REPORT DOCUMENTATION PAGE

Form Approved OMB No. 074-0188

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE
April 14, 1997

3. REPORT TYPE AND DATES COVERED

4. TITLE AND SUBTITLE
Forced Acoustic Field Effects on Incineration Processes: Research on U.S. Navy Shipboard Waste Disposal

5. FUNDING NUMBERS
N/A

6. AUTHOR(S)
Jerald A. Cole, David W. Hansell, Neil C. Widmer, Wm. Randall Seeker, Kenneth J. Wilson, Timothy P. Parr

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Energy and Environmental Research Corporation
18 Mason
Irvine, CA 926182706

Weapons Division
Naval Air Warfare Center
China Lake, CA 93555-6001

8. PERFORMING ORGANIZATION REPORT NUMBER
N/A

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
SERDP
901 North Stuart St. Suite 303
Arlington, VA 22203

10. SPONSORING / MONITORING AGENCY REPORT NUMBER
N/A

11. SUPPLEMENTARY NOTES
This work was supported in part by contract number N-00014-95-C-0310. Presented at The Combustion Institute 1997 Spring Meeting, Livermore, CA, Paper 97S-043.

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release: distribution is unlimited.

12b. DISTRIBUTION CODE
A

13. ABSTRACT *(Maximum 200 Words)*
Waste thermal treatment is a preferred method for waste handling on board Naval platforms. It can accomplish several goals of at-sea treatment of shipboard wastes, including volume reduction, sterilization, and detoxification. It is also considered to be the most cost-effective approach available and among the safest, requiring littl especialized personnel training. Unfortunately neither land-based nor existing seaworthy incinerator designs can meet the Naval requirements of compactness and light weight. This has lead to the exploration of novel approaches, such as the use of forced acoustics to improve heat transfer, turbulent mixing, and firing density in order to reduce the size and increase the throughput of incineration systems.

EER has designed and constructed two experimental facilities to study the application of forced acoustics for the improvement of waste thermal treatment as it might be applied to the next generation of Naval platforms that are now only in the conceptual phase of development. The status of these research efforts, preliminary experimental results, and plans for future development are discussed.

14. SUBJECT TERMS
incineration; shipboard waste disposal; SERDP; SERDP Collection

15. NUMBER OF PAGES
19

16. PRICE CODE N/A

17. SECURITY CLASSIFICATION OF REPORT
unclass.

18. SECURITY CLASSIFICATION OF THIS PAGE
unclass.

19. SECURITY CLASSIFICATION OF ABSTRACT
unclass.

20. LIMITATION OF ABSTRACT
UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

CP34/887

Forced Acoustic Field Effects on Incineration Processes: Research on U.S. Navy Shipboard Waste Disposal

Jerald A. Cole, David W. Hansell, Neil C. Widmer, Wm. Randall Seeker
Energy and Environmental Research Corporation
18 Mason
Irvine, California 92618-2706

Kenneth J. Wilson, Timothy P. Parr
Naval Air Warfare Center, Weapons Division
China Lake, CA 93555-6001

Paper 97S-043
Western States Section / The Combustion Institute
1997 Spring Meeting

ABSTRACT

Incineration, or more politically, waste thermal treatment, is a preferred method for waste handling on board Naval platforms. It can accomplish several goals of at-sea treatment of shipboard wastes, including volume reduction, sterilization, and detoxification. It is also considered to be the most cost-effective approach available and among the safest, requiring little specialized personnel training. Unfortunately neither land-based nor existing seaworthy incinerator designs can meet the Naval requirements of compactness and light weight. This has lead to the exploration of novel approaches, such as the use of forced acoustics to improve heat transfer, turbulent mixing, and firing density in order to reduce the size and increase the throughput of incineration systems.

EER has designed and constructed two experimental facilities to study the application of forced acoustics for the improvement of waste thermal treatment as it might be applied to the next generation of Naval platforms that are now only in the conceptual phase of development. One of these facilities is an experimental secondary oxidation chamber, following the work of Parr, et al., that might be coupled with any number of primary waste pyrolysis units. Preliminary tests indicate that up to a factor of eight in volume reduction might be achievable with this design while reducing the weight by as much as a factor of ten over current industrial practice. The data further indicate no increase in priority pollutant emissions relative to existing technologies, while the acoustic forcing opens the opportunity for adoption of closed-loop active control of the thermal treatment process.

The second facility is based upon a 30-year-old design for a shipboard blackwater sludge incinerator. Through acoustic forcing it is expected that the process throughput can be substantially increased, principally as a result of enhanced heat and mass transfer between the primary combustion products and the waste stream. At the same time, intelligent design changes and the potential for active control of the incineration process will enable the thermal treatment of a wider range of liquid shipboard waste streams. The status of these research efforts, preliminary experimental results, and plans for future development are discussed.

second stage is an afterburner intended to destroy the gaseous products of waste pyrolysis.

In our example incinerator both the rate of pyrolysis product production and the composition of those products depend on the current state of the system and the nature of the waste being processed. The afterburner must be designed so that under the worst case scenario there will be no significant release of undesirable products of incomplete combustion released to the atmosphere. Depending on local regulatory jurisdiction, this means that the minimum temperature at the exit of the afterburner must be from 1700 to 2000 °F (925 to 1100 °C) and the minimum residence time 1 - 2 s. This sets strict physical limits on the volume and weight of the afterburner. By coupling forced acoustic controlled combustion with a closed-loop feedback control system able to respond in millisecond time frames, these requirements could be drastically altered with the result being a much smaller, lighter, more robust afterburner having better emission characteristics than conventional systems.

EER and the Naval Air Warfare Center (NAWC) are part of a project team that is examining applications for forced acoustics in waste thermal treatment systems for use on U.S. Navy warships. Two specific applications are under study. The first is an advanced afterburner, and the second is a sludge incinerator. The approaches for the two systems are different, but both use forced acoustics as a means to improve specific aspects of the system operation.

BACKGROUND

Blackwater sludge is the term for raw sewage that has been processed through a macerator pump to produce a slurry containing about 98 percent water and slightly less than 2 percent solids. Presently, there are about 30 U.S. Navy ships using blackwater sludge incinerators. These incinerators, illustrated in Figure 1, are based on a 1950s technology and were first commissioned by the Navy in the mid 1960s. Sewage is introduced through a coarse hollow-cone spray nozzle at one end of the incinerator. The majority of the spray droplets impact on the inconel walls of the unit where they evaporate and pyrolyze and the resulting gases are incinerated. A tangentially-mounted burner, fueled with JP-5, induces a vortical flow in the incinerator and heats the walls. Exhaust is removed through a large air cooled port located on axis at the end opposite the sludge nozzle.

At present this sludge incinerator design is capable of treating only blackwater sludge and has a throughput capacity of 30 gph, its emission characteristics are not well known, and there are no regulations covering its operation. The U.S. Navy wants to change the operation of this sludge incinerator in a number of ways to make it more compatible with current and planned shipboard operations.

The Navy is presently developing polishing technogies to clean up "grey water", that is water collected from showers and sinks, and possibly galleys. This water is being cleaned up to comply with Clean Water Act standards so it will not introduce pollutants to the oceans when dumped overboard. Along a similar vein the Navy has developed oil separation systems to remove oil and solvents from bilge water so it to can be dumped overboard. The residuum from these clean up operations is targeted for treatment in the blackwater sludge incinerator. On top of these efforts, the Navy is also looking into systems for removing half of the water from the blackwater sludge, that is, doubling the solids concentration. After all, one of the main functions of the blackwater sludge incinerator is to evaporate water, which is a very energy-intensive process. Removing half the water will increase the solids concentration to nearly 4 percent, which will change the spray characteristics considerably. Finally, the Navy wants to increase the throughput of blackwater sludge by 30 to 50 percent.

Possible effects of these changes include increased particulate matter production, increased alkali in ash, introduction of chlorinated solvents with concomitant corrosion issues, and reduced residence time in the combustion chamber. Forced acoustics is being considered as one part of a suite of technologies used to address the Navy needs to adapt the blackwater sludge incinerator to the new process stream compositions. The combination of increased heat and mass transfer induced by a high sound pressure level (SPL) acoustic field can both increase droplet evaporation rates[6] and enhance the firing density of the primary fuel.

The controlled vortex afterburner has been under development by NAWC for several years. Their efforts have yielded a number of accomplishments including derivation of scaling criteria and the discovery that NOx and CO emissions could be simultaneously reduced by proper control of their system[7,8]. The basic operation of the controlled vortex afterburner is illustrated in Figure 2. Starting on the left of the figure we have a central air jet issuing past a dump plane. This jet induces the periodic formation of annular vortices. Fuel can be introduced through an annular opening in the surface of the dump plane coaxial with the air jet so that it is entrained into the vortices and mixed with the vortex gases through strain-enhanced diffusion and convection. If the system is ignited, the vortex will consist of air mixed with hot reacting combustion products. As fuel is added to the vortex its ignition will be strain delayed, resulting in reduced NOx emissions (as a result of lower peak combustion temperatures) and reduced products of incomplete combustion (as a result of improved mixing and elimination of "cold" pockets).

The behavior of the system is enhanced dramatically if acoustic forcing is used on both the central air jet and the annular fuel stream. The production of vortices by the central air jet is periodic with a natural frequency. However if the intervals between successive vortex shedding events are measured and recorded, a probability density function (PDF) can be constructed, as shown on the left of Figure 3, that shows a broad distribution of time intervals centered around the natural frequency. By forcing the jet at or near its natural frequency the PDF is collapsed to a narrow spike, illustrated on the right of Figure 3, allowing the vortex shedding events to be accurately predicted and controlled. Likewise, the annular fuel jet can be modulated with acoustic forcing. By setting the two frequenicies equal and adjusting the phase angle between the two forcing functions the fuel can be introduced at the optimal point for entrainment and mixing with the vortices.

Further improvement to this system was achieved by introduction of a secondary air stream introduced annularly and coaxially with the fuel stream[8]. By modulating the secondary air rather than the fuel is it possible to "gate" the introduction of the fuel, and enhance performance even more. The work of Parr, et al.[7,8] showed that DREs for benzene increased from about 3-nines to better than 5-nines (detection limit), CO emissions were reduced from 2900 to as low as 2 ppm and significant reductions in both NOx and unburned hydrocarbons were observed. The basic system design has been scaled up in stages from about 4.7 kW to 300 kW with most of the tests conducted in open air, but with some work done using an open-end tubular enclosure. The combined effort by EER and NAWC extends this work to an enclosed system to simulate the environment in an actual incinerator afterburner.

BLACKWATER SLUDGE INCINERATOR

The blackwater sludge incinerator effort is in the design stage. A full-scale mockup of the incinerator, shown in Figure 4, has been constructed according to design criteria that include matching all physical dimensions and reactant flow rates, plus simulation of the thermal boundary conditions of the original unit. Ports have been added both for optical access and to permit gas and particulate sampling, and the incinerator has been instrumented with thermocouples to monitor temperatures and heat fluxes through the walls.

EER has also engaged the services of Hersh Acoustical Engineering, Inc. to design an acoustic driver system for the blackwater sludge incinerator. An array of acoustic ports will be installed on the spray nozzle end of the incinerator according to the layout shown in Figure 5. This array of eight loudspeakers will permit the simultaneous excitation of multiple acoustic modes in the incinerator so as to induce large SPLs and SPL gradients throughout the combustion chamber volume.

Tests scheduled on the blackwater incinerator simulator will first include establishment of a baseline performance characterization. This will include operation of the system at 30 gph of 2 percent solids sludge. Measurements will be made of gaseous and solids emissions, gas and surface temperatures, and visual observation of operational characteristics. Once the acoustic array is added to the system a series of tests will be conducted in which both the burner firing rate and the sludge feed rate are increased to the point of system failure. System failure occurs when sludge accumulates in the bottom of the incinerator and exhaust temperatures rise due to reduced sludge boil-off. The load and firing rate at system failure will be noted and then the tests repeated with longitudinal acoustic excitation at 1000 Hz and 150 dB SPL. It is the objective of these brute-force tests to demonstrate and observe any increase in system throughput attainable through the use of acoustic forcing.

Future plans for the blackwater sludge incinerator simulation unit include first the study of acoustic modes other than the longitudinal mode. The eight-loudspeaker array is designed to take advantage of spinning and rotating acoustic modes through phase delay sequencing of the driver signals to the individual speakers. Depending on the magnitude of effects noted with alternate acoustic modes, alternate system geometries may be employed. For example, to take full advantage of the acoustic impacts on heat transfer, it will be desirable to eliminate the existing hollow-cone spray nozzle in favor of a solid cone nozzle that will produce smaller droplets with a lower droplet velocity. This will give the droplets more time to evaporate, while simultaneously reducing their evaporation time. This, of course, means changing fundamentally the way in which the incinerator operates and may necessitate further geometric changes to accomodate the differences.

Other plans include blending of simulated bilge water sludge with the blackwater sludge, working with a more concentrated blackwater sludge, and possibly changing the burner geometry to an axial firing configuration.

CONTROLLED VORTEX AFTERBURNER

The final design of the controlled vortex afterburner tested at EER is shown in Figure 6. This device was attached to a 24-inch inside diameter cold wall package boiler in the configuration shown in Figure 7. Parametric tests were then conducted to determine whether the work of Parr could be extended to closed systems, and how enclosure would impact performance. In these initial tests CO was used as a surrogate for system performance. Although unburned hydrocarbons were monitored for DRE, in all cases where acoustic excitation was used the measured levels were below the detection threshold of the instrumental hydrocarbon analyzer and so were of limited use in the parametric studies.

The existence of an optimal frequency for acoustic excitation is illustrated by Figure 8 which shows the effect of driving frequency on CO emission levels at two different system stoichiometries. For the most fuel-lean case very little effect of driving frequency is evident because CO levels are already low even in the absence of acoustic forcing. However, at Phi = 0.8, where CO concentrations of 420 - 550 ppm were measured in the absence of acoustic forcing, a very distinct minima in CO was detected at 241 Hz. This is very near the calculated optimum of 220 Hz. The difference may be due to uncertainties in jet velocities, or may be related to changes in the jet fluid properties due to the radiant heat loading from the heated refractory in the package boiler. Once this optimal frequency was identified, it was used for the majority of further tests.

Figure 9 shows the impact of oxygen level on CO emissions in the absence of acoustic excitation. The system behaves similarly to any combustion system in that the CO levels decrease as oxygen increases. However, the magnitude of the CO levels suggest that in the absence of acoustic excitation mixing of fuel and air in this system is poor. When the secondary air flow rate is increased from 2 to 45 scfm the CO levels increase even further to nearly 900 ppm (dry, 7% O_2) in the worst case shown in Figure 9. However, as acoustic power is added to the system the CO levels drop dramatically as shown in Figure 10. The power levels shown in the figure are estimates based on linearization of the manufacturer's laboratory test data on the Ling acoustic transducer. However, even if the power levels shown are not highly accurate the results of these tests suggest that an acoustic power level *on the order* of 100 W is sufficient to reduce CO levels to about 40 - 50 ppm. It should also be noted that while the worst unforced emission levels were obtained using a secondary air flow rate of 45 scfm, with acoustic forcing the CO emissions were comparable to the best results obtained.

To date, no data have been collected in the EER system with phase synchronous acoustic excitation of either the secondary air or the fuel stream. However it is to be expected, based on open-air tests conducted at China Lake, that modulating the fuel will result in even lower emissions. We are also upgrading our analytical equipment to provide for NOx emissions data, as well as benzene detection limits at least two orders of magnitude lower than the present instrumentation. These additional data will help to provide a more comprehensive picture of the promise of acoustic afterburners for closed-loop active control of emissions in waste thermal processing systems.

SUMMARY

EER and NAWC are investigating the use of acoustic forcing to improve the performance of two incinerator technologies with the objective of fielding advanced incinerator concepts for fleet operation. A blackwater sludge incinerator simulator has been built and is scheduled for testing in the upcoming months. It is expected that acoustic forcing will permit an increased throughput of blackwater sludge, and that modifications to the sludge sprayer and burner will allow for greater flexibility in waste feed with no deterioration in performance.

An advanced afterburner based on controlled vortex entrainment has been constructed and undergone preliminary testing in a simulated secondary oxidation chamber. Results mirror previous work conducted at China Lake and suggest that the concept will be effective for enclosed systems such as practical afterburner designs.

Forced acoustics also provides an additional diagnostic for use in active feedback control of both the controlled vortex afterburner and the blackwater sludge incinerator. By measuring both the speed of sound and phase angle shifts using carefully placed acoustic transducers deductions can be drawn about the gas molecular weight, and hence effectiveness of the incinerator. Since this information is delivered at the speed of sound, millisecond response times are possible and this opens the door for new levels of performance assurance for all waste thermal treatment systems.

ACKNOWLEDGEMENTS

Financial support for this work is provided by the Strategic Environmental Research and Development Program of the Joint Chiefs of Staff under contract N00014-96-C-0105. Dr. Klaus C. Schadow is the Project Technical Monitor.

REFERENCES

1. MARPOL refers to three international treaties: The Convention for the Prevention of Marine Pollution by Dumping from Ships and Aircraft, adopted at Oslo on 15 February 1972; The International Convention for the Prevention of Pollution form Ships, 1973, adopted at London on 2 November 1973; and The Protocol of 1978 Relating to the International Convention for the Prevention of Pollution from Ships, 1973, adopted at London on 17 February 1978.

2. This program was mandated by 33USC1902(c).

3. *Solid Waste Processing Equipment Installation Ship Impact Study:Plasma Arc Thermal Destruction System.* Report No. 95-013 prepared by John J. McMullen Associates, Inc. under contract N00024-87-0-4503 to Naval Sea Systems Command. 21 July 1995.

4. Karagozian, A.R. *Technical Issues Pertaining to Environmentally Sound Ships.* Defense Science Study Group, Institute for Defense Analyses. November 1995.

5. *Shipboard Pollution Control: U.S. Navy Compliance with MARPOL Annex V.* Committee on Shipboard Pollution Control, Naval Studies Board, National Research Council. National Academy

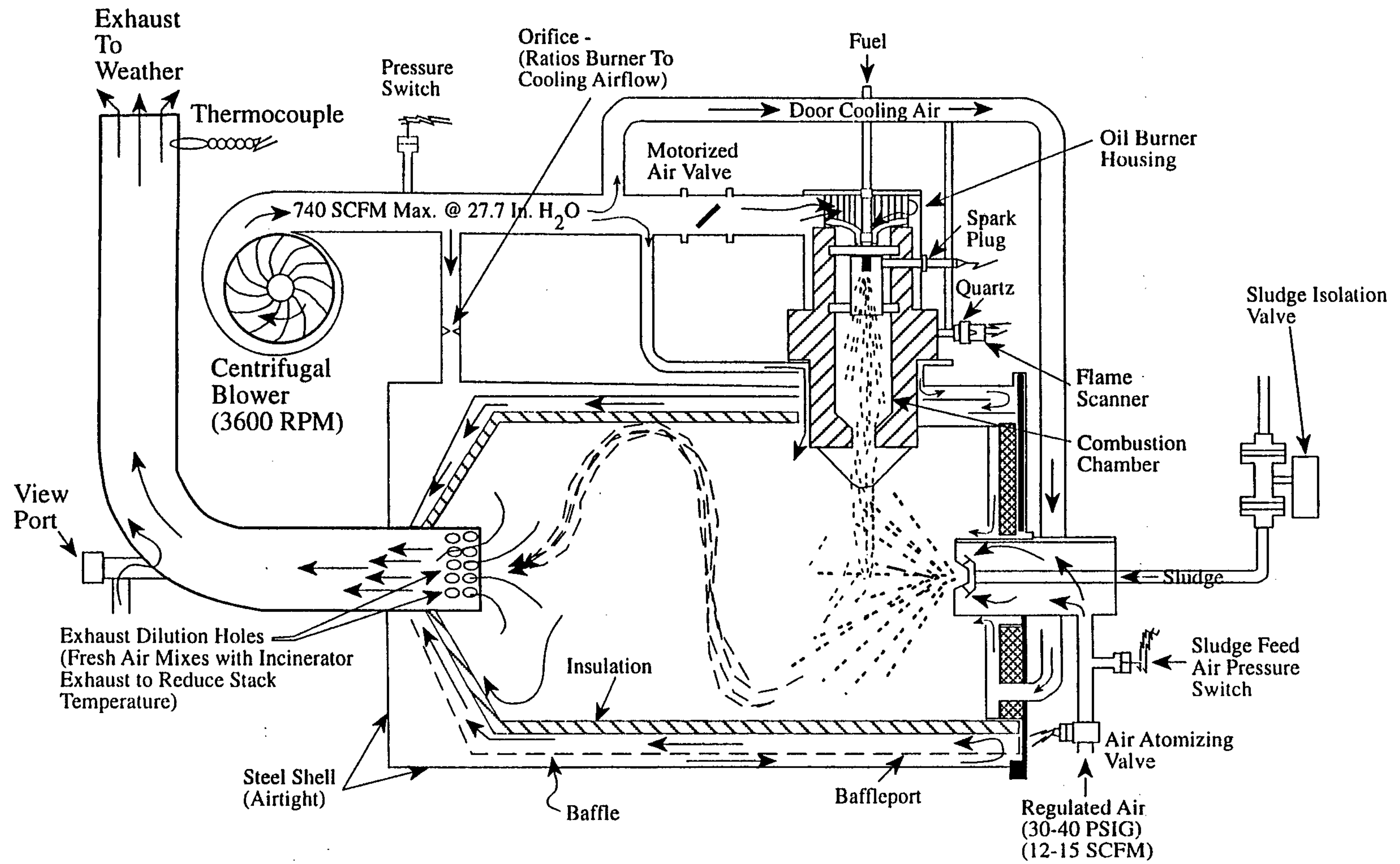
Press, Washington, D.C. 1996.

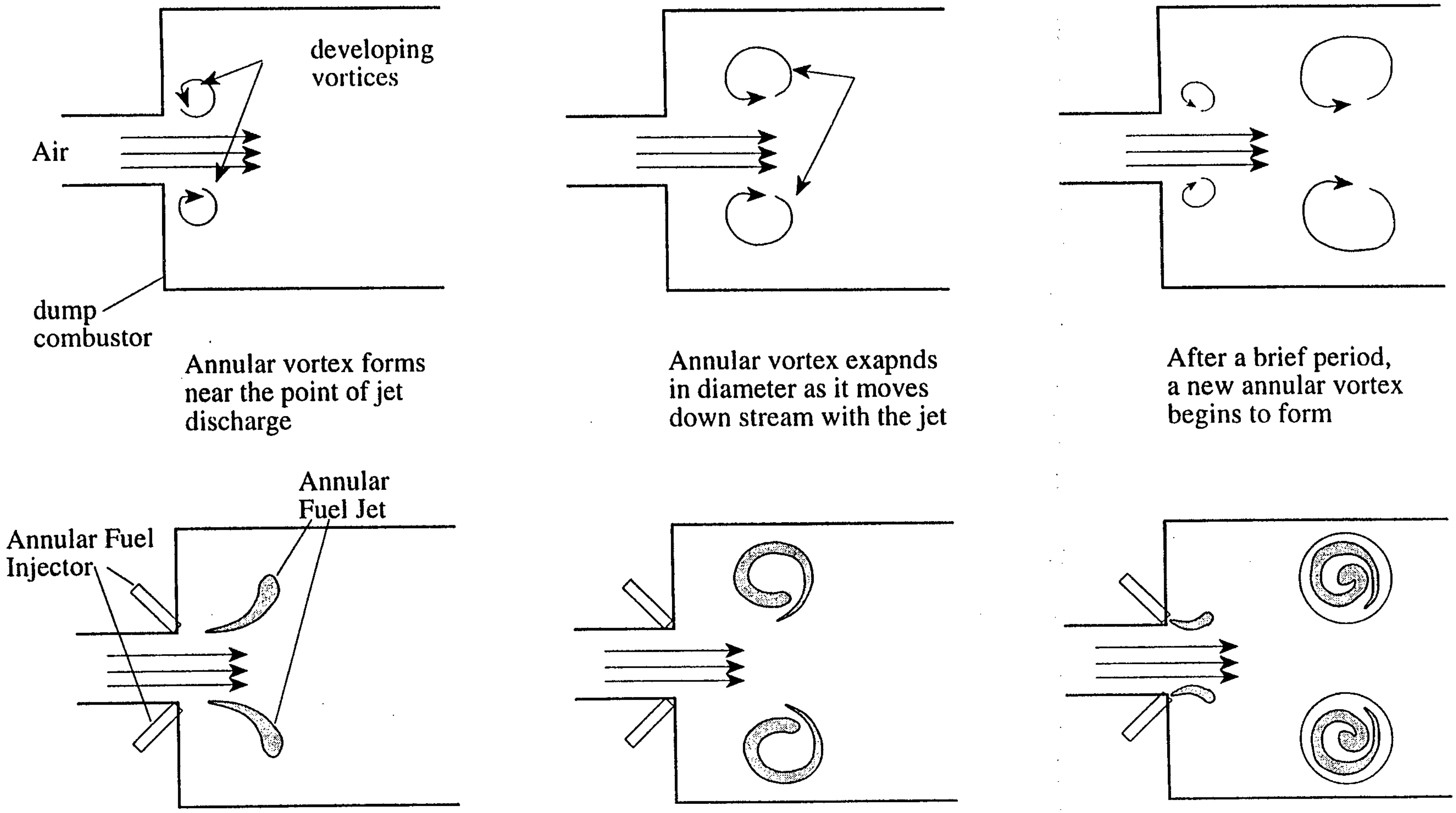
6. Dubey, R.K., Erickson, P.A., and McQuay, M.Q. *Combustion Characteristics of an Ethanol Spray-Fired Rijke-Tube Combustor in an Actively Controlled Acoutic Field.* 1996.

7. *Parr, T.P., Gutmark, E.J., Wilson, K.J., Hanson-Parr, D.M., Yu, K., Smith, R.A., and Schadow, K.C. Compact Incinerator Afterburner Concept Based on Vortex Combustion*, Presented at: Twenty-Sixth International Symposium on Combustion. July 28 - August 2, 1996. Naples, Italy.

8. Parr, T.P., Wilson, K.J., Yu, K., Smith, R.A., and K.C. Schadow *Actively Controlled Afterburner for Compact Waste Incinerator* Presented at: 15th International Conference on Incineration and Thermal Treatment Technologies, Savannah, GA, May 1996.

LIST OF FIGURES


Exhaust To Weather
Thermocouple
Pressure Switch
Orifice - (Ratios Burner To Cooling Airflow)
Fuel
Door Cooling Air
Oil Burner Housing
Motorized Air Valve
740 SCFM Max. @ 27.7 In. H_2O
Spark Plug
Quartz
Sludge Isolation Valve
Centrifugal Blower (3600 RPM)
Flame Scanner
Combustion Chamber
View Port
Sludge
Exhaust Dilution Holes (Fresh Air Mixes with Incinerator Exhaust to Reduce Stack Temperature)
Insulation
Sludge Feed Air Pressure Switch
Air Atomizing Valve
Steel Shell (Airtight)
Baffle
Baffleport
Regulated Air (30-40 PSIG) (12-15 SCFM)



Annular vortex forms near the point of jet discharge

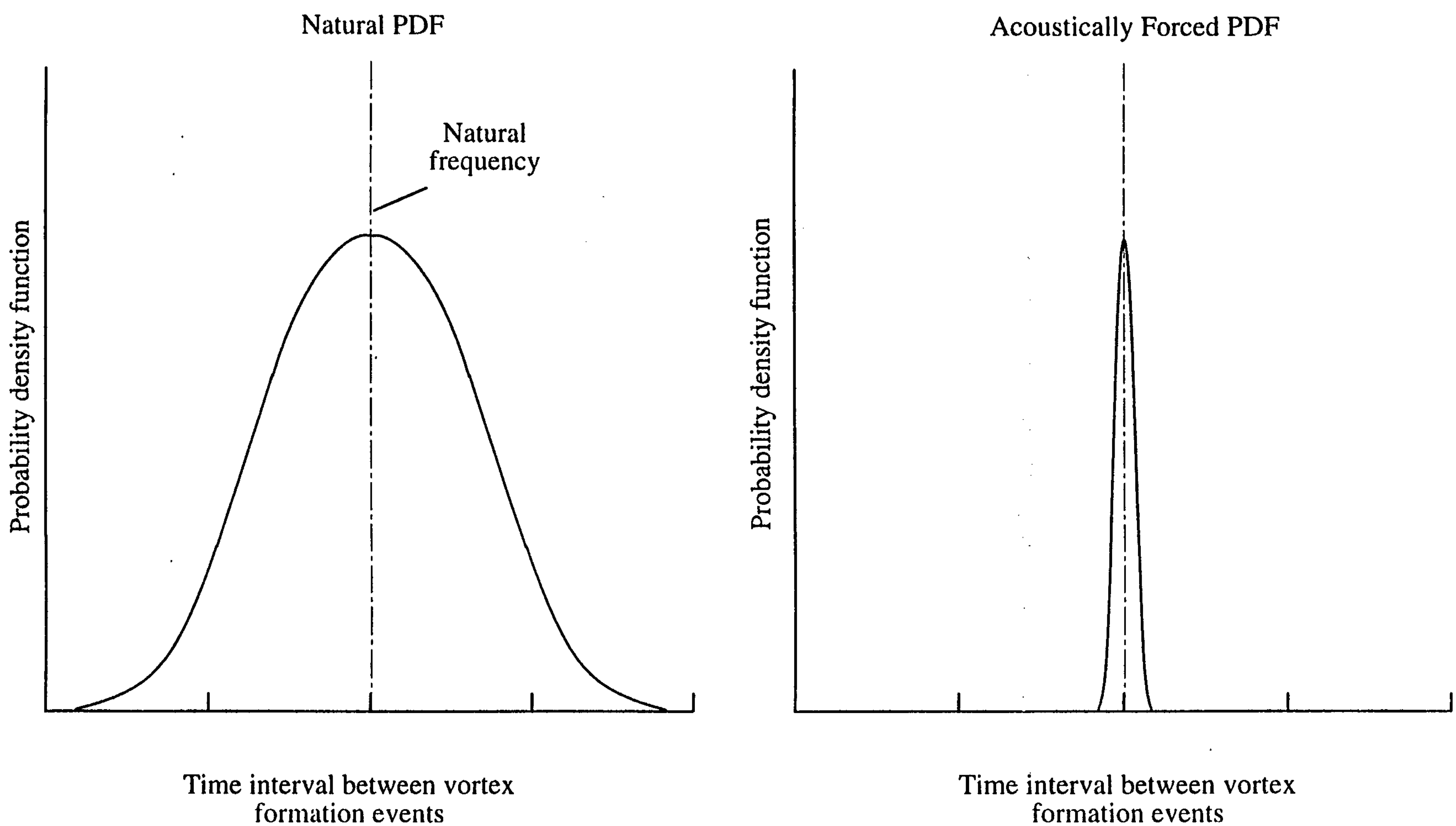
Annular vortex exapnds in diameter as it moves down stream with the jet

After a brief period, a new annular vortex begins to form

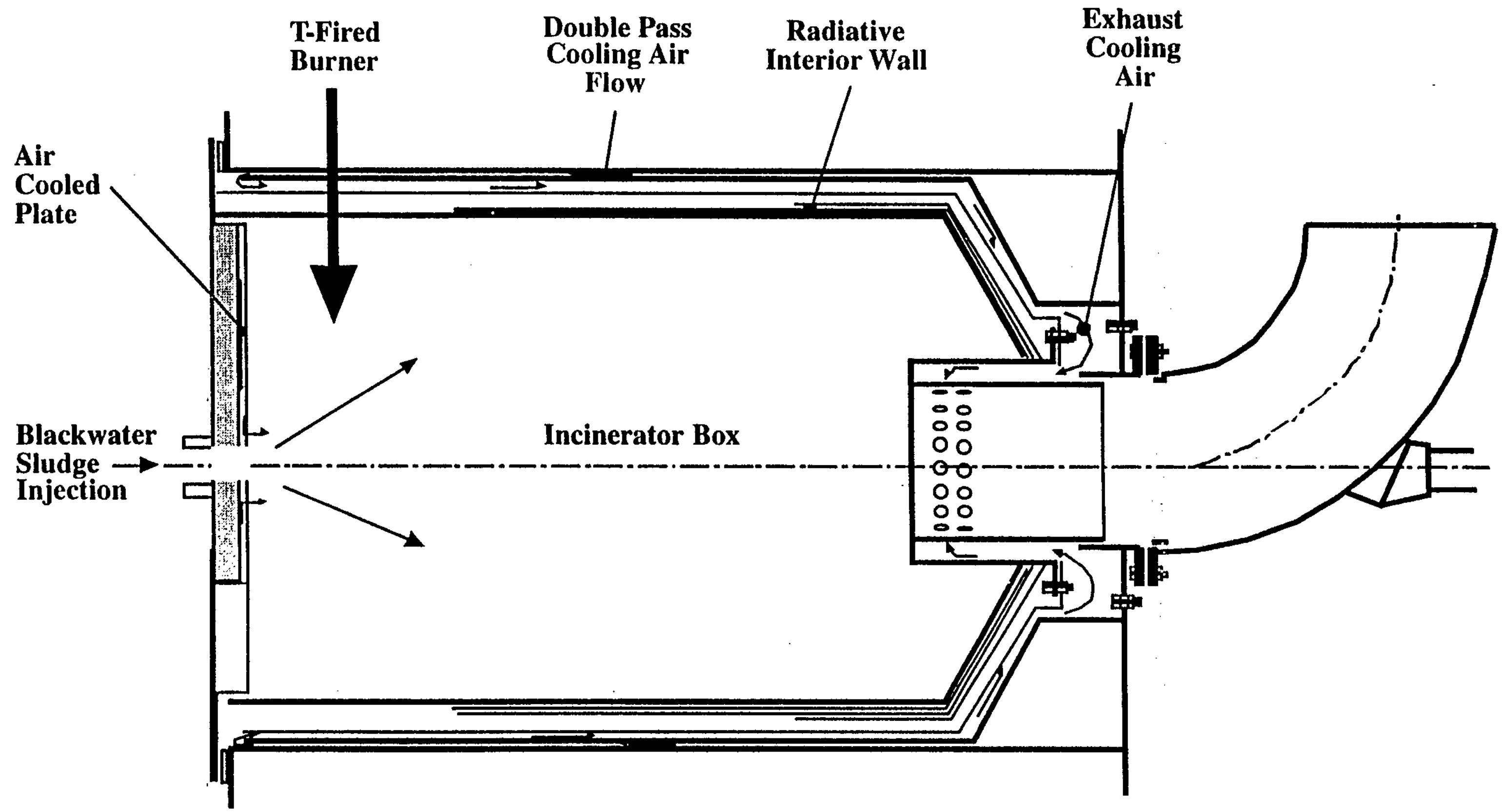
Injected fuel is entrained into the vortex as it "peels" away from the central air jet

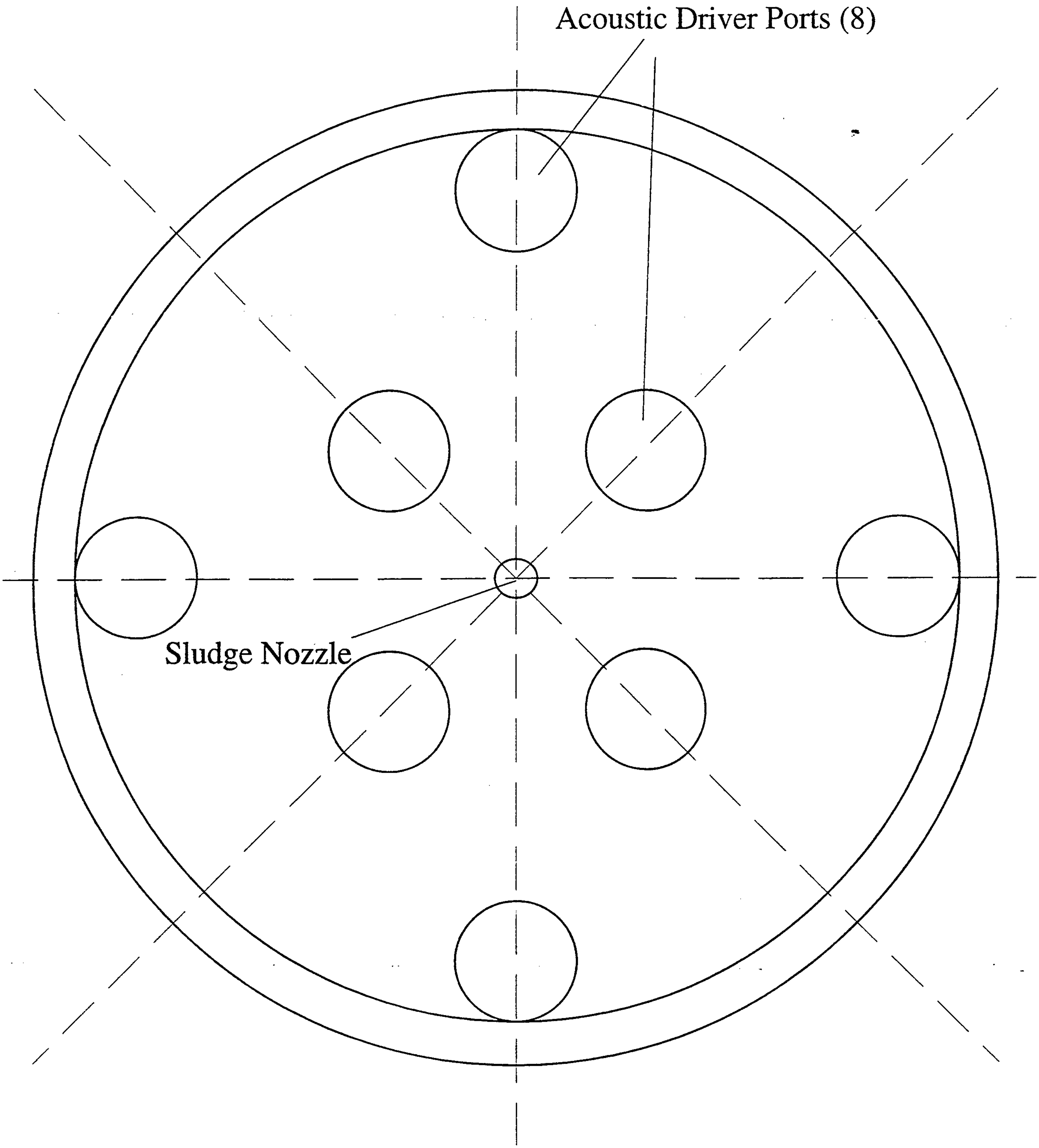
As the vortex continues to rotate and entrain hot gases from the surroundings the fuel is stretched and mixed

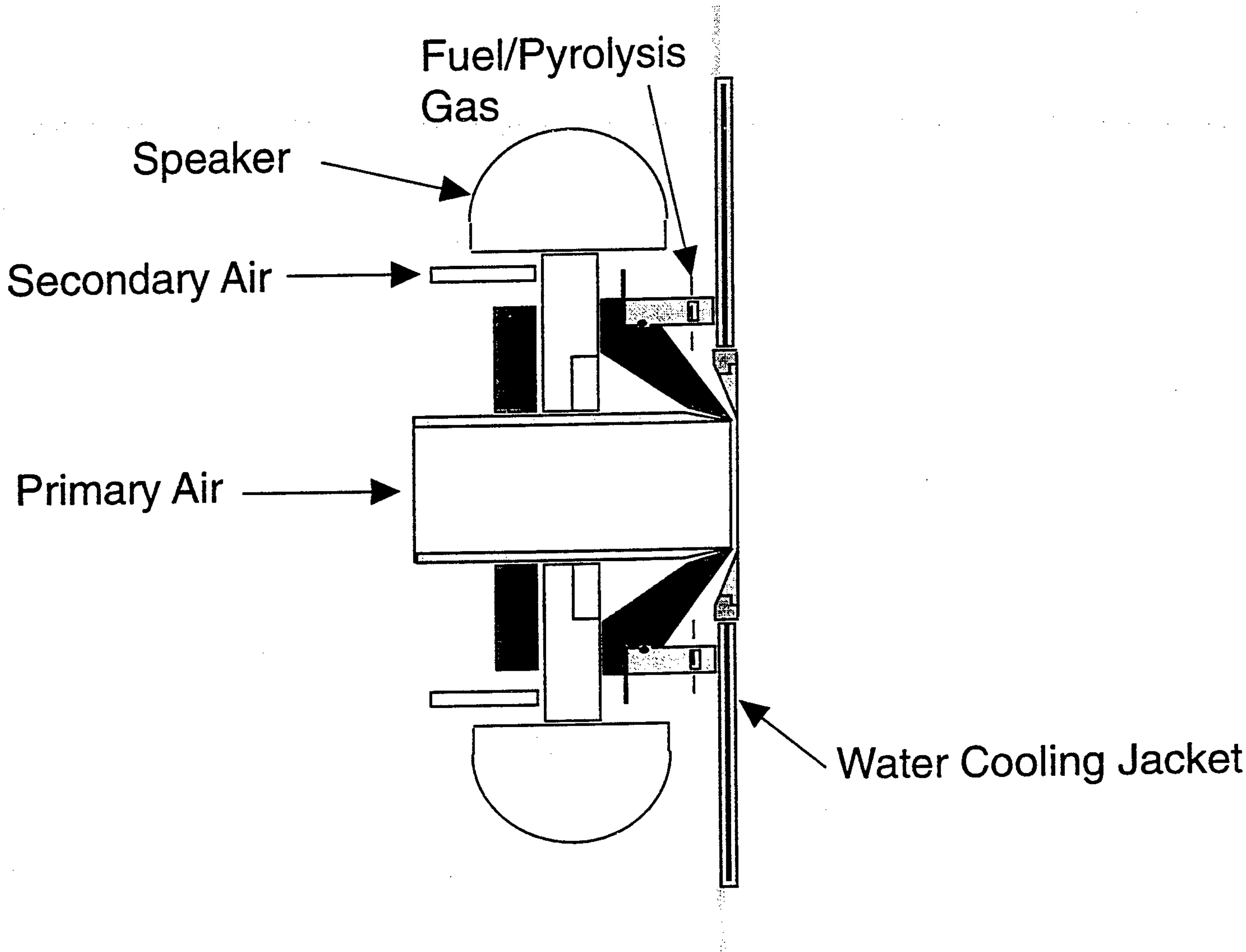
Eventually the vortex completely envelops the pocket of fuel. The resulting structure eventually ignites and the fuel burns at a reduced temperature in a well-mixed environment.

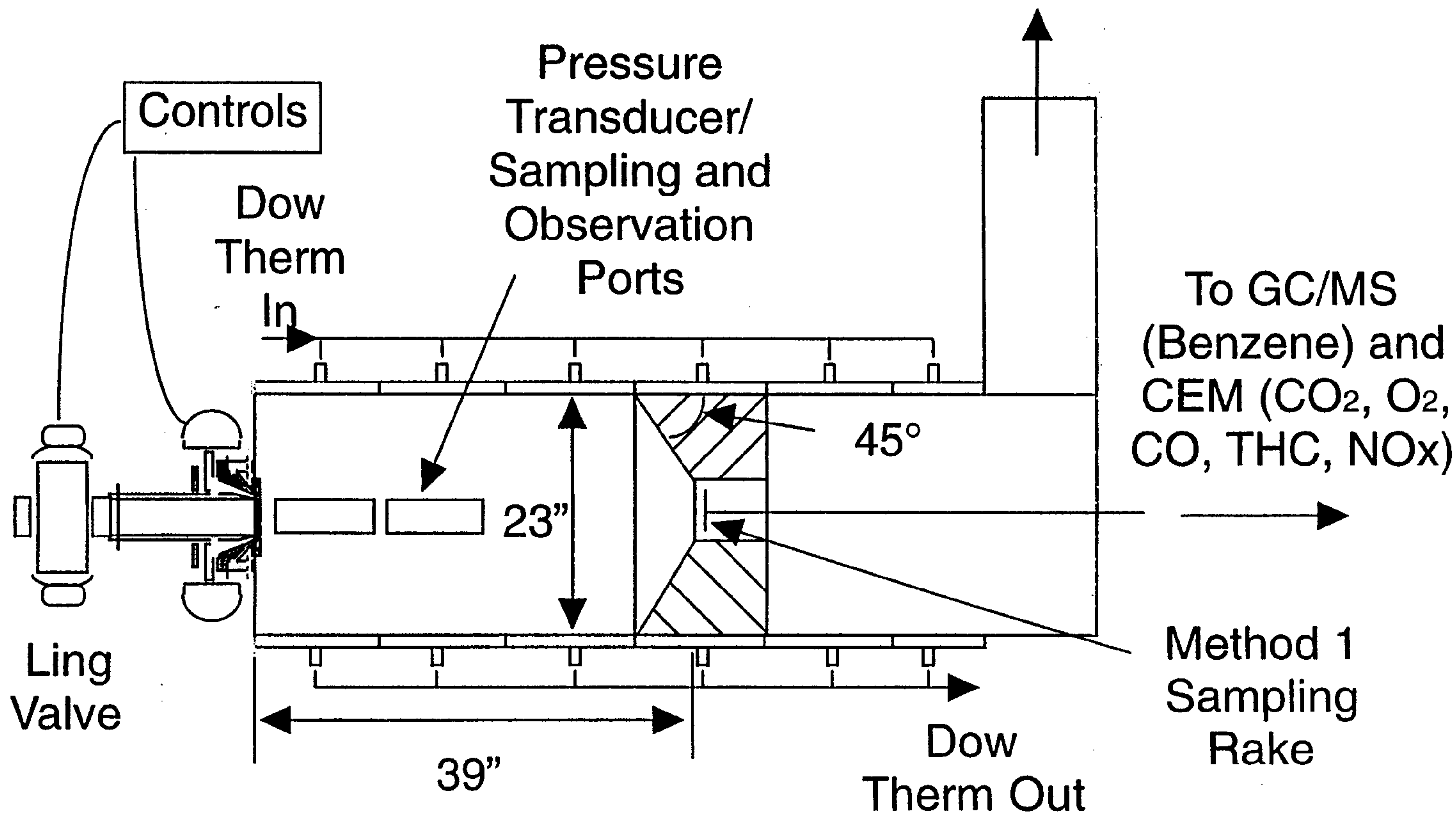


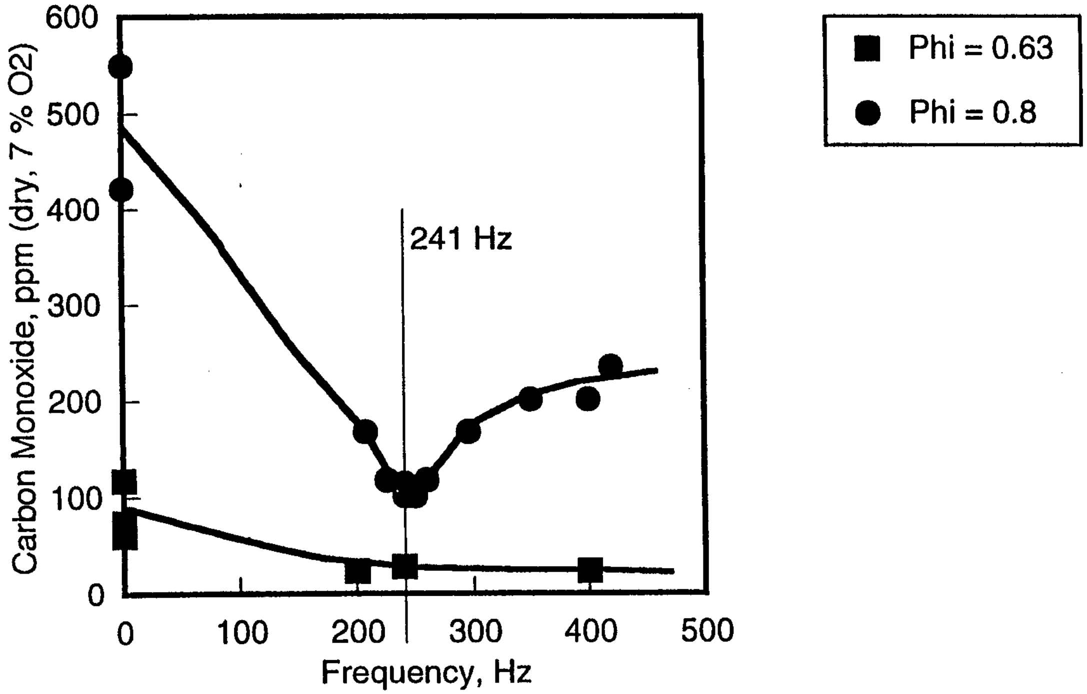
Natural PDF
Natural
frequency
Probability density function
Time interval between vortex
formation events
Acoustically Forced PDF
Probability density function
Time interval between vortex
formation events

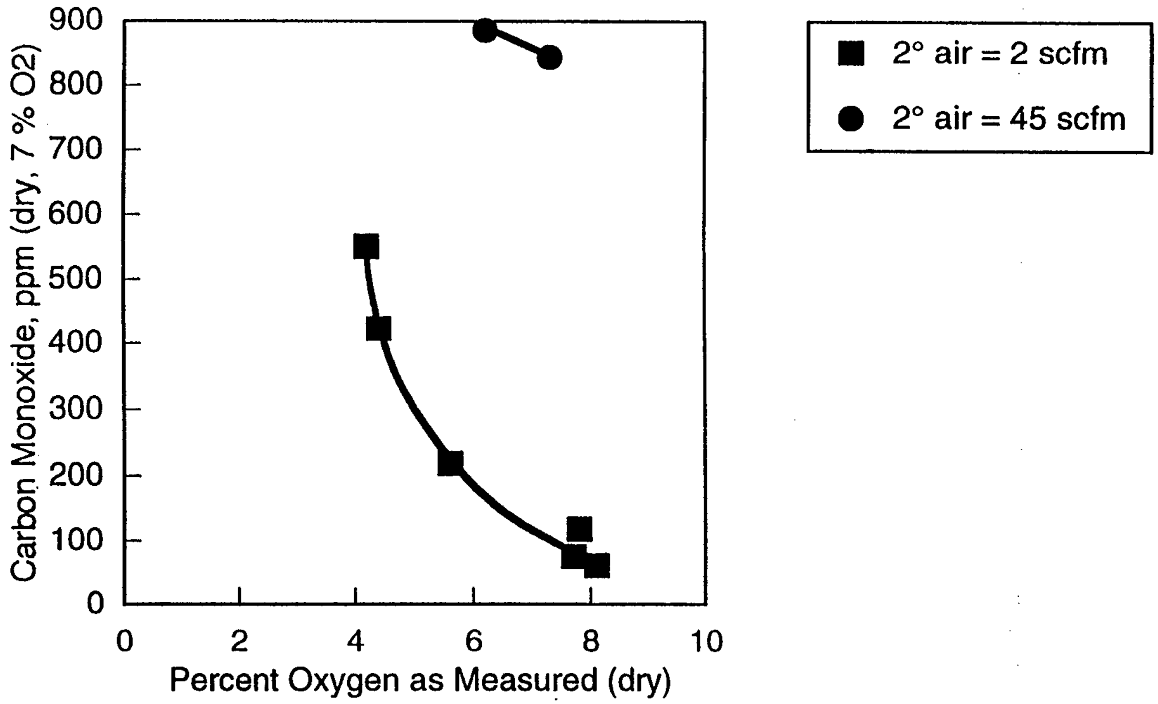

T-Fired
Burner
Double Pass
Cooling Air
Flow
Radiative
Interior Wall
Exhaust
Cooling
Air
Air
Cooled
Plate
Blackwater
Sludge
Injection
Incinerator Box

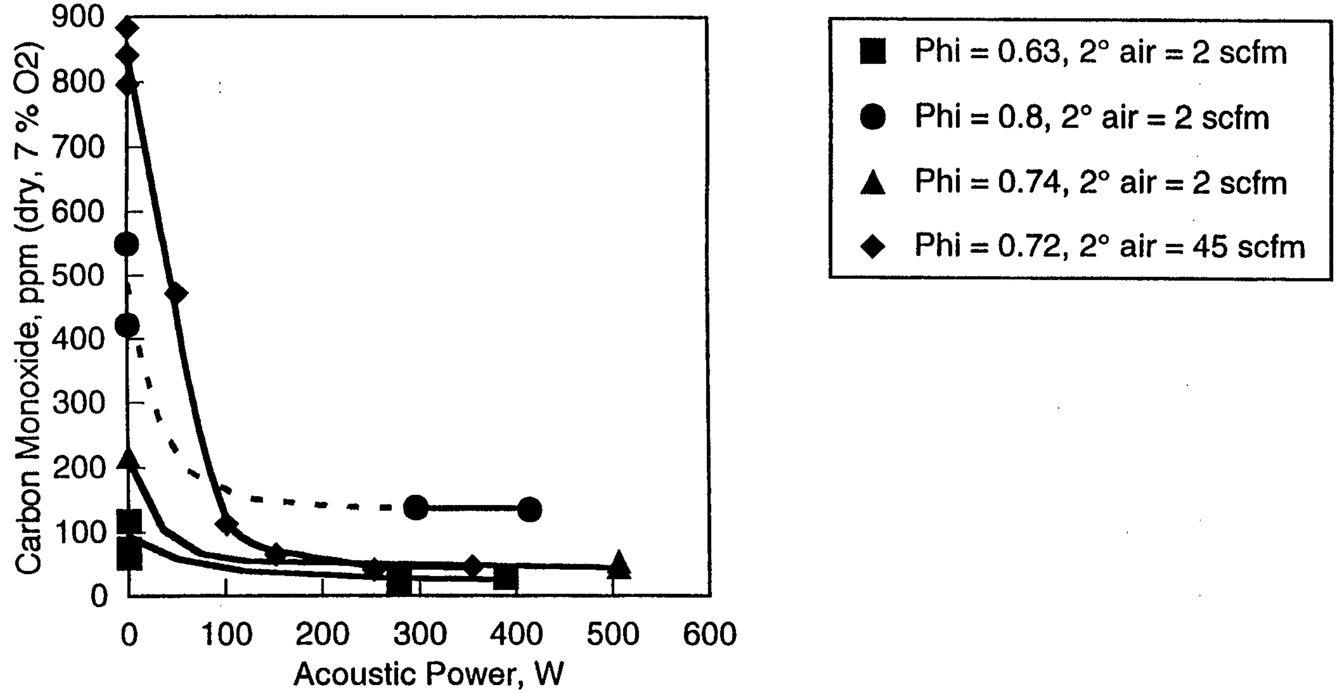

Acoustic Driver Ports (8)
Sludge Nozzle


Fuel/Pyrolysis Gas
Speaker
Secondary Air
Primary Air
Water Cooling Jacket


Controls
Dow
Therm
In
Pressure
Transducer/
Sampling and
Observation
Ports
23"
45°
To GC/MS
(Benzene) and
CEM (CO_2, O_2,
CO, THC, NOx)
Ling
Valve
39"
Dow
Therm Out
Method 1
Sampling
Rake


Carbon Monoxide, ppm (dry, 7 % O2)
600
500
400
300
200
100
0
0
100
200
300
400
500
Frequency, Hz
241 Hz
Phi = 0.63
Phi = 0.8


900
800
700
600
500
400
300
200
100
0
Carbon Monoxide, ppm (dry, 7 % O2)
0
2
4
6
8
10
Percent Oxygen as Measured (dry)
2° air = 2 scfm
2° air = 45 scfm


Carbon Monoxide, ppm (dry, 7 % O2)
900
800
700
600
500
400
300
200
100
0
0
100
200
300
400
500
600
Acoustic Power, W
Phi = 0.63, 2° air = 2 scfm
Phi = 0.8, 2° air = 2 scfm
Phi = 0.74, 2° air = 2 scfm
Phi = 0.72, 2° air = 45 scfm