THERMAL ACTIVELY CONTROLLED SLUDGE TREATMENT

SERDP CP 1132

FINAL REPORT
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Project Title: THERMAL ACTIVELY CONTROLLED SLUDGE TREATMENT

Performing Organizations:

Naval Air Warfare Center Weapons Division (NAWCWD) (Lead)
GE Energy and Environmental Research Corporation (GE EER)
Dr. Klaus Schadow, Consultant

Background:

The SERDP Program CP 1132 was started in FY99 to develop a combustion system for the treatment of shipboard generated oily and non-oily wastes, which have to be disposed in an environmentally acceptable manner according to International Maritime Organization (IMO) regulations. To comply with IMO MARPOL ANNEX 1 and 6 (proposed), on-board thermal destruction (incineration) in compact, efficient, and continuously monitored combustion devices may be required to avoid the high cost of storage, off-loading, treatment, and disposal. IMO standards require CO emissions of less than 200 milligram (mg)/megajoule (MJ) (equivalent to approximately 420 parts per million (ppm) corrected to 7% O_2) and exhaust emission opacity (smoke) of less than 20%, which corresponds to a Bacharach number of 3. The selected incinerator concept was based on a high performance Vortex Containment Combustor (VCC), which provides high firing density and high particulate matter trapping.

In addition to the treatment of shipboard generated wastes, shore and harbor applications were explored in sub-scale experiments. For this purpose, the VCC was integrated with an efficient, compact, actively controlled afterburner (AB). Initially it was planned to also use the integrated VCC/AB for shipboard applications; however the IMO performance could be obtained without AB.

The VCC is a demonstrated technology for combustion of pulverized coal and other fuels (Ref. 1). The concept involves a spinning combustion zone with long residence times for liquid droplets & solid particles and a classic cyclone-type flow for separation and trapping of noncombustible solids as ash (Figure 1). In the present program the VCC was modified for the treatment of marine sludge with highly variable characteristics and heat content.

The AB has been developed under SERDP program CP 887 and provides efficient and compact afterburning in actively stabilized air vortices using open and closed-loop control (Ref. 2). For open loop control, the air-flow is forced (periodically modulated) to generate air vortices into which pyrolysis gases are injected by air ejectors (Figure 2). The size of the vortices is inversely proportional to the forcing frequency.

The sludge characteristics to be treated in full-scale VCC (without AB) consist of mixtures of non-oily and oily wastes. The non-oily wastes consist of water with 1% organic solids (from vacuum collected black water or sewage) and 2% organic solids (from membrane/bioreactor treated gray water or galley waste). The oily wastes are derived from bilge water and consist of water and oil from 0.5% (oily concentrate from membrane separator) up to 10% (bulk oil from oil water separator mixed with water). Current standard marine incinerators are unable to treat these sludge types with highly variable composition and do not meet IMO standards for these waste streams.

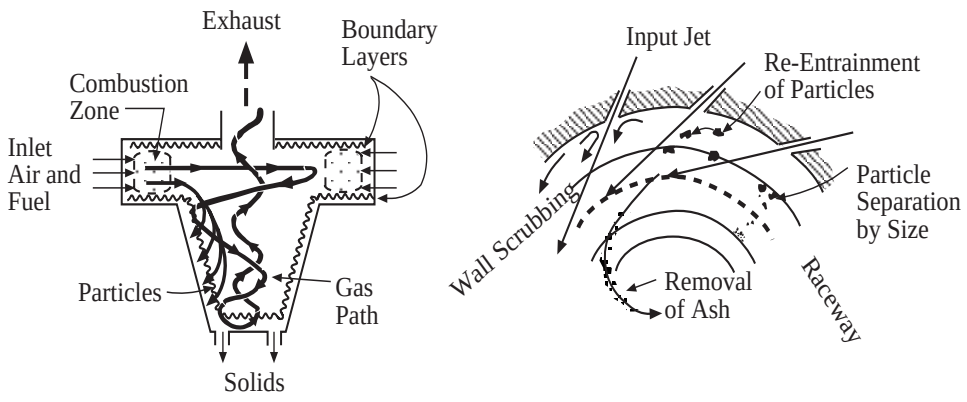


Figure 1. Conceptual Operation of the Vortex Containment Combustor (VCC). The top view of the suspended reaction region (right) and the side view of the overall gas and particle paths (left) are shown.

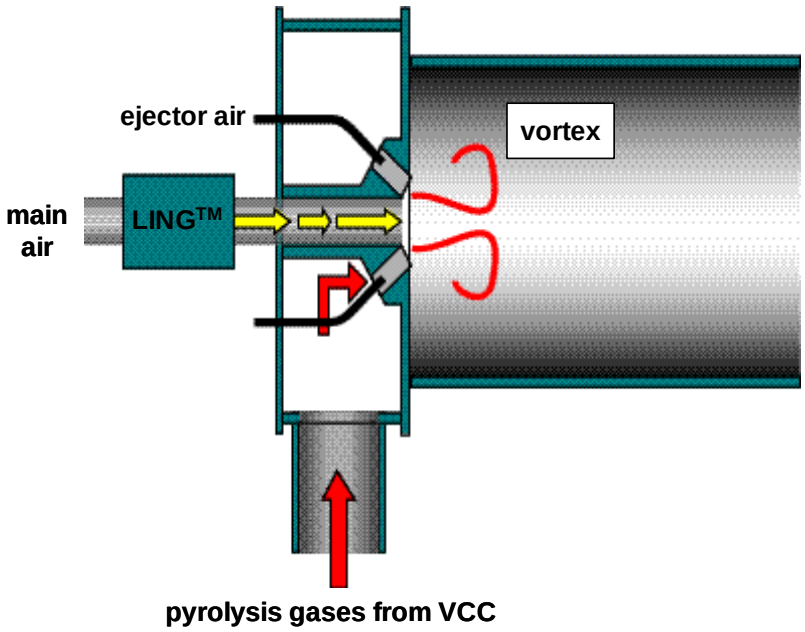


Figure 2. Compact Afterburner (AB) using Open-Loop Control.

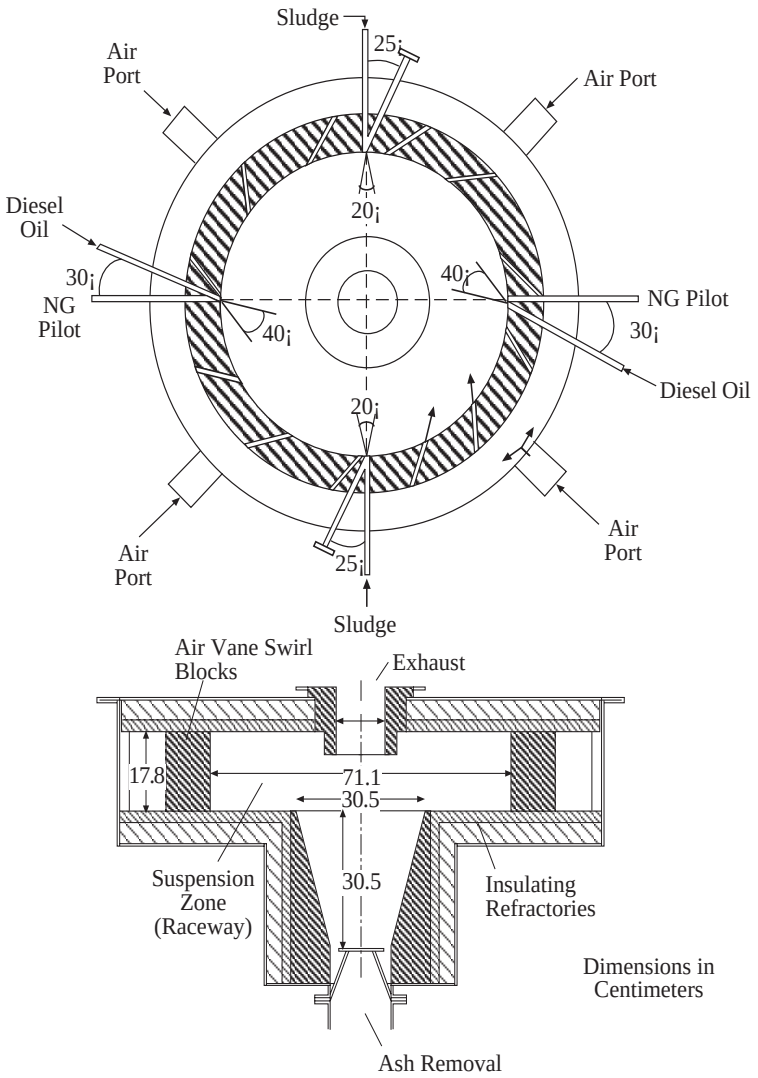


Figure 3. Details of the Full-Scale VCC Dimensions and Internal Layout. The top view illustrates the injector and air-port locations. The insulation and internal dimensions are shown in the side view.

Objectives:

(1) Develop a compact, efficient, and automated combustion system for shipboard sludge treatment, (2) modify VCC for operation with a wide variety of shipboard generated oily and non-oily sludge, (3) determine full-scale VCC performance with shipboard sludge surrogates, and (4) explore sub-scale VCC performance enhancement with integrated AB for potential shore applications.

Technical Approach:

Sub-scale and full-scale experiments were performed to provide physical insight into the VCC mixing and combustion processes and to determine VCC performance for varying sludge characteristics. The various test fixtures are described in the following.

At NAWCWD, the sub-scale VCC Laboratory Combustor (VCC LC) with optical access was used in cold flow studies to determine aerodynamic suspension and retention of particles in the spinning "combustion" zone with laser diagnostics as function of swirl conditions, particle injection parameter, and particle size and density. The VCC LC was also used for combustion tests with a heat capacity of 55 kilowatt (kW) (minimum) and a sludge flow rate goal of 0.75 liter per minute (l/m) or 12 gallons per hour (gph). The test complexity was sequentially increased from tests with gaseous auxiliary fuel to liquid (diesel) auxiliary fuel and from water to water plus ethanol as sludge surrogates. The VCC LC performance was compared with and without AB. The VCC LC combustor was also used to develop a simple controller to maintain optimum performance during variable sludge characteristics.

At GE EER, a 1 megawatt (MW) isothermal VCC model was used to study sludge injection techniques and aerodynamic suspension & retention of sludge sprays. Sludge surrogates consisting of water and solid particles were injected from practical injectors. The results were flow pattern and information on droplet and particle retention as function of operation conditions with the goal to control angular momentum and optimize particle retention efficiency.

Also at GE EER, a full-scale VCC with 500 kW heat release and 3.2 l/m or 50gph sludge flow was used to determine VCC performance. The top diagram in Figure 3 shows the ceramic inserts with the tangential slots for air injection and two injectors each for auxiliary fuel (diesel oil) and sludge. A natural gas (NG) or diesel pilot flame maintained auxiliary diesel oil ignition during VCC operation. The final arrangement of the injector designs was based on VCC floor surface temperature measurements using thermocouples embedded in the ceramics. For performance, measurements were made of nitric oxide (NO), hydrocarbons, oxygen, exit temperature, and carbon monoxide (CO). Measurements of particulate matter escaping the VCC through the exhaust were also made using EPA method 5. Key results from these tests were auxiliary fuel requirements for flame stability limits, evaporation limits, and effective sludge burn-out. Also ash trapping efficiency and throughput capacity were determined.

Initial full-scale VCC combustion tests were performed with the so-called VCC Test Unit, which allowed easy variation of critical design parameters. Based on the Test Unit results the VCC was modified to have the complexity of the final demonstration system, the so-called Process Development Unit (PDU). Design features of this unit for performance measurements with realistic sludge surrogates included diesel piloted burner system, optimized injection schemes, optimized ash collection and removal systems, exhaust gas quenching system, and controller to maintain optimum performance.

Summary:

A compact and efficient combustion system based on the VCC concept was developed for the treatment of shipboard generated non-oily and oily sludge types. The VCC combustor as shown in Figure 4 is approximately five to ten times smaller than conventional waste treatment units. It treats efficiently high water-content waste with minimal auxiliary-fuel input. The 640 kW or 2.2 MMBTU/hr combustor operates on auxiliary diesel fuel and can process 3.2 l/m or 50gph of blackwater, grey water and bilge water wastes generated on a 100 person Navy ship. Operation at a minimum heat release rate of 3.4 kWh/kg or 5,300 BTU per pound of wastewater establishes a minimum combustor temperature for effective waste treatment.

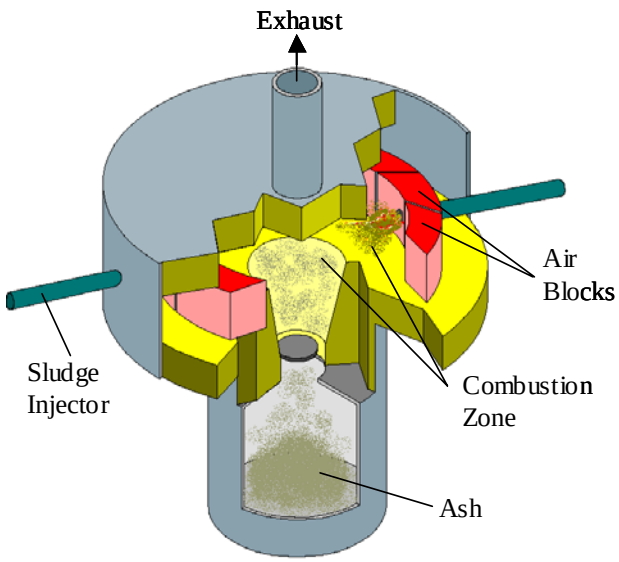


Figure 4. Schematic of Vortex Containment Combustor (VCC) for Sludge Treatment

The VCC accepts a wide range of sludge wastes. Demonstrations were conducted with water, blackwater surrogate sludge, and mixed oily water sludge and oily blackwater sludge. Results showed that the VCC was able to meet IMO standards for exhaust emissions, carbon in ash levels, and plume visibility. The CO emissions for the various sludge types tested were below the IMO standard of 420 ppm corrected for 7 percent O2 with less than 60 ppm for oily water sludge and less than 200 ppm for oily blackwater surrogate sludge. The carbon in ash level was 4 to 5 percent and below the IMO standard of 10 percent. The plume was consistently judged to meet IMO standards of a Bacharach No.3 or less.

The VCC also incorporates a controller to allow automated processing of sludge with highly varying heating values. The controller logic controlled oxygen and temperature by regulating the auxiliary-fuel and sludge flow rates. The automated VCC controller system was demonstrated on non-oily and oily sludge types. The controller can process sludge with up to 7.5 percent oil by mass and with oil fluctuations up to 3.5 percent. As shown in Figure 5 the controller can maintain a desired exhaust oxygen concentration of 3.5 percent when the sludge is varied from blackwater without oil to blackwater with 3.5 percent oil and back to blackwater without oil. During testing, it was noted that the forced disturbance created a sudden increase in CO emissions; however, the CO emissions returned to their original levels once the controller had readjusted the auxiliary-fuel and sludge flow rates. For best performance a homogeneous sludge having variations of no greater than 3.5 percent in oil content is recommended to avoid the need for rapid response excess oxygen sensors in the exhaust.

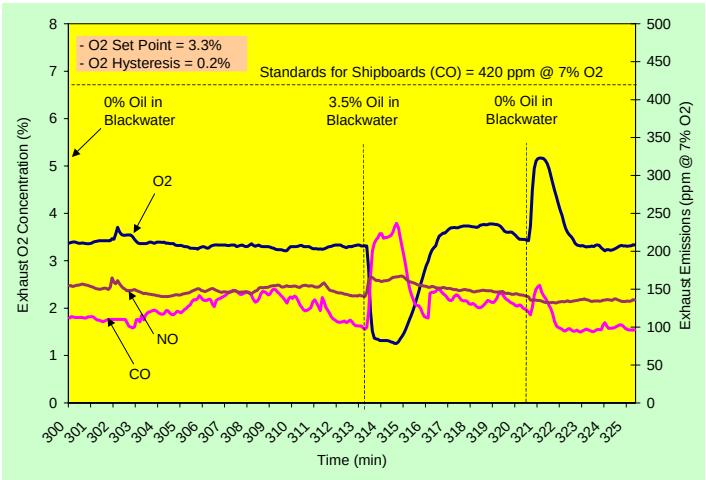


Figure 5. Controller Maintains Desired Oxygen Exhaust Concentration for Varying Sludge Characteristics.

The CO exhaust emission was significantly reduced when the VCC was integrated the actively controlled afterburner (Figure 6). In subscale experiments reductions of a factor by 10

were obtained at selected operational conditions. Optimum results were obtained at forcing frequencies of 300 Hertz. This subscale combustor also provided critical insight into the injection and suspension/retention characteristics of particles in the spinning flow regime using laser diagnostics, and was used for the development of the controller algorithm.

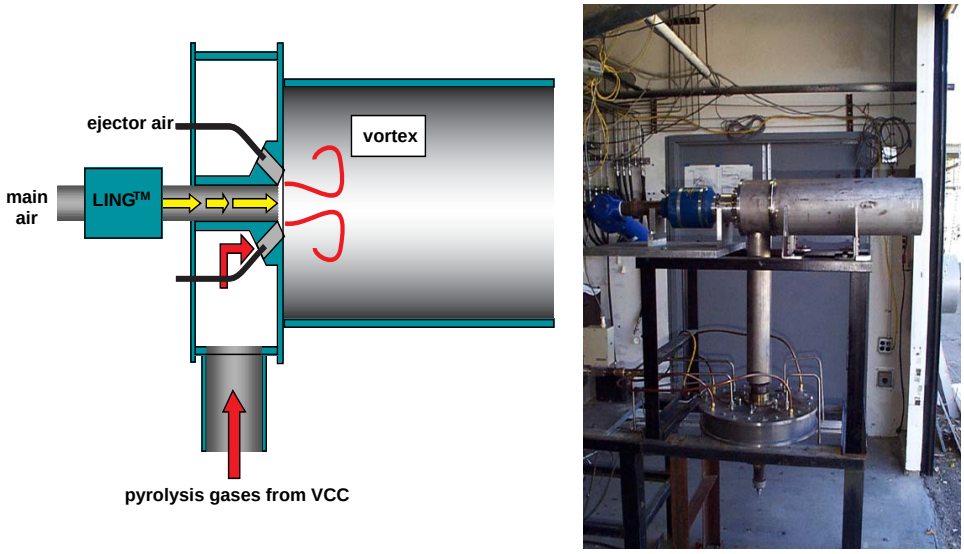


Figure 6. Integrated VCC/AB Laboratory Combustor.

Details of the VCC system is described in Ref. 3 (Appendix 1) with operational flow charts, drawings and part lists of system components, waste streams and equipment configurations, and information on VCC maintenance. Details on the integrated VCC/AB system are described in Ref. 4 (Appendix 2).

Project Accomplishments:

The accomplishments of the program are described in detail in Ref. 3 to 8, which are attached as Appendices 1 to 6. In the following a brief summary of the important accomplishments is given. (1) Results from cold flow experiments to study VCC particle trapping and retention in the spinning flow regime will be summarized. (2) The performance of the sub-scale VCC LC with and without AB will be compared, and tests with water plus ethanol as sludge surrogate will be described. (3) Development of the controller in the sub-scale VCC will be discussed. (4) Experiments with the full-scale Test Unit will be summarized. (5) Component development for the PDU will be discussed. (6) PDU experiments with controller and realistic sludge surrogates will be summarized.

(1) VCC Particle Trapping

The original VCC was designed to burn finely pulverized coal. In the present program the particle retention was evaluated for larger particles of various sizes and density, using the VCC LC with cold flow conditions (Ref. 2, 6, and 8 – Appendices 2, 4, and 6). Particles included non-fat dry milk at a density of about 1.4 gm/cm^3 as well as baking soda at 2.2 gm/cm^3, and talc at 2.75 gm/cm^3. Particles were followed through quartz windows using a diode laser (670 nm) and right angle Mie scattering with a filtered photo-diode. Figure 7 shows particle retention times for various density and sized particles. As expected larger particles are trapped for longer times (the concentration decays slower). This can be seen in Figure 7 by comparing the triangles (130 μm) with the circles (60 μm) for tests with baking soda (2.2 gm/cm^3). Also, denser particles are

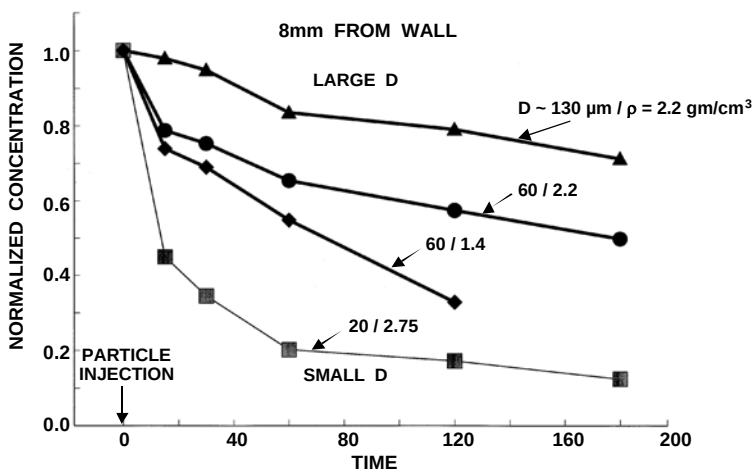


Figure 7. Retention Time for Varying Particle Characteristics

trapped longer than lighter ones as can be seen from comparing the circles (2.2 gm/cm^3) with the diamonds (same size, 1.4 gm/cm^3). The squares are for talc, which, although sieved to 60 μm, is

actually considerably smaller and therefore has a shorter retention time. Even these small particles had a 1/e retention time of about 20 seconds in the sub-scale VCC.

(2) Integration of VCC LC and AB

The VCC LC was integrated with the actively controlled afterburner (AB) to evaluate the performance of the VCC alone (operated fuel lean or at an equivalence ratio, ϕ, smaller than 1) and the VCC plus AB (operated fuel-rich). These tests were done with ethylene as VCC fuel without sludge; the AB has no auxiliary fuel input (Ref. 2, 6 and 8 – Appendixes 2, 4, and 6). Table 1 shows the operating parameters, and performance.

Table 1. Performance of VCC alone compared with VCC + AB with and without active control. The fuel is ethylene, and the units are liters per minute.

	VCC Air	Fuel	AB Air	VCC kW	AB kW	CO ppm
VCC only at $\phi = 0.7$	800 l/m	39 l/m	-	39	-	481
VCC at $\phi = 2.5$ + AB No Control	800 l/m	140 l/m	1940 l/m	55	82	870
VCC at $\phi = 2.5$ + AB With Control	800 l/m	140 l/m	1940 l/m	55	82	47

It is clear from Table 1 that the AB substantially improves the performance of the system over the VCC alone. The CO was reduced by a factor of ten. This was despite the heavy soot load from the VCC when operated fuel rich. There were no visible soot emissions from the AB. The VCC/AB combination suspends particulate matter in the VCC and insures its gasification, while the AB completes the combustion of the resulting pyrolysis gases and fine particulates (soot) in a high mixing rate and high combustion intensity environment for low emissions. This improvement is obtained at the expense of extra auxiliary fuel.

Subsequently, the system performance was evaluated with water plus 5% and 10% by volume ethanol. Ethanol was chosen to include some form of combustible material in the 'surrogate sludge' while not requiring constant stirring of non-miscible components. Specifically, the ethanol was added to the water to evaluate destruction of volatile organics (for example oil) introduced via the sludge input. In these tests, which were done only on the combined VCC / AB system, the surrogate sludge was introduced via swirl based fogger nozzles with very fine droplets, which enhances evaporation within the VCC.

Figure 8 shows the performance of the VCC/AB combination as function of forcing frequency, which is inversely proportional to the air vortex sizes. There were no substantial CO emission changes when comparing results with water only and with water plus 5% and 10% ethanol. The emission for 10% alcohol optimized at 7 ppm at about 300 Hz forcing. The NOx increased from 7 ppm to 20 ppm with the 5% ethanol. The increase was probably due to the slight increase in stoichiometry.

The performance of the sub-scale VCC and VCC/AB was compared with the performance of the current Navy Blackwater Sludge Vortex Incinerator for varying percent of volatile organics in the feed. Recent tests with this T-Thermal built incinerator at Naval Sea

Warfare Center Carderock Division (NSWCCD) showed a dramatic increase in CO emission, when the percentage of volatile organics in the grey and black water sludge increased to 1% and higher. This is probably due to the poor mixing characteristics of this unit. However, for the VCC tests with alcohol as volatile organics surrogate the CO emission remained very low up to 10% organics.

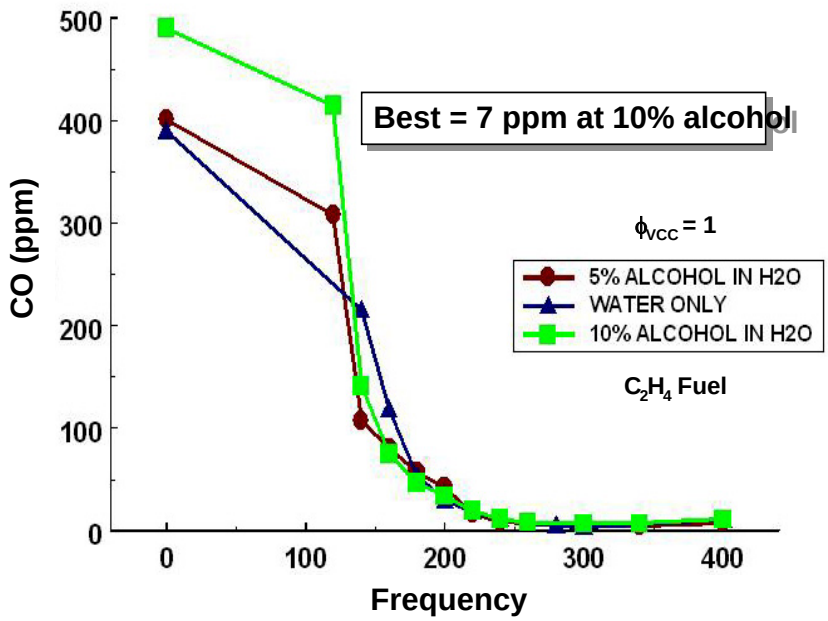
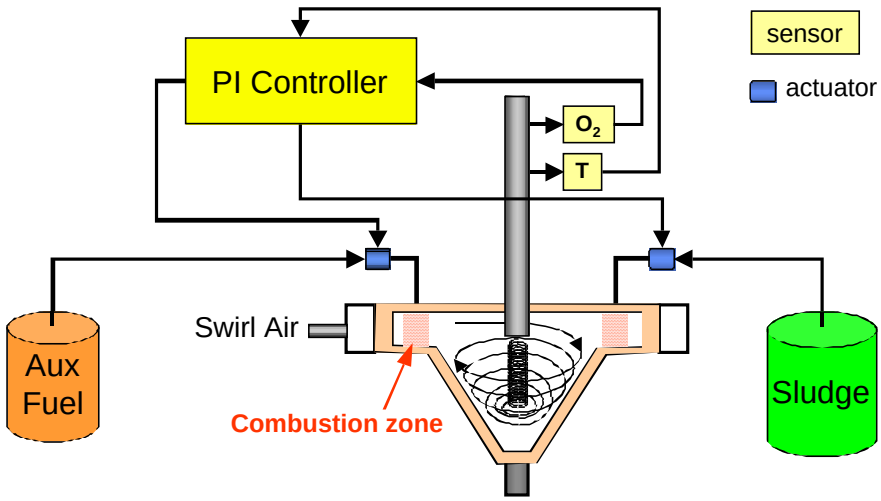


Figure 8. VCC/AB LC Performance With Water and Water Plus Alcohol as Function of Forcing Frequency.

(3) Controller Development

To maintain optimum performance with varying sludge characteristics, the control concept shown in Figure 9 was developed at NAWCWD using a proportional/integrative controller algorithm (Ref. 8 – Appendix 6). The control is achieved by varying the auxiliary-fuel and sludge flow rates when the exhaust temperature and oxygen concentration deviate from the desired values (set points). When the auxiliary fuel is reduced to zero and oxygen remains below the set point (when treating high heating-value sludge), the sludge flow rate is reduced, while considering only the oxygen set point and ignoring the temperature set point. The functioning of the controller is shown in Figure 10. The controller adjusts the auxiliary fuel when the sludge

composition is changed from water to water plus ethanol. The goal of maintaining oxygen concentration at 5% is demonstrated.



Controller algorithm:

If T > setpoint then increase sludge flow, if T < setpoint then decrease sludge flow
If O_2 > setpoint then increase auxiliary fuel, if O_2 < setpoint decrease auxiliary fuel
If O_2 < setpoint AND auxiliary fuel rate = 0 then decrease sludge flow and ignore T

Fig. 9. Control System to Maintain Optimum Operational Conditions at Varying Sludge Compositions. The System includes the Proportional Integrative (PI) controller.

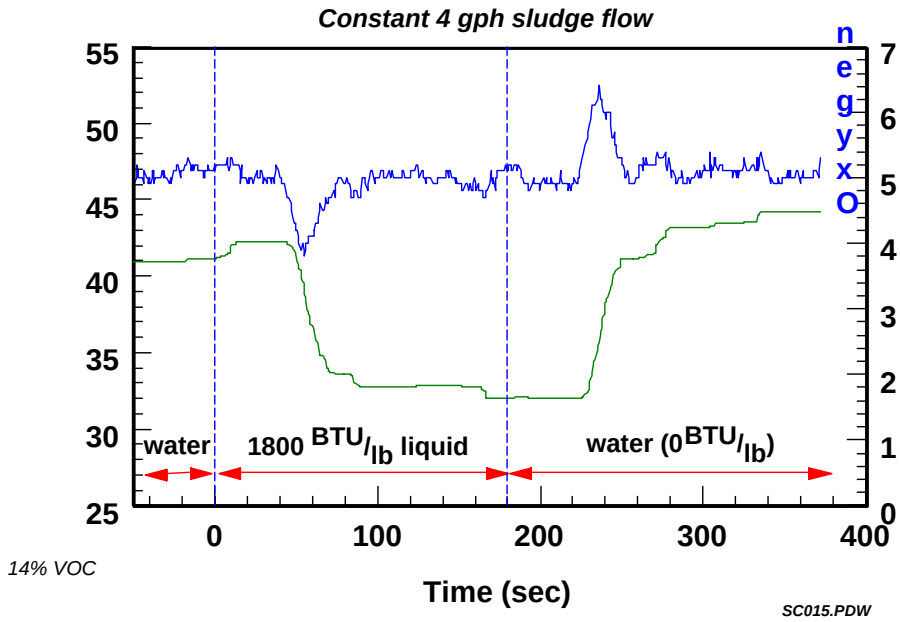
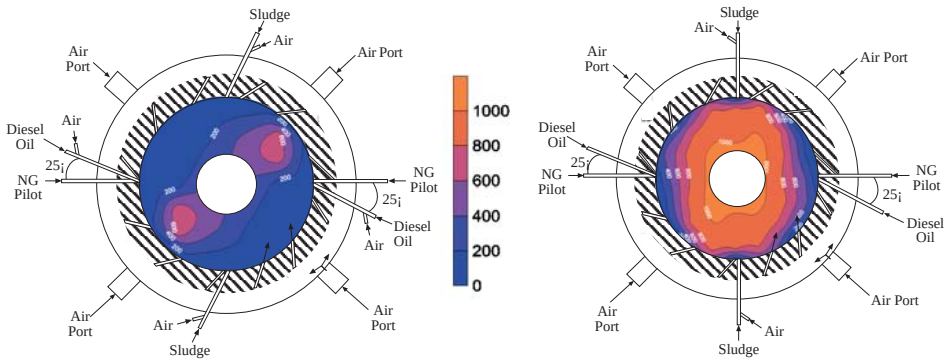


Figure 10. Controller Adjust Auxiliary Fuel Rate to Maintain Oxygen at 5%

(4) VCC Test Unit Experiments

Test Unit tests were performed to determine flame stability limits, performance, and operation specifications (Ref. 5, 7, and 8 – Appendix 3, 5, and 6).

Stability and Mass Flow Limits. The regions of stable combustion (flame stability) and limits of evaporation were extended to the 3.2 l/m (50 gph) sludge flow rate goal by optimizing auxiliary fuel & sludge injection and operational conditions. At initial design conditions and unsatisfactory performance, thermocouple diagnostics in the reacting VCC identified that the sludge was impinging on the VCC walls and collecting on the floor. This resulted in low floor temperatures that reached the boiling point of water upon failure as discussed in more detail in the context of Figure 11.



(a) (b)

Figure 11. VCC Floor Temperature Contours for (a) Original Configuration at 1.3 l/m Water Feed and (b) Final Configuration at 2.6 l/m Water Feed.

The floor temperatures for the initial (unsatisfactory) VCC configuration operating at a sludge evaporation limit of 1.3 l/m (20 gph) are compared in Figure 11 to the floor temperatures of the final configuration operating with 2.6 l/m (40 gph). The initial configuration caused low floor temperatures of 230 C with only 1.3 l/m sludge injection. For the improved configuration operating at 2.6 l/m sludge injection, the average floor temperature was 730 C and decreased to only 520 C with 2.6 l/m sludge injection. Improvements to achieve the target sludge rate of 50 gph included:

- Increasing the number of auxiliary fuel injectors from one to two, which produces a more uniform thermal profile in the VCC.
- Moving the sludge injector to a radial injection orientation to inject the sludge towards the vortex core region. Isothermal flow studies suggested that limited penetration of the core would occur. This orientation avoids that sludge impinges on the opposite wall, which leads to the failure mode.
- Equipping the auxiliary fuel injectors with commercial off-the-shelf pressure nozzles. The optimal nozzle characteristics included a 40° spray angle with a flat spray orientated horizontally in the VCC spinning combustion zone.
- Doubling the sludge atomization air from 140 to 280 standard l/m (5 to 10 scfm) per injector to improve atomization and subsequent evaporation.

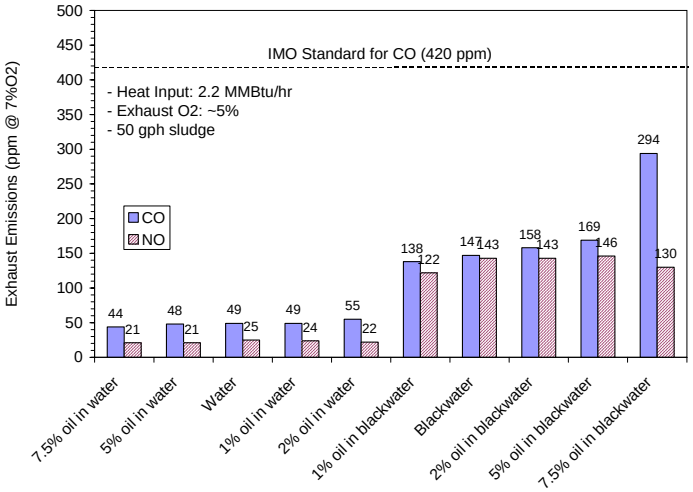


Figure 12. CO and NO Emissions for Varying Sludge Characteristics.

Subsequently, the VCC Test Unit was tested on a wide range of sludge types. The sludge wastes included pure water, simulated blackwater, oily-water concentrations (at 1, 2, 5, 7.5% oil), and oily blackwater concentrations (at 1, 2, 5, 7.5% oil). The blackwater surrogate was comprised of 1.6% dry dog food, 0.2% salad oil, 0.2% paper products, and 98% water. A summary of the CO and NO emissions corrected to 7% O2 for these tests is presented in Figure 12. In all cases the total heat input from auxiliary fuel plus waste oils was kept constant. As is evident, the CO emissions fall well below the IMO standard of 200 mg/MJ (approximately 420 ppm @ 7% O2). For the simulated blackwater tests, the carbon-in-ash from the ash drum collection system was below 1%, which is well below the IMO standard of 10%. During these tests, the exhaust stack flue gas particulate concentrations measured was 0.15 gr/dscf @ 7% O2 with no visible plume also meeting IMO standards.

The repeatability and consistency of the CO performance was demonstrated during a 5-hour operation when different sludge types were treated and the sludge mass flow was varied. The sludge type was changed from 3.2 l/m water to 3.2 l/m water plus 1% oil, 3.2 l/m blackwater sludge surrogate with 2% organic solids, and 3.2 l/m blackwater sludge plus 1% oil. As shown in Figure 13, the CO emission was below the IMO standard of 420 ppm for all sludge types and increased from 20 ppm for water plus oil to nearly 200 ppm for blackwater sludge plus oil. For the latter sludge surrogate, the CO was reduced to 60 ppm when the sludge flow rate was reduced to 2.2 l/m. The NO emission increased to about 150 ppm with the blackwater surrogate sludge plus oil. The stack temperature varied around an average value of 1100 C.

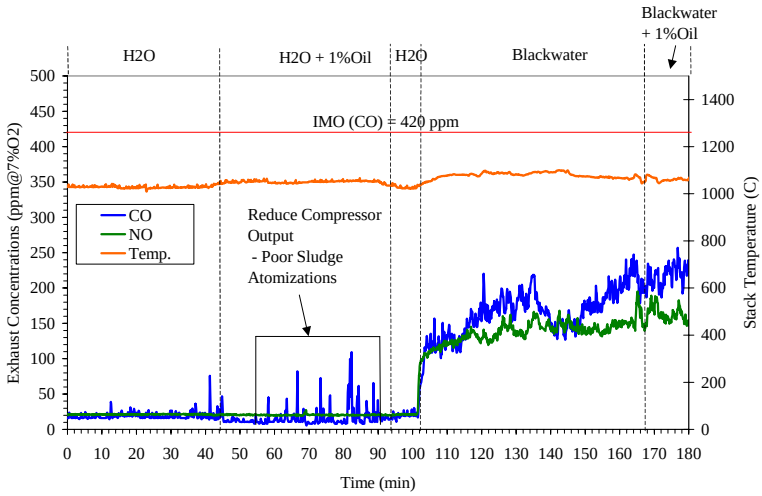


Figure 13. VCC Test Unit Emission Performance for Varying Sludge Type.

After satisfactory operation of the VCC system was achieved, the specification limits for operation regions yielding the best performance in terms of CO and NO emissions were identified. The results are summarized in Table 2.

Table 2. VCC Operating Specifications

Parameter	**Unit**	**Specification**
Heat Input	kW (MMBtu/hr)	640 (2.2)
Sludge Feed Rate (max.)	lpm (gph)	3.2 (50)
Heat Rate (Heat input per mass of waste)	MJ/kg (MMBtu/lb)	12.3 (5,300)
Excess Oxygen	%	5.0
Sludge Atomization:		
Air to Sludge Mass Ratio	kg/kg	0.2
Air Pressure	kPa (psi)	250 (36)
Exhaust Temperature	°C (°F)	1030 (1890)

(5) Component Development for PDU

In preparation for the final VCC set-up, several components were developed, and the combustor designs were optimized. These included diesel pilot burner development, optimization of combustion chamber and combustor throat, and testing of ash collection and quench systems.

Diesel Pilot Burner. Continuously operating pilot burners are required to stabilize the auxiliary diesel fuel flame. From several burner configurations the configuration illustrated in Figure 14 was selected. This configuration consists of two air streams: one for fuel atomization (Air 1) and another for combustion air (Air 2). The diesel pilot burners were designed to match the natural gas pilot burner specifications proven in earlier tests. Critical pilot burner specifications included similar heat input, operating stoichiometry, and pilot burner jet momentum to achieve similar interactions with the diesel burner jet.

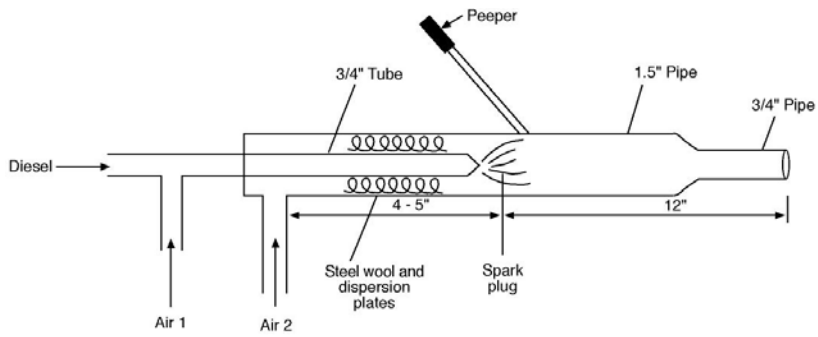


Figure 14. Diesel Pilot Burner Design

Combustion Chamber Design. In initial VCC tests a particulate matter (PM) retention efficiency of approximately 50% with a cut-off particle diameter of approximately 20 microns was achieved. This relatively low PM retention was due to unsatisfactory vortical strength in the VCC, because the liquid sludge was injected in radial direction into the combustion chamber. This reduced the total tangential input momentum and, since the vaporized sludge represents approximately 30% of the total VCC gas flow, the subsequent PM retention. To improve PM retention, the rotational velocity (angular momentum) in the combustion chamber was increased by 14%, by decreasing the throat diameter by 6%, increasing the throat penetration into the combustor by a factor of 2.5, and decreasing the vane gap size by a factor of 2. The pressure drop increase with these changes was tolerable. Calculations showed that the increase in the tangential velocity reduces the particle cut off diameter from 20 microns to 17 microns. This is estimated to improve the particle retention efficiency by over 15%.

Comment [NCW1]: Verify the cut-off diamter, i.e. should be the particle mean diameter for mulite batch.

Ash Collection System. In initial tests, the ash collected from the VCC had carbon-in-ash levels on the order of 25%, which is above the IMO standard of 10% or less. A detailed sample analysis revealed that 80% of the carbon-in-ash could be volatilized at or below the boiling point of diesel at approximately 330 C. It was therefore anticipated that the carbon-in-ash content could be reduced to approximately 5% at temperatures of 330 C and above. The sample analysis also implied that the carbon was substantially unburned diesel, possibly caused by condensation in the drum. The ash collection system was re-designed to maintain a minimum skin temperature of 330 C at all locations of the drum. An insulated 20-gallon drum was tested on the VCC and the minimum drum temperature was 400 C.

Quench System. The IMO standard requires all shipboard incinerators to quench the flue gas from a minimum of 850 C at the combustion chamber outlet to a maximum temperature of

Comment [NCW2]: You are just hoping someone will ask you to write a paper explaining why dioxin and furan formation is reduced and perhaps add additional EPA testing to you program to verify no dioxin and furan formation.

350 C within 2.5 meters (8.2 ft). A VCC quench system was designed, which operates with air injection directly into the stack. Figure 15 illustrates the quench design. The key aspects include an air plenum to uniformly introduce air through multiple ports around the circumference of the exhaust, a flow dampening system (damper valve 2) to maintain VCC chamber pressure, and an induced draft fan. The other damper and butterfly valves shown in Figure 15 are for process development.

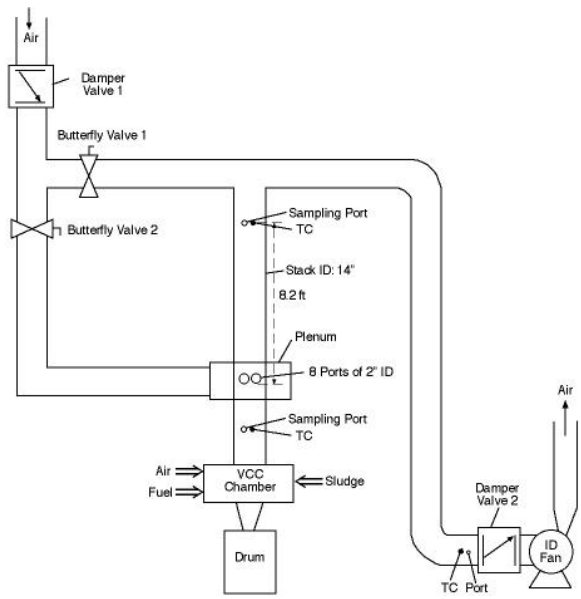


Figure 15. VCC Quench System

Exhaust Throat Design. Initial Lab test on a magnesia-stabilized zirconia cylinder was promising; however, the cylinder broke after 2 days of operation on the actual VCC combustor. We replaced it with a stainless steel cylinder. This cylinder was used for over 3 months with no degradation observed. It was believed that due to the sludge radial injections (towards the exhaust cylinder) the temperatures may be lower near the cylinder area. It may be possible that some droplets are hitting the cylinder before being evaporated just maintaining a lower temperature on the actual cylinder.

The new components and design concepts were integrated into the VCC to build the PDU for performance testing with realistic sludges and operation with controller.

(6) PDU Performance with Controller.

For the VCC tests with the controller (Ref. 1) the oxygen concentration set point was selected at 3.3 percent. This is the mid-point for safe VCC operation. For oxygen concentrations below 1.5 percent, CO emissions were above the IMO standard; for oxygen concentrations over

5 percent, the VCC failed to maintain stable operation. The exhaust temperature set point was selected at 1150°C. This corresponds to the temperature for VCC operation at 3.3% excess oxygen and a sludge flow rate of 50 gph.

With automated operation of the VCC, the temperature is regulated by the sludge flow rate. The maximum sludge flow rate was selected to avoid operating conditions for which the VCC would operate. This is at exhaust temperatures below 1010°C, where a stable flame in the combustion zone cannot be maintained, resulting in high CO emissions and eventually in system shut-down due to flameouts. The minimum sludge flow rate was selected to avoid operation of the VCC at exhaust temperatures exceeding 1350°C. Operation above this temperature may result in system overheating and material degradation.

During VCC operation, the controller regulates the auxiliary-fuel and/or the sludge flow rates when the actual oxygen and/or temperature readouts are outside of the set points hysteresis bands. These are +/-0.2% for oxygen and +/-20 °C for the temperature. For example, the controller adjusts the auxiliary-fuel flow rate when the oxygen concentration readout falls outside of the 3.1 to 3.5 % range and the temperature outside of the 1130 to 1170°C range.

To optimize VCC performance, the controller needs to provide quick response times. The response time is defined as the time required for the controller to return to its set point, following a disturbance. Three control variables impact the controller's response: the cycle time, fuel step size and sludge step size. The optimum control variable settings were established as follows: a cycle time of 2 seconds, a fuel step size of 0.1 gph, and a sludge step size of 1 gph.

Figure 16 illustrates the controller's response behavior for these settings in tests with blackwater and 3.5% oil surge. As seen in this figure, a response time of approximately 3.2 minutes was required to allow the oxygen concentration and temperature to return to their respective preferred range. After that time, the CO and NOx emissions remained within acceptable limits. During testing, it was noted that the forced disturbance created a sudden increase in CO emissions; however, the CO emissions returned to their original levels once the controller had readjusted the auxiliary-fuel and sludge flow rates. As for the NOx emissions, the forced disturbance did not impact their behavior. The tests showed that the controller has a longer recovery time when the sludge undergoes a sudden heat input increase (from oil) than when the sludge undergoes a sudden heat input loss.

It should be noted that the response time can be significantly reduced by reducing the response time of the oxygen sensor.

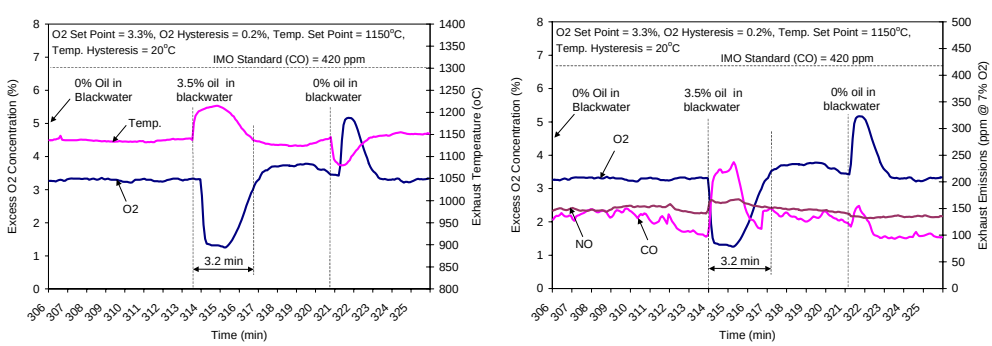


Figure 16. Controller's Behavior for a 3.5 percent Oil Surge in Blackwater Sludge for Optimum Controller Variables Settings. (a) Oxygen and Temperature Responses and (b) Oxygen and Exhaust Emissions Responses

Conclusions:

A compact and efficient combustion system based on the Vortex Containment Combustor (VCC) concept was developed for the treatment of shipboard generated non-oily and oily sludge types. The VCC combustor, which is approximately five to ten times smaller than conventional waste treatment units, treats efficiently high water-content waste and oily wastes with minimal auxiliary-fuel input. The 640 kW or 2.2 MMBTU/hr combustor operates on auxiliary diesel fuel and can process 3.2 l/m or 50 gph of varying sludge types. Demonstrations were conducted with water, blackwater surrogate sludge, oily water, and oily blackwater sludge, and the VCC was able to meet IMO standards for exhaust emissions, carbon in ash levels, and plume visibility. The VCC incorporates a controller to allow automated processing of sludge with highly varying heating values. The controller logic can maintain desired oxygen and temperature set points by regulating the auxiliary-fuel and sludge flow rates. For the development and demonstration of the VCC the following tasks were successfully completed:

(1) The VCC particle trapping and retention in the spinning flow regime were studied in cold flow experiments using the subscale VCC Laboratory Combustor (LC). Particles were followed through quartz windows using a diode laser (670 nm) and right angle Mie scattering with a filtered photo-diode. The high particle retention times associated with the VCC design were demonstrated for various particle densities and sizes.

(2) The performance of the sub-scale VCC LC with and without the actively controlled afterburner (AB) was compared using ethylene and water plus ethanol as sludge surrogate. The CO emission was reduced with the AB by a factor of 10 at selected operational conditions, which makes the integrated VCC/AB attractive for shore-based applications. In the final year of the program, the decision was made to focus on shipboard waste treatment using the full-scale VCC without AB.

(3) The controller was developed in the sub-scale VCC LC to maintain optimum performance with varying sludge characteristics. The control is achieved by varying the auxiliary-fuel and sludge flow rates when the exhaust temperature and oxygen concentration deviate from the desired values (set points). When the auxiliary fuel is reduced to zero and oxygen remains below the set point (when treating high heating-value sludge), the sludge flow rate is reduced, while considering only the oxygen set point and ignoring the temperature set point. The controller was adapted to the full-scale VCC.

(4) Initial full-scale VCC combustion tests were performed with the VCC Test Unit, which allowed easy variation of critical design parameters. Flame stability limits and performance were optimized, and operation specifications were determined. Optimization was achieved by optimizing sludge and auxiliary-fuel injection characteristics utilizing results from combustor floor temperature measurements. Based on the Test Unit results the VCC was modified to have the complexity of the final demonstration system or Process Development Unit (PDU).

(5) Component development for the PDU included diesel pilot burner, ash collection system, and quench system. Also combustion chamber design and combustor throat material were optimized.

(6) PDU experiments with the controller using varying sludge surrogate types were performed to demonstrate the controller's response behavior in tests with blackwater and imposing a 3.5% oil surge. The controller maintained the desired oxygen concentration and combustion temperature at a response time of approximately 3.2 minutes.

Transition Plan:

Close interactions were maintained with Naval Sea Systems Command (NAVSEA – Carl Adema) and Naval Sea Warfare Center Carderock Division (NSWCCD - Mike Bonanno) throughout the SERDP program. At its beginning in 1999, the Navy pursued the option of a liquid sludge incinerator for shipboard treatment of oily and non-oily sludge wastes. Because of the superior performance of the VCC compared to standard Navy sludge incinerator, both NAVSEA and NSWCCD were interested to evaluate the VCC at NSWCD after successful completion of the SERDP program. However in 2001, the Navy R&D effort on liquid waste incineration was terminated, and therefore a transition of the VCC to the Navy did not materialized. Contacts have been established to Newport News Shipbuilding (NNS – Arthur Holloway) to explore their interest in the VCC for the future aircraft carrier CVNX. Also, contacts to TeamTec, Norway, are being pursued to discuss potential transition. Details of the transition efforts are described in the following.

The Navy R&D effort in 1999 included NSWCCD's effort to extend the existing Navy Blackwater Vortex Incinerator to mixed waste streams. This effort, however, did not produce the desired results. Tests showed that for mixtures of blackwater with oil the CO emission of this incinerator exceeded the IMO limits when the oil (volatile) content was increased above 0.3 to 0.9% (Figure 17). In comparison, the VCC met the IMO regulations for the higher volatile contents. As shown in the Figure 17, the CO emission for the VCC was independent of the volatile concentration up to 5%. The superior performance is due to the unique VCC design and the possibility to operate the VCC at higher combustion temperatures (Table 3). Table 3 also shows that the VCC was lighter than the Navy incinerator (1200 vs. 1400 lb), even at a higher flow capacity for the VCC (50 vs. 30 gph). The Navy was interested in exploring the VCC in the NSWCCD laboratory with real sludge types, as long as the Navy liquid waste R&D program existed.

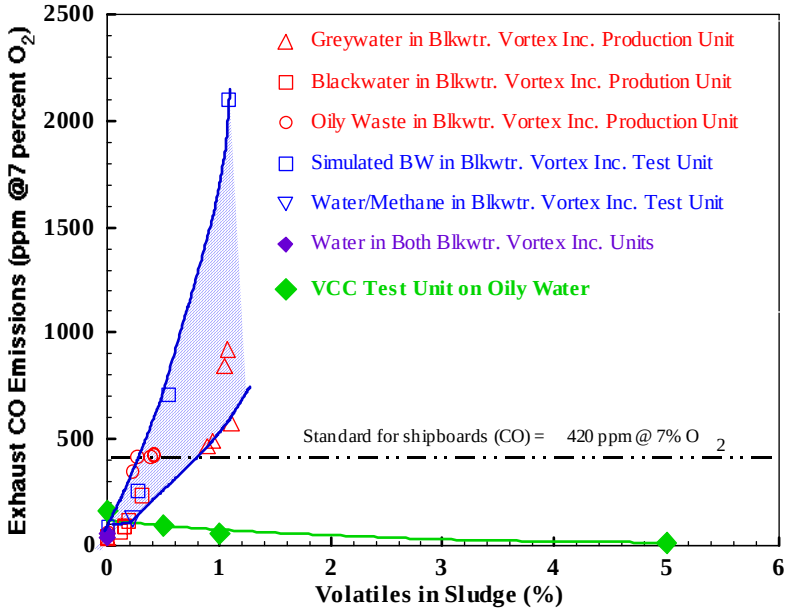


Figure 17. Comparison of CO Emission as Function of Volatile Content in Sludge for Existing Navy Blackwater Vortex Incinerator and VCC

Contacts have been established to NSS. NSS, which has the lead for future aircraft carrier designs, has been tasked by the Navy to explore the need and potential implementation of shipboard waste treatment. For oily bilge water treatment, one option

Table 3. Comparison of VCC with Navy Blackwater Vortex Incinerator and TeamTec Sludgekiller

Technology Comparison	VCC Test Unit	Navy Blackwater Vortex Incinerator	TeamTec Sludgekiller
Compactness:			
Processing (external), gph/ft3	1.6	1	0.1
Weight, lb	1,200	1,400	16,500
External Volume, ft3	31	30	652
Fuel Efficiency:			
Heat Input, MMBtu/hr	2.2	0.9	5.3
Processing, gal/MMBtu	22.7	33.3	12.6
Temperature, oF	1850-2100	1300	2100
Capacity:			
Sludge, gph	50	30	67
CO Emissions, ppm @ 7%O2:			
IMO Emission Standard	**420**	**420**	**420**
Blackwater	147(1)	118(2)	
Oily Sludge (1% oil in water)	49	510	-
NOx Emissions, ppm @ 7%O2:			
IMO Emission Standard	**None**	**None**	**None**
Blackwater	143(1)	214(2)	-
PM Emissions, gr/dscf @ 7%O2:			
IMO Emission Standard	**None**	**None**	**None**
Blackwater	0.15(1)	0.33(2)	-
Plume Visibility, Bacharach #:			
IMO Standard	**3**	**3**	**3**
Blackwater	3 or less	3 or less	-

(1) Surrogate Blackwater with 1.8% solids and 1.2% volatiles
(2) NSWC Carderock Division results for blackwater with .57% solids, 0.18% volatiles

has been mentioned, for which the VCC may be of interest. This option is a liquid waste incinerator to destroy a mixture of oily waste (oil and oily waste concentrates from the membrane ultrafiltration units) and liquified garbage grinder waste.

There are currently no plans for the CVNX to incinerate grey water and blackwater. The raw sewage can be collected over a period of 30 days (maximum) and brought back to shore or pump overboard when beyond a certain distance from shore. Presently this distance is 3 miles; it will be extended to 12 miles with new IMO regulations. Dumping of pre-treated sewage would be allowed between 3 and 12 miles.

The decision on CVNX shipboard waste treatment needs will be affected by factors still under investigation. For example, the new CVNX design may reduce the amount of generated bilge water to such an extend, that onboard treatment may be not required. On the other hand, the possible extension of the mission duration above the current 30 days may make collection of bilge water not feasible. In any case, a decision on future shipboard sludge treatment needs has not been made.

We are discussing the VCC results also with TeamTec, Norway, which is developing the "Sludgekiller" (OG 1500) for treatment of oily wastes. The goal is to combust pre-treated oily wastes with up to 40% water content at a flow rate of 150 l/h (38 gph). With its outside dimensions of 4545 x 1715 x 2400 mm and a weight of 7500 kg, the Sludgekiller is heavier and larger than the VCC with its 50gph capacity (see Table 3). The Sludgekiller is for the treatment of oily wastes from bilge water, engines, and fuel tanks on commercial transport ships, which produce only a limited volume of black and grey water. In the future TeamTec is considering the possibility to treat black and grey water concentrates. One option would be to combine the VCC with its compactness of the combustion process and with its high flame stability and low CO emission for the low BTU wastes (water) with TeamTec sludge treatment system. This system is required for treatment of the fuel waste on commercial vessels, since the fuel is more viscous than the VCC fuel and requires heating to 90C to achieve satisfactory atomization and CO emission.

Recommendations:

(1) Evaluate VCC with real shipboard sludge wastes.
(2) Maintain contact with the Navy and NNS to follow need assessment for shipboard treatment of oily and non-oily wastes.
(3) Maintain contact with TeamTec for potential transition of VCC technology.

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(4) T. P. Parr, K. J. Wilson, R. A. Smith, K. C. Schadow, J. Cole, N. Widmer, and R. Seeker. "Sludge Combustor Using Swirl and Active Combustion Control," The Nineteenth IT3 Conference, Portland, Oregon, May 2000.
(5) N. C. Widmer, J. A. Cole, W. R. Seeker, K. J. Wilson, T. P. Parr, and K. C. Schadow. "Actively Controlled Vortex Disposal System For Sludge Wastes," The Nineteenth IT3 Conference, Portland, Oregon, May 2000.
(6) Klaus C. Schadow and Wm. Randall Seeker, "Development of Incinerator Technologies for Ship-Board and Port/Shore Operations," International Conference on Ship Waste – Management and Treatment in Ports and Shipyards, Bremerhaven, Germany, June 2000.
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(8) N.C. Widmer, K.J. Wilson, P. Gauthier, T.P. Parr, Wm.R. Seeker, and K.C. Schadow, "Emission Reductions for Sludge Combustor Using Swirl and Active Combustion Control", presented at 6th International Conference on Technologies and Combustion for a Clean Environment, 9-12 July 2001, Oporto, Portugal.

Appendix A, Publications:

1) GE Energy & Environmental Research Corporation, "Vortex Containment Combustor System for Shipboard Sludge Waste Disposal", Final Report for Office of Naval Research Contract N00014-01-C0326, June 24, 2002. (Technical Report)
2) T. P. Parr, K. J. Wilson, R. A. Smith, K. C. Schadow, J. Cole, N. Widmer, and R. Seeker. "Sludge Combustor Using Swirl and Active Combustion Control," The Nineteenth IT3 Conference, Portland, Oregon, May 2000. (Conference Proceedings)
3) N. C. Widmer, J. A. Cole, W. R. Seeker, K. J. Wilson, T. P. Parr, and K. C. Schadow. "Actively Controlled Vortex Disposal System For Sludge Wastes," The Nineteenth IT3 Conference, Portland, Oregon, May 2000. (Conference Proceedings)
4) Klaus C. Schadow and Wm. Randall Seeker, "Development of Incinerator Technologies for Ship-Board and Port/Shore Operations," International Conference on Ship Waste – Management and Treatment in Ports and Shipyards, Bremerhaven, Germany, June 2000. (Conference Proceedings)
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APPENDIX 1

Energy

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FINAL REPORT

Vortex Containment Combustor System for Shipboard Sludge Waste Disposal

Office of Naval Research
Contract No. N00014-01-C-0326

June 24, 2002

Prepared for:
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VORTEX CONTAINMENT COMBUSTOR SYSTEM FOR SHIPBOARD SLUDGE WASTE DISPOSAL

ABSTRACT

In environmentally sensitive areas, the U.S. Navy is required to comply with International Maritime Organization (IMO) emission standards. In order to achieve this with minimal impact to the Navy's prime directive of national security, the Navy is interested in developing new compact technologies for efficient thermal treatment of liquid wastes. A program has been set up to develop such a system. For this program, a team comprising GE Energy and Environmental Research Corporation, the United States Naval Air Warfare Center, Weapons Division and Dr. Klaus Schadow has developed a compact and efficient combustion system for the treatment of shipboard generated non-oily and oily sludge wastes. The combustor concept is based on a high firing density and particulate matter retention Vortex Containment Combustor (VCC) system developed for coal firing applications. The thermal treatment of liquid sludge wastes is accomplished in this innovative cyclone-fired combustor that has been re-engineered for sludge treatment. The VCC combustor resembles a cyclone particle separator. The combustor design establishes an aerodynamic separator that provides long residence time for particle burnout in a compact chamber and effectively separates particles and fly ash from the exhaust gases via centrifugal forces.

The VCC combustor is approximately five to ten times smaller than conventional waste treatment units. The combustor also efficiently treats high water-content wastes with minimal auxiliary-fuel input. The 2.2 MMBTU/hr combustor operates on liquid fuels and can process 50 gallons per hour (3.2 lpm) of blackwater, greywater and bilge water wastes generated from a 100 person Class 9 destroyer. Operation at a minimum heat rate of 5,300 Btu per pound of wastewater (3.4 kWh/kg) establishes a minimum combustor temperature for effective waste treatment.

The VCC combustor accepts a wide range of sludge wastes. Recent demonstrations were conducted with water, blackwater surrogate sludge, oily water sludge and oily blackwater surrogate sludge. Results showed that the VCC combustor was able to meet the IMO standards for exhaust emissions, carbon in ash levels and plume visibility. The CO emissions for the various sludge types tested were below the IMO standards of 420 ppm corrected to 7 percent O2 with less than 60 ppm for oily water sludge and less than 200 ppm for oily blackwater surrogate sludge. The carbon in ash level was 4 to 5 percent and below the IMO standard of 10 percent. The plume was consistently judged to meet the IMO standard of a bacharach No.3 or less.

The VCC also incorporates a controller to allow automated processing of sludges with highly varying heating values. The controller logic controlled oxygen and temperature by regulating the auxiliary-fuel and sludge flow rates. The automated VCC controller system was demonstrated on non-oily and oily sludges. Tests results showed that the VCC controller could process sludges with up to 7.5 percent oil by mass and with oil fluctuations up to 3.5 percent. For best performance a homogeneous sludge having variations no greater than 3.5 percent in oil content is recommended to avoid the need for rapid response excess oxygen sensors in the exhaust.

To date, the full-scale VCC combustor showed successful thermal treatment of liquid sludge wastes. The combustor met the shipboard IMO requirements for a wide range of surrogate sludge wastes. The next step in the successful deployment of the VCC requires operation on real shipboard sludge wastes.

INTRODUCTION

Historically, ships at sea have simply pumped liquid wastes overboard without concern for possible environmental damage. Currently U.S. Navy ships are equipped with incinerators to handle blackwater (sewage from toilets), but do not have the incineration capabilities necessary to deal greywater (sewage from showers, laundry and sinks) or bilge water (water from the ship's bilge contaminated with oil and dirt).

In the case of automobiles and other vehicles with relatively short services lives, the common practice has been to limit the application of new environmental regulations to new vehicles. Ships, however, have very long service lives and consequently the regulations of the International Maritime Organization (IMO) are applicable to existing ships including those of the U.S. Navy. These regulations will require incineration of not only blackwater, but also of greywater and bilge water which will place severe demands on current incineration systems.

The incinerator's processing capacity must be increased in order to meet the new IMO regulations. Due to space limitations on ships, retrofitting with higher capacity (and thus larger) incinerators poses new problems. While a ship's incinerator may be replaced with a new incinerator, that new incinerator has to fit into an existing space on the ship and meet existing ship's requirements with respect to fuel and electricity consumption. It will readily be appreciated that merely improving the design of an incinerator so that it could handle the increased throughput and oily waste content of blackwater, greywater and bilge water would not meet the need if the improved incinerator was substantially larger than the incinerator it must replace. For example, the Blackwater Vortex incinerator unit used on U.S. destroyers has an external volume of 30 cubic feet and a blackwater sludge capacity of 30 gallons per hour giving it a processing rate of 1.0 gph/ft^3. The blackwater vortex incinerator is not capable of processing oily waste and cannot process 50 gph of non-oily sludge wastes. Since space for a larger incinerator would be available only with great difficulty, a new incinerator is needed in which the processing rate is increased to 50 gph in an approximately 30 ft^3 volume, or a processing rate of 1.67 gph/ft^3. Furthermore, in order to meet air quality standards this increased processing rate must achieve CO emissions below 420 ppm corrected to 7 percent O_2. Shipboard incinerators must also meet the IMO standards for plume visibility of bacharach #3 or less and for unburned carbon in the ash of less than 10 percent. Finally, the incinerators must meet these standards while processing three types of sludge wastes: blackwater, greywater and bilge water.

Because of the limited space on ships, there is a general need to substantially increase the processing rate while meeting plume, carbon in ash levels, and CO emissions requirements. As is well known, these requirements interact strongly. It is quite simple to increase the sludge waste throughput but, of course, increased throughput reduces combustion temperature, decreases combustion time and runs the risk of combustion instability and flame-out. Thus increasing throughput in a given incinerator without causing unacceptable increases in plume visibility, carbon in ash levels, and/or CO emissions is a far more difficult task.

Advanced combustion techniques for shipboard waste processing are being developed by the U.S. Navy to replace existing treatment systems. These advanced systems must handle an increasing variety and throughput of wastes and be of essentially the same size as existing onboard units. Sludge processing rates are expected to double although the sludge streams will still comprise mostly water. The sludges to be treated consist of non-oily wastes of 1% organic solids (from vacuum collected blackwater or sewage) and 2 percent organic solids (from membrane/bioreactor treated greywater or galley waste), and oily waste derived from membrane separation of bilge water consisting of 0.5 percent oil. The treatment system must be capable of processing these wastes either separately or in combination. Current marine incinerators used on board Navy ships are unable to meet IMO standards when processing these wastes.

The technology concept developed for the shipboard application is based on a high firing density and particulate matter retention Vortex Containment Combustor (VCC) system developed for coal firing applications. The approach involved converting the coal combustor to fuel oil operation and integrating liquid sludge thermal treatment. GE Energy and Environmental Research Corporation (GE EER), a wholly owned subsidiary of General Electric Power Systems, has worked in conjunction with the Naval Air Warfare Center, Weapons Division and Dr. Klaus Schadow to develop a compact system for thermal treatment of these sludge wastes. This paper describes the unique design of the VCC system, and also presents the VCC's performance for a wide variety of surrogate sludges.

In addition to shipboard applications, this technology has applications to a wide variety of oily sludge wastes generated in the military by activities such as vehicle and aircraft wash down. These oily wastes

can contain significant levels of water and particulate matter including toxic metals and must be treated in an environmentally acceptable manner.

BACKGROUND

While some wastes are readily combustible, it is nearly universal practice for incinerators to use an auxiliary-fuel to stabilize combustion performance. For wastes that contain relatively large amounts of combustible material, the amount of additional fuel may be small. For blackwater, greywater and bilge water, however, the primary component of the waste is water. The heat of vaporization of water is high so to successfully treat these wastes one must burn sufficient auxiliary-fuel to heat the waste to an acceptable treatment temperature.

In principal, the waste is heated by spraying the fluid into the hot gases generated by combustion of auxiliary-fuel. The liquid spray must be suspended in the hot gases long enough for complete evaporation and avoid liquid impinging on the combustor walls. In the event the liquid impinges on the walls, a failure mode may precipitate because the local wall temperature drops causing water collection. Heat transfer from the hot gas to the water is then insufficient to vaporize the water and eventually the cold wall region spreads until untreated liquid pours out the VCC. Solid organic material in the spray must likewise be retained in the chamber for sufficient time to achieve adequate thermal treatment. It is important to avoid fouling the walls so the solids must be suspended in the gas flow. However, the solid materials require longer treatment time than the gaseous materials so it must be retained in the combustor until it is completely oxidized. Another concern with injecting low heating value waste into the hot gases is temperature suppression and flame instability. This requires careful orientation of the waste injection and places limits on the sludge processing rate.

In the early 1980s, EER began development of a coal combustor technology retrofit for oil-fired boilers. The purpose was to enable coal combustion in boilers that were not designed to handle high ash loading. The approach involved effective ash retention in the combustor that was achieved by cyclone separation. The combustor traps and suspends solids in a fire ring and produces a largely ash-free exhaust gas [1].

The VCC concept, illustrated in Figure 1, involves a ring-shaped combustion chamber in a classic cyclone-type device. Air is introduced into the combustion chamber through a number of tangentially directed slots. The large diameter, narrow raceway combustion chamber establishes a high performance aerodynamic separator that effectively traps droplets and fly ash in the combustor via centrifugal forces. Co-injection of fuel into the “raceway” generates a suspended reaction zone. Sludge and fuel particles retained in the reaction zone evaporate and burn leaving fine ash particles. As the particle size decreases, aerodynamic drag forces overcome centrifugal forces and the particles are carried into the hopper section. The high rotational gas velocity in the hopper section increases the centrifugal separation forces driving fine ash particles to the walls. Along the walls, the particles enters the aerodynamic boundary layer were they are retained and collected for later removal from the system. Particles that escape the boundary layer continue to be carried downward with the swirling gases. Eventually the swirling gases reverse direction and exit upward along the combustor’s axis. At the point of reversal, an aerodynamic stagnation zone occurs and nearly all of the remaining particles fall away from the moving gases by gravitational force.

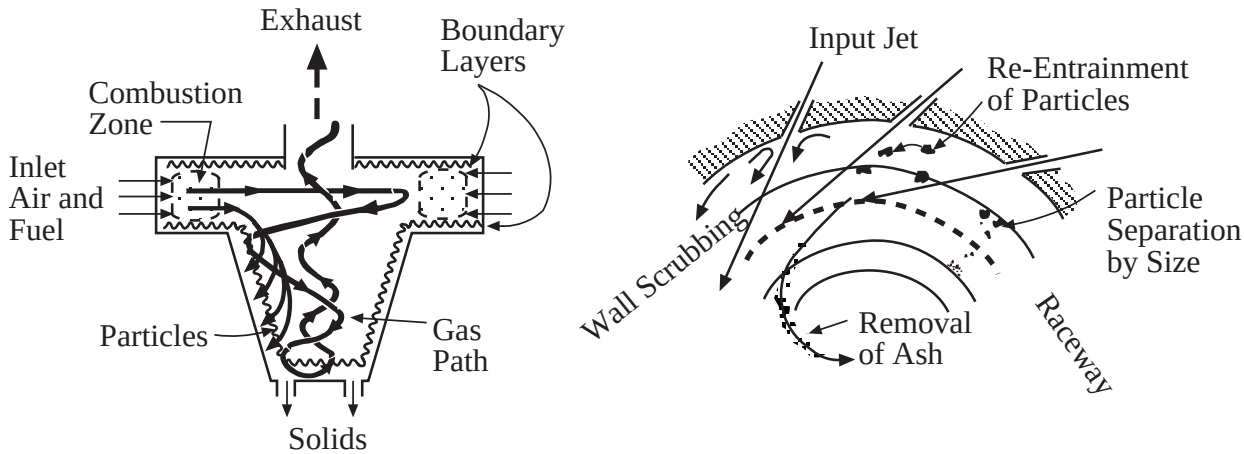


Fig. 1. Conceptual Operation of the Vortex Containment Combustor Showing the Top View of the Suspended Reaction Region (right) and the Side View of the Overall Gas and Particle Paths (left).

Nearly all waste thermal treatment systems for processing solid or sludge wastes operate with two process stages: the first being nominally fuel-rich and the second fuel-lean. The reason for this is simple. Fuel-rich waste thermal treatment requires less air, and hence is more quiescent. This enables solid to be retained for long periods to undergo gasification with only the gaseous effluent being further oxidized in the secondary chamber. The VCC concept is uniquely different in this regard. By design it has a very turbulent primary chamber, but achieves particulate retention through aerodynamic means. The ability of the VCC to retain particulate has been demonstrated in coal combustion systems by a number of investigators, including research teams from EER, as well as TRW and Babcock and Wilcox. Design features of the VCC include compactness, high temperature, long solids retention times, very low particulate emissions and good turndown capability.

To adapt the VCC to sludge treatment involves operating on liquid fuels and integrating liquid waste injection and suspension techniques. Currently specifications have been developed for stable combustion with fuel oils and specifications have been assessed for injection and suspension of sludge wastes.

VCC DESCRIPTION

Sludge Waste Injection Integration System

The conversion of the coal-fired VCC to sludge treatment required operation on liquid fuels such as fuel oil and integrating sludge wastes injection and suspension techniques. The integration of the sludge injection system posed some technical challenges to maintain stable combustion and to complete sludge evaporation.

While achieving stable combustion in the absence of sludge injection is not a problem, early tests showed that the introduction of small amounts of water caused unstable combustion, and flame-out occurred at sludge flow rates of 20 to 25 gph. The reason was that the suspended combustion of the VCC essentially relies on hot gas entrainment for flame stability. So as water is injected into the combustor chamber, the hot gases are quenched until they no longer can support ignition. The result is a rising instability culminating in flame-out at some threshold water injection level. To overcome the effect of water injection, better stabilization of the flame is required. A flame stabilizer system was developed and incorporated into the injector configuration. The flame stabilizer consists of employing a pilot flame at the exit of the auxiliary-fuel injector. Under this configuration, the system exceeds the target sludge injection rates without combustion instabilities.

Critical to achieving rapid evaporation and burnout is establishing a suspended phase of sludge droplets. This means that the sludge must be atomized into droplets small enough to be suspended in the flow. On the other hand, atomization must avoid imparting excessive ballistic energy that can cause the droplets to impinge on the combustor walls. Because the sludge nozzles require large orifice diameters in order to

pass solid particles, atomization is essential. With large orifices, liquid water would flow in a cohesive stream. Tests performed on a full scale isothermal model showed that this stream was seen to break up in the swirling air but did not produce a suspended droplet phase and water impinged heavily on the upper and lower walls of the combustor chamber. To avoid this impingement finer droplets are required and this is achieved by atomization. A minimum atomization level is needed to generate fine droplets. A compromise between droplet size and jet momentum is required to avoid over driving the fluid and impinging the sludge on the far wall of the combustor. To further reduce jet momentum, a minimum of two injectors was employed. The use of two injectors also produces a more uniform thermal profile in the combustor.

Engineering assessments of the droplet retention, evaporation and burnout times, indicate that the maximum droplet size target for the injectors is approximately 300 microns. Larger droplets could fall out of suspension and collect on the walls leading to a failure mode. Smaller droplets are desirable, however impinging the spray on the walls will cause cold local wall temperatures to spread because of poor gas-to-liquid heat transfer at the wall. In time, this would lead to untreated sludge entering in the ash drum. Additionally, based on the isothermal model evaluation of particle retention time, the current system is capable of providing up to 2 seconds of suspended phase residence time for aerodynamically entrained particles. Based on droplet evaporation modeling, small droplets injected into the suspension zone will evaporate very rapidly in less than 50 ms and allow adequate time (100 ms) for burnout of remaining organic matter. The large droplets, of roughly 100 µm size will evaporate in 200 ms, but these droplets are suspended for up to 2 seconds, which allows adequate time at temperature for oxidation.

Injectors Arrangements and Specifications

To achieve the target injection rates, optimize flame stability and extend the evaporation limits, several fuel and sludge injection configurations were investigated. Figure 2 illustrates the final injection configuration that enables the system to exceed the target sludge processing rate without evidence of combustion instabilities or incomplete evaporation. In this system, air is directed into the suspension zone through 12 circumferential air vanes, orientated 45° from radial. The auxiliary-fuel is fed with two injectors located on opposite sides of the combustion "raceway". The 30° from radial injection of fuel ensures that the fuel is not driven to the walls. The air atomized sludge waste is also introduced through two injectors that are directed towards the center of the combustor (radial injection). The fuel, air and waste mix and react in the "raceway" and the reacting gases and fine ash products spiral into the lower hopper region. As a flame stabilizer, two diesel pilot burners are used. The diesel pilot burners are oriented radially, and provide an attached-flame at the exit of the auxiliary-fuel injectors. These pilot burners burn approximately 7 percent of the total fuel and provide a stabilized ignition source for the auxiliary diesel fuel. Complete specifications for the injectors are summarized in Table 1. A full-scale isothermal model was used to guide specification of the sludge injection systems including spray angle, injection angle, spray momentum, and droplet size.

Additionally, an engineering assessment of the vortex radial and angular (tangential) momentum has been performed. A compromise between the two momentums was required. A high angular momentum may result of sludge impingement on the far wall of the combustor while a low angular momentum may reduce the cyclone strength and decrease the particle retention efficiency. Table 2 summarizes the different jet momentums for which the full scale VCC combustor was operated.

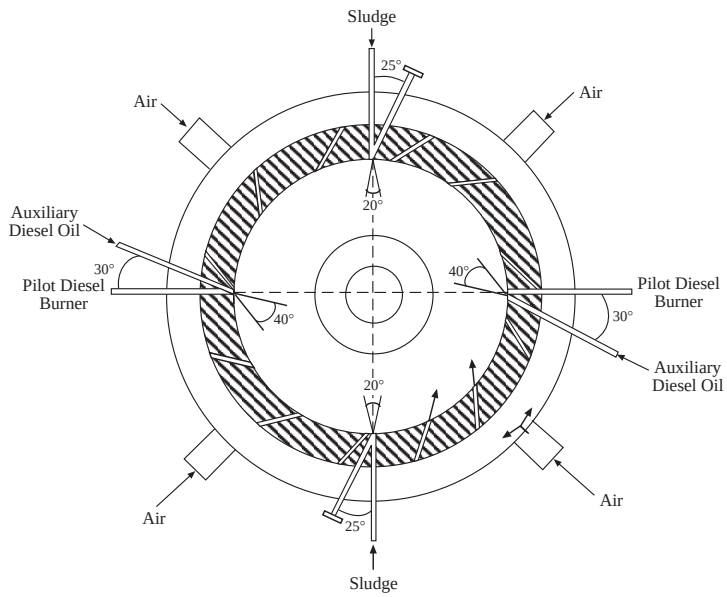


Figure 2. VCC Injectors Layout and Air Port Locations (Top View).

Table 1: Injectors Specifications

Sludge Injectors Specifications	
Spray Angle	Narrow (~20°)
Injection Angle	Radially
Sludge Orifice Diameter	0.175 in
Atomization Air/Water Mass Ratio	~ 20%
Maximum Droplet Size	300 microns
Atomization Air Pressure	70 psig
Air Orifice Inside Diameter	0.50 in
Air Orifice Outside Diameter	0.53 in
Auxiliary Fuel Injectors	
Fuel Type	Diesel # 2
Nozzle Type	Pressure Nozzles
Spray Angle	~ 40° Flat Spray
Spray Orientation	Horizontal
Injection Angle	~ 30° from Radial
Air Vanes	
Number of Vanes	12
Vane Angle	~ 45° from Radial
Vane Size Gaps	0.5 in
Vane Heights	7 in
Diesel Pilot Burners	
Fuel Type	Diesel # 2
Firing Rate (each)	~ 70,000 Btu/hr
Stoechiometry	0.85
Atomization Air/Combustion Air Ratio	0.064
Pipe Size	0.75 in

Table 2: Jet Radial and Tangential Momentums (Momentum = Mass * Velocity)

Injectors	Mass flux	Velocity	Angle from Radial	Radial Momentum	Tangential Momentum
	lb/s	ft/s	°	lbf	lbf
Main Air (from air vanes)	0.56	25.7	45	0.317	0.317
Diesel Injector (2 injectors)	0.03	92.7	30	0.083	0.048
Sudge Atomizer (2 injectors)					
Air	0.02	952	0	0.710	0.000
Sludge	0.12	5.56	0	0.020	0.000
Pilot Burners (2 injectors)	0.02	29.5	0	0.015	0.000
Total Momentum				1.145	0.365

Combustion Chamber Internal Dimensions

Figure 3 provides a cut view of the VCC chamber and insulation. The main chamber has an internal diameter of 28 inches with an internal height of 7 inches. The external combustion chamber has a diameter of 4 feet. The combustor also incorporates castable refractory insulation. Figure 4 illustrates a schematic of the full-scale VCC combustor unit. The unit also includes an insulated 20-gallon drum that is attached under the combustion chamber to collect the solids. The ash collection system was designed to maintain a minimum drum temperature of 330°C to avoid any condensation of sludge and unburned fuel vapors. For a 20-gallon drum size, the shipboard may operate the VCC combustor for a minimum of seven 10 hours days without removing the drum. The overall height of the VCC unit is approximately 4 feet (combustion chamber with drum). The full-scale unit was designed to operate at 2.2 x 10^6 Btu/hr (640 kW).

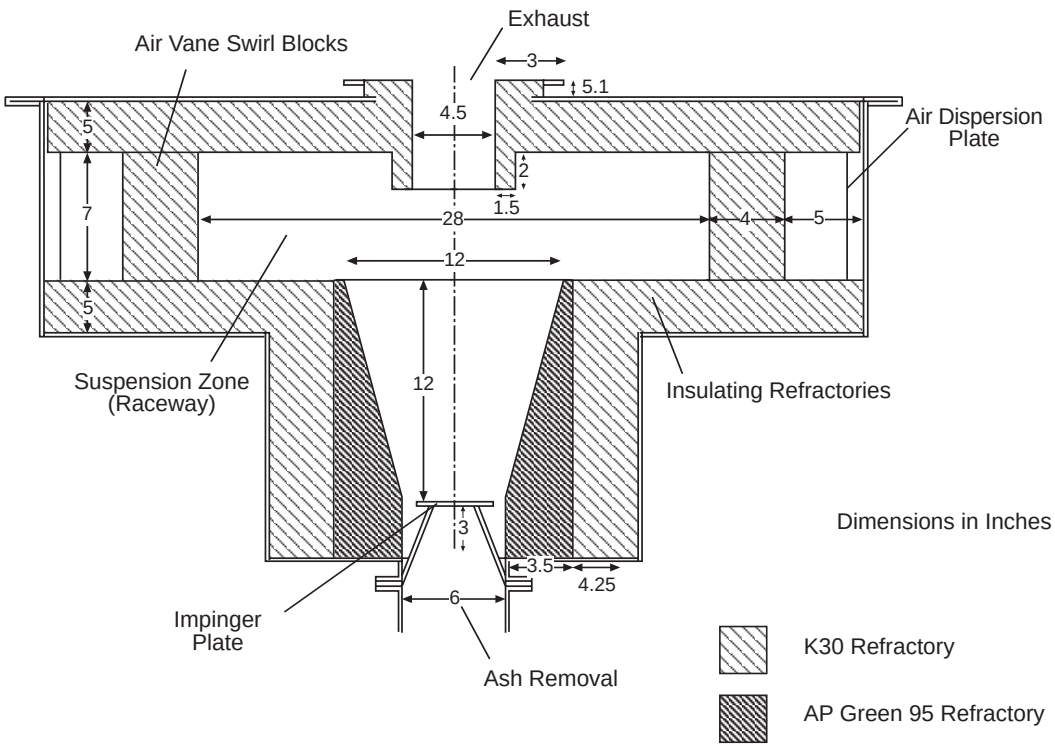


Figure 3. VCC Combustor Dimensions and Internal Layout.

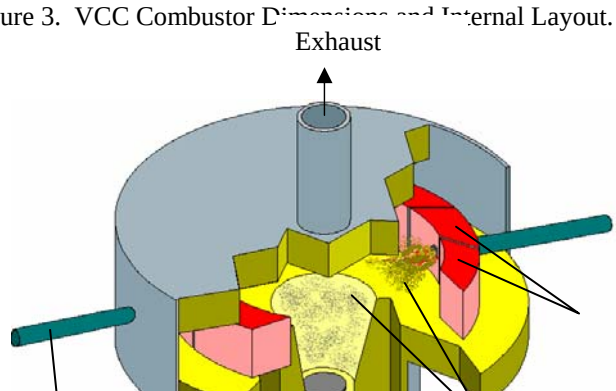


Figure 4. 3-D Illustration of the Full-Scale VCC Combustor

VCC TEST UNIT

Facilities

The development of the VCC for sludge waste applications was conducted using three test facilities: a sub-scale combustor [2,5], a full-scale isothermal model and a full-scale combustor unit [3,4]. This paper focuses on the full-scale development efforts and results.

Concurrent efforts were conducted on two full-scale facilities. The full-scale isothermal model was used to guide specification of the sludge injection systems including spray angle, injection angle, spray momentum, and droplet size. The isothermal model comprises a plexi-glass replica of the internal dimensions of the full-scale combustor illustrated in Figures 2 and 3. The full-scale combustor incorporates castable refractory insulation along with access ports for flame safety systems, diagnostic probes and various fuel and sludge injection locations and angles.

The full-scale VCC facilities were used to develop specifications for flame stabilization, sludge injection and particle trapping. Efforts conducted to date have successfully switched the early VCC coal combustor to fuel oil firing, developed VCC operating and injection specifications and demonstrated stable combustion and environmental compliance at the target sludge processing rate of 50 gallons per hour. The full-scale VCC combustor unit was able to process a wide range of surrogate sludges.

Full-Scale Combustor Unit

The operating process for the full-scale VCC combustor is illustrated in Figure 5. The combustor was operated with approximately 450 cubic feet per minute of combustion air directed into the suspension zone via a forced draft (FD) fan. The fuel, consisting of diesel fuel oil, was introduced using a liquid fuel pump. The sludge, consisting of greywater, blackwater and/or oily bilge water waste was introduced in a similar way. The fuel, air and sludge waste reacted in the VCC combustion chamber, and the reacting gases exited from the top of the combustion chamber. The fine ash residues were collected in a drum mounted under the combustion chamber. The VCC's operating differential pressure, measured between the combustion air inlet and the exhaust duct, was approximately 14 inches of water.

The VCC combustor also includes an air quench system. For shipboard thermal treatment technologies, the International Maritime Organization requires that combustion flue gas be shock-cooled to a maximum temperature of 350°C within 2.5 meters of the combustion chamber flue gas outlet. Therefore, the VCC combustor unit includes a quench system, with the quench air drawn directly into the stack through a plenum via an induced draft (ID) fan located downstream of the quench system.

However, during shakedown, it was noted that the air quench system was not cooling the exhaust flue gas to its desired temperature of 350°C or less. Actual temperature measurements downstream of the quench system showed temperatures in the ranges of 700°C. It was determined that pressure drop in the air quench

system was too high for the selected induced draft fan. Further evaluation of the quench system was not pursued since it would not affect emission results. Instead, focus was placed on more critical elements including the evaluation of VCC performance for a wide range of surrogate sludges, and the evaluation of an automated control system.

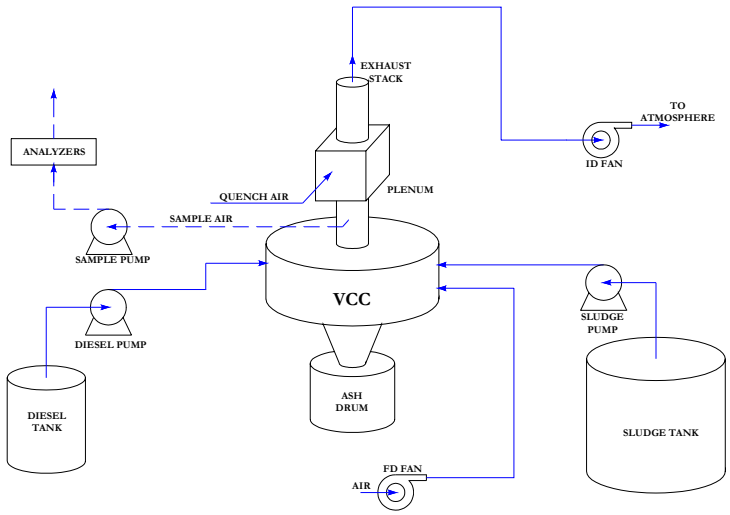


Figure 5. Full-Scale VCC Combustor Process Flow Diagram

Monitoring

The full-scale VCC combustor was equipped with fuel, sludge and air feed control and monitoring systems. The VCC operational differential pressure was measured between the air inlet and the exhaust duct. The exhaust gas temperature was measured with a B-type thermocouple located in the center of the stack pipe 2 feet from the top of the combustion chamber, upstream of the quench system. An extractive gas-sampling probe was located in the exhaust. The gas sample was delivered to a water knockout and then to a continuous emission monitoring system for measurement of oxygen (O_2), carbon dioxide (CO2), carbon monoxide (CO) and nitric oxide (NO) concentrations. Measurements from this location were used to set the automated controller's baseline.

VCC TESTING

Tests Wastes

The full-scale VCC combustor has been developed for the treatment of the Navy's blackwater, greywater and oily bilge water wastes. The surrogate sludge waste streams used for testing included a) city water (e.g. municipal water), b) 1 percent to 7.5 percent fuel oil in city water, and c) 2 percent solid-content blackwater surrogate that included up to 7.5 percent fuel oil contaminant. The blackwater surrogate was comprised of 1.6 percent dry dog food, 0.2 percent salad oil, 0.2 percent paper products and 98 percent water and exceeded the total solids and total volatile solids content of both the greywater and the blackwater waste streams reported in Table 3 for Navy wastes.

Table 3: Comparison of the Surrogate Waste Composition with the Navy's Wastes Compositions

%	Surrogate Waste	Navy's Blackwater	Navy's Greywater
Total Solids	1.80	0.57	1.27
Volatile Content in Solids	1.23	0.18	1.01

VCC Operating Specifications

The system requirements involve processing high volumes of various liquid wastes in a compact unit while minimizing the use of auxiliary-fuel. Since many of the shipboard sludge streams have little, if any heating value, a minimal auxiliary-fuel is required to establish combustion temperatures suitable to oxidize the

solid particles found in sludge wastes. The conditions and heating rate shown in Table 4 allowed the VCC to meet IMO standards for CO emissions when processing the various sludge wastes. The IMO CO standard is 200mg/MJ or approximately 420 ppm corrected to 7 percent O_2. For these specifications, the full scale VCC combustor unit maintained stable combustion and achieved complete evaporation of waste for sludge feed rates up to 50 gallons per hour. This demonstrates that the combustor unit can achieve a processing rate of at least 1.67 gph/ft3. The fuel input is determined by the excess oxygen concentration set point.

Table 4: VCC Operating Specifications

Parameter	Operating Conditions
Main Combustion Air	450 scfm
Excess Oxygen	5%
Exhaust Temperature	1030 C
Heat input	2.2 MMBtu/hr
Pilot Burners (each):	
Diesel Fuel	0.65 gph
Atomization Air	35 cfh @ 15 psi
Combustion Air	370 cfh @ 30 psi
Sludge atomization:	
Sludge Feed Rate	50 gph
Air Sludge Atomizer	480 cfh @ 70 psi

Figure 6 illustrates the VCC performance for city water sludges. The sludge flow rates were 50 gallons per hour for each test. Results from figure 6.a) showed an increase in the CO emissions with excess oxygen concentrations. It should be noted that an increase in the oxygen concentration corresponds to a fuel input reduction. For all cases, the CO emissions were well below the IMO standard; however, it can be observed that operation of the VCC from 5 to 6 percent excess oxygen increased the CO emissions by 118 percent. This increase was mainly caused by unstable combustion. Indeed, the fuel input required to operate under this condition is too low to maintain the minimum combustion chamber temperature needed to ensure complete sludge evaporation. Tests performed on the VCC combustor showed that unstable combustion may occur for exhaust temperatures below 1010°C. At 6 percent oxygen, the exhaust temperature measured was 985°C. In addition, operation of the VCC in an unstable mode may cause flameouts and system shutdowns. Therefore, to ensure operation in a stable combustion mode, the surrogate sludges were tested at oxygen concentrations of 5 percent or less. This corresponds to a minimum VCC heat input rate of 2.2 MMBtu/hr.

Further testing showed that the VCC combustor could maintain stable combustion for sludge flow rates up to 53 gallons per hour when operating at 5 percent excess oxygen. This was achieved with a sludge comprising no heating value (e.g. 100 percent water). For sludge flow rates above 53 gph, the sludge atomizers were unable to meet the waste atomization quality (droplet size and droplet size distribution) required to successfully operate the VCC combustor. For these flow rates, the poor atomization led to incomplete evaporation, causing the VCC combustor to fail.

Figure 6.b) illustrates the repeatability and consistency of the CO and NOx emissions for test runs conducted on different days at identical operating conditions. The VCC was operated with 5 percent excess oxygen and with a sludge flow rate of 50 gallons per hour. The sludge was 100 percent city water. As shown in the figure, the CO emissions are well below the IMO standard. Results showed an average CO concentration of 55.0 ppm with a standard deviation of 8.7 ppm, and an average NOx concentration of 24.3 ppm with a standard deviation of 2.8 ppm.

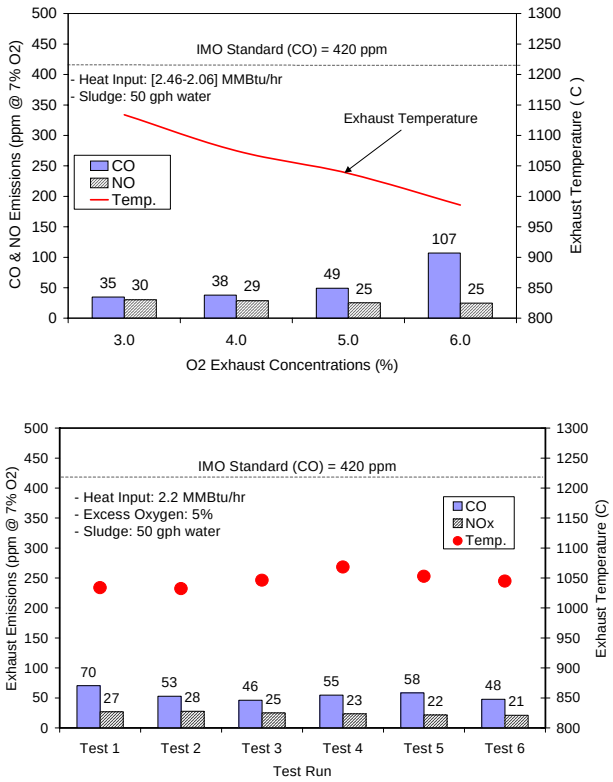


Figure 6. VCC Baseline Operating Specifications using Water Sludges for (a) Emissions Performance with Excess Oxygen Concentrations and for (b) Emissions Performance Repeatability.

Emissions Performance

The full-scale VCC combustor was tested on a wide range of sludge types. The sludge wastes included pure water, simulated blackwater, oily water of various concentrations (1, 2, 5 and 7.5 percent oil), and oily blackwater at various concentrations (1, 2, 5 and 7.5 percent oil). The VCC operating specifications were identical as the ones shown in Table 4. In all cases, the total heat input from auxiliary-fuel plus waste oils was held constant. To compensate for the oil in the waste streams, the heat input rate of auxiliary-fuel was reduced. A summary of the CO and NO emissions corrected to 7 percent O2 for these tests is presented in Figure 7. As is evident, the CO emissions fall well below the IMO standard of 420 ppm corrected to 7 percent O2. For these cases, the total hydrocarbon emissions were below 10 ppm and NO emissions were between 21 and 25 ppm for non-blackwater tests and between 122 and 146 ppm for blackwater tests. Blackwater contains fixed nitrogen that, if completely converted, could account for up to 50,000 ppm of NO in the exhaust; thus, the levels of the NOx increase seen for blackwater are not unreasonable.

Tests performed on the VCC combustor also showed that the oil content in waste can not exceed a maximum of 7.5 percent. Beyond this limit, the VCC combustor operates in an unstable mode, causing an increase in the CO emissions. This was observed during the test performed on a blackwater surrogate sludge containing 7.5 percent oil. For this oil concentration, the waste oil accounts for 22 percent of the total heat input. Any further turndown of the auxiliary-fuel resulted in unstable combustion and flameouts.

Figure 8 illustrates the impact of sludge flow rate on emissions. Results from this figure show that the CO emissions decrease with decreasing sludge flow rates, and that the NOx emissions are not significantly impacted by sludge flow rates at these operating conditions. Decreasing the sludge flow rate by 20 percent (from 50 to 40 gph) reduced blackwater sludge emissions by 50 percent and water sludge CO emissions by 35 percent. For the blackwater surrogate sludge, CO emissions were reduced to 74 ppm, below the land-based standards of 100 ppm, by reducing the sludge flow rate to 40 gallons per hour. This effectively

increased the heating rate to 6,700 Btu/lb of waste feed. The increased operating temperature is the main cause of the CO reductions. However, it should be noted that this temperature increase was not significant enough to impact the "thermal NOx". Finally, the CO and NOx emissions are more significant for the blackwater sludge because that sludge has a higher fixed carbon and fixed nitrogen content than city water sludge.

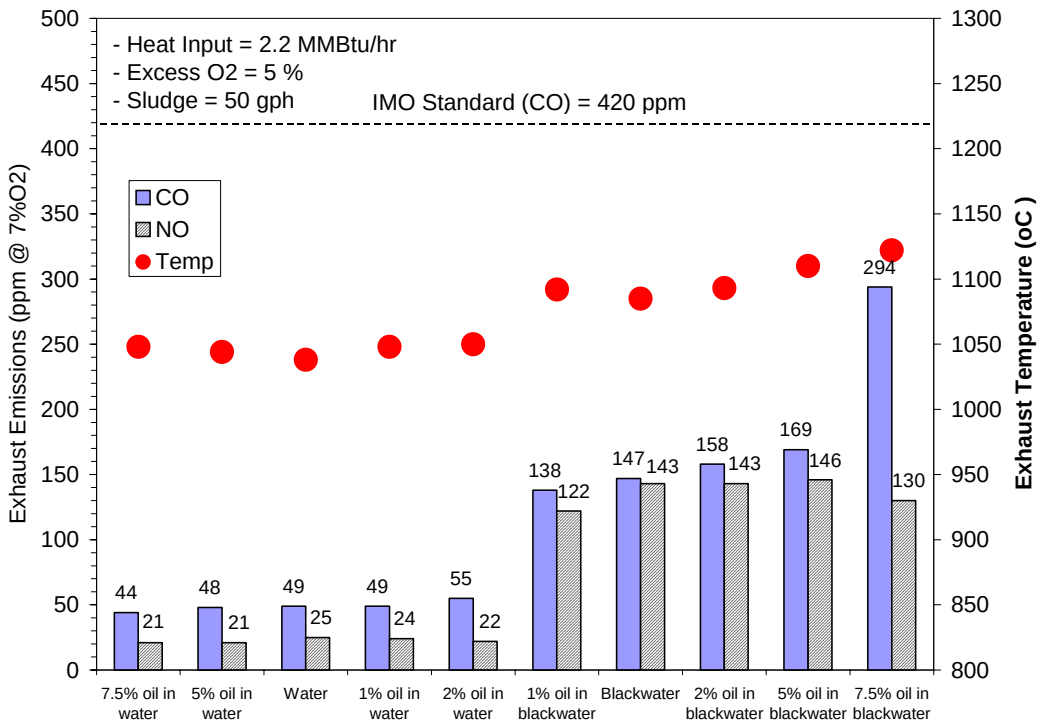


Figure 7. VCC Emission Performance for Varying Sludge Types Fed at 50 gph.

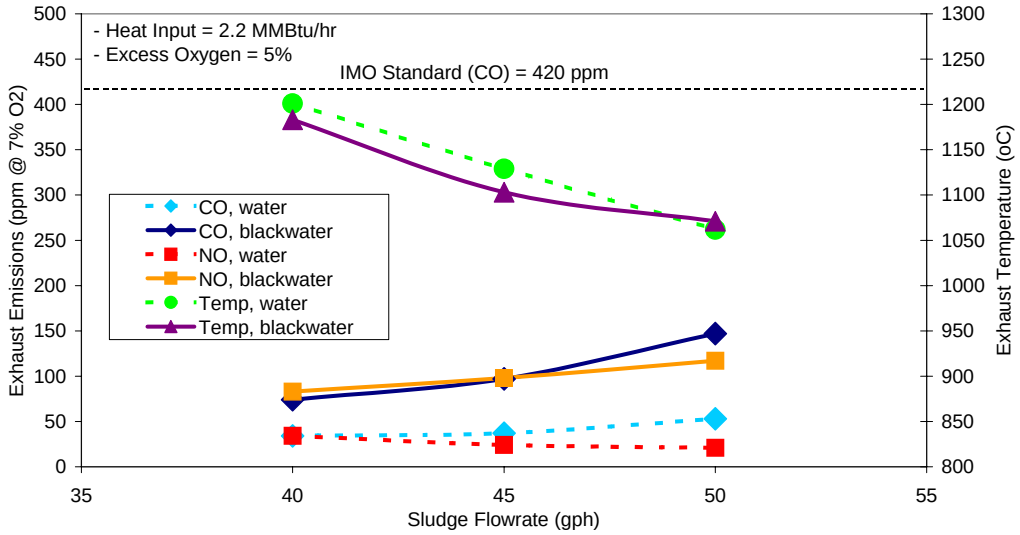


Figure 8. VCC Emission Performance for Varying Sludge Flow Rates

Carbon-in-Ash Levels

For shipboard thermal treatment technologies, the International Maritime Organization requires that the unburned components in ashes be less than 10 percent by weight. To verify that this requirement was met,

ashes produced during blackwater sludge processing were analyzed for carbon content. Results consistently showed carbon-in-ash levels below 5 percent. These low carbon contents can mainly be attributed to the drum temperature. In order to avoid any condensation of unburned fuel vapors, the ash collection system was designed to maintain a minimum drum temperature of 330°C. The temperature profile measured during VCC operation showed that a minimum temperature of 400°C was achieved inside the drum. At this temperature, the unburned fuel vapors do not condensate on the ash; thus, reducing the carbon-in-ash.

Plume Visibility

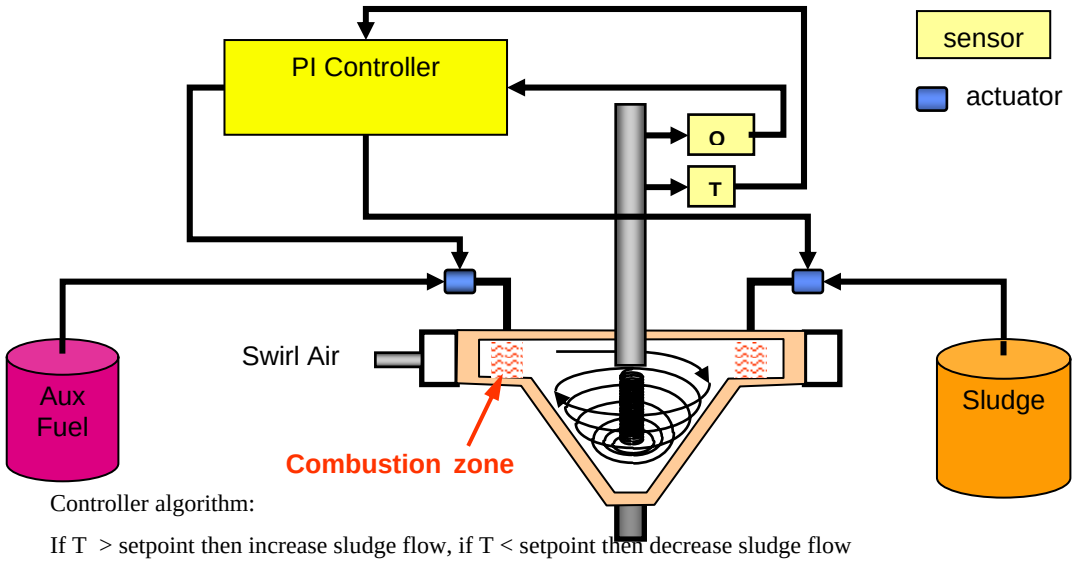
For incinerators both on land and onboard ships, plume visibility has the potential to become a significant public relations problem, depending on how visible the plume is. The IMO has a standard for plume visibility of bacharach #3 or less for shipboard incinerators. This, however, is a situation in which subjective perception is as important as objective measurement. If an experienced observer assesses the plume as bacharach #3 or less, the measurement of the plume is likely to be unnecessary. If the observer estimates that it is greater than bacharach #3, one is likely to have a public relations problem even if measurements show that it is bacharach #3 or less. For the blackwater tests, plumes were consistently judged to be bacharach #3 or less. The exhaust stack flue gas particulate concentrations measured was 0.15 gr/dscf corrected to 7 percent O2.

VCC AUTOMATED CONTROLLER

VCC Controller Concept

In actual service onboard a naval vessel, the VCC will encounter a variety of waste sludges, with differing characteristics and heating values. In order to maintain stable operation of the VCC under these continuously changing conditions, a control method is required.

The control scheme shown in Figure 9 has been implemented in the VCC combustor. The controller installed is a visual basic software program developed at China Lake Naval Air Warfare Center Weapons Division and adapted for the VCC. The controller algorithm utilizes proportional integrative (PI) logic to maintain optimal performance with varying sludge characteristics and heating values. This is achieved by varying the auxiliary-fuel and sludge flow rates when the oxygen concentration and temperature deviate from their desired values (set points). In this control scheme, the auxiliary-fuel flow rate is regulated to control the exhaust oxygen concentration set point, and the sludge flow rate is regulated to control the exhaust temperature set point.



Controller algorithm:

If T > setpoint then increase sludge flow, if T < setpoint then decrease sludge flow

If O_2 > setpoint then increase auxiliary-fuel, if O_2 < setpoint decrease auxiliary-fuel

Figure 9. Controller Concept to Maintain Optimal VCC Combustor Operation with Varying Sludge Type

Controller Set Points

In order to determine the controller's set points and range of operation, preliminary testing was performed on the VCC to investigate its performance with sudden changes in the waste sludge feed characteristics or heating values. For example, the impact of a sudden change from a sludge that has no heating value to a sludge that has a high heating value could lead to operation of the VCC in or near the fuel rich mode. As a result, the lack of oxygen from this operating condition could increase the CO emissions to levels above the IMO standard. Additionally, the VCC operating temperature could increase to a temperature beyond the safe operation of the VCC system. However, this condition is only temporary since the auxiliary-fuel flow rate and the sludge flow rate are readjusted to return the oxygen and VCC temperature to their respective set points. Conversely, the impact of a sudden change from a sludge that has a high heating value to a sludge that has no heating value could lead to a VCC shutdown mode. In this case, the total fuel input provided to the system may not be sufficient to maintain a hot stable flame in the combustion chamber. This may lead to flame-outs, causing system shutdowns.

Tests performed on the VCC showed that it operates safely for excess oxygen concentrations between 1.5 and 5 percent. For oxygen concentrations below 1.5 percent, CO emissions were above the IMO standard and for oxygen concentrations over 5 percent, the VCC failed to maintain stable operation. Therefore, the oxygen concentration set point was set at the midpoint: 3.3 percent. For this set point, it was found that the VCC could conservatively process a maximum surge of 3.5 percent oil in sludge. Larger fluctuations of oil in sludge could potentially drive the oxygen concentration to levels above or below the oxygen limits.

Since the oxygen concentration is regulated by the auxiliary-fuel flow rate, it was determined that the auxiliary-fuel flow rate should range between 14.3 and 17.8 gallons per hour. For these flow rates, the oxygen concentration is maintained within the boundary limits of 1.5 and 5 percent, if the sludge contains no more than 3.5 percent oil. The controller settings are summarized in Table 5. The exhaust temperature set point is 1150°C. This corresponds to the temperature of the VCC operation with 3.3 percent excess oxygen and a sludge flow rate of 50 gph. With automated operation of the VCC, the temperature is regulated by the sludge flow rate. The maximum sludge flow rate was selected to avoid operating conditions in which the VCC would operate at exhaust temperatures below 1010°C. It has been demonstrated previously that the VCC could not maintain a stable flame in the combustion zone when operated below 1010°C. This resulted in high CO emissions, and eventually to system shut-down due to flameouts. The minimum sludge flow rate was selected to avoid operation of the VCC at exhaust temperatures exceeding 1350°C. Operation above this temperature may result in system overheating and material degradation.

Table 5: Controller Settings

Controller Outputs	Set Points	Hysteresis	
Excess Oxygen (%)	3.30	0.2	
Exhaust Temperature (^{o}C)	1150	20	
Controller Inputs	Min	Max	Step Size
Diesel Flow Rate (gph)	15.6	19.1	0.2
Sludge Flow Rate (gph)	40	52	2
Cycle Time (s)	-	-	2

During VCC operation, the controller regulates the auxiliary-fuel and/or the sludge flow rates when the actual oxygen and/or temperature readouts are outside of the set points hysteresis bands. For example, the controller adjusts the auxiliary-fuel flow rate when the oxygen concentration readout falls outside of the 3.1 to 3.5 percent range. In a similar way, the controller adjusts the sludge flow rate when the temperature readout falls outside of the 1080 to 1120°C ranges.

Controller's Response

To optimize VCC performance, the controller needs to provide quick response times. The response time is defined as the time required for the controller to return to its set-point, following a disturbance. Three control variables impact the controller's response: the cycle time, fuel step size and sludge step size. Cycle time is defined as the time span in which the auxiliary-fuel and the sludge flow rates are permitted to take their respective maximum steps, or any step less than the maximum step. After each time span has

elapsed, the controller is permitted to again take the maximum step for the auxiliary-fuel and sludge flow rates.

To optimize controller operation, a method called "design of experiment – full factorial" was utilized to determine the best control variable settings to minimize response time. The method consisted of combining the upper and lower limits for each of the three control variables and combining them into every possible combination, for a total of 8 experiments. The experiments were all performed under identical conditions, except for variations of the 3 control variables: cycle time, fuel step size and sludge step size. The tests used blackwater surrogate sludge with the introduction of 3.5 percent oil to create a disturbance. The response for each test was recorded, and the combined data used to create a transfer function. The transfer function was then used to hypothesize the response time for any combination of the control variables within their original upper and lower limits. Using the transfer function and the test data, the optimum control variable settings were established as follows: a cycle time of 2 seconds, a fuel step size of 0.1 gph and a sludge step size of 1 gph. Figure 10 illustrates the controller's response behavior for these settings. As seen in this Figure, a response time of approximately 3.2 minutes was required to allow the oxygen concentration and temperature to return to their respective preferred range. After that time, the CO and NOx emissions remained within acceptable limits. During testing, it was noted that the forced disturbance created a sudden increase in CO emissions; however, the CO emissions returned to their original levels once the controller had readjusted the auxiliary-fuel and sludge flow rates. As for the NOx emissions, the forced disturbance did not impact their behavior. Finally, testing showed that the controller has a longer recovery time when the sludge undergoes a sudden heat input increase (from oil) than when the sludge undergoes a sudden heat input loss.

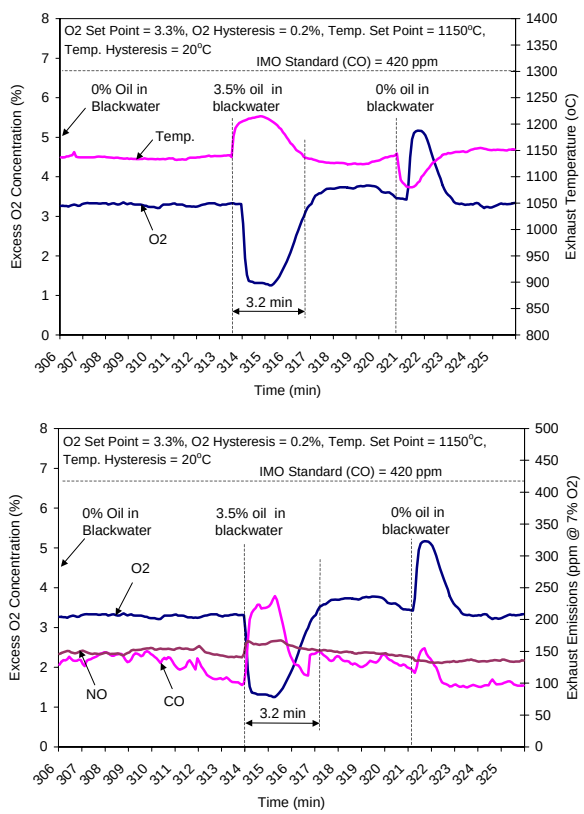
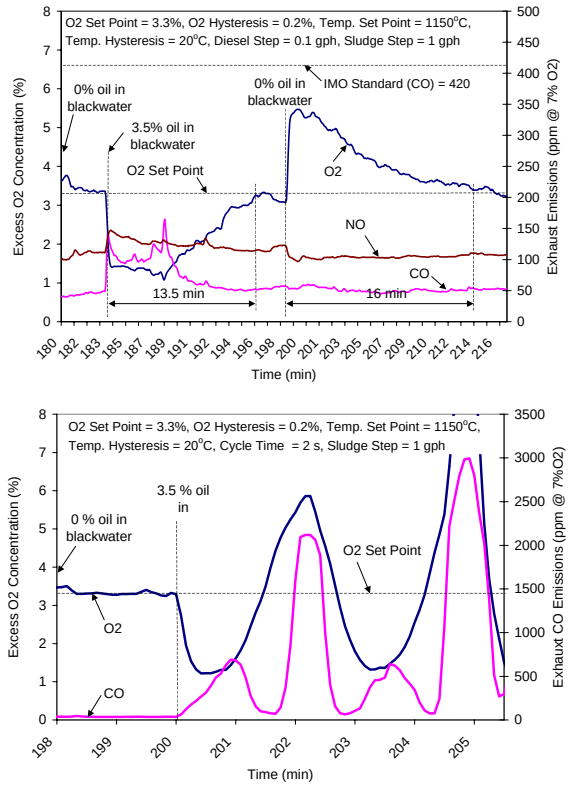


Figure 10. Controller's Behavior for a 3.5 percent Oil Surge in Blackwater Sludge for Optimum Controller Variables Settings (a) Oxygen and Temperature Responses and (b) Oxygen and Exhaust Emissions Responses

In general, the experimental tests showed that proper settings for the control variables (e.g. cycle time, fuel step size and sludge step size) are essential to successful operation of the VCC. The impact of improper

controller settings on VCC's operation is illustrated in Figure 11. For one case, the cycle time was set at 10 seconds. Results from figure 11.a) show an extremely slow response time of approximately 13 minutes. Consequences of such slow response times may result into the VCC operating near its boundary limits for a longer time period; thus, accelerating the deterioration of the VCC unit and reducing the overall performance of that unit. For another case, the fuel step size was set at 1 gph. In this case, the combination of a large fuel step size and a short cycle time led the controller to a divergent response. As shown in figure 11.b), the controller was unable to return the oxygen level back to its original set point. Instead, this oxygen level would continue to oscillate until the system completely failed.



(a) (b)

Figure 11. Controller's Response Behavior for Improper Variable Settings such as (a) cycle = 10 sec and (b) diesel step = 1 gph

In summary, the control system was demonstrated to show the feasibility of automated VCC operation. The automated VCC controller system was demonstrated on non-oily and oily sludges. It was determined that the VCC could conservatively process surges up to 3.5 percent oil in sludges. For optimum control, it is suggested that each sludge batch be well-mixed to avoid any sudden changes of oil concentrations in the sludge feed system. Finally, the control logic from the visual basic software program could be used in a PLC-type controller to eliminate the need for a computer interface.

TECHNOLOGY COMPARISONS

Table 6 summarizes the performance of current and future thermal treatment technologies to process shipboard sludge wastes. The Blackwater Vortex Production Unit is currently used on shipboards while the full-scale VCC combustor unit is still in development. A commercial off-the-self (COTS) unit has also been included in the table. Compared to the Blackwater Vortex Production unit, the VCC combustor and the COTS unit can both process a wider range of wastes at higher processing rates. The VCC combustor also offers a few advantages over the COTS unit with regard to compactness and fuel processing efficiency.

Table 6: Technology Comparisons

Technology Comparison	VCC Combustor Unit	Blackwater Vortex Production Unit	COTS [(a)] Unit
Compactness:			
Processing (external), gph/ft3	1.6	1	0.1
Weight, lb	1,200	1,400	16,500
External Volume, ft3	31	30	652
Fuel Efficiency:			
Heat Input, MMBtu/hr	2.2	0.9	5.3
Processing, gal/MMBtu	22.7	33.3	12.6
Temperature, oF	1850-2100	1300	2100
Capacity:			
Sludge, gph	50	30	67
CO Emissions, ppm @ 7%O2:			
IMO Emission Standard	**420**	**420**	**420**
Blackwater	147[(b)]	118[(c)]	
Oily Sludge (1% oil in water)	49	510	-
NOx Emissions, ppm @ 7%O2:			
IMO Emission Standard	**None**	**None**	**None**
Blackwater	143[(b)]	214[(c)]	-
PM Emissions, gr/dscf @ 7%O2:			
IMO Emission Standard	**None**	**None**	**None**
Blackwater	0.15[(b)]	0.33[(c)]	-
Plume Visibility, Bacharach #:			
IMO Standard	**3**	**3**	**3**
Blackwater	3 or less	3 or less	-

(a) Commercial off-the-self (COTS) Unit
(b) Surrogate Blackwater with 1.8% solids and 1.2% volatiles
(c) NSWC Carderock Division results for blackwater with .57% solids, 0.18% volatiles

CONCLUSION

A compact and efficient combustion system based on the VCC concept was developed for the treatment of shipboard generated non-oily and oily sludges. The VCC combustor operates on liquid fuels and can process 50 gallons per hour of sludge waste. The combustor also efficiently treats high water-content wastes with minimal auxiliary-fuel input. Operation at a minimum heat rate of 5,300 Btu per pound of wastewater establishes a minimum combustor temperature for effective waste treatment

The VCC combustor accepts a wide range of sludge wastes. Recent demonstrations were conducted with water sludge, blackwater surrogate sludge, oily water sludge and oily blackwater surrogate sludge. Results showed that the VCC combustor was able to meet the IMO standards for exhaust emissions, carbon in ash levels and plume visibility. The CO emissions for the various sludge types tested were below the IMO standards of 420 ppm corrected to 7 percent O2 with less than 60 ppm for oily water sludge and less than 200 ppm for oily blackwater surrogate sludge. The carbon is ash level was 4 to 5 percent and below the IMO standard of 10 percent. The plume was consistently judged to meet the IMO standard of a bacharach No.3 or less.

The VCC combustor also incorporates a controller to allow automated processing of sludges with highly varying heating values. The controller logic controlled oxygen and temperature by regulating the auxiliary-fuel and sludge flow rates. The automated VCC controller system was demonstrated on non-oily and oily sludges. Tests results showed that the VCC controller could process sludges with up to 7.5 percent oil bymass and with oil fluctuations up to 3.5 percent. For best performance a homogeneous sludge having variations no greater than 3.5 percent in oil content is recommended to avoid the need for rapid response excess oxygen sensors in the exhaust.

To date, the full-scale VCC combustor showed successful thermal treatment of liquid sludge wastes. The combustor met the shipboard IMO requirements for a wide range of surrogate sludge wastes. The next step in the successful deployment of the VCC requires operation on real shipboard sludge wastes.

ACKNOWLEDGMENT
The project was funded by the Strategic Environmental Research and Development Program (SERDP). Contributions made by the United States Naval Air Warfare Center, Weapons Division and Dr. Klaus Schadow (consultant), are gratefully acknowledged.

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3 Widmer, N. C., Cole, J. A., Seeker, Wm. R., Wilson, K. J., Parr, T. P. and Schadow, K. C., "Actively Controlled Vortex Disposal System For Sludge Wastes," Presented at the 19th International Conference on Incineration and Thermal Treatment Technologies, Portland, Oregon, May 2000.
4 Widmer, N. C., Gauthier, P.J., Cole, J. A., Maly, P.M., Seeker, Wm. R., Wilson, K. J., Parr, T. P. and Schadow, K. C., "Vortex Containment Combustor System for Shipboard Sludge Waste Disposal," Presented at the 20th International Conference on Incineration and Thermal Treatment Technologies. Philadelphia, Pennsylvania, May 2001.
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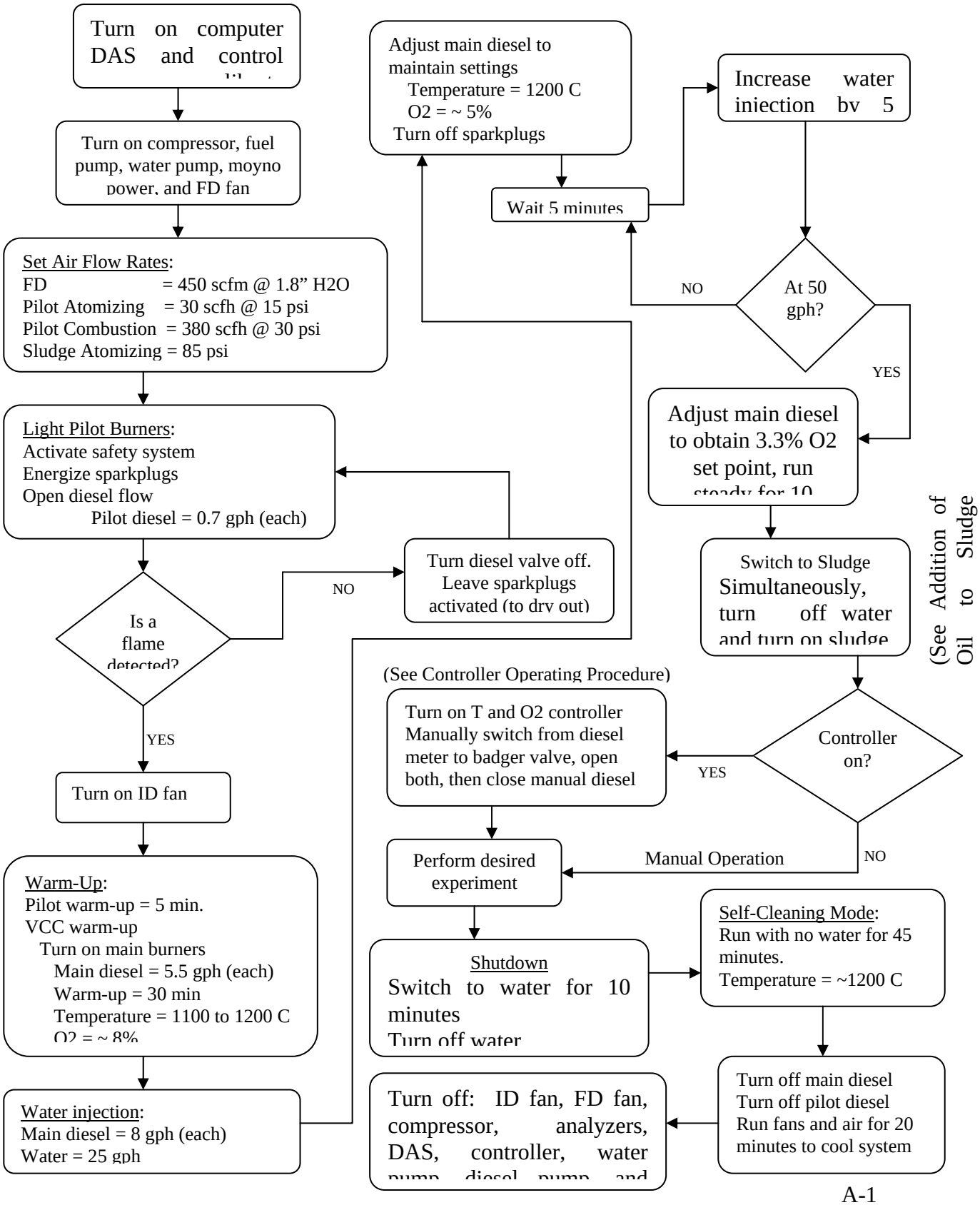
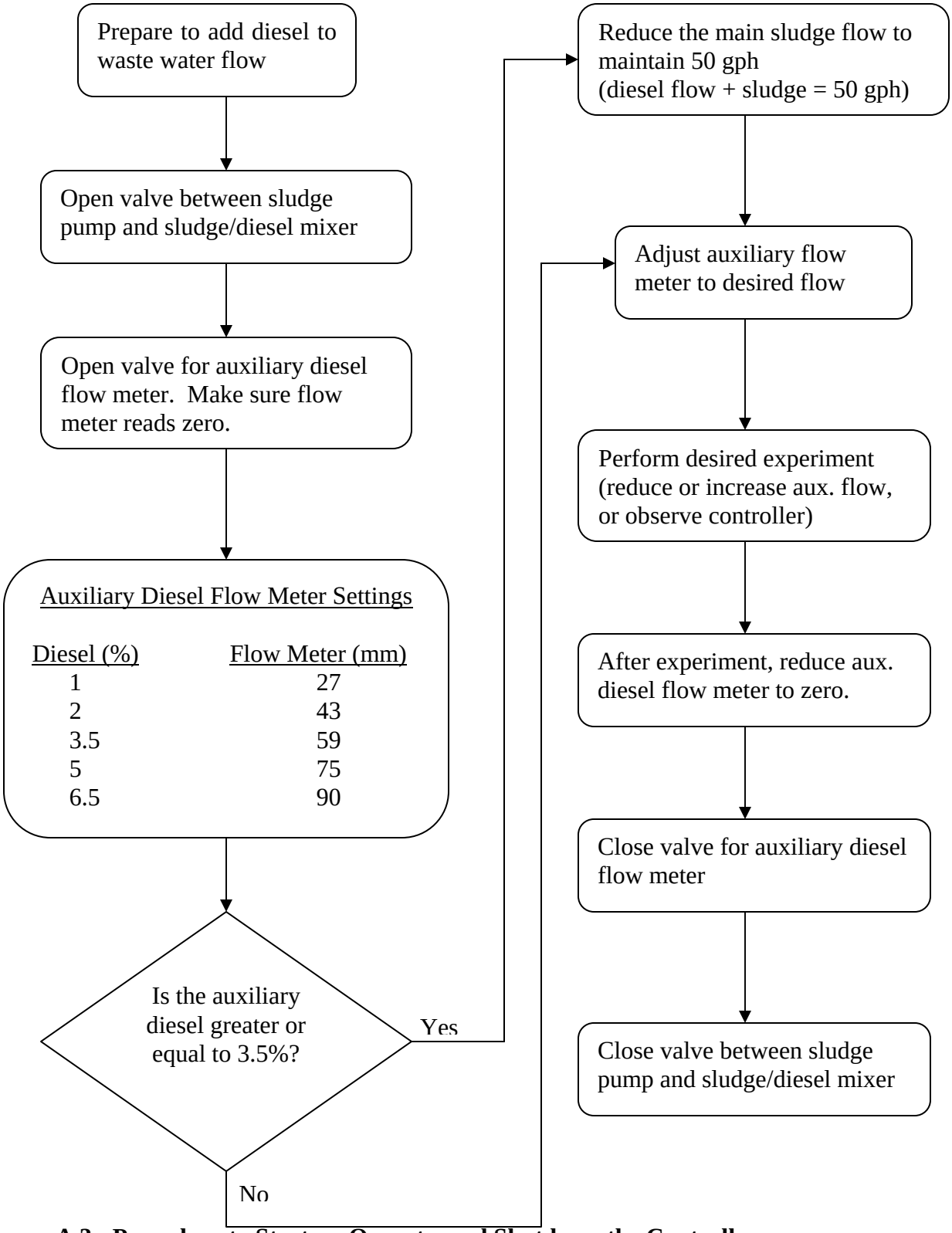
APPENDICES

Appendix A

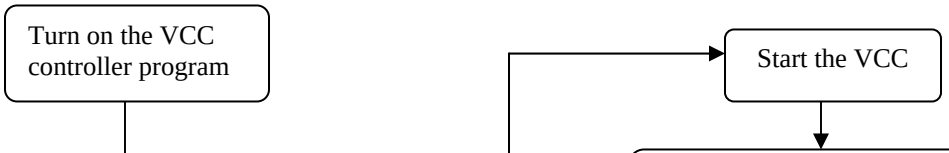
A.1: Procedure to Startup, Operate, and Shutdown VCC



A.2: Procedure to Add Oil in the Sludge Waste



A.3: Procedure to Startup, Operate, and Shutdown the Controller



A.4: Process Failure Modes and Effects Analysis

Process Step/Part Number	Potential Failure Mode	Potential Failure Effects	Potential Causes	Current Controls	Actions Recommended	SEV	OCC	DET	RPN
Setting diesel fuel flow rate	Reduced stack temperature	Incomplete evaporation of blackwater; incomplete combustion; high CO levels	Heat input too low; malfunction of diesel pump; empty diesel drum; flow rate drift	Standard range of heat input operating conditions; monitor diesel level in drum; verify pump operation during test	Set limits for operation; use better controls for diesel flow rate to prevent drift	8	5	2	80
Flow of blackwater through injectors	Clogging of injectors	Asymmetric flow of blackwater; modified VCC gas-phase mixing characteristics; increased particulate in exit gas	Injector design; blackwater characteristics; alignment, placement of injectors (coking on outer surface of injector if inserted too far)	Inspection of injectors; procedure and measurements for injector alignment and placement	Document injector alignment and placement procedure	7	4	6	168
Flow of blackwater through injectors	Clogging of injection line	No flow through injector (s)	Poor blackwater mixing; lines not purged; inconsistent flow through lines led to settling and buildup of particulate	Monitor performance of blackwater mixer; purge lines with water after tests; avoid leaving blackwater in lines for long periods without purging lines.	Document procedure for purging lines and preventing settling in lines; develop method for verifying mixer performance	7	4	6	168
Continuous system operation	safety system triggered (peepers not seeing flame)	continued injection of blackwater, wetting refractory walls; reduced surface temperature; difficult re-start-up	Peeper malfunction; plugging in the peeper line of sight of flame; excessive steam production obscuring flame	Proper placement and alignment of peepers; periodic checking of peeper ports for build-up	Document procedure for alignment and placement of peepers	8	3	2	48
Continuous system operation	flame out	safety system triggered; continued injection of blackwater, wetting refractory walls; reduced surface temperature; difficult re-start-up	Inconsistent diesel flow rate; diesel supply drum depleted; flame quenched by excessive blackwater injection	Routine maintenance of diesel pump; checking diesel levels in tank; limiting blackwater injection rates; increasing blackwater injection gradually	Document procedures for consistently maintaining diesel and blackwater injection rates	8	3	1	24
Injection of blackwater	Incomplete atomization of blackwater	Impinging flow of blackwater onto refractory walls, collection of blackwater in barrel	Insufficient atomization air pressure (must be greater than 80 psi)	Ensure that atomization air level is sufficient for each type of blackwater (at least 80 psi)	Evaluate need for detailed study of injector and atomization with different blackwater types	6	2	3	36
CEMS analysis of stack gases	Invalid CEMS analyses	Misleading results; unnecessary adjustment of operating conditions; possible damage to analyzers	Overflow of water from knock-out into sampling line going to analyzers; analyzer drift; leak in sampling line (upstream of sampling pump)	Routinely check water level in knock-out system; identify transient conditions that could lead to increased moisture levels in the stack gases; routinely zero and span analyzers; leak check sampling line	Evaluate need for alternative knockout systems, including continuous systems with automatic draining of accumulated liquid.	6	2	3	36
Temp. measurement	Faulty TC measurements	Lack of information about thermal profile of system	Exceeding rated temperature for TC type; faulty connections to data recording system	Avoid transient high temperature operation; protect integrity of wiring and secure connections.	Replace faulty TC's as needed; use appropriately rated TC's; routinely check TC connections.	5	1	2	10
Automatic Controller	Sudden change in O2 or temperature readings	System flooding or shutdown.	Upper and lower limits not properly set in GUI	Enter correct limits	Check limits every time controller is turned on	6	1	3	18

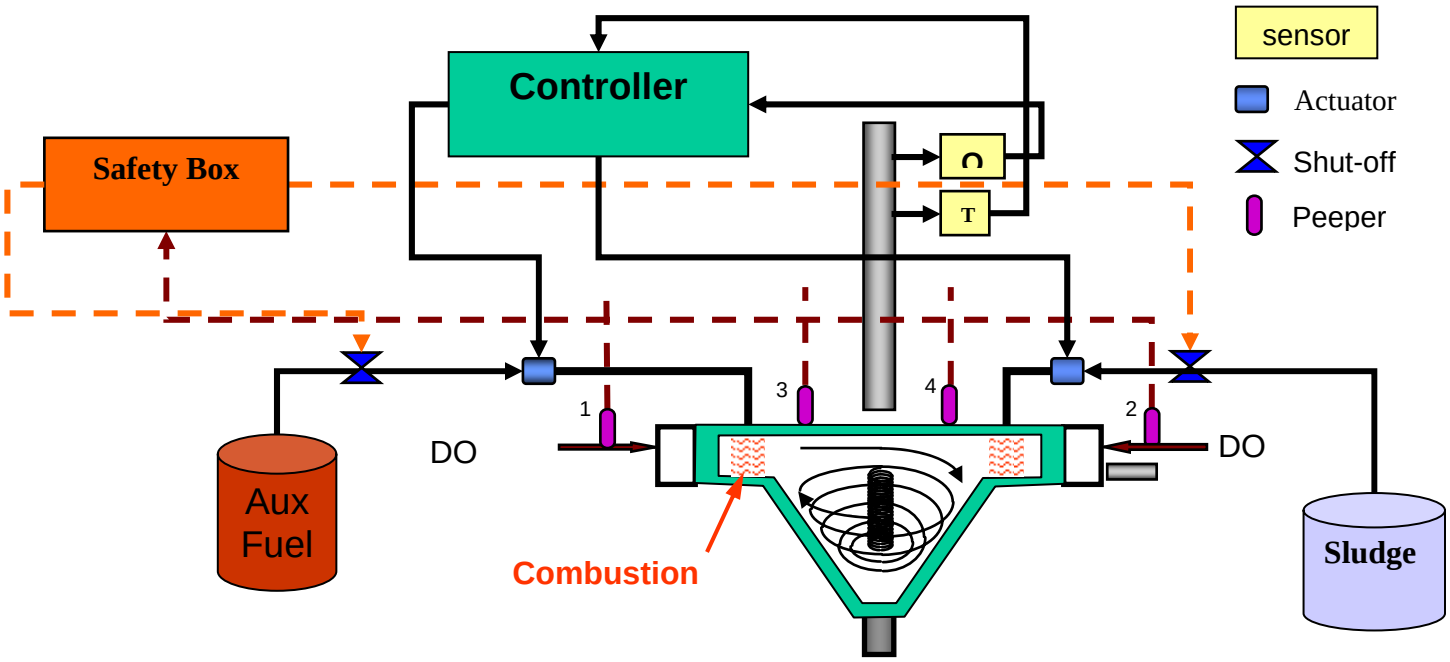
SEV = Severity; OCC = Occurrence; DET = Detection; RPN = Risk Priority Number

A.5: Safety Procedures

A.5.1: Potential Hazards

DESCRIPTION OF JOB OR TASK	POTENTIAL HAZARD	PREVENTIVE SAFE WORK CONDITIONS, SAFE WORK PRACTICES, OR PERSONAL PROTECTIVE EQUIPMENT
Testing or maintenance of the VCC PDU at SWS	General	The VCC must be operated by trained personnel only.
		Compressed gases must be handled by trained personnel
	Exposure to Hazardous Gases (Organic Vapor Inhalation)	Read and understand MSDS's for all gases being used.
		Don all Personal Protective Equipment (PPE) as required by MSDS and Respirator Selection Guide.
		Before testing begins: the fuel feed system will be leak checked; the flame safety system will be fully operational; and sample ports in combustor will be closed and leak free.
		If fuel is leaking, the flame safety system will be manually activated and the leak repaired before testing begins again.
		Ensure all analyzer exhaust gas lines are vented to atmosphere.
		If a flame out occurs or primary air or coolant supply is interrupted, all fuel feeds will be shut off. The source of the problem will be located are repaired before continuing.
		When opening or working near open ports, an individual will wear a respirator with organic cartridge. Organic cartridge use is NOT sufficient for exposure to pyrolysis gases. In the event of open ports with pyrolysis gases, the port must be under negative pressure or the port must be sealed.
	Burns	Wear protective gloves when working with heated or hot components of facility
	Diesel Spills and Containment	Diesel tank refill procedures: Use 55 gallon drums with top access only. Drums must be on approved secondary containment skid. Prepare area for refueling with oil absorbent materials around fill port, below hose and at the refueling truck hose connection.
		Diesel firing system: place oil absorbent materials around diesel equipment and fitting. All oil spills must be absorbed and disposed of.
		Place oily materials in an approved flammable waste disposal trashcan.
		Read MSDS for additional information on safety precautions, and proper cleanup and disposal methods.
		Personnel will wear appropriate personal protective equipment.
	Electrocution	All electrical equipment should be properly shielded
		External electrical equipment (safety box, etc...) should be placed in a water proof box

A.5.2: Safety System

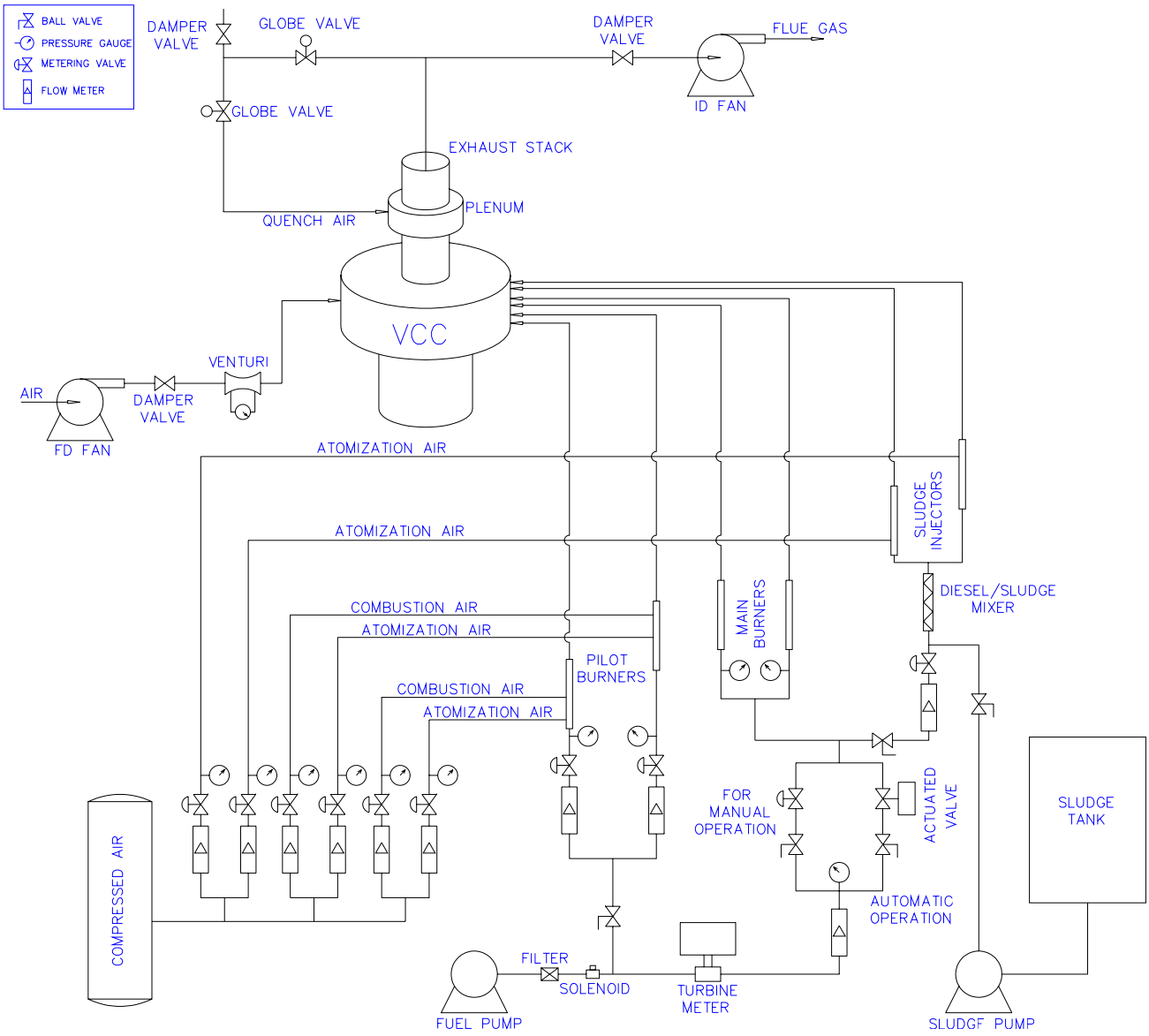


O Peepers

- O If peeper 1 does not detect flame → Shutdown
- O If peeper 2 does not detect flame → Shutdown
- O If peepers 3 **and** 4 do not detect flame → Shutdown

Appendix B

B.1: Process Instrumentation Diagram



B.2: Combustion Chamber Layout

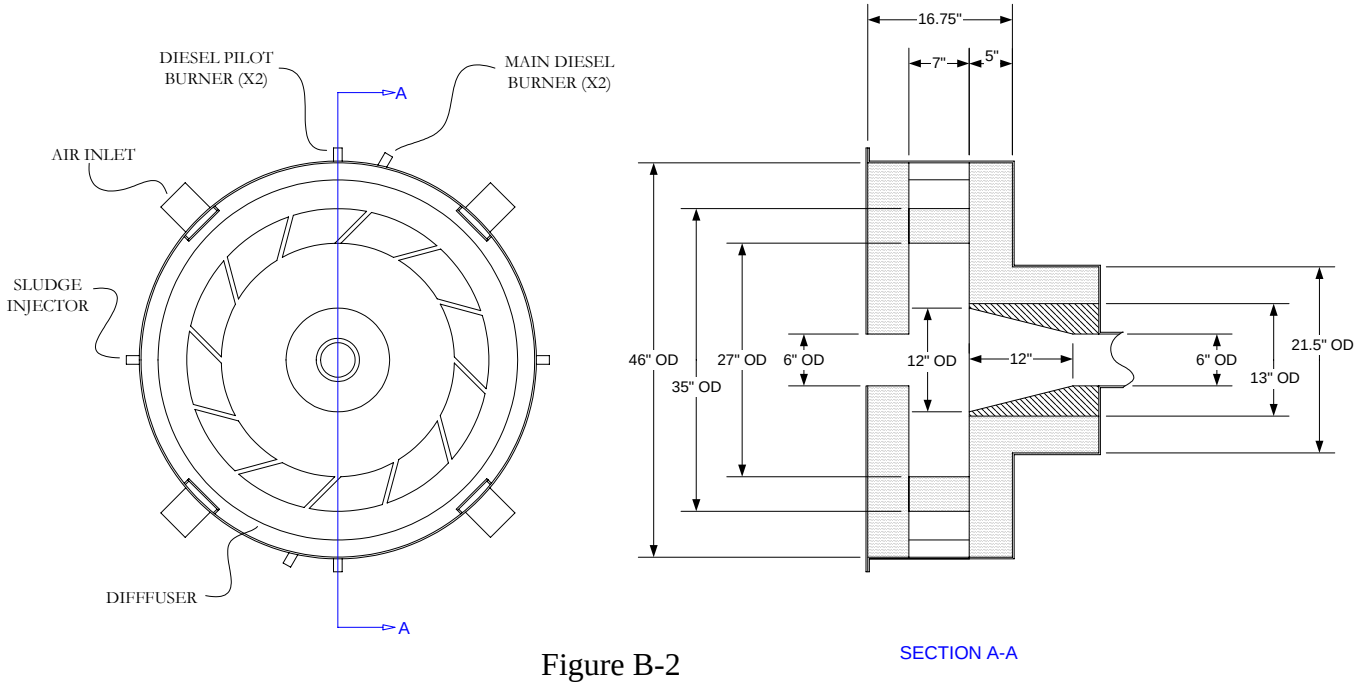


Figure B-2

Figure B-2 shows an overhead layout of the VCC combustion chamber (with the VCC ceiling removed) and a cutaway side view, sectioned at A-A.

B.3: Sludge Injector

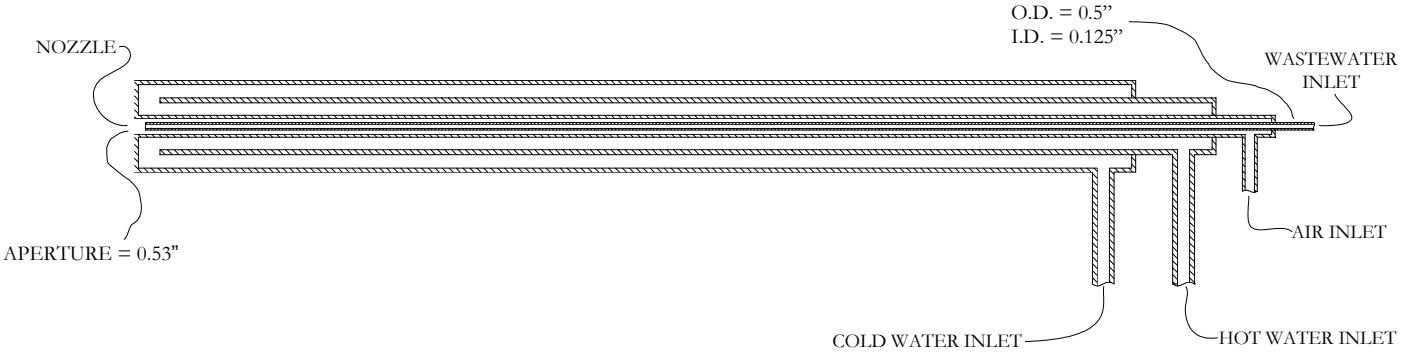


Figure B-3

A cross section of the sludge injector is shown in Figure B-3.

B.4: Diesel Pilot Burner

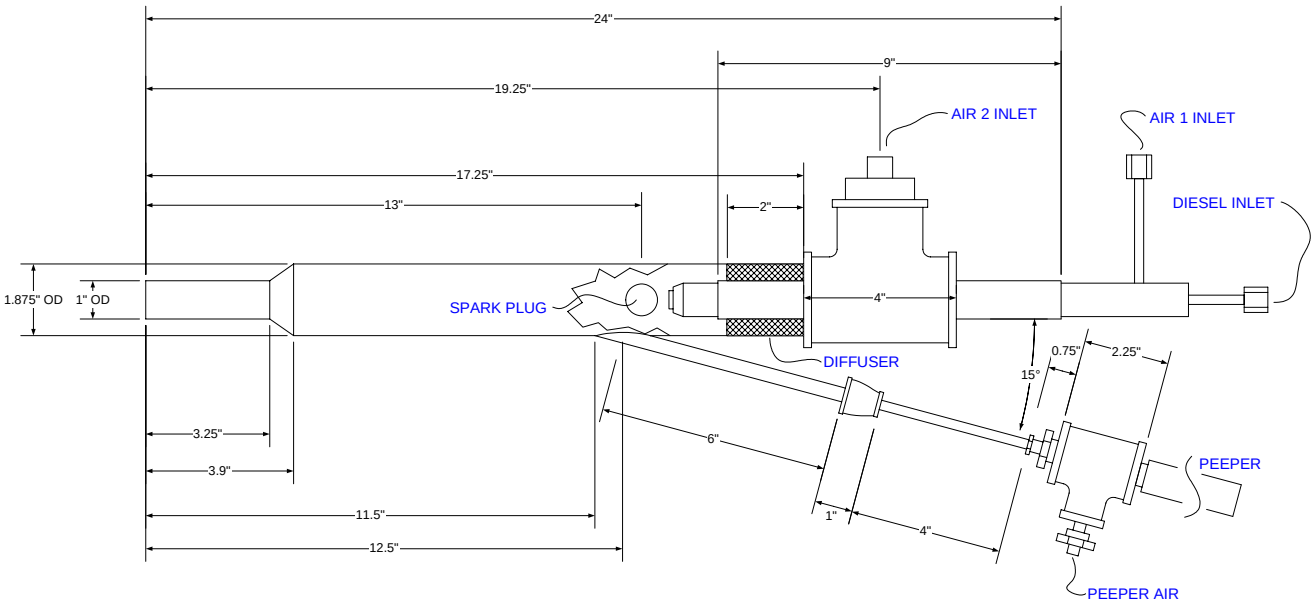


Figure B-4

Figure B-4 shows a layout of the diesel pilot burner, with partial cutaway to reveal the injector nozzle, spark plug aperture, and diffuser.

B.4.1: Nozzle Parts List

Nozzle	Vendor	Part Number	Description
Siphon Nozzle	Delavan	30610-5 & 29713-2	Siphon nozzle & adaptor
Nozzle A	Spraying Systems	1/4 JH-SS-SU11-SS	1/4" air atomizing nozzle
Nozzle B	Spraying Systems	1/8 JJ-SS-SUJ12A-SS	1/8" air atomizing nozzle

Although all of the nozzles were tested, Nozzle B was chosen for the final testing of the VCC.

B.4.2: Nozzle B Flow Settings

Nozzle B was utilized during the testing of the VCC.

Diesel (gph)	Combustion Air (cfh @ psi)	Atomizing Air (cfh @ psi)
0.6	380 @ 30	30 @ 15

For further details, see the Diesel Pilot Burner section of Appendix E

B.5: Auxiliary Diesel Injector

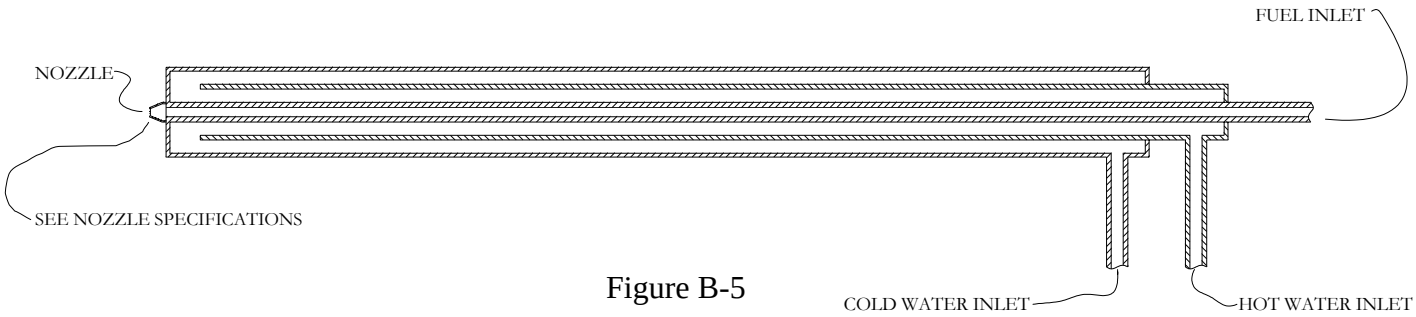


Figure B-5

A cross section of the main diesel injector can be seen in Figure B-5.

Nozzle Specifications

Nozzle Type	Pressure Nozzle
Fuel Type	Diesel #2
Spray Angle	~ 40 ^{o} Flat Spray
Spray Orientation	45 ^{o}
Injection Angle	~ 30 ^{o} from Radial
Maximum Flow Rate	10 gph

B.6: Controller Hardware and Software Parts List

1. Visual Basic Professional Version 6
2. Desktop Computer (PC)
    a. Pentium III Processor 900 Mz
    b. 256 MB RAM
    c. 20 GB hard drive
    d. Empty PCI slot
    e. Windows 2000
3. SimpleTech SimpleStation Internal PC Card Drive (PCI version)
4. Computer Boards PC card (DAS16/12-AO) PCMCIA
5. Computer Boards Universal software drivers
6. Computer Boards 50 pin micro to 50 pin socket IDC 39” cable
7. Computer Boards Shielded terminal breakout box
8. Omega optical isolator

Appendix C

C.1: Addition of Oil in Sludge Waste Stream:

In order to simulate bilge water, diesel oil #2 was injected into water flowing to the sludge injectors, as can be seen in Figure B-1. Valve A was used to adjust the amount of diesel being introduced to the water flow. In a similar manner to the diesel in water setup, diesel can also be injected into blackwater.

Diesel in Water/Blackwater Setup

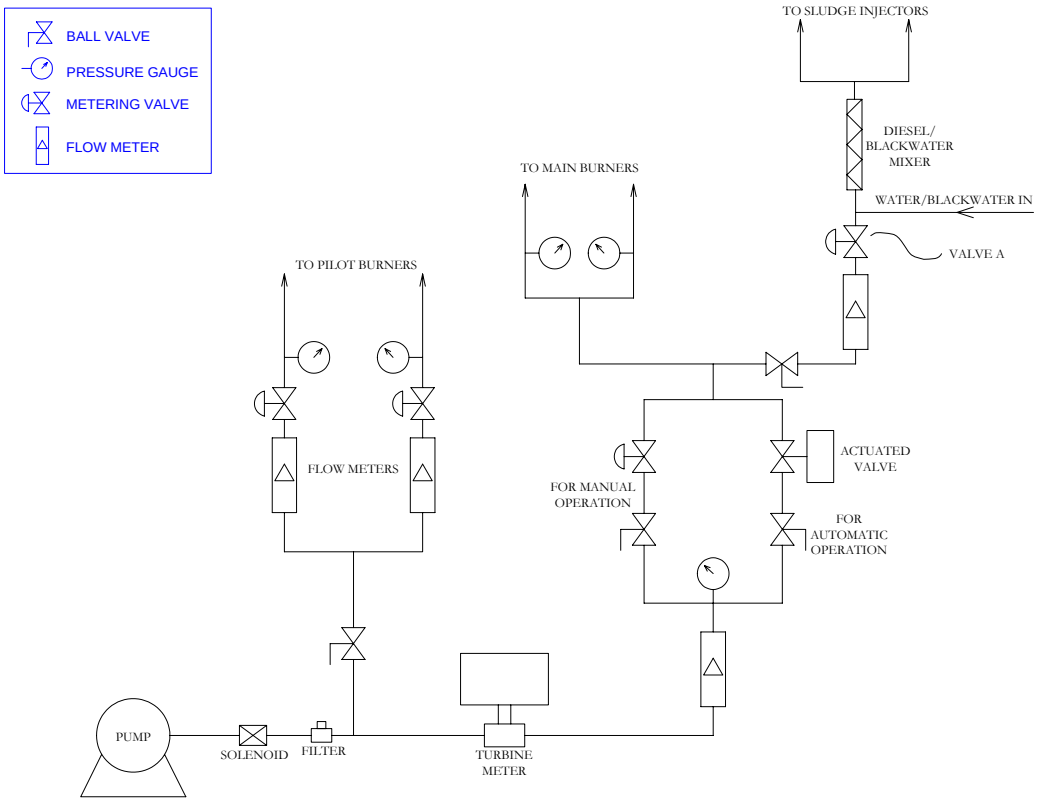
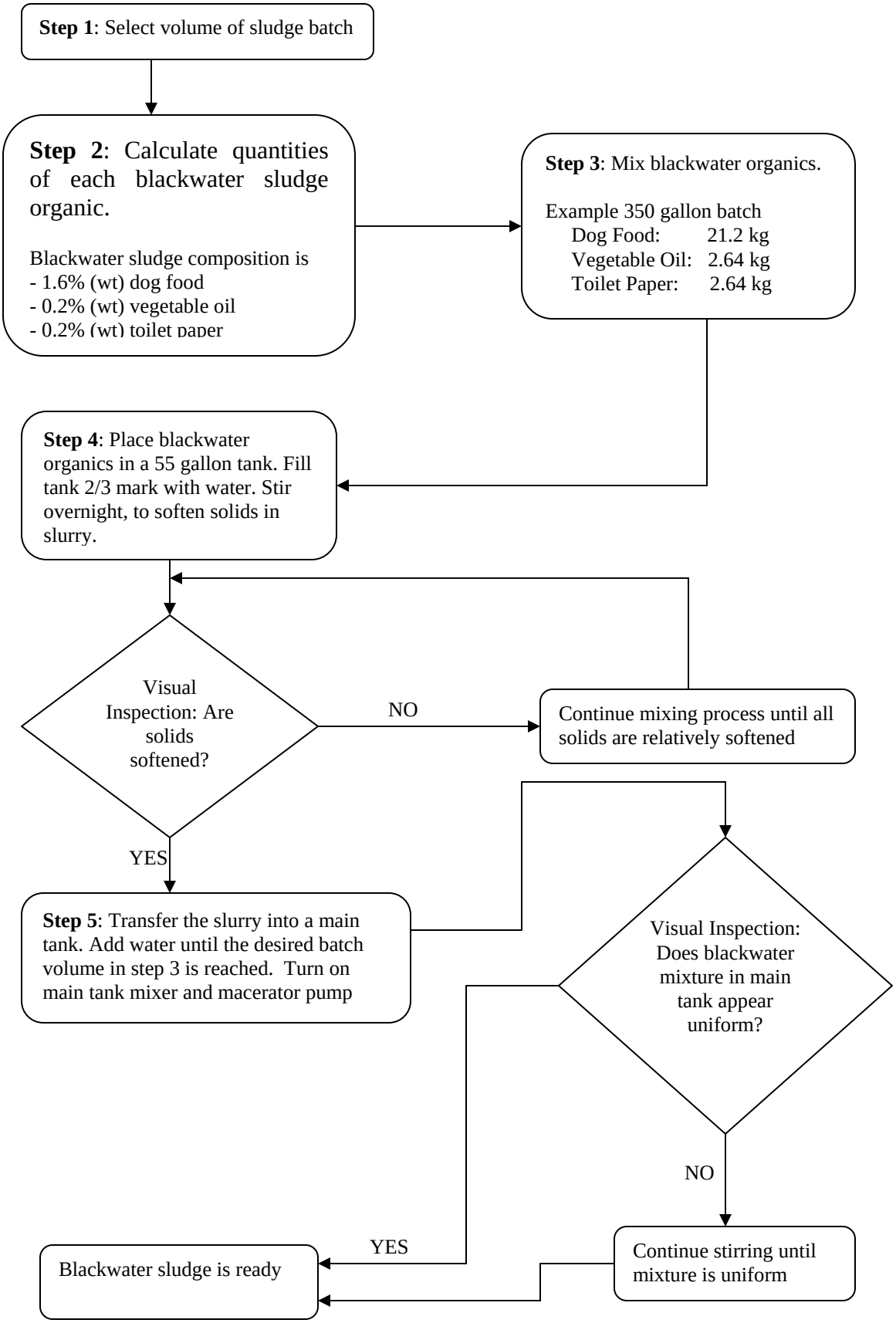


Figure C-1

C.2: Blackwater Preparation Procedure



C.3: Blackwater Assay

The following brands of ingredients were utilized for every batch of blackwater.

1. Smart and Final brand dog food (red and white bag)
2. Charmin toilet paper
3. Mazola corn oil

Assay of Dog Food Used in Surrogate	
Proximate	
Moisture, wt. %	8.61
Ash, wt. %	10.73
Volatile, wt. %	68.06
Fixed Carbon, wt. %	12.60
HHV, BTU/lb	7607
Ultimate	
Moisture, wt. %	8.61
Ash, wt. %	10.73
Sulfur, wt. %	0.34
Carbon, wt. %	42.36
Hydrogen, wt. %	6.04
Nitrogen, wt. %	4.26
Oxygen, wt. %	27.66

Appendix D

D.1: Diesel Injector Alignment:

In order to insure correct relative alignment of the diesel pilot and main diesel injector, an alignment procedure is outlined. The procedure is to be performed on both pairs of injectors before each experiment. The configuration of the injectors can be seen in Figure C-1.

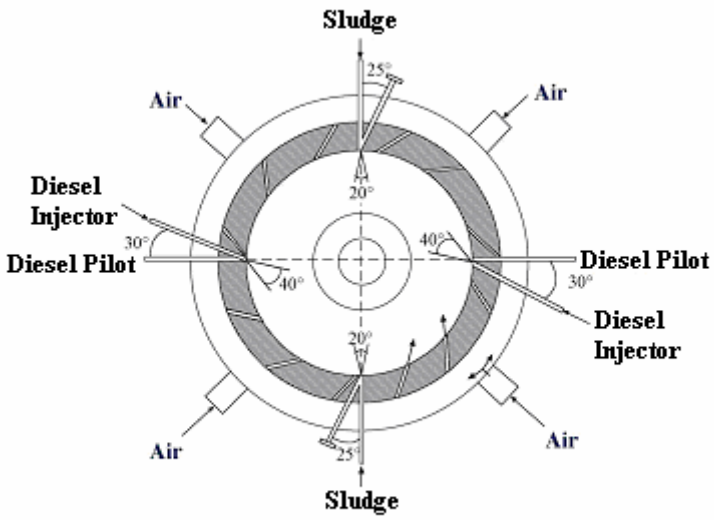


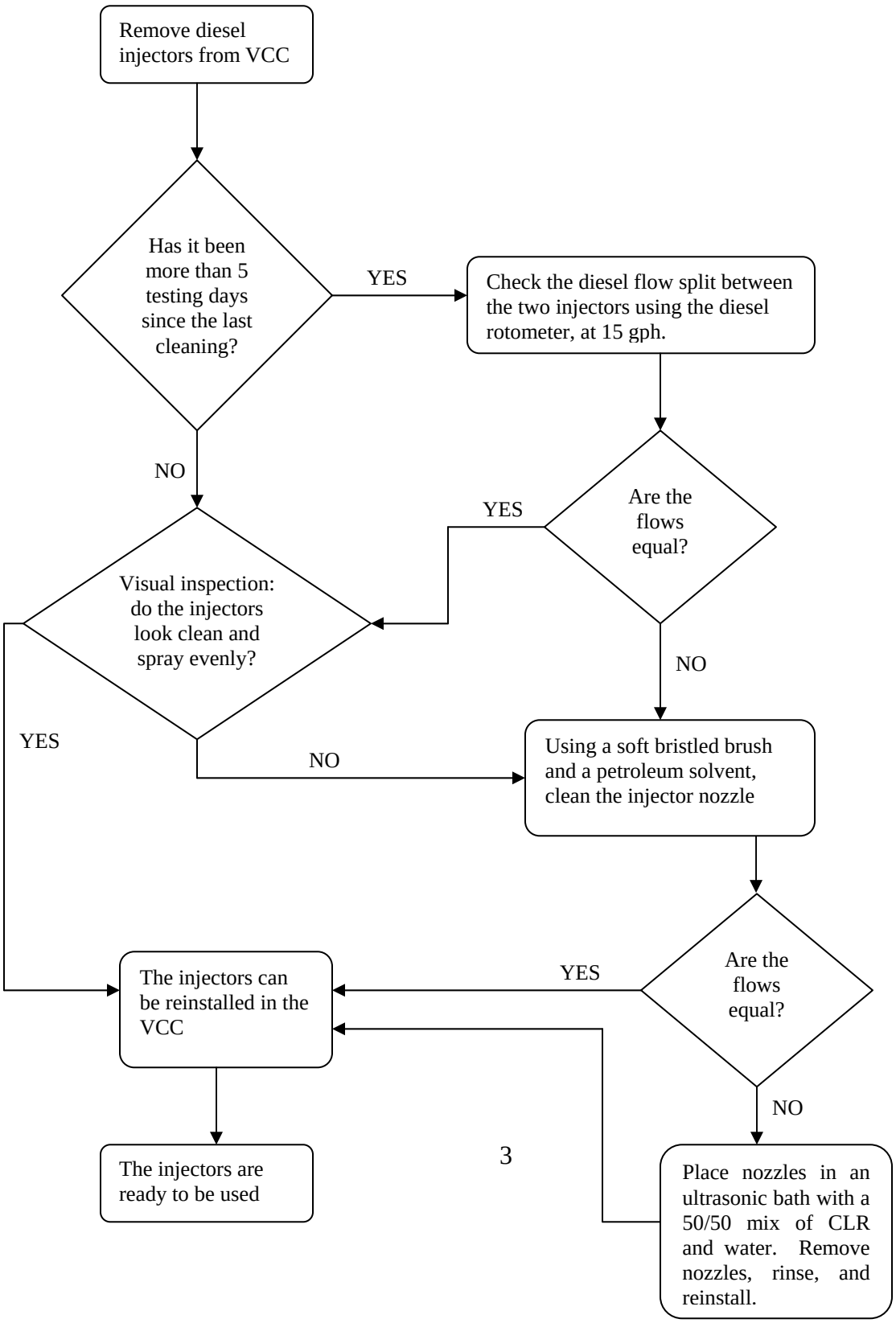
Figure D-1

1. Remove main injectors and diesel pilots
2. Inspect all diesel nozzles
    a. Tighten all connection
    b. Clean and brush off injector tips and apertures
    c. Check for slag development in diesel pilot casings
3. For each pair of main-pilot injectors carefully:
    a. Loosen shaft collars
    b. Insert main injector as far as possible
    c. Insert diesel pilot, until the tip contacts the main injector
        i. Mark diesel pilot's position, relative to the pilot aperture
        ii. This is the correct position of the diesel pilot
    d. Maintaining the initial position mark, pull back the main injector and push in diesel pilot as far as possible
    e. Push in main injector, until the tip contacts the diesel pilot casing
    f. Pull out diesel pilot
    g. Push in main injector 0.25", mark position relative to main injector aperture

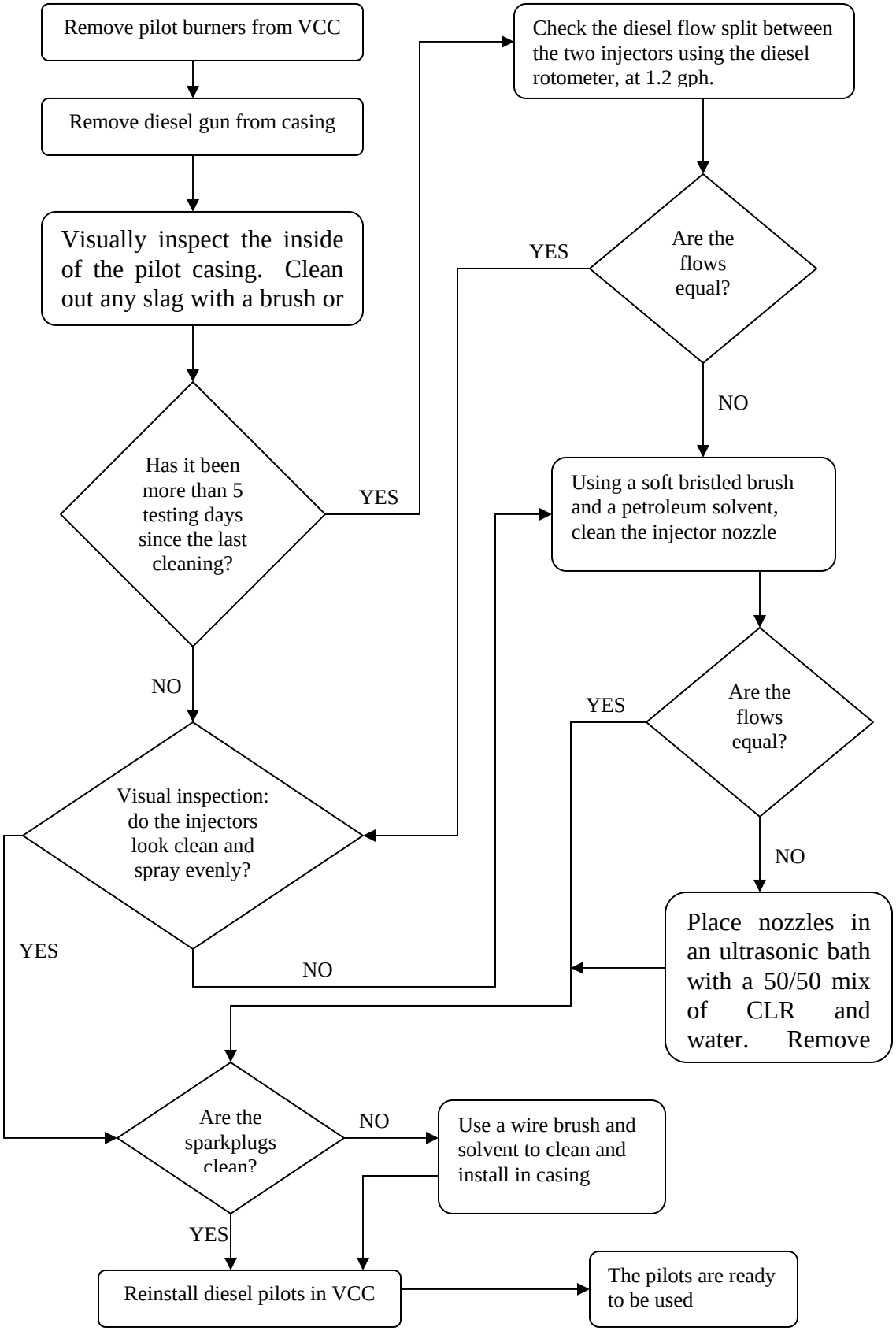
h. Tighten shaft collars on marked positions for the main injector and for the diesel pilot
i. Insert main injector and diesel pilot, butting shaft collar against apertures to seal openings
j. Repeat for opposite side of VCC

4. Setting the injection angle of the main injectors
    a. The spray pattern of the main injector nozzle is a flat-V shape. It has been experimentally determined that the planar surface of the spray pattern should be set at a 45° angle relative to the floor of the VCC combustion chamber. The vertex of the two planes should be downstream (in the vortex), with the high end of the spray being upstream.
        i. With the main injector removed, note the angle of the spray nozzle; mark the outer casing of the injector, as a reference for setting the injector spray angle.
        ii. Install main injector in the correct position
        iii. Using an angle measurement tool, use the reference mark to set a 45° spray angle.
        iv. Tighten clamping bolt to maintain set angle

D.2: Auxiliary Diesel Injector Maintenance



D.3: Diesel Pilot Maintenance



D.4: VCC Interior Inspection

Before each experiment, the VCC interior should be thoroughly inspected for sludge build-up, refractory damage, or other potential issues.

1. When the VCC is cool (at least 12 hours from last operation), remove all diesel and sludge injectors; remove the exhaust port door, steel exhaust stack, and ash barrel.
2. Lower a light through the exhaust stack port and into the combustion chamber, for the initial inspection.
3. Look through the open injector ports to perform the initial visual inspection.
    a. Look for sludge debris, skewed vane blocks, clogged vane gaps, or other potential issues.
4. Remove the light fixture; and lower a digital camera through the exhaust port.
5. Take a picture of each section of the combustion chamber
    a. Download the photos into a computer for the next inspection stage
        i. Again, look for potential issues.
6. If debris is found, follow the "self-cleaning" procedure outlined in the maintenance section.
7. After the inspection and appropriate corrective actions are taken, the VCC components should be reassembled
    a. Install all injectors, as described in the "Alignment of Diesel Injectors" section.
    b. The tip of the sludge injector should be 0.5" from the inner wall of the combustion chamber.
    c. Replace insulation and spacers on metal exhaust stack (if worn). Reinstall steel exhaust stack, being sure it is concentric to the exhaust stack aperture and tightly sealed.
    d. Install exhaust port door
    e. Check seal on ash barrel, and reinstall.

D.5: Analyzers:

Before and after each experiment, the O_2, CO, CO_2, and NO analyzer, as well as any other analyzer, should be calibrated using span and zero gases. The instruction manual for each individual analyzer should be read, to determine the proper calibration method. During the calibration procedure, the data collection system should be observed to confirm that the readout on the computer matches the analyzer readout. During the experiment, care must be taken to ensure all analyzed exhaust gases are safely vented.

D.6 General Maintenance:

Before, during, and after an experiment, inspection tours should be regularly taken in order to observe and prevent any potential failure issue, or any other concerns that may affect the accuracy of the data being collected.

1. Pre-Startup Walk
    a. Visually inspect the control room, diesel storage area, balckwater storage area, the VCC itself, and the VCC area instrument panel.
        i. Control Room, check the following
            1. The DAS and control programs are on and logging to a file named with the experiment date
            2. On the control panel, the moyno pump and cooling water pump are both on
            3. All the analyzers are on and calibrated
            4. The exhaust gas vent tube is properly situated to vent the exhaust gas to atmosphere, without causing a safety hazard.
            5. The CO alarm is turned on
        ii. Diesel Storage Area, check the following
            1. Diesel barrels are correctly stored on the appropriate capture pallet and under a protective cover (such as a tent or shed)
            2. There is no diesel on the ground or on any equipment surface which is located off a capture pallet
            3. There are no diesel leaks in any of the diesel lines or fixtures
            4. The diesel pump is properly grounded
            5. No flame sources or reactive materials near the diesel area
            6. The VCC is drawing from two full barrels of diesel, free of water
            7. The diesel pump is on and the water knockout empty
            8. The fuel pressure is set to 90 psi
        iii. Blackwater Storage Area, check the following
            1. The blackwater is properly contained, and in no danger of spilling
            2. All electrical connections are not situated in or near water
            3. All hoses and cords pose no tripping hazard
            4. The blackwater stirring motor is on
            5. The blackwater has been macerated for at least 30 minutes
            6. No visible large particles in blackwater
            7. The Dayton pump is circulating the blackwater
        iv. VCC, check the following
            1. No leaks in diesel lines or fixtures
            2. All injectors are installed correctly
            3. Sludge injector valves are open

4. Main diesel injector and diesel pilot valves are closed
5. Barrel is installed and sealed
6. Barrel insulation has no diesel soaked areas
7. Exhaust port door is sealed shut
8. A ground wire electrically connects the pilot burner casing to the VCC
9. Pilot burner injector guns are clamped in place
10. Main diesel injector set to 45°
11. Area immediately surrounding VCC is clear of tripping hazards
12. Sample pump is turned on, with clean filter
13. Sample probe is in place
14. All thermocouples are in place
15. ID fan damper closed, until operating temperature is reached
16. All tools and instruments are removed from all surfaces of the VCC

v. VCC Area Instrument Panel

1. All thermocouples are properly connected to meters and DAS
2. Amperage meter for the ID fan is on (maximum fan current = 38 A)
3. Compressed air is on and at least 90 psi
4. Flow meters for the combustion air and atomizing air are on and at correct levels
5. Main diesel and pilot diesel valves are off
6. All magnahelics are in place and operational
7. Moyno pump is on at 50 Hz, water is spraying out through the bypass
8. Safety system in turned on, peepers are operational

2. Observations during Operation

a. While the VCC is in operation, many of the areas mentioned in the pre-startup walk should be regularly checked. Several more items should also be checked.

i. Control Room, check the following

1. Observe the DAS data often, to detect signs of potential issues (i.e.: high CO levels or temperature levels out of the operational band)
2. The venturi is set correctly
3. The controller values are set correctly and operational

ii. Diesel Storage Area, check the following

1. The diesel barrels are not empty
2. The bypass diesel tank is not full and overflowing
3. The diesel pump is on

iii. Blackwater Storage Area, check the following

1. The Dayton pump is operational

        2. The blackwater level in the tank is above the blackwater outlet port
    iv. VCC, check the following
        1. Main injector and pilot valves are open
        2. No water is dripping from bottom of VCC
        3. Drum is not emitting excessive amounts of smoke
    v. VCC Area Instrument Panel
        1. All diesel levels are at correct levels
        2. All compressed air flows and pressures are at correct levels
        3. All thermocouple readouts are operational
        4. Safety system is on and operational

3. Post-Experiment Inspection
    a. After the experiment has been completed, and the system has been completely shut down according to procedures, a final post-experiment inspection should be completed.
        i. Control Room, check the following
            1. The ID fan, FD fan, moyno pump, and cooling water switches are off
            2. Data is transferred from the computers to the server
            3. Computers are off
            4. All analyzer pumps are off, the NO analyzer is off
            5. Span and zero bottle valves are closed
        ii. Diesel Storage Area, check the following
            1. Diesel pump is off
            2. No diesel spills
            3. Drums on capture pallets
        iii. Blackwater Storage Area, check the following
            1. Moyno and macerator off
            2. If there is blackwater in tank:
                a. The stirring motor is on
                b. The tank is covered
            3. No blackwater spills
        iv. VCC, check the following
            1. All diesel valves off
            2. No flammable items near VCC
            3. Sample pump is off
        v. VCC Area Instrument Panel
            1. All electronic components are off and covered or stored in lab
            2. Instrument panel off
            3. All compressed air off (turn off compressor)
            4. All diesel valves off

APPENDIX 2

Sludge Combustor Using Swirl and Active Combustion Control

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Sludge Combustor using Swirl and Active Combustion Control

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ABSTRACT

A research program directed at developing technology for compact shipboard incinerators for sludges is described. The concept utilizes previously developed Vortex Containment Combustor (VCC) as a primary unit with an active combustion control afterburner (AB).

The overall power scale of the combined system is 0.15 MJoule/sec and has a target sludge processing rate of 0.75 liter/min. Tests were undertaken to evaluate the particulate suspension qualities of the VCC and the overall performance of the combined VCC / active control AB processing intermediate levels of a surrogate 'sludge'.

The VCC operates like a combusting cyclone separator. Air is introduced circumferentially to create swirl in the combustion zone. This swirl suspends and traps particulate matter until it combusts or pyrolyzes to a size small enough to escape. Particle suspension was enhanced with flow directors that created a net upward velocity component near the floor of the VCC to prevent formation of dunes in the boundary layer. Particles were found to have very long residence times in the combustion zone of the VCC: 43 μm particles had a 1/e lifetime of over 20 seconds. The VCC was operated successfully both fuel lean and fuel rich. The VCC flame was found to be stable at a 'surrogate sludge' (water) flow rate of 0.35 liter/min. Tests at higher flow rates are pending.

In addition, mixing has been enhanced in a dump combustor configuration afterburner using active combustion control. The technology is based on injection of waste gases circumferentially into the shear layer of a central air jet from which sheds an acoustically controlled coherent spanwise vortex. The waste is rapidly entrained into the air vortex and the good large and fine scale mixing allows compact high efficiency combustion with high destruction and removal efficiency (DRE) and low emissions.

The performance of the combined system was evaluated with and without 'surrogate sludge'. It was found that the actively controlled AB efficiently combusts all of the pyrolysis gases and soot coming from the VCC: there was no visible soot emission and the carbon monoxide (CO) levels were below 50 ppm without sludge and below 70 ppm with a flow rate of 0.35 liter/min. In addition it was seen that the combined system efficiently destroys organics introduced into the 'surrogate sludge': the CO levels were virtually unchanged when 5% ethanol was added to the water 'surrogate sludge'. This implies greater than 99.9% destruction of the organic content in this yet to be optimized system.

INTRODUCTION

Fluid dynamics control performance in many practical combustion applications such as air breathing propulsion, energy conversion power plants, waste incinerators and other industrial burners. The importance of organized coherent large-scale vortical structures in large scale fluid mixing has been illustrated (1-3). Active manipulation of these vortical structures can lead to enhancement of the mixing process via an increase of the natural spreading rate of the shear layer. This can be realized using acoustic driving of the initial shear layer (4, 5). Through the use of advanced laser diagnostic techniques (6), the importance of controlling large and small scale mixing in combustion was

determined (7). Active control by shear layer excitation has been used to enhance energy release (8-11) and to reduce emissions (12) and enhance hazardous waste incineration (13, 14).

At the Naval Air Warfare Center Weapons Division (NAWCWPNS), China Lake, work on active combustion control included open and closed loop control of small scale (~10kW) and large scale (~1MW) combustors to enhance their performance by increasing energy release, extending the lean flammability limit, and stabilizing the combustion (15). The focus of the investigations shifted to emphasize practical applications such as the investigation of techniques for the development of compact waste incinerators for use aboard Navy ships. The common underlying concept of the combustion processes discussed in the present paper is vortex combustion. The combustion in many practical burners is partially diffusion controlled and this means localized regions have fuel to air ratios not conducive to low emission performance. The vortex combustion technique ensures that the combustion is confined to regions (i.e., vortices) within the combustor where optimal local conditions can be maintained. The vortex provides intense mixing and long residence time necessary for a complete combustion process. The high strain rate in the vortex roll-up region also delays ignition until partial premixing is obtained. Thus vortex control, via acoustic excitation, can turn a sooty yellow benzene diffusion flame into a perfectly blue clean flame.

Recent work (16-21) emphasized the practical aspects of implementing active control vortex technology on an afterburner (AB) on a real incinerator. These included evaluating performance on more realistic waste surrogates, evaluating self excited (passive) configurations, looking at simplified designs, reducing back pressure, and quantifying performance at full scale (~1MW).

We have now initiated a Strategic Environmental Research and Develop Program (SERDP) funded program which addresses the thermal treatment of oil/water separator sludge. The program addresses the difficult problem of disposal of oily sludge from the wide variety of oil/water separators used in the military. These oily sludges which contain oil, water, and particulate matter have highly variable properties depending on their source of generation and must be disposed in an environmentally acceptable manner in compact equipment. The NAWCWPNS has teamed with GE Energy and Environmental Research Corporation to develop an advanced oil/water separator sludge thermal disposal system. The technology concept combines the features of a high performance Vortex Containment Combustor (VCC), which is an advanced unit ideal for low fuel value sludge, with an actively controlled afterburner, which is a direct outgrowth of studies sponsored by SERDP for the development of Compact, Closed-Loop Controlled Waste Incineration. As described in last years paper, the actively controlled afterburner is a dump combustor design with circumferential injection of pyrolysis gases into the roll-up region of a strong coherent axial vortex generated in the afterburner air flow. This greatly speeds mixing and leads to a compact afterburner with low emissions.

In this paper we will discuss preliminary results from a small scale unit combining the VCC with an properly scaled actively controlled afterburner. This is a 0.15 MJoule/sec unit with a target sludge throughput of 0.75 liter per minute. A companion paper (22) discusses a much larger VCC unit with a target sludge throughput of 3.2 liter per minute. The definition of 'full scale' depends on the application. If only the oily sludge from shipboard oil/water separators were the waste stream, then the small unit would be nearly full scale. However, if low duty cycle operation were required, or if gray and black water were processed, then the larger unit would be full scale.

The projected performance features of the actively controlled vortex containment combustor include the following: 1) compactness due to the high intensity VCC and compact afterburner, 2) flexibility and robustness for a wide range of sludge properties due to simple injection schemes, insensitivity of the combustion process and high combustion intensity, 3) very low NOx due to mixing features of the afterburner design (21), 4) automatic control using advanced active combustion control technology, 5) very high destruction efficiency (>99.9999%) due to high performance VCC and active control afterburner, 6) very low carbon in ash due to long particle residence times in VCC burning zone

which acts as an aerodynamic bottle to keep particles contained until they are completely combusted, 7) low particulate emissions due to centrifugal separation in VCC, 8) no organic (or dioxin) emissions due to high combustion efficiency and very low particulate emissions, 9) continual performance assurance due to continuous monitoring and active control, and 10) meeting all current and proposed IMO and land-based standards for sludge disposal.

EXPERIMENTAL

Figure 1 shows a side cross section of the VCC portion of the incinerator. The device has cylindrical symmetry so the combustion region, the central 356 mm outside diameter by 74 mm tall region, is circular. The actively controlled afterburner previously described (21) is adapted to the exhaust of the VCC.

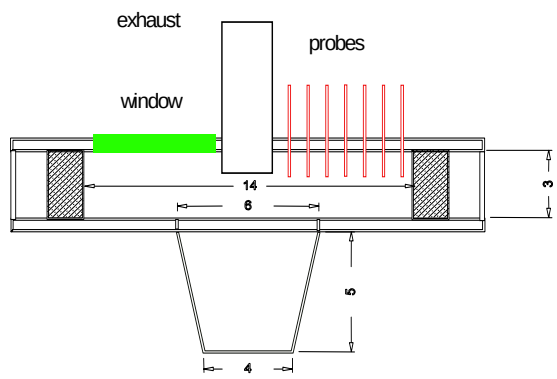


Fig. 1 VCC schematic configuration, side cross section. All dimensions shown are in inches. This is the small scale system for experimental investigation of parametric effects on performance.

The dimensions shown in Fig. 1 are for the experimental system fabricated for investigation of parametric variation of geometry and operating conditions on performance. The power level of this system is 55 kW to 170 kW depending on operating conditions. The power level of the full scale unit has not be decided upon pending a survey of sludge generation rates. The experimental unit was designed with optical access to assess the combustion region as well as allow laser diagnostic measurements on particulates in the flow. There is also provisions for introducing thermocouple or sampling probes at various radii in the combustion zone. The exhaust diameter was 65 mm down to 50 mm for some tests (the lower diameter greatly increases exit swirl at the expense of much larger pressure drop).

The VCC works by injecting the combustion air into the central circular combustion region circumferentially at a tangential angle to create swirl. One of the design parameters being studied is this air injection angle; all preliminary results shown here are for an injection angle of 45 degrees. The swirl acts like a centrifugal trap for particulates so that larger particles stay in the combustion "bubble" until they are reduced to a size small enough to move towards the center (22). The swirl flow and exhaust configuration creates a stagnation zone within the cone like bottom portion of the VCC where non-combustible particulates are trapped. There are, therefore, two separate particulate retention zones in the VCC design: one in the combustion zone and one in the particle trap below. Optimization of both will enhance the burnout of combustible particles and trap

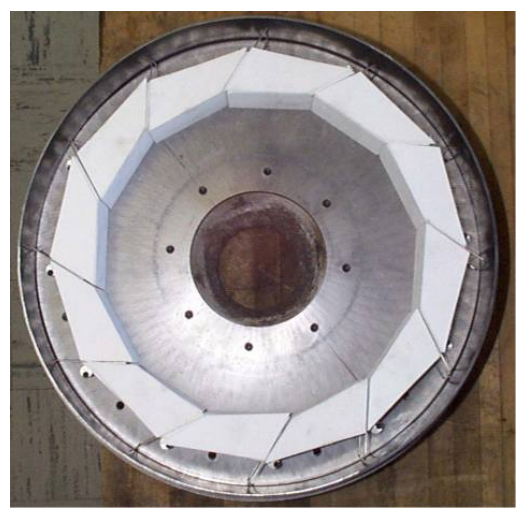


Fig. 2 Top internal view of VCC. Outside the white blocks is the air plenum. Inside is the swirling combustion zone.

non-combustible particles, thereby leading to very low particulate emissions, and, therefore, low dioxin emissions. Any fine combustible particles that escape the VCC are combusted, along with the pyrolysis gases leaving the VCC, in the actively controlled afterburner.

Figure 2 is a top photo of the scale VCC. The swirl introduction wall was made from twelve ceramic foam blocks. The gap between the blocks is adjustable to allow parametric variation of the swirl introduction velocity. The baseline VCC air flow was 1000 liter/min. With the narrower gap of 0.81 mm the immediate swirl air injection velocity was 18.5 m/s. With the larger gap of 1.62 mm the nominal velocity was 9.3 m/s. The tangential velocity within the combustion zone was not directly measured; if one assumes the flow fills the chamber top to bottom and the same region radially then the average swirl velocity is 3.2 m/s. Obviously, the generation of swirl comes at a price of pressure loss. The pressure losses of the system were quantified under combusting conditions. Even with the narrow gaps (highest swirl level) the total pressure loss was only about 8 inches of water column. About half of this was the pressure drop between the air plenum and combustion zone and half due to the swirl (combustion chamber to exit).

The blocks are set for a 45 degree injection angle off tangent from a radius to the injection location. A separate set of blocks would be required for evaluating a different injection angle. Fuel and sludge surrogate were injected into the combustion zone from the top plate. In the companion paper (22) the fuel and sludge are injected circumferentially through the swirl injection wall.

Since the most difficult case for the sludge is no heating value, i.e. totally water, that is what was used as a surrogate sludge for the preliminary tests. Subsequent tests will first introduce combustible content to the water, by adding diesel or alcohol, and then introduce solids into the water as well. For the preliminary tests the fuel used was gaseous ethylene and the water injected via fogger nozzles similar to those used in desert locations for outdoor evaporative cooling.

Figure 3 shows a schematic diagram of the actively controlled afterburner (16-21). Briefly it consists of an acoustically forced central air jet of diameter 45.7 mm opening into a dump of diameter 210 mm and length 0.61 m. The pyrolysis gases from the VCC are introduced into the afterburner (AB) circumferentially around the central air jet via 16 equally spaced ejectors. Each ejector exit diameter was 9.5 mm diameter and the ejector nozzle a 6.35 mm OD tubing squashed into an elliptic jet (for enhanced ejector performance, ref. 23). Less than 10% of the total AB air was introduced via the ejectors. The AB central air jet average velocity was 20.8 m/s and this was acoustically modulated to create coherent span-wise vortices. The frequency of operation was in the 230 Hz range for a Strouhal number around 0.48.

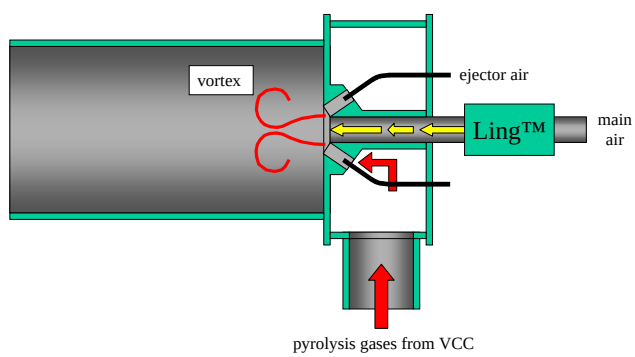


Fig. 3 Schematic diagram (not to scale) of actively controlled afterburner. The Ling™ is an acoustic driver that modulates the air velocity thereby actively creating a periodic coherent vortex in which the afterburner combustion occurs.

Emissions from the system were monitored with a water cooled rake probe and a Cosa™ 6000 stack gas analyzer (16-21).

RESULTS AND DISCUSSION

Effect of Swirl on the Afterburner

The output of the VCC is expected to have considerable residual swirl so the first aspect of the combined system tested was the effect of swirl on the actively controlled afterburner performance. Figure 4 shows that while swirl alone enhances mixing and reduces emissions (tracked here as CO), the active controller was not adversely affected by the swirl and was able to reduce emissions below that obtained with high swirl alone.

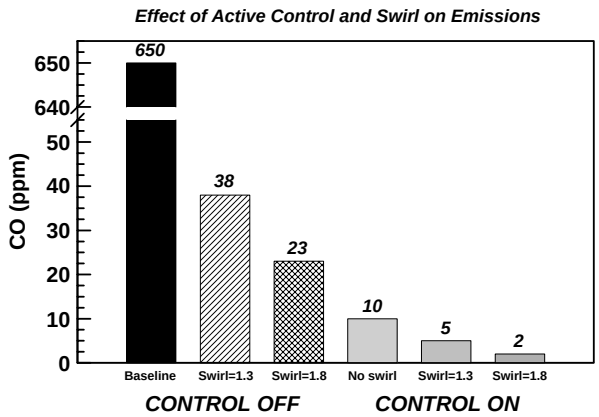


Fig. 4 The effect of swirl on the emissions from the actively controlled afterburner. The values listed for swirl are the ratio of the calculated swirl tangential velocity at the exit of the pyrolysis gas plenum to the main AB dump, to the main AB air jet average velocity.

However, it was found that the swirl created self excited acoustics in the AB and that could adversely affect closed loop active feedback control as the system will oscillate at it's own desired frequency and not allow external changes to a more optimum frequency. Figure 5 shows the frequency effects seen in these tests. As the swirl was increased the self oscillation intensity increased and the resonant frequency and mode changed. This might adversely affect an external controller ability to drive the system. However, the results of Figs. 4 and 5 were obtained from a prior AB design that did not have ejectors as shown in Fig. 3. Instead the pyrolysis gas plenum just exited into the AB vortex region via an annular slot. The flow straightening nature of the ejector ports of the current design are expected to significantly reduce the effect of swirl entering via the VCC output. Indeed, in combined VCC / AB tests described below, there was no effect of swirl in the AB and no self excitation of the AB.

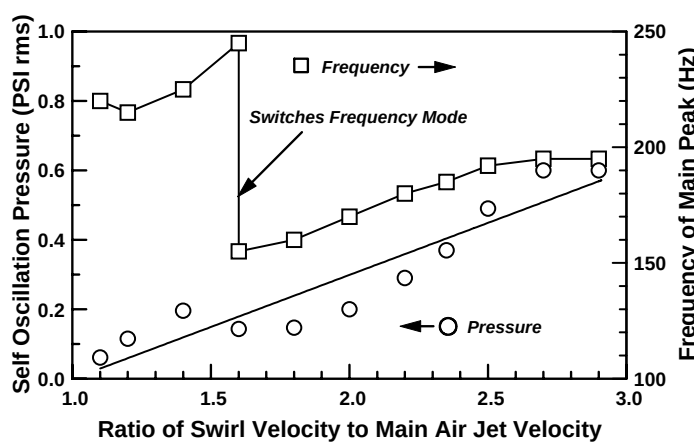


Fig. 5 Effect of swirl on active control of afterburner.

Fuel Rich Operation of the VCC

The original EERC work was done fuel lean in the VCC. If we decide to adapt the VCC to our previously designed AB then the VCC would, of course, have to be run significantly fuel rich to provide for combustibles in the AB. Since the air flow of the VCC defines the swirl and particulate suspension, we kept that constant and increased the fuel flow rate to up the stoichiometry. We were able to operate the scale VCC successfully over a stoichiometry range of 0.8 to 2.5. Figure 6 shows that as the stoichiometry is increased the flame moves from tighter radii towards the swirl injection wall at larger radii. At the highest stoichiometry the VCC emitted large quantities of soot. In subsequent tests with the AB adapted to the VCC no visible soot was emitted; it is all consumed in the AB.

VCC Particle Trapping for Large Particles

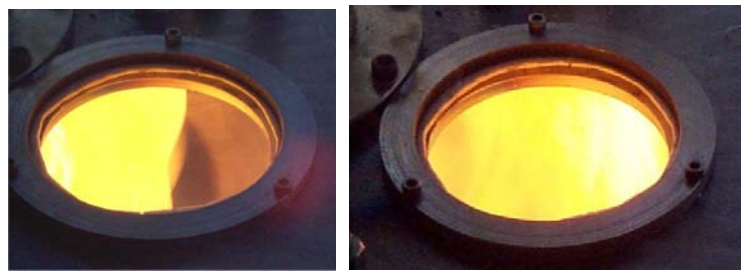


Fig. 6 View into the combustion zone of VCC through quartz window. The left image was taken for a stoichiometry of 0.8 (i.e. fuel lean) while the right is for 2.5 (fuel rich). The left side of each image is towards the centerline of the VCC.

The original EERC VCC was designed to burn finely pulverized coal, but we do not anticipate being able to atomize the sludge to small particles, so it was necessary to evaluate the performance of the VCC for larger particles. Particles of various size and density were tested in the experimental VCC under cold flow conditions. The particles used were those that were readily available and included non-fat dry milk at a density of about 1.4 gm/cm^3 as well as baking soda at 2.2 gm/cm^3, sand at 2.65 gm/cm^3 and talc at 2.75 gm/cm^3. Obviously in real sludge tests the particles would have significant organic content and densities that were near water or lower, but we wished to use particles that would not evaporate and were dry. Since real sludge would also contain some high density particles (dirt) the tests with sand (a relatively coarse particle) and talc (fine particles) were relevant. The particles were sieved to the desired size. The particles were injected from a transient fluidized bed. A burst diaphragm of aluminum foil was placed upstream of the particle injection tube. This tube entered what would be the combustion zone of the VCC (these tests were cold flow) and turned 90 degrees so that the particles were ejected with a velocity in the plane of the VCC. We investigated the direction of particle injection, but the best seemed to be along the swirl flow direction (i.e. along a tangent). Particles were followed using a diode laser (670 nm) and collection of right angle Mie scattering using a filtered photo-diode. This system monitored the particles through the quartz windows. It was mounted on a stepper motor slide stage to map out radial profiles. The window allowed reaching all the way to the wall by slightly canting the angle of the optical system.

It was found that larger particles fell to the floor of the VCC and formed dunes. It was thought that these would burn slowly in the boundary layer. It was calculated (via particle settling velocities) that dry milk particles bigger than 50 μm would not even make a single turn around the VCC before hitting the floor. Particles larger than 200 μm would not even complete 25 degrees before hitting the floor. Therefore the internal height of the swirl zone was reduced to 48 mm by adding a bottom plate that was 25 mm thick. This increased the swirl level by reducing the cross-sectional area for swirl flow. The area was reduced by about 35%. Ramps were machined into the bottom plate that intercepted each of the swirl air introduction slots (Fig. 7). A portion of the incoming swirl air was in this way deflected in the up direction giving an upward velocity vector to the air flow to counter the settling velocity of the particles. This modification was found to greatly reduce the accumulation of particles on the floor and enhance dispersion within the combustion region. The dunes no longer formed as particles that did manage to make it to the floor were re-injected into the flow when they fell off the

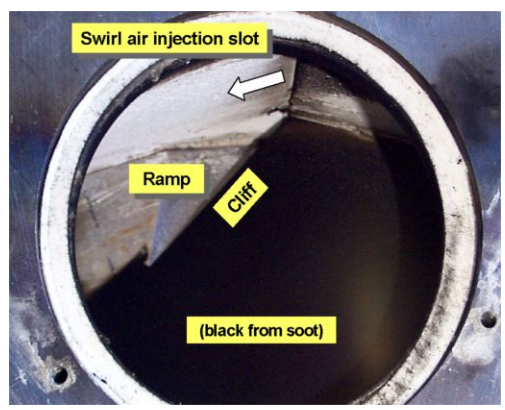


Fig. 7. Looking into the combustion zone of the VCC through the window port at the base plate with swirl flow deflection ramp. The white arrow shows where the swirl air flow exits the slot in the outer wall.

'cliffs' shown in Fig. 7 into the upward directed portion of the swirl flow. All subsequent results presented here are for this configuration.

With the problem of particle settling solved we continued to quantify particle retention times and suspension locations. Figure 8 shows the particle radial distribution and retention time, within the combustion region, for particles of density 1.4 gm/cm^3 and diameter of about 60 μm or below. Note that the particles group near the outsize diameter of the combustion zone and that the retention time is quite long. These particles would be trapped in the combustion zone for a very long time insuring good burnout.

Figure 9 shows particle retention times for various density and sized particles. As expected larger particles are trapped for longer times (the concentration decays slower). This can be seen in Fig. 9 by comparing the triangles (150 μm) with the circles (60 μm) for baking soda (2.2 gm/cm^3. Also, denser particles are trapped longer than lighter ones as can be seen from comparing the circles (2.2 gm/cm^3) with the diamonds (same size, 1.4 gm/cm^3). The squares are for talc which although sieved to 60 μm is actually considerably smaller, and therefore has a shorter retention time. Microscopic analysis of these particles showed an average diameter of 13 μm and a d_{43} of about 43 μm. Even these small particles had a 1/e retention time of about 20 seconds in the scale VCC. Unfortunately we did not have access to sieves or low density particles considerably smaller than 60 μm.

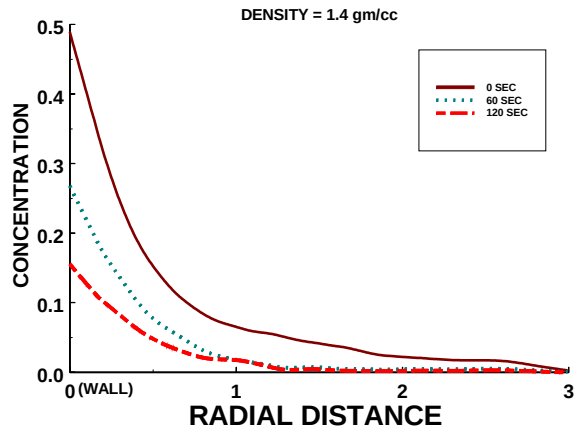


Fig. 8 Radial distribution of particles, measured via laser light scattering, as a function of time after injection. The top curve is a time 0, the second down at 1 minute, and the third at 2 minutes. The horizontal axis is inches. The dry milk particles were sieved to around 60 μm or below.

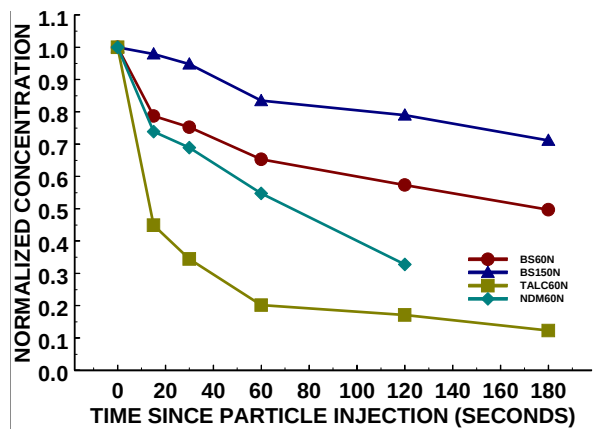


Fig. 9 Particle retention time plots for various particles measured 6 mm from the wall. Triangles are for 150 μm particles of density 2.2 gm/cm^3, circles for 60 μm particles of 2.2 gm/cm^3, squares for <<60 μm particles of 2.75 gm/cm^3, and diamonds for 60 μm particles of 1.4 gm/cm^3.

Integration of VCC and AB

Since we were convinced by the particulate tests that the VCC particle suspension and trapping was adequate, we adapted the output of the VCC to the input of a properly scaled version of our actively controlled afterburner (AB). We wished to evaluate the performance of the VCC alone, operated fuel lean, and the VCC + AB. We suspected that while the VCC alone suspends particulate matter for long burn out times the gas mixing might not be ideal leading to emissions. In combined tests the VCC was operated fuel rich ($\Phi = 2.5$) so that there would be combustibles left for proper operation of the AB. The AB has no auxiliary fuel input; it works solely off the residual combustibles from the VCC. Table I shows the operating parameters, and performance, of the VCC alone versus the VCC +

AB. These tests were without sludge or any sludge surrogate, like water. We wished to evaluate the baseline capabilities of the system alone. Clearly, if the no-sludge operation has higher than allowable emissions, adding sludge will not improve the performance.

Table I Performance of VCC alone compared with VCC + AB with and without active control. The fuel is ethylene and the units are liters per minute.

	VCC Air	Fuel	AB Air	VCC kW	AB kW	CO ppm
VCC only at $\Phi = 0.7$	800 l/m	39 l/m	-	39	-	481
VCC at $\Phi = 2.5$ + AB No Control	800 l/m	140 l/m	1940 l/m	55	82	870
VCC at $\Phi = 2.5$ + AB With Control	800 l/m	140 l/m	1940 l/m	55	82	47

It is clear from Table I that the AB substantially improves the performance of the system over the VCC alone: the CO was reduced by a factor of ten. This was despite the heavy soot load from the VCC when operated fuel rich: there were no visible soot emissions from the AB. So the VCC / active AB combination is a good one: the VCC suspends particulate matter and insures its gasification while the AB completes the combustion of the resulting pyrolysis gases and fine particulate (soot) in a high mixing rate high combustion intensity environment for low emissions. This improvement is obtained, of course, at the expense of quite a bit of extra fuel.

Performance with Surrogate 'Sludge'

As mentioned in the experimental section, we decided to start with simple sludge 'surrogates' to evaluate the system performance with sludge of nearly zero heating value. So we used either pure water or water with 5% by volume of ethanol. Ethanol was chosen to include some form of combustible material in the 'surrogate sludge' while not requiring constant stirring of non-miscible components. The ethanol was added to the water to evaluate destruction of organics introduced via the sludge input. We wanted to make sure that there was no cold escape path from sludge input to system output. The 'surrogate sludge' tests were done only on the combined VCC / AB system so the destruction location, VCC or AB, for the organics added via the sludge input is unknown. As mentioned in the experimental section the 'surrogate sludge' was introduced via swirl based fogger nozzles. These probably produce very fine droplets which enhances evaporation within the VCC. Real sludge would not pass through these nozzles. Sludge nozzle technology evaluations are discussed in the companion paper (22).

The combined VCC / active AB was operated with a 'surrogate sludge' rate of 0.35 liter/min introduced into the VCC. The VCC and AB flames were still stable at this flow rate. Higher flow rates have not yet been investigated. Figure 10 shows the performance of the combined VCC / active AB as a function of the forcing frequency for the AB main air flow with and without water flow (at 0.35 liter/min). This normally optimizes at a given frequency that is equal or near to the preferred mode of the AB air jet. The system optimizes at approximately 230 Hz which is a Strouhal number of 0.48. Also indicated in Fig. 10 is the performance level of the VCC alone, operated fuel lean. It can be seen from Fig. 10 that the performance of the system is slightly worse with the 0.35 liter/min water flow present: the minimum CO without water flow is 47 ppm and with water it is 69 ppm. Understandably, the NOx is much lower with water injection, 7 ppm vs. 40 ppm, as the water drops the gas temperature: the measured pyrolysis gas temperature input to the AB was 555 °C without water and 422 °C with.

However, another disturbing effect comes from water injection: the optimal frequency of the AB control forcing is changed. We do not know why this occurs. It is possible that with high water content the AB flame is further downstream; indeed it looked to be. The combustion would then be occurring in a region where the vortex had grown bigger. Forcing at a higher frequency would make slightly smaller starting vortices and possibly recover the same size vortex at the further downstream location of the combustion with water vs. without. Nevertheless, the important aspect is that the frequency dependence on feed conditions might necessitate the use of a adaptive controller.

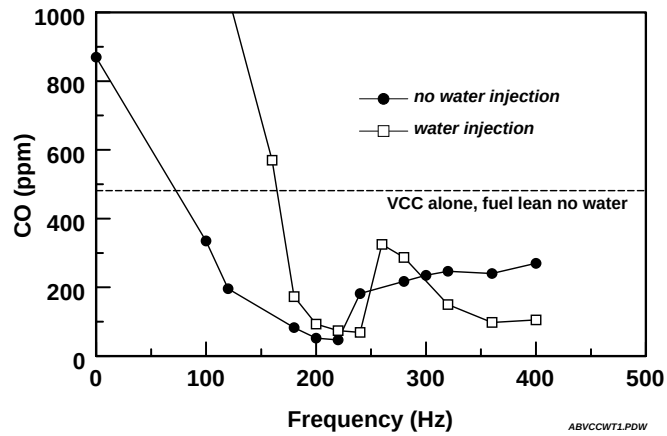


Fig. 10 Performance of the VCC / active AB combination with and without 'surrogate sludge', i.e. water, injection. The water flow rate was 0.35 liter/min. The abscissa is the frequency of operation of the active controller, i.e. the frequency of vortex shedding driven in the AB main air flow.

Figure 11 also shows controller operational differences caused by 'surrogate sludge' injection: the intensity of forcing required for a given performance level was increased. The high water content combustion in the AB apparently requires even stronger more coherent vortices to give the same mixing and low emissions as when water is present at lower levels. We do not think that the temperature of the AB input gases is the controlling parameter: prior work has shown good performance of the actively controlled AB even with room temperature gas input.

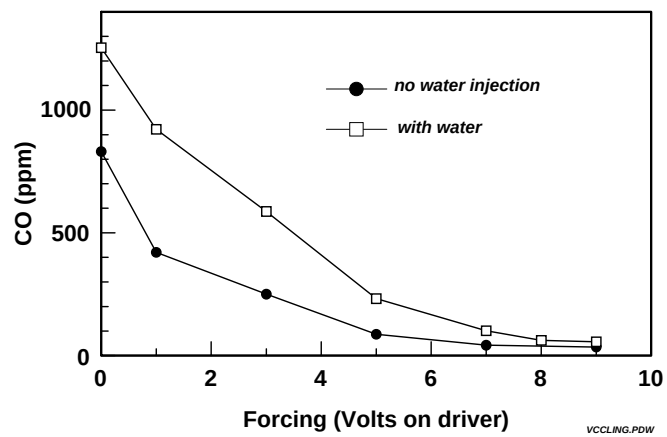


Fig. 11 Performance of the combined VCC / AB with and without 'surrogate sludge' injection as a function of active control intensity (the RMS volts to the acoustic driver).

Figure 12 shows that the optimum overall system stoichiometry was not strongly affected by 'surrogate sludge' injection. The water flow rate of 0.35 liter/min is the maximum studied to date but it is only about one half of the design point (22) which is set for a VCC gas temperature of at least 1000 °C. Work in the immediate future will be to evaluate performance at elevated 'surrogate sludge' flows.

Finally, to judge the fate of organics in the 'surrogate sludge', ethanol was added to the water (at 5% by volume). Figure 13 shows how this affected the performance of the VCC / AB combination. There were no substantial changes. The differences in CO level at the optimum control conditions was within the resolution of the monitoring instrument (1 ppm). If we assume the variability of the monitoring instrument was 5 ppm, and we assume that unburned ethanol is converted all to CO, then the minimum combustion efficiency of the ethanol in the water was 99.90% (our monitor saw no differences in unburned hydrocarbons but its resolution is only 0.01%). The system was re-optimized for stoichiometry, but the best conditions with ethanol injection (vs. pure water) turned

out to be the same ethylene fuel flow and a somewhat lower overall fuel to air ratio (due to the ethanol). The NOx went up: with pure water it was 7 ppm and with the 5% ethanol test it was 20 ppm. The increase was no doubt due to the slight increase in stoichiometry.

Finally, Fig. 14 compares the present VCC system with a fielded Navy black water incinerator being used in a sludge incineration application. The figure clearly shows that the current Navy incinerator cannot be extended to sludges with much VOC content or emissions skyrocket. The present VCC based system, however, easily handles high VOC sludges with low emissions.

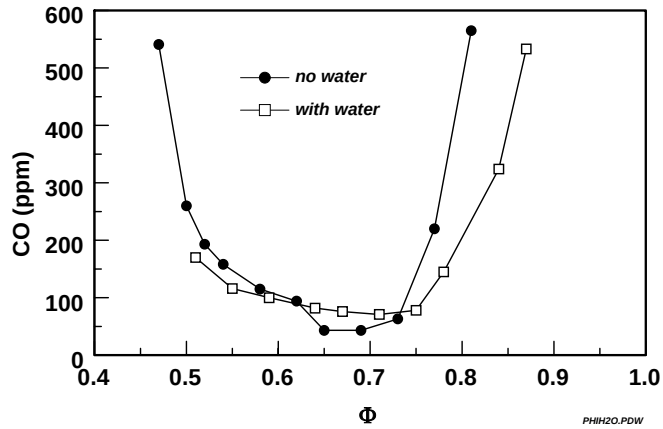
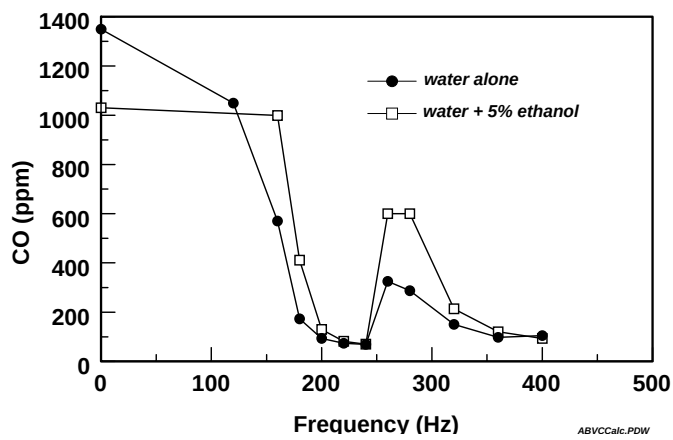


Fig. 12 Effect of water addition to the VCC / AB system stoichiometric optimization. Φ is the overall fuel to air stoichiometry of the combined system.



SUMMARY

A sludge incineration technology has been assembled from a Vortex Confinement Combustor (VCC) based primary unit coupled to an actively controlled annular dump combustor afterburner (AB). The overall power scale of the combined system is 0.15 MJoule/sec and has a target sludge processing rate of 0.75 liter/min. Tests were undertaken to evaluate the particulate suspension qualities of the VCC and the overall performance of the combined VCC / active control AB processing intermediately levels of a surrogate 'sludge'.

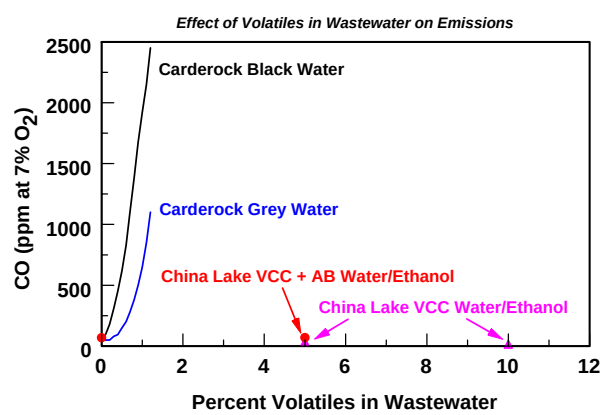


Fig. 14 Current results compared to fielded Navy incinerator operating on sludges with varying VOC content.

The VCC operates like a combusting cyclone separator. Air is introduced circumferentially to create swirl in the combustion zone. This swirl suspends and traps particulate matter until it combusts or pyrolyzes to a size small enough to escape. Particle suspension was enhanced with flow directors that created a net upward velocity component near the floor of the VCC to prevent formation of dunes in the boundary layer. Particles were found to have very long residence times in the combustion zone of the VCC: even 43 μm particles had a 1/e lifetime of over 20 seconds. The VCC was operated successfully both fuel lean and fuel rich. The VCC flame

was found to be stable at a 'surrogate sludge' (water) flow rate of 0.35 liter/min. Tests at higher flow rates are pending.

In addition, mixing has been enhanced in a dump combustor configuration afterburner using active combustion control. The technology is based on injection of waste gases circumferentially into the shear layer of a central air jet from which sheds an acoustically controlled coherent spanwise vortex. The waste is rapidly entrained into the air vortex and the good large and fine scale mixing allows compact high efficiency combustion with high destruction and removal efficiency (DRE) and low emissions.

The performance of the combined system was evaluated with and without 'surrogate sludge'. It was found that the actively controlled AB efficiently combusts all of the pyrolysis gases and soot coming from the VCC: there was no visible soot emission and the CO levels were below 50 ppm without sludge and below 70 ppm with a flow rate of 0.35 liter/min. In addition it was seen that the combined system efficiently destroys organics introduced into the 'surrogate sludge': the CO levels were virtually unchanged when 5% ethanol was added to the water 'surrogate sludge'. This implies greater than 99.9% destruction of the organic content in this yet to be optimized system.

Future work will be addressed at 1) increasing the 'sludge' flow rate to the design point, 2) introducing diesel oil into the sludge component, 3) firing the VCC on diesel oil, and 4) including some solids in the sludge.

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APPENDIX 3

ACTIVELY CONTROLLED VORTEX DISPOSAL SYSTEM FOR SLUDGE WASTES

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ACTIVELY CONTROLLED VORTEX DISPOSAL SYSTEM FOR SLUDGE WASTES

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ABSTRACT

The development of an advanced sludge treatment concept is underway for applications to sludge wastes. The concept integrates primary treatment of sludge in an advanced vortex containment combustor (VCC) with subsequent post treatment in an actively controlled acoustic afterburner. Past efforts have advanced the application of the acoustic afterburner while current activities are focused on development of the VCC. The VCC resembles a cyclone particle separator that is specifically engineered to generate a suspended, spinning combustion zone. In the VCC, combustion air is introduced through a number of tangentially directed slots into a conical shaped combustor. The design establishes an aerodynamic separator that effectively traps particles and fly ash in the chamber via centrifugal forces. The tangential co-injection of fuel and sludge into the large radius, narrow width region of the combustor generates a suspended cloud of fuel and sludge particles. The particles remain in a tight spinning reaction zone just above the air injection vanes where they burn in a suspended phase away from the walls. Fine ash particles are then selectively separated from the combustion region and move to the ash removal cone. The ash eventually migrates to the bottom of the chamber where it is removed.

Design features of the VCC combine compactness with long particle retention times that allows for complete burnout, very low particle emissions and good turndown ratio. The VCC has demonstrated over 99.9% combustion efficiency and better than 90% ash retention with pulverized bituminous coal.

The development work currently underway is intended to transition the VCC from coal combustion application to the thermal treatment of sludge wastes. Under this program, a team comprising GE Energy and Environmental Research Corporation and the U.S. Naval Air Warfare Center, Weapons Division are developing specifications for various critical elements of the VCC. The team is developing these specifications by integrating small-scale tests, isothermal modeling, engineering assessments and full-scale combustion tests. The critical elements to be

demonstrated include transition from coal and gaseous fuels to diesel oil, integrating mechanical sludge injection, establishing a suspended combustion region, demonstrating effective particle burn out and ash trapping and optimizing combustion stability. The results of these efforts are presented. Ultimately two modes of operation will be evaluated. Initially a conventional fuel-lean combustion mode will be assessed. Finally the transition to a fuel-rich pyrolysis mode will be investigated to allow integration with a compact actively controlled afterburner. This effort is part of a multi-year program sponsored by U.S. Navy Strategic Environmental Research and Development Program.

INTRODUCTION

Advanced combustion techniques for shipboard waste processing are being developed by the U.S. Navy to replace existing treatment systems. These advanced systems must handle an increasing variety and throughput of wastes and be of essentially the same size as existing onboard units. Currently only blackwater waste is treated onboard, however, in order for the Navy to comply with International Maritime Organization standards, future waste streams will include gray water and oily bilge water sludges. Sludge processing rates are expected to double although the sludge streams will still comprise mostly water. After pretreatment, the solid content is expected to double to 4 percent while the oil content may reach maximum levels of 20 percent.

In addition to shipboard applications, this technology has applications to a wide variety of oily sludge wastes generated in the military by activities such as vehicle and aircraft wash down. These oily wastes can contain significant levels of water and particulate matter including toxic metals and must be treated in an environmentally acceptable manner. Energy and Environmental Research Corporation (EER), a wholly owned subsidiary of General Electric Company, is working with the Naval Air Warfare Center, Weapons Division in the development of a compact thermal treatment system for these sludge wastes. Past efforts (1,2,3) have focused on the development of an acoustic afterburner component of the active combustion control system. This afterburner technology demonstrated robust operation and low emissions in a compact device. The current effort, which is the subject of this paper, involves development of a compact primary thermal treatment technology. The approach involves converting a high firing density coal combustor to fuel oil operation and integrating liquid sludge injection for thermal treatment. To date the project has been successful in converting the combustor to fuel oil operation and is developing design and operating specifications for demonstrating thermal treatment of sludge wastes.

BACKGROUND

In the early 1980's, EER began development of a coal combustor technology retrofit for oil-fired boilers. The purpose was to enable coal combustion in boilers that were not designed to handle high ash loading. The approach required effective ash retention in the combustor that was achieved by cyclone separation. The combustor, called the Vortex Containment Combustor (VCC), traps and suspends solids in a fire ring and produces a largely ash-free combustion gas (4).

The VCC concept, illustrated in Figure 1, involves a ring-shaped combustion chamber coupled to a classic cyclone-type device. Air is introduced into the combustion chamber through a number of tangentially directed slots. The large diameter, narrow raceway combustion chamber establishes a high performance aerodynamic separator that effectively traps droplets and fly ash in the combustor via centrifugal forces. Co-injection of fuel into the "raceway" generates a suspended reaction zone. Sludge and fuel particles retained in the reaction zone evaporate and burn leaving fine ash particles. As the particle size decreases, aerodynamic drag forces overcome centrifugal forces and carry the particles down into the cyclone section of the combustor. The high rotational velocity in the cyclone section increases the centrifugal separation forces driving fine ash particles to the walls. Along the walls, the particulate enters the aerodynamic boundary layer were they are retained and collected for later removal from the system. Particles that escape the boundary layer are convected downward with the swirling gases. Eventually the swirling gases reverse direction and exit upward along the combustor's axis. At the point of reversal, an aerodynamic stagnation zone occurs and nearly all of the remaining particles fall away from the moving gases by gravitational force.

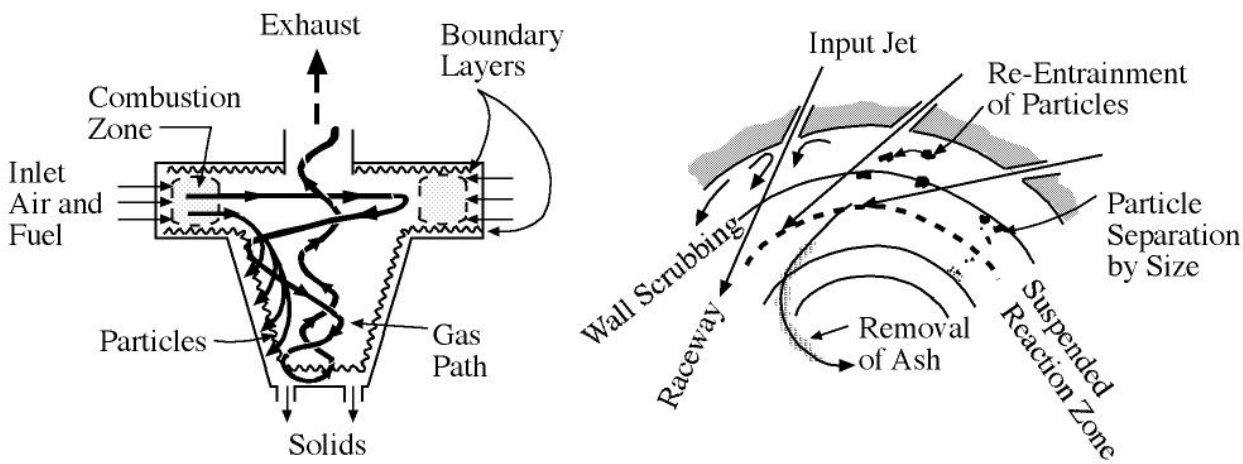


Fig. 1. Conceptual operation of the vortex containment combustor showing the top view of the suspended reaction zone (right) and the side view of the overall gas and particle paths (left).

Nearly all the waste thermal treatment systems for processing solids or sludges operate with two process stages: the first being nominally fuel-rich and the second fuel-lean. The reason for this is simple. Fuel-rich waste thermal treatment requires less air, and hence is more quiescent. This enables most of the solid residue to be retained in the primary chamber for eventual recovery, treatment, and disposal, while only the gaseous effluent is further oxidized in the secondary chamber. The VCC concept is uniquely different in this regard. By design it has a very turbulent primary chamber, but achieves particulate retention through aerodynamic means. The ability of the VCC to retain particulate has been demonstrated in coal combustion systems by a number of investigators, including research teams from EER, as well as TRW and Babcock and Wilcox.

Design features of the VCC include compactness, high temperature, long solids retention times, very low particulate emissions and good turndown capability.

To adapt the VCC to sludge treatment involves operating on liquid fuels and integrating liquid waste injection and suspension techniques. Currently specifications have been developed for stable combustion with fuel oils and specifications are being assessed for injection and suspension of sludge wastes.

FACILITIES

The development of the VCC for sludge waste applications was conducted on three test facilities; a sub-scale combustor, a full-scale isothermal model and a full-scale 500 kW combustor. This paper focuses on the full-scale development efforts. Sub-scale efforts are presented separately (5).

Concurrent efforts were conducted on two full-scale facilities. A full-scale isothermal model was used to guide specification of the sludge injection systems. This unit was used to evaluate various injector characteristics including spray angle, injection angle, spray momentum, and droplet size. The isothermal model comprises a plexi-glass replica of the internal dimensions of the full-scale combustor that is shown in Figure 2. The full-scale combustor incorporates castable refractory insulation and a number of ports to allow for flame safety systems, diagnostic probes and various fuel and sludge injection locations and angles.

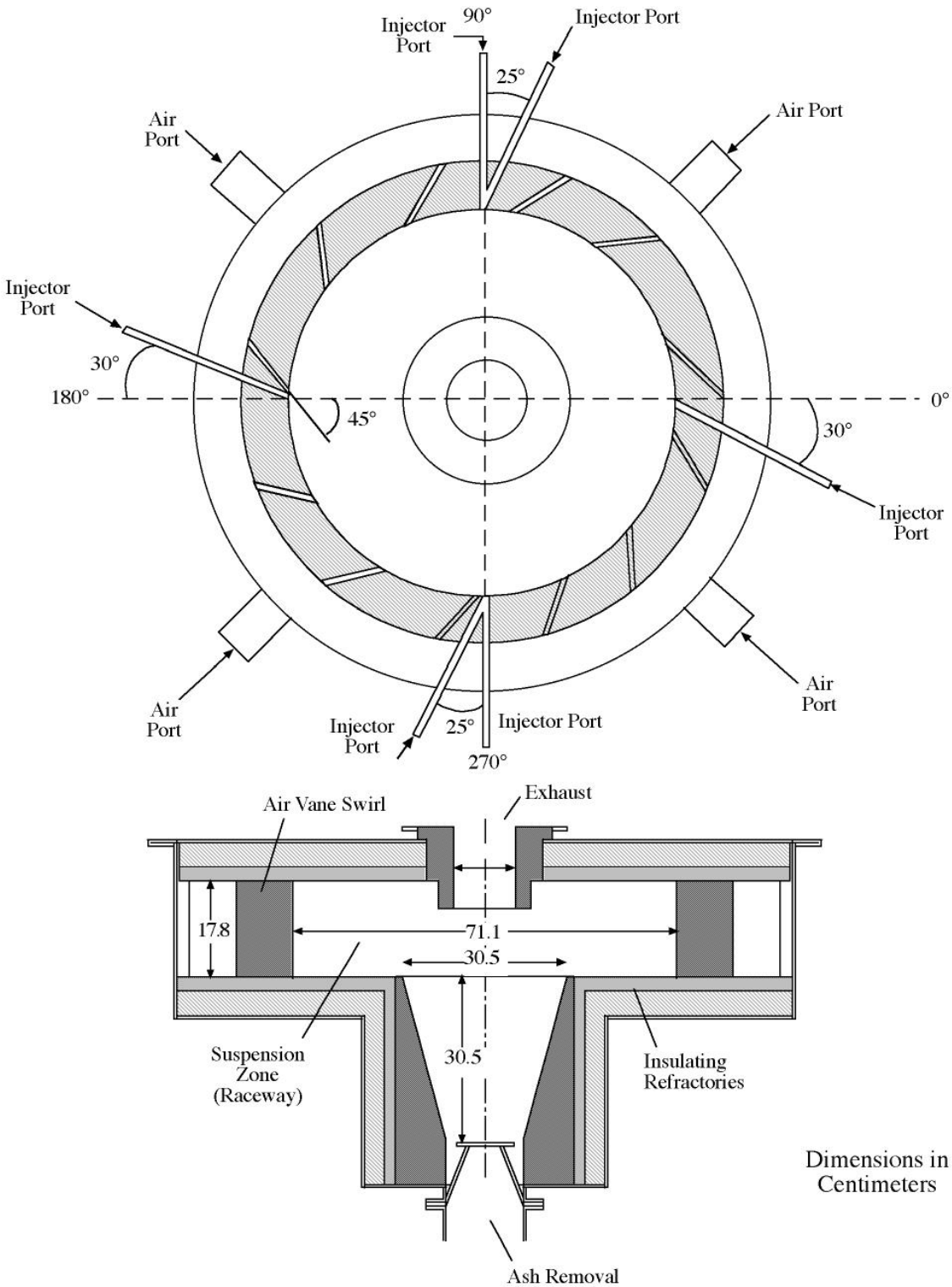


Fig. 2. Details of the full-scale VCC dimensions and internal layout. The tope view illustrates the injector and air port locations (above). The insulation and internal dimensions are shown in the side view (below).

The combustor was operated with approximately 14 cubic meters per minute of air supplied by four radial ports on the outer plenum. The air was then directed into the suspension zone through 12 circumferential air vanes, orientated 45° from radial. The fuel, comprising either natural gas or fuel oil, was injected from discrete radial locations into the combustion raceway. The injection of fuel was angled more radial than the air to ensure the fuel was not driven to the walls. The fuel and air mix and react in the raceway prior to the gas products spiraling into the lower cone region. The gas products then reverse direction and exit upward through the combustor exhaust. The swirl strength in the upward flow is largely governed by the exhaust diameter. Except for boundary-layer friction losses, the rotational energy of the flow in the large diameter raceway is conserved by the flow through the small diameter exhaust. Therefore the angular velocity of the upward exhaust flow is very high and entrained particles are rejected to the walls. The separated ash and particles are then collected in the lower cone region and removed from the combustor.

The full-scale combustor was equipped with fuel, sludge and air feed control and monitoring systems. The operating differential pressure of the VCC was measured between the air inlet and the exhaust duct. Additionally the air vane pressure drop was measured between the air inlet and the VCC chamber. A K-type thermocouple was recessed 10 mm from the surface of the upper refractory wall to provide relative chamber temperatures. An extractive gas-sampling probe was located in the exhaust. The gas sample was delivered to a water knockout and then a continuous emission monitoring system for measurement of oxygen (O_2), carbon dioxide, carbon monoxide (CO) and nitric oxide (NO) concentrations.

The two full-scale VCC test facilities were used to develop specifications for flame stabilization, sludge injection and particle trapping. The efforts conducted to date have focused on switching to fuel oil firing and demonstrating stable combustion with target levels of water injection. Water was selected as an extreme low-heat value surrogate sludge. Also injection specifications for suspending the sludge droplets and trapping particles have been developed.

STATUS AND RESULTS

The target capacity for sludge injection is 3.2 liter per minute (lpm) comprising as much a 98 percent water. The range of sludge compositions that will finally be demonstrated includes up to 4 percent solids and 20 percent oil. Initial development has focused on demonstrating operation with water to evaluate impact on combustion stability.

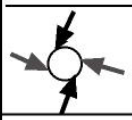
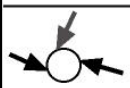
As a course of action, first the VCC combustor was operated on natural gas to confirm target aerodynamic and thermodynamic performance. The target operating conditions produced approximately 3 kPa pressure drop on isothermal model, however, the increased boundary layer friction from rough walls on the full-scale combustor reduced the pressure drop to 1.7 kPa under ambient operation. When operated at high temperature, the increased volumetric flow rate effectively doubled this pressure drop. The increased pressure drop results from increased kinetic energy rather than rotational energy and the net effect of hot operation is, as expected, a decrease in vortical strength (4). Despite the decreased vortical strength of high temperature operation, the

particle trapping performance of the system remains high even for moderately low-pressure drops.

Various natural gas injector configurations were investigated generally relying on a dual point introduction of fuel injecting 30° from radial. Operation with natural gas produced stable combustion and good burnout. CO emissions were below 35 ppm (corrected to 7% O_2). Firing of fuel oil was accomplished with both pressure nozzle and air atomized nozzle injectors. Fuel oil was injected into the suspension region at 25° to 30° from radial. The combustion of fuel oil was likewise stable with low CO emissions. The only noticeable difference in the two flames was the strong radiance of the fuel oil flame that more clearly showed the suspended combustion behavior. Under both natural gas and fuel oil operation the interior surface temperatures were approximately 600°C and pressure drop was 3.5 kPa (14 inches of water column).

In the absence of sludge injection, achieving stable combustion was never much in doubt. However, justifying our concerns on integrating sludge injection, combustion was seen to destabilize with water injection and flame out occurred at flow rates of 1.3 to 1.6 lpm. The suspended combustion approach essentially relies on hot gas entrainment for stability. So as water is injected into this region, the hot gases are quenched until they no longer can support ignition. The result is a rising instability culminating in flame out at some threshold water injection level.

To achieve the target injection rates and optimize flame stability, several injection configurations, shown in Figure 3, were investigated. Figure 3 presents the fuel and sludge injection locations around the VCC raceway and illustrates the flameout threshold water input levels. Essentially for the first round of fuel injector configurations, #1 through #4, the best success was achieved with configuration #1, a single point injection of high velocity natural gas and configuration #4, a dual-point pressure nozzle injection of fuel oil. in these cases, the natural gas jet velocity exceeded 100 m/s while the pressure nozzle injection is similarly energetic. The result is that fuel entrains surrounding gases more rapidly and reduces the quenching effect thus extending the stability limit of the flame. However, the ultimate outcome was only a moderate increase in the water injection capacity up to 1.9 lpm.

Configuration	Injection Characteristics		Water Injection, lpm					
	Location	Description	0.63	1.3	1.9	2.5	3.2	3.8
Unstabilized #1		NG, one 1/2" dia. injector Water, one injector	X	X	X	0		
#2		NG, two 3/4" dia. injector Water, one injector	X	X	0			
#3		D.O., air atomized nozzle Water, one injector	X	X	0			
#4		D.O., pressure nozzles Water, two injectors	X	X	X	0		
#5 Stabilized		NG, one 1/2" dia. injector Water, two injectors	X	X	X	X	X	X
#6		D.O., air atomized nozzle Water, two injectors	X	X	X	X	X	

X - Stable
0 - Flame Out

Water
Fuel

Fig. 3. Flame stability map as a function of water injection for various injection configurations.

To overcome the effect of water injection, better stabilization of the flame is required. A new configuration of fuel injectors was tested (#5 and #6) employing an attached-flame pilot at the exit of the fuel injector. The pilot burns approximately 5 percent of the fuel and provides a stabilized ignition source for the main fuel. Under this configuration, the system exceeded the target sludge injection rates without evidence of combustion instabilities. Once a flame stabilizer was incorporated, combustion was very stable over the entire flow range of water injection. The CO emissions at various water injection rates for fuel oil operation are presented in Figure 4. CO emissions were below 30 ppm at target injection levels. The quenching effect of water also reduced thermal NOx formation and this is illustrated in the NO emission presented in Figure 4. Furthermore the flame was seen to be stable, as characterized by CO emissions, over a wide operating equivalence ratio (Fig. 5) and firing range (Fig. 6).

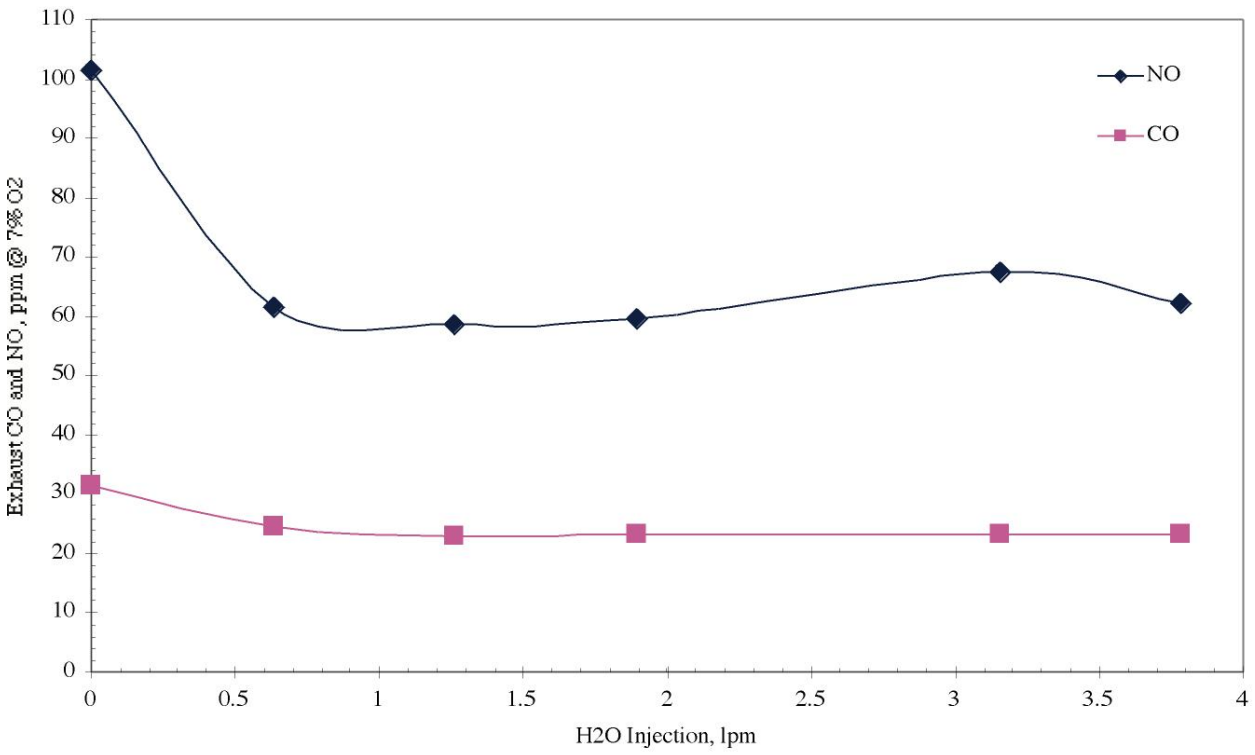


Fig. 4. Illustrations of CO and NO exhaust emissions for the VCC operating at 500 kW.

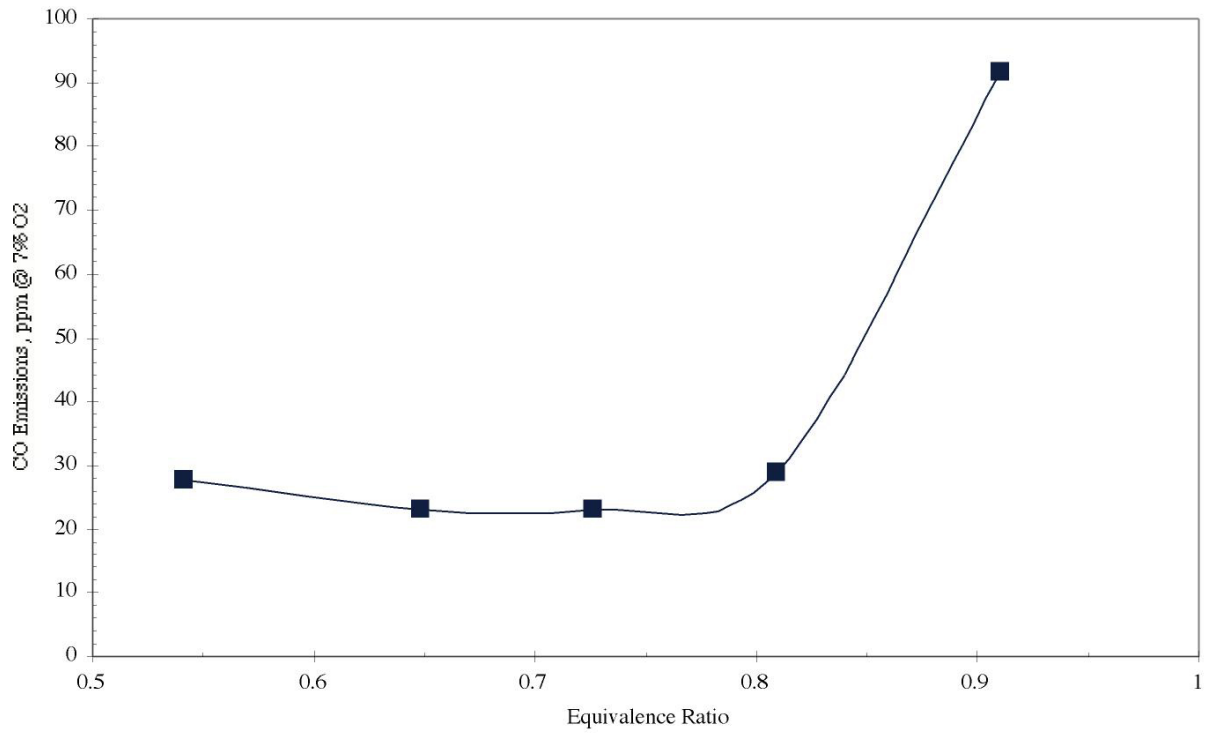


Fig. 5. Illustration of VCC exhaust CO emissions at various equivalence ratios. The VCC was fired at 500 kW with 1.9 lpm of sludge water injection.

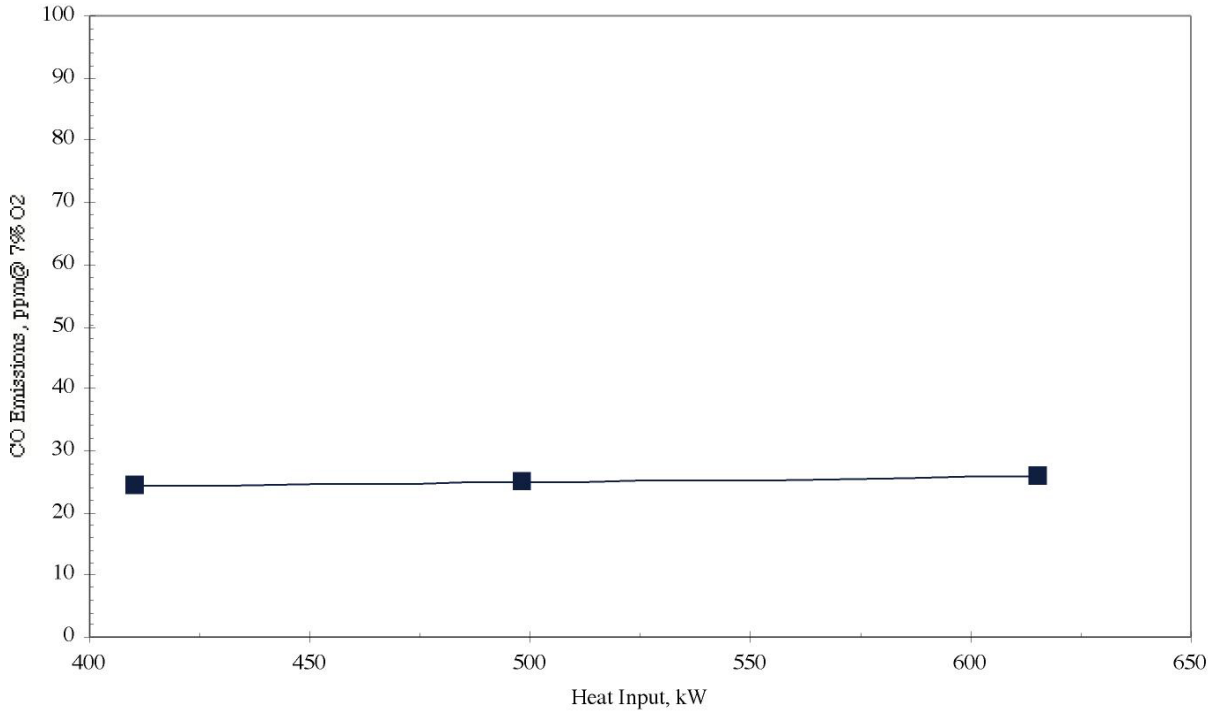


Fig. 6. Illustration of VCC CO exhaust emissions operating at various heat input. The VCC equivalence ratio was 0.69 and sludge water injection was 1.9 lpm.

The sludge injector specifications were guided by isothermal modeling studies. From these efforts the parameters recognized to be most important included spray angle, injection angle, jet momentum and atomization quality, i.e. droplet size. Other parameters that effect the injection specification included droplet evaporation rate, gas and particle residence time, particle oxidation rates and other practical consideration for injection of sludge wastes. All these parameters were evaluated to develop the injection specification listed in Table I.

TABLE I
Sludge Injector Specifications

Spray Angle	Narrow (5 to 20°)
Injection Angle	Radially (0 to 30°)
Maximum Droplet Size	300µm
Atomization Air/Water Mass Ratio	15%
Atomization Air Pressure	30 psig
Orifice Size	< 5 mm
Number of Injectors	minimum 2

Based on the isothermal model evaluation of particle retention time, the current system is capable of providing up to 2 seconds of suspended phase residence time for aerodynamically entrained particles. Large particles on the other hand are retained indefinitely in the combustor. The smallest particles remain in the active zone a minimum of 150 ms and only particulate below 3µm escape the VCC. Based on droplet evaporation modeling, small droplets injected into the suspension zone will evaporate very rapidly in less than 50 ms and allow adequate time (100ms) for burnout of remaining organic matter. The large droplets, of roughly 100µm size will evaporate in 200 ms but these droplets are suspended for up to 2 seconds which allows adequate time at temperature for oxidation.

Critical to achieving rapid evaporation and burnout is establishing a suspended phase of sludge droplets. This means that sludge must be atomized into droplets small enough to be suspended in the flow. On the other hand, atomization must avoid imparting excessive ballistic energy that can cause the droplets to impinge on the combustor walls. Because the sludge nozzles require large orifice diameters in order to pass solid particles, atomization is essential. With large orifices, 3.2 lpm of water would flow in a cohesive stream. On the isothermal model, this stream was seen to breakup in the swirling air but did not produce a suspended droplet phase and water impinged heavily on the upper and lower walls. To avoid this impingement finer droplets are required and this is achieved by atomization. A minimum atomization level was needed to generate fine droplets corresponding to an air to water mass ratio of 7 percent and an air pressure of 70 kPa (10 psig). A compromise between droplet size and jet momentum is required to avoid over driving the fluid and impinging the sludge on the far wall of the combustor. To further reduce jet momentum, a minimum of two injectors was considered. With two injectors the maximum levels of atomization that still avoided impingement was a 15 percent air to water mass ratio and 250 kPa air pressure. Under these conditions, the injectors produced a finely atomized spray of

suspended droplet with little wall impingement. The use of two injectors will also conceivably reduce temperature stratification in the suspension zone.

Two nozzle spray angles were also evaluated. A wide spray angle (60°) nozzle caused excessive upper and lower wall wetting that was expected to cause problems during hot operation. Sludge impinging on the walls will cause cold local wall temperatures that can spread due to poor gas to liquid heat transfer at the wall. This would in time lead to a failure mode. A narrow spray angle nozzle on the other hand was shown to be relatively effective in producing a suspended mist of droplets. The preferred nozzle had a 20 degree full spray angle. Additionally the injection angle for sludge was also evaluated. Like with fuel injection, the sludge injection is more radial than the air to avoid throwing the sludge against the walls. Three injection angles were considered at –25°, 0° and +25° from radial. From the isothermal model it was clear that the –25° injection which is slightly counter flow caused poorer suspension of droplets. No obvious difference was observed for the other two injection angles.

Engineering assessments of the droplet retention, evaporation and burnout times, indicated that the maximum droplet size target for the injectors was approximately 300 µm. Larger droplets could fall out of suspension and could lead to a failure mode. Smaller droplets are desirable however impinging the spray on the walls must be avoided. Work has begun on evaluating these injector specifications on the full-scale combustor but the effort has been limited to a single fuel injection configuration with two sludge injectors of the following specification: spray angle 20°, injection angle 30°. Under this configuration, complete evaporation of the water was not accomplished. Additional modifications to the VCC have been proposed and will be evaluated during the continuation of this project.

CONCLUSIONS AND FUTURE ASSESSMENT

The initial efforts of the program were successful in identify operating conditions for the VCC and converting the unit to fuel oil operation. The emission performance was very good and stable combustion was achieved with target levels of sludge injection.

Currently testing with the specified sludge injector under fuel oil operation has not optimized the integration of sludge injection. The initial tests were conducted with a single fuel injector and two sludge injectors and as such uniform thermal conditions were not produced. Operation with a single fuel injector demonstrated the “proof-of-concept” for combustion stabilization. Future plans will evaluate multi-point fuel injection, narrower sludge spray angles and different sludge injection angles. Further diagnostic efforts are planned that include detailed temperature mapping to identify potential impingement or condensate locations.

Initial performance of the combustor, showed the capacity to produce effective combustion of both natural gas and fuel oils with low levels of CO emissions. Combustion is stable and emissions were not deteriorated by water injection. In fact the lower temperature of combustion reduced thermal NOx formation and overall NO levels were 60 ppm (corrected to 7% O_2).

Ultimately, these levels of performance must be maintained when firing real sludge wastes. Based on the engineering assessment of droplet evaporation and particle conversion times and the available retention time in the high temperature oxidizing environment, excellent performance should be maintained.

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APPENDIX 4

Development of Incinerator Technologies for Shipboard and Port/Shore Operations

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Development of Incinerator Technologies for Ship-Board and Port/Shore Operations

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ABSTRACT

Technologies are being explored to improve combustion characteristics for compact solid and liquid waste incinerators. For solid waste, active combustion control was applied to achieve efficient and controlled mixing/afterburning of starved-air pyrolysis gases. The waste throughput of a commercially available marine incinerator was increased by a factor of 3.2 and the CO emission rate was decreased by a factor of 9. For liquid waste (sludge), the actively controlled afterburner was integrated with a Vortex Containment Combustor, which suspends particulate fuels in a spinning combustion zone for efficient burn-out and separates inert particles from the gas phase in the cyclone section. In laboratory tests with water, and water plus alcohol as sludge surrogates, the afterburner efficiently combusted the pyrolysis gases and soot from the VCC. The CO levels for the solid and liquid waste experiments were extremely low, as low as 7 ppm, which shows that the developed technologies have the potential to meet shore and port emission requirements.

INTRODUCTION

The Naval Air Warfare Center Weapons Division (NAWCWD) and GE Energy and Environmental Research Corporation (GE EER) have collaborated over the past 6 years to explore technologies for combustion improvements of solid and liquid waste incinerators under the Strategic Environmental Research and Develop Program (SERDP). From 1994 to 1999, active combustion control using exhaust sensors, controller, and flow / acoustic actuators in a closed loop was applied to achieve efficient and controlled mixing / afterburning of starved-air solid waste pyrolysis products in acoustically stabilized air vortices. This work, which has been discussed at prior Maritime Conferences and will be summarized in the following, has shown the potential of meeting International Maritime Organization (IMO) and port/shore emission requirements in compact designs. Presently the actively controlled afterburner is being integrated with a cyclone-type Vortex Containment Combustor (VCC) for the treatment of liquid wastes

(sludges). The status of this work will be discussed in this paper. Sub-scale tests under laboratory-type operational conditions have also shown the potential of meeting port and shore requirements.

Solid Waste

Active control was utilized to increase the waste throughput of a commercially available marine incinerator by a factor of 3.2 and to reduce the carbon monoxide (CO) emissions rate by a factor of 9 by integrating a novel actively controlled afterburner. This performance increase was achieved by using an open-loop, actively controlled afterburner design. Further performance improvements were demonstrated with a sub-scale afterburner design using closed-loop control with diode laser emission sensors and a controller. This new technology has potential application in future compact, efficient marine and shore / port based incinerators with active combustion control, continuous emission monitoring, and automated control (Ref. 1 to 3).

The afterburner (Figure 1) adds about 15% volume to the Golar 500 marine incinerator, which was manufactured by TeamTec (Norway). Normally the Golar operation is fuel-lean in a single chamber. Modifications to the Golar were made for fuel-rich operation and for its integration with the NAWCWD actively controlled afterburner. The primary afterburner air is acoustically forced at about 150 hertz (Hz) to generate coherent air vortices at the dump plane. Ejectors are used to reduce pressure drop as they entrain waste gases into the air vortices to achieve efficient burn-out. These “tapered-elliptic” ejectors, which achieve high performance through the generation of axial vortices, were driven by secondary air. This afterburner design is a simplified version of an afterburner concept with both air and indirect fuel modulation. Prior to its integration with the Golar unit, the simplified afterburner was tested at full scale with hot, sooty pyrolysis gases from a fuel-rich gas generator with 1000C output temperatures. The CO levels were as low as 15 ppm (parts per million) and NO_x was about 35 ppm for a residence time of only 62 milliseconds (ms). No visible soot emission was observed.

Subsequently, tests were undertaken at GE EER using solid waste to evaluate the performance of the simplified afterburner adapted to the Golar incinerator. The performance baseline chosen was the IMO certification test results for the Golar unit. In those tests IMO Class II waste was fed at 78 kg/hr (173 lb/hr) or 220 kW (0.67 MMBtu/hr) and auxiliary fuel fired at 500 kW (1.53 MMBtu/hr). The tests of the integrated Golar/controlled afterburner unit used a waste consisting of 70% green waste (10% moisture content) and 30% plastic (polypropylene) at 86 kg/hr (191 lb/hr) or 690 kW (2.1 MMBtu/hr). The auxiliary fuel was diesel at 15 l/hr (3.8 gal/hr) and propane at 200 SLM (Standard Liter Minute) (7 Standard Cubic Feet Minute (SCFM) for a total of 500 kW (1.53 MMBtu/hr)). The waste batches weighted 4.3 kg (9.5 lb) and were fed every 3 minutes.

The integrated system significantly reduced the CO emissions relative to the baseline when operated at the increased energy throughput, despite a significant increase in oxygen demand. The variable afterburner stoichiometry, which was due to batch

feeding at constant auxiliary and diesel fuel flows, did not cause problems for the afterburner operation. Although the waste Btu throughput was increased by a factor of 3.2 for the integrated system, CO emissions decreased by roughly an order of magnitude relative to the baseline conditions, from 256 ppm to a range of 8 to 28 ppm. There was no visible soot emission either at the stack or on an exhaust gas filter in the sampling system when the afterburner was operating. Modification of the Golar from air-rich to air-starved operation posed several operational problems. For future work a new airtight primary chamber will be required.

The afterburner performance can be further improved with real-time closed-loop control to vary the auxiliary fuel flow during batch feeding of variable Btu waste. This closed-loop control concept was demonstrated with a 50-kW actively controlled afterburner using Stanford University-developed diode laser sensors and a Pennsylvania State University-developed controller. For these closed-loop-control experiments the primary afterburner air flow was modulated at the preferred-mode jet frequency to generate coherent vortices. At this forcing frequency, vortices of the largest possible size are developed, which are associated with the shear layer width at the end of the inlet-jet potential core. The pyrolysis surrogate (N_2 and C_2H_4, or N_2, H_2, and CO) was preheated to 900 K and introduced circumferentially normal to the primary air. The pyrolysis gases were indirectly modulated by acoustically forced secondary air, which provided a gating mechanism. Without forcing (control off), the flame was yellow with high concentrations of CO (800 ppm) and NO_x (60 ppm). With forcing at the proper phase and frequency, the flame was blue with significantly reduced concentrations of CO (2 ppm) and NO_x (10 ppm). The controller's ability to modulate auxiliary fuel in response to variations in the heating value of the pyrolysis surrogate was demonstrated, such that the afterburner heat release rate was kept constant at a condition that promoted low CO emissions.

Thermal Sludge Treatment

In 1999, a program was started which addresses the thermal treatment of sludges from oil/water separators and concentrated sludges from gray (showers, sink, urinals) and black (sewage) water. These sludges contain oil, volatile organics, organic & inert particulate matter, and water with highly variable properties or heating value depending on their source of generation. The technology concept for sludge treatment combines the features of a high performance Vortex Containment Combustor (VCC) with the actively controlled afterburner.

The VCC is a demonstrated technology for combustion of pulverized coal and other fuels (Ref. 4). The VCC concept (Figure 2) involves a ring-shaped combustion chamber surrounding a classic cyclone-type device for particulate separation from the gas phase. The air is introduced through a number of tangentially directed slots to generate a spinning combustion zone. The injected fuel droplets and particles remain in this spinning reaction zone until they have burned or pyrolyzed to the point where aerodynamic drag forces can overcome centrifugal forces and carry the particles down into the cyclone section of the combustor. As the entrained particles move down into the conical cyclone region, increased rotational velocity and decreased VCC diameter results

in increased centrifugal force. Ash particles are driven to the wall boundary layer of the cyclone and slowly fall downward out of the system. Eventually the swirling gases reverse direction and exit the combustor upward along the axis. At the point of reversal an aerodynamic stagnation zone occurs and nearly all of the remaining particulate falls away from the moving gases by gravitational force. The VCC can be operated either fuel lean or fuel-rich. When operated fuel-rich, the VCC exhaust gases will be efficiently combusted in the AB, using the demonstrated active control process with efficient combustion in actively stabilized air vortices.

The extension of the VCC and AB for treating sludges poses several technical challenges. For the VCC they include (1) the demonstration of stable and efficient operation with auxiliary diesel fuel, which is required when the sludge heating value is too low, (2) injection and dispersion of semisolid waste, (3) aerodynamic suspension and retention of droplets and particulates in the spinning combustion zone, (4) flame stability and control for varying heating values and firing rates, (5) operation with high water content, and (6) efficient inorganic residue separation in the VCC cyclone section. For the AB the challenges include (1) demonstration of active control with highly spinning/swirling inlet flow, (2) efficient burnout and flame stability with highly varying fuel heat content, (3) AB integration with the VCC while maintaining low-pressure drop characteristics of the present design, (4) scaling, and (5) a simplified control strategy for the VCC/AB.

A small-scale unit (55 kW) and full-scale unit (500 kW) have been built to explore the use of the VCC for sludge treatment. In this paper, preliminary results from the small-scale unit combining the VCC with a properly scaled actively controlled afterburner will be summarized. Additional details are given in Ref. 5.

EXPERIMENTAL SET-UP

Figure 3 shows a side cross-section of the small-scale VCC Laboratory Combustor (VCC LC). The device has a cylindrical symmetry with a combustion chamber of 356 mm diameter and 74 mm height. The actively controlled afterburner is adapted to the exhaust of the VCC (Figure 4).

The power level of VCC LC is 55 kW to 170 kW depending on operating conditions. The experimental unit was designed with optical access to assess the combustion region as well as allow laser diagnostic measurements on particulates in the flow. Thermocouples or sampling probes could be introduced at various radii in the combustion zone.

The VCC LC unit was designed for an average combustion temperature of 1000C (1800F), 7 gal/hr (28 l/hr) water (simulating sludge with lowest heating value), and a water-to-auxiliary fuel ratio of 6. Target sludges are oily wastes with zero to 20% oil content and sludges with zero to 5% inert and organic solids.

The full-scale unit (500 kW) with a combustion chamber diameter of 711 mm was built for treating a total of 50 gal/hr (200 l/hr) of oily sludge and concentrated sludges from black and gray water.

RESULTS AND DISCUSSION

VCC Particle Trapping

The original GE EER VCC was designed to burn finely pulverized coal. It was therefore necessary in this program to evaluate the performance of the VCC for larger particles. Particles of various sizes and density were tested in the VCC LC under cold flow conditions. The particles used were those that were readily available and included non-fat dry milk at a density of about 1.4 gm/cm^3 as well as baking soda at 2.2 gm/cm^3, and talc at 2.75 gm/cm^3. The particles were sieved to the desired size and injected from a transient fluidized bed. Particles were followed through quartz windows using a diode laser (670 nm) and right angle Mie scattering using a filtered photo-diode. The monitoring system was mounted on a stepper motor slide stage to map out radial profiles. The window allowed reaching all the way to the wall by slightly canting the angle of the optical system.

Figure 5 shows particle retention times for various density and sized particles. As expected larger particles are trapped for longer times (the concentration decays slower). This can be seen in Fig. 5 by comparing the triangles (130 μm) with the circles (60 μm) for baking soda (2.2 gm/cm^3). Also, denser particles are trapped longer than lighter ones as can be seen from comparing the circles (2.2 gm/cm^3) with the diamonds (same size, 1.4 gm/cm^3). The squares are for talc, which, although sieved to 60 μm, is actually considerably smaller and therefore has a shorter retention time. Even these small particles had a 1/e retention time of about 20 seconds in the scale VCC.

Integration of VCC LC and AB

The VCC LC was integrated with the actively controlled afterburner (AB) to evaluate the performance of the VCC (operated fuel lean) alone and the VCC (operated fuel-rich) plus AB. These tests were done with ethylene as VCC fuel without sludge; the AB has no auxiliary fuel input. Table I shows the operating parameters, and performance.

Table I. Performance of VCC alone compared with VCC + AB with and without active control. The fuel is ethylene and the units are liters per minute.

	VCC Air	Fuel	AB Air	VCC kW	AB kW	CO ppm
VCC only at $\phi = 0.7$	800 l/m	39 l/m	-	39	-	481
VCC at $\phi = 2.5$ + AB No Control	800 l/m	140 l/m	1940 l/m	55	82	870
VCC at $\phi = 2.5$ + AB With Control	800 l/m	140 l/m	1940 l/m	55	82	47

It is clear from Table I that the AB substantially improves the performance of the system over the VCC alone: the CO was reduced by a factor of ten. This was despite the heavy soot load from the VCC when operated fuel rich. There were no visible soot emissions from the AB. The VCC/AB combination suspends particulate matter in the VCC and insures its gasification while the AB completes the combustion of the resulting pyrolysis gases and fine particulate (soot) in a high mixing rate and high combustion intensity environment for low emissions. This improvement is obtained, of course, at the expense of extra auxiliary fuel.

Performance with Water as Sludge Surrogate

The combined VCC/AB LC was operated with water as 'surrogate sludge' and compared to the performance without water. Figure 6 (left) shows the performance of the combined VCC/AB as a function of the forcing frequency for the AB primary air flow with and without water flow (at 0.35 l/min). The system optimizes at approximately 230 Hz. This frequency corresponds to the preferred jet mode Strouhal number of 0.48 (Ref. 6). The CO emission with water is slightly higher: the minimum CO without water flow is 47 ppm and with water it is 69 ppm. The NOx is much lower with water injection, 7 ppm vs. 40 ppm, as the water drops the gas temperature, with a measured pyrolysis gas temperature input to the AB was 555C without water and 422C with water. Also shown in Fig. 6 (right) is the performance level of the VCC alone, operated fuel lean. It achieves CO below 100 ppm with and without water in a narrow equivalence ratio range of about 0.7. This means that the VCC alone cannot tolerate variations of the sludge fuel content to maintain optimum conditions and has to be operated at its design point.

The tests also showed that the optimal frequency and amplitude for the AB control forcing changed with water injection (Figure 7). The important aspect of this result is that the frequency and amplitude dependence on feed conditions requires the use of an adaptive controller to adjust to the forcing to varying sludge characteristics.

In the small-scale VCC LC stable combustion was demonstrated for a maximum water-to-fuel mass ratio of 6.3 (Figure 8). At higher mass ratios water was collected at the bottom of the VCC. For the full-scale unit, stable combustion was demonstrated for 60 gal/hr (240 l/hr) water injection using water and fuel injection configuration #5 (Figure 9), however the maximum mass ratio without water drainage from the VCC was only 3.5 (Ref. 7). Performance improvements are being presently explored by increasing the number of fuel injectors.

Performance with Water and Ethanol as Sludge Surrogate

Subsequently, the system performance was evaluated with water plus 5% and 10% by volume ethanol. Ethanol was chosen to include some form of combustible material in the 'surrogate sludge' while not requiring constant stirring of non-miscible components. Specifically, the ethanol was added to the water to evaluate destruction of

volatile organics introduced via the sludge input. The 'surrogate sludge' tests were done only on the combined VCC / AB system. Therefore the destruction location, VCC or AB, for the organic is unknown. The 'surrogate sludge' was introduced via swirl based fogger nozzles with very fine droplets, which enhances evaporation within the VCC. Real sludge would not pass through these nozzles.

Figure 10 shows the performance of the VCC/AB combination as function of forcing frequency. There were no substantial CO emission changes when comparing results with water only and water plus 5% and 10% ethanol. The emission for 10% alcohol optimized at 7 ppm at about 300 Hz forcing. The NOx went up: with pure water it was 7 ppm and with the 5% ethanol test it was 20 ppm. The increase was no doubt due to the slight increase in stoichiometry.

Figure 11 shows the performance with water plus alcohol for the VCC alone. The CO emission decreased to 17 ppm with 10% alcohol in a narrow equivalence range . In these tests unburned hydrocarbon (UHC) emission was not detected at the optimum conditions (Figure 12).

The performance of the small-scale VCC and VCC/AB was compared with the performance of the current Navy Blackwater Sludge Vortex Incinerator for varying percent of volatile organics in the feed (Ref. 8). Recent tests with this T-Thermal built incinerator at Naval Surface Weapons Center Carderock Division (NSWCCD) showed a dramatic increase in CO emission, when the percentage of volatile organics in the gray and black water sludges increased to 1% and higher. This is probably due to the poor mixing characteristics of this unit. However, for the VCC tests with alcohol as volatile organics surrogate the CO emission remained very low up to 10% organics (Figure 13).

CONCLUSION

Technologies are being explored to improve combustion characteristics for compact solid and liquid waste incinerators.

For solid waste, active combustion control has been applied to achieve efficient and controlled mixing/afterburning of starved-air pyrolysis gases. This new afterburner concept was able to increase the waste throughput of a commercially available marine incinerator by a factor of 3.2 and reduce the CO emission rate by a factor of 9, from 256 ppm to a range of 8 to 28 ppm. These full-scale experiments were conducted with IMO Class 2 solid wastes.

For liquid waste (sludge), the actively controlled afterburner was integrated with a Vortex Containment Combustor, which suspends particulate fuels in a spinning combustion zone for efficient burn-out and separates inert particles from the gas phase in the cyclone section. The performance of the combined system was evaluated with and without surrogate sludge (water and water plus alcohol). The afterburner efficiently combusted the pyrolysis gases and soot from the VCC. The CO levels were as low as 7 ppm with water plus 10% alcohol (volatile organic surrogate) without visible soot

emission. These experiments were conducted using a sub-scale, laboratory unit. Experiments with the full-scale unit have started to evaluate realistic sludges.

The demonstrated CO emission levels show that the developed technologies have the potential to meet shore and port emission requirements.

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(2) Schadow, K.C. and Seeker, W.R., "Compact, Closed-Loop Controlled Waste Incinerator", 33rd Nat'l. Heat Transfer Conf., Albuquerque, NM, August 1999.

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(4) LaFone, J.F. and Payne, R., "Development of Coal Burning Vortex Containment Combustor", Proceedings of Second Annual Pittsburgh Coal Conference, 1985.

(5) T. P. Parr, K. J. Wilson, R. A. Smith, K. C. Schadow, J. Cole, and R. Seeker. "Sludge Combustor Using Swirl and Active Combustion Control," The Nineteenth IT3 Conference, Portland, Oregon, May 2000.

(6) S.C. Crow and F.H. Champagne, "Orderly Structure in Jet Turbulence," J. Fluid Mechanics, Vol. 48 (1971), pp. 545-591.

(7) N. C. Widmer, J. A. Cole, W. R. Seeker, K. J. Wilson, T. P. Parr, And K. C. Schadow. "Actively Controlled Vortex Disposal System For Sludge Wastes," The Nineteenth IT3 Conference, Portland, Oregon, May 2000.

(8) N. C. Widmer, J. A. Cole, and S. H. Brown. "Performance Assessment of the U.S. Navy Blackwater Incinerator," The Nineteenth IT3 Conference, Portland, Oregon, May 2000

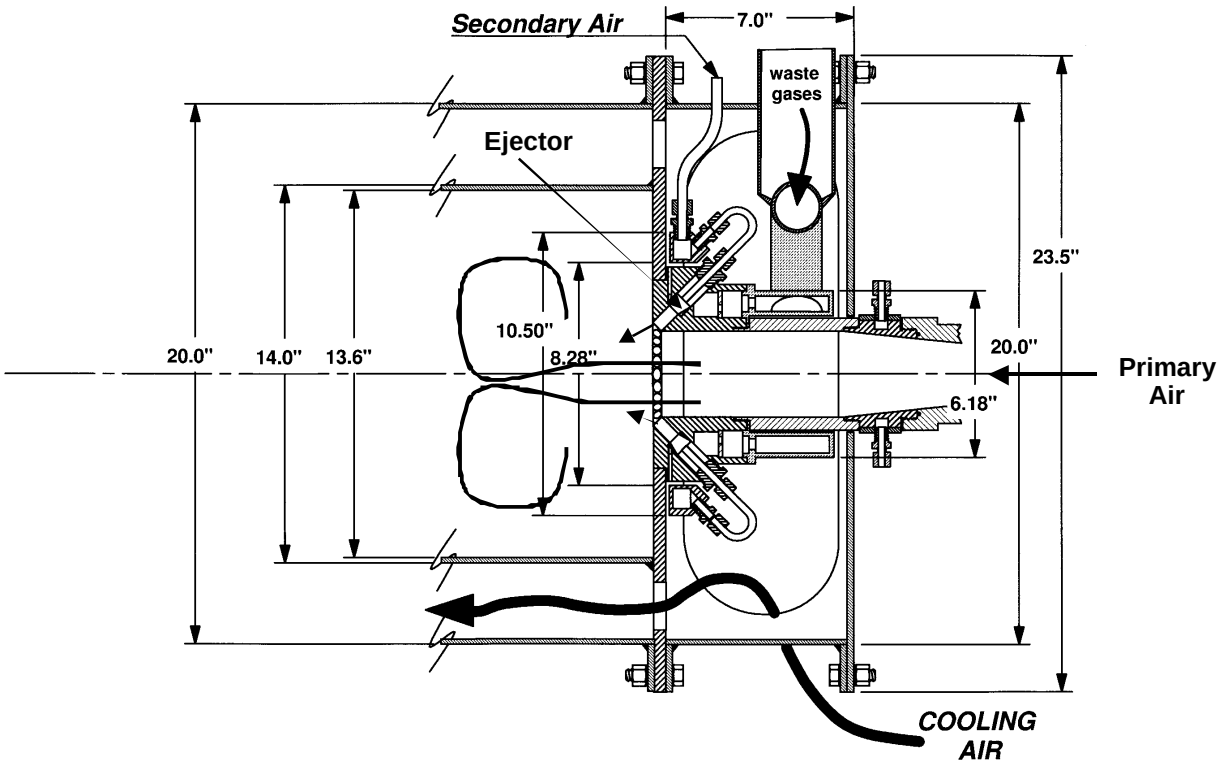


Figure 1. Afterburner Design for Golar 500 Experiments.

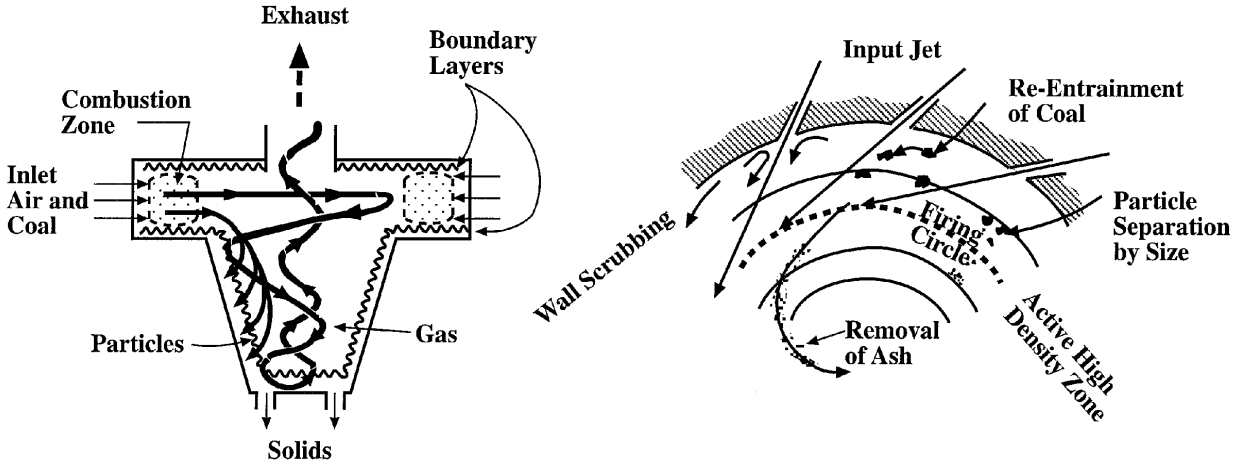


Figure 2. Vortex Containment Combustion (VCC) With Aerodynamic Suspension of Particulates in Combustion Zone and Particulate Separation from Gas Phase in Cyclone Section.

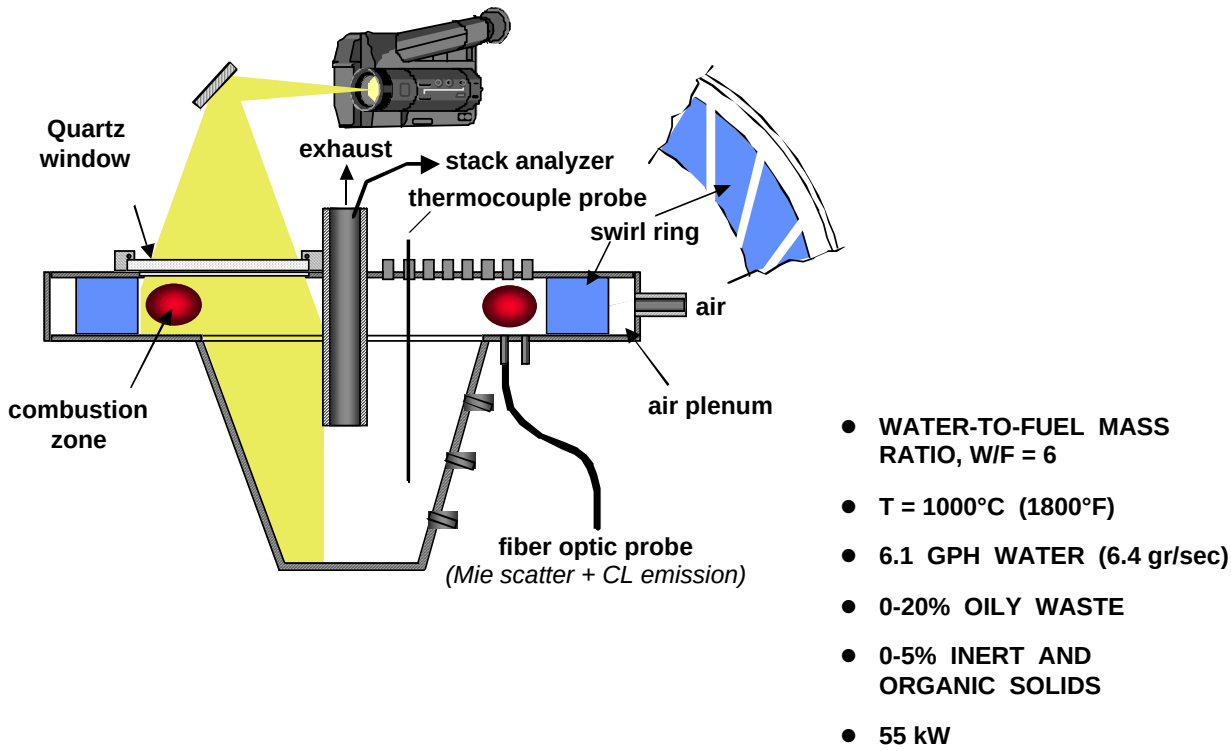


Figure 3. VCC Laboratory Combustor (VCC LC).

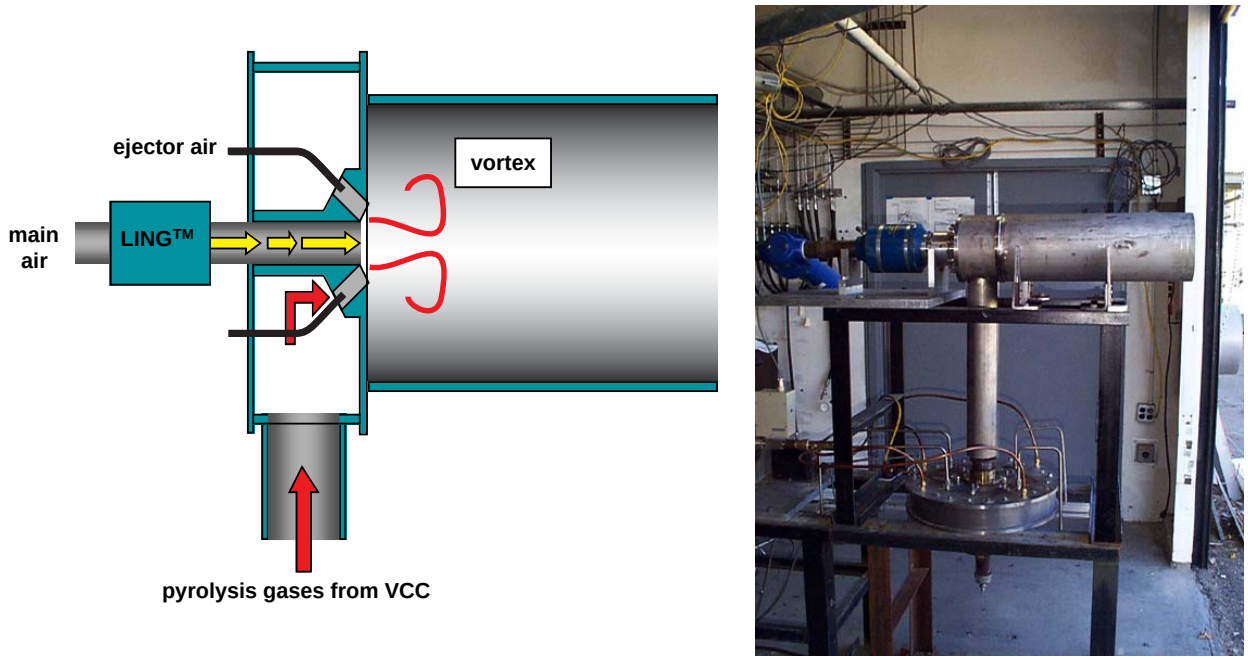


Figure 4. Integrated VCC/AB Laboratory Combustor.

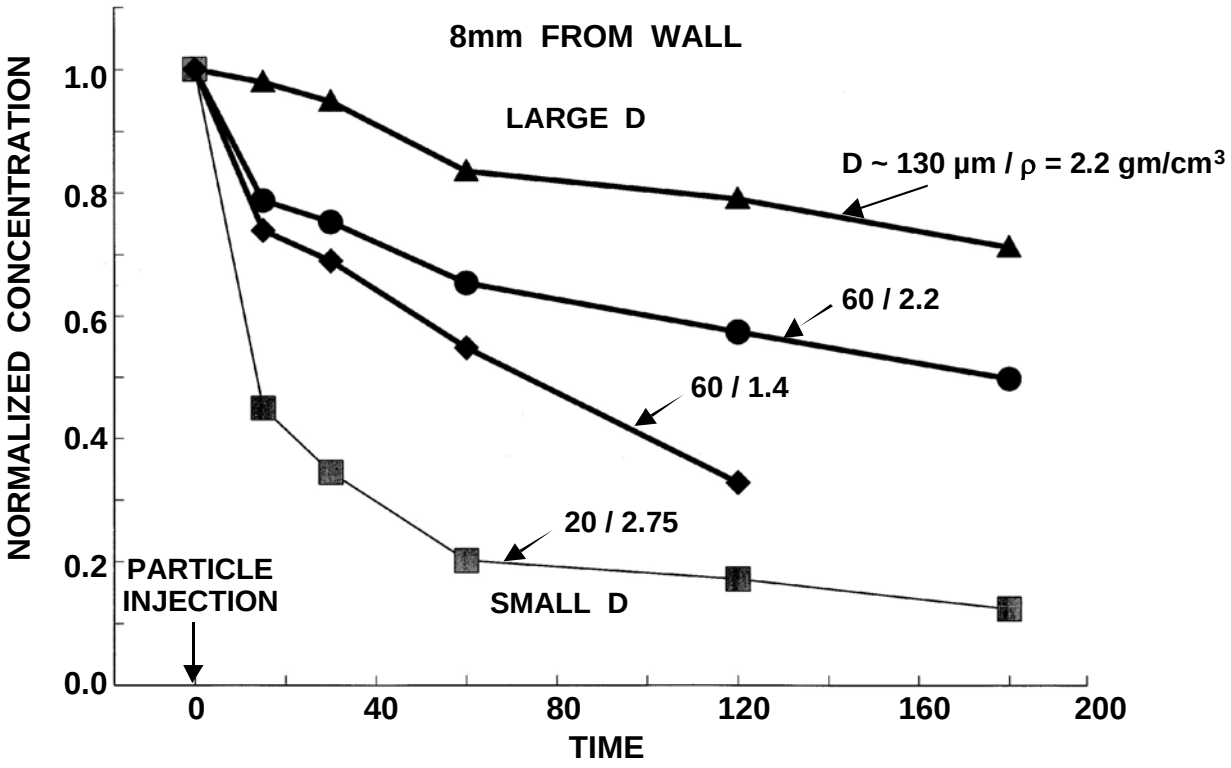


Figure 5. Retention Time for Varying Particle Characteristics (Cold Flow VCC LC Tests).

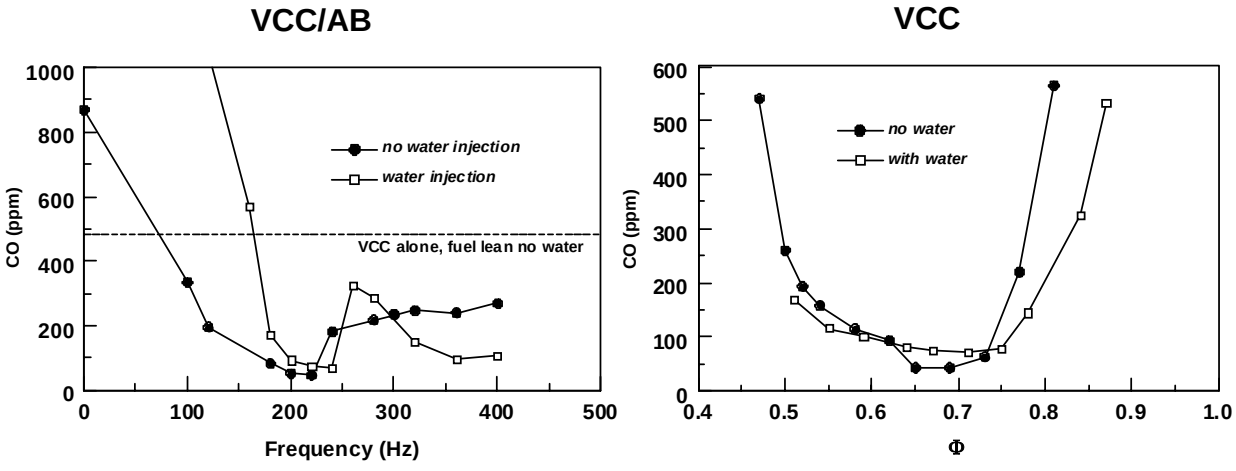


Figure 6. VCC LC Performance With and Without AB Using Water as Sludge Surrogate.

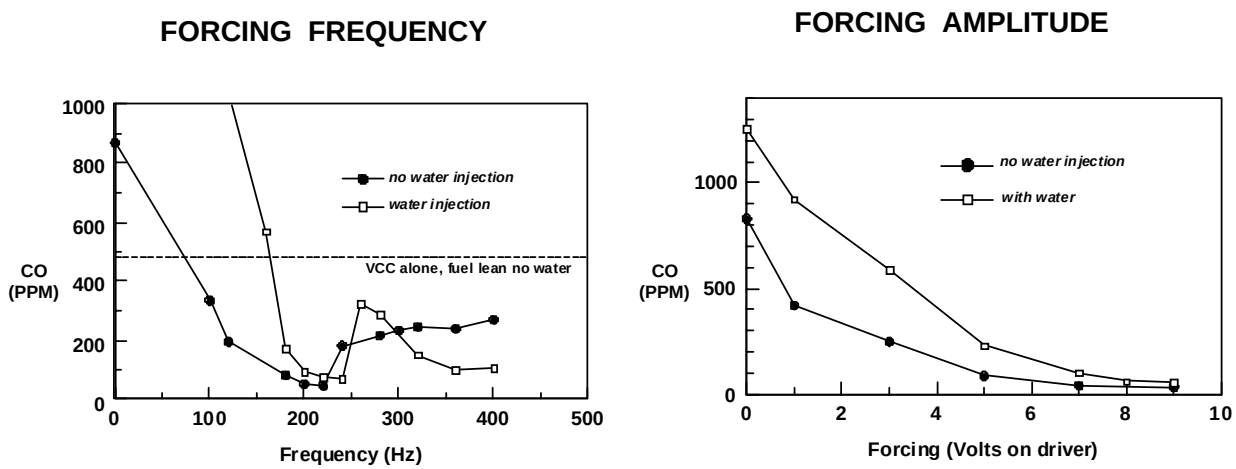


Figure 7. CO Emission as Function of Forcing Frequency and Amplitude on Feed Characteristics.

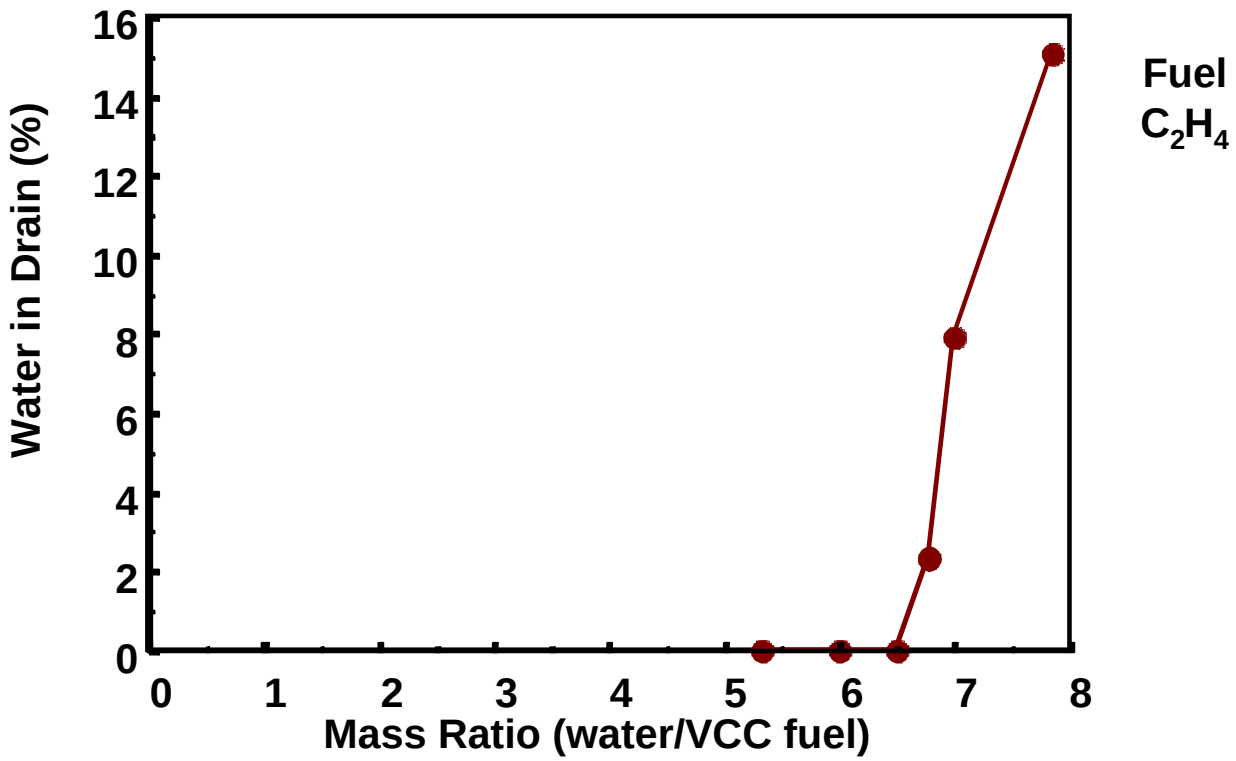
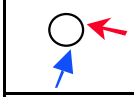
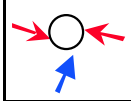
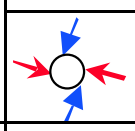
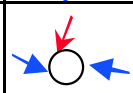
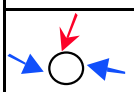


Figure 8. Water Drainage From VCC LC as Function of Water-to-VCC Fuel Mass Ratio.

Configuration		Injection Characteristics		Water Injection, gph					
		Location	Description	10	20	30	40	50	60
Unstabilized	#1		NG, one 1/2" dia. injector	X	X	X	O		
	#2		NG, two 3/4" dia. injector	X	X	O			
	#3		D.O., air atomized nozzle	X	X	O			
	#4		D.O., pressure nozzles	X	X	X	O		
Stabilized	#5		NG, one 1/2" dia. injector	X	X	X	X	X	X
	#6		D.O., air atomized nozzle	X	X	X	X	X	

X = Stable
O = Flame Out

Water
Fuel

T = 1000°C
$(W/F)_{max}$ ~ 3.5

Figure 9. Flame Stability Map for Full-Scale VCC With Diesel Fuel.

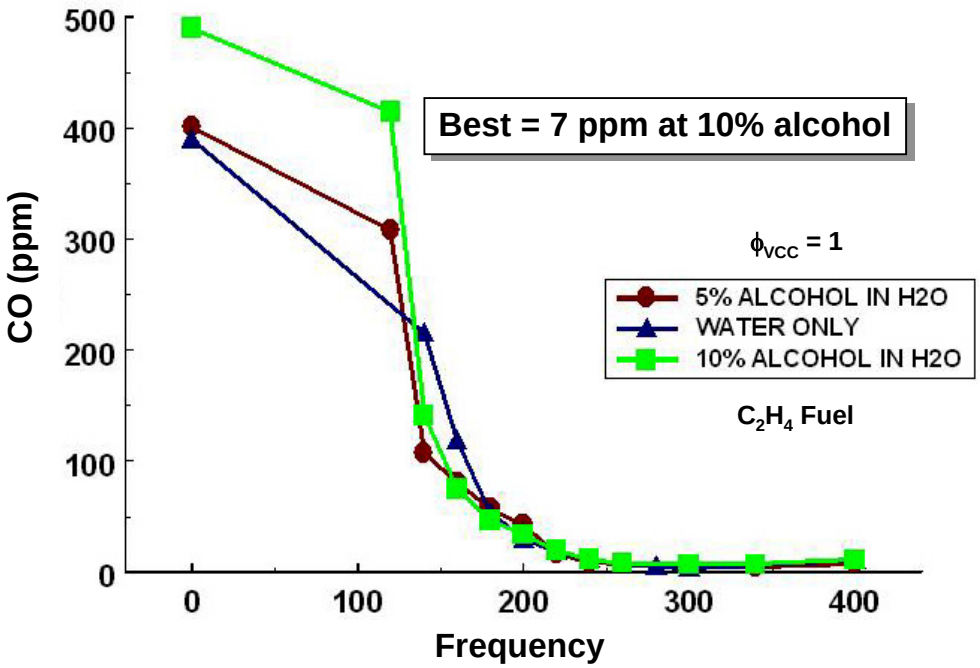


Figure 10. VCC/AB LC Performance With Water and Water Plus Alcohol as Function of Forcing Frequency.

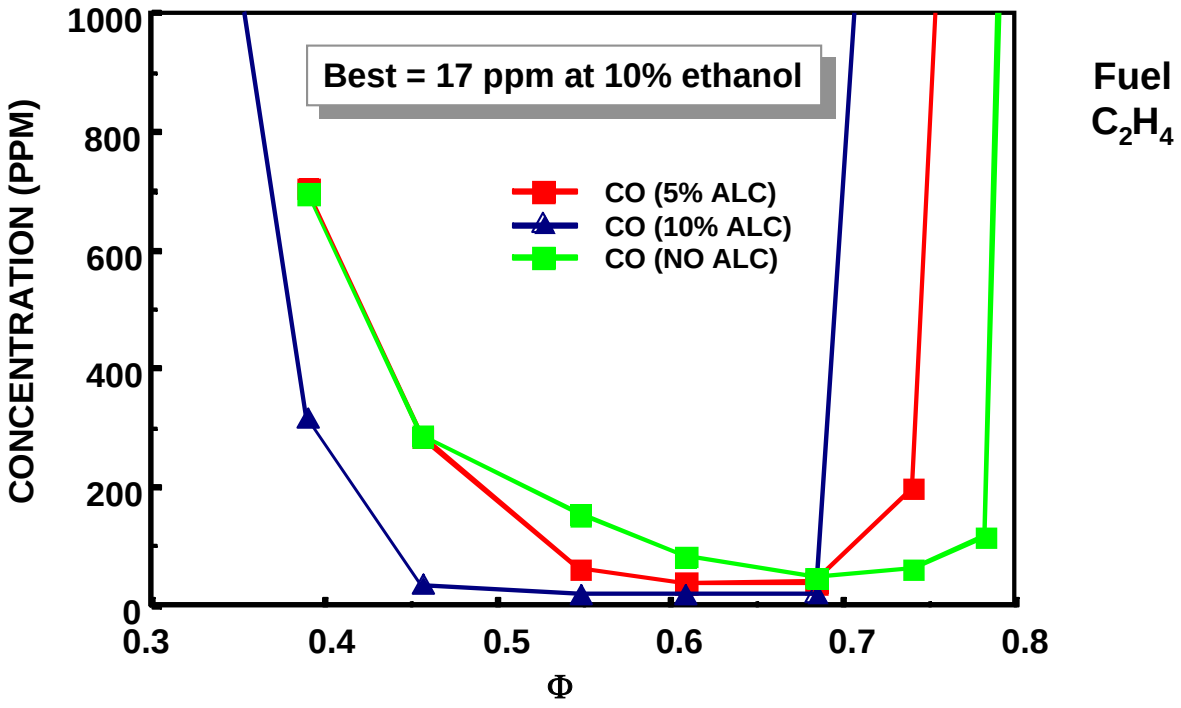


Figure 11. VCC LC Performance (CO) With Water and Water Plus Alcohol as Function of Equivalence Ratio.

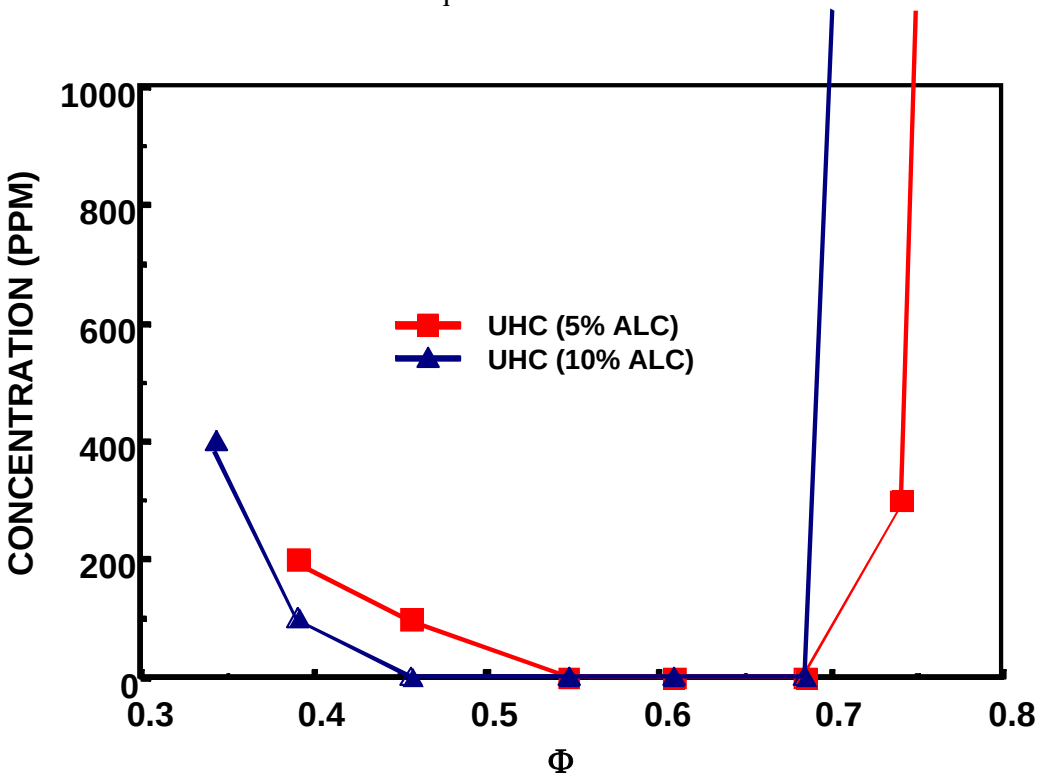


Figure 12. VCC LC Performance (UHC) With Water Plus Alcohol as Function of Equivalence Ratio.

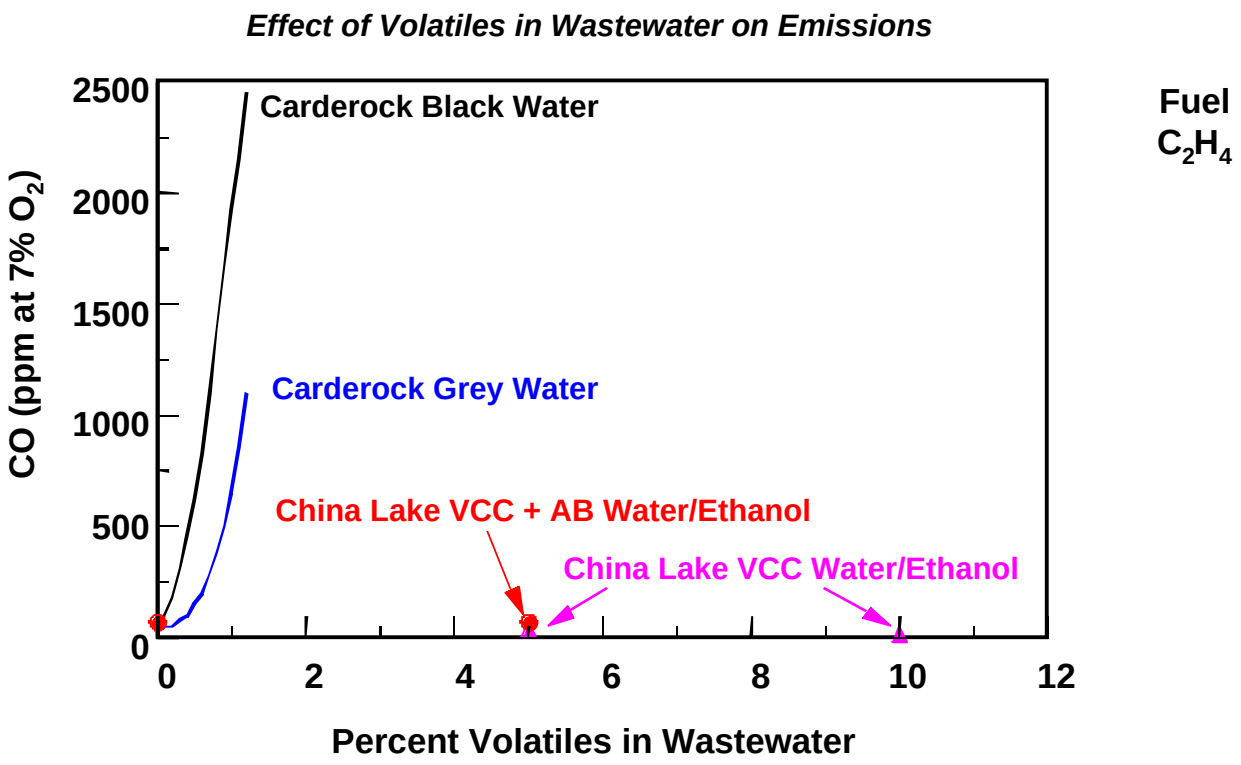


Figure 13. Comparison of VCC and VCC/AB LC With Navy Blackwater Sludge Vortex Incinerator.

APPENDIX 5

Vortex Containment Combustor System for Shipboard Sludge Waste Disposal

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Presented at 20th IT3 Conference, May 2001

VORTEX CONTAINMENT COMBUSTOR SYSTEM FOR SHIPBOARD SLUDGE WASTE DISPOSAL

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ABSTRACT

In environmentally sensitive areas, the U.S. Navy is required to comply with International Maritime Organization emission standards. In order to achieve this with minimal impact to the Navy's prime directive of national security, the Navy is interested in developing new compact technologies for efficient thermal treatment of liquid wastes. A program is currently underway to development such a system. The thermal treatment of liquid wastes is accomplished in an innovative cyclone-fired combustor that has been re-engineered for sludge treatment. The combustor resembles a cyclone particle separator. Combustion air that is introduced tangentially through multiple ports around the chamber generates a spinning, doughnut-shaped combustion region in the upper chamber. Fuel and sludge are injected into the spinning combustion region or "raceway" and generate a suspended cloud of fuel and sludge particles. These particles are held in the "raceway" where they oxidize. Combustion gases and fine ashes exiting the "raceway" then spiral down to the cone-shaped region of the combustor. Here the combustion gases undergo a flow reversal and develop a strong vortex flow upward along the center of the combustor. Because of the flow reversal and strong vortex field, ashes are effectively thrown to the walls from where they migrate to a collecting drum for disposal.

This combustor design establishes an aerodynamic separator that provides long residence time for particle burnout in a compact chamber and effectively separates particles and fly ash from the exhaust gases via centrifugal forces. The combustor is approximately five to ten times smaller than conventional units but the particle retention enables effective waste treatment. The combustor also efficiently treats high water-content wastes with minimal auxiliary fuel. The combustor is designed to process 3.2 liters per minute (50 gph) of blackwater, gray water and bilge water wastes generated from a 100 person Class 9 destroyer. Operation at a minimum heat rate of 3.3-kilowatt hours per kilogram of wastewater (5,060 BTU/lb) establishes a minimum combustor temperature for effective waste treatment. By design, the combustor achieves low particulate matter emissions and allows for deeper particle capture by reducing exhaust diameter. The main implication of which is increasing operating pressure above the current level of 3.5 kilopascals (14 inches of water column). The unit also accepts a wide range of sludge wastes. Recent demonstrations were conducted with a 2 percent solid content blackwater and 0.5 to 10 percent oil in blackwater. Emissions in all cases were far below IMO standards and also demonstrated compliance with land-based carbon monoxide standards of 100 parts per million corrected to 7 percent oxygen.

For this program, a team comprising GE Energy and Environmental Research Corporation, the United States Naval Air Warfare Center, Weapons Division and Dr. Klaus Schadow has developed various critical elements of the combustor and is evaluating the combustor performance on a wide range of liquid sludge wastes representative of shipboard waste streams. The program has successfully transition the combustor from coal and gaseous fuel operation to liquid fuel-oil operation, integrated injection of organic and oily sludge wastes, established suspended combustion dynamics, achieved stable combustion and demonstrated effective burn out and emission performance. This effort is part of a multi-year program sponsored by Strategic Environmental Research and Development Program (SERDP).

INTRODUCTION

Advanced combustion techniques for shipboard waste processing are being developed by the U.S. Navy to replace existing treatment systems. These advanced systems must handle an increasing variety and throughput of wastes and be of essentially the same size as existing onboard units. Currently only blackwater waste is treated onboard, however, in order for the Navy to comply with International Maritime Organization (IMO) standards in environmentally sensitive areas, future waste streams will include gray water and oily bilge water wastes. Sludge processing rates are expected to double although the sludge streams will still comprise mostly water. After pretreatment, the non-oily wastes will consist of 1% organic solids (from vacuum collected blackwater or sewage) and 2% organic solids (from membrane/bioreactor treated gray water or galley waste). The oily waste is derived from bilge water and consists of water and oil at 0.5% (oily concentrate from membrane separator) and 80% (bulk oil from oil water separator). The treatment system must process wastes separately or combined. Current standard marine incinerators used on board Navy ships are unable to meet IMO standards for wastes with these highly variable compositions.

In addition to shipboard applications, this technology has applications to a wide variety of oily sludge wastes generated in the military by activities such as vehicle and aircraft wash down. These oily wastes can contain significant levels of water and particulate matter including toxic metals and must be treated in an environmentally acceptable manner. GE Energy and Environmental Research Corporation (GE EER), a wholly owned subsidiary of General Electric Company, is working with the Naval Air Warfare Center, Weapons Division and Dr. Klaus Schadow in the development of a compact system for thermal treatment of these sludge wastes. The approach involves converting a high firing density coal combustor to fuel oil operation and integrating liquid sludge thermal treatment. To date the project has been successful in converting the combustor to fuel oil operation and has demonstrated effective thermal treatment of sludge wastes representative of those produced on Naval vessels.

BACKGROUND

In the early 1980's, GE EER began development of a coal combustor technology retrofit for oil-fired boilers. The purpose was to enable coal combustion in boilers that were not designed to handle high ash loading. The approach involved effective ash retention in the combustor that was achieved by cyclone separation. The combustor, called the Vortex Containment Combustor (VCC), traps and suspends solids in a fire ring and produces a largely ash-free exhaust gas (1).

The VCC concept, illustrated in Figure 1, involves a ring-shaped combustion chamber in a classic cyclone-type device. Air is introduced into the combustion chamber through a number of tangentially directed slots. The large diameter, narrow raceway combustion chamber establishes a high performance aerodynamic separator that effectively traps droplets and fly ash in the combustor via centrifugal forces. Co-injection of fuel into the "raceway" generates a suspended reaction zone. Sludge and fuel particles retained in the reaction zone evaporate and burn leaving fine ash particles. As the particle size decreases, aerodynamic drag forces overcome centrifugal forces and the particles are carried into the hopper section. The high rotational gas velocity in the hopper section increases the centrifugal separation forces driving fine ash particles to the walls. Along the walls, the particles enters the aerodynamic boundary layer were they are retained and collected for later removal from the system. Particles that escape the boundary layer continue to be carried downward with the swirling gases. Eventually the swirling gases reverse direction and exit upward along the combustor's axis. At the point of reversal, an aerodynamic stagnation zone occurs and nearly all of the remaining particles fall away from the moving gases by gravitational force.

Nearly all the waste thermal treatment systems for processing solid or sludge wastes operate with two process stages: the first being nominally fuel-rich and the second fuel-lean. The reason for this is simple. Fuel-rich waste thermal treatment requires less air, and hence is more quiescent. This enables solid to be retained for long periods to undergo gasification with only the gaseous effluent being further oxidized in the secondary chamber. The VCC concept is uniquely different in this regard. By design it has a very turbulent primary chamber, but achieves particulate retention through aerodynamic means. The ability of the VCC to retain particulate has been demonstrated in coal combustion systems by a number of investigators, including research teams from GE EER, as

well as TRW and Babcock and Wilcox. Design features of the VCC include compactness, high temperature, long solids retention times, very low particulate emissions and good turndown capability.

To adapt the VCC to sludge treatment involves operating on liquid fuels and integrating liquid waste injection and suspension techniques. Currently specifications have been developed for stable combustion with fuel oils and specifications are being assessed for injection and suspension of sludge wastes.

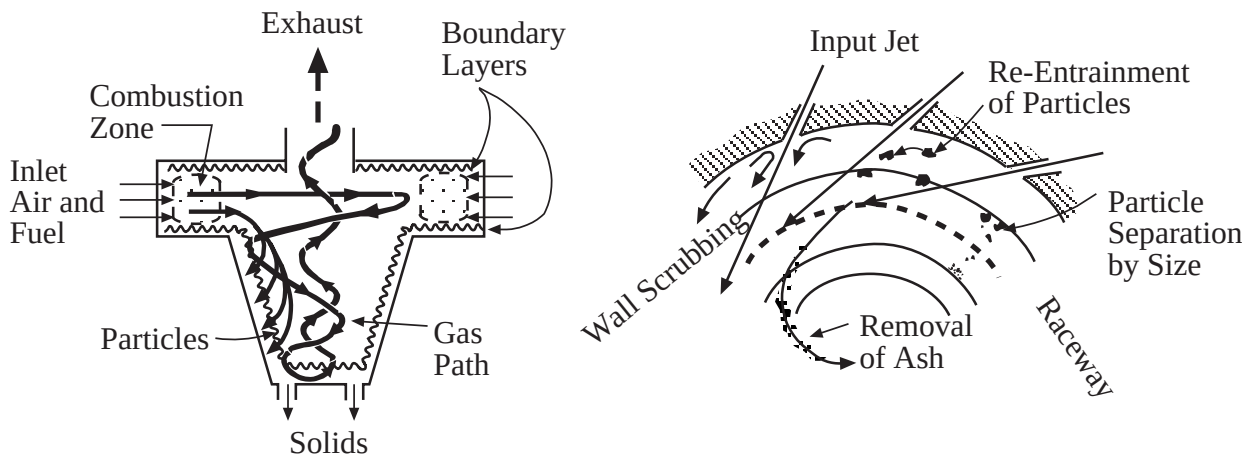


Fig. 1. Conceptual operation of the vortex containment conbustor showing the top view of the suspended reaction region (right) and the side view of the overall gas and particle paths (left).

FACILITIES

The development of the VCC for sludge waste applications was conducted on three test facilities; a sub-scale combustor (2), a full-scale isothermal model and a full-scale 640 kW combustor (3). This paper focuses on the full-scale development efforts and results.

Concurrent efforts were conducted on two full-scale facilities. The full-scale isothermal model was used to guide specification of the sludge injection systems including spray angle, injection angle, spray momentum, and droplet size. This isothermal model comprises a plexi-glass replica of the internal dimensions of the full-scale combustor illustrated in Figure 2. The full-scale combustor incorporates castable refractory insulation along with access ports for flame safety systems, diagnostic probes and various fuel and sludge injection locations and angles.

The combustor was operated with approximately 13 cubic meters per minute of air directed into the suspension zone through 12 circumferential air vanes, orientated 45° from radial. The fuel, consisting of diesel fuel oil was fed with two injectors located on opposite sides of the combustion “raceway.” The 25° from radial injection of fuel ensured the fuel was not driven to the walls. The air atomized sludge waste was also introduced through two injectors that were directed towards the center of the combustor. The fuel, air and waste mix and react in the “raceway” and the reacting gases and fine ash products spiral into the lower hopper region. The gas products then reverse direction and exit upward through the centrally located combustor exhaust. Swirl strength in the upward flow is very high. The momentum of the entrained ash particles precludes them from following the flow field and the particles are rejected to the walls. The separated particles are then collected in the lower hopper region and removed from the combustor.

The full-scale combustor was equipped with fuel, sludge and air feed control and monitoring systems. The operating differential pressure of the VCC was measured between the air inlet and the exhaust duct. A K-type thermocouple was recessed 10-mm from the surface of the upper refractory wall to provide relative chamber wall temperatures. During a series of tests to establish the best operating and injection configuration, the upper and lower walls of the

“raceway” were instrumented with interior surface thermocouples to identify cold and hot spots. A thermocouple and extractive gas-sampling probe was located in the exhaust. The gas sample was delivered to a water knockout and then a continuous emission monitoring system for measurement of oxygen (O_2), carbon dioxide, carbon monoxide (CO) and nitric oxide (NO) concentrations. Total hydrocarbon readings were also made at various conditions.

The full-scale VCC facilities were used to develop specifications for flame stabilization, sludge injection and particle trapping. The efforts conducted to date have successfully switched the VCC to fuel oil firing, developed VCC operating and injection specifications and demonstrated stable combustion and environmental compliance at the target sludge processing rate of 3.2 liter per minute (50 gallons per hour). The sludge waste streams included city water, 0.1% to 10% fuel oil in water and 2% solid-content blackwater surrogate that included up to 1% fuel oil contaminant. The blackwater surrogate comprised 1.6% dry dog food, 0.2% salad oil, 0.2% paper products and 98% water and exceeded the total solids and total volatile solids content of both gray and blackwater waste streams reported for Navy wastes.

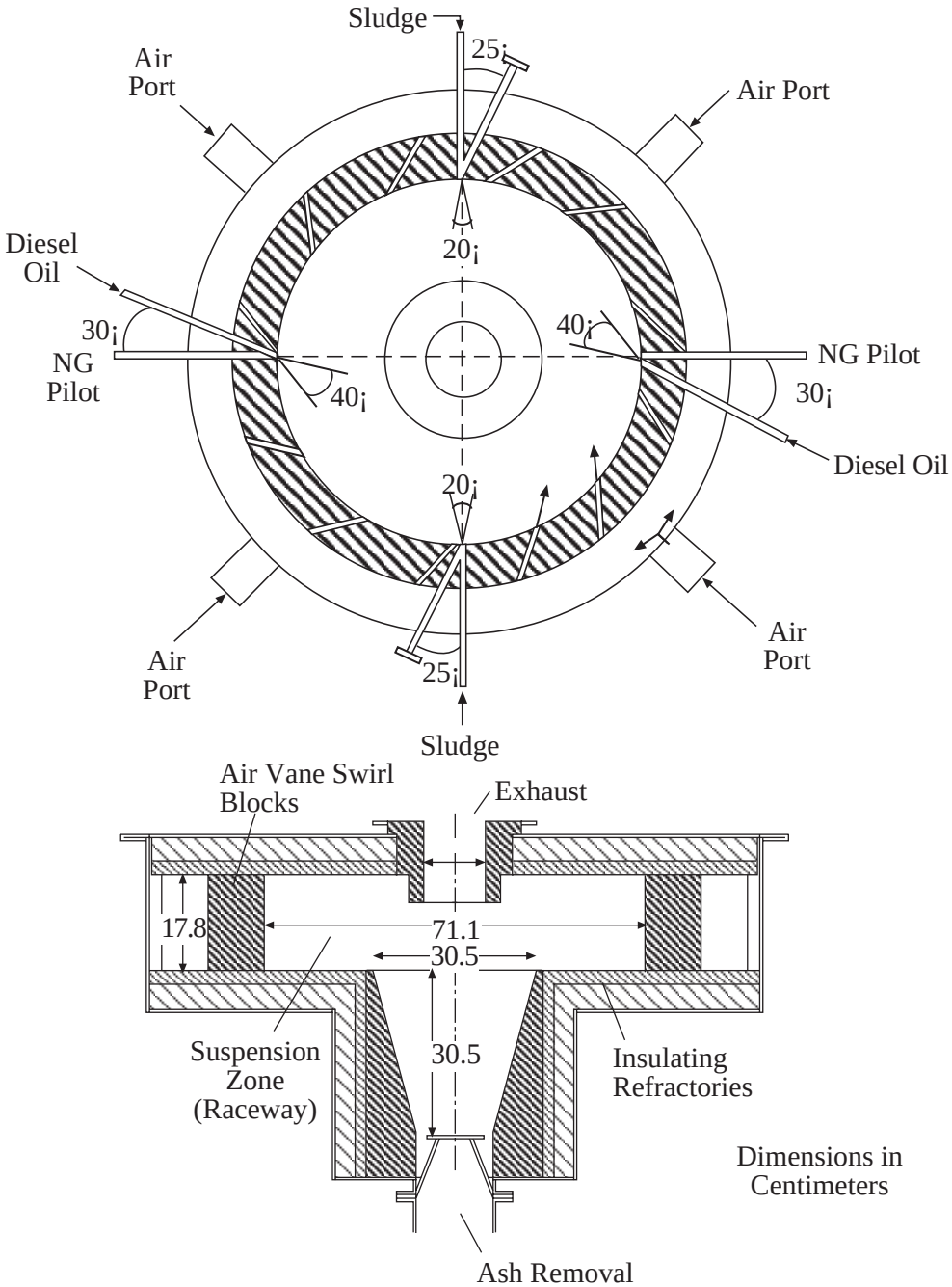
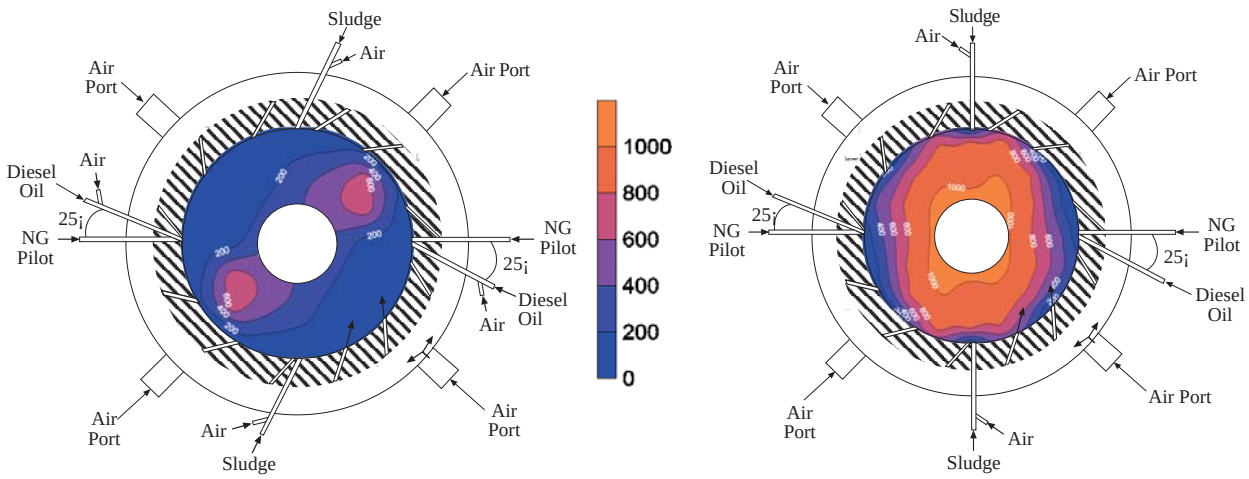


Fig. 2. Details of the full-scale VCC dimensions and internal layout. The top view illustrates the injector and air port locations (above). The insulation and internal dimensions are shown in the side view (below).

RESULTS

The program has successfully transitioned the VCC to fuel oil operation, extended the sludge evaporation limit and demonstrated stable combustion and emissions performance at the target sludge processing rate. In previous work,

the burner stability limits were extended to enable 3.2 lpm of water injection but work remained in extending the evaporation limit of the water past 1.7 lpm. In order to diagnose the evaporation failure mode and assess new configurations, the upper and lower floor of the VCC "raceway" was instrumented with thermocouples. Data shown in Figure 3a illustrate the surface temperature for the initial configuration operating with 1.3 lpm (20 gph) of water injection-just under the evaporation limit. The surface temperatures are relatively cold so that as the water injection is increased evaporation from the surface cannot be maintained. The average surface temperature was 230°C. After reconfiguring the VCC, the water evaporation limit was extended above 3.2 lpm. The surface temperature at 2.6 lpm (40 gph) water injection is shown in Figure 3b. Even though the firing rate is unchanged and water input has doubled, the wall temperature is hotter and can support additional evaporation. At 3.2 lpm the average wall temperature is still 520°C and considerably above failure mode conditions.



(a) (b)

Fig. 3. VCC floor temperature contours for (a) original configuration at 1.3 lpm water feed and (b) final configuration at 2.6 lpm water feed.

Essential features of the VCC reconfiguration that made extending the evaporation limit possible included multiple fuel and sludge injection points, pilot stabilized main flame, radial sludge injector orientation, increased sludge atomization air and optimized heat input and excess air. The VCC operating specifications are presented in Table I.

Table I. VCC Operating Specifications

Parameter	**Unit**	**Specification**
Heat Input	kW (MMBtu/hr)	640 (2.2)
Sludge Feed Rate (max.)	lpm (gph)	3.2 (50)
Heat Rate (Heat input per mass of waste)	MJ/kg (MMBtu/lb)	12.3 (5,300)
Excess Oxygen	%	5.0
Sludge Atomization:		
Air to Sludge Mass Ratio	kg/kg	0.2
Air Pressure	kPa (psi)	250 (36)
Exhaust Temperature	°C (°F)	1030 (1890)

The system requirements involve processing high volumes of various liquid wastes in a compact unit while minimizing use of auxiliary fuel. Since many of the shipboard sludge streams have little to no heat value, a minimal auxiliary fuel heat input is required to establish combustion temperatures suitable to oxidize the solid particles found

in sludge wastes. The conditions and heat rate identified in Table 1 allowed the VCC to meet IMO standards for CO emissions when processing the various sludge wastes. The IMO CO standard is 200mg/MJ or approximately 420 ppm corrected to 7% O_2.

The VCC has been tested with the full range of sludge types while operating under the conditions presented in Table 1. The sludge wastes include pure water, 2% inert (mullite) in water, 5.0% ethanol in water, simulated blackwater, 0.5, 1.0 and 5.0% fuel oil in water and 1.0% fuel oil in simulated blackwater. In all cases the total heat input from auxiliary fuel and waste oils was kept constant. A summary of the CO and NO emission corrected to 7% O_2 for these tests is presented in Figure 4. As is evident, the CO emissions fall well below the IMO standard. For these cases total hydrocarbon emissions were also below 10 ppm and NO emissions were between 17 and 33 ppm for non-blackwater tests and between 139 and 169 ppm for blackwater tests. Blackwater contains fixed nitrogen that if completely converted to NO could account for up to 50,000 ppm of NO in the exhaust so the levels of NO increase seen for blackwater are not unreasonable.

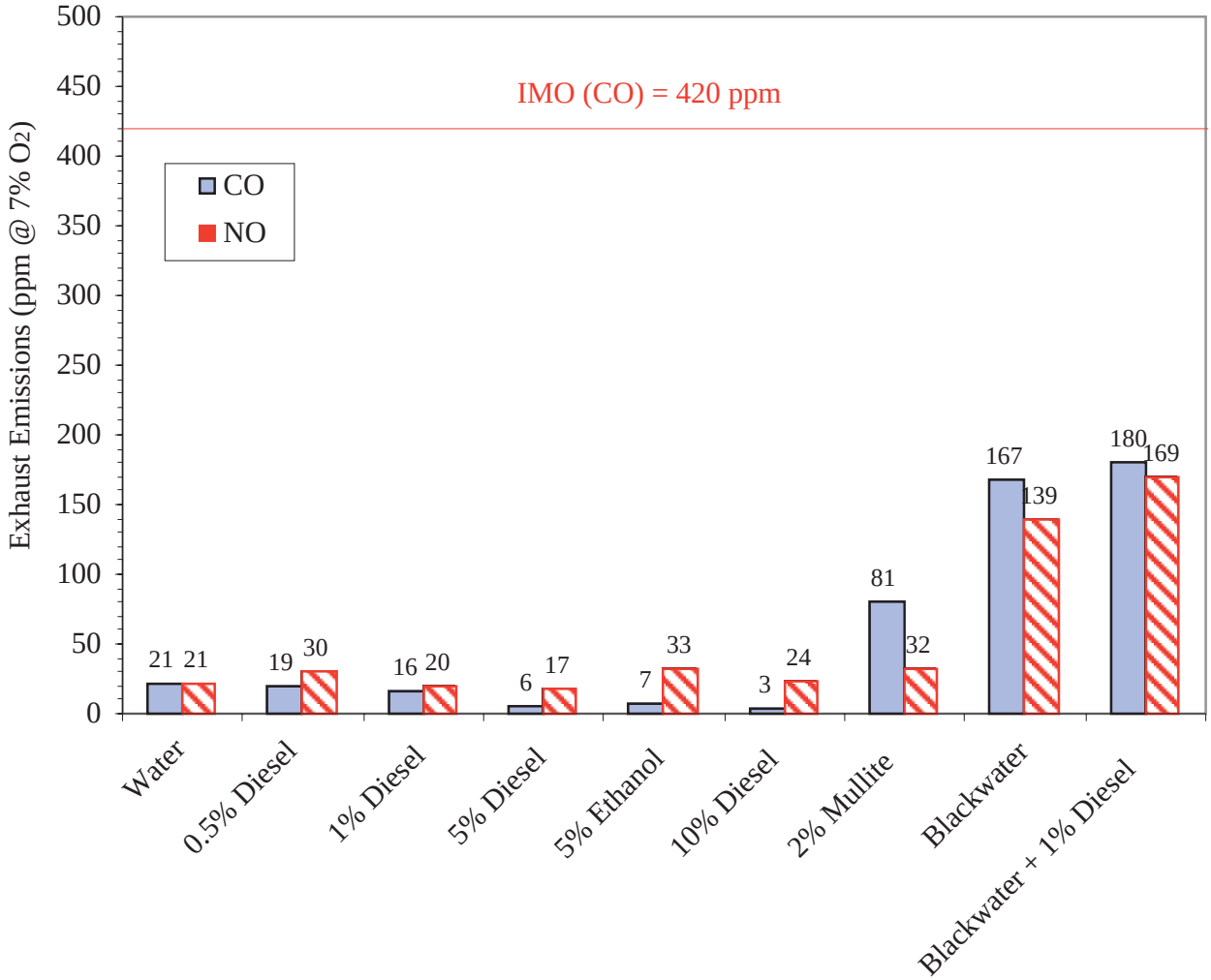


Fig. 4. VCC emissions of CO and NO for various sludge types fed at 3.2 lpm. The VCC was operated at nominally 640kW and 5% O_2.

In all tests, the total oil input from fuel and waste streams was kept constant. When operating at 3.2 lpm of waste input, the maximum oil content in waste cannot exceed 10%. The waste oil then accounts for 30% of the total heat input. Any further turndown of auxiliary fuel resulted in unstable combustion and flameouts. Reducing the waste-processing rate such that the waste heat input is limited to 30% of the total heat input can allow feeding higher bulk oil waste concentrations up to 80 and even 100%. Because of the reduced water input, the VCC would operate at higher temperatures and produce less CO emissions. Currently the bulk oil waste generated onboard at approximately 18 liters (5 gallons) a day, is only a fraction of the total waste stream and can be processed separately within 1 hour or combined with other wastes within 1 to 5 hours.

For the tests with 2% inert mullite particles in water and simulated blackwater sludge, manual gas sampling of the exhaust using EPA Method 5 was conducted. The moisture content in the exhaust gas confirmed that complete sludge evaporation was achieved. The VCC particle trapping efficiency was approximately 50% for the mullite particles. For a mean diameter of 26 microns for the mullite particles the capture performance was relatively good, however, optimization of particle trapping is still in progress. The exhaust particulate matter from the simulated blackwater sludge tests also showed that essentially all organic solids were burned out prior to exiting the VCC.

The repeatability and consistency of the CO performance was demonstrated during a 5-hour verification test when different sludge types were treated and the sludge mass flow was varied. The sludge type was changed from 3.2 lpm water to 3.2 lpm water plus 1% oil, to 3.2 lpm blackwater surrogate sludge, to 3.2 lpm blackwater sludge plus 1% oil. As shown in Figure 5, the CO emissions were below the IMO standard of 420 ppm for all sludge types and increased from 20 ppm for water plus oil to nearly 200 ppm for blackwater sludge plus oil. For the latter sludge, the CO was reduced to 60 ppm, below land-based standards, by reducing the sludge flow rate to 2.2 lpm (35 gph) (Figure 6). This effectively increased the heat rate to 17.6 MJ per kg of waste feed (7,600 Btu/lb).

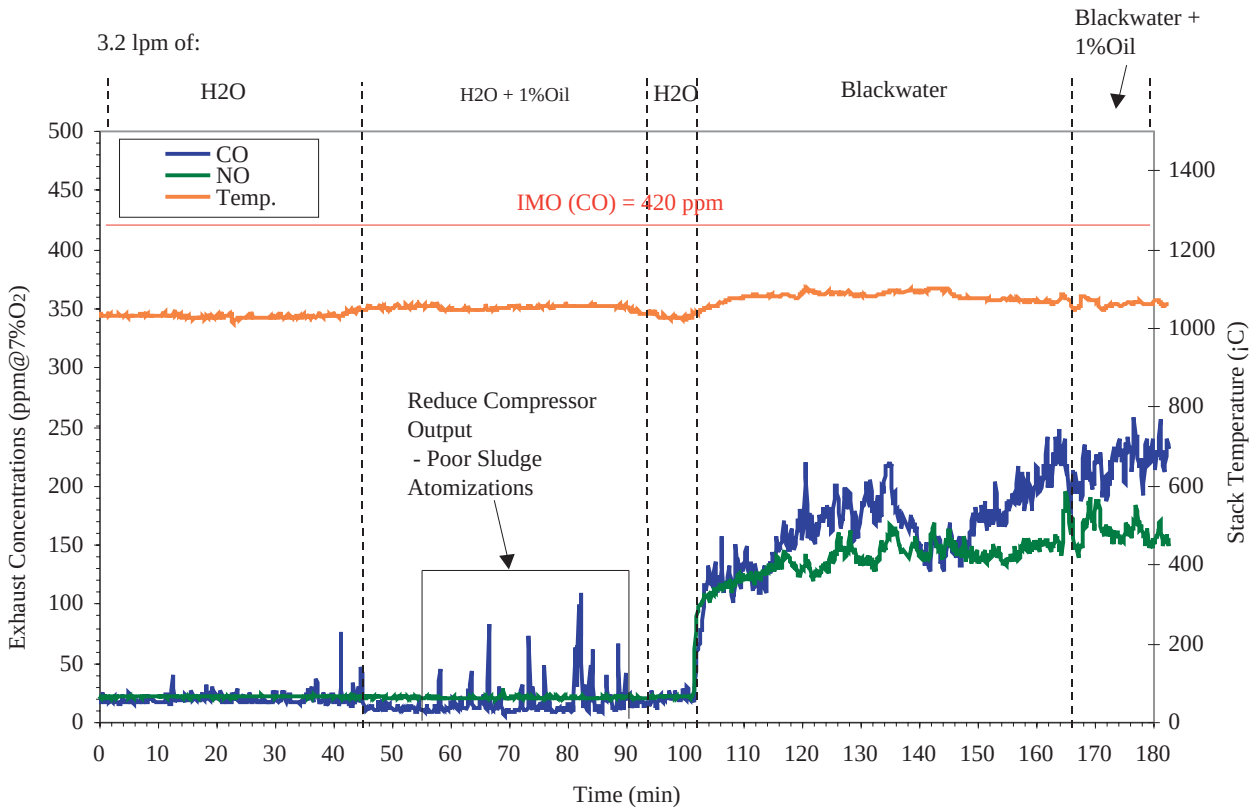


Fig. 5. VCC emission performance for varying sludge types.

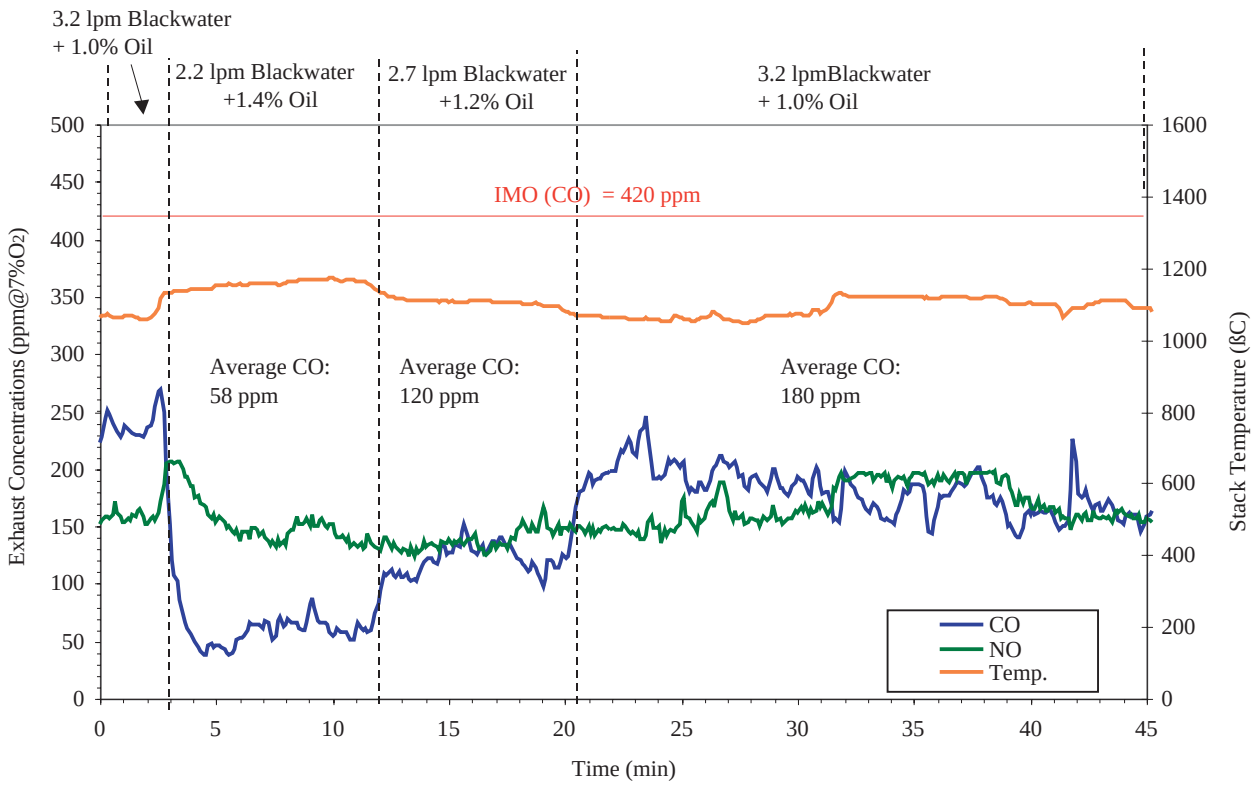


Fig. 6. VCC emission performance for varying sludge flow rates.

CONCLUSIONS AND FUTURE ASSESSMENT

Flame stability, evaporation limit and emissions goals were met by optimizing the auxiliary-fuel and sludge injector arrangements. The VCC can process the various Navy shipboard wastes at required rates by processing waste streams separately and in combination. At 640 kW heat input and 3.2 lpm waste input, the heat rate is just 12.3 MJ/kg (5,300 Btu/lb), while emissions of CO were well below IMO standards for all blackwater and oily water waste combinations. The CO emissions for blackwater are higher than for oily water wastes likely due to the solids content. Emissions of NO also increase for blackwater and can be a result of waste bound nitrogen. Reducing blackwater feed rate by 30% reduced CO emissions by 60%. The improved combustion can be attributed to a combination of increased heat rate (i.e. higher combustion temperature) and decreased solids loading. THC emissions were low for all wastes tested. The sludge wastes tested included water with up to 10% oil or ethanol and a 2% solid content sludge with up to 1% oil.

Expected particle capture performance has decreased slightly compared with the coal-fired application and is believed to be due to the radial injection of sludge. The evaporated sludge water comprises 30% of the exhaust gas volume. This water is directed toward the VCC center to avoid wall impingement that leads to incomplete evaporation. However, that means the total angular momentum of the incoming streams is reduced. As part of work in progress, the VCC air inlet and exhaust throat designs will be modified to increase cyclone strength and particle retention.

Presently the VCC is being modified. Modifications include material selection to optimize thermal conditions and reduce weight and adjustments to the air-inlet vanes and exhaust throat diameter to increased cyclone strength and therefore particle trapping efficiency. An exhaust quench section, ash collection system and diesel-fuel piloted

burner will also be integrated into the design. Additionally a controller will be incorporated to adjust auxiliary-fuel and sludge flow rates to maintain optimum conditions as sludge compositions vary.

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2 Parr, T.P., Wilson, K.J., Smith, R.A., Schadow, K.C, Widmer, N.C., Cole, J.A., and Seeker Wm.R., "Sludge Combustor Using Swirl and Active Combustion Control." Presented at the 19th International Conference on Incineration and Thermal Treatment Technologies. Portland, Oregon, 2000.

3 Widmer, N. C., Cole, J. A., Seeker, Wm. R., Wilson, K. J., Parr, T. P. and Schadow, K. C., "Actively Controlled Vortex Disposal System For Sludge Wastes," The Nineteenth IT3 Conference, Portland, Oregon, May 2000.

APPENDIX 6

Emission Reductions for Sludge Combustor Using Swirl and Active Combustion Control

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ABSTRACT
A compact and efficient combustion system is being developed for the treatment of shipboard generated non-oily and oily sludges with the combustor concept based on a high performance Vortex Containment Combustor (VCC). Flame stability and evaporation limits were extended to a sludge-processing rate of 3.2 liters per minute or 50 gallons per hour by optimizing the auxiliary-fuel and sludge injector arrangements. The CO emissions for the various sludge types tested were below the IMO standards with less than 20 ppm for water plus 10% oil (full-scale tests) and 10% ethanol (sub-scale tests) and less than 200 ppm for a blackwater sludge surrogate plus 1% oil (full-scale tests). Nonreacting and combustion experiments provided insight into the characteristics of auxiliary-fuel and sludge injection and also particle retention using visible observation, particle tracking with laser diagnostics, and VCC floor temperature measurements. A controller concept for the VCC was developed to allow automated processing of sludges with highly varying heating values. In sub-scale tests, the CO emission was further reduced to 7 ppm by integrating the VCC with an efficient, compact, actively controlled afterburner. This concept has the potential for land and harbor applications.
Keywords: incineraton, sludge

INTRODUCTION
A combustion system for the treatment of sludges from various sources is being developed. Current effort is focusing on the treatment of shipboard generated oily and non-oily wastes, which have to be disposed according to International Maritime Organization (IMO) regulations with less than 200 mg/MJ CO emission or approximately 420 ppm corrected to 7% oxygen (O_2). The technology concept being developed for the shipboard application is based on a high performance Vortex Containment Combustor (VCC). For potential land and harbor applications, integration of the VCC with an efficient, compact, actively controlled afterburner (AB) is also explored.

The VCC is a demonstrated technology for combustion pulverized coal (LaFond et al. (1985)). The concept involves a spinning combustion zone, which is generated by tangential air injection and provides long solid particle residence times, and a classic cyclone-type flow, which separates and traps non-combustible solids as ash (Figure 1). The AB is a new concept and provides efficient and compact afterburning in actively stabilized air vortices using open- and closed-loop control (Parr et al. (1996)). In this concept, the afterburner air is modulated at its preferred mode frequency (Crowe et al. (1971)) to generate large-scale vortices. The fuel-rich products are entrained with an ejector into the vortices for controlled, efficient afterburning in the core of the vortices (Figure 1). Full-scale tests with the afterburner have demonstrated a 3.2 times increase in solid waste heating-value throughput and an order of magnitude drop in CO emission from baseline experiments (Cole et al. (2000), Schadow (1999)). Further performance increases were achieved with closed-loop active control using synchronized (forced) fuel injection into the air vortices (Schadow (1999)). In these tests a complex controller was used to generate the actuator signals for air and fuel forcing based on on-line exhaust emission measurements.

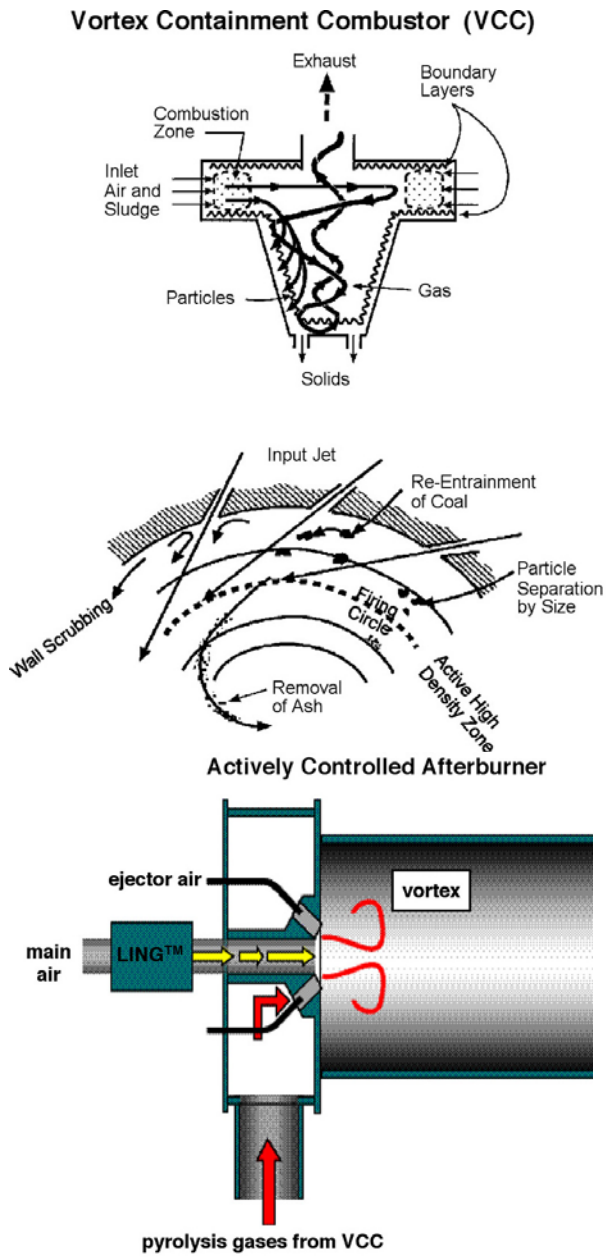


Figure 1. Vortex Containment Combustor (VCC) and Actively Controlled Afterburner (AB).

In the present program, the VCC is being modified for the treatment of marine sludges with highly variable characteristics using additional auxiliary fuel for low heating-value sludges. Full-scale VCC tests are performed to determine performance without AB using a simple controller for auxiliary-fuel and sludge flow rate variations. In sub-scale tests, the VCC was integrated with the AB to determine open-loop performance without controller for potential land and harbor applications.

The sludges to be treated in the sub-scale VCC/AB and full-scale VCC consist of non-oily wastes of water with 1% organic solids (from vacuum collected blackwater or sewage) and 2% organic solids (from membrane/bioreactor treated gray water or galley waste). The oily waste is derived from bilge water and consists of water and oil from 0.5% (oily concentrate from membrane separator) up to 80% (bulk oil from oil water separator). The sludges have to be treated in separate streams and as mixtures. Current standard marine incinerators used onboard Navy ships are unable to meet IMO standards for these sludges with highly variable compositions.

OBJECTIVES

(1) Develop compact, efficient, and automated combustion system based on the VCC concept for onboard treatment of a wide variety of shipboard generated oily and non-oily sludges, (2) determine VCC performance with realistic ship-board sludges, and (3) explore performance of VCC with AB for potential land and harbor applications.

EXPERIMENTAL SET-UP

A sub-scale VCC/AB Laboratory Combustor (VCC/AB LC) (Parr et al. (2000) and a full-scale VCC (Widmer et al. (2000)) were used to determine (1) aerodynamic suspension of fuel particles, (2) trapping and collection of inert particles at the bottom of the VCC cyclone section, (3) auxiliary fuel requirements for flame stability limits and evaporation limits, and (4) performance, primarily based on CO emission, for varying sludge compositions using a simple controller. Additional details are given in the following.

The sub-scale VCC/AB LC (Figure 2) was used in cold flow studies to determine aerodynamic suspension and retention of particles as a function of swirl conditions, particle injection parameter, and particle size and density. Particle trajectories were followed through quartz windows using a diode laser (670 nm) and a filtered photo-diode for Mie scattering. The retention time was measured based on particle concentration decays in the swirling flow. The VCC/AB LC with a 55 kW heat capacity was also used for combustion tests, conducted sequentially with increasing complexity, from tests with gaseous to diesel auxiliary fuels using water and water plus ethanol as sludge surrogates. The performance was determined without and with AB, in the latter case using additional auxiliary-fuel injection after the VCC (Figure 2). The sub-scale VCC LC was also used to develop strategies for the simple controller. For the VCC without AB, the controller will monitor stack oxygen and temperature and adjust auxiliary fuel and sludge flow rates. For operation with the AB, the controller would also be required to adjust the frequencies and amplitudes of the air forcing, as shown in the sub-scale experiments. However, this complex controller for AB operation was not developed during the current phase of the program.

The full-scale VCC with 640 kW (nominally designed for 500 kW) and a sludge flow rate goal of 3.2 liters per minute (lpm) or 50 gallons per hour (gph) was used to evaluate VCC performance. The cutaway in Figure 3 shows the ceramic inserts with the tangential slots for air injection, and two injectors each for auxiliary fuel (diesel oil) and sludge injection. A natural gas pilot flame maintained diesel oil ignition during VCC operation. The VCC floor surface temperatures were measured using thermocouples embedded in the ceramics. Nitrous oxide (NO), CO, hydrocarbons, oxygen, exit temperature, and carbon dioxide were routinely measured. Measurements of particulate matter emissions in the exhaust were made using EPA Method 5. Critical information on sludge injection techniques and aerodynamic suspension & retention of sludge sprays were gained from a full-scale isothermal VCC model.

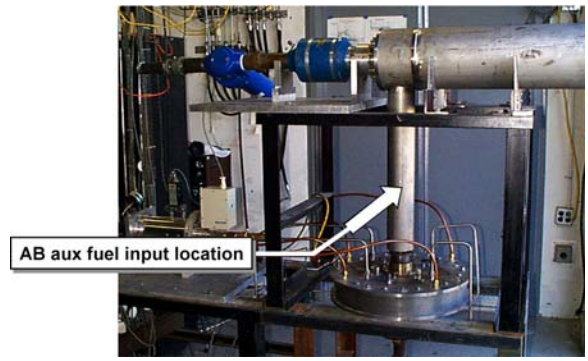


Figure 2. 50kW VCC/AB Laboratory Combustor.

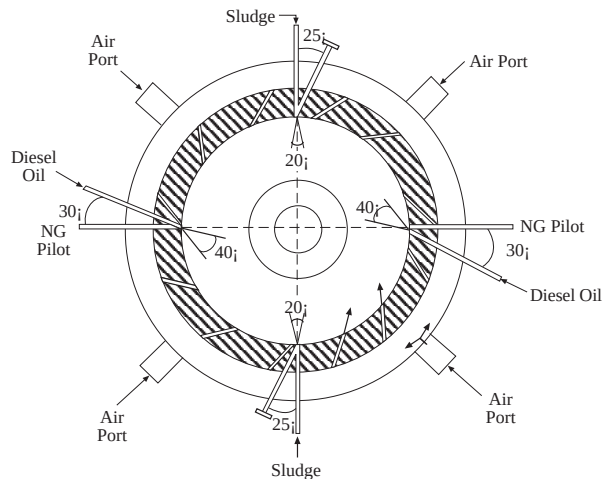


Figure 3. 640 kW VCC.

RESULTS AND DISCUSSIONS

First, sub-scale experiments will be discussed to determine particle retention in the nonreacting VCC LC, to compare VCC performance without and with AB, to compare VCC and VCC / AB performance with a current Navy Sludge Incinerator based on volatile organic sludge content, and develop a simple controller for VCC. Subsequently, full-scale nonreacting and combustion experiments will be discussed to extend stable combustion regions and evaporation limits and to determine processing performance of non-oily and oily sludge surrogates, characteristic of shipboard generated sludges.

VCC Particle Retention in Swirling Flow

Particles of various sizes and density were tested in the VCC LC under cold flow conditions. The particles included non-fat dry milk at a density of about 1.4 gm/cm^3, baking soda at 2.2 gm/cm^3, and talc at 2.75 gm/cm^3. Figure 4 shows particle retention results for one axial location at 8 mm from the VCC wall: larger particles were retained in the swirling flow for longer times, and denser particles were retained longer than lighter ones. Even the smallest particles had a 1/e retention time of about 20 seconds in the VCC LC, showing the VCC capability to suspend particles for efficient burn-out.

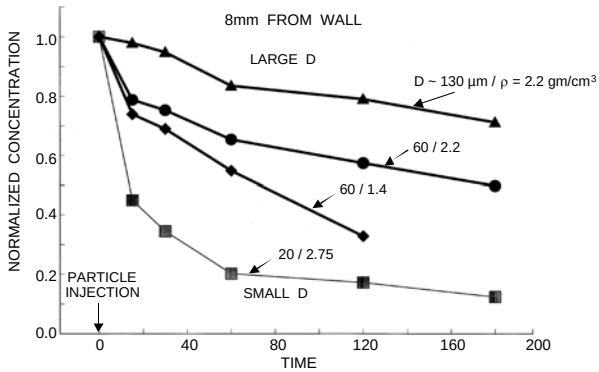


Figure 4. Retention Time for Varying Particle Diameter and Density in VCC LC (Cold Flow Experiments).

Integration of VCC LC and AB

The VCC LC was integrated with the actively controlled AB to evaluate the performance of the VCC (operated fuel lean) alone and the VCC (operated fuel rich) plus AB. Ethylene was used as VCC fuel without sludge. The AB with open-loop control (air forcing on) substantially improved the performance of the system over the VCC alone (Table 1). The CO was reduced by a factor of ten to 47 ppm. The CO without air forcing (controller off) was higher than with the VCC alone. The performance improvements with the actively controlled AB were achieved despite the heavy soot load from the VCC when operated fuel rich. There were no visible soot emissions from the AB. The VCC/AB combination suspends particulate matter in the VCC and insures its gasification, while the AB completes the combustion of the resulting pyrolysis gases and fine particulate (soot) in a high mixing rate and high combustion intensity environment for low emissions provided by the acoustically stabilized vortices. This improvement with AB is obtained at the expense of extra auxiliary fuel.

Table 1. Performance of VCC LC and VC / AB LC With and Without Active Control (Ethylene Fuel).

	VCC Air,, l/m	Fuel, l/m	AB Air, l/m	VCC kW	AB kW	CO ppm
VCC only at Φ = 0.7	800	39	---	39	---	481*
VCC at Φ = 2.5 + AB No Control	800	140	1940	55	82	870
VCC at Φ = 2.5 + AB With Control	800	140	1940	55	82	47

Ethylene Fuel
*Not optimal

Performance with Water as Sludge Surrogate

The VCC/AB LC was operated with water as 'surrogate sludge'. The CO emission was 69 ppm at optimized afterburner-air forcing of 230 Hz, which corresponds to preferred-jet mode forcing of the air (Figure 5). At this forcing, the largest possible vortices corresponding to the width of shear layer at the end of air-jet potential core are generated. The NOx was much lower with water injection, 7 ppm vs. 40 ppm, as the water dropped the gas temperature. The measured pyrolysis gas temperature input to the AB was 555 C without water and 422 C with water. The performance level of the VCC alone, operated fuel lean, achieved CO below 100 ppm with and without water in a narrow equivalence ratio range of about 0.7. This means that the VCC alone cannot tolerate variations of the sludge fuel content to maintain optimum conditions and has to be operated at its design point.

The tests also showed that the optimal frequency and amplitude for the afterburner-air forcing changed with water injection. The important aspect of this result is that the frequency and amplitude dependence on feed conditions requires the use of an adaptive controller to adjust the forcing to varying sludge characteristics. This complex controller was not developed in the current phase of the program.

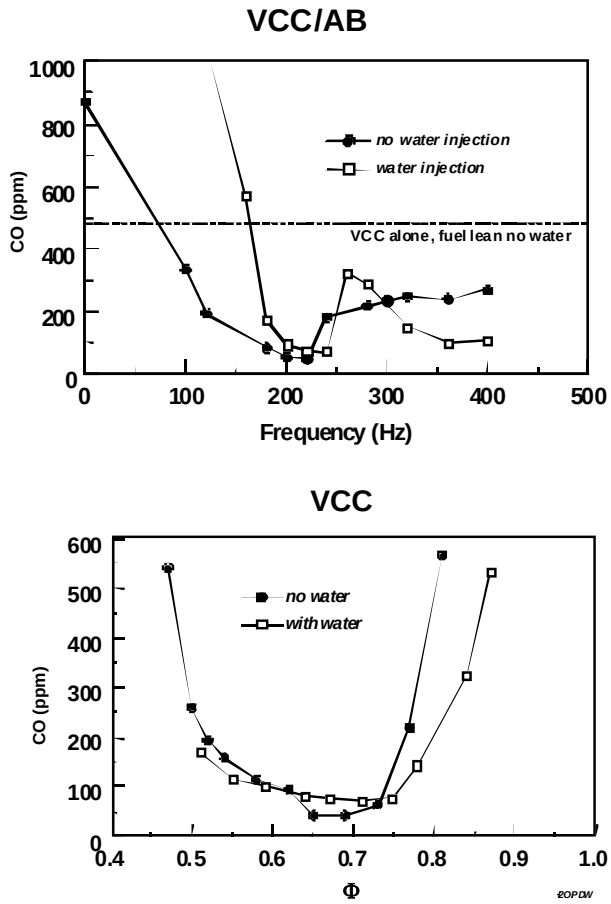


Figure 5. VCC LC Performance With and Without AB Using Water as Sludge Surrogate.

Performance with Water and Ethanol as Sludge Surrogate

Subsequently, the performance of the VCC/AB LC was evaluated with water plus 5% and 10% by volume ethanol. The CO emission for 10% alcohol optimized at 7 ppm at about 300 Hz jet preferred-mode forcing. For the VCC alone using water plus alcohol, the CO emission decreased to 17 ppm with 10% alcohol in a narrow equivalence range. In these tests unburned hydrocarbon (UHC) emission was not detected at the optimum conditions.

The performance of the sub-scale VCC LC and VCC/AB LC was compared with the performance of the current Navy Sludge Incinerator for varying percent of volatile organics in the feed (Figure 6). While the current incinerator showed a dramatic increase in CO emission, when the percentage of volatile organics in the gray and black water sludges increased to 1% and higher, the CO emission of the VCC remained very low up to 10% organics.

The performance of the VCC/AB LC was maintained when the auxiliary fuel type was changed from ethylene to diesel fuel.

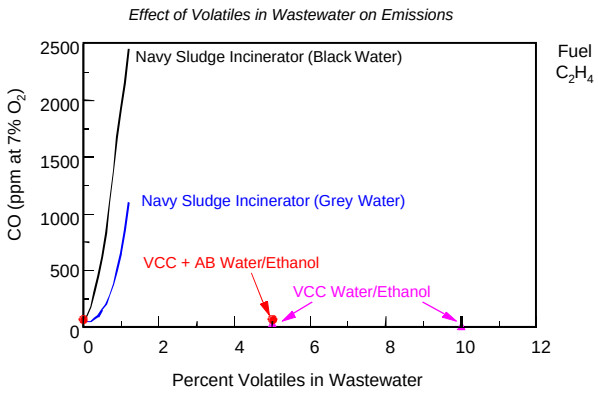
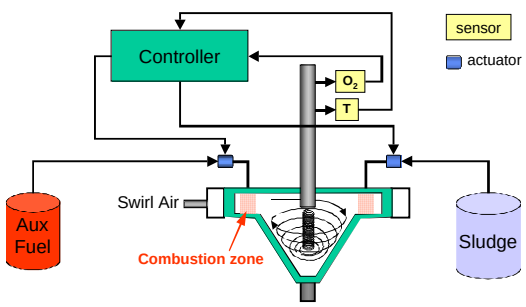


Figure 6. VCC / AB LC with Water and Ethanol as Sludge Surrogate (Comparison with Navy Sludge Incinerator).

Controller Design

The control concept shown in Figure 7 is being implemented. A proportional/integrative controller algorithm was developed to maintain optimal performance with varying sludge characteristics or heating values. This is achieved by varying the auxiliary-fuel and sludge flow rates when the exhaust temperature and oxygen concentration deviate from the desired values (set points). When the auxiliary fuel is reduced to zero and oxygen remains below the set point when treating high heating-value sludges, the sludge flow rate is reduced, while considering only the oxygen set point and ignoring the temperature set point. The controller concept is being explored in sub-scale tests and will be transitioned to the full-scale VCC.



Controller algorithm:

If T > setpoint then increase sludge flow, if T < setpoint then decrease sludge flow

If O_2 > setpoint then increase auxiliary fuel, if O_2 < setpoint decrease auxiliary fuel

If O_2 < setpoint AND auxiliary fuel rate = 0 then decrease sludge flow and ignore T

Figure 7. Controller Concept to Maintain Optimal VCC Operation with Varying Sludge Type.

Stable Combustion Regions and Evaporation Limits with Full-Scale VCC

The regions of stable combustion (flame stability) and limits of evaporation were extended to the 3.2 lpm (50 gph) sludge flow rate goal. At initial design conditions and unsatisfactory performance, visible observations in the isothermal plexiglas VCC and thermocouple diagnostics in the reacting VCC identified that the sludge was impinging on the VCC walls and collecting on the floor. This resulted in low floor temperatures that reached the boiling point of water upon failure. The improvement in throughput was accomplished by incremental changes in the injector configurations and operating conditions. The floor temperatures for the initial (unsatisfactory) VCC configuration operating at a sludge evaporation limit of 1.3 lpm (20 gph) are compared in Figure 8 to the floor temperatures of the final configuration operating with 2.6 lpm (40 gph). The initial configuration caused low floor temperatures of 230 C with only 1.3 lpm sludge injection. For the improved configuration operating at 2.6 lpm sludge injection, the average floor temperature was 730 C and decreased to only 520 C with 2.6 lpm sludge injection. Improvements to achieve the target sludge rate of 50 gph included:

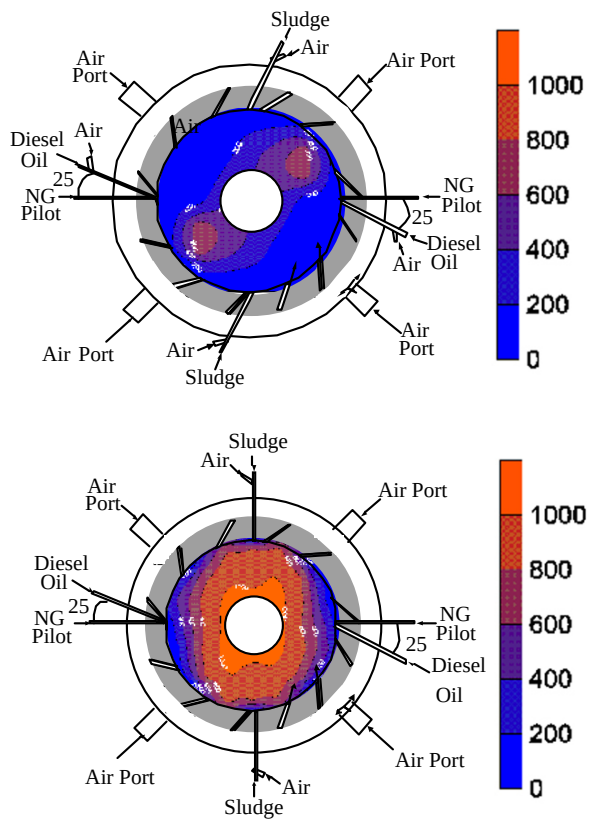


Figure 8. VCC Floor Temperature Contours for (a) Original Configuration at 20 GPH Low Heating Value Sludge (Water) and (b) Final Configuration at 40 GPH.

- Increasing the number of fuel injectors from one to two: this produces a more uniform thermal profile in the VCC.
- Moving the sludge injector to a radial injection orientation: this injects the sludge towards the vortex core region. Isothermal flow studies suggested that limited penetration of the core would occur. This orientation avoids that sludge impinges on the opposite wall, which leads to the failure mode.
- Equipping the fuel injectors with commercial off-the-shelf pressure nozzles: the optimal nozzle characteristics included a 40° spray angle with a flat spray orientated horizontally in the VCC spinning combustion zone.
- Doubling the sludge atomization air from 140 to 280 standard lpm (5 to 10 scfm) per injector to improve atomization and subsequent evaporation.

Sludge Processing Performance of Full-Scale VCC

The performance for various sludge compositions was determined under air-rich operation. The separate sludge surrogate streams investigated included 100% water, 2% inert (mullite) particles in water, 5% ethanol in water, 0.5, 1.0 and 5.0% diesel fuel number 2 in water, and simulated blackwater

sludge consisting of 98% water, 1.6% dog food, 0.2% vegetable oil, and 0.2% toilet paper. A summary of the CO emissions for these tests is presented in Figure 9. It is evident, that the CO emissions for all sludge types fall well below IMO standards for shipboard waste processing. For these cases total hydrocarbon emissions were also low below 10 ppm and NO emissions were below 150 ppm @ 7% O_2 for all cases. It should be noted that the fixed nitrogen in the blackwater would account for 50 000 ppm if converted.

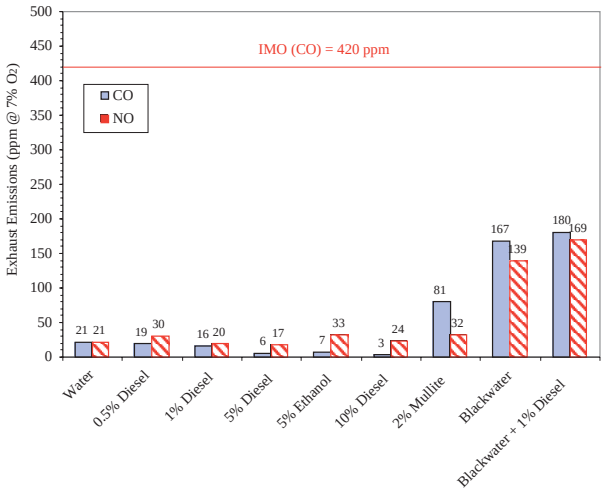


Figure 9. VCC emissions of CO and NO for various sludge types fed at 3.2 lpm. The VCC was operated at nominally 640kW and 5% O_2.

For the tests with 2% inert particles in water and simulated blackwater sludge, manual gas sampling of the exhaust using EPA Method 5 was conducted. The moisture content in the exhaust gas confirmed that 100% sludge evaporation was achieved. The VCC particle trapping efficiency was approximately 50% for the 2% inert particles in water. For a mean diameter of 26 microns for the mullite particles the capture performance was relatively good, however, optimization of particle trapping is still in progress. The Method 5 results from the simulated blackwater sludge tests showed that essentially all organic solids were burned out prior to exiting the VCC and no organic solids were detected in the exhaust.

The repeatability and consistency of the CO performance was demonstrated during a 5-hour operation when different sludge types were treated and the sludge mass flow was varied. The sludge type was changed from 3.2 lpm water to 3.2 lpm water plus 1% oil, 3.2 lpm blackwater sludge surrogate with 2% organic solids, and 3.2 lpm blackwater sludge plus 1% oil. As shown in Figure 10, the CO emission was below the IMO standard of 420 ppm for all sludge types and increased from 20 ppm for water plus oil to nearly 200 ppm for blackwater sludge plus oil. For the latter sludge surrogate, the CO was reduced to 60 ppm when the sludge flow rate was reduced to 2.2 lpm (Figure 11). The NO emission increased to about 150 ppm with the surrogate sludge plus oil. The stack temperature varied around an average value of 1100 C.

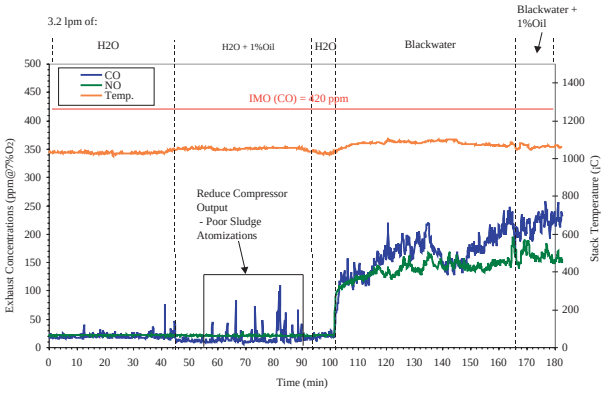


Figure 10. VCC Emission Performance for Varying Sludge Types.

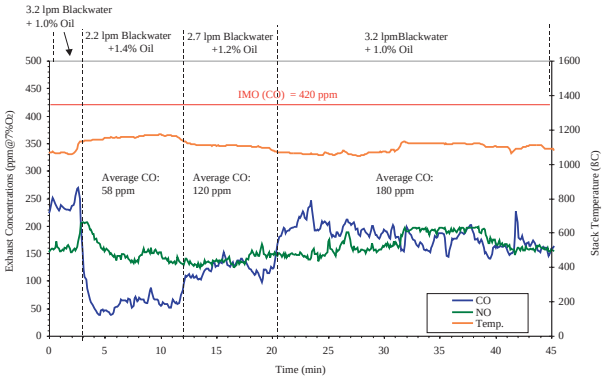


Figure 11. VCC Emission Performance for Varying Sludge Mass Flow Rates.

Based on all of the VCC data, upper and lower specification limits for operation regions yielding the best performance in terms of CO and NO emissions were identified. Parameters included total heat input 690 to 615 kW (2.36 to 2.1 MMBTU/hr), air-flow rate 12.9 to 12.6 m3/min (454 and 446 scfm), excess oxygen (5.0 and 4.5 %), and exhaust gas temperature (1050 and 1010 C).

CONCLUSIONS

A compact and efficient combustion system based on the VCC concept was developed for the treatment of shipboard generated non-oily and oily sludges. Flame stability and evaporation limit goals were achieved by optimizing the auxiliary-fuel and sludge injector arrangements. The CO emissions for the various sludge types tested were below the IMO standards with less than 20 ppm for water plus 5% oil (full-scale tests) and 10% ethanol (sub-scale tests) to 200 ppm for blackwater sludge plus 1% oil (full-scale tests). The VCC particle-trapping efficiency was approximately 50%, which is relatively good for the very fine particles used in the experiments, however, optimization of inert particle trapping is still in progress. In the sub-scale VCC tests, the CO emission was further reduced to 7 ppm by adding the AB. Non-reacting sub-scale and full-scale experiments provided insight into the characteristics of auxiliary-fuel and sludge injection and particle retention. This physical understanding together with VCC floor temperature profiles was critical to achieve the goals for sludge processing rate and CO emission. A controller concept for the VCC was developed in sub-scale tests to allow automated processing of sludges with highly varying heating values.

FUTURE PLANS

Presently the VCC design is being optimized to further improve performance and maintainability. Modifications include updated material selection to reduce weight, and improved vortical air-flow injection channels for increased cyclone strength and therefore particle trapping efficiency. In addition a modular exhaust quench section (to avoid dioxin formation), an ash collection system (to improve trapping efficiency), an integrated diesel-fuel piloted auxiliary-fuel burner, and the controller (to adjust auxiliary-fuel and sludge flow rates to maintain optimum operation with varying sludge type) will be integrated into the VCC system.

ACKNOWLEGEMENT

The project was funded by the Strategic Environmental Research and Development Program (SERDP) (Dr. Robert Holst, Program Manager).

NOMENCLATURE

AB	Afterburner
C	Celsius
gpm	Gallons per minute
gm/cm^3	Grams per cubic centimeter
Hz	Hertz
IMO	International Maritime Organization
kW	Kilowatt
lpm	Liters per minute
LC	Laboratory combustor
mm	Millimeter
mg	Milligram
MJ	Megajoule
NO	Nitrous oxide
ppm	Parts per million
VVC	Vortex containment combustor
UHC	Unburned hydrocarbon

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