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ABSTRACT

This paper describes a secondary combustion chamber (SCC) for hazardous waste treatment systems that uses a plasma arc torch as the heat source. Developed under a cooperative research and development agreement (CRADA) between Retech, Inc. and Lawrence Livermore National Laboratory (LLNL), the unit is intended primarily to handle the off-gas from a Plasma Arc Centrifugal Treatment (PACT) system. It is designed to heat the effluent gas which may contain volatile organic compounds, and maintain the gas temperature above 1000 C for two seconds or more. The benefits of using a plasma arc gas heater are described in comparison to a conventional fossil fuel heated SCC. Thermal design considerations are discussed. Analysis and experimental results are presented to show the effectiveness in destroying hazardous compounds and reducing the total volume of gaseous emissions.

INTRODUCTION

The Plasma Arc Centrifugal Treatment (PACT) system uses heat from a plasma torch to treat a wide variety of hazardous waste materials. Figure 1 is a diagram of a typical PACT system. To process waste, material is fed into a sealed centrifuge where it is exposed to intense heat from a transferred-arc plasma torch. Organic materials are thermally decomposed soon after entering the primary chamber and become an effluent gas. When treating hazardous substances, this off-gas must pass through a secondary combustion chamber (SCC) to assure complete oxidation of hydrocarbons and destruction of toxic compounds. Nonvolatile inorganic materials are melted in the primary PACT chamber and reduced to a molten slag. The centrifugal motion of the refractory lined tub and the pressure of the plasma arc serve to uniformly heat and mix the material.

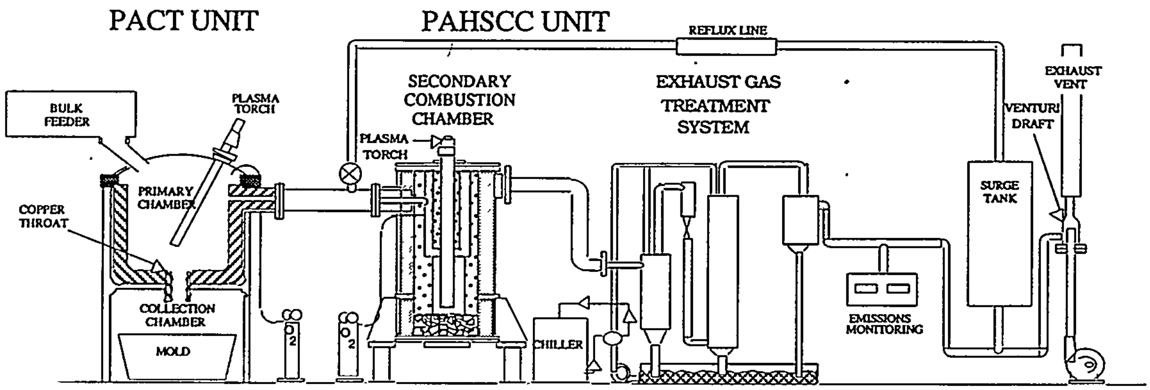

Figure 1. Plasma-Arc Centrifugal Treatment (PACT) System

An oxygen lance is used to provide supplementary oxygen that gets consumed by oxidizing metals and organics. By slowing the centrifuge, molten slag is discharged through the throat region into a collection mold in the collection chamber below. The final product is a glass-like solid that easily passes toxicity characteristic leachability procedures (TCLP) and may therefore be disposed of safely.

RATIONALE FOR A PLASMA HEATED SCC

The purpose of the SCC is to ensure that all of the volatile organic and inorganic material leaving the PACT unit has been completely oxidized and effectively destroyed. To achieve destruction and removal efficiency (DRE) of 99.999% or greater for organic material, the standard design for a secondary chamber keeps the gas at 1000 C in an oxygen rich environment for at least two seconds . The conventional method to achieve this temperature is to use a combustion burner fueled by oil or natural gas. This adds a substantial amount to the gas stream. A plasma torch heated SCC is more efficient in heating gas and can provide more heat for a given volume of added gas than a fossil-fuel burner. For example, a 200-kW plasma torch operates with a typical gas flow rate of 8.5 Nm^3/h. Assuming a nominal loss of 40 kW in the torch head, the plasma torch system can provide 18.8 kWh/Nm^3 of process energy at temperatures above the needed 1000 C. In comparison, a standard natural gas burner consuming a stochiometric amount of oxygen derived from air, at best provides only 5.3 kWh/Nm^3 for the same volume flow rate. Typically, for an equivalent heat input, a plasma torch will introduce only one eighth the gas flow added by a natural gas burner. This increased efficiency reduces the volume of the SCC as well as any downstream gas scrubbing equipment and auxiliary systems.

PACT-1.5 OFF-GAS MEASUREMENTS

To gain a better understanding of the process conditions that the SCC must contend with, we measured and analyzed the gaseous output from a representative PACT unit. Measurements were made for selected feed materials under various operating conditions. LLNL developed a diagnostic module that could be inserted into Retech's existing PACT-1.5 experimental testbed. The PACT-1.5 is a small (1.5-foot diameter) unit suitable for batch processing. The gas sampling section included thermocouples to measure gas and wall temperatures, pitot tubes to measure flow rates, and sampling lines to extract hot gases for on-line or subsequent off-line chemical and particulate analysis.

The basic feed material for all of these experiments was soil from Mendocino County, California. The composition of the soil is approximately 64% SiO_2, 15% Al_2O_3, 8% Fe_2O_3, 4% MgO, and 3% CaO, along with minor amounts of other trace elements. The total organic content in the soil was determined to be approximately one percent. The water content is estimated to be between five and ten percent. Diesel fuel was used as a representative organic contaminant material. Polyethylene (PE) and polyvinyl chloride (PVC) were added in modest quantities to the feed soil for some tests. Nitrogen was used as the primary torch gas, but helium and air were also tested.

Figure 2 represents typical data from one series of runs. It shows the gas temperature (Tg2) rising rapidly after starting the plasma torch and increasing as the system begins to warm up. The gas temperature drops dramatically when the torch is turned off to make adjustments to control settings. The inner wall temperature (Ts4) of the gas sampling section is lower than the gas temperature and indicates the amount of heat loss through the thermal insulation as well as the inefficient convective heat transfer from the gas to the wall.

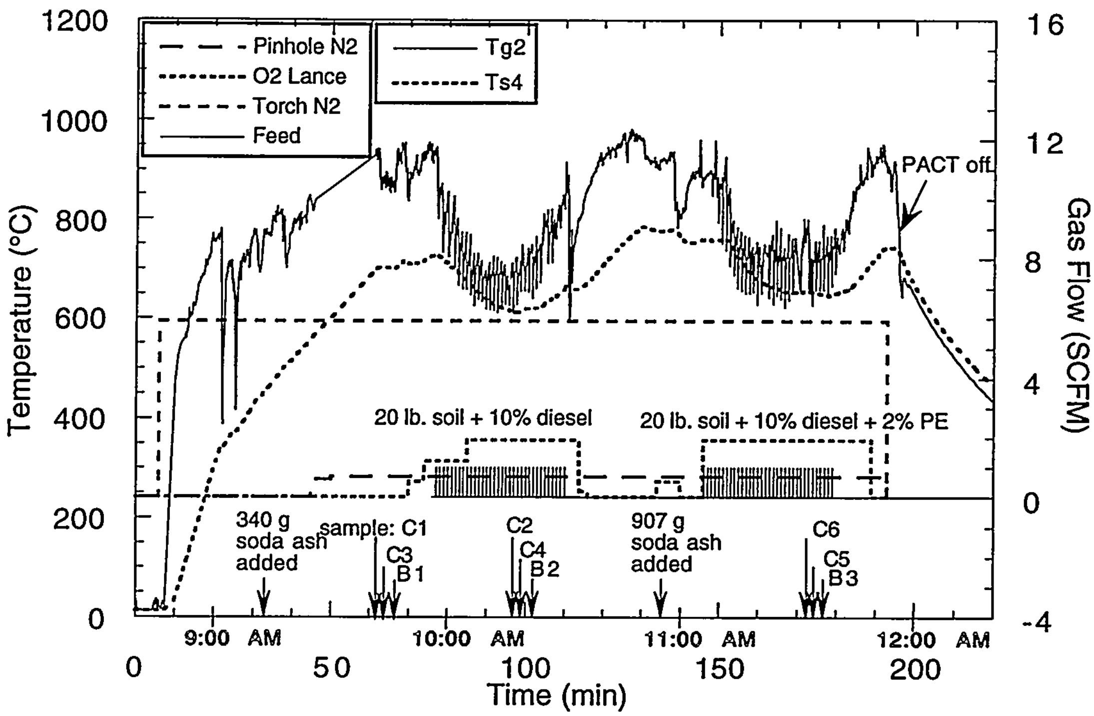

Figure 2. Plot of data from PACT-1.5 Off-gas Measurements

Figure 2 also shows the amount of gas (in scfm) introduced by the plasma torch, oxygen lance, and the pinhole camera viewport for these runs, as well as the times when gas samples were drawn into cylinders (C-x) or bags (B-x). The comb-like trace indicates when and how material was fed in using an Archimedes-screw feeder. Each spike represents one turn of the screw feeder which introduces approximately 350 g of soil containing 10% diesel fuel. For this series of runs the feed was added incrementally at a rate of one turn every minute. A sharp temperature excursion can be seen each time material is fed in, while there are slower changes in average temperature as equilibrium conditions are reached for different processing conditions.

With these experiments we were able to quantify the amount and chemical composition of gaseous effluent the SCC has to handle for typical PACT operating conditions. Table I has summary information for some of the experiments. Each column represents a different set of run conditions. It is worth noting that in four of these runs there was insufficient oxygen introduced for full combustion of all the hydrocarbons. The last column contains data from the run where enough oxygen was added for complete combustion. With an SCC there will be flexibility in adding supplemental oxygen either in the primary or the secondary chamber and adjusting the process heat source accordingly.

Table I - Summary of PACT-1.5 feed materials and effluent gas constituents

Feed Materials:			Soil 10% D	Soil 10% D 2% PE	Soil 10% D 8% PE	Soil 10% D 5% PE	Soil 10% D 5% PE
Torch gas			N2	N2	N2	He	Air
Feed amounts							
Nitrogen	N2	g/s	3.890	3.890	3.890	0.410	3.820
Oxygen	O2	g/s	1.290	1.290	1.290	1.290	2.340
Helium	He	g/s				0.720	
Argon	Ar	g/s					0.060
Hydrogen	H	g/s	0.092	0.102	0.196	0.097	0.097
Carbon	C	g/s	0.367	0.434	0.935	0.444	0.444
O2 needed for all HC		g/s	1.715	1.973	4.061	1.952	1.952
Gas Constituents			mol%	mol%	mol%	mol%	mol%
Hydrogen	H2		3.73	9.01	3.31	1.26	0.03
Helium	He					64.57	0.22
Nitrogen	N2		74.54	66.17	75.26	16.72	71.69
Oxygen	O2		7.73	6.29	1.81	2.37	11.26
Argon	Ar		0.14	0.12	0.17	0.16	0.80
Carbon Monoxide	CO		3.96	9.53	5.80	3.37	0.47
Carbon Dioxide	CO2		9.44	8.04	13.41	11.50	15.23
Nitric Oxide	NO		0.03	0.02	0.16	0.04	0.30
Nitrogen Dioxide	NO2						
Methane	CH4		0.24	0.50	0.06		
Acetylene	C2H2		0.10	0.18			
Ethylene	C2H4						
Ethane	C2H6		0.01	0.05			
Benzene	C6H6		0.02	0.04			
Hydrogen Cyanide	HCN		0.04	0.06			
Water	H2O		0.02	0.01	0.03	0.01	0.04
	Total	%	100.0	100.0	100.0	100.0	100.0

Chemical analysis of the gas samples showed good agreement with the expected gas makeup for the process conditions and gas inputs. While time-averaged gas sampling and chemical analysis can provide sufficient information to determine destruction and removal efficiency (DRE) of targeted compounds, time-resolved chemistry measurements are important in understanding the chemical kinetics and ways to optimize the SCC performance.

Calculations of kinetic chemical reactions were performed by LLNL for several gas mixtures resembling the chemical composition of the effluent gas from a PACT system treating contaminated soils. The chemical kinetics code follows a Lagrangian element (bubble of gas) in its path through a chemical reactor. This time-dependent, zero-dimensional code can calculate the chemical reactions and chemical composition for any number of chemical species. The objective of these calculations is to find the optimum conditions of temperature and residence time for the destruction and oxidation of any remaining hydrocarbons and carbon monoxide in the PACT effluent gas.

Calculations show that for a temperature of 1000 C, and an abundance of oxygen 30 %

greater than the stoichiometric amount, all the hydrocarbons exiting the PACT-1.5 are oxidized below the levels currently measurable. Carbon monoxide (CO) is the most difficult compound to oxidize, especially to levels below 10 ppm. Figure 3 shows a series of curves indicating the CO abundance verses time for different gas temperatures. These calculations were run for 20 seconds. In this particular calculation the temperature was kept constant as a function of time. While higher temperatures (1200 C) reduce the CO abundance quite rapidly, the final asymptotic value is relatively high. With lower temperatures (700 C) the reaction takes longer to complete, but reaches a much lower final level. These results imply that a preferred temperature profile would heat the effluent gases very rapidly to 1200 C and then allow the gases to cool down to 800 C in two seconds while passing through the SCC. This scenario is certainly possible with a plasma arc gas heater in the secondary combustion chamber. Experiments are needed to to confirm these predictions.

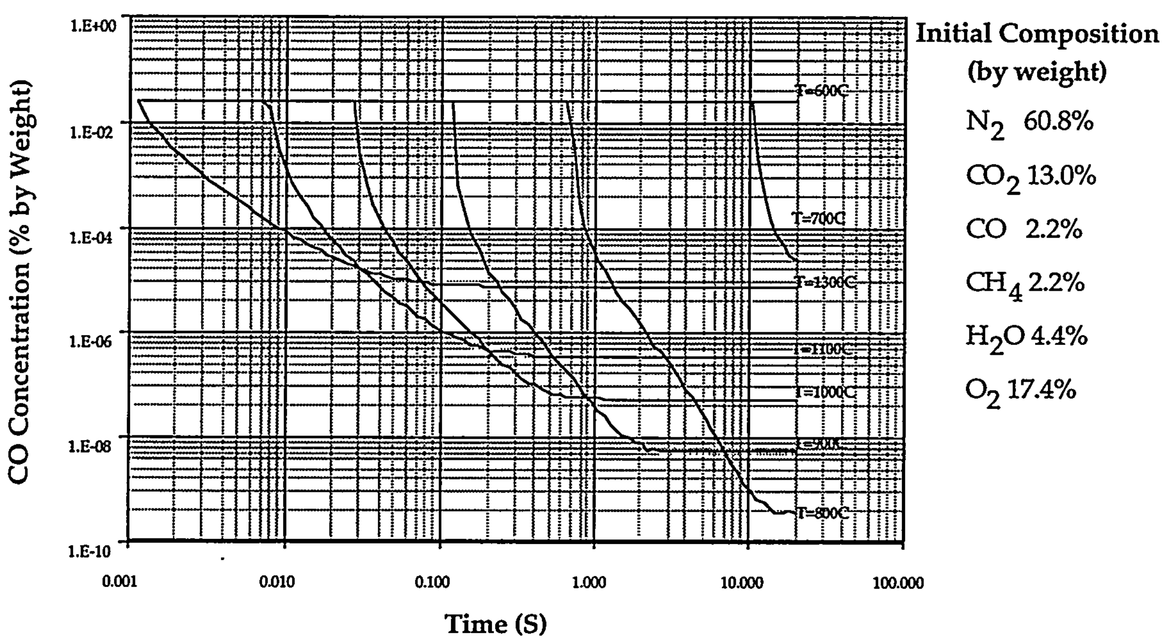

Figure 3. Calculations of kinetic chemical reactions in SCC

SCC DESIGN CONSIDERATIONS

A prototype secondary combustion chamber was designed and constructed, and has been operational since July of 1994. Whereas the PACT unit typically employs a transferred-arc plasma torch, the SCC uses a non-transferred-arc plasma torch. Schematic diagrams of both types of plasma torches are shown in Figure 4. These swirl-flow, hollow-electrode plasma torches can operate with a wide variety of gases at moderate flow rates.

The basic chamber design for a plasma heated secondary chamber is a refractory lined cylinder incorporating an inner baffle to divert the gas flow. A schematic of the chamber is shown in Figure 5. The chamber is water cooled utilizing the double jacketed steel construction. This insures all seal surfaces are maintained at or near room temperature. This type of design minimizes the possibility of leaking unprocessed off-gas from the secondary chamber, and minimizes the possibility of air leakage into the chamber. The plasma torch is also water cooled and is further protected by a surrounding layer of refractory material.

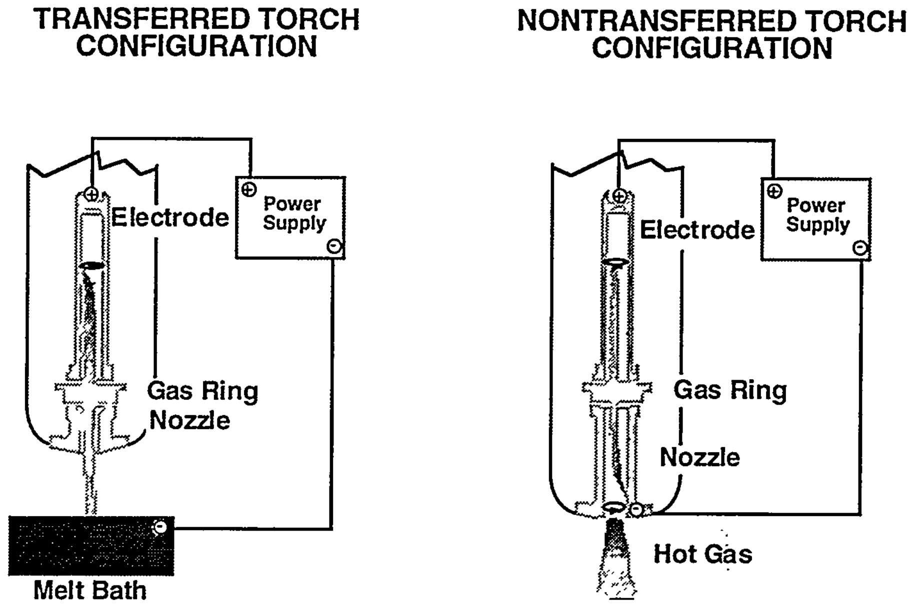

Figure 4. Plasma Torch Types

Maintaining the exhaust gas stream at 1000 C for two seconds requires a well insulated vessel. High temperature refractories, having melt temperatures ranging from 1500 C to 2200 C, are used for insulation. The insulation material and thickness was chosen to limit the heat losses but keep the inside wall temperatures below the melt rating. A temperature gradient exists along the axial direction of the inner walls because the torch preferentially heats the region nearest it.

The insulation in the SCC stores a significant amount thermal energy. A typical warm-up time was estimated to be approximately five hours based on an instantaneous temperature rise at th inside refractory wall to 1500 C . Once steady state operation is reached in the SCC, the plasma torch only needs to provide enough power to heat the effluent gases from the PACT along with any supplemental oxygen, and to compensate for any heat losses. The primary heat loss is by conduction heat transfer through the insulated walls of the chamber and the jacket surrounding the water cooled torch. The exhaust gas exiting the SCC also represents a heat loss to the system. Estimates of these heat losses are given in Table II, along with the required torch power, assuming an 80% torch efficiency.

Table II. Heat flow analysis for various PACT-1.5 Gas Flow Conditions

- Case 1: feed rate - 20 lb/hr of soil with 10% diesel
- Case 2: feed rate - 20 lb/hr of soil with 10% diesel and 10% polyethylene
- Case 3: feed rate - 40 lb/hr of soil with 10% diesel
- Case 4: feed rate - 40 lb/hr of soil with 10% diesel and 10% polyethylene
- Total SCC loss includes conduction losses and total heat added to the gases
- Total torch power includes losses in the torch assuming 80% efficiency

	PACT Torch N2 (slpm)	PACT Other gases (slpm)	SCC Suppl. O_2 (slpm)	Heat for PACT gases (W)	Heat for SCC O_2 (W)	Heat for Total Gas (W)	Total SCC loss (W)	Total Torch Power (W)
Case 1	160	44	7	1113	181	1294	12,994	16,243
Case 2	160	88	14	1436	363	1799	13,499	16,874
Case 3	160	88	14	1436	363	1799	13,499	16,874
Case 4	160	176	28	2082	725	2807	14,507	18,134

PRELIMINARY RESULTS WITH PROTOTYPE SCC

A series of test runs were conducted during July of 1994 in which 2500 grams of polyvinyl chloride (PVC) was fed into the PACT-1.5. Under ideal conditions, PVC (C_2H_2HCl polymer) will convert completely to carbon dioxide, water vapor, and hydrogen chloride. The expected concentrations of O_2, CO_2, H_2O and HCl were calculated based on the PVC feed rate and rates of gas flow into the PACT and SCC, assuming complete burning. Continuous emissions monitoring during these experiments recorded the quantities of these same compounds in the effluent stream before the gas scrubber.

Table III compares the calculated estimates and the measured quantities of gas concentrations when PVC is being fed into the PACT unit. The measurements during run times are in agreement with the predicted values to within a few percent. This shows that a simple analysis can be used to estimate the amount of oxygen to feed into the PACT unit for a particular waste stream. To handle waste streams with widely varying amounts of organic material, the SCC should have on-line monitoring of oxygen levels and proportional control of oxygen feed to insure conditions for complete combustion.

Table IIIa. Comparison of calculated and measured amounts of selected components in SCC off gas for PACT-1.5 experiment Run 5 on July 21, 1994.

	Warm-Up		Run		Holding		SCC off	
	Calc.	Meas.	Calc.	Meas.	Calc.	Meas.	Calc.	Meas.
O_2	0	10.1%	18.4%	16.5%	13.5%	15.4%	30.3%	23.2%
CO_2	0	0.1%	4.4%	5.2%	0	0.25%	0	0.1%
H_2O	0	4.1%	2.2%	4.1%	0	4.1%	0	4.1%
CO	0	1ppm	0	10ppm	0	10ppm	0	10ppm
NOx	0	0.39%	0	0.44%	0	0.44%	0	0.36%
HCl	0	NM	2.8%	NM	0	NM	0	NM

Table IIIb. Comparison of calculated and measured amounts of selected components in SCC off gas for PACT-1.5 experiment Run 6 on July 21, 1994.

	Warm-Up		Run		Run	
	Calc.	Meas.	Calc.	Meas.	Calc.	Meas.
O_2	0	8.1%	16.6%	17.1%	16.7%	16.2%
CO_2	0	0.3%	5.4%	6.3%	5.4%	5.8%
H_2O	0	6.1%	2.7%	6.1%	2.7%	6.1%
CO	0	10ppm	0	10ppm	0	10ppm
NOx	0	0.33%	0	0.46%	0	0.43%
HCl	0	NM	3.5%	NM	3.5%	NM

Table IIIc. Comparison of calculated and measured amounts of selected components in SCC off gas for PACT-1.5 experiment Run 7 on July 22, 1994.

	Run		Run		Hold	
	Calc.	Meas.	Calc.	Meas.	Calc.	Meas.
O_2	20.6%	16.0%	20.6%	18.8%	0	8.0%
CO_2	6.4%	7.1%	6.4%	7.2%	0	0.8%
H_2O	3.2%	6.3%	3.2%	6.3%	0	6.3%
CO	0	100ppm	0	10ppm	0	10ppm
NOx	0	0.40%	0	0.42%	0	0.26%
HCl	4.1%	NM	4.1%	NM	0	NM

During this same series of test runs, calorimetry measurements were taken on all the SCC cooling circuits. The readings from the SCC chamber circuit show that chamber heat losses had not reached steady state levels by the end of the run. This is as expected since the operating time for the SCC during any one of the tests was less than 80 minutes. The greatest heat loss from the SCC chamber circuit was 8 kW.

The average torch power into the SCC during this series of tests runs was 130 kW. An average of 90 kW was removed from the SCC by the torch cooling system. During these tests, the torch was fully extended into the hot center of the chamber and was not fully covered with insulating refractory material, therefore becoming a sizable heat sink. Approximately 40 kW was available to heat the off gas and chamber walls. Previous analysis had predicted that 16 to 18 kW of torch power would be needed for steady state operation. Measurements made with thermocouples placed at selected points within the SCC showed that temperatures never exceeded 1500 C; however, it was apparent that substantially more power was being applied than was needed for steady state operation. Further testing must be done to gain operational experience and provide a thorough evaluation of the SCC performance.

SUMMARY

A plasma-arc heated secondary combustion chamber is being developed under a CRADA between Retech, Inc. and LLNL. The unit is being designed to handle the effluent gas from Retech's PACT system. Experiments have been conducted to characterize the off-gas flows from a PACT system processing contaminated soils. Design analysis shows the unit will meet the requirements of heating the effluent gas and maintaining its temperature above 1000 °C for two seconds. Calculations of kinetic chemical reactions are being performed to investigate optimal processing conditions. A prototype unit has been in operation since July 1994, and work is proceeding to demonstrate and validate its performance in actual processing runs as part of a PACT-2 system.

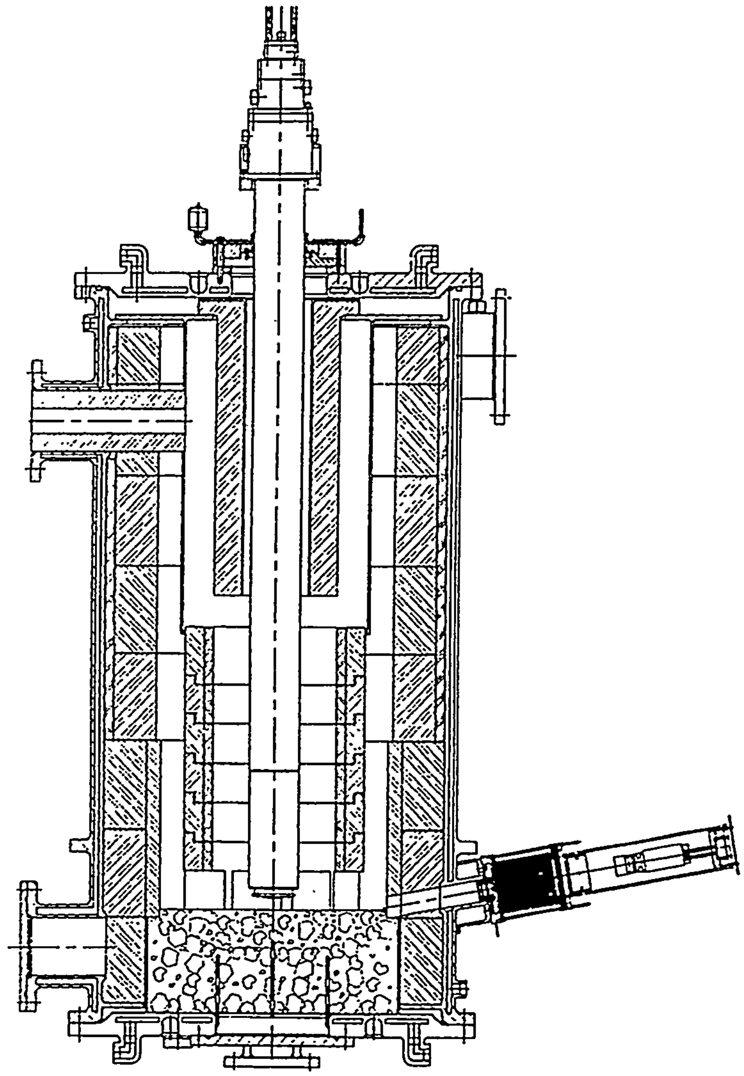

Figure 5. Plasma-Arc Heated Secondary Combustion Chamber

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