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Project Summary

SITE Program Evaluation of the Sonotech Pulse Combustion Burner Technology

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A series of demonstration tests was performed at the Environmental Protection Agency's (EPA's) Incineration Research Facility (IRF) under the Superfund Innovative Technology Evaluation (SITE) program. These tests, 12 in all, evaluated a pulse combustion burner technology developed by Sonotech, Inc., of Atlanta, Georgia. The burner system incorporates a pulse combustor, the pulsation frequency of which can be tuned to induce large amplitude sonic pulsations inside a combustion process unit such as a boiler or an incinerator.

The primary objective of the test program was to develop test data to allow evaluating whether the Sonotech pulse combustor applied to the IRF rotary kiln system (RKS), when compared to conventional, non-pulsating combustion, resulted in: decreased flue gas NO_x, CO, and soot emissions; increased POHC DRE; decreased combustion air requirements; decreased auxiliary fuel requirements; and increased incinerator capacity. The waste feed for all tests was a mixture of contaminated materials from two manufactured gas plant (MGP) Superfund sites. One component of the test waste was a combination of pulverized coal and contaminated sludge waste from the Peoples Natural Gas Company site in Dubuque, Iowa. The other components of the test waste consisted of soil borings and a tar waste from an oil gasification process obtained from an MGP site in the southeast U.S. To address the demonstration objectives 12 tests were performed under four different test conditions. Each condition consisted of three identical tests to obtain data in triplicate. Test data were statistically evaluated using the rank sum test. When the rank sum test is applied to two data sets, each containing three data points, the data sets are different, at the 95 percent confidence level, when corresponding ranges do not overlap.

The results addressing the primary test objectives of the test program are as follows: the average CO emissions at the afterburner exit decreased from 20 ppm (range of 8.0 to 40.0 ppm) for test condition 2 to 14 ppm (range of 12.6 to 16.0 ppm) for test condition 3; the average NO_x decreased from 82 ppm (range of 78.3 to 85.1 ppm) for test condition 2 to 77 ppm (range of 68.0 to 87.1 ppm) for test condition 3; the average soot emissions decreased from 1.9 mg/dscm (range of 0.9 to 2.7 mg/dscm) to less than 1.0 mg/dscm (range of <0.8 to 0.9 mg/dscm). Benzene DRE for all 12 tests was greater than 99.994 percent. Naphthalene DRE for all 12 tests was greater than 99.998 percent. The combustion air requirements showed a decrease from the 38,400 to 40,600 dscfh range to the 34,800 to 39,900 dscfh range when the Sonotech combustor was used; the auxiliary fuel requirements (natural gas) were practically equal under conventional and Sonotech conditions; and the waste feedrate capacity increased by 13 percent with the Sonotech burner operational. As the demonstration waste had a significant heat content (8,500 Btu/lb), the capacity increase may be translated into a reduction in auxiliary fuel needed to treat a unit mass of waste from 21.1 kBtu/lb for conventional combustion to 18.0 kBtu/lb for the Sonotech system.

This Project Summary was developed by EPA's National Risk Management Research Laboratory, Cincinnati, OH, to announce key findings of the research project that is fully documented in a separate report of the same title (see

Project Report ordering information at back).

Introduction

Sonotech, Inc., of Atlanta, Georgia, has developed a pulse combustion burner technology that claims to offer benefits when applied in a variety of combustion processes. The burner system incorporates a pulse combustor that can be tuned to excite large-amplitude sonic pulsations inside a combustion chamber such as a boiler or incinerator. Sonotech claims that these pulsations serve to increase the rates of heat, mixing (momentum), and mass transfer in the combustion process; and claims that these rate increases are sufficient to result in more complete combustion.

Sonotech has targeted waste incineration as a potential application for this technology. Accordingly, to demonstrate the claimed benefits of the technology within a well-established forum for providing technically sound and unbiased evaluations, Sonotech proposed a technology evaluation test series under the Superfund Innovative Technology Evaluation (SITE) program. The Sonotech proposal was accepted, and an evaluation test program was performed at EPA Incineration Research Facility (IRF) in Jefferson, Arkansas.

Description of the Technology

A pulse combustor typically consists of an air inlet, a combustor section, and a tailpipe. Periodic variations in fuel oxidation and heat release produce pulsations in the combustor section pressure, temperature, and gas velocities. When properly applied, a pulse combustor can excite large-amplitude (150 dB or greater) pulsations within a cavity downstream of the pulse combustor tailpipe. This cavity could be the combustion chamber of a boiler or an incinerator, for example.

A retrofit application of the Sonotech pulse combustion system was evaluated in this test program. Specifically, the kiln section of the RKS at the IRF was retrofitted with a pulse combustion burner capable of delivering up to 73 kW (250,000 Btu/hr) of heat input from natural gas fuel to the kiln. This corresponds to 15 to 20 percent of the typical heat input to the kiln. The RKS was configured as shown in Figure 1, with the Sonotech combustion system retrofitted into the end plate at the ash discharge end of the kiln.

Demonstration Objectives

Sonotech claims that the application of pulse combustion technology to an incineration system has several significant advantages over conventional (non-pulsating) incineration. Thus, the general objective of the demonstration test program was to develop the data needed to allow objective and quantitative evaluation of these claims. Accordingly, the primary test program objective was to develop test data to allow evaluating whether the Sonotech pulse combustion technology applied to the IRF RKS, when compared to conventional, non-pulsating combustion, resulted in:

- Increased incinerator capacity or productivity
- Increased principal organic hazardous constituent (POHC) destruction and removal efficiency (DRE)
- Decreased flue gas CO emissions
- Decreased flue gas NO_x emissions
- Decreased flue gas soot emissions
- Decreased combustion air requirements
- Decreased auxiliary fuel requirements

The secondary test program objective was to develop test data to allow evaluating whether the application of the Sonotech technology, when compared to conventional, non-pulsating combustion:

- Reduced the magnitude of transient puffs of CO and total unburned hydrocarbons (TUHC)
- Allowed reduced incineration costs
- Caused significant changes in:

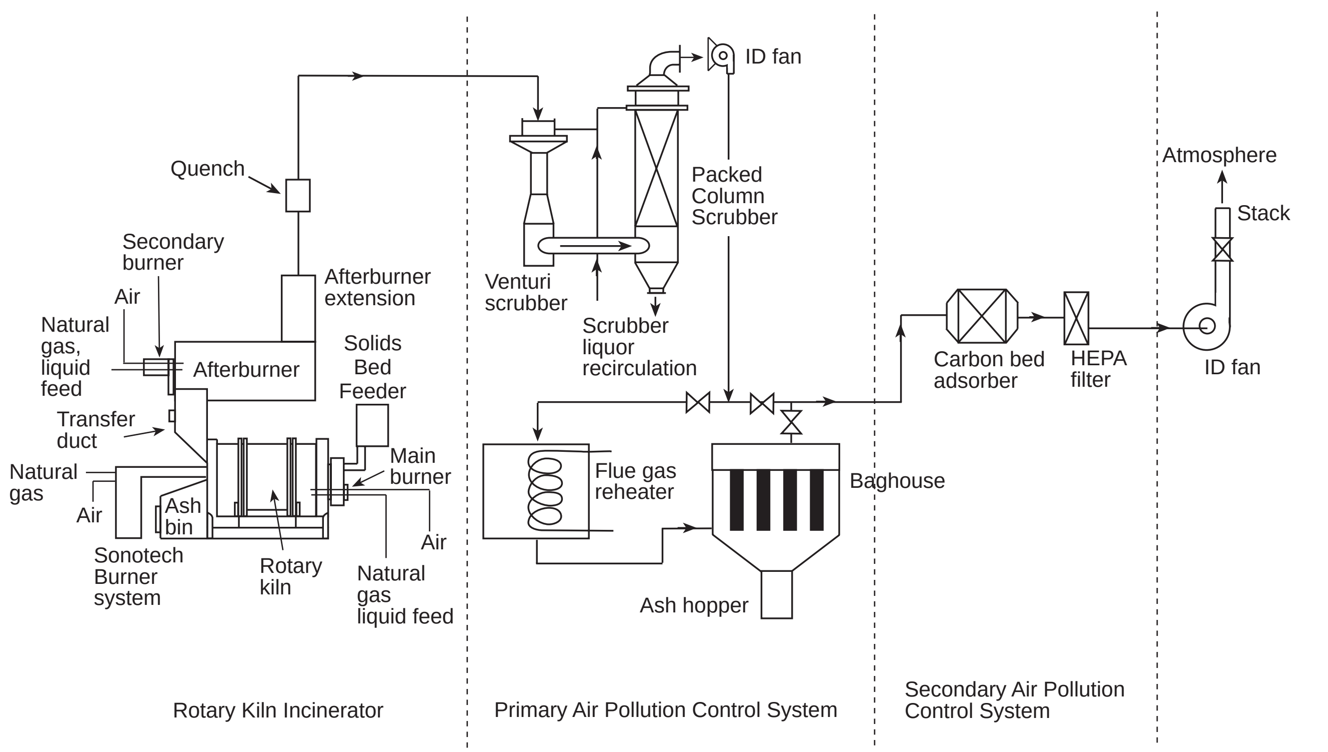

Figure 1. Schematic of the IRF rotary kiln incineration system.

- — The distribution of hazardous constituent trace metals among the incineration system discharge streams (kiln bottom ash, scrubber liquor, baghouse flyash, and baghouse exit flue gas)
- — The leachability of the toxicity characteristic leaching procedure (TCLP) trace metals from kiln bottom ash, scrubber liquor, and baghouse flyash

This last secondary objective item does not relate to any Sonotech claim, but is of general interest to the overall IRF research program.

Test Program

To address the test program objectives, tests at the following four different incineration system operating conditions were performed:

- Test Condition 1: Conventional combustion under baseline, typical RKS operation (28 kg/hr [61 lb/hr])
- Test Condition 2: Conventional combustion at the maximum RKS waste feedrate without pulsations (33 kg/hr [73 lb/hr])
- Test Condition 3: Sonotech pulse combustion at nominally the same feedrate and conditions as Test Condition 2 (34 kg/hr [74 lb/hr])
- Test Condition 4: Sonotech pulse combustion at the maximum RKS waste feedrate with pulsations (37 kg/hr [82 lb/hr])

The test waste feed for all tests was a mixture of contaminated materials from two manufactured gas plant (MGP) Superfund sites. (The specific components of this feed are discussed later.) This waste feed was batch fed to the RKS via the system's fiberboard container ram feed system, which feeds 1.5-gal (5.7-L) fiberboard containers to the kiln at virtually any specified feed frequency. When a relatively high heat content material is being fed, the maximum allowable waste feedrate is established based upon the onset of puffs of incompletely combusted organic constituents (CO and TUHC) that survive the afterburner.

Given this, Test Condition 1 was at a waste feedrate consistent with stable incinerator operation under conventional combustion, with infrequent spikes of CO and/or TUHC at the afterburner exit. Test Condition 2 was at an increased waste feedrate that resulted in routine afterburner CO spikes. This condition could be termed borderline acceptable incinerator operation under conventional combustion. Test Condition 3 was at the same waste feedrate as Test Condition 2, but with the Sonotech pulse combustion system in operation. Test Condition 4 was at a further increase in waste feedrate, with the pulse combustor in operation, such that routine afterburner exit flue gas CO spikes recurred. This condition could be termed borderline acceptable operation under pulse combustion operation. Three test runs (triplicate testing) at each test condition were completed to allow the precision of each emission and discharge stream composition measurement to be assessed.

As indicated above, the test waste feed material for the test program was a mixture of materials from two MGP Superfund sites. One component of the material was a combination of pulverized coal and contaminated sludge/soil waste from the Peoples Natural Gas Company Superfund site in Dubuque, Iowa. This site is an abandoned coal MGP site, and the sludge waste at the site contains high concentrations of coal tar constituents. The other components of the test feed material were contaminated soil borings and a tar waste from an oil gasification process, both obtained from an MGP site in the southeastern United States.

The hazardous constituent contaminants of all three test waste components were several polynuclear aromatic hydrocarbon (PAH) compounds, and the VOCs benzene, toluene, ethylbenzene, and xylenes (BTEX). Although concentrations of several contaminant compounds were quite high in at least the tar component of the waste mixture, it was decided that spiking the waste feed with benzene and naphthalene would be necessary to guarantee meaningful DRE calculations.

To address the test program objectives, the composite waste feed, the kiln ash discharge, the scrubber system liquor, the collected baghouse ash, the afterburner exit flue gas particulate, the afterburner exit flue gas, and the baghouse exit flue gas for each test were sampled and analyzed for sample-matrix-specific combinations of PAHs, VOCs, contaminant trace metals, polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofurans (PCDDs/PCDFs), and TCLP-leachable trace metals. In addition, the total organic carbon (TOC) content of the afterburner exit flue gas particulate was determined and used as the measure of soot emissions. Later in the test program, measuring the heating value of each test's kiln ash discharge was added as an indication of waste treatment residue quality in terms of completeness of waste burnout.

Test data from the program were evaluated using the rank sum test. The rank sum test says the two data sets, each containing three data points (the case for this program) are statistically different at the 95 percent confidence level when the data ranges in each set do not overlap.

Test Results

Incinerator Operating Conditions

Table 1 provides a summary of the average incineration system operating conditions for each of the four program test conditions. Each operating parameter noted in the table was recorded nominally every 30 seconds over a 4- to 5-hour flue gas sampling period for each test by the RKS data acquisition system. Test averages were calculated for each parameter. The data in Table 1 represent the average value determined for the three tests performed for each test condition.

The data in Table 1 show that the kiln exit gas temperatures collected for all conditions averaged close to the test program target of 925°C (1,700°F), and that average afterburner exit gas temperatures were right at the test program target of 1,095°C (2,000°F). Afterburner exit flue gas O_2 levels averaged close to 9 percent for all test conditions, although slightly lower average levels existed for Test Conditions 3 and 4, the two pulse combustion test conditions.

The baseline (Test Condition 1) waste feedrate was 27.7 kg/hr (61.0 lb/hr). This feedrate was increased to 33.1 kg/hr (72.8 lb/hr) to give the borderline acceptable operation associated with Test Condition 2. Test Condition 3, with the pulse combustion system in operation, was performed at nominally the same (just slightly higher) feedrate as Test Condition 2, as planned. The Test Condition 3 feedrate was 21 percent greater than the Test Condition 1 feedrate. A further 13-percent feedrate increase over that for Test Condition 2 was possible before incinerator operation entered the borderline acceptable regime with the pulse combustion system in operation. Thus, with respect to the Sonotech claim that increased incinerator capacity can be realized with pulse combustion, test data show that a capacity increase in the range of 13 percent (comparing Test Condition 4 to Test Condition 2) can indeed be realized.

The data in Table 1 further show that the total system heat input needed to maintain target incineration temperatures was relatively constant for all four test conditions at about 645 kW (2.2 MBtu/hr). Specifically comparing the auxiliary fuel use for Test Condition 3 to that for Test Condition 2 shows that the auxiliary fuel requirements were nominally the same.

Table 1. Test Condition Operating Data

Parameter	Test condition average (3 tests) 1 Conventional baseline	 2 Conventional max. feed	 3 Pulsations feed as in 2	 4 Pulsations max. feed
Waste feedrate, kg/hr (lb/hr)	27.7 (61.0)	33.1 (72.8)	33.5 (73.6)	37.5 (82.4)
Kiln				
Gas temperature, °C (°F)	935 (1,720)	940 (1,730)	925 (1,700)	925 (1,700)
Solids bed temperature, °C (°F)	965 (1,770)	990 (1,810)	1,020 (1,870)	1,030 (1,890)
Afterburner exit gas temperature, °C (°F)	1,095 (2,000)	1,095 (2,000)	1,095 (2,000)	1,095 (2,000)
Afterburner exit O_2, %	9.3	9.3	8.7	8.5
Heat input, kW (kBtu/hr)				
Waste feed	153 (522)	176 (601)	184 (628)	204 (697)
Kiln auxiliary fuel				
Main burner	193 (659)	148 (506)	82 (282)	60 (205)
Sonotech burner	0 (0)	0 (0)	59 (200)	59 (200)
Total kiln	193 (659)	148 (506)	141 (482)	119 (405)
Afterburner auxiliary fuel	297 (1,012)	303 (1,035)	321 (1,094)	317 (1,082)
Total auxiliary fuel	489 (1,668)	454 (1,551)	462 (1,576)	436 (1,487)
Total system heat input, kW (kBtu/hr)	642 (2,190)	630 (2,152)	646 (2,204)	640 (2,184)
Auxiliary fuel consumption per unit of waste treated, MJ/kg (Btu/lb)	63.6 (27,400)	49.2 (21,100)	49.7 (21,400)	41.8 (18,000)

Thus, the Sonotech claim that decreased auxiliary fuel use would be possible with the application of pulse combustion is not supported by the test data. However, because the waste treated in these tests had significant heat content, the capacity increase noted above equates to a corresponding decrease in the auxiliary fuel consumed per unit of waste treated. Comparing the auxiliary fuel consumption per unit of waste treated for Test Condition 4 to that for Test Condition 2 shows that the feedrate increase allowed by the Sonotech system yields a corresponding decrease in auxiliary fuel use per unit of waste treated from 49.2 MJ/kg (21,200 Btu/lb) to 41.9 MJ/kg (18,000 Btu/lb). Visual observations suggest that the Sonotech system produced visually improved mixing in the kiln chamber.

With respect to combustion air requirements, the data in Table 1 show that less combustion air was required, when the same feedrate was used, for the pulse combustion test condition compared to the conventional combustion test condition.

POHC DREs and Residue Quality

The POHC DREs and emission rates at the two flue gas locations sampled are summarized in Table 2. As shown in the table, naphthalene DREs measured at both the afterburner exit and the baghouse exit were uniformly 99.999 percent or greater for all tests, and were not affected by the different test conditions or different waste feedrates. Benzene DREs measured at the two locations were uniformly 99.994 percent or greater (one baghouse exit benzene DRE measurement was 99.989 percent), and again not affected by the different test conditions.

The average naphthalene emission rate at the afterburner exit was reduced from 1.2 mg/hr (range of 0.4 to 2.6 mg/hr), for conventional combustion at Test Condition 2, to 1.1 mg/hr (range of <0.3 to 2.5 mg/hr), with the Sonotech system at the Test Condition 3. The average benzene emission rate at the afterburner exit was reduced from 7.7 mg/hr (range of 2.1 to 12), for Test Condition 2, to 5.7 mg/hr (range of 3.4 to 6.9), for Test Condition 3. However, the significance of the decreases is also difficult to judge because both fall within the precision of the respective flue gas concentration measurement methods. With respect to this, it bears noting that benzene emissions increased from Test Condition 2 to Test Condition 3 when measured at the baghouse exit.

The kiln ash heating value data shown in Table 1 suggest that incineration residue quality, as measured by residue (kiln ash) heating value, was improved with pulse combustion. A decrease in kiln ash heating value from 3.1 MJ/kg (1,340 Btu/lb), for Test Condition 2, to <1.1 MJ/kg (<500 Btu/lb), for Test Condition 3, at the same nominal feedrate but with pulse combustion, was seen. The solids bed temperature data shown in the table are consistent with this decrease. Solids bed temperatures were measured at four axial locations in the kiln during the tests. The temperature at the location recording the peak temperature for each test was averaged over the flue gas sampling period for that test. The entries in Table 1 represent the average of these individual test averages for the three test runs at each test condition. The data show an increase in average peak solids bed temperature of from 965°C (1,770°F) (Test Condition 1)

Table 2. Test Program POHC DRE Summary

	Benzene					Naphthalene				
		Afterburner exit		Baghouse exit			Afterburner exit		Baghouse exit	
	Feed-rate g/hr	Emission rate, mg/hr	DRE, %	Emission rate, mg/hr	DRE, %	Feed-rate g/hr	Emission rate, mg/hr	DRE, %	Emission rate, mg/hr	DRE, %
Condition 1										
Test 1	**253.1**	**44**	**99.99**	**<1.2**	**>99.999**	**378.0**	**6.2**	**99.998**	**5.9**	**99.998**
Test 6	**253.1**	**7.6**	**8**	**2.1**	**99.999**	**378.0**	**2.9[a]**	**99.999**	**3.1[a]**	**99.999**
Test 10	**244.1**	**14.8**	**99.99**	**3.4**	**99.998**	**364.5**	**<0.3**	**>99.999**	**2.5[a]**	**99.999**
Average		**8.9**	**6**	**2.2**	**99.999**		**3.1**	**99.999**	**3.8**	**99.999**
		99.99								
		4								
		99.99								
		6								
Condition 2										
Test 2	**298.3**	**9.0**	**99.99**	**31.0**	**99.989**	**445.5**	**2.6[a]**	**99.999**	**6.0**	**99.999**
Test 7	**307.3**	**2.1**	**6**	**<0.9**	**>99.999**	**459.0**	**0.6[a]**	**99.999**	**<0.3**	**>99.999**
Test 11	**289.2**	**12.0**	**99.99**	**0.6**	**99.999**	**432.0**	**0.4[a]**	**99.999**	**3.5[a]**	**99.999**
Average		**7.7**	**9**	**1.5**	**99.996**		**1.2**	**99.999**	**3.3**	**99.999**
		99.99								
		5								
		99.99								
	7									
Condition 3										
Test 3	**289.2**	**6.9**	**99.99**	**6.4**	**99.997**	**432.0**	**2.5[a]**	**99.999**	**2.4[a]**	**99.999**
Test 5	**307.3**	**3.4**	**7**	**1.5**	**99.999**	**459.0**	**<0.3**	**>99.999**	**0.6[a]**	**99.999**
Test 9	**307.3**	**6.7**	**99.99**	**2.9**	**99.999**	**459.0**	**0.5[a]**	**99.999**	**1.6[a]**	**99.999**
Average		**5.7**	**8**	**3.6**	**99.998**		**1.1**	**99.999**	**1.5**	**99.999**
		99.99								
		7								
		99.99								
	7									
Condition 4										
Test 4	**343.5**	**10.4**	**99.996**	**2.5**	**99.999**	**513.0**	**0.6[b]**	**99.999**	**1.4[b]**	**99.999**
Test 8	**334.4**	**11.7**	**99.996**	**<1.5**	**>99.999**	**499.5**	**0.5[b]**	**99.999**	**2.2[b]**	**99.999**
Test 12	**334.4**	**50.9**	**99.998**	**1.1**	**99.999**	**499.5**	**1.3[b]**	**99.99**	**0.4[b]**	**99.999**

[a]Average concentration of three pairs of M0030 VOST tubes.

[b]Analyte detected below lowest calibrated level.

"<" = Analyte below method detection limit.

to 990°C (1,810°F) (Test Condition 2), for conventional combustion, to 1,020°C (1,870°F) (Test Condition 3) to 1,030°C (1,890°F) (Test Condition 4), for pulse combustion. Specifically, comparing the data for Test Condition 3 to those for Test Condition 2 shows an increase from 990°C (1,810°F), for conventional combustion, to 1,020°C (1,870°F), for pulse combustion, at the same waste feedrate and other system operating conditions. These data suggest that the Sonotech claim of increased heat transfer rates with pulse combustion, specifically to the solids bed, is justified. An increase in heat transfer rate to the solids bed would cause the increased bed temperatures seen and the corresponding decrease in kiln ash discharge heating value.

CO, NO_x, and Soot Emissions

Table 3 summarizes the continuous emissions monitor (CEM) and soot emissions data for the test program. As for the operating conditions data, summarized in Table 1, CEM readings were recorded at nominally 30-second intervals on the RKS data acquisition system. These readings were averaged over the flue gas sampling period for each test. The CEM entries in Table 3 represent the average of each test's average for the three tests at each test condition.

The data in Table 3 show that average kiln exit CO levels substantially increased with pulse combustion, from 68 ppm at 7 percent O_2 for the two conventional combustion test conditions (1 and 2), to 117 ppm at 7 percent O_2 for Test Condition 3 and to 153 ppm at 7 percent O_2 for Test Condition 4. This increase is consistent with both the kiln solids bed temperature and the kiln ash residue quality data in Table 1. As discussed above, pulse combustion caused increased kiln solids bed temperatures and decreased kiln ash heating values, suggesting that pulse combustion caused a greater degree of waste feed organic content devolatilization into the kiln combustion gas. The observation that kiln exit CO levels were increased with pulse combustion suggests that the greater amounts of devolatilized organics were not completely destroyed in the kiln.

Average afterburner exit CO levels were decreased to 15 ppm at 7 percent O_2 (range of 8.7 to 25.6 ppm), for Test Condition 1, and to 20 ppm at 7 percent O_2 (range of 8.0 to 40.0 ppm), for Test Condition 2. Compared to conventional combustion, pulse combustion produced slightly lower average afterburner exit CO levels. Comparing Test Condition 3 (pulse combustion) to Test Condition 2 (with conventional combustion), both of which had the same waste feedrate, shows that pulse combustion resulted in decreased average afterburner exit CO emissions of 14 ppm at 7 percent O_2 (range of 12.6 to 16.0 ppm. Even at the increased waste feedrate achieved with pulse combustion for Test Condition 4, afterburner exit CO levels were only marginally increased, to 17 ppm at 7 percent O_2 (range of 10.5 to 26.2 ppm) — higher than the Test Condition 3 level, but still lower than the Test Condition 2 level.

CO is the final incomplete combustion product in the series of reactions that converts the carbon in organic constituents to CO_2. Thus, an explanation for why afterburner exit CO levels under pulse combustion operation were lower than under conventional combustion operation, while kiln exit levels were higher, may be that organic constituent combustion in the kiln was more complete under pulse combustion operation. More complete organic constituent combustion can result in higher CO (the final incomplete combustion product) levels, while other unburned hydrocarbon levels, including soot, would be decreased. In such cases, the burden on the afterburner to carry the destruction process to completeness would be lessened, resulting in lower afterburner exit CO levels.

The afterburner exit soot emissions data (measured as TOC in the afterburner exit particulate) show a consistent pattern. The soot emission levels given in Table 3 again represent the average of the levels measured for each of the three tests at each respective condition, with the exception of the level noted for Test Condition 1. The afterburner exit particulate for only one Test Condition 1 test was analyzed for TOC, so the Test Condition 1 value in Table 3 reflects only this one measurement. Soot emission levels were <1.3 mg/dscm at 7 percent O_2 for Test Condition 1, the baseline, conventional combustion test condition. They were increased, to 1.9 mg/dscm at 7 percent O_2 (range of <0.9 to 2.7), for Test Condition 2. However, with pulse combustion at the same feedrate for Test Condition 3, soot emissions decreased to <1.0 mg/dscm at 7 percent O_2 (range of<0.8 to 0.9). Even at the increased waste feedrate achieved for Test Condition 4, afterburner exit soot emissions, at 1.3 mg/dscm (range of <0.9 to 1.8), were less than those measured for Test Condition 2.

Afterburner and baghouse exit NO_x emissions were comparable from test condition to test condition and were 90 and 88 ppm at 7 percent O_2 (ranges of 85.5 to 93.9 and 85.8 to 91.1), respectively, for Test Condition 1, and a slightly decreased 82 and 85 ppm at 7 percent O_2, (ranges of 78.3 to 85.1 and 83.6 to 86.3) for Test Condition 2. Levels of afterburner and baghouse exit NO_x were, respectively, 77 and 78 ppm at 7 percent O_2 (ranges of 68.0 to 87.1 and 76.6 to 79.6), for Test Condition 3 (under pulse combustion), and 78 and 72 ppm at 7 percent O_2 (ranges of 73.7 to 81.4 and 68.7 to 75.5), for Test Condition 4 (also under pulse combustion). Although the Sonotech claim that pulse combustion would result in decreased NO_x emissions was confirmed by the test data, the reductions achieved were small, and from low initial NO_x levels.

Table 3. Continuous Emissions Monitor Data

	Test condition average (3 tests)			
Constituent	1 Conventional baseline	2 Conventional max. feed	3 Pulsations feed as in 2	4 Pulsations max. feed
Kiln exit:				
CO, ppm at 7% O_2	68	68	117	153
Afterburner exit:				
CO, ppm at 7% O_2	15	20	14	18
NO_x, ppm at 7% O_2	90	82	77	78
Soot[a], mg/dscm at 7% O_2	<1.3[b]	1.9	<1.0	1.3
Baghouse exit:				
NO_x, ppm at 7% O_2	88	85	78	72

[a]Measured as TOC in particulate.

[b]Measured for only one test.

Residue Discharge Composition

No PAH or BTEX constituent, with the exception of benzene in a few cases, was detected in any kiln ash or scrubber liquor sample from any test. Detection limits for PAHs were 0.1 to 0.3 mg/kg, in kiln ash, and 1 to 3 µg/L, in scrubber liquor. Detection limits for BTEX constituents were 1 to 10 mg/kg, in kiln ash, and 1 to 10 µg/L, in scrubber liquor. Benzene was found in the kiln ash samples from one Test Condition 2 test, from one Test Condition 3 test, and from all three Test Condition 4 tests, but at levels only slightly above the method detection limit of 1 mg/kg.

Incinerator feed, flue gas, and residue discharge samples were analyzed for antimony, barium, beryllium, cadmium, chromium, lead, and mercury. No antimony or mercury was found in any test program sample. The data show that the distribution of these metals in the kiln ash discharge did not vary from test condition to test condition. Concentrations of barium and chromium in the scrubber liquor were slightly lower and in the baghouse exit flue gas were higher for the pulse combustion operating conditions.

The concentrations of the five metals in TCLP leachates of test feed, kiln ash, and scrubber liquor samples ranged from not detected to low. At the concentrations measured, neither the test waste feed or the incineration residual discharges would be a toxicity characteristic (TC) hazardous waste for any test condition, and no significant variation in leachate concentrations with test conditions was seen.

Dioxin Emissions

Chlorinated dioxins and furans were measured in the baghouse exit flue gas for all tests. Test condition average flue gas concentrations are summarized in Table 4 in terms of the two summary concentration measures commonly reported: total PCDD/PCDF and 2,3,7,8-TCDD toxicity equivalents (TEQs). The entries in Table 4 are cited as ranges. This arises from the fact that, in many cases, a congener group or specific isomer concentration is reported as not detected. Thus, for concentrations reported as a range, the low value corresponds to assuming constituents not detected were present at zero concentration; the high value corresponds to assuming these constituents were present at their detection limit.

The data in Table 4 show that total PCDD/PCDF emissions at the baghouse exit were quite low, at 0.15 ng/dscm at 7 percent O_2 or less, for all test conditions, and were not affected by the test condition differences. On a TEQ basis, emissions were 0.005 ng/dscm at 7 percent O_2, or less, and, again, were not affected by the test condition differences.

Table 4. Dioxin/Furan Emission Results

Test condition	Condition average concentration, ng/dscm at 7% O_2 — Total PCDD/PCDF	TEQ
Condition 1	0.13 to 0.15	0.0004 to 0.0054
Condition 2	0.092 to 0.099	0.0004 to 0.0050
Condition 3	0.10 to 0.11	0.0003 to 0.0041
Condition 4	0.13 to 0.14	0.0006 to 0.0046

Conclusions

The objectives of this test program were to develop test data to permit the evaluation of Sonotech's claims regarding the performance of the Sonotech pulse combustion technology applied to a hazardous waste incinerator in comparison with the performance of conventional combustion technology. In evaluating the claims, test data were evaluated using the rank sum test. The rank sum test allows an assessment of whether observed differences in data sets are statistically significant. When comparing two data sets, each containing three data points, the two data sets are different, at the 95 percent confidence level, when there is no data overlap. With respect to the Sonotech claims, test data show that the application of the Sonotech pulse combustion technology resulted in:

- *Increased incinerator capacity.* Application of the Sonotech pulse combustion system allowed a waste feedrate increase of 13 percent compared to corresponding operating conditions under conventional combustion. Because the waste treated had significant heat content, the capacity increase equated to a corresponding decrease in the auxiliary fuel consumption per unit of waste treated from an average of 21.1 kBtu/lb (range of 21.0 to 21.3 kBtu/lb) to an average of 18.0 kBtu/lb (16.6 to 19.0 kBtu/lb).
- *Increased POHC DRE.* POHC DREs measured for all test conditions were uniformly 99.994 percent or greater, with no observable benefit, or detriment, due to pulse combustion. Benzene emission rates at the afterburner exit were reduced from an average of 7.7 mg/hr (range of 2.1 to 12) to an average of 5.7 mg/hr (range of 3.4 to 6.9). Naphthalene emission rates at the afterburner exit were reduced from an average of 1.2 mg/hr (range of 0.4 to 2.6) to an average of 1.1 mg/hr (range of <0.3 to 2.5).
- *Decreased flue gas CO emissions.* Average afterburner exit flue gas CO levels were reduced, from 20 ppm at 7 percent O_2 (range of 8.0 to 40.0) in a maximum waste feedrate operating condition under conventional combustion operation, to an average of 14 ppm at 7 percent O_2 (range of 12.6 to 16.0) at the same feedrate with pulse combustion. Pulse combustion allowed a higher waste feedrate to be achieved, with average afterburner exit CO emissions of 18 ppm at 7 percent O_2 (range of 10.5 to 26.0), still below the conventional combustion maximum feedrate condition.
- *Decreased flue gas NO_x emissions.* Both afterburner exit and baghouse exit NO_x emissions were marginally decreased from 82 (range of 78.3 to 85) to 85 (range of 83.6 to 86.3) ppm at 7 percent O_2, respectively, in a conventional combustion maximum waste feedrate operating condition, to averages of 77 (range of 68.0 to 87.1) and 78 (range of 76.6 to 79.6) ppm at 7 percent O_2 at the same feedrate with pulse combustion. At the higher waste feedrate achievable with pulse combustion, average NO_x emissions were 78 (range of 73.7 to 81.4) and 72 (range of 68.7 to 75.5) ppm at 7 percent O_2.
- *Decreased flue gas soot emissions.* Average afterburner exit flue gas soot emissions, measured as total organic carbon or particulate, were decreased from 1.9 mg/dscm at 7 percent O_2 (range of <0.9 to 2.7), in the conventional combustion maximum waste feedrate operating condition, to <1.0 mg/dscm (range of <0.8 to 0.9), with pulse combustion at the same feedrate. Even in

the increased-feedrate pulse combustion test condition, afterburner exit soot emissions were still lower, at an average of 1.3 mg/dscm at 7 percent O_2 (range of <0.9 to 1.8), than in the conventional combustion maximum feedrate condition.

- *Decreased combustion air requirements.* Total system combustion air requirements decreased from an average of 39,500 dscf/hr (range of 38,400 to 40,600) under conventional combustion to an average of 37,600 dscf/hr (range of 34,800 to 39,900) with pulse combustion, based on stoichiometric calculations.
- *Decreased auxiliary fuel requirements.* No measurable change in auxiliary fuel requirements to establish a given set of combustion conditions was observed.

A secondary test program objective was distribution of hazardous constituent trace metals among the incineration system discharge streams. Test data show that no significant differences in metals distributions among the test conditions are apparent, with the exception that barium and chromium concentrations were slightly lower in the scrubber liquor, and were higher in the baghouse exit flue gas with pulse combustion.

Although not the subject of the initially defined project objectives, heating value determinations performed on kiln ash residue samples show that pulse combustion operation improved residue quality by producing a kiln ash discharge with lower heating value than that measured in kiln ash from conventional combustion operation. The observation that pulse combustion operation caused increased kiln solids bed temperatures, likely the result of improved heat transfer to the solids bed, is consistent with the lower-heating-value kiln ash observed.

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The complete report, entitled "SITE Program Evaluation of the Sonotech Pulse Combustion Burner Technology," (Order No. PB97-189732; Cost: $35.00, subject to change) will be available only from

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