Flaring Hot Spots

A CBE Report

Assessment of episodic local air pollution associated with oil refinery flaring using sulfur as a tracer

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CBE

Founded in 1978, **Communities for a Better Environment** (CBE) is an environmental health and justice organization that works with urban communities directly affected by industrial pollution. CBE provides organizing skills and legal, technical and scientific resources that assist communities in taking control of the decisions that affect their quality of life. We believe that environmental health is a human right, fundamental change comes from the grass roots up, and that environmental solutions can only be sustained in concert with social and economic justice.

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Summary and discussion

This report documents localized episodic air pollution associated with flaring by Bay Area oil refineries. The new findings are timely, because on July 20, 2005, the Bay Area Air Quality Management District plans to consider adopting what could become the first rule in the nation that comprehensively targets refinery gas disposal in flares.

When refineries flare, nearby residents report foul odors, burning eyes and asthma attacks, among other symptoms of exposure to episodic air pollution. Oil refiners, however, dispute the need for enforceable flare control rules. Their spokespeople point to smog problems in areas miles from the refineries and say that automobile emissions, not refinery flares, cause most of that smog. Meanwhile, data from years of continuous monitoring at refinery fence lines for two pollutants emitted by flares–sulfur dioxide and hydrogen sulfide–sit ready for comparison with the new monitoring of flare emissions that has been required by the Air District in recent years.

This report assesses whether newly available data 1) support community observations of episodically elevated air pollutant exposures associated with flaring, 2) identify changes in flaring that affect local air quality, and 3) support a quantitative estimate of locally increased episodic air pollution caused by flaring. Its purpose is to provide new information on these issues to the public and public officials as the Air District considers its proposed flare control rule. Flare data needed for comprehensive comparisons across the five refineries were reported only recently. CBE first received the fence line air data analyzed here in June, 2005. To our knowledge, this is the first assessment pairing these emission and air quality data.

The report assesses flare data over a cumulative five-refinery total of 3,233 days during parts of 2001 and 2002 and from January 1, 2004–March 31, 2005. It matches these data with 510,978 hourly data from 35 ground-level monitors at the refinery fence lines and 3,675 daily maximum-hour data from five ambient air monitoring network stations near three refineries. It assesses whether this official monitoring record supports community observations of an episodic pollution problem caused by flaring, by comparing changes in flare emissions with changes in sulfur dioxide and hydrogen sulfide concentrations at the two types of monitoring locations using analysis of maxima, percentiles, ranks, probability analysis, and regression analysis.

These data and analyses support five major findings:

Finding 1. During major flaring at two refineries, ambient monitoring network stations in nearby communities, but set away from the refinery fence lines, measured sulfur gases in the air at record-high levels for those stations while ground-level monitors closer to the flares measured even higher levels at the refinery fence lines. These fence line monitors consistently recorded higher maximum levels of sulfur gases than the ambient network stations. This evidence documents episodic air pollution hot spots near the fence lines of these refineries, and implicates flaring as a major source of episodic air pollution.

Finding 2. Each refinery flared on the very day when sulfur pollution reached its record-high level in the air near that particular refinery. At four refineries, the 28 highest daily maximum-hour concentrations were all recorded on days when the refinery near that monitor flared. The probability that this occurred because of random chance alone is less than one in a billion.

Finding 3. Increasing sulfur dioxide concentrations in the air near four refineries are associated with increasing sulfur emissions from their flares. This association is significant at the 99% confidence level for flare emissions concentration ($p = 0.0001$) and mass ($p = 0.0013$), and applies to the highest eight percent of daily maximum-hour concentrations during 2004 and early 2005 at the Chevron, ConocoPhillips, Tesoro and Valero refineries.

Finding 4. Continued flaring at current rates can be predicted to increase highest daily maximum-hour sulfur dioxide concentrations near refinery fence lines by an average of about 50%. This estimate is based on the findings above, and on a comparison of the highest hourly concentrations measured near four refineries when no flaring occurred with the higher levels measured on days the refinery flared.

Finding 5. Except for sulfur dioxide and hydrogen sulfide, present monitoring can not detect and quantify any of the other toxic pollutants in episodic flare plumes at most refinery fence lines–and health risk can not be estimated accurately while ignoring unmeasured pollutants. Until these other pollutants are monitored continuously at refinery fence lines, sulfur can be used as a tracer for the short-term movement of flare plumes to the refinery fence line. This analysis suggests that flares cause episodic local exposures to many pollutants.

The findings support the adoption of enforceable requirements to prevent and reduce flaring as a matter of environmental justice for disproportionately impacted low-income communities on refinery fence lines. Bay Area refinery flaring impacts local air quality. Analysis based on data from 2004 and early 2005 shows that these impacts are ongoing.

This report sheds new light on key policy details as well. The analysis supporting Finding 3 found that pollutant mass and concentration in flare emissions predicts changes in local air quality caused by a flaring episode more reliably than does the volume of gases flared. Requirements based on flare gas volume alone–such as the proposed 500,000 cubic feet/day trigger for remedial investigation (root cause analysis) of flare episodes–are not a reliable substitute for a limit on the concentration of sulfur in the fuel gas that is flared. This supports requirements to limit the sulfur concentration allowed in fuel gas flared, and to perform root cause analysis of high-mass emission flaring–especially at low gas flows.

Lastly, the findings suggest an issue for future assessment. The data might be used to confirm the effectiveness of efforts to stop unnecessary flaring in cleaning up local air quality. CBE received the ground-level monitor data assessed in this report recently, and could not complete this last assessment before the July 20, 2005 policy decision.

Scope, data, methods and limitations

This report compares measurements of flaring activity and intensity at five major Bay Area refineries with the continuous monitoring of two pollutants in the air near the plants to assess flaring impacts on local air quality. It assesses whether these data 1) support community observations of episodically elevated air pollutant exposures associated with flaring, 2) identify changes in flaring that affect local air quality, and 3) support a quantitative estimate of locally increased episodic air pollution caused by flaring.

The purpose of the report is to provide new information on these issues to the public and public officials as the Bay Area Air Quality Management District (BAAQMD) considers adoption of the first emission control rule comprehensively targeting the use of flares for refinery gas disposal. Flare data needed for comprehensive comparisons across the five refineries were reported only recently, and the fence line air data in this report were first obtained by CBE in June, 2005. To our knowledge, this is the first assessment pairing these emission and air quality data.

Data are from four sources. Flare data for the period from January 1, 2004 through March 31, 2005 are from refiners' reports under new BAAQMD Rule 12-11. Flare data for the period before Rule 12-11 are from the BAAQMD Technical Assessment Document for further study of flares. Hourly average ambient air monitoring data from sulfur dioxide (SO_2) and hydrogen sulfide (H_2S) measurements at ground-level monitors (GLMs) around the refinery fence lines are from BAAQMD documents provided for CBE's review pursuant to the California Public Records Act. Daily maximum-hour data for these pollutants that were collected at ambient air quality monitoring network stations, established by air quality agencies, operating near three of the refineries during the period studied are from Air Resources Board (ARB) public data reports.

Descriptive statistics summarizing these data are shown in Table 1 below. Air data from monitors near each refinery are included for the same dates when daily data on flare gas flow and sulfur content are available from that refinery. The period of this comparison starts earlier for the Chevron-Richmond and ConocoPhillips-Rodeo/Crockett comparisons because flare data reporting including sulfur data began earlier for these plants.

Review of Table 1 reveals large data sets. Flare activity and nearby ambient concentrations of SO_2 and H_2S were monitored continuously across five refineries and 40 monitors for a cumulative total of 3,233 days. Flaring was reported on 1,895 of these days. Volumes of refinery gases flared, flare sulfur data, and hourly average air concentrations are used in the comparisons.

Data were compared across the entire time periods shown in Table 1, and for the period from January 1, 2004 through March 31, 2005. These daily flaring data are matched with the

Table 1. Summary description of data used in this report.

	Chevron	ConocoPhillips	Shell	Tesoro	Valero
Period flare gas & sulfur data reported	5/1/01-7/8/02 & & 1/1/04-3/3105	1/1/02-8/31/02 & 1/1/04-3/3105	6/1/02-8/31/02` & 1/1/04-3/3105	6/1/02-8/31/02 & 1/1/04-3/3105	6/1/02-8/31/02 & 1/1/04-3/3105
Total days	890	699	548	548	548
Flare days	317	238	548	350	442
Ground-level SO_2 monitors	3	7	1	3	3
Hourly data	61,448	85,593	—	38,889	38,705
Ground-level H_2S monitors	3	4	4	4	3
Hourly data	61,584	80,811	52,414	52,078	39,456
Ambient net-work SO_2 stn.	7th Street Richmond	Kendall Ave.. Crockett	Jones Street Martinez	None nearby	None nearby
Max/day data	890	695	546	0	0
Ambient net-work H_2S stn.	7th Street Richmond	Crockett &/or Rodeo 3rd St.	None nearby	None nearby	None nearby
Max/day data	882	662	0	0	0

Flare data from BAAQMD Technical Assessment Document and Rule 12-11 reports. GLM data from BAAQMD response to Public Records Act request. Network monitoring data from ARB. Daily data in appendices 1-6.

daily maximum-hour SO_2 and H_2S concentrations measured near each refinery. All data inputs to this analysis are data as reported in the four data sources discussed above. Data inputs were double-checked for accuracy. All data inputs for each analysis were checked by the primary researcher. A random sample of the input data base was then checked independently by a second researcher. Both checks supported the accuracy of data inputs to the analysis. The daily data are shown for each refinery in appendices 1-5. Hourly data assessed for one flaring episode are shown in Appendix 6.

Analysis was done in three ways. First, air concentrations at ground-level monitors were compared with those at nearby ambient network stations to identify patterns in air quality related to flaring. Second, air concentrations measured at monitors near each refinery on days when the refinery flared were compared with those measured at the same location on days when no flaring was reported at the plant. Patterns identified from this second comparison were assessed for significance using probability analysis. Third, changes in SO_2 concentrations near each refinery were compared with changes in its flare gas flow, sulfur mass emission, and emission concentration using regression analysis. This third comparison was performed on the highest 10th Percentile of air concentration data, to elucidate effects at high pollution levels. SO_2 is the major sulfur compound expected in flare emissions, and results of the other analyses suggest that limitations in the data are less likely to mask any real effects of changes in flaring on SO_2 than on H_2S.

The data are limited by the number of air monitoring locations, the accuracy of the flare emission estimates, and the number of pollutants measured. Too few nearby monitors are in place to ensure that all the flare plumes are detected. There is no appropriately situated ambient monitoring network station near the Tesoro or Valero plants. No network station near Shell measures hydrogen sulfide, and the Shell refinery has only one SO_2 GLM. False-negative results are apparent in the data for some periods during large flaring episodes, and the association between flaring and air quality appears less robust at refineries with fewer monitors. In the most extreme case, the lone ground-level SO_2 monitor at Shell never detected measurable SO_2 despite episodically elevated H_2S concentrations at Shell's H_2S GLMs, episodically-elevated SO_2 at the nearby network station, and occasional major flaring. Shell's flare emission pattern also differs from those of other refiners, and it flared virtually every day in the flare data period. Since there is no other SO_2 GLM at Shell, these apparently conflicting data for Shell are difficult to interpret.

Because of these limitations, the comparison of GLMs with corresponding network stations is limited to the Chevron-Richmond and ConocoPhillips-Rodeo/Crockett data sets, and data on nearby air quality could not be analyzed for days when Shell did not flare.

Flare data accuracy for the period before January 2004 is inconsistent, and though flare gas volume is reported hourly starting in 2004, data for fuel gas quality and sulfur are reported as daily averages throughout the flare data period in most cases. Due to these limitations regression is performed using the 2004-2005 data, and using daily rather than hourly data.

Lack of flare combustion efficiency measurements–a problem in estimating hydrocarbon emissions–is not a significant limitation for this analysis because flare combustion does not destroy sulfur. Both SO_2 and H_2S emit from flares, with SO_2 the major sulfur compound emitted unless combustion efficiency is very poor. While a drop from 98% to 96% combustion efficiency results in doubling hydrocarbon emissions, it should cause only a small drop in the percentage of sulfur compounds emitted as SO_2, and no change in total sulfur emissions.

The ground-level monitors do not measure any other pollutant in flare emissions besides SO_2 and H_2S. Flares emit smog-forming hydrocarbons, nitrogen oxides, and toxic chemicals such as benzene, toluene, xylenes, carbon-disulfide, PAHs, mercury, carbon monoxide, particulate matter and other air pollutants. The health threat from flaring is the cumulative toxicity of all the pollutants emitted, and it is not appropriate to ignore unmeasured pollutants, so this is a significant limitation in the data. Fortunately, this limitation can be mitigated because different gases may be expected to move initially from a stack to a nearby receptor along similar paths–and SO_2 and H_2S are measured at fence line as gases. The crucial point: sulfur gases can serve as a tracer for other toxic gases in flare plumes at the fence line.

Concentrated episodic air pollution near refineries

Maximum hourly-average air pollutant levels (highest hour of the day) are higher at refinery fence line monitors than at comparable nearby ambient monitoring network stations.

Table 2 below compares statistics describing the highest daily maximum-hour concentrations measured at two refiners' ground-level monitors with those measured at the network station near each refinery. It compares sulfur dioxide (SO_2) concentrations, then compares levels of hydrogen sulfide (H_2S). Chevron GLM levels are three times network monitor levels for both pollutants. ConocoPhillips GLM levels are twice the network levels for SO_2 and 50-254% higher for H_2S. Averaged across all statistics in Table 2, the fence line monitor levels are 248% higher than the network monitor levels.

These data reveal episodically elevated maximum pollution levels at the refiners' fence lines.

A pollution gradient extends from the fence lines of these two refineries to the ambient network stations. On 16 of the 20 days when the highest daily maximum-hour SO_2 levels were found at the Richmond and Crockett stations, maximum-hour SO_2 levels were higher at the GLMs, and on 12 of these days the refinery near the station flared. These 12 days include the single highest maximum daily hour for SO_2 at each network station, as detailed below.

Table 2. Highest daily maximum-hour sulfur dioxide and hydrogen sulfide concentrations at ground-level monitors and ambient air quality monitoring network stations where both types of stations are located near a refinery.

Sulfur dioxide	**Chevron GLMs**	**7th Street Richmond**	**Percent change**
95th Percentile	50.55 ppb	12.00 ppb	321%
99th Percentile	71.11 ppb	19.00 ppb	274%
Maximum	125 ppb	39 ppb	221%
	ConocoPhillips GLMs	**Kendall Ave.-Crockett**	**Percent change**
95th Percentile	55.00 ppb	15.00 ppb	267%
99th Percentile	90.10 ppb	33.06 ppb	173%
Maximum	215 ppb	50 ppb	330%
Hydrogen sulfide	**Chevron GLMs**	**7th Street Richmond**	**Percent change**
95th Percentile	8.00 ppb	2.00 ppb	300%
99th Percentile	14.00 ppb	3.00 ppb	367%
Maximum	22 ppb	6 ppb	267%
	ConocoPhillips GLMs	**Crockett / Rodeo[a]**	**Percent change**
95th Percentile	3.00 ppb	2.00 ppb	50%
99th Percentile	10.00 ppb	4.00 ppb	150%
Maximum	46 ppb	13 ppb	254%

Based on continuous monitoring for 890 days (SO_2) and 882 days (H_2S) in Richmond and for 695 days (SO_2) and 662 days (H_2S) in Rodeo-Crockett during the periods shown in Table 1, and data from BAAQMD and ARB. See appendices 1-5. **[a]** H_2S site shifted from Crockett-Pomona to Rodeo-Third St. station during the period.

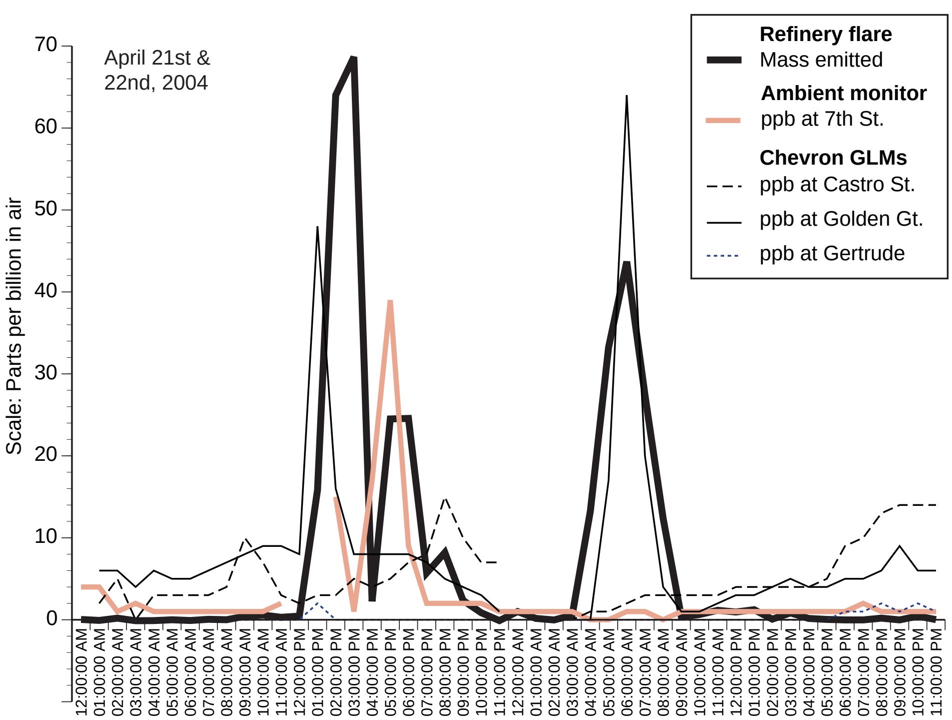
Highest-hour air pollution on flaring days

All the worst hours of air pollution with sulfur compounds, near every refinery and throughout the flare data period, were on days when the refinery near the monitor flared.

Figure 1 below illustrates one example of this finding. The figure plots the hourly change in flare sulfur emissions (thick black line), and sulfur dioxide concentrations in air (other lines). It shows two days including the highest maximum hour recorded during the flare data period at the 7th Street-Richmond ambient monitoring network station. The ambient monitor peaked at 39 ppb on April 21, 2004 while Chevron's flares emitted 7,500 pounds of SO_2 that day. Hourly concentrations of SO_2 in air are plotted for each ground-level monitor at the refinery as well as for the 7th Street monitor. High concentrations appear in the chart as vertical peaks.

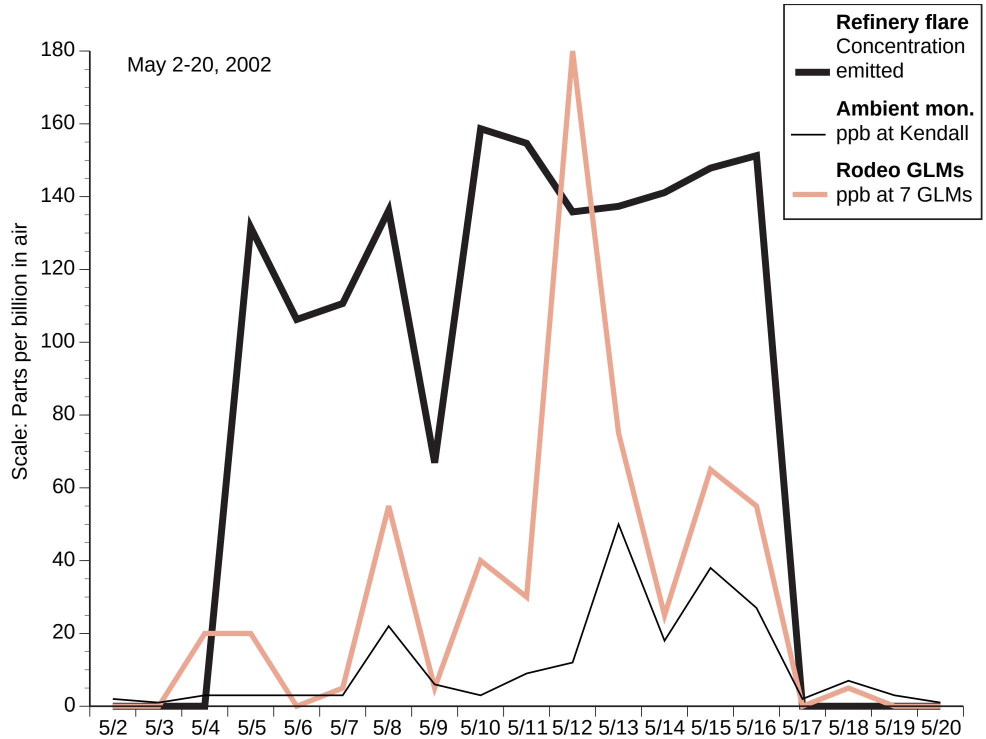
Review of Figure 1 shows that air concentrations for one monitor or another peak during part or all of every peak in flare emissions. Fence line concentrations peak earlier and higher than those measured at the network monitor. Different monitors peak at different levels and at different times. These observations describe a large, changing emission plume that is more concentrated near the refinery than further away, and shifts in the wind to hit or miss various monitors over the duration of the flaring episode.

Figure 1. Hourly profile of flare sulfur emissions and SO_2 concentration in air at fence line and ambient monitors when the ambient monitor hit its highest hour: Chevron



Data from BAAQMD: Rule 12-11 report, and response to Public Records Act request. Data shown in Appendix 6.

Figure 2. Daily profile of flare sulfur emissions and SO_2 concentration in air at fence line and ambient monitors when the ambient monitor hit its highest hour: ConocoPhillips.



Daily maximum-hour SO_2 concentration data from BAAQMD response to Public Records Act request and ARB air quality data reports. Flare data from BAAQMD Technical Assessment Document. Data shown in Appendix 2.

Figure 2 illustrates a similar pattern of observations in a second example, based on daily measurements around the flaring episode associated with the record-high 50 ppb hourly SO_2 concentration measured at the Crockett-Kendall Avenue network station on May 13, 2002. Sulfur dioxide peaked at the Rodeo GLMs on May 12, 2002 during flaring at the ConocoPhillips refinery – the day before the May 13, 2004 maximum hour reached at the network station. The 180 ppb hourly SO_2 concentration on May 12th is the second-highest recorded at the Rodeo GLMs in the flare data period. Hydrogen sulfide (not shown) also reached the second-highest level recorded at the Rodeo GLMs for that pollutant on May 12th, at 18 ppb.

The highest daily maximum-hour SO_2 and H_2S levels on days of flaring near four refineries are listed in Table 3 below. The table also lists the maximum hour recorded on all days when the nearby refinery did not flare for each refinery, pollutant and monitoring location.

All the flaring day concentrations in the right-hand column of Table 3 are higher than any hourly level recorded at the same location on a day the refinery did not flare. For example, the maximum-hour concentration on all days in the flare data period when the Chevron refinery did not flare was 85 ppb for SO_2 at the Chevron ground-level monitors, 21 ppb for SO_2 at 7th Street-

Table 3. Twenty-eight observations of maximum-hour sulfur dioxide or hydrogen sulfide concentrations at nearby monitors on days when the refinery flared.

Refinery	Pollutant	Monitor	Max-hour all days with no flaring	Days with higher hourly levels when the refinery flared
Chevron	SO_2	GLMs	85 ppb	125 ppb on May 29, 2002
Chevron	SO_2	GLMs	85 ppb	93 ppb on March 21, 2004
Chevron	SO_2	GLMs	85 ppb	91 ppb on July 18, 2001
Chevron	SO_2	GLMs	85 ppb	90 ppb on January 4, 2004
Chevron	SO_2	GLMs	85 ppb	88 ppb on July 27, 2001
Chevron	SO_2	7th Street	21 ppb	39 ppb on April 21, 2004
Chevron	SO_2	7th Street	21 ppb	34 ppb on May 15, 2001
Chevron	SO_2	7th Street	21 ppb	31 ppb on April 12, 2002
Chevron	SO_2	7th Street	21 ppb	28 ppb on September 10, 2001
Chevron	SO_2	7th Street	21 ppb	27 ppb on May 14, 2001
Chevron	SO_2	7th Street	21 ppb	24 ppb on May 30, 2004
Chevron	H_2S	7th Street	5 ppb	6 ppb on October 10, 2001
ConocoPhillips	SO_2	GLMs	110 ppb	215 ppb on April 10, 2004
ConocoPhillips	SO_2	GLMs	110 ppb	180 ppb on May 12, 2002
ConocoPhillips	SO_2	GLMs	110 ppb	140 ppb on March 20, 2004
ConocoPhillips	SO_2	GLMs	110 ppb	120 ppb on September 8, 2004
ConocoPhillips	SO_2	Kendall Ave.	45 ppb	50 ppb on May 13, 2002
ConocoPhillips	H_2S	GLMs	13 ppb	46 ppb on October 31, 2004
ConocoPhillips	H_2S	GLMs	13 ppb	18 ppb on May 12, 2002
Tesoro	SO_2	GLMs	80 ppb	220 ppb on July 10 , 2002
Tesoro	SO_2	GLMs	80 ppb	212 ppb on August 9, 2002
Tesoro	H_2S	GLMs	16 ppb	21 ppb on October 6, 2004
Valero	SO_2	GLMs	3 ppb	6 ppb on March 15, 2004
Valero	SO_2	GLMs	3 ppb	4 ppb on March 16, 2004
Valero	SO_2	GLMs	3 ppb	4 ppb on June 24, 2004
Valero	H_2S	GLMs	13 ppb	18 ppb on June 24, 2002
Valero	H_2S	GLMs	13 ppb	16 ppb on June 4, 2004
Valero	H_2S	GLMs	13 ppb	15 ppb on October 3, 2004

Air quality data from June 21, 2005 BAAQMD response to Public Records Act request, and ARB reports for Richmond-7th St. and Crockett-Kendall stations. Flare data from BAAQMD Technical Assessment Document and Rule 12-11 reports. See appendices 1-5 for daily data.

Richmond ambient network station, and 5 ppb for H_2S at 7th Street-Richmond. Chevron flared on five days when the GLMs recorded hourly SO_2 concentrations higher than 85 ppb, on six more days when the network station recorded SO_2 concentrations higher than 21 ppb, and on one day when the network station recorded a hydrogen sulfide level higher than 5 ppb.

Review of Table 3 shows that the 28 highest daily maximum-hour concentrations were all recorded on a day when the refinery near that monitor flared. The significance of this finding is confirmed by the probability calculation shown in Table 4 below. Given the number of days when air quality was monitored continuously while flare activity was monitored at each refinery,

Table 4. Probability table for 28 observations of maximum-hour concentrations across the refineries and pollutant-monitors shown in Table 3.

Pollutant & location	Chance of one max. level on a flare day	# max. levels on flare days	Probability this occurred randomly: within that location	across locations
Richmond SO_2 GLMs	890 days ÷ 317 days refinery flared	5	0.0056[a]	
7th St. SO_2 Network Stn	890 days ÷ 317 days refinery flared	6	0.0019	1.1E-05
7th St. H_2S Network Stn.	882 days ÷ 317 days refinery flared	1	0.3564	4.0E-06
Rodeo SO_2 GLMs	699 days ÷ 238 days refinery flared	4	0.0132	5.3E-08
Rodeo H_2S GLMs	699 days ÷ 238 days refinery flared	2	0.1156	6.1E-09
Kendall Ave.. SO_2	695 days ÷ 238 days refinery flared	1	0.3424	2.1E-09
Avon SO_2 GLMs	547 days ÷ 350 days refinery flared	2	0.4090	8.5E-10
Avon H_2S GLMs	547 days ÷ 350 days refinery flared	1	0.6398	5.6E-10
Benicia SO_2 GLMs	548 days ÷ 442 days refinery flared	3	0.5240	2.9E-10
Benicia H_2S GLMs	548 days ÷ 442 days refinery flared	3	0.5240	**1.5E-10**

Based on the BAAQMD and ARB data summarized in tables 1 and 3 and shown for each day in appendices 1-5. Shell Martinez refinery data not shown in this table or table 3 because this refinery flared every day.

[a] Example calculation for SO_2 at Richmond GLMs: (317÷890) x ((317-1)÷(890-1)) x ((317-2)÷(890-2)) x ((317-3)÷(890-3)) x ((317-4)÷(890-4)) = 0.0056.

and the number of these days when each refinery flared, the probability of observing all 28 of the highest daily maximum-hours on flaring days because of random chance alone is 1.5E-10, or less than one in a billion. Accordingly, the null hypothesis–that maximum pollution hours occur when refineries flare by random chance–must be rejected. The data support a significant association between flaring and the highest daily maximum-hour SO_2 and H_2S concentrations in air near four of the Bay Area refineries.

Maximum pollution hours continued to occur on days refineries flared throughout the flare data period. Half of the 28 observations in Table 3 were recorded in 2004. In addition, four of the five highest SO_2 daily maximum-hours and three of the five highest H_2S hours recorded by monitors near the Shell refinery on days Shell flared were recorded in 2004 or 2005.

Increase in highest-hour pollution associated with flaring

Changes in flare emissions that can be compared with pollutant levels in air near the refineries to explore flare impacts on air quality are summarized in Table 5 below. The table shows refinery-specific data for the volume of gases flared (in million standard cubic feet or MMSCF), sulfur emission (lbs expressed as SO_2), and emissions concentration (expressed as lbs/MMSCF).

Significant differences between flare episodes exist for each refinery. The 99th Percentile highest day of flare gas volume, sulfur emissions mass, and emission concentration is between 250% and 2,200% greater than the average in the 15 comparisons for these three emission factors across the five plants. This shows emissions differ between flaring episodes at each plant. The Shell refinery flaring pattern appears significantly different from that of the other refineries. Its flare gas flow is 600-2,600% higher than those of the other refineries, but its flare emissions mass and concentration are only 2-40% as high as those of the other plants, in the 36 comparisons in the table. Shell's flaring may affect air quality differently from that of the other plants.

It should be noted that the statistics in Table 5 represent the days in each refinery monitoring period when the refinery actually flared, not long-term averages of all days in the period.

Regression analysis was performed for the highest 10th Percentile of daily maximum-hour SO_2 concentrations, on days the refinery near the monitor flared, during the period from January 1, 2004 through March 31, 2005. This analysis pairs each daily maximum-hour near a refinery

Table 5. Average, 95th Percentile and 99th Percentile gas volume disposed, pounds sulfur emitted, and emission concentration for flare episodes.[a]

	Chevron	ConocoPhillips	Shell	Tesoro	Valero
Days of flaring	317	238	548	350	442
MMSCF gases flared					
Average by day:	3.260	2.762	12.78	3.059	1.002
95th Percentile:	10.47	10.38	153.0	9.650	5.673
99th Percentile:	21.38	16.76	153.0	16.55	13.55
Lbs SOx emitted					
Average by day:	1,765	3,350	176	6,126	662
95th Percentile:	8,849	20,570	1,181	20,680	2,977
99th Percentile:	18,490	38,030	1,850	32,480	14,070
Lbs SOx/MMSCF					
Average by day:	1,213	1,059	47	1,775	1,330
95th Percentile:	5,808	4,019	123	3,663	2,669
99th Percentile:	12,830	9,583	967	17,185	4,745

[a] For the periods when flare data are available for each refiner, as shown in Table 1 (no data excluded to force start- and end-dates of refinery periods to match). Data from BAAQMD Technical Assessment Document and Rule 12-11 reports. Daily data shown in appendices 1-5. MMSCF = million standard cubic feet.

with that refiners' flare gas flow, sulfur mass emission, and sulfur emission concentration for that day. The air concentration is expressed as a percentage of the mean for the monitoring location to allow analysis across refineries.[1] However, regression was performed separately for the Shell-Martinez data set because Shell flares differently from the other refiners. Results suggest that increasing air concentrations may be associated with increasing flare sulfur emissions concentration at the Shell refinery, but the results are not statistically significant ($p = 0.31$).

Table 6 below summarizes results of the regression on the paired data from the Chevron-Richmond, ConocoPhillips-Rodeo/Crockett, Tesoro-Avon, and Valero-Benicia data sets. The intercept value shown in the table (212 which represents 212% of the mean air concentration) approximates the lowest SO_2 air concentrations within the top 10th Percentile of the refiners' data sets. For flare gas volume, the positive coefficient indicates a positive association between increasing flare gas flow and increasing air concentration. However, the lower bound of the 99% confidence interval dips below zero, and the result is not statistically significant ($p = 0.8$). Flare gas flow may not be a reliable predictor of local air quality impacts from flaring. Thus, data assessed here support the need to address *sulfur concentration* in addition to *gas volume* for effective protection against local air quality impacts from flaring episodes.

In contrast, increasing flare sulfur mass emission is positively associated with increasing SO_2 air concentrations *and* this association is significant at the 99% confidence level ($p = 0.0013$). Similarly, increasing flare sulfur emission concentration is associated with increasing SO_2 in air, and this association is significant at the 99% confidence level ($p = 0.0001$). The 10th Percentile of highest SO_2 daily maximum hours includes eight percent of the days in this data set. Increasing sulfur dioxide concentration is associated with increasing flare sulfur emission on the worst eight percent of bad air days near these four refineries.

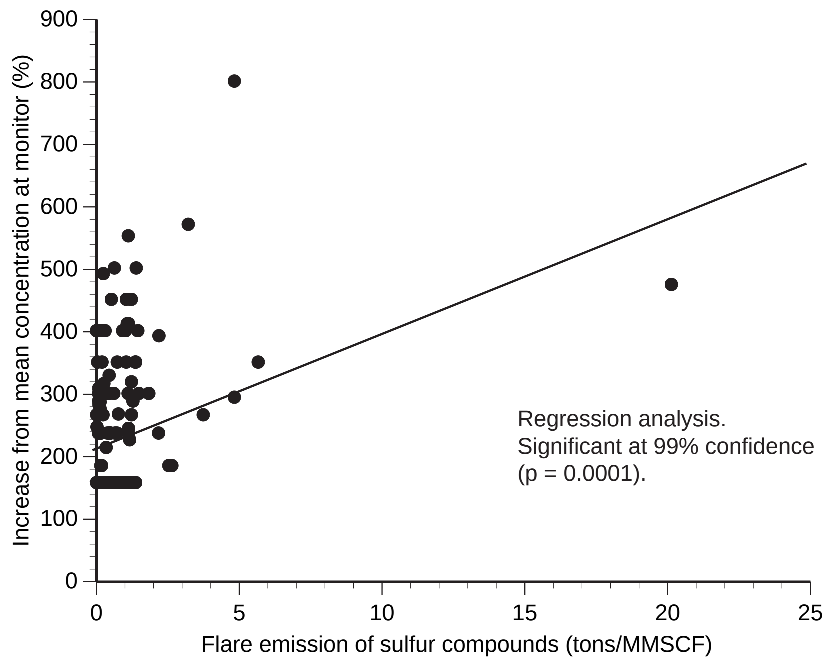
Table 6. Results of regression analysis: y = change in daily maximum-hour from mean, in percent v. x_1 = flare gas volume, in SCF, x_2 = flare sulfur mass emission, in lbs, and x_3 = flare sulfur emission concentration, in tons/MMSCF.[a]

Multiple R	0.5030067			
Observations	141			
	Coefficients	**P-value**	**Lower 99.0%**	**Upper 99.0%**
Intercept	212.304095	4.2247E-45	186.148023	238.460167
Gas flared (SCF)	7.5699E-07	0.8381816	-8.907E-06	1.0421E-05
Mass SO_2 emitted (lbs)	0.006869	0.00131099	0.00140061	0.01233738
Concentration (lbs/MMSCF)	18.3729555	0.0001182	6.26518883	30.4807223

[a] Based on daily maximum-hour SO_2 measurements near the Chevron, ConocoPhillips, Tesoro and Valero refineries on days the refineries flared during the period from January 1, 2004–March 31, 2005. Regression performed on those data at or above the 90th Percentile in each refinery data set.

[1] For example, a daily maximum-hour of 2 ppb at a station where the mean is 1 ppb is expressed as 200, for 200%. This transformation was checked in trial runs of individual refinery data sets and did not change the results.

Figure 3. Association of highest 10th Percentile daily maximum-hour sulfur dioxide levels with flare sulfur concentration.



Based on daily maximum-hour SO_2 measurements near the Chevron, ConocoPhillips, Tesoro and Valero refineries on days the refineries flared. Regression performed on 141 paired observations during January 2004 through March 2005 including all data at or above the 90th Percentile value in each refinery-specific data set. Data shown in appendices 1-5.

The line fit plot for SO_2 emission concentration (as tons/MMSCF) is shown in Figure 3 above. The broad scatter of observations suggests that other factors–changing winds carrying plumes away from the few existing monitors, other pollution sources in or near the refineries, and flare mass emissions–can cause different pollution levels than those that the regression line predicts on any given day.

There is more than one way to estimate the increase in maximum episodic pollution levels associated with flaring from these data. The regression line prediction in the figure above shows one method (if the impact of mass emission is added). Another method would simply calculate the difference between direct measurements of the highest levels near each refinery when it flared and did not flare. These direct measurements are available, as shown in Table 3. Given the variability shown in Figure 3, the more straightforward, transparent approach seems appropriate.

Accordingly, the direct observations of highest levels with and without flaring at each location are compared for the estimate presented here. The percentage increase is calculated directly

Table 7. Change in daily maximum-hour sulfur dioxide concentration in air near four refineries that is associated with flaring.

Monitor location	Highest hour when refinery does not flare	Higher daily maximum-hours when refinery flares	Percent increase
Chevron-SO_2 GLMs	85 ppb	125 ppb	47%
Chevron-SO_2 GLMs	85 ppb	93 ppb	9%
Chevron-SO_2 GLMs	85 ppb	91 ppb	7%
Chevron-SO_2 GLMs	85 ppb	90 ppb	6%
Chevron-SO_2 GLMs	85 ppb	88 ppb	4%
Chevron-SO_2 7th St.	21 ppb	39 ppb	86%
Chevron-SO_2 7th St.	21 ppb	34 ppb	62%
Chevron-SO_2 7th St.	21 ppb	31 ppb	48%
Chevron-SO_2 7th St.	21 ppb	28 ppb	33%
Chevron-SO_2 7th St.	21 ppb	27 ppb	29%
Chevron-SO_2 7th St.	21 ppb	24 ppb	14%
ConocoPhillips-SO_2 GLMs	110 ppb	215 ppb	95%
ConocoPhillips-SO_2 GLMs	110 ppb	180 ppb	64%
ConocoPhillips-SO_2 GLMs	110 ppb	140 ppb	27%
ConocoPhillips-SO_2 GLMs	110 ppb	120 ppb	9%
ConocoPhillips-SO_2 Kendall	45 ppb	50 ppb	11%
Tesoro-SO_2 GLMs	80 ppb	220 ppb	175%
Tesoro-SO_2 GLMs	80 ppb	212 ppb	165%
Valero-SO_2 GLMs	3 ppb	6 ppb	100%
Valero-SO_2 GLMs	3 ppb	4 ppb	33%
Valero-SO_2 GLMs	3 ppb	4 ppb	33%
Estimated increase in highest 20 daily maximum hours associated with flaring:			**50%**

Observations from Table 3 used in calculation as reported from monitor measurements provided by BAAQMD and ARB. Estimate by CBE in ***Flaring Hot Spots,*** based on BAAQMD and ARB data included and analyzed in the report.

from each paired observation, and it is conservatively assumed that the average of these percentages, rather than the maximum, is a representative estimate. An advantage of this method is that every data input is measured, and can be confirmed by direct comparison of measurements to be a higher value than any observed in a comparable period when the refinery did not flare, as detailed in the discussion of Table 3.

This assessment predicts a 50% increase in the highest daily maximum-hour sulfur dioxide concentration associated with flaring at emission rates observed in the period examined. The calculation is shown in Table 7 above.

Closing

Findings are summarized on page 5 above. This report documents localized episodic air pollution associated with flaring by Bay Area oil refineries. Its findings support the adoption of enforceable requirements to prevent and reduce flaring as a matter of environmental justice for disproportionately impacted low-income communities on refinery fence lines.

References

ARB, various dates. Air Quality Reports. Data for Ambient Air Quality Monitoring Network stations. California Air Resources Board. Sacramento, CA. Now available by internet: www.arb.ca.gov

BAAQMD, 2002. Draft Technical Assessment Document: Potential Control Strategies to Reduce Emissions from Flares. Further Study Measure 8. Bay Area Air Quality Management District. San Francisco, CA. Now available by internet: www.baaqmd.gov

BAAQMD, various dates. Rule 12-11 Reports. Flare monitoring reports required by Rule 12-11. Bay Area Air Quality Management District. San Francisco, CA. Daily gas flow, SOx and hydrocarbons emission data now available by internet: www.baaqmd.gov

BAAQMD, 2005. Hourly Average Ground-level Monitoring Data for Refinery GLMs. Documents provided by BAAQMD June 21, 2005 in response to CBE's request for opportunity to review documents under the California Public Records Act. Bay Area Air Quality Management District. San Francisco, CA.

CBE, 2005. Comments of CBE regarding the Notice of Preparation of Draft Environmental Impact Report and Initial Study for adoption of District Regulation 12. April 26, 2005. Communities for a Better Environment. Oakland and Huntington Park, CA. Available from CBE. (510) 302-0430.

May et al., 2004. Refinery Flaring in the Neighborhood: Routine flaring in the San Francisco Bay Area, the need for new regulation and better environmental law enforcement, and the community campaign to get there. A CBE Report. Spring, 2004. Communities for a Better Environment. Oakland and Huntington Park, CA. Available from CBE. (510) 302-0430.

Strosher, 1996. Investigations of Flare Gas Emissions in Alberta: Final Report to Environment Canada Conservation and Protection, the Alberta Energy and Utilities Board, and the Canadian Association of Petroleum Producers by M. Strosher, Environmental Technologies, Alberta Research Council, Calgary, Alberta. November 1996. Now available by internet: www.baaqmd.gov