

07/22/1980

VOC410722801

**Category:** 41 – Afterburners

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

DATE: JUL 22 1980

SUBJECT: Thermal Incinerator Performance for NSPS, Addendum

FROM: David C. Mascone  
Chemical Manufacturing Section

TO: Jack R. Farmer, Chief  
Chemicals and Petroleum Branch

After reviewing the recent memo on incinerator performance, (Thermal Incinerator Performance for NSPS, June 11, 1980, DCM to Jack Farmer), you indicated several areas where further discussion was desired. These areas were as follows:

- continuous compliance of thermal incinerators
- the impact of compound on efficiency
- the impact of inlet concentration on cost effectiveness and efficiency

These three areas are discussed below preceded by a summary of the conclusions.

Conclusions

In the absence of a demonstrated continuous VOC monitor for thermal incinerators, CPB is investigating alternate methods. After study of the cost and effectiveness of several such methods, the following should be considered: continuous temperature and flow monitoring and bi-annual compliance testing and inspection/maintenance. For example, in monitoring temperature and flow, a company could be required to run the incinerator between +/-50 degrees F of the temperature, and between +20 percent and -50 percent of the flow, measured during the performance test.

Detailed analysis shows that type of compound does affect incinerator efficiency. However, due to the complexity of the relationship, no attempts were made in the June 11 memo to draw fine-tuned efficiency conclusions relating different efficiencies to different compounds at different temperatures. Rather, a more conservative approach was taken in which the efficiency conclusions were based on the most difficult compounds to combust. These conclusions, based on such a worst case analysis, would then apply regardless of compound.

Detailed analysis also shows that inlet concentration affects incinerator efficiency. However, unlike type of compound, statistical study of the relationship between inlet concentration and efficiency was possible. Based

on this study, the conclusions in the June 11 incinerator memo are expressed in both ppmv and percent reduction. This dual format accounts for the effect of inlet concentration.

Inlet concentration also affects cost effectiveness. One effect is that as inlet concentration drops the energy content of the waste gas drops, increasing supplemental fuel use. However, this is not the major effect. By far the largest effect of inlet concentration on cost effectiveness is to change the amount of VOC controlled. Over a typical range of inlet concentrations (i.e. 10,000 to 500 ppm) and for an incinerator with 70 percent recuperative heat recovery, increasing fuel use can increase cost effectiveness 5 to 50 percent while decreasing VOC can increase cost effectiveness 5 to 2000 percent.

### Discussion

Monitoring - One CPB goal is continuous monitoring of air pollution control equipment. At present, we are limited in achieving this goal for incinerators by the lack of a demonstrated continuous VOC monitor. Given this limitation, CPB is studying alternate monitoring methods, such as measuring firebox temperature, to indicate incinerator performance.

To develop alternate monitoring methods, two goals were considered. First, these alternate methods should detect all or most cases of poor incinerator performance. Second, the methods should have reasonable costs and impose reasonable recordkeeping requirements.

To meet these goals, the variables that affected incinerator performance were analyzed. These variables are temperature, mixing, type of compound, inlet concentration, residence time, and flow regime. Of these variables, the last three were judged of little concern when considering continuous monitoring. These three variables are essentially set after incinerator construction and adjustment and/or have only small impact on incinerator performance. The three remaining variables were then analyzed in more detail to define their impact on performance and the ability to monitor them.

Temperature was analyzed first. This analysis was based on data in the previous incinerator memo. Even with good mixing, the Union Carbide lab data and kinetic theory show that lower temperatures cause significant decreases in efficiency. In addition, the L.A. data indicate that increasing temperature can also adversely affect efficiency, apparently by changing mixing. In terms of cost, temperature monitors are inexpensive, costing less than \$5000 installed with strip charts, and are easily and cheaply operated. Given the large effect of temperature on efficiency and the low cost of temperature monitors, this variable is clearly an effective parameter to monitor.

As an example, a specific requirement could be that an incinerator cannot be operated for more than three hours at an average firebox temperature above 50 degrees F over, or under 50 degrees F below, the average temperature recorded during performance testing. If an operating range greater than 100 degrees F is desired, a company could perform performance tests at more than one temperature. The three hour time period would correspond to the period

required for integrated bag sampling in a typical performance test. This would make the averaging period for temperature monitoring similar to that of the performance test. Finally, the company could be required to install, operate, and calibrate the monitor according to manufacturer's specifications. These specifications generally cover proper placement of the monitor.

The next variable studied was mixing. The most likely item to affect mixing, given a constant temperature and an already constructed incinerator, would be flow. No direct field data is available on the effect of flow on mixing efficiency. However, based on engineering judgement, increasing flow may lead to "short-circuiting," where the increased kinetic energy of higher flow streams causes waste gas to jet through the incinerator unmixed. Decreased flow may lead to the opposite, where lower flow rates result in insufficient kinetic energy for complete mixing. As with temperature, flow monitors are inexpensive and easily operated. Given the potential impact of flow on efficiency, and the low cost of flow monitors, flow rate is also an effective parameter to monitor.

As an example, a specific requirement could be that an incinerator cannot be operated for more than three hours at an average flow less than 50 percent or greater than 120 percent of the average waste gas flow recorded during a performance test. The permissible range would be intentionally broad due to the lack of field data on the impact of flow on mixing and efficiency. The upper restriction would be tighter than the lower since increase flow not only may adversely affect mixing but decreases residence time. Any adverse effects of decreased flow may be offset by the increased residence time. The above discussion for temperature on widening the operating range, the three hour time limit, and installation, operation and calibration of the monitor would hold for this flow monitoring example.

The final variable analyzed was type of compound. For most incinerator applications, the compounds in the waste gas are set by the process to which the incinerator is attached. Thus, type of compound is of no concern. However, certain applications may have differing compounds in the waste gas. A coating operation may have at one time a solvent with an MEK base, and then switch to a solvent with a toluene base. MEK is oxidized easier than toluene, and thus an incinerator which achieves compliance on an MEK stream may be inadequate for the toluene stream.

The judgement on this item is that no general monitoring requirement on type of compound can be specified. Most cases will have the waste gas compounds set by the process. In those that do not, considerable difficulty is envisioned in defining, in a general way, when the waste gas compounds have changed enough to require additional compliance tests. For example, differentiating between solvent formulations would be difficult. The same generic name of solvent may show greater variations in composition than two different name specialized solvents. However, though a general requirement on type of compound cannot be set, specific requirements may be desired for certain standards.

Temperature and flow monitoring do not measure incinerator performance directly. Thus, concern exists over the long term stability of incinerator

performance, even with temperature, flow and type of compound held constant. Data on this issue is shown in Table 1. The top part of the table shows data from L.A. County where the same incinerator was tested in different years. The bottom part lists possible incinerator malfunctions that could affect performance, without changing temperature and flow.

Based on Table 1, incinerators, if properly designed and adjusted, are judged to have fairly stable performance over time. The L.A. units showed only small changes in efficiency over time. The efficiencies of these units changed less than two percentage points over several years, except one case. In addition, the listed malfunctions are judged to occur infrequently. This is based on several factors. First, these malfunctions involve non-moving parts subject to little wear. Also, the typical waste gases are not highly corrosive and the typical incinerator fuels, natural gas and fuel oil, have low sulfur and ash content. Finally, even though incinerators undergo wide temperature swings, incinerator components are designed to withstand these changes, given proper cooling and heating of the unit.

The above conclusion should not be overstated. Though fairly stable, all four L.A. data sets show some drop in performance over time. And though improbable, incinerator malfunctions are not impossible. Thus, the conclusion from the data is not that no additional requirements are needed over temperature and flow monitoring. Rather, the conclusion is that the costs and recordkeeping of additional monitoring requirements must be carefully balanced against emissions potentially prevented by them.

After this balance was studied, two additional requirements were considered. These are bi-annual performance testing and bi-annual inspection and maintenance (I & M) for incinerators. The performance testing would follow the method specified in the standard. The I & M would involve visual inspection for items such as corrosion and firebox deterioration, calibration and testing of control instrumentation, and so on. Such I & M could most likely be performed at the same time as a process turnaround.

These two additional monitoring methods would effectively detect drops in incinerator performance not detected by temperature and flow monitoring. Performance testing is the most direct means of detecting poor efficiency. The I & M will catch drops in performance by spotting equipment failures or impending failures that could lead to poor performance. The I & M has the added advantage that impending failures which could lead to incinerator shutdown would also be spotted. The two year period for compliance testing and I & M is based on the rate at which incinerator performance is likely to deteriorate. The two year period for I & M also corresponds to the typical time between process turnarounds. Thus, with a bi-annual I & M the incinerator I & M could be performed at the same time as process equipment I & M, and it would not be necessary to shut down the process just to check the incinerator. Finally, the timing of the performance test and the I & M are not linked. They can be done together in any order or apart.

Type of Compound - One factor which affects incinerator efficiency is type of compound. The June 11 memo on incinerator efficiency excludes this factor from its conclusions, but discusses only briefly the reasons for this

exclusion. This section discusses the impact of this factor on efficiency and explains in more detail the reasons for its exclusion.

In terms of the impact of compound on efficiency, the available incinerator data does show a moderate impact. The Union Carbide lab data demonstrates this most clearly. In cases where different compounds were incinerated at the same temperature, residence time, and flow regime, variations in efficiency of up to 5 percent points occurred for temperatures above 1400 degrees F. At lower temperatures, the efficiency variations increased up to 20 and 30 percentage points.

However, as a practical matter, including compound as a factor in an efficiency conclusion would be difficult. First, a precise quantitative relation between compound and efficiency could not be determined. As with mixing, no single value could be assigned to an individual compound to represent ease of combustion. Thus, analysis of the relation between efficiency and compound was limited. Second, even if a relationship could be devised, it would be complex and difficult to apply. The relationship would likely involve kinetic rate constants, autoignition temperatures, factors for molecular configuration and structural groups and similar variables.

To avoid these difficulties, an alternative approach was taken. No initial attempts were made at drawing a fine-tuned efficiency conclusion showing differing efficiencies at differing temperatures for different compounds. Rather, a conservative approach of choosing a simple set of incinerator conditions and efficiencies based on the most difficult compounds to combust was pursued. This approach proved successful.

Several factors aided in the success of this approach. First, the available test data covered a wide range of compounds. The compounds on which test data were available included C1 to C5 alkanes and olefins, aromatics such as benzene, toluene, and xylene, oxygenated compounds such as MEK and isopropanol, nitrogen containing species such as acrylonitrile and ethylamines and chlorinated compounds such as vinyl chloride. With such a range of compounds and the consideration of kinetics, it was concluded that worst case compounds had been taken into account. The second factor was the discovery that increasing combustion temperature resulted in only negligible energy penalties and moderate cost increases. Thus, choosing a higher temperature to cover the worst cases did not make incinerators unaffordable or too energy intensive.

Inlet Concentration - A second factor which affects efficiency is inlet concentration. Unlike type of compound, an allowance for this factor gas was included in the efficiency conclusions. Specifically, these conclusions included not only an efficiency of 98 percent but a minimum exit concentration of 20 ppmv by compound. Thus, as inlet concentration drops, the minimum ppmv lowers the efficiency required. For example, with a 500 ppmv inlet concentration for a waste gas containing oxygen, the 20 ppmv minimum translates to a 96 percent efficiency; with a 250 ppmv inlet a 92 percent efficiency. This section explains in more detail the reasons for this allowance for inlet concentration.

The test results from L.A. County form the major basis for this allowance. These results show a strong trend where lower inlet concentration results in lower efficiency. For example, for inlet concentrations less than 1600 ppmv as carbon, the median L.A. efficiency was approximately 92 percent. For inlet concentrations between 1600 and 2400, the median L.A. efficiency was approximately 94 percent. For inlet concentrations above 2400, the median efficiency was approximately 97 percent.

Kinetic considerations also support the allowance for inlet concentration. The most likely Kinetic model where inlet concentration does not affect efficiency is a first order model. However, available literature indicates that combustion follows complex reaction mechanisms.<sup>1,2</sup> In cases, these mechanisms can be fit to a first order model. However, as a general rule, these mechanisms, which involve chain reactions, free radicals and multiple pathways, cannot be reduced to first order models.

The June 11, 1980, incinerator memo concluded that the L.A. incinerators did not all achieve proper mixing. This improper mixing may have caused or influenced the relation between efficiency and inlet concentration in the L.A. data. If this is the case, then an allowance for inlet concentration may permit lower efficiencies than are actually achievable in incinerators with proper mixing. However, the possible effect of poor mixing on the relation of efficiency and inlet concentration remains just that, possible; no conclusive statement can be made. Given this, a more conservative approach was taken and lower efficiencies for lower inlet concentrations were allowed.

Inlet concentration also impacts cost effectiveness, i.e. costs per unit weight VOC controlled. The precise impact depends on molecular weight, the size of the incinerator and the ratio of waste gas energy content to VOC. Figure 1 show these impacts.

A surprising conclusion in the analysis of inlet concentration vs. cost effectiveness is the role of supplemental fuel. The increasing cost for supplemental fuel as inlet ppm drops is not a major factor in cost effectiveness. Incinerator size and the amount of VOC being destroyed are much more important factors. An illustrative example is a 5000 SCFM incinerator burning benzene in nitrogen. The extra fuel required when dropping the inlet concentration from 5000 to 500 ppmv increases the cost effectiveness only 20 percent. The fact that only one-tenth the benzene is being destroyed for about the same cost increases the cost effectiveness 1000 percent. And decreasing the stream size to 1000 SCFM increases the cost effectiveness about 300 percent. Clearly, increasing fuel costs at lower ppmv is only a minor factor.

---

<sup>1</sup> Rolke, R.W., et. al. Afterburner System Study, U.S. Environmental Protection Agency, Report 5-14121, Shell Development Company, 1971.

<sup>2</sup> Barnes, R.H., et. al Chemical Aspects of Afterburner Systems, IERL Report U.S. Environmental Protection Agency, EPA-600/7-79-096. Batelle Columbus Laboratories, April 1979.

Table 1  
Long Term Incinerator Performance

| Part A – Test Data <sup>a</sup> |          |          |                        |                   |                      |                          |
|---------------------------------|----------|----------|------------------------|-------------------|----------------------|--------------------------|
| Company                         | Test No. | Date     | Inlet<br>(ppmv carbon) | Outlet<br>carbon) | % VOC<br>Destruction | Flow(SCFM)/<br>Temp. (F) |
| Day & Night<br>Manufacturing    | 1754     | 10-30-73 | 443                    | 33                | 92.5                 | 3270/1300                |
|                                 | 2442     | 7- 7-76  | 1030                   | 91                | 91.4                 | 2020/1300                |
|                                 | 2443     | 8-10-78  | 716                    | 94                | 87.3                 | 2050/ –                  |
| Glasteel, Inc.                  | 2286     | 5-12-75  | 6020                   | 52                | 99.0                 | 1210/1260                |
|                                 | 2402     | 2-17-76  | 5860                   | 71                | 98.9                 | 4150/1375                |
| National Can                    | 1430     | 6-10-70  | 4900                   | 31                | 99.4                 | 2520/1500                |
|                                 | 1746     | 3-21-74  | 7370                   | 104               | 98.6                 | 1990/1500                |
| National Can                    | 1451     | 6-10-70  | 3500                   | 22                | 99.4                 | 4620/1460                |
|                                 | 1746     | 3-21-74  | 6247                   | 82                | 98.0                 | 4620/1460                |
|                                 |          |          |                        | 7370              | 79                   | 98.0                     |

| Part B -Possible Incinerator Malfunctions <sup>b</sup>  |  |
|---|--|
| Malfunction   | Cause  |
| <ul style="list-style-type: none"> <li>• Firebrick Deterioration</li> </ul>                               | Improper heating & cooling of incinerator during start-up & shutdown; firebox temperature too high |
| <ul style="list-style-type: none"> <li>• Insulation Loss from Incinerator Exterior</li> </ul>             | General weathering & corrosion from rain, cold, incinerator start-up & shutdown & so on            |
| <ul style="list-style-type: none"> <li>• Corrosion of ducts, baffles &amp; other exposed metal</li> </ul> | Ash, acids, salts, etc. in fuel or waste gas   |

Table 1 (Cont'd)  
Long Term Incinerator Performance

---

Part B -Possible Incinerator Malfunctions<sup>b</sup>

---

| Malfunction   | Cause   |
|---|---|
| <ul style="list-style-type: none"> <li>• Plugging of Burners</li> </ul>                                   | Ash & carbon build-up   |
| <ul style="list-style-type: none"> <li>• Breaking of Recuperative Heat Exchanger Seals</li> </ul>         | General corrosion; temperature warping from hot spots in the exchanger, improper heating & cooling during start-up & shutdown                 |
| Malfunction   | Possible Effect on VOC Control  |
| <ul style="list-style-type: none"> <li>• Firebrick Deterioration</li> </ul>                               | Deteriorated wall allows local heat loss resulting in cool spots in firebox, and thus potentially lower destruction efficiency in those spots |
| <ul style="list-style-type: none"> <li>• Insulation Loss from Incinerator Exterior</li> </ul>             | Same as previous; insulation loss leads to local heat loss & cool spots in the incinerator  |
| <ul style="list-style-type: none"> <li>• Corrosion of ducts, baffles &amp; other exposed metal</li> </ul> | Severe corrosion of metal parts affects the gas flow patterns through and around them, potentially affecting mixing & thus efficiency         |

---

Table 1 (Cont'd)  
Long Term Incinerator Performance

---

Part B -Possible Incinerator Malfunctions<sup>b</sup>

---

| Malfunction                                     | Possible Effect on VOC Control  |
|---|---|
| • Plugging of Burners                           | A plugged or partially plugged burn affects the flow patterns & temperature profiles in the firebox potentially lowering destruction efficiency |
| • Breaking of Recuperative Heat Exchanger Seals | Inlet waste gas leaks into the out flue gas without passing through the firebox.  |

---

<sup>a</sup> The listed data are from incinerators which were tested in more than one year.

<sup>b</sup> The listed malfunctions include only those which would likely not affect temperature at a single point firebox temperature monitor or inlet/outlet flow.

Figure 1 - Notes and Explanation

Figure 1 shows the cost effectiveness of thermal incinerators by inlet concentration and waste gas flow. The cost effectiveness is in hundred dollars per 2000 pound ton; inlet concentration is ppmv by compound; and the flow rate is in SCFM. The costs in the figure assume a waste gas deficient in air, and a compound with a molecular weight of 80 and a heat of combustion of 15,000 BTU/lb VOC. The thermal incinerator operates at 1600 degrees F and .75 seconds and achieves 70 percent recuperative heat recovery.

The figure can be used to approximate cost effectiveness for situations other than that described in the above paragraph. For compounds with different molecular weights, the x-axis scale should be increased by 80 over the molecular weight of the compound. For example, for a compound with molecular weight of 40, the x-axis scale would read 2000, 4000, and 6000. For cases where the waste gas contains sufficient oxygen for combustion, the cost effectiveness should be decreased by the following percentages:

|       |      |     |
|-------|------|-----|
| 1000  | SCFM | 7%  |
| 2500  | SCFM | 14% |
| 5000  | SCFM | 21% |
| 10000 | SCFM | 26% |
| 25000 | SCFM | 30% |

This adjustment accounts for the smaller size and lower fuel requirements of these cases. Finally, for cases where the combustion value of the stream per pound of VOC is higher, the below listed decreases approximate the costs. These adjustments assume 30,000 BTU/lb VOC.

|                                |               |      |     |
|--------------------------------|---------------|------|-----|
| for ppmv <500                  | No adjustment |      |     |
| for ppmv between<br>500 & 3000 | 1000          | SCFM | 5%  |
|                                | 2500          | SCFM | 10% |
|                                | 5000          | SCFM | 15% |
|                                | 10000         | SCFM | 20% |
|                                | 25000         | SCFM | 25% |
| for ppmv >3000                 | No adjustment |      |     |

This adjustment accounts for the lower fuel use at higher BTU/lb levels.

EVALUATION OF "DEGREE OF CONVERSION OF  
FLARE GAS IN REFINERY HIGH FLARES",  
by K. D. SIEGEL

Prepared for:

OFFICE OF AIR QUALITY PLANNING AND STANDARDS  
U. S. ENVIRONMENTAL PROTECTION AGENCY  
RESEARCH TRIANGLE PARK, NORTH CAROLINA 27711

Prepared by:

ENERGY AND ENVIRONMENTAL ANALYSIS, INC.  
2607A Carver Street  
Durham, North Carolina 27705

27 August 1980

## 1. Introduction

The purpose of this report is to evaluate the thesis entitled "Degree of Conversion of Flare Gas in Refinery High Flares" by K. D. Siegel. Little published flame performance data exists, especially in terms of the combustion efficiency. In the recent Ph. D. dissertation submitted to the University of Karlsruhe, West Germany, Siegel performed an extensive experimental study of a small industrial sized flare, including measurements of combustion efficiency.

### 1.1 Background

As a prelude to evaluating Siegel's thesis, a discussion of pertinent background material in the literature is appropriate to give a framework in which to place Siegel's work. Only a few studies are known which report the combustion efficiency of flares. The ones that are known are of questionable value for two reasons: (1) they were performed on small model flares without tested scaling laws with which to apply the results to larger industrial-sized flares, and (2) conclusions for flare performance often were derived from single point measurements which are difficult to reproduce and may not convey enough information about the plume. The following constitutes a summary of the references pertinent to the discussion:

- Grumer et. al.<sup>3\*</sup> studied the effect of crosswinds on hydrogen flares. The flare used was 9.2 centimeters in diameter. The fluid flows were 0.28 - 3.5 meter/second for hydrogen and 7.6 and 11.9 meter/second for the crosswind. They were unable to measure any discharge of hydrogen.
- Guenther and Lenze performed calculations on eddy detachment and burnout of detached eddies. They assumed 50 percent burnout of detached eddies and estimated, as a result of batch detachment, a maximum of 1 percent loss of the gas throughput.
- Becker performed measurements on model flares in a wind tunnel. With natural gas as the fuel, he performed tests with wind velocities between 5 and 10 meter/second and measured burnout values between 99.8 and 99.9 percent.
- Lee calculated the amount of substance detached from flares subject to crosswinds. Using a flare of 50 centimeters in diameter, he measured a loss of 0.4 percent for a wind velocity of 1 meter/second and up to 12 percent for a wind velocity of 5 meter/second.
- Straits reports conversion of 99 percent in natural gas flares without steam addition. For sooty flames of other fuel gases, he showed conversions of 75 percent without steam addition. According to Straits, the validity of the data is difficult to verify due to poor data reproducibility.

---

<sup>3</sup> See Table 1 for bibliographical listings.

## 1.2 Thesis Conclusions by Siegel

Siegel's experiments were performed on a small industrial sized flare and are recorded and summarized in his thesis, "Degree of Conversion of Flame Gas in Refinery High Flares." A synopsis of his pertinent conclusions is as follows:

- In soot-free flare flames, the conversion factor was at least 0.99 in the absence of cross-flow winds.
- In sooty flare flames, the emission factor for the pollutants part in combustion products was less than 1 percent of the mass of carbon originally chemically bound in the flare gas.
- Local burnout degree, a parameter used by the author, did not correlate with the operating parameters -- mass flow, density, steam/gas mass ratios, and wind velocity; in nearly all cases it was 0.99 or greater. (Local burnout degree indicates the degree to which combustion is complete. In a condition of excess air, which is typical of a flare, the combustion process would be complete when all the carbon was in the form of carbon dioxide. Local burnout degree is measured by the concentration of carbon dioxide divided by the combined concentrations of carbon dioxide, carbon monoxide, and unburned hydrocarbons.)

At first glance these conclusions lead one to believe that a major breakthrough had been made in assigning a value for the flare combustion efficiency. Additionally, the author suggests that the measured combustion efficiency of 99 percent obtained during his tests could be universally applied to flares in general. An examination of the thesis consists of a corroboration of the experimental and theoretical methodology and then a corroboration of the conclusions. The salient factors on which the conclusions are based are flare head design and operation, flare gas composition, and carbon mass balance.

## 2. Flare Head

The flare head design in Siegel's experiments may have played an important role in the results produced. In the particular flare head design used, fuel-air-steam admixing took place prior to exit from the flare tip. The result was a partially premixed gas issuing from the flare and being ignited.

Some proof of the premixing is found by examining Siegel's data. In a couple of runs, he measured the oxygen concentration at the flare tip. In one case he measured an oxygen concentration of 8.2 percent. However, in none of the cases did he measure across the flare tip to give an idea of the extent of premixing achieved.

### 2.1 Design

Some general statements about the flare head design and its ramifications follow:

- A flame in which the fuel and air are premixed prior to ignition is expected to have a shorter flame than one in which the fuel and air mix after issuance from the flare because the number of locations in the plume where fuel and air are in ignitable concentrations occurs more quickly in premixed flames. Furthermore, the distribution of fuel-air concentrations can be expected to be narrower and closer to an optimum concentration for combustion. This implies that the combustion efficiency from a premixed flame would be equal to or higher than one in which fuel and air mixing is important.
- In the flare head design used by Siegel, the tip was in the shape of a truncated cone and the flare head emitted the gas in the shape of a diverging cone, while many flare head configurations emit the gas vertically. Therefore, the plume reported by Siegel may be wider and the flame shorter than other elevated flares. This could explain why the flame lengths in Siegel's experiments are a factor of 1.5 shorter than flames typically calculated by standard correlations.
- Siegel's flare head configuration is not unknown. Flare head designs which employ the Coanda effect -- where steam and gas flow in the head induces air infiltration and mixing inside the tip -- are used worldwide. In the United States, however, less than 10 percent of the installed flares employ this tip configuration. American plant operators are reluctant to use flare configurations which have combustible mixtures below the flare tip, for two reasons: (1) flashback, the traveling of the flame into the flare, which causes a shut down of the flare, can occur, and (2) combustion will start inside the flare tip which may contribute to reduction of the flame tip life. In one of the cases where Siegel measured the oxygen concentration at the flare tip center, it was nearly zero but the temperature was nearly 400 degrees C, which is typical of conditions in which combustion already has started inside the flare head. In spite of these concerns, this flare head design can be operated successfully. Currently, Exxon is employing this design in many of its flaring applications.

## 2.2 Operating Conditions

The important operating conditions reported by the author are:

|                               |   |                             |
|-------------------------------|---|-----------------------------|
| Flare gas mass flow           | : | 0.13-2.9 t/h                |
| Flare gas density             | : | 0.54-1.86 kg/m <sup>3</sup> |
| Steam/gas mass ratio          | : | 0 - 1.73 kg/kg              |
| Relative cross (lateral) flow | : | 0 - 6 m/s                   |

The conversion factor was unaffected by the operating parameters over the entire range of operating conditions. The flare head is designed for fuel-air-steam mixing before the exit. The author states that under normal operating conditions the flare flame does not burn as a diffusion flame, one in which mixing is important, but burns as a partially premixed flame. He concluded that the conversion factor was not affected by this range of operating conditions. In the normal course of designing an experiment, it is important to choose appropriate operating parameters for demonstrating control over the experiment. The author chose parameters which would affect the flare as if mixing was important. Given that the flame was partially premixed he could have chosen parameters appropriate to that condition. Oxygen concentration and distribution across the flare head, both important measures of the degree of premixing, could have been systematically varied to demonstrate its effect on the flare performance.

In the United States, flares are typically designed to have a velocity between 0.2 - 0.4 times the speed of sound during upset discharges. During normal operation, the actual velocity may be between 1 - 5 percent of that value. Even with these fluctuations, the flow can still be considered turbulent. Siegel's flares were at the low end of the normal operational range even for the high values of his volume flow rates. The effect of his operating choice may be that the flare used in Siegel's experiments would be more affected by outside forces, such as crosswind, at the lower flow rates. In addition, at such low flow rates, eddy detachment is less of a possibility than at higher flow rates since the plume momentum is considerably lower. The effect on conversion efficiency in this case is difficult to predict because there are conflicting mechanisms at play. The low flow would result in a longer residence time for the fuel in the combustion zone which would tend to increase combustion efficiency. However, for the same conditions, low flow rates would reduce the rate of air entrainment and fuel-air mixing could reduce the combustion efficiency.

### 3. Flare Gas Composition

#### 3.1 Combustion Process

Combustion of fuel occurs in a condition where a number of distinct physical mechanisms interact simultaneously. Combustion equilibrium, chemical kinetics, and mixing are primary mechanisms which could control the process. If either of these physical or thermodynamic mechanisms occurs in a time scale much slower than the others, then the process rate is limited by that mechanism and can be characterized by the equations which apply to that mechanism. The experimental conditions were tested to determine if a rate limiting step exists. For a representative gas analysis given by the author, an equilibrium calculation was performed using the NASA Chemical Equilibrium Calculation Program,<sup>4\*</sup> which indicated complete conversion of the carbon chemically bound in the fuel to carbon dioxide (CO<sub>2</sub>) and carbon monoxide (CO). Further, the flare conversion is not chemical kinetically limited either. In a diffusion flame the characteristic reaction times are considerably smaller than the characteristic times needed for mixing; therefore, mixing is the rate-controlling step. Hence, for the flare gases used by the author, the combustion process was not limited by equilibrium or chemical kinetics.

#### 3.2 Hydrogen Content

Another important factor affecting the conversion is the composition of the flare gas. An examination of the constituents of the flare gases and their composition reveals a high hydrogen concentration in almost all of the samples analyzed, with the hydrogen concentration varying mostly between 50 to 64 percent (by volume). This has an interesting bearing on the reported results. The flammability limits of hydrogen in air are among the widest known (with the exception of acetylene) as shown in Table 2. The lower and upper flammability limits are 4 percent and 75 percent (by volume), respectively. The upper limit is considerably higher than that of most hydrocarbons (except acetylene). This means that hydrogen combustion can be initiated in relatively fuel rich conditions. This point becomes important in the light of two facts – (1) the high hydrogen concentrations in the flare gas samples used in the experimental work of Siegel, and (2) the mixing controlled nature of diffusion flames. Thus, despite the relatively slower rate of mixing, flare gas combustion (of the hydrogen) could have been initiated very close to the flare tip with a smaller addition of air. This could at least partly explain the occurrence of a temperature peak very close to the flare tip and the high conversions observed by the author. The combustion of hydrogen could provide an abundant supply of free radicals (e.g., the hydroxyl radical, OH) which could initiate and propagate the hydrocarbon combustion reactions. These radicals could also play a part in the conversion of soot. Therefore, the high hydrogen concentration could influence considerably the results reported.

Flare gases in the chemical industry typically have a much higher hydrocarbon concentration than that in Siegel's samples. This may mean narrower flammability limits, a decrease in the supply of free radicals from the hydrogen combustion reactions, and an increase in the steam requirements

---

<sup>4</sup> See Table 1 for bibliographical listing

to suppress soot formation. Another possible effect of higher hydrocarbon content is that the eddies could have greater unburned carbon content due to the possible incomplete combustion. This could be important if eddy detachment was significant. However, a counterpoint to this argument is that since the lower flammability limits of most hydrocarbons are lower than hydrogen, they could burn considerably fuel lean, -- conditions typical of the outer regions of a flare. Since most of the eddy detachment occurs from the outer regions, these eddies could still have a low unburned carbon content.

Generally, the more complex the hydrocarbon, the more difficult it is to combust. For example, benzene is more difficult to combust than methane. In fact methane is an intermediate product of the benzene destruction process. The high conversion efficiencies recorded by Siegel may be peculiar to his choice of fuel with the low hydrocarbon concentration and may not be applicable to those gases in the chemical industry which have high hydrocarbon concentrations.

### 3.3 Btu Content

The stream chosen by Siegel has a Btu value of over 1000 Btu/scf. However, some gases flared in the industry have high inert concentrations and low Btu contents of around 125 - 200 Btu/scf. Although a quantitative relationship between combustion efficiency and Btu content is not known, it is known that it is difficult to sustain the combustion of gases with a low Btu content. Addition of a high Btu gas, like methane, is one technique employed to sustain combustion.

### 3.4 Summary

Because of the particular gas compositions in Siegel's work, the ramifications of all of these differences have not been explored, and the scope of his results can only be considered to be limited.

#### 4. Carbon Mass Balance

A conversion efficiency of 99 percent or greater is a potentially important conclusion of this thesis. Testing its validity would entail examining the method by which it is determined. The parameter used in the thesis is called the degree of conversion, which is calculated by measuring the mass flows of the carbon found in the incoming fuel and in the carbon monoxide, unburned hydrocarbons, and soot which leave the combustion zone.

The carbon mass flow calculation is achieved by multiplying the local density by the associated velocity and integrating across the cross-sectional area. The mass balance entails comparing this value with that for the incoming fuel. The author collected this specific data for use in the carbon mass balance. Local mass concentration of the combustion products in the plume cross-section was measured using a sampling probe. Simultaneously a velocity measurement using a pitot tube is taken at the same location. In the instances reported by the author, the average measured carbon mass flow in the plume was 50 percent of the carbon mass flow in the fuel. Siegel hypothesized that the source of the discrepancy in these results was that the velocity measurements were not taken in the main axis of the flow, and, thus, resulted in low readings. When these values were used in mass calculations they would yield the low values obtained. Siegel closed the carbon mass balance by assuming that the remainder of the unmeasured carbon was in the form of carbon dioxide. Neither carbon monoxide nor the unburned hydrocarbons could be large contributors to unaccounted for carbon mass flow since their concentrations at the edge of the plume were low, (.01 percent and 10 parts per million, respectively.)

We examined the experimental and analytical procedures employed by Siegel to outline possible factors affecting the closure of the carbon balance. Whereas Siegel only used the edge concentration of carbon monoxide and unburned hydrocarbons as stated above, we attempted to close the mass balance using the mass concentrations of all three species -- unburned hydrocarbons, carbon monoxide, and carbon dioxide. Using the reported edge concentrations, the calculation was extended to the theoretically calculated edge of the plume which was larger than that measured experimentally. This procedure still did not achieve a substantial improvement to mass conservation closure.

The identification of possible sources of the mass conservation discrepancy or possible improvements to the reported procedures must start with the velocity measurement procedure. Velocity was measured using a pitot tube. When it was suspected that the velocity measurement was dubious, Siegel could have instituted a test procedure where the angular orientation of the pitot tube relative to the direction of flow is systematically altered to determine the largest average velocity vector. This procedure can be repeated in a number of locations revealing important information concerning the nature of the flow in the plume. Alternately he could have used a multiport pitot tube which would achieve the same result.

Unresolved questions concerning the carbon mass balance could have been answered by taking more measurements in cross-sectional traverses at different plume axial locations. Siegel took a single cross-sectional traverse near the end of the flame tip, when he could have taken more traverses closer to the

flare head. This would have served two functions. First, measurements close to the flare tip could have determined if there were detachment losses. The assumption in Siegel's paper is that the mass losses due to eddy detachment were negligible. If the measurements at different axial locations reveal that the total mass measured decreased farther away from the flare head, the importance of eddy detachment has been demonstrated. If the measurements at different axial locations reveal that the total mass measured remained constant, then the assumption that eddy detachment is negligible is supported.

Overall mass conservation calculations were performed only on flames with no crosswind and no soot. A mass balance could not be performed for a crosswind circumstance since a perpendicular cross-section was difficult to identify. In the sooty flame situation, an overall mass conservation could not be calculated due to the carbon held in soot particles which could not be constantly measured. The author used the data for a flare with no wind and then extrapolated the results to the other conditions. Siegel implies that since he nowhere measured less than 99 percent conversion efficiency (at least locally) that his extrapolation was valid.

#### 4.1 Local Burnout Degree

Local burnout degree is calculated by dividing the density of carbon dioxide by the densities of carbon dioxide, carbon monoxide, and unburned hydrocarbons measured at a sampling point. The author makes an adjustment to the calculation of the parameter for sampling locations upstream of the flame. He hypothesizes that one-half of the carbon monoxide will ultimately oxidize to carbon dioxide and adds it to the numerator, increasing the value of the parameter. Even if the assumption were valid, the value calculated does not represent the actual degree of conversion which is at that location. A few experimental points were recalculated to see its effect on the reported values of 99 percent. If the effect is small, less than 1 percent, then the point is moot. However, the magnitude of the change varied by 3 - 5 percent. Rather than values of 99 percent, the calculated local burnout degree became 95 - 97 percent. Although it is clear that a high degree of conversion existed, it is tenuous that the conversion was 99 percent or greater in every case.

#### 4.2 Sampling Procedures

Siegel's probe temperature control raises questions concerning the relative concentrations of carbon dioxide and carbon monoxide reported. Straits reported that a hot probe temperature, which would allow continued reaction even in the probe, is important to control. It also is known to keep the temperature inside the sample line above 100 degrees C to prevent condensation of water inside the line. If the water were to condense, then the concentration of water inside the gas would change and the relative quantities of carbon monoxide and carbon dioxide would shift. Siegel reports that the temperature in the sample drops to 60 degrees to 100 degrees C in the system.

Siegel concludes that for an overall flare conversion efficiency in a soot-free flare, the result of 99 percent was found in the absence of a cross-wind. An industrial flare is rarely operated in a condition of no cross-wind. If the cross-wind effect is later found to be critical, the extrapolation of these results to other operating conditions would be severely

limited. An overall conversion factor for sooty flares was not determined since a mass balance could not be achieved. Rather the author made conclusions regarding the amount of conversion achieved in the gas phase based on measurements of local burnout degree in excess of 99 percent. He made a separate calculation regarding the mass present in the soot.

#### 4.3 Uncombusted Eddy Detachment

There are other factors in the method by which flares in a cross-wind were examined which limit his extrapolating his conclusion. Siegel confirms that in a cross-wind unburned material is discharged above the flare head. This is supported by articles referenced in Table 1. He says, however, that this material cannot be counted on as having been emitted as unburned since it is driven back towards the flame and burned.

Measurements were made on two planes -- one perpendicular to the flare head on the windward side and one parallel to the flare head above the flame. The data on these planes supported his conclusions, but Siegel's data points are insufficient to conclusively show that discharge of unburned material is insignificant. On the planes measured, eddies which are separated from the plume would return due to the wind. There are other planes which could be important. Eddies which are detached from the sides of the plume would be carried away from the plume, as would eddied from the leeward, underside of the plume. Each of these should come under experimental scrutiny.

#### 4.4 Summary

The problem is that Siegel's conclusions based on the mass balance he did perform are specious. The carbon mass balance never approached 50 percent closure. In addition, the suggested source of the discrepancy, the velocity measurement, was not substantiated. Furthermore, the uncertainty regarding the carbon mass balance that was achieved is unnecessary and detracts from the impact this work could represent.

## 5. Summary Comments on Siegel's Data

A summary of the important aspects of the thesis as well as the important observations is presented as follows:

- This thesis contains many measurements of concentration, temperature, and velocity profiles at different locations. This was a contribution to existing knowledge.
- Most of the concentration measurements at the end of the flame indicate complete combustion.
- Data grid was not extensive enough for the conclusions advanced especially in the case of flares with cross-winds.
- Operating parameters which would affect a premixed flame and demonstrate the researcher's control over the experiment were never chosen.
- The mass conservation method was an integral part of the author's approach, yet it was never brought to better than 50 percent closure on the average. The identified source of the discrepancy, the velocity measurement, was never tested.
- High hydrogen concentrations may contribute to high conversion efficiencies.
- Partially premixed flames are not typical of flares in this country.

## 6. Conclusions

There is some evidence which supports 99 percent combustion efficiency for a flare with a partially premixed type flare head, using a gas with a high hydrogen concentration in the absence of a cross-wind. However, not enough evidence exists to support the extension of the conclusion to flares which are not premixed, operate in a cross-wind, are sooty, or use fuels in which there is high inert gas concentrations or low hydrogen concentrations.

There remains questions regarding the important aspects of the work which detracts from the results. Although the data suggests high local conversion, there is not enough data to support the quantification of conversion efficiency at 99 percent or the extension of this value to other situations.

Table 1  
Partial Bibliographical Listing from

K. D. Siegel's Thesis

J. F. Straits, III, "Flaring for Gaseous Control in the Petroleum Industry" Annual Meeting of the Air Pollution Control Association, 1978, Paper-No. 75-38.8.

T. A. Br\_\_\_\_\_wski, Prog. Energy Combustion Science, 2, 129/141 (1976).

R. Becher. "Faekelbrenner fur rauchlose und gerauscharme Verbrennung", KT1 - F\_\_\_\_\_, 1976.

R. Gunther. B. Lenze, "Gutachten Uber den Urnsetzungsgrad des Fackelgases in den Heckfackelm der Oberrheinischen Minarolol-Werke GmbH in Karlsruhe", 1972.

\_\_\_\_\_ Lee, "Der Yerbrennungverlauf in auftriebsbehafteten Flammen mit und \_\_\_\_\_ WindeinFlu\_", Dissertation, Universitat Karlsruhe, 1977.

J. F. Straits, "Hydrogen Flare Stack Diffusion Flames", Department of the Interior, Bureau of Mines, (1970), Report of Investigation 7457.

TABLE 2 is not readable.