Effect Of A Packed-Bed Scrubber Using Radox Catalyst On The Emission of Odors And Volatile Organic Compounds From A Commercial Poultry Rendering Plant

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EXECUTIVE SUMMARY

By-products from meat animal slaughter are often incinerated on-site at the processing facility in thermal treatment systems to reduce the handling and transport of malodorous, and potentially infectious animal by-products. Complete combustion of organic animal by-products (fat, intestinal tract tissue, digesta, feathers, and epidermal layers) liberates non-odorous materials including carbon dioxide, water, nitrogen gas, sulfate, elemental sulfur, as well as malodorous, partially-combusted intermediates including volatile organic compounds (VOC) and trace levels of hydrogen sulfide.

Many animal processing plants have adopted emission abatement strategies in an effort to curb malodorous emissions, and to promote a positive community image. These strategies may include biofiltration, impaction, filtration, wet scrubbers, and chemical oxidation. In this study, we compared the effect of two types of chemical oxidants – chlorine dioxide, and a proprietary Radox catalyst – on reduction of VOC emitted from a packed-bed scrubber installed in a commercial poultry rendering facility in KY.

The Radox catalyst was shown to be significantly more effective than chlorine dioxide (ClO_2) for reducing the concentration of malodorous VOC and total VOC emitted from poultry rendering. Samples from Radox-treated air streams had (**1**) a $42 \pm 14\%$ (the average plus or minus the standard deviation) higher concentration of carbon dioxide (CO_2), (**2**) $69 \pm 9\%$ lower concentrations of the highly malodorous aldehyde compounds, and (**3**) $52 \pm 13\%$ lower total VOC, when compared to untreated, or ClO_2-treated samples. The concentration of highly malodorous aldehyde compounds, which were responsible for a majority of the poultry rendering odor, were not changed by the ClO_2 treatment. Additionally, there was a 5-fold higher concentration of indole in the ClO_2 samples when compared to Radox-treated samples. This is important because indole is a highly odorous metabolite from protein degradation that has an odor threshold of 0.0019 mg/m^3 (Zahn et al., 2001). The Radox treatment reduced the total perceived odor intensity by $74 \pm 19\%$, while the ClO_2 treatment did not significantly alter the odor intensity.

FIGURE 1. Proposed oxidation of volatile organic compounds emitted from poultry thermal rendering waste gas by the Radox catalyst at 66.7° C.
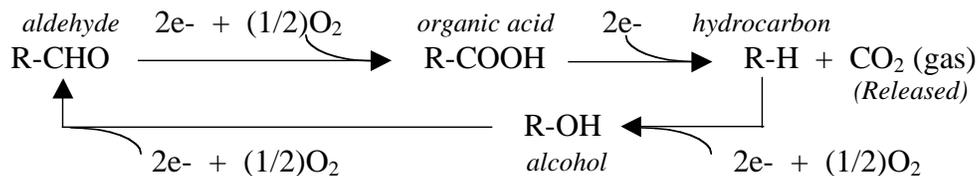
A model was developed to describe the mode of action of the Radox catalyst. In this model, Radox oxidizes VOC through a series of two electron steps, with carbon dioxide gas as the final end product. Low concentrations of alcohols, aldehydes, and volatile fatty acids are evolved as incomplete oxidation products from the Radox catalyst. The oxidation process defined in this model appears similar to the bacterial oxidation of methane, or ammonia, which is catalyzed by metalloenzymes containing copper, heme

and non-heme iron, molybdenum, tungsten, and calcium (Zahn and DiSpirito, 1996; Zahn et al., 1996).

A reaction stoichiometry was estimated by dividing total CO_2 produced (7,554,652,463 relative TIC units) by the total VOC destroyed (5,596,044,830 relative TIC units). The experimentally-derived oxidation quotient (OQ = 1.35) was within 45% of the theoretical OQ value of 2.45. This result is important because it confirms that a major fraction of the VOC destroyed through Radox treatment of rendering waste gas is being converted to the non-odorous gas, carbon dioxide (CO_2).

The overall lower concentration of malodorous aldehyde compounds (69 ± 9%), and lower total VOC (55.9 ± 13%) present in Radox-treated samples were correlated with a 74 ±19% reduction in total percieved odor as measured by total integrated peak area for gas chromatography-olfactometry (GC-O) chromatograms.

PROCEDURES

Odorants were collected on absorbent resins from the waste gas air streams emitted from poultry thermal rendering processes on May 2-3, 2001. Inlet air from the rendering process was passed through a spray condenser and a packed-bed scrubber that contained the proprietary product, Radox. Outlet and inlet air to the Radox packed bed scrubber was sampled simultaneously using ¼" I.D. x 7" Tenax GR absorbent tubes (Gerstel, Baltimore, MD). During air sampling, the inlet air temperature was 77.8° C (172° F) and the outlet temperature was 66.7° C (152° F). Odorants collected on Tenax GR absorbent resin were desorbed (280°C) and cryofocused in a Gerstel cooled inlet system (CIS; minus 50°C) during a 8 minute desorption period, at a desorption flow rate of 10 ml/min. Following complete desorption of the Tenax GR tube, the cooled inlet was purged with helium and then rapidly heated to 280°C. The odorant compounds were transferred and separated by capillary gas chromatography using two separate methods listed below.

Each of these methods used two detectors – the Agilent 5973N mass selective detector and the Gerstel ODP2 olfactory detection port for olfactory analysis by a single human panelist. The detectors were operated in parallel with equal split (0.9 ml/min to 0.9 ml/min) of effluent from the capillary column.

Method 1: Desorbed analytes from the Gerstel cooled injection system (CIS) were transferred at a helium (99.9999%) flow rate of 1.8 ml/min to an Agilent Innowax capillary column (0.25 mm x 30 m). Effluent from the column was split equally between an olfactory detection port and an Agilent 5973 mass spectrometer for odorant and compound identification, respectively. This method was effective for quantification of volatile fatty acids, alcohols, phenols, cresols, and indolic compounds; however, it was less efficient than "Method 2" for quantification of C2-C5 aldehyde compounds.

Method 2: Desorbed analytes from the Gerstel cooled injection system (CIS) were transferred at a helium (99.9999%) flow rate of 1.8 ml/min to an Agilent Plot-Q (divinylbenzene/styrene porous polymer; 0.32 mm x 30 m; #19091P-Q04). Effluent from

the column was split equally between an olfactory detection port and an Agilent 5973 mass spectrometer for odorant and compound identification, respectively. This method was effective for quantification of aldehyde and other VOC with low boiling points.

RESULTS AND CONCLUSIONS

I. Identification of Major Odorants from the Poultry Thermal Rendering Process.
Thirty-three major odorant compounds were detected in three different poultry rendering exhaust air samples using gas chromatography-olfactometry (Method 1). The odorant quality of these compounds varied between pleasant-smelling (e.g., fruity, minty, and celery-like) to highly offensive odorants (e.g., rancid, rancid grease, and fecal-like). Several odorants detected by olfactory method gave neutral responses or could not be assigned to comparative olfactory stimuli (Table 1).

There were five structurally-related odorant compounds exhibiting a chromatographic retention between 2.2 and 3.3 minutes that were found to represent a major portion (>55% in each of the three samples analyzed) of the odor offensiveness in the air samples. The odorant quality for these compounds was identified as either rancid or rancid grease-like and the structural class of these organic compounds was identified as straight or branched chain aldehydes (Table 1). In addition to aldehyde compounds, other minor odorants in the air samples are listed below in order of chromatographic retention (Table 1). Odorant concentration was determined for structurally-assigned compounds using authentic chemical standards, and for unassigned compounds was predicted using chemical standards of the nearest neighboring known compound. The accuracy of this method is considered to be within an error range of 35% (Van Den Dool and Kratz, 1963). The accuracy of determining odorant concentration for structurally-assigned compounds was ± 4% based on the analysis of authentic chemical standards.

Two conclusions were drawn from human olfactory analysis of VOC present in untreated air from the poultry thermal treatment waste gas:

1. Malodorous aldehyde compounds, including propanal, 2-methyl propanal, 3-methyl butanal, pentanal, and 2-methyl pentanal are responsible for over 54% of odors emitted from the poultry rendering process. This conclusion is based integrated peak area for GC-olfactometry chromatograms as described in table 1.

2. Odor remediation strategies for poultry rendering should be specifically targeted on reducing the concentration of aldehyde compounds listed in Table 1.

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TABLE 1. Olfactory and chemical properties of odorants detected in air samples from thermal rendering stack emissions by gas chromatograph-olfactometry-mass spectrometry using method 1 (124 kPa headpressure). * = precursor aldehyde is converted to the corresponding organic acid by the Radox catalyst.

	Retention time (min)	Odorant quality	Odorant structural assignment	Odorant concentration ($\mu g*m^{-3}$)
1	2.034	Neutral	Unassigned	<54
2	2.226	Light, ammonia	N,N-Dimethyl-methanamine	531
3	2.241	Rancid	Acetaldehyde *(precursor to acetic acid)**	1,524
4	2.292	Rancid	Propanal *(precursor to propionic acid)*	637
5	2.458	Rancid	2-Methyl propanal *(precursor to isobutyric acid)*	1,219
6	2.759	Stench, Rancid grease	3-Methyl butanal *(precursor to isovaleric acid)*	1,397
7	2.974	Stench, Rancid grease	Pentanal *(precursor to valeric acid)*	1,071
8	3.086	Rancid grease	2-Methyl pentanal *(precursor to isohexanoic acid)*	584
9	3.369	Mushrooms	Unassigned	<27
10	3.473	Earth	Unassigned	<27
11	3.615	Celery	Unassigned	<54
12	3.795	Stench	3-Methyl-thiopene	55
13	4.373	Sulfur	Diethyldisulfide	19
14	4.674	Popcorn	5-Methyl-2-hexanone	65
15	5.605	Musty leaves	2-Pentyl-furan	79
16	5.793	Dandelions	Below MS detection	-
17	6.425	Fecal	Nonanal	159
18	6.556	Cucumber	Unassigned	<27
19	6.699	Neutral	Unassigned	<27
20	6.934	Neutral	Unassigned	<27
21	7.177	Neutral	Unassigned	<27
22	7.334	Neutral	Unassigned	<27
23	7.660	Neutral	1-Heptanamine	49
24	7.844	Neutral	Below MS detection	-
25	8.081	Neutral	Benzaldehyde	106
26	8.525	Neutral	Unassigned	<27
27	9.143	Acidic	Acetic acid	76
28	9.808	Acidic	Propionic acid	49
29	11.241	Stench	Butanoic acid	52
30	14.936	Neutral	Unassigned	<14
31	15.210	Neutral	Unassigned	<14
32	15.464	Neutral	Below MS detection	-

| 33 | 17.946 | Heavy, mothballs | Indole | 22 |
| 34 | 19.486 | Neutral | Below MS detection | - |

II. Effect of Radox treatment on diversity of volatile organic compounds emitted in air from a combustion poultry rendering process. Fifteen air samples collected in the study were separated into five groups with 3 samples in each group: "Radox Only", "chlorine dioxide (ClO_2) + Radox", "chlorine dioxide (ClO_2)", "Non-Condensable", and "Force Flash". The name of each compound was assigned using the commercially available Wiley 6th edition spectral library and spectral similarity-matching algorithms. Identities were confirmed by injection of authentic chemical standards for each of the unknowns.

Information concerning identity of individual compounds was compiled into a composite list of volatile organic compounds to identify common or unique volatile organic compounds associated with each treatment process (see Table 2). Four conclusions were drawn from these results:
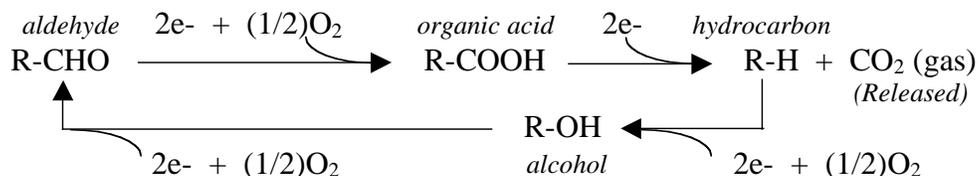
1. The triplicate analysis (different sample volumes) showed that replicate samples were highly similar in VOC profiles (i.e., highly reproducible).

2. Samples labeled "chlorine dioxide (ClO_2)" contained a higher total odor concentration (measured by GC-O), greater diversity in the types of VOCs present when compared to "ClO_2 plus Radox", and no significant reaction intermediates. This result shows that ClO_2 is ineffective in reducing the concentration malodorous aldehydes and other VOC in the waste gas stream from poultry rendering.

   There was a higher concentration of indole in the ClO_2 samples when compared to the samples from the Radox treatment. This is important because indole is a highly odorous metabolite from protein degradation that has an odor threshold of 0.0019 mg/m^{3} (Zahn et al., 2001). The indole levels in these samples were 5-fold higher than the "chlorine dioxide (ClO_2) + Radox" samples, were 2-fold higher than "force flash" samples, and were 2.3-fold lower than the "non-condensable" samples (Table 2).

3. The "non-condensable" VOC samples (untreated exhaust stream from the combustion furnace) contained the highest concentration and greatest diversity for many of the VOC compounds that were detectable by gas chromatography-mass spectrometry.

4. Samples labeled "1" "2", and "3" "Radox only" were chemically similar to the "chlorine dioxide (ClO_2) + Radox" samples. These samples had (1) 42% higher concentrations of CO_2, (2) an average of 46% higher concentrations of volatile fatty acids, (3) an average of 70% lower concentrations of the highly malodorous aldehyde compounds, and (4) 56 - 71% lower total VOC, when compared to control, or ClO_2 treatment samples (see section 3).

These results show that the Radox treatment process is significantly more effective than chlorine dioxide for reducing the concentration of highly malodorous aldehydes from poultry rendering. Secondly, the concentration of carbon dioxide, volatile fatty acids, certain alcohols, and aldehydes were found to be higher in the Radox-treated air, while the concentration of total aldehydes (Table 2 and 3) and total VOC (Table 3) were reduced in the Radox-treated air.

FIGURE 1. Proposed oxidation of volatile organic compounds emitted from poultry thermal rendering waste gas by the Radox catalyst at 66.7° C.

$$\textit{aldehyde} \quad 2e\text{-} + (1/2)O_2 \quad \textit{organic acid} \quad 2e\text{-} \quad \textit{hydrocarbon}$$
$$R\text{-}CHO \longrightarrow R\text{-}COOH \longrightarrow R\text{-}H + CO_2 \ (gas)$$
$$(Released)$$
$$R\text{-}OH$$
$$2e\text{-} + (1/2)O_2 \qquad \textit{alcohol} \qquad 2e\text{-} + (1/2)O_2$$

A model was developed to describe the mode of action of the Radox catalyst. In this model, Radox oxidizes VOC through a series of two electron steps, with carbon dioxide gas as the final end product. Carbon dioxide gas is liberated spontaneously due to a combination of the elevated temperature in the packed-scrubber, and the presence of the Radox catalyst. Low concentrations of alcohols, aldehydes, and volatile fatty acids are evolved as incomplete oxidation products from the Radox treatment process.

The overall lower concentration of malodorous aldehyde compounds ($69 \pm 9\%$), and lower total VOC ($55.9 \pm 13\%$; Table 3) present in Radox-treated samples were correlated with a $74 \pm 19\%$ reduction in odor as measured by total integrated peak area for gas chromatography-olfactometry-mass spectrometry (GC-O-MS) chromatograms. These observations provide additional support for the proposed model, in which the Radox catalyst oxidizes volatile organic compounds through a series of two electron steps to the final end product, carbon dioxide. In contrast, the samples for the chlorine dioxide treatment did not show oxidation product intermediates, indicating that it was ineffective in oxidizing odorant compounds to less odorous gases. The total VOC emissions from the chlorine dioxide treatment source were not significantly different from the controls (force flash and non-condensable samples), which indicated that the chlorine dioxide treatment was not effective.

Low molecular weight aldehyde compounds (acetaldehyde, propionaldehyde, isovaleraldehyde, isocaproaldehyde) were not completely resolved on the capillary column using method 1. Studies on the hypo-bromous acid treatment process using a porous polymer chromatography column showed that the poultry rendering process produced extremely high concentrations of acetaldehyde, propionaldehyde, and isobutyraldehyde. Section 1 of these report demonstrated that these aldehyde compounds were responsible for a major (>50%) fraction of the odors released from poultry rendering. Improved resolution of aldehydes was therefore necessary, and was completed using a porous polymer capillary column (i.e., Plot-Q; divinylbenzene/styrene porous polymer) as described in analytical Method 2, and discussed in section 3 of the "Results and Conclusions".

TABLE 2. Qualitative and quantitative analysis of 68 volatile organic compounds in untreated air (non-condensable, NC, and force-flash, FF) and treated air (chlorine dioxide catalyst (ClO$_2$), and/or Radox) emitted from poultry rendering. Analytical characterization using method 1 (119 kPa head pressure).

Volatile organic compound and chromatographic retention (min)	Sample identity				
	Volatile organic compound presence and concentration ($\mu g*m^{-3}$)				
	NC	FF	ClO$_2$	ClO$_2$ + Radox	Radox Only
Carbon Dioxide (2.18)					
2-Butanone (2.31)		-			
Carbon Dioxide (2.34)					
Acetaldehyde (2.41)	(1,674)	(1,350)	(1,396)	(690)	(428)
Propionaldehyde (2.55) (IUPAC name = propanal)	(849)	(905)	(792)	(199)	(180)
Toluene (2.73)					
Isobutyraldehyde (2.79) (IUPAC name = 2-methyl propanal)	(1,470)	(1,564))	(1,399)	(109)	(87)
Dimethyl disulfide (2.92)		-			
Isovaleraldehyde (2.99) (IUPAC name = pentanal)	(1,166)	(1,189)	(1,194)	(620)	(511)
2-Methylthiophene (2.92)	-		-		-
Methy ethyl disulfide (3.21)	-		-		
5-Methyl-2-heptanone (3.49)	-	-	-		
Limonene (3.54)			-		-
2-Pentyl furan (3.75)			-		
1-Butanol (3.79)	-		-	-	-
1-Methyl-2-isopropyl benzene (4.14)		-	-	-	-
2-Octanone (4.30)			-		-
Methyl thiazole (4.54)	-		-	-	
4-Methyl-1-pentanol	-	-	-	-	
Methylethenyl-benzene (4.67)	-		-	-	-
3-Hexanone (4.84)	-		-	-	-
1-Hexanol (5.00)	-			-	
Dimethyl trisulfide (5.30)		-			
2-Nonanone (5.30)			-	-	-
2-Hexanone (5.48)	-	-	-		-
2-Butoxy-ethanol (5.58)	-		-	-	-
3-Ethyl-2-methyl-1,3-hexadiene (5.76)		-	-	-	-
1-Heptanol (6.02)			-	-	-
Acetic acid (6.11)	-	(35.08)	(79.51)	(833.3)	(1177.4)
2-Ethyl hexanol (6.37)	-				
Tetradecane (6.50)	-	-			-
2-Decanone (6.52)		-	-		-
n-Heneicosane	-	-	-		-
Octanenitrile (6.66)	-		-	-	-
Pyrrole (6.81)		-	-	-	-
Benzaldehyde (6.94)					
Propionic acid (7.09)	-	(17.87)	(44.60)	(1135.20)	(1369.4)

Compound					
1-Octanol (7.13)	-		-		
Isobutyric acid (7.31)	-	-			
Trans-caryophyllene (7.60)		-	-	-	-
n-Heneicosane (7.61)	-	-	-		-
Benzonitrile (7.83)	-	-			
Butyric acid (8.03)			-		
3,5-Diisopropylpyridine (8.12)	-		-	-	-
Acetic acid-decyl ester (8.27)	-		-	-	-
Tetrahydrothiophen-3-one	-	-		-	-
1-Phenyl ethanone (8.33)			-	-	
Isovaleric acid (8.40)	-	(21.60)	(32.21)	(606.74)	(1171.2)
2-Furanmethanol (8.42)			-	-	-
n-Heneicosane (8.70)	-	-		-	-
5-Octadecene (8.92)	-	-		-	-
2-Furancarboxylic acid (9.05)	-		-	-	-
Valeric acid (9.19)	-	-			-
Naphthalene (9.32)	-	-		-	-
, -Dimethyl benzenemethanol (9.42)	-				
2-Phenyl-2-propanol (9.43)	-		-	-	-
Isocaproic acid (9.87)	-	-	-		
Caproic acid (10.31)	-	-	-		-
Ethyl-3-phenylpropionate (10.74)		-	-	-	-
Heptanoic acid (11.39)	-	-	-		-
Benzothiazole (11.54)	-	-			-
Phenol (12.00)					
p-Cresol (12.74)				-	-
3-Phenyl thiophene		-	-	-	-
2-Piperidinone (13.35)	-	-			
N,N-Dimethyl benzamide (13.55)	-			-	-
Hexadecanoic acid-ethyl ester (14.20)	-	-	-		
Indole (16.02)	(29.08)	(5.34)	(12.78)	(2.07)	(0.31)
3-Methyl indole (16.39)	-	-	-	-	-

$^=$ Control stream samples = (NC = Non-condensable samples; FF = Force flash samples); Treatment stream samples = (ClO_2 = Chlorine dioxide-treatment samples; ClO_2+R = Chlorine dioxide plus Radox-treatment samples; "Radox Only" Samples labeled 1 through 3 on the sampling tube).
and (##) = compound was detected in air samples, and the (concentration) of select organic compounds in $\mu g*m^{-3}$.

III. Measured abatement efficiency of VOC emissions using the Radox - packed-bed scrubber treatment process: Chromatography Method 2. Emission measurements of VOC indicated that the Radox treatment significantly reduced the concentration of VOC emitted in the exhaust air from the poultry rendering process. The VOC abatement efficiency for the Radox treatment was determined by direct comparison of integrated peak area for total ion current chromatograms for inlet air from the rendering process, and outlet air that was passed through a packed-bed scrubber that contained the Radox catalyst. A second study using analytical method 1 was performed to further investigate the Radox mechanism of action.

The Radox treatment reduced the concentration of 69 of the 97 VOC detected by gas chromatography-mass spectrometry in inlet air to the packed-bed scrubber containing Radox (Table 3). Forty-eight of these VOC that were reduced in concentration by the Radox process were reduced below detection of GC-MS (>99% destruction efficiency; Table 3). Twenty-seven of the 97 compounds were found at higher concentrations in exhaust air (these are the reaction intermediates generated by the Radox-catalyzed oxidation) from the Radox process than in inlet air entering the packed-bed scrubber. Twenty-six of these 27 compounds were below detection in the inlet air, but were easily detected in exhaust air from the packed-bed scrubber (produced from the Radox process and denoted as the letter "P").

Compounds that were produced (P) by the Radox process were separated into two subcategories, P1: Compounds produced by the Radox catalyst through an unknown mechanism; and P2: Compounds produced by the Radox catalyst that are consistent with the reaction model proposed in Figure 1. The criterion for designation as "P2" was that the compound had to fall into one of the four reaction intermediate classes: (1) organic acid, (2) aldehyde, (3) alcohol, or (4) ketone. Seven of the 26 compounds (27%) were separated into the P1 class, while the remaining 19 compounds (73%) were considered reaction intermediates (P2) from the Radox treatment.

Organic acids represented the largest (>70%) fraction of reaction intermediates produced from the Radox catalyst. This result was expected because aldehyde compounds were the most significant air pollutant, both from the perspective of total mass and odorant intensity that were emitted in untreated air from the poultry rendering stack. Mass balance estimates based on data in Table 3, however, demonstrated that the total aldehyde concentrations in inlet air was 43% higher than the concentration of the corresponding organic acids in the outlet from the Radox packed-bed scrubber. This result suggested that aldehydes were not simply being converted to their corresponding organic acids, but were being transformed to other compounds (i.e., CO_2).

To further address this point, a reaction stoichiometry for the Radox treatment process was performed using an average molecular weight for VOC emitted from the thermal rendering of poultry by-products. This reaction stoichiometry was based on an average molecular weight of VOC as 70 g/mole [75% carbon] and CO_2 as 44 g/mole. If one mole of VOC was completely oxidized to CO_2, the oxidation reaction would liberate 2.45 moles of CO_2 [((70 g VOC/mole VOC x 0.75 carbon/mole VOC)/12 g carbon/mol)) x 0.559 Radox VOC destruction efficiency]. Detector response for the 5973N mass spectrometer was similar for compounds listed in Table 3, and therefore, a reaction stoichiometry was estimated by dividing total CO_2 produced (7,554,652,463 relative TIC units) by the total VOC destroyed (5,596,044,830 relative TIC units). The experimentally-derived oxidation quotient (OQ = 1.35) was within 45% of the theoretical OQ value of 2.45, which confirmed that a major fraction of the VOC destroyed through Radox treatment of rendering waste gas was converted to CO_2.

Measurements of CO_2 liberated from the packed-bed scrubber were considered to be conservative due to the low efficiency for capture of CO_2 (low break-through volume for

absorbent) by the absorption tube sampling method. Break-through volume decreases proportionally to the concentration of CO_2 in the sample, and therefore, at higher concentrations, the reported CO_2 concentrations become less reliable. Due to these sampling issues, the true value for the experimentally-derived OQ value is likely to be more similar to the theoretical value of 2.45. Future studies should be conducted using direct measurement techniques (infrared spectrometry, magnetic sector mass spectrometry), or Tedlar bag grab sampling and packed-column gas chromatography to improve the accuracy of CO_2 measurements.

TABLE 3. Effect of a scrubber using Radox on the concentration of 97 individual volatile organic compounds released from a poultry rendering process. The comprehensive VOC table contains low-level analytes that were omitted from the analysis presented in Table 2. Data reported as the mean from three separate samples using analytical method 2 (119 kPa head pressure). Negative values and those designated "P" for "percent reduction" represents compounds that increase in concentration, or are produced by the Radox treatment. See the table footer for P1 and P2 designations.

Compound	Retention time (min)	Inlet (TIC area)	Outlet (TIC area)	Percent reduction (%)
Carbon dioxide (*non-VOC*)	2.01	13134935622	20221426841	**-35**
2-Butanone	2.26	3165863859	748646422	76.4
Carbon dioxide (*non-VOC*)	3.31	503007383	971168627	**-48.2**
Acetaldehyde	2.39	622846387	210418705	66.2
Propionaldehyde	2.57	52242705	13739832	73.7
Toluene	2.72	1326929924	155502567	88.3
Isobutyraldehyde	2.81	154360516	1512733	99
Dimethy disulfide	2.89	-	110437844	P
Isovaleraldehyde	3.08	900614284	522348193	42
3-Methyl-pentanal	3.33	-	28885148	P
Limonene	3.44	166198440	99502768	40.1
2-Pentyl-Furan	3.64	230197886	75960330	67.0
1-Butanol	3.80	224808309	-	>99
1-Methyl-2-isopropyl benzene	4.01	181630379	-	>99
1,3,5,7-Cyclooctatetraene	4.08	-	39822601	P
Octanal	4.34	-	27326559	P
2-Octanone	4.30	143990027	-	>99
Methyl-thiazole	4.54	72271645	27650581	61.7
(1-Methylethenyl)-benzene	4.66	81996537	-	>99
Heptenal	4.75		8409375	P
3-Hexanone	4.84	73471103	-	>99
3-Ethyl-2,5-dimethyl-1H pyrrole	4.85	-	8128467	P
1-Hexanol	5.00	177265792	20310954	88.5
2-Nonanone	5.30	248526114	-	>99
Nonanal	5.37	-	62627937	P
2-Butoxy-Ethanol	5.58	150618375	-	>99
2-Dodecenal	5.82	-	10145775	P
Methylphloroglucinol	5.94	81655557	-	>99

Heptanol	5.96	142176298	-	>99
Acetic acid	5.98	-	547594300	P
2-Methyl-decane	6.27	32584168	-	>99
2-Ethyl-hexanol	6.38	98017693	62660563	36.07
2-Decanone	6.57	72882507	-	>99
Octanenitrile	6.66	60660850	-	>99
1,2-Dimethyl-hydrazine dichloride	6.70	-	9171738	P
Pyrrole	6.80	43230024	11640327	73.07
Benzaldehyde	6.93	130552411	-	>99
Propanoic acid	7.03	54018059	116186040	-115.09
1-Octanol	7.14	66320247	-	>99
2-Methyl-pyrrole	7.21	36157503	-	>99
Isobutyric acid	7.25	-	539349320	P
3-(Methylthio)-1-propene	7.35	28561569	-	>99
3-Acetyl-6-methyl-2H-pyran-2,4(3H)-dione	7.48	28361999	-	>99
Trans-caryophyllene	7.58	27895773	-	>99
2,5-Dimethyl-1H-pyrrole	7.71	25308664	-	>99
Benzonitrile	7.82	23810263	23378689	1.81
1-(Methoxy-3-pyranzinyl)-1-ethanone	7.93	14892316	-	>99
Isobutyric acid	7.99	-	12167687	P
Butyric acid	8.00	64111387	-	>99
1-Phenyl-ethanone	8.33	158713051	-	>99
Isovaleric acid	8.40	-	731754397	P
2-Furanmethanol	8.40	72900382	-	>99
9-Octadecyne	8.57	23207240	-	>99
Trans-(-)-5-methyl-3-(1-methylethenyl)-cyclohexene	8.72	17906118	-	>99
5-butyl-3-methyl-1,2,3-8A-tetrahydroindolizine	8.87	36050419	-	>99
2-Furancarboxylic acid	9.06	44551918	-	>99
Valeric acid	9.18	13270767	10657070	19.70
Naphthalene	9.27	13541945	5243074	61.28
, -Dimethyl benzenemethanol	9.43	109559896	9756225	91.10
Acetamide	9.60	-	7628787	P
N,N-dibutyl-Formamide	9.61	16734841	-	>99
1-Piperidinecarboxaldehyde	9.72	12687009	-	>99
4-Methyl-pentanoic acid	9.88	57698704	38644484	33.02
Caproic acid	10.31	-	16587261	P
Methylnapthalene	10.45	8157746	-	>99
1,2-Benzenedicarboxylic acid	10.61	28078375	-	>99
Benzenemethanol	10.72	-	9381071	P
Ethyl 3-	10.74	8425789	-	>99

phenylpropionate				
5-isopropyl-4-phenyl-3-hydroxy-1,2,4-Triazole	10.87	9973954	-	>99
Benzeneethanol	11.09	12717398	-	>99
2-Ethylhexanoic acid	11.35	8200937	-	>99
Heptanoic acid	11.39	-	6882761	P
Benzothiazole	11.55	17215119	5044136	70.70
2,5,8,11,14-Pentaoxahexadecan-16-ol	11.84	7051843	-	>99
Phenol	12.00	62103620	17940265	71.11
4-Hydroxydodecanoic acid lactone	12.27	3855261	-	>99
Octanoic acid	12.44	-	2568781	P
2-Pyrrolidinone	12.44	6530866	-	>99
3-acetyl-4-hydroxy-2(5H)-Furanone	12.52	-	3562707	P
p-Cresol	12.74	48854030	3948475	91.92
Piperidinone	13.35	-	7940500	P
1-isocyanato-Octadecane	13.35	5626101	-	>99
Nonanoic acid	13.43	-	2042096	P
N,N-dimethyl-Benzamide	13.55	-	5876509	P
4-Carboxamidonicotinic acid	13.56	10861186	-	>99
4-Vinyl-2-methoxy-phenol	13.82	3319794	-	>99
3-Phenyl -Thiophene	14.06	-	9673862	P
Decanoic acid	14.17	100314425	-	>99
Pentadecanoic acid	14.19	-	2716120	P
1,6-Dioxacyclododecane-7,12-dione	14.87	-	3608968	P
1-Heptadecanol	15.33	-	4323434	P
Thiosulfuric acid	15.33	23837911	-	>99
Benzoic acid	15.83	4455828	2112619	52.59
Indole	16.02	41361145	5720122	86.17
Lycopersen	17.69	3331154	-	>99
(Z)-9-Octadecenoic acid	17.83	2453643	-	>99
(Z)-9-Octadecenoic acid	18.68	3775678	-	>99
Hexanedioic acid	18.89	830346	-	>99
Total TIC Area		**10,003,184,010**	**4,407,139,179**	**55.9% Reduction***

"-" = Not detected.

P1 = compound was not detected in inlet air and is presumably produced by the Radox treatment process through an unknown mechanism.

P2 = compound was not detected in inlet air and is presumably produced by the Radox treatment process through chemical oxidation of organic compounds.

* = data reported as the mean from three separate samples.

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