical additive consisting of ABS and a proprietary catalyst targeting acetaldehyde. Testing events took place in 3rd quarter 2008 and 2011, respectively. Despite an increase in ethanol production at the plant, emissions of acetaldehyde were nearly halved due to use of VOXOut.

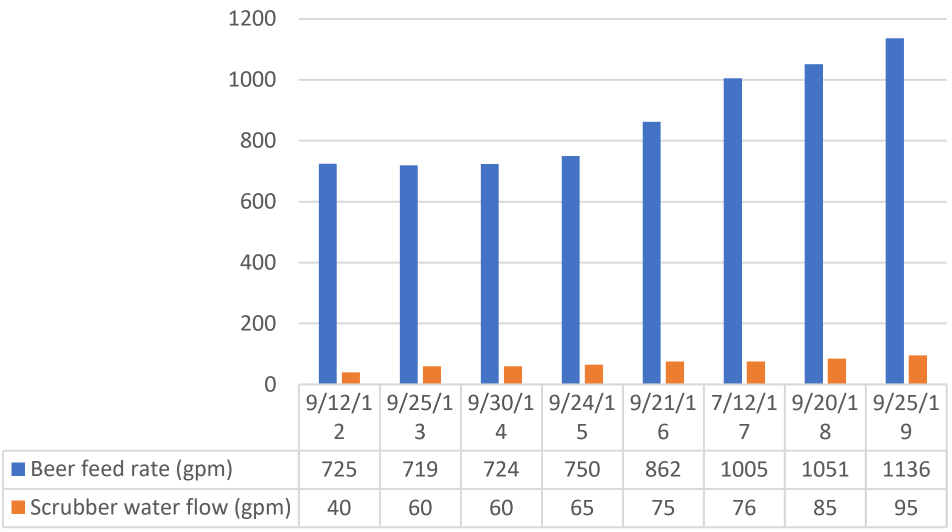
Figure 8 - Chemical additive rate effect on HAP control



Chemical addition rate	Scrubber Water Flow Rate	Scrubber pressure differential	Beer feed rate
250 mL/min	96 gpm	7.9 in H_2O	1470 gpm
240 mL/min	91 gpm	9.7 in H_2O	1400 gpm

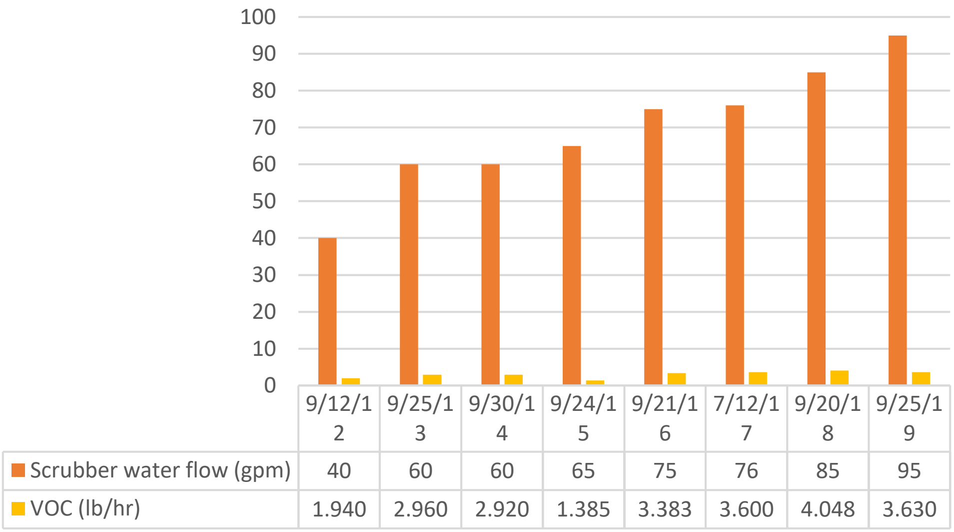
Above is an example of HAP emission rates seen at an ethanol plant utilizing the same chemical additive, but at marginally different injection rates. Testing events took place in 3rd quarter 2018 and 2019, respectively. As shown in the figure above, despite lower overall production levels (expressed here as beer feed rate), and a reduction of only 10 mL/min of chemical addition rate, acetaldehyde emissions were roughly doubled.

Figure 9a - Production & scrubber water flow



	9/12/12	9/25/13	9/30/14	9/24/15	9/21/16	7/12/17	9/20/18	9/25/19
Beer feed rate (gpm)	725	719	724	750	862	1005	1051	1136
Scrubber water flow (gpm)	40	60	60	65	75	76	85	95

Figure 9b - Scrubber water flow & VOC emission rates

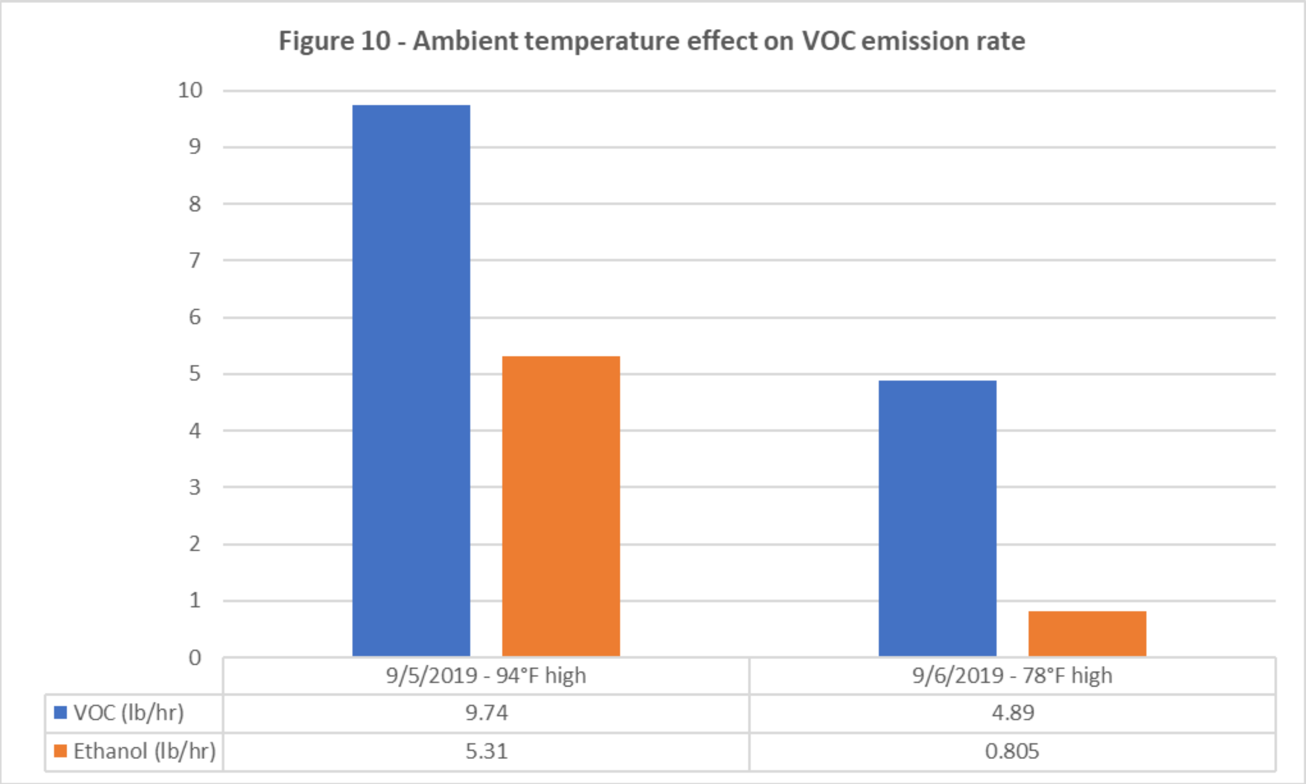


	9/12/12	9/25/13	9/30/14	9/24/15	9/21/16	7/12/17	9/20/18	9/25/19
Scrubber water flow (gpm)	40	60	60	65	75	76	85	95
VOC (lb/hr)	1.940	2.960	2.920	1.385	3.383	3.600	4.048	3.630

Scrubber water flow acts as a means of VOC emissions control. These two charts demonstrate an ethanol plant’s gradual increase in production levels over a 7-year period. As we saw in previous examples, an increase in ethanol production capacity often correlates with an increase in potential VOC emission rates, primarily ethanol.

The plant counteracted this increase in potential VOC emission rates through a corresponding increase in scrubber water flow rates. The overall result shows scrubber water usage more than doubling over the 7-year time frame while VOC emission rates were contained to a relatively stable range of 1.385-4.048 lbs/hr.

Ambient temperature and seasonal variability



Date	Ambient temperature	Scrubber Water Flow Rate	Scrubber pressure differential	Beer feed rate
9/5/19	94°F	91 gpm	9.8 in H_2O	1400 gpm
9/6/19	78°F	105 gpm	9.5 in H_2O	1400 gpm

Above is an example of seasonal temperature variation and its effects on potential VOC emission rate. The plant tested on back-to-back dates in 2019, with the main intention of testing two different chemical additives for HAP control efficiency. However, ambient temperature experienced a sharp drop on the second day of testing, resulting in comparatively lower VOC emissions (primarily ethanol). Note that the facility responded to the high VOC emission rate seen on 9/5/19 by increasing scrubber water flow rate, which could also account for some of the decline in VOCs on 9/6/19.

This dataset and equations were utilized for the model which can be found in Table 1a and Table 1b on page 5 of this document.

Ideal gas:
n= 1 mol
V= 1 L
R= 0.082 (L*atm)/(K*mol)

Antoine's[6]:
Ethanol:
A: 8.20417; B: 1,642.89; C: 230.3

Molar mass of ethanol[5]:
$M_{etoh,Metric}$= 46.07 g/mol
$M_{etoh,Imperial}$= 0.101567 lb/mol

Ethanol Scrubber Inlet Concentration:
Outlet etoh conc. = 129 ppmv
Scrubber efficiency = 0.95
Inlet etoh conc. = 2,580 ppmv
X_{etoh}= 0.00258

T [F]	T [C]	T [K]	P [atm]	P [pa]	C [mol/m^3]	C [lb/ft^3]	*P* [mmHg]
33.8	1	274.15	0.057999	5876.766	11165.86	32.11	12.63
35.6	2	275.15	0.058211	5898.203	11206.58	32.23	13.55
37.4	3	276.15	0.058422	5919.639	11247.31	32.35	14.53
39.2	4	277.15	0.058634	5941.075	11288.04	32.46	15.57
41	5	278.15	0.058845	5962.512	11328.77	32.58	16.67
42.8	6	279.15	0.059057	5983.948	11369.50	32.70	17.85
44.6	7	280.15	0.059269	6005.384	11410.23	32.82	19.09
46.4	8	281.15	0.05948	6026.821	11450.96	32.93	20.42
48.2	9	282.15	0.059692	6048.257	11491.69	33.05	21.82
50	10	283.15	0.059903	6069.693	11532.42	33.17	23.30
51.8	11	284.15	0.060115	6091.129	11573.15	33.28	24.87
53.6	12	285.15	0.060326	6112.566	11613.88	33.40	26.53
55.4	13	286.15	0.060538	6134.002	11654.60	33.52	28.29
57.2	14	287.15	0.060749	6155.438	11695.33	33.64	30.15
59	15	288.15	0.060961	6176.875	11736.06	33.75	32.11
60.8	16	289.15	0.061173	6198.311	11776.79	33.87	34.19
62.6	17	290.15	0.061384	6219.747	11817.52	33.99	36.38
64.4	18	291.15	0.061596	6241.184	11858.25	34.10	38.69
66.2	19	292.15	0.061807	6262.62	11898.98	34.22	41.13
68	20	293.15	0.062019	6284.056	11939.71	34.34	43.70
69.8	21	294.15	0.06223	6305.493	11980.44	34.46	46.41
71.6	22	295.15	0.062442	6326.929	12021.17	34.57	49.26

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[5] https://pubchem.ncbi.nlm.nih.gov/compound/Ethanol
[6] http://ddbonline.ddbst.com/AntoineCalculation/AntoineCalculationCGI.exe?component=Ethanol

T [F]	T [C]	T [K]	P [atm]	P [pa]	C [mol/m^3]	C [lb/ft^3]	*P* [mmHg]
73.4	23	296.15	0.062653	6348.365	12061.89	34.69	52.27
75.2	24	297.15	0.062865	6369.802	12102.62	34.81	55.43
77	25	298.15	0.063077	6391.238	12143.35	34.92	58.75
78.8	26	299.15	0.063288	6412.674	12184.08	35.04	62.25
80.6	27	300.15	0.0635	6434.111	12224.81	35.16	65.93
82.4	28	301.15	0.063711	6455.547	12265.54	35.28	69.79
84.2	29	302.15	0.063923	6476.983	12306.27	35.39	73.84
86	30	303.15	0.064134	6498.419	12347.00	35.51	78.10
87.8	31	304.15	0.064346	6519.856	12387.73	35.63	82.57
89.6	32	305.15	0.064558	6541.292	12428.46	35.74	87.25
91.4	33	306.15	0.064769	6562.728	12469.18	35.86	92.16
93.2	34	307.15	0.064981	6584.165	12509.91	35.98	97.31
95	35	308.15	0.065192	6605.601	12550.64	36.10	102.71
96.8	36	309.15	0.065404	6627.037	12591.37	36.21	108.36
98.6	37	310.15	0.065615	6648.474	12632.10	36.33	114.27
100.4	38	311.15	0.065827	6669.91	12672.83	36.45	120.46
102.2	39	312.15	0.066038	6691.346	12713.56	36.56	126.93
104	40	313.15	0.06625	6712.783	12754.29	36.68	133.70
105.8	41	314.15	0.066462	6734.219	12795.02	36.80	140.78
107.6	42	315.15	0.066673	6755.655	12835.75	36.92	148.18
109.4	43	316.15	0.066885	6777.092	12876.47	37.03	155.91
111.2	44	317.15	0.067096	6798.528	12917.20	37.15	163.98
113	45	318.15	0.067308	6819.964	12957.93	37.27	172.40
114.8	46	319.15	0.067519	6841.401	12998.66	37.38	181.19
116.6	47	320.15	0.067731	6862.837	13039.39	37.50	190.36
118.4	48	321.15	0.067942	6884.273	13080.12	37.62	199.92
120.2	49	322.15	0.068154	6905.71	13120.85	37.74	209.89
122	50	323.15	0.068366	6927.146	13161.58	37.85	220.29
123.8	51	324.15	0.068577	6948.582	13202.31	37.97	231.11
125.6	52	325.15	0.068789	6970.018	13243.04	38.09	242.39
127.4	53	326.15	0.069	6991.455	13283.76	38.20	254.13
129.2	54	327.15	0.069212	7012.891	13324.49	38.32	266.35
131	55	328.15	0.069423	7034.327	13365.22	38.44	279.06
132.8	56	329.15	0.069635	7055.764	13405.95	38.56	292.29
134.6	57	330.15	0.069847	7077.2	13446.68	38.67	306.05
136.4	58	331.15	0.070058	7098.636	13487.41	38.79	320.35
138.2	59	332.15	0.07027	7120.073	13528.14	38.91	335.22
140	60	333.15	0.070481	7141.509	13568.87	39.02	350.66
141.8	61	334.15	0.070693	7162.945	13609.60	39.14	366.70
143.6	62	335.15	0.070904	7184.382	13650.33	39.26	383.36

T [F]	**T [C]**	**T [K]**	**P [atm]**	**P [pa]**	**C [mol/m^3]**	**C [lb/ft^3]**	***P* [mmHg]**
145.4	63	336.15	0.071116	7205.818	13691.05	39.38	400.66
147.2	64	337.15	0.071327	7227.254	13731.78	39.49	418.61
149	65	338.15	0.071539	7248.691	13772.51	39.61	437.23
150.8	66	339.15	0.071751	7270.127	13813.24	39.73	456.55
152.6	67	340.15	0.071962	7291.563	13853.97	39.84	476.58
154.4	68	341.15	0.072174	7313	13894.70	39.96	497.35
156.2	69	342.15	0.072385	7334.436	13935.43	40.08	518.87
158	70	343.15	0.072597	7355.872	13976.16	40.20	541.18
159.8	71	344.15	0.072808	7377.308	14016.89	40.31	564.28
161.6	72	345.15	0.07302	7398.745	14057.62	40.43	588.21
163.4	73	346.15	0.073231	7420.181	14098.34	40.55	612.99
165.2	74	347.15	0.073443	7441.617	14139.07	40.66	638.64
167	75	348.15	0.073655	7463.054	14179.80	40.78	665.18
168.8	76	349.15	0.073866	7484.49	14220.53	40.90	692.64
170.6	77	350.15	0.074078	7505.926	14261.26	41.02	721.04
172.4	78	351.15	0.074289	7527.363	14301.99	41.13	750.42
174.2	79	352.15	0.074501	7548.799	14342.72	41.25	780.78
176	80	353.15	0.074712	7570.235	14383.45	41.37	812.17