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STUDY FOR EVALUATION OF
INCINERATION AND MICROWAVE TREATMENT OF
HUMAN FECAL MATTER FOR SPACECRAFT OPERATION

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for

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SUMMARY

In a closed life support system one of the processes that is likely to be involved in reclaiming usable products is the incineration of feces. Information is available on characteristics of the incineration process such as the specific heat of wastes, ignition temperature and overall oxygen requirements. Little or no information is available concerning the characteristics of effluent products formed, and the effects of incineration operating parameters on these products.

This program has been concerned with experimental evaluation of both incineration and microwave treatment of feces, and with characterizing the effluent products formed in each process. The influence of pressure, oxygen concentration, temperature, and power level on these processes has been evaluated, and the concentration ranges and identities of liquid, gaseous and solid products have been established.

The major gaseous products of complete oxidation during incineration were primarily carbon dioxide and some nitrogen, with less than a total of 0.1% of minor gases such as carbon monoxide, methane and nitrogen oxides. When

incomplete oxidation occurred the minor gas concentrations increased to as high as 20%. The water condensate in both complete and incomplete oxidation contained up to 1 mg/ml of NH_4^+ , SO_3^- , SO_4^- , Cl^- and particulate matter, and was generally acidic, but with a pH ranging from 1 to 8. The solid residue was generally a grey-white ash. The condensate and solid residue were characteristically sterile, but in isolated cases showed bacterial growth which might have been externally introduced.

Pressure and oxygen concentrations above stoichiometric during incineration did not appear to influence product characteristics. The incineration process occurred in three phases: 1) drying, 2) pyrolysis combined with separate oxidation of pyrolysis gases, and 3) final oxidation of remaining solids.

The gaseous products from microwave treatment were minimal amounts of carbon dioxide, carbon monoxide, methane and hydrogen sulfide. The condensate escaping the reactor appeared sterile. The solid residues were sterile only in those instances where exposure to boiling was maximized. Pressure affected the microwave process only in relation to depression of the water boiling-point.

INTRODUCTION

In the closed spacecraft environment the accommodation and treatment of fecal waste constitute a primary phase of the overall waste management system. For extended missions, the recovery of water and other possible by-products, such as carbon dioxide or methane, from drying and incineration of fecal material could constitute a source for water and food supplement raw materials. This program has been concerned with investigation of the parameters controlling drying and incineration of feces, and with identifying the products resulting from these processes. Both thermal and microwave energy systems were evaluated in this investigation.

Objectives

The major objectives of this program were to identify the products resulting from drying and incineration of feces, and to demonstrate the effects of parameters such as pressure, oxygen concentration, temperature and power level, on the composition of these products. Two processes for feces treatment were to be evaluated and compared: 1) Thermal incineration with oxygen in a dynamic flow-type reaction system, and 2) Microwave processing in a recirculation-type system. Both of these processes were to be evaluated in a single system having both thermal incineration and microwave treatment capabilities.

The gaseous, liquid, and solid products of these processes were to be characterized as to appearance, color, odor, chemical composition, and bacteriological purity. Corollary objectives were to achieve complete

incineration with little or no excess oxygen, at minimum temperature levels, and to establish specific properties, such as the ignition temperature, and oxygen demand for typical fecal samples. Specific objectives of microwave testing were to evaluate the effect of power level on feces drying, and to establish the nature of decomposition products formed during drying.

Approach

The general approach taken was to fabricate and assemble a system capable of separate or combined thermal incineration and microwave treatment, to conduct preliminary tests to evaluate the systems and processes, and finally, to conduct definitive tests and derive the required performance and reaction product data. The system was sized to accommodate the average amount of feces generated by one man. No attempt was made to optimize the system for power or weight.

The preliminary tests served to demonstrate the process routine and typical test conditions. Subsequent definitive tests were conducted at specific selected pressures, temperature levels, oxygen concentrations and power input levels in a pattern which would indicate the effects of these parameters on product quantity, composition, and bacteriological purity. The products formed were subjected to physical, biological, and quantitative chemical analyses. All of the fecal test specimens used were collected randomly from healthy adult males without imposition of measures to regulate the composition of the specimens.

EQUIPMENT AND PROCEDURES

The main components in the incineration and microwave treatment system were the main reactor assembly, microwave generator, catalytic reactor, power and temperature controls, feed gas controls, back-pressure regulator, and the product collection components. The system was arranged so that either incineration or microwave treatment could be conducted without alteration on the assembly. All of the system components except the collection apparatus are shown in Figure 1.

During testing, fecal samples were subjected to thermal heating or microwave energy in the main reactor chamber. The gases and vapors evolved in the incineration process were passed through the catalytic reactor to the product collection system; the products evolved during the microwave tests were passed directly to the collection system.

The same analytical tests were performed on both incineration and microwave final products. Gaseous products were analyzed by gas chromatography and infra-red techniques. In later tests the concentrations of oxygen and carbon dioxide in the effluent gas stream were also continuously monitored by polarographic and nondispersive infra-red analyzers respectively. Condensate components were subjected to physical, biological, and quantitative chemical analyses. Ash residues were weighed and subjected to biological analysis.

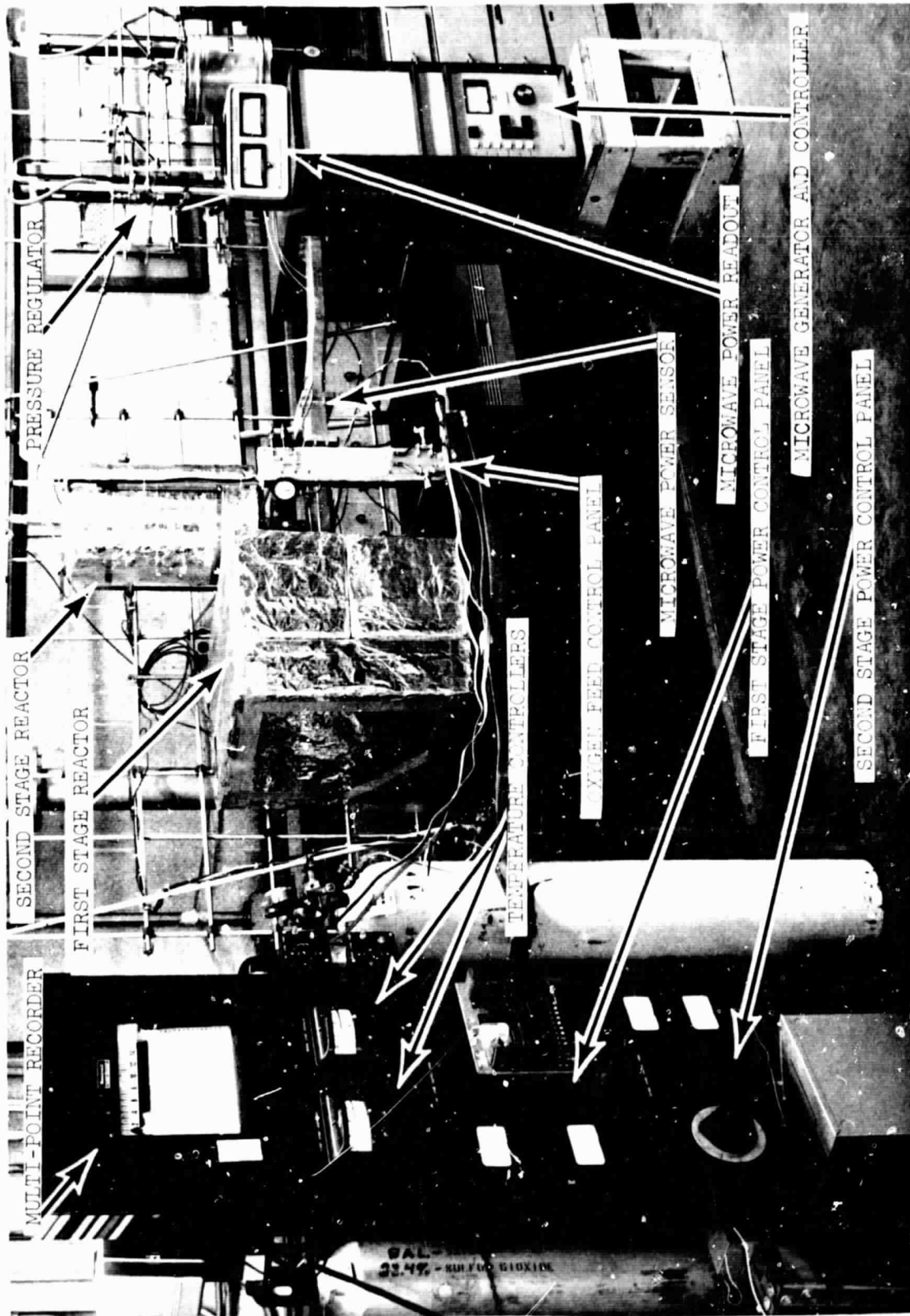


Figure 1. REACTOR ASSEMBLY AND CONTROL APPARATUS

Apparatus

The main reactor consisted of an eight-inch long stainless steel cylinder with a removable flanged end plate for access. A rectangular guide tube for directing the microwave beam into the six-inch diameter reactor was welded into the center of the opposite fixed end plate. The main vapor vent line, oxygen feed line, and thermocouple penetrations were also attached to the fixed end plate. The main reactor was heated by two semi-cylindrical heaters with a combined rating of two kilowatts. A 25 psig safety burst-disc was located in the vapor vent line leading to the catalytic reactor. Eight-inch thick insulation was used on the main six-inch diameter reactor so that the outer surface of the insulation remained below 100°F.

The opposite flanged end of the two-foot long microwave guide tube remained cool and was fitted with a microwave-transparent Teflon window, cemented in place, perpendicular to the path of the microwave beam. The Teflon window sealed the tube and prevented gas leakage into or out of the main reactor. However, after several incineration tests the tube was shortened to four inches and sealed shut with a stainless steel flanged plate for incineration tests. The long tube had acted as a condensation site for combustible vapors, and a minor detonation occurred within the tube during testing. In microwave testing the flanged end containing the Teflon window was attached to the microwave generator.

The catalytic reactor consisted of a three inch diameter, ten inch long stainless steel cylinder, with bolted flange plates on each end, for more flexible access. Two stainless steel wire mesh screens and interlock rings

retained the 700 cc. catalyst bed of eighth-inch cylindrical 0.5% palladium on alumina pellets. Two pairs of semi-cylindrical heaters with a combined capacity of 950 watts were used to heat the reactor. A three-inch layer of insulation enclosed the reactor.

The microwave generating system was a product of the Eimac Division of Varian Associates Inc. The system consisted of the following: 1) 2.5 kW generator and controller 2) WR 340 flexible waveguide, and 3) power monitor system. The generator was capable of 0 to 2.5 kW output at 2.45 Ghz (\pm .05Ghz). The power monitor system consisted of two units: a directional power sensor and a read-out panel. In operation, the microwave radiation propagated from the generator through the flexible waveguide, the power sensor unit, and the reactor waveguide tube into the main reactor cavity. The power monitor system provided read-out of the forward and reflected power levels. Generator protection was provided by the monitor system which automatically shut the generator off when the reflected power reached a predetermined level. The shut-off point could be varied from 0 to 750 watts, which was the maximum reflected power level that could be tolerated without harming the generator.

Analyses

The analyses discussed in the following sections were performed only on the products resulting from both incineration and microwave treatment experiments. No biological or chemical analyses other than standard COD tests were performed on the feces samples used for test purposes. All samples were furnished by adult males in apparent good health

Residue Analysis - The ash or residue remaining within the main reactor after incineration was analyzed for weight, odor, and sterility. A stainless steel liner which conformed quite closely to the shape and inner dimensions of the first stage reactor was used to contain the fecal sample and to insure complete recovery of the ash. The ash odor level was noted by subjective observation and recorded. The ash was then prepared for bacteriological analyses. One gram portions of the ash were blended with 100 ml of sterile buffered water in a blender. Two aliquots of this suspension one ml each, were then inoculated into sterility test media consisting of Brewer modified thioglycolate broth. Turbidity in one or both tubes was regarded as a positive indication of viable microorganisms.

Condensate Analyses - The condensate accumulated in the cold traps was submitted to a series of physical, chemical and biological analyses. The physical analyses were intended to demonstrate the gross character of the condensate. Turbidity and color determination were initially performed by the techniques outlined in Standard Methods for the Examination of Water and Wastewater. However, after several experiments these methods were discarded in favor of subjective observation because of the very high color and turbidity values obtained. The color in every case exceeded 100 chloroplatinate units and 25 Jackson turbidity units. Odor levels were also determined subjectively. Total solids were determined by evaporating to constant weight at 103°C. The residue from this analysis was salvaged for sulfate analysis. A calibrated conductivity bridge and cell were employed for conductivity measurements. Table I presents a summary of the chemical

Table I

CHEMICAL ANALYSES OF CONDENSATE QUALITY

Test Description	Method	Instrument	Sensitivity
pH	Electrochemical	Beckman Expanded Scale pH meter	0.01 pH units
Total Carbon	Combustion	Beckman Total Carbon Analyzer	0.5 ppm
Ammonia	Colorimetric	Bausch & Lomb Spectronic 20 Colorimeter	3 ppm
Chloride	Titrimetric	Microburet	3 ppm
Nitrogen Dioxide	Colorimetric	B & L Spectronic 20 Colorimeter	1 ppm
Sulfur Dioxide	Colorimetric	B & L Spectronic 20 Colorimeter	1 ppm
Sulfate	Nephelometric	Coleman Model 7 Nephelometer	1 ppm

analyses performed on the condensate. The table lists the parameters measured and the method and instrumentation used.

Analyses were performed for dissolved sulfur dioxide and nitrogen dioxide to aid in identifying the distribution of these gases in the effluent. The biological purity of the condensate was determined largely by sterility tests. Duplicate tubes of thioglycolate broth were inoculated with one ml aliquots of condensate. The condensate was stored in sterile containers at 35°F to be used if needed for additional tests. If biological activity was indicated, the condensate was then submitted to aerobic and anaerobic plate counts. The coliform population was estimated by the most probable number technique (MPN) using lactose broth fermentation tubes.

Gas Analyses - The analytical techniques and methods of accumulating and sampling effluent gases were changed during the course of the test program as various test results showed the need to provide more reliable information in a shorter time. The initial approach for gas analysis consisted of accumulating all gaseous products formed in a collection bag, and then conducting detailed chemical analyses and total volume measurements. Infrared absorption, using a variable path length gas cell, was employed as the initial gas analysis method and a wet test meter was used for volume measurement. After a sufficient number of tests it became apparent that in-process effluent analysis was necessary for effective oxygen management and attainment of complete combustion. Infrared analysis was eliminated because of the large sample volumes, 1.0 to 1.5 liters, necessary for analysis, because water and nitrogen oxides attacked the cell windows and because a relatively long period of time was required for each analysis. Emphasis was

placed on analysis methods capable of rapid response and execution requiring only small sample volumes.

Gas chromatography was substituted to accomplish in-process and cumulative analysis of nearly all components of interest.

As tests progressed it became evident that continuous monitoring of oxygen and carbon dioxide in the effluent gas stream was required. A Beckman polarographic oxygen sensor, and a Mine Safety Appliances infra-red carbon dioxide sensor were used for this purpose. With these two sensors the O_2 and CO_2 content were continuously indicated, with only about a ten second delay between actual and indicated composition, due mainly to the eight foot length of the sampling line. These instruments were calibrated daily when in use. Two chromatographs were employed to accomplish the analyses; a Beckman GC-2 and an Aerograph Model-90-2. The Aerograph instrument was fitted with a Porapak Q column for sulfur dioxide analysis, and the Beckman instrument was fitted with molecular sieve and silica gel columns to analyze hydrogen, methane, carbon dioxide, carbon monoxide, oxygen and nitrogen. Helium was employed as the carrier gas in both instruments. The Porapak Q, silica gel, and molecular sieve columns were maintained at 120°, 160° and 10°C respectively. An external water cooled bath was used to maintain the sieve column at 10°C.

In the silica gel-molecular sieve configuration, the gas sample moved from the injector port through the silica gel column and into one side of the thermal conductivity detector. From the detector, it moved through an empty coil of tubing, into the mole sieve column and through the other side of the detector. The empty coil provided sufficient delay to permit all

gases to elute from the silica gel column before the more mobile components eluted from the mole sieve column.

Because of the broad range of concentrations and the number of gases of interest, comprehensive calibration curves at each attenuation level for each gas were not prepared. Peak height correlations were obtained for a fixed sample size of each pure gas. From these correlations a conversion factor for peak height versus composition was determined. The accuracy of this approach was established with gas mixtures of known compositions. The percent composition values obtained by the above technique fell within $\pm 1\%$ of the real value throughout the attenuation range employed.

Special methods were employed for the analysis of nitrogen dioxide and hydrogen sulfide in the accumulated volume collected in the total sample gas bag. Nitrogen dioxide was measured by a modified Saltzman colorimetric technique.*. A special reagent mixture was employed which absorbed and formed a stable violet color with nitrogen dioxide. The technique is capable of reproducible results in the parts per billion range. In performing the analysis 10 ml of the reagent mixture was drawn into a 30 ml syringe. A 5 ml gas sample was then drawn into the syringe from the gas collection bag followed by 5 ml of pure oxygen. The addition of pure oxygen accomplished conversion of nitric oxide to nitrogen dioxide. The syringe was shaken vigorously several times during the 15 minute color development period. Absorbance of the test solution was measured on a Bausch and Lomb Spectronic 20 Colorimeter with the concentration obtained from a calibration curve

* Saltzman B. E. Anal. Chem Vol 26, No. 12, December, 1954.

based on sodium nitrite standards. Hydrogen sulfide was determined by colorometric change in a tube of absorbent, where the length of the absorbent changed indicated the sulfide content. The calibrated syringe and reagent tubes were manufactured by the Union Industrial Equipment Corp. and were capable of analyzing concentrations of hydrogen sulfide from 5 to 1,700 ppm. This technique was limited by the possible interference of sulfur dioxide or mercaptans.

INCINERATION

Three series of preliminary tests were performed before incineration testing was started. These preliminary tests were concerned with determining a) the reactor heating temperature time relationship at selected power levels, b) the chemical oxygen demand (COD) of typical human fecal samples, and c) the total carbon content of the samples (TC) as a parallel indicator of oxygen demand. After the preliminary tests were completed, a total of fifty-two incineration tests were conducted to demonstrate the feasibility of complete combustion of human fecal material, and to show the effects of pressure, temperature, and oxygen feed on product composition and bacteriological purity. Tables of complete test data for all fifty-two incinerator tests are shown in the Appendix.

Preliminary Tests

Thermal History Determinations - In these tests the temperature history of the main and catalytic reactors was recorded at various constant power levels. A precision watt meter (Weston Electrical Instruments Corp.) was employed to monitor power input to each stage. Reactor skin temperatures were allowed to reach 650 and 480°C for the main and catalytic stages, respectively, at which time the power was cut off. The temperature record was continued during the cool down period. The temperature levels indicated represented the maximums to which each stage would be heated during incineration and microwave experiments.

Figures 2 and 3 indicate the thermal history of the main and catalytic reactors respectively. As indicated in Figure 2, the main reactor was

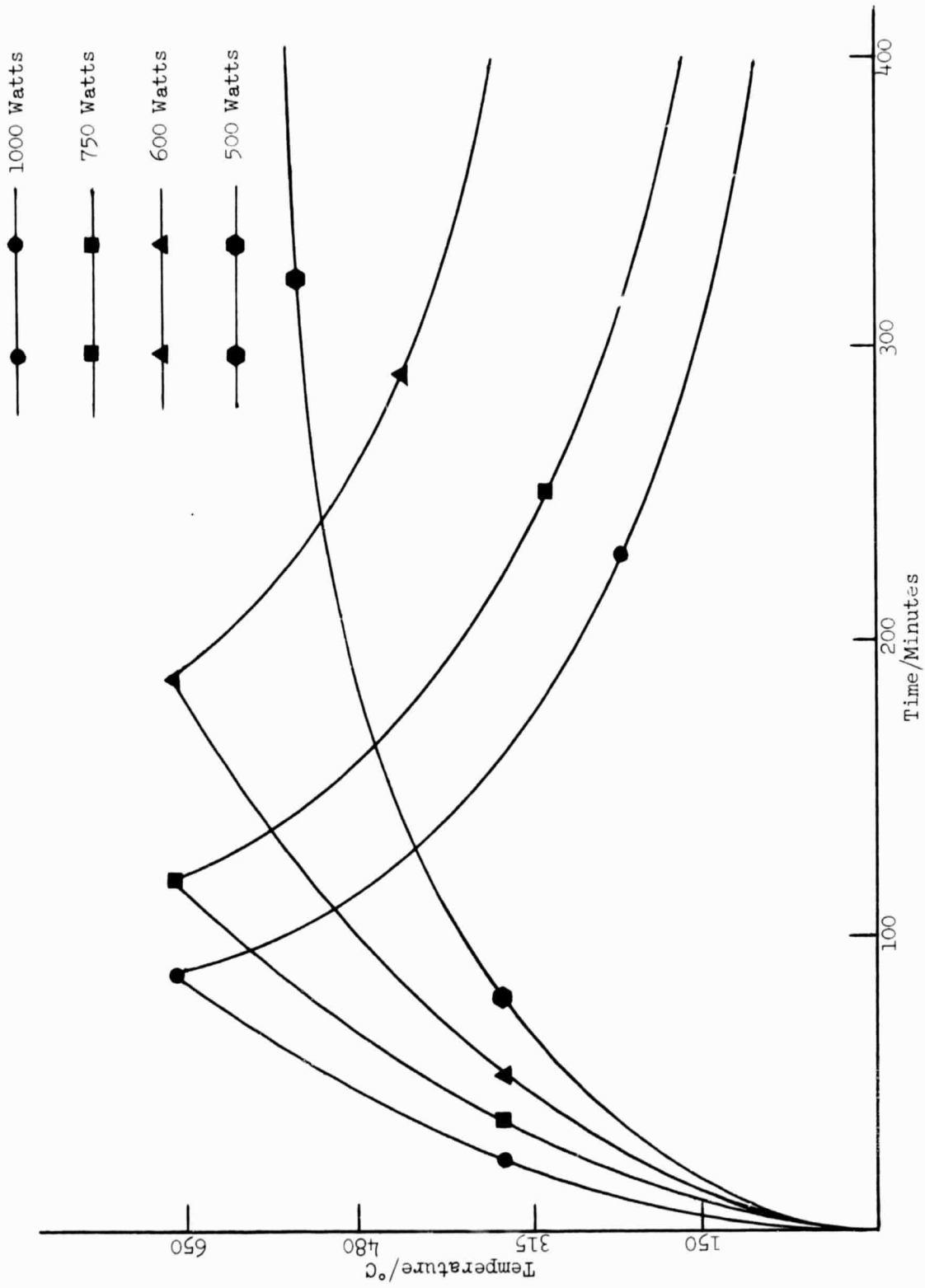


Figure 2. PRIMARY REACTOR-THERMAL HISTORY

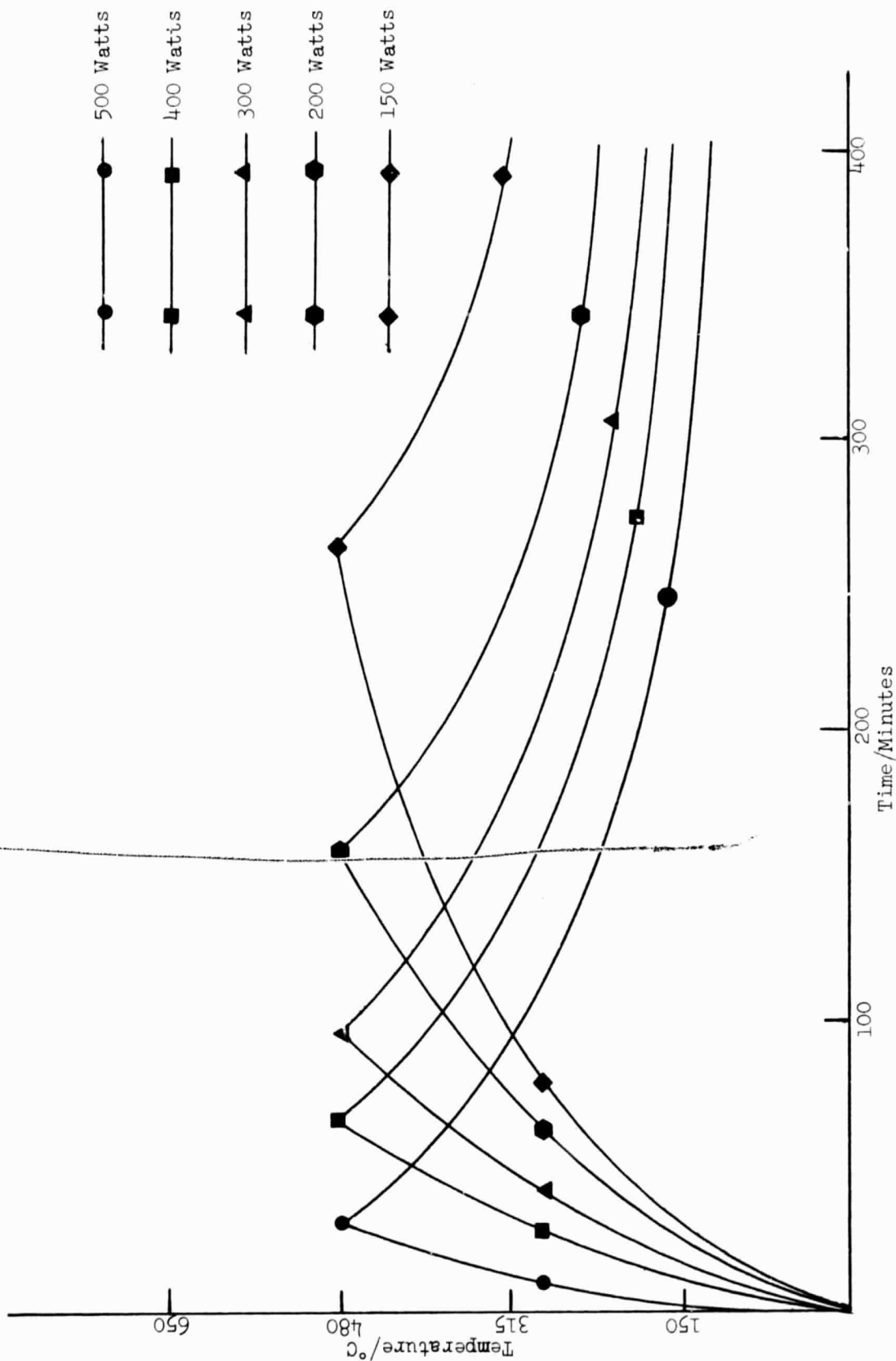


Figure 3. CATALYTIC REACTOR - THERMAL HISTORY

operated at 4 power levels in the range of 500 to 1000 watts. The catalytic reactor was operated at 5 power levels and in the range of 150 to 500 watts as shown in Figure 3. The marked difference in power requirement between the two reactors is due to a) the considerably larger mass of the main reactor, and b) the heat losses which occur through the waveguide extension of this stage.

These relationships indicated the temperature behavior of the reactors, and showed primarily the power required to achieve incineration temperatures within a specific time.

Oxygen Demand Experiments - These experiments were directed toward identifying the oxygen required for combustion of typical human feces on the basis of APHA chemical oxygen demand tests (COD). The tests were conducted to show the distribution of the oxygen requirement between the volatile and nonvolatile fractions of fecal matter.

In these tests, a 250 gram fecal specimen was heated in the main reactor to a temperature of 150°C, over a three hour period, and the volatiles collected in dry ice-acetone traps. The catalytic reactor was by-passed. Upon completion of heating the system was evacuated to insure complete recovery of volatiles. The solid residue remaining and the collected condensate were then submitted to COD analyses.

Table II shows the weight of condensate and solid residue for each sample and the total weight per cent recovered. The table also presents the volume of oxygen, calculated from COD values, required for combustion of the specimen compared to the volumes required by the corresponding residue and

Table II

Chemical Oxygen Demand of 250 gm Fecal Samples

Test No.	Conden. Weight Gm.	Residue Weight Gm.	Specimen Recovery Wt. %	COD Std. Liters			Residue COD % of Tot.
				Unheated	Residue	Condensate	
OD1	158.5	46.5	82.0	36.38	11.28	1.18	31.0
OD2	179.0	55.5	93.8	51.96	25.56	0.96	52.0
OD3	151.0	55.5	82.6	61.40	26.60	1.14	43.3
OD4	205.5	33.0	95.4	28.70	4.90	2.60	17.1
OD5	176.0	40.0	86.4	42.34	22.70	3.56	53.6

condensate. Tests 1 through 3 were conducted according to the above procedure while tests 4 and 5 were modified slightly. The differences in procedure in these last tests consisted in allowing the specimen temperature to reach 500°F in test 4, and in maintaining a helium atmosphere throughout the usual heating period in test 5.

The results indicate a wide variation in the chemical oxygen demand for typical fecal matter. The proportion of the total oxygen required for the volatile and non-volatile components was determined from oxygen requirements for the non-volatile, solid residue, since the oxygen values for the condensate appeared to be considerably less than anticipated. The oxygen required for the residue ranged from 31 to 54% of the total sample oxygen for specimens treated at 150°C, only 17% for the specimen raised to 260°C.

The combined residue-condensate oxygen requirements accounted for only 35 to 60% of the oxygen needed for the total sample despite 82 to 96% test specimen recovery. This data appeared to indicate that, during heating of the sample, pyrolysis occurred releasing non-condensable but oxidizable vapors or gases. Superficially, the overall results indicated that about half of the oxygen required would be used for combustion of solid residues, and the other half for volatile components.

COD/TC Comparison Tests - The objective of these tests was to develop a shorter and less complicated technique for determining the oxygen requirement of each test specimen prior to starting an experiment. The natural variation of typical feces specimens prevented accurate assignment of an average value for this requirement and, although the COD analysis provided a

Table III
COD/TC COMPARISON TEST DATA

Specimen Number	COD Value *	TC Value **	COD/TC Ratio
CT 1	0.457	0.0740	3.17
CT 2	0.371	0.118	3.15
CT 3	0.244	0.0715	3.13
CT 4	0.348	0.0800	4.35
COD 4r	0.2122	0.3736	0.57
COD 4c	0.0250	0.0083	3.02
COD 5r	0.8115	0.270	3.06
COD 5c	0.0289	0.0097	2.98

* COD values = mg O₂/mg substrate

** TC values = mg C/mg substrate

reasonable estimate of the oxygen demand, it required two hours for completion. Total carbon (TC) content could be determined in 10 to 15 minutes with a total carbon analyzer. The purpose of these tests, therefore, was to generate a correction factor for converting TC values to COD values and thereby reduce the time delay in testing.

The relationship between analytical values was investigated by performing parallel COD and TC analyses on the same specimen. Table III presents the data obtained from these tests. Specimen numbers CT 1 through CT 4 represent fresh feces samples collected on different days from various donors. Specimen numbers COD 4r through COD 5c consisted of portions of residue and condensate (identified in the table by r and c respectively) generated during COD tests 4 and 5 in Table II.

The values for the ratio of COD/TC indicate a reasonably close agreement for the first three samples while the fourth is considerably higher. In the residue-condensate samples, three values are quite close while a fourth is markedly lower. Each of the values presented in the COD and TC column are based on averages of two determinations. Although there are occasional variations in the COD/TC ratio, it would appear that a conversion factor based on these ratios is relatively accurate for estimating the oxygen requirement of human fecal matter in terms of COD equivalents.

Incineration Evaluation Experiments - Three system evaluation tests were conducted prior to the incineration tests. These were performed to evaluate the general performance of the reactor assemblies and product collection system.

The first two experiments were performed under the following conditions: 1) 25 psia, 2) 30% excess oxygen, 3) Main reactor power: 1000 watts and 4) Catalytic reactor temperature: 480°C. The catalyst employed consisted of 0.5% palladium on 1/8" alumina pellets. Palladium was selected on the basis of its acceptable performance in prior catalytic oxidation systems and for its resistance to sulfur poisoning.

The first experiment was completed at these conditions without major difficulty. However, during the second experiment an explosion occurred shortly after starting the oxygen feed to the main reactor. The sample temperature at the time of the explosion was 140°C. The explosion ruptured the blow-out disc and caused a marked distortion of the waveguide adapter. Beyond this distortion no other damage to the apparatus resulted from the explosion.

The explosion was attributed to condensation and accumulation of residues within the microwave guide adapter. These residues had been deposited during COD tests conducted prior to the evaluation experiments. The adapter protruded approximately two feet outside of the main reactor insulation. The waveguide served to provide a cooled junction with the main microwave assembly and the directional power sensor assembly. However, the cooled guide tube also provided a site for condensation of volatiles. This problem was eliminated by reducing the length of the adapter to four inches. The microwave apparatus was disconnected and the adapter sealed during incineration tests.

The third test was conducted without any further detonations, but demonstrated control difficulties with the back-pressure regulator. An all stainless steel regulator was substituted to overcome the corrosion caused by the vapors and gases generated during incineration.

System Operation

After the evaluation experiments were completed six preliminary incineration tests, Nos. 1-6, were conducted to collect basic operating information. The six tests were conducted at the following conditions: 1) 20 psia, 2) No excess oxygen, 3) Main reactor power: 600 watts, and 4) Catalytic reactor temperature: 480°C.

During all of these tests except one all of the oxygen for each complete sample was fed at a constant rate to only the catalytic reactor; in one test it was fed equally and simultaneously to both the main and catalytic reactors. The average oxygen feed rate was determined from the COD for each sample divided by the amount of time required to reach 650°C for the main reactor power input. At 600 watts the total time was estimated at 200 minutes.

The condensate obtained from these experiments was cloudy yellow in color, smelled strongly of octane and ammonia and contained solids which settled out readily. The pH of the condensate ranged from 7.9 to 8.7, with ammonia values from 4620 mg/l to 7500 mg/l. Trace quantities of sulfur dioxide and chloride were also present. The remaining residue or ash was black to dark brown, friable, and smelled slightly of coal tar. Preliminary qualitative infra-red analyses of the final total gas volume indicated the presence of low molecular weight alkanes, mercaptans, carbon monoxide, nitrogen, and hydrogen sulfide, in addition to carbon dioxide.

These results indicated incomplete combustion and were attributed to improper distribution of the oxygen volume specified by COD analysis. The

results showed that the oxygen demand varies considerably during incineration. This suggested the need for an oxygen feed program to distribute or parcel out portions of the total oxygen requirement at appropriate intervals during incineration.

Oxygen Management

Twelve tests, Nos. 7-18, were conducted at the following conditions; 1) 20 psia, 2) 30% excess oxygen, 3) Main reactor power: 450 watts, 4) Catalytic reactor temperature: 480°C. 5) Catalyst: Palladium on alumina, and 6) Fecal sample: 250 grams. The objective of these tests was to develop an oxygen feed program which would provide sufficient oxygen for complete combustion throughout the experiment, preferably within the 30% excess based on COD analysis. In contrast to prior tests, oxygen was added directly to the main and/or catalytic reactors only after initial boil-off of water was completed, indicated when the sample temperature began rising rapidly above the 105°C level.

At this time oxygen was fed into the main reactor at rates between 200 and 1000 cc/min, and into the catalytic reactor at 400 to 1500 cc/min. From 105° to 200°C the oxygen demand in the main reactor approximated 200 cc/min. and combustion was relatively under control. In the temperature range from 200° to 370°C, sample ignition appeared to take place, and only a very low flow of oxygen, 100 cc/min or less, could be admitted while still maintaining controlled combustion. Once oxygen was introduced the combustion rate accelerated very rapidly, along with rapid temperature rise, and release of

large quantities of volatiles. After this occurred the demand for oxygen could not be satisfied, even when as much as an additional 1000 cc/min was admitted to the catalytic reactor.

At this time during the test large amounts of CH_4 , CO and H_2 , were found in the product gases. At times the transient gas concentrations reached as high as 12% CH_4 , 25% CO , 5% H_2 , and up to 4% N_2 with the remaining gas essentially CO_2 . The gas composition was measured intermittently by a gas chromatograph, with samples taken downstream of the back-pressure regulator and upstream of the water traps. After the sample reached 370°C , oxygen could be fed to the main reactor without causing incomplete combustion. Combustion then continued smoothly up to 650°C , and ceased rather abruptly with a decrease in sample temperature and a simultaneous reduction of carbon dioxide output.

The condensate formed in those tests where incomplete combustion occurred was yellow and somewhat cloudy, had a pH from 8 to 9, and smelled strongly of naphthalene or gasoline; where nearly complete combustion was achieved the condensate was clear, slightly yellow, had a pH from 1 to 2, and had a slight odor of petroleum products. Condensate samples from each of the tests exhibited no growth in thioglycolate broth after 72 hours, indicating sterility.

The ash residues ranged from 2 to 4% of the original sample weight, were grey-black to grey-white in color, and had no odor. These residues were readily crushable and in some cases resembled tobacco ashes.

Some difficulties were encountered in effectively establishing the correct oxygen feed rate, particularly to the main reactor. The oxygen demand vs.

temperature relationship differed markedly from sample to sample as did the total oxygen requirement. These variations made it virtually impossible to develop an effective oxygen feed program. As a result the degree of sample combustion varied considerably and uncontrollably from one experiment to another.

A possible explanation for this variance in rate and completeness of combustion is that the fecal sample apparently contained substances which were released as distillation or reaction products over a broad temperature range from 150 to 550°C. The rate at which these substances were generated was a function of the specific temperature, so that oxidation accelerated the generation rate. Thus, if the temperature increased too rapidly oxidation and pyrolysis products were generated faster than could be safely oxidized.

The results achieved up to this point indicated that the total oxygen demand varied significantly from sample to sample and that an accurate indication of oxygen requirement could not be obtained prior to a test by means of chemical oxygen demand (COD) or total carbon (TC) values. Dichromate digestion, the fundamental process in a COD determination, might not have been sufficiently vigorous to completely oxidize all the oxidizable constituents in feces.

Intermittent Effluent Analyses

The next nine tests, Nos. 19-27, were conducted at the following conditions: 1) 20 psia, 2) 85 to 160% excess oxygen, 3) Main reactor power: 800 watts, 4) Catalytic reactor temp: 480°C and 5) Sample wt: 100 gm.

The previous group of tests demonstrated that specific sample temperature ranges were associated with the three stages of the overall incineration

process. These stages and sample temperatures were: 1) water boil-off, ambient to 105°C, 2) pyrolysis and catalytic oxidation of pyrolysis vapors, 105 to 550°C, and 3) direct oxidation (incineration) after pyrolysis, 550 to 700°C. The previous tests also showed that the oxygen demand changed significantly within each of these phases.

Therefore, the goal of this group of experiments was to develop a relation between oxygen demand and phase of combustion as indicated by sample temperature. This temperature was then used to match supply with demand. At the same time intermittent effluent gas analyses were used to show a lack or excess of oxygen during various phases of incineration. The separate oxygen feeds to the main reactor and the catalytic reactor were then adjusted accordingly.

After water boil-off admission of oxygen to the main reactor caused rapid temperature increases and generally uncontrollable, and incomplete combustion in the temperature range from approximately 200°C. to 550°C. In several instances feeding oxygen to the main reactor in this range caused a series of minor explosions with the system. These results indicated that highly combustible materials were being released as pyrolysis products in this temperature range, and that these reacted rapidly with oxygen, generating large amounts of heat and causing detonations. The resulting accelerated and uncontrolled temperature increase caused the release of additional pyrolysis products, at a rate greater than the oxygen supply rate, resulting in incomplete combustion. These tests showed that complete combustion required pyrolysis of the fecal sample from 105° to approximately 550°C, followed by separate catalytic oxidation of the gases generated by pyrolysis.

In this group of tests, during pyrolysis essentially no oxygen was fed to the main reactor, but rather the entire feed was directed to the catalytic reactor where complete catalytic oxidation of pyrolysis gases and vapors occurred. The oxygen feed rate to the catalytic reactor averaged 400 cc/min but varied from 50 to 1300 cc/min during the oxidation process. Complete combustion was achieved in this manner and was verified by the combined concentration of CO and CH_4 being below 0.1% in the effluent gases. The end of pyrolysis and the corresponding 550°C temperature level were determined from effluent gas analysis, indicated by a sharp increase in unconsumed oxygen, typically increasing from 20% to 70%.

As the feed to the catalytic reactor was stopped, feed to the main reactor was started to incinerate the remaining solids which were essentially carbon and mineral components. Adequate oxygen was supplied to insure complete combustion. The oxygen feed rate averaged 700 cc/min, but ranged from 50 to 900 cc/min. The end of incineration was again determined from effluent gas analysis, as signified by a sharp increase in oxygen concentration, typically from 20% to 70%. The sample temperature rose at a higher rate than during pyrolysis, slightly exceeded the incinerator skin temperature, and finally reached 700°C; a subsequent sharp 30°C decrease also signified the end of incineration.

Complete combustion was achieved in six tests, and nearly complete combustion in the remaining three. Combustion was considered complete when the unburned CO and CH_4 amounted to less than 0.1% of the total effluent product; nearly complete combustion was signified by unburned gases, primarily methane,

in concentrations from 0.3 to 1.2% in the total effluent gas product. In all of the nine tests large excesses of oxygen were used, ranging from 85 to 160% of the oxygen consumed.

Although more than adequate oxygen was supplied for complete combustion, this did not occur, because the time delay involved in gas-chromatographic analysis prevented supplying the proper input rate of oxygen at the proper time. Large amounts of oxygen were fed to the system when they were not required, and, conversely inadequate oxygen was supplied when the actual demand was high.

The use of COD analyses did not alleviate this problem, primarily because the oxygen demand rate varied sharply during the overall combustion process. Also, the amount of oxygen indicated by the COD analysis varied significantly from the actual amounts consumed.

An analysis of the products of combustion is shown in Table IV. The values indicated are nominal but representative levels for the characteristics listed. The gaseous products of incineration were primarily CO_2 and H_2O vapor. Traces (under 0.1%) of SO_2 , and NO or NO_2 were formed when combustion was complete, while traces of H_2S , and between 0.3 and 1.2% CO and CH_4 were present after incomplete combustion. The 100 gram fecal samples consumed between 12 and 30 liters of oxygen for combustion.

Between 79 and 84 gm of condensate were generated during combustion. After complete combustion the condensate was clear-yellow and smelled mildly acidic with a pH of 1 to 6; after incomplete combustion the condensate was turbid-yellow and smelled strongly of petroleum oil, with a pH of 6.5 to 8.5. The ash residue was grey-white, sterile, and odorless in both cases.

Table IV

Product AnalysisTest Nos. 19-27

<u>Effluent Gas</u>	<u>Complete Combustion</u>	<u>Incomplete Combustion</u>
Yield	31-56 Std. liters	34-46 Std. liters
CO ₂	32-39%	38-47%
O ₂	53-58%	43-58%
N ₂	6-10%	9-19%
CO + CH ₄	<0.1%	0.1%-1.25%
<u>Condensate</u>		
Weight	79.0-88 gm	78.0-91 gm
pH	1.5-6.5	6.5-8.5
Appearance	Clear-Yellow	Turbid-Yellow
Odor	Mild-Acrid	Strong Petroleum
Ammonia	270 to 2,470 mg/l.	70 to 2,320 mg/l
Sulfate	42 to 1,765 mg/l.	8.5 to 1,395 mg/l
Total Carbon	40-172 mg/l	49-165 mg/l
Chloride	15.1-105.7 mg/l	12.1 to 96.8 mg/l
Bacteriological Purity	Sterile	Sterile
<u>Ash</u>		
Weight	2.1-3.2 gm	1.4-2.3 gm
Bacteriological Purity	Sterile	Sterile
Odor	None	None

Continuous Effluent Analysis

The primary objective of these tests was to achieve complete combustion by increasing or decreasing the oxygen feed rate according to continuously monitored effluent oxygen concentration. The use of intermittent monitoring was shown inadequate for reasonable control of oxygen in the previous group of tests.

This group of four tests, Nos. 28-31, was conducted under the following conditions: 1) Pressure: Atmospheric, 2) Main reactor power: 800 watts, 3) Catalyst bed temperature: 480°C, 4) Catalyst: Palladium, and 5) Sample weight: 100 gm. The effluent exiting from the catalytic reactor was continuously analyzed for oxygen and carbon dioxide content. The monitoring apparatus was arranged so that the effluent gas flowed through the system in the following sequence: 1) an ice-water cold trap, 2) a gas cell containing an oxygen sensor probe, 3) a calcium sulfate bed for water absorption, and 4) an infrared carbon dioxide analyzer. The effluent was then vented to the atmosphere. In addition, a port for obtaining effluent samples for analysis by gas chromatography was located at the inlet of the ice-water cold trap. A Beckman polarographic analyzer and a Mine Safety Appliances infrared analyzer served for oxygen and carbon dioxide monitoring, respectively. Detailed analyses of residue and condensate were not performed.

Oxygen was fed exclusively to the catalytic reactor during pyrolysis up to 550°C, at rates from 100 to 1600 cc/min, averaging 400 cc/min, for periods varying from 35 to 60 minutes. The peak flow rates occurred for periods of 0.5 to 3 minutes, in the 370° to 450°C temperature zone when large amounts of

highly combustible products were apparently released.

When the sample reached 550°C pyrolysis was usually complete, as indicated by a sharp rise in the exit oxygen concentration, and flow to the catalytic reactor was stopped or reduced to a nominal 30-50 cc/min. Oxygen was then fed into the main reactor until incineration was completed at 700°C. The oxygen flow rate to the main reactor varied from 100 to 1600 cc/min, averaging 300 cc/min for periods ranging from 25 to 75 minutes. Peak feed rates, lasting from 1 to 2 minutes, were needed in the 550° to 600°C temperature zone, apparently for the rapid combustion of essentially pure carbon remaining after pyrolysis.

The oxygen needed to achieve complete combustion varied significantly with each 100 gram specimen, both in the demand rate during peak periods, and in the amount of oxygen necessary for total incineration. In the 370° to 450°C zone the peak rate varied from 850 to 1600 cc/min, and at 550° to 600°C, from 1100 to 1600 cc/min. Total oxygen varied from 32 to 56 std. liters; there was an evident excess of oxygen, but the exact quantity was not determined.

This group of tests showed: a) the feasibility of continuous oxygen feed control and resulting complete combustion, b) the need to program oxygen feed separately to both stages at specific periods during incineration, and c) that oxygen demand rate and duration at similar temperature levels varied somewhat from sample to sample. Utilizing this information, the next series of tests was performed at selected levels of pressure and excess oxygen.

Controlled Complete Combustion

The objective of this group of controlled complete combustion tests was to evaluate the effects of pressure, amount of excess oxygen, and incineration temperature as a power level criterion, on the characteristics of the condensate, effluent gases, and ash residue. Seven tests were conducted at 20 psia, varied levels of excess oxygen, and two temperature levels; twelve tests were conducted at 10 psia, varied levels of excess oxygen, and 700°C.

This group of nineteen experiments was conducted under the following conditions: 1) Pressure: 10 and 20 psia, 2) Excess oxygen (nominal values): 0%, 30%, 3) Main reactor Power: 800 watts, 4) Final incineration temperature: 550° and 700°C, 5) Catalytic reactor temperature: 480°C, 6) Catalyst: Palladium, 7) Sample weight: 100 grams. The effluent product sampling system for continuous monitoring was as described for the previous four tests, except that in the 20 psia tests a pressure-regulator preceded the sampling system, while in the 10 psia tests a vacuum-regulator and a vacuum-pump followed the system. The total volume of effluent gases in either case discharged into an expandable Aclar bag for final total gas analysis.

The oxygen feed rate again was controlled manually and continuously according to visual observation of both the gas analyzers. The oxygen analyzer continuously showed the percent of oxygen in the effluent gases, and the carbon dioxide analyzer showed the percent of carbon dioxide percent. Since water vapor was condensed out, the sum of these two percentages was 100%, nominally, when complete combustion was occurring. When incomplete combustion occurred the oxygen concentration would drop to zero; the extent of incomplete combustion was then indicated by how much the CO₂ concentration was below 100%.

20 PSIA Tests (Nos. 32-37, 50) - Five of the tests at 20 psia were conducted with continuous effluent gas monitoring to permit proper oxygen supply for complete combustion. The final temperature at the end of incineration was allowed to rise to 700°C to insure that the solid residue had been totally oxidized to inorganic ash products. The two levels of oxygen to be supplied during combustion were nominally to be 0% excess and a 30% excess. Due to a time delay caused by the cooling line between the sample exit from the catalytic reactor and the oxygen analyzer, it was not possible to supply exactly the stoichiometric requirement, i.e., no excess; therefore, 9% excess oxygen represented the practical minimum level which still accomplished complete combustion under these conditions. The 30% level was nominally achieved by tests at 22 to 41% excess oxygen.

In these five tests, shown in Table V, the two different nominal levels of excess oxygen did not have a proportionately different effect on the characteristics of the combustion products. Complete combustion, arbitrarily designated as such when the total CO + CH₄ gas content is 0.1% or less, was accomplished in three of the tests, one at 9% and two at 38 and 41% excess oxygen.

Oxygen was fed into only the catalytic reactor until pyrolysis was complete in the main reactor at the 400° to 550°C level; it was then fed into the main reactor for residue oxidation to complete the incineration process at the 700°C level. In general, the greater portion of the feed was directed to the main reactor but this was actually governed by demand based on the effluent oxygen concentration.

Table V

Combustion Product Analysis

20 PSIA Tests

Total Incineration - 700°C

Test No.	O ₂ , Liters		Excess O ₂ , %	Product Gas, Liters			Trace Gases %			Condensate			Residue		
	Fed	Used		CO ₂	O ₂	N ₂	Total	CH ₄	CO	NO ₂	Yield Gm.	pH	T.C. Bact. mg/l	Yield Bact. Gm.	Bact.
50	49.7	44.9	9	21.0	8.2	2.2	31.4	.02	0	.02	87.2	2.1	70	3.5	S
34	36.3	29.7	22	21.7	10.0	1.9	36.8	.7	1.5	.01	88.7	7.5	1900	2.6	S
32	42.8	30.9	38	24.0	15.3	5.1	44.0	.1	0	.01	75.5	1.9	20	3.0	S
33	41.1	29.2	41	23.2	15.3	1.7	41.1	.1	0	.01	84.3	2.2	30	3.1	G
35	45.0	34.7	30	20.7	13.7	1.5	37.1	.3	0	.04	82.5	2.2	40	2.5	S

Combustion of Pyrolysis Gases Only - 550°C

36	19.7	15.2	29	12.6	7.9	1.4	22.0	.3	0	.08	79.3	2.0	30	5.	G
37	38.3	28.8	42	10.4	12.9	2.0	25.7	.1	0	.08	78.8	2.5	50	5.7	S

S - Sterile, G - Growth

The highly significant factor in these tests was that complete combustion was achieved in the 10 to 35% excess oxygen range, as opposed to the 85 to 160% range required in all prior tests. In addition, no pre-test information such as a COD analysis, was used to predetermine the amount of oxygen needed for complete combustion; oxygen was supplied solely on the basis of demand, as indicated by the effluent gas oxygen concentration.

An additionally significant factor is that in the other two tests, at 22 and 30% excess oxygen, truly complete combustion did not occur, primarily due to improper programming of the oxygen feed supply. Accomplishing complete combustion is therefore dependent more on proper programming of oxygen than on providing an overall excess of oxygen.

The condensate in these five tests was cloudy-yellow initially, but clear on settling, contained a small amount of suspended black particulate matter, smelled either of SO_2 or naphthalene, was sterile, and ranged in weight between 75 and 89 grams. The pH ranged from 1.9 to 7.5; however when combustion was complete the pH was 1.9 to 2.5, and when incomplete the pH was high, at 7.5 in one case. The pH of the condensate therefore appeared to be a fair indicator of completeness of combustion. During complete combustion the sulfur in the sample is probably oxidized to SO_2 , or even SO_3 , both of which are readily absorbed or reacted with water to form a highly acidic condensate. When combustion is incomplete the amount of sulfur oxides might be less, the degree of protein and ammonia oxidation less, and the pH, therefore, correspondingly higher. Although the pH appeared to be related to completeness of combustion, the separate NH_4^+ , $\text{SO}_4^{=}$, and Cl^- concentrations, total carbon content, total solids, and conductivity did not appear to be directly related.

The ash residue was grey-white, odorless, and sterile, and ranged in weight between 2.5 and 3.5 grams.

The remaining two tests at 20 psia were conducted at 29 and 42% excess oxygen, but with oxygen fed only to the catalytic reactor for combustion of pyrolysis gases; the test was terminated when the main reactor reached approximately 550°C, at the end of pyrolysis of the fecal sample. The primary objective was to terminate operation at a lower temperature, and demonstrate the effects on combustion products of lower temperature, and resulting lower total power input. Corollary objectives were to determine the composition of the pyrolysis residue, and to convert the fecal sample to a minimal volume, unoffensive, and sterile product, thus, requiring a considerably lower amount of oxygen than for total incineration.

Terminating the process after combustion of pyrolysis gases was complete did not qualitatively affect the combustion products as shown in Table V. In the first test the amount of oxygen consumed, and carbon dioxide formed were approximately half of the volumes for total incineration, as might be expected.

The condensate generated was approximately the same as in total incineration. The combined output of nitrogen (as NH_3 , NO_2 , N_2) and sulfur (as SO_4 and SO_2) in the condensate was similar to that observed in previous tests. This suggests that the solids remaining after pyrolysis are primarily carbon and inorganic residues, and that nearly all of the available nitrogen, sulfur, and hydrogen can be recovered by pyrolysis and catalytic oxidation of the pyrolysis gases.

The residue was heavier, with a considerable amount coated as a fine black soot-like material on the interior of the main reactor. The residue mass plus the soot weighed an average three grams more than in total incineration; this amount is probably essentially pure carbon, and if oxidized would account for the additional amount of CO_2 expected from total incineration. The residue was black and odorless, and not sterile, but was possibly contaminated externally in the process of collection and removal from the main reactor walls.

The major effect observed in stopping the combustion process at the 550°C level was the generation of soot deposits in the main reactor. No appreciable power savings was realized; the time elapsed for total incineration was only slightly longer than for the pyrolysis gas oxidation process. The soot-deposit is undesirable because it interferes with combustion of any subsequent fecal material.

In the second test a number of minor explosions occurred, even during pyrolysis, attributable primarily to soot deposits from the previous test. The overall results indicated that total incineration to ash is the more desirable and feasible process. On this basis all subsequent tests were conducted through complete incineration to the 700°C level.

10 PSIA Tests (Nos. 51, 52) - A total of twelve tests were conducted at 10 psia. The first two preliminary tests were used to show the technique and problems of low pressure system operation. These tests were concerned with vacuum regulation, oxygen feed, and O_2 and CO_2 sensor operation at reduced pressure. The tests showed the feasibility of complete combustion at reduced

pressure, and the typical formation of product gases, condensate and ash residue.

The next ten tests, shown in Table VI, indicated primarily the effects of combustion at 10 psia at two nominal levels of oxygen concentration. The tests were in the 0-15% and the 15-45% excess oxygen range. Although the differences are not extremely great, the product gas contained less CO_2 in the 0-15% tests than in the 15-45% tests. This type of behavior was not seen in the 20 psia tests. Also, a similar result was noted in the amount of ash residue, with somewhat higher residues in the 0-15% excess oxygen range.

The condensate in these ten tests was clear, contained a small amount of suspended, black, particulate matter, smelled slightly of moth balls, and ranged in weight from 77 to 91 grams. In two tests bacterial growth was apparent, one each during complete and incomplete combustion. The pH ranged from 1.5 to 8.2; however in the three incomplete combustion tests the pH ranged from 1.8 to 4.3; in the other seven tests the pH was under 1.9 for all but one, which was 8.2. No reason was apparent for this behavior, or for the lack of similarity to the 20 psia tests. In general, the lower pH values appeared related to completeness of combustion.

Again the separate NH_4^+ , SO_4^- and Cl^- concentrations, total carbon content, total solids, and conductivity, did not appear to be related to degree of combustion, and did not differ significantly from the values observed at 20 psia operation.

The ash residue was grey-white, odorless and sterile in all but one case. The sample exhibiting bacterial growth could have been inadvertently contaminated in handling and the presence of growth is not necessarily significant. The

Table VI

Combustion Product Analysis

10 PSIA Tests

Total Incineration - 550°C

Test No.	O ₂ , Liters		Excess O ₂ , %	Product Gas, Liters			Trace Gases %			Condensate			Residue		
	Fed	Used		CO ₂	O ₂	N ₂	Total	CH ₄	CO	NO ₂	Yield Gm.	pH	T.C. Bact. mg/l	Yield Gm.	Bact.
47	21.5	21.9	0	9.7	3.2	2.6	15.8	.3	1.4	.34	76.8	4.3	360	6.5	S
45	40.0	39.0	2.6	15.5	4.4	2.7	22.6	0	0	.13	89.2	1.6	250	4.1	G
46	27.6	25.6	7.6	10.0	5.3	3.4	19.0	.08	.01	.21	84.5	1.5	70	5.5	S
44	49.3	43.2	14.0	17.8	9.4	3.3	31.0	0	0	.37	90.1	1.9	80	3.8	S
42	41.1	36.0	14.5	12.3	8.6	8.5	30.5	.01	.01	.17	89.8	1.8	170	3.8	S
49	44.3	37.7	17.5	18.8	10.0	7.1	35.6	.01	.01	.11	87.9	8.2	800	3.4	S
40	49.9	40.6	22.8	9.9	12.7	1.6	24.2	.1	0	.10	90.7	1.8	60	4.0	S
41	54.3	42.9	26.6	20.2	14.7	3.8	38.5	0	0	.14	88.1	1.8	40	3.8	S
48	58.3	45.1	29.3	21.0	16.6	6.4	40.8	0.3	0.1	.13	89.7	1.8	120	3.2	S
43	47.5	33.0	44	33.0	17.9	5.7	63.1	0.1	0.3	.01	88.9	1.9	80	4.0	S

S - Sterile, G - Growth

ash samples ranged in weight from 3.2 to 6.5 grams. Some relationship between the amount of CO₂ produced and residue weight appeared probable since lower CO₂ production occurred simultaneously with higher residue weight in several tests.

Combustion Properties of Dried Fecal Matter

In several earlier incineration tests minor detonations and one explosion occurred when oxygen was admitted to the essentially dry fecal sample after water boil-off was complete. This behavior indicated a high reaction rate and a possible hazard when oxygen is contacted indiscriminately with a dried fecal sample at sufficiently high temperatures. Two tests were conducted to examine this behavior specifically and to observe the effects of extreme excesses of oxygen on the combustion rate.

The first test was conducted in the main reactor under the following conditions; 1) 20 psia, 2) 30% excess oxygen 3) Main reactor power: varied 4) Catalyst bed temperature: 480°C, 5) Sample weight: 100 gm. The power supplied to the first stage was varied throughout the test in an attempt to moderate the pyrolysis/combustion phenomenon observed in previous tests.

Initially, 1 kW was supplied until the reactor skin temperature reached 120°C the power was then reduced to 200 watts to maintain the main reactor skin temperature at 200° to 230°C during water boil-off. Approximately 100 cc/min of oxygen were fed to only the main reactor during the boil-off period which lasted 38 minutes. The specimen temperature then increased gradually; power was increased continuously to maintain an approximate 80°C difference between the skin and sample temperatures. After 40 minutes, the power was at

500 watts and the sample had reached 250°C. During this period 250 cc/min of oxygen was fed to the main reactor and no additional oxygen to the catalytic reactor. The oxygen content of the effluent in this period was 40% by volume and was falling rapidly as the sample approached 250°C. The oxygen feed to the main reactor was increased to 400 cc/min. Within 30 seconds after the above increase, a loud explosion occurred rupturing the burst disc. The specimen and reactor skin temperature were 250° and 360°C, respectively, at detonation. The power and oxygen feed were immediately cut off.

With the power off, 5-6 lpm of oxygen were then fed to the main reactor. Very dense, yellow-grey smoke curled out of the rupture disc housing followed by a bright white flash and a very loud report. Oxygen was stopped and the reactor was then flushed with helium for 15 minutes to displace the obviously explosive gases. Oxygen was then fed again to the main reactor at 5 to 6 lpm. No further detonations occurred. The sample temperature increased from 260° to 930°C within one minute and then decreased to 370°C over a 4 minute period. The oxygen feed was then cut off.

Extensive gas analyses could not be performed because of the pressure loss occasioned by rupture of the burst disc. The residue was cream colored, odorless, and sterile. The condensate collected up to the point of detonation, 71.6 grams, was of a quality similar to that obtained from complete combustion.

A second test was performed in a glass vessel to permit visual monitoring. A two liter beaker served for this purpose as the main reactor. An oxygen manifold ring was formed from 1/4" tubing and placed at the bottom of the

beaker. A chromel-alumel thermocouple was wedged between the manifold and beaker bottom. A 54 gram quantity of dried fecal residue was crumbled into assorted size lumps and placed over the manifold. The dried fecal residue was obtained from a 200 gram fecal specimen dried in separate apparatus at 100°C. The beaker was covered with aluminum foil, placed on a hot plate, and flushed with 500 cc/min of oxygen for twelve hours.

The test was initiated by turning the hot plate on at maximum power and increasing the oxygen feed to 1 lpm. Twenty one minutes were required for the sample to reach 135°C at which time a thin light colored smoke was noted emanating from the sample. Smoke generation appeared to increase with temperature and at 175°C after 29 minutes, the oxygen feed was turned off in order to observe smoke generation. The vessel was almost instantly filled with a thin yellow-white smoke. The oxygen feed was returned to the former level within 30 seconds. Ignition occurred at 220°C after 32 minutes, and was initiated by a small localized spark or glowing body. Ignition was accompanied by an sound similar to that heard at ignition in an oil or gas furnace. The entire mass ignited more or less uniformly and the temperature increased beyond the 1000°C limit of the recorder in less than 30 seconds after ignition. During this time black soot and smoke were evident. The oxygen feed was increased to several liters/min without eliminating the smoke or soot. The residue burned with an intense white flame which persisted over a 3 minute period. The flame gradually faded leaving isolated glowing bodies. The above process, from ignition to burn out required 6-7 minutes.

These tests confirmed the ignition temperature of feces at 220°C, and demonstrated the extreme reaction rate and intense heat generated by oxidizing fecal residues with pure oxygen. The tests also contrasted the effects of high oxygen concentration and feed rate on incineration conducted in open and closed vessels. The tests showed that dried feces would constitute a fire or explosion hazard if stored in an oxygen atmosphere where elevated temperatures might occur.

MICROWAVE TREATMENT

A total of fifteen microwave tests were conducted in two groups. The first group consisted of nine preliminary tests, six performed with distilled water as the load, and three with fecal material, to obtain basic operating data and to refine the test apparatus. The second group, consisted of six drying tests with fecal material, showed the effects of power levels and reactor pressures on the drying process and on the composition and bacteriological composition of the end products.

Preliminary Tests

In the first three preliminary tests distilled water was used to simulate the load inside the main reactor cavity. Water was selected as the load material because of its uniformity and predictable response characteristics. The objective of these tests was to determine power utilization characteristics and boil-off behavior in the cavity.

Water volumes of 200, 300, and 500 ml produced liquid levels in the horizontal cylindrical chamber ranging from 1/2 to 1 1/2 inches below the line-of-sight path of the incoming microwave radiation. Each water sample was exposed to varying input power levels in the range of 0.2 to 1.0 kW. The tests were conducted at ambient pressure and no attempt was made to collect the effluent vapors.

The forward and reflected microwave power levels were measured and indicated by a directional power meter assembly. The forward to reflected power ratios appeared to vary primarily with the amount of steam vapor present. Ratios of 1.3 to 1.5 were observed at start-up with all water

volumes, indicating that only 23 to 33% of the input power was being absorbed in the cavity. The ratios reached peak values of 1.7 to 1.9 as steam began venting from the reactor. Input power level did not appear to exert a material influence on the power ratio.

The above ratios indicate inefficient utilization of the available input power. Improper load location relative to the line of sight path of the input radiation was the probable cause of the inefficiency. Absorption of energy by the water vapor generated was the probable cause for the difference in start up ratios and those observed during steam generation.

The next three tests were conducted with the water load placed directly in the path of the incoming radiation. A Teflon plate was placed horizontally across the diameter of the cavity in line with and adjacent to the bottom edge of the wave guide. A cut down polypropylene beaker served to contain the load. Both Teflon and polypropylene are relatively transparent to microwave radiation. This container, capable of holding 300 ml of material, was placed on the Teflon sheet and positioned in front of the wave guide opening. This location centered the load completely in the path of the incoming radiation. Identical 250 ml. water samples were used in each test. Input power was varied in the range of 0.2 to 1.0 kW. The tests were conducted at ambient pressure without collection of the effluent vapors.

The forward to reflected power ratios showed marked improvement as a result of the above modification. The initial ratios were 2.1 to 2.3, or 52 to 57% absorption, with peaks of 2.7 to 2.9 occurring at the onset of steam generation. The ratios decreased to 1.1 to 1.2 as the load container apparently approached dryness. The higher ratios indicated a relation

between load location and efficient utilization of input power for this cavity configuration. Five to ten ml of water remained in the container after completing each test. Also, approximately half the starting water volume accumulated as condensate within the externally unheated main reactor cavity. The cavity was heated only by the steam generated during heating and by direct microwave radiation. Heat losses and the large mass of the reactor tend to keep the cavity cooler than the prevailing steam temperature. The main reactor was not heated externally during microwave testing because of the potential interfering effects of other power sources on the overall relation between drying and microwave and power input.

The first test on a 250 gram fecal sample in a polypropylene beaker was conducted at the 500 watts forward input power level. The initial forward to reflected power ratio was 2.4; the maximum ratio of 3.3 occurred when the reactor pressure reached 20 psia. An abrupt increase in specimen and vapor temperature from the normal 110°C level indicated completion of drying. The power ratio and cavity pressure decreased simultaneously with the temperature increase. The complete drying process required 32 minutes. The solid residue was hard and porous, dark brown in color and had a fecal odor. A total of 118 grams of condensate were collected, 96 condensing on the walls of the unheated main reactor cavity and 22 grams in an external cold trap. The cavity condensate was cloudy, while the trap condensate was clear; both were yellow and had a fecal odor.

The next test was conducted at the 750 watts level on a 250 gram fecal sample at 20 psia. The initial and maximum power ratios were identical to

those observed in the previous test. Audible crackling sounds occurred sporadically in the cavity throughout the test accompanied by momentary increases in the power ratios to 4 or 5 with corresponding transient specimen temperature peaks as high as 595°C. Completion of drying was indicated by decrease in pressure. The drying process required 18 minutes for completion.

The portion of the residue closest to the waveguide port was charred black while the remaining portion was similar in appearance to the residue in the 500 watt test. The Teflon support shelf was badly distorted and blackened, and the polypropylene container had melted on the side closest to the wave guide port. The condensate had a strong fecal odor and contained black solids and an oily scum.

The crackling noises, the high temperature peaks, and the charred, overheated specimen and container indicated that arcing was probably occurring within the cavity. A possible cause of arcing was the location of the metal sheathed thermocouple used to measure the specimen temperature. This thermocouple was introduced through the vapor vent line and passed downward through the center of the radiation path into the specimen. The extremes of temperature indicated that arcing probably occurred between the thermocouple tip and the walls of the cavity.

In the last test, a stainless steel plate and a 300 ml ceramic dish were used to support and contain the fecal specimen. To increase the distance between the thermocouple and wave guide port the thermocouple was routed from the top of the cavity down along the walls and into the dish from the side.

The pressure and power levels were the same as in the previous test. The power ratios observed were similar to those in the previous tests, 2.2 at start up and 3.2 as cavity pressure reached 20 psia. Arcing and overheating did not occur. Six minutes were required to raise the specimen temperature up to 110°C, and drying required an additional 23 minutes. The condensate collected in the cavity weighed 147 grams while 38 grams were collected in the trap. The residue weighed 64 grams and had a strong fecal odor. Both cavity and trap condensate were yellow in color, contained suspended matter, and had a fecal odor.

Microwave Feasibility Tests

This group consisted of six tests, three conducted at 10 and three at 20 psia, with 250, 500, and 750 watts of input power at each pressure. A 250 gram specimen was used in the first test. The specimen size was reduced to 200 grams in the remaining five tests to reduce feces spillage noted in the first test. The specimen was maintained in the line-of-sight path of the incoming radiation in the ceramic dish supported on the stainless steel shelf.

The effluent collection system consisted of the dry-ice acetone trap and flexible Aclar gas bag used in the preliminary tests. For the 10 psia tests a back-pressure vacuum regulator and a vacuum pump were located between the dry ice-acetone trap and the gas collection bag.

The tests were initiated by inserting the specimen in the cavity and sealing the flange plate. The cavity contained air, and no additional gases were fed to the system during the tests. The power was turned on and set to the desired level. Vapor, specimen, and inside wall temperatures were

recorded along with pressure and power ratios. The specimen was regarded as dry when the specimen and vapor temperature increased abruptly beyond the boiling temperature.

Upon completion of testing, gas samples were taken from the collection bag for analysis by gas chromatography and special techniques described previously. The total effluent gas volume was next determined by pumping the bag contents through a wet test meter. The condensate traps were then removed and stored at 2°C until detailed analysis could be accomplished. The condensate which accumulated in the cavity was drained into sterile bottles and stored at 2°C for later analysis. A 10-12 gram portion of each residue specimen was taken immediately after the test and stored in a similar manner.

The overall results of the six tests are shown in Table VII. The boiling temperatures were 90° and 110°C ($\pm 2^\circ\text{C}$) for 10 and 20 psia operation, respectively. The specimen heat-up rate varied with power input and pressure. Rates of 12° to 17°C per minute were observed at 20 psia through the 250 to 750 watt power levels. At 10 psia, the rate varied from 8° to 18°C per minute through the power range employed. The length of time required for drying varied chiefly with power input, requiring from 12 to 32 minutes. The power ratios observed were quite similar from test to test. The initial ratios were 2.2 to 2.4 with peak values of 3.1 to 3.3 when the pressure reached its proper upper level. Initial heat-up time to boiling ranged from 14 minutes at 250 watts to 6 minutes at 750 watts. The length of time to complete boil-off varied from 6 to 22 minutes.

The condensate, gas, and dried residue yields were quite similar in

Table III

Microwave Drying Product Analyses

TEST NO.	TEST CONDITIONS				TOTAL TIME Min.	EFFLUENT GAS Liters	PRODUCT WIELD		EFFLUENT GAS									
	FRCS. Wt. Gm.	SYS. PRCS. FSTA	ROLLING TEMP °F	POWER INPUT W/CTS			HEAT RATE °F/Min.	TIME AT BOILING Min.	COMBEN-SATE Gm. I II	SOLID RESIDUE Gm.	H ₂ %	O ₂ %	CO ₂ %	CH ₄ %	CO %	H ₂ S %	SO ₂ %	
1	250	20	225	750	30	10	17	6.9	128	48	63.5	60	27	12	0.4	0.02	0.15	0.2
2	200	20	225	500	28	10	18	6.6	121	21	36.0	72	20	9	0.1	0.04	0.10	0
3	200	20	225	250	22	22	32	6.0	134	8	43.6	76	22	4	0	0.05	0	0
4	200	10	195	750	32	6	12	5.6	82	65	41.1	74	22	2	0	0.05	0	0
5	200	10	195	500	19	12	22	6.1	94	49	48.4	76	21	3	0	0.02	0	0
6	200	10	195	250	14	18	32	5.8	94	47	47.2	78	21	0.3	0	0.01	0	0

TEST NO.	CONDENSATE COMPOSITION										RESIDUE											
	PH		TOTAL CARBON mg/lx100	TOTAL SOLIDS mg/lx100	NI ₄ mg/lx100	CONDUCT. mhos	Cl ⁻	SO ₄	SO ₂	Plate Count Bact./ml Aero.	Coliforms Density MPN/100ml	Plate Count Bact./gm100 Aero. Anae.										
1	5.1	4.7	73	36	32	25	18	0.1	.007	.005	29	32	570	6	0	32	0	3	<2.2	11	6	
2	5.3	5.3	72	69	15	13	34	26	.010	.014	0	45	400	90	0	320	0	<2.2	<2.2	0	7	0
3	5.0	NA	57	NA	73	NA	72	NA	.007	NA	29	19	400	0	0	4	0	<2.2	<2.2	0	0	0
4	4.9	4.5	50	30	13	13	88	6	.005	.004	3	29	220	260	0	90	0	23	<2.2	118	150	0
5	4.8	4.6	45	29	11	17	9	8	.005	.005	3	35	160	0	0	8	0	<2.2	<2.2	9.2	51	0
6	4.9	4.7	41	25	3	2	13	9	.005	.005	1	29	80	0	0	1	0	<2.2	<2.2	0	0	0

* NA - Not Analyzed

each test. The 250 gram specimen used in the first test yielded 63.5 grams of residue and 176 grams of condensate. The yields from the 200 gram specimens ranged from 36.0 to 48.4 grams of residue and 141 to 147 grams of condensate. In all of the tests the solid residue accounted for 19 to 25% of the initial specimen weight, while the condensate accounted for 71 to 74%. In the 20 psia tests, the condensate drained from the main reactor cavity constituted 74 to 97% of the liquid yield, and in the 10 psia tests 55 to 65% of the condensate accumulated in the cavity. The gas yield ranged from 5.6 to 6.9 liters and appeared to vary randomly.

The gas collected was composed chiefly of air. The CO₂ content ranged from 0.3 to 12% with the highest CO₂ value occurring in the 20 psia, 750 watt test. Methane and carbon monoxide were detected only in the 750 and 500 watt tests at 20 psia. Values for CO and CH₄ ranged from 0.02 to .04% and 0.1 to 0.4% respectively. Sulfur dioxide at 0.2% was detected only in the 750 watt 20 psia test. Hydrogen sulfide ranged from 0.01 to 0.15% in all the tests with the high values occurring at 20 psia and 500 and 750 watts. Nitrogen oxides were not detected in any of the tests.

The chief difference between the cavity and trap condensate was the presence of bits of moist fecal material in the cavity condensate indicative of probable specimen spattering during water boil-off. Both condensate portions had a strong fecal odor and were yellow in color. The detailed composition did not appear to be influenced by test conditions. The pH of both was essentially 5. Total carbon ranged from 2,500 to 7,300 mg/liter. Values of 0.1 to 88 mg/liter were obtained for ammonia content. The chloride and sulfate concentration were each below 50 mg/l in all six tests. Dissolved

SO₂ values ranged from 400 to 570 mg/l in the 20 psia tests and from 80 to 220 in the 10 psia tests. Twenty microliter aliquots of each condensate sample were injected into the gas chromatograph without obtaining peaks for SO₂. The dissolved SO₂ values probably indicate the combined SO₂, H₂S, and mercaptan concentration. Nitrogen oxides were not detected in either condensate portion.

The trap condensate was sterile in all tests. The cavity condensate showed decreasing bacterial contamination levels with increasing boiling time. Coliform bacteria were detected only in the 750 watt tests at both 10 and 20 psia. The test at 10 psia showed the highest coliform count (23/100 ml). This test also had the shortest time at boiling and the lower of the two boiling temperatures. The decrease in contamination level appeared to be related to increased thermal exposure.

The residue was porous, quite hard, and dark brown in color in each case and was quite similar in appearance to feces dried by conventional electric heating. Each residue sample had a pronounced fecal odor. The residues from each 250 watt test experiencing the longest time at boiling were sterile. The residues from the other tests contained varying concentrations of aerobic and anaerobic bacteria. The highest concentrations, 11,800/gm aerobic and 15,000/gm anaerobic, were obtained from the 10 psia - 750 watt test, which experienced the shortest time at boiling.

In summary, the input power level appeared to exert a major influence on the process. The composition of the gases indicated that some pyrolysis occurs at high input power levels. With the exception of pH and SO₂ concentration the values obtained for each condensate composition parameter

were lower than those obtained in complete combustion. Bacteria survival in the condensate and residue appeared to be unaffected by microwave power and showed a time-at-temperature dependency. The bacterial survival coupled with the tendency of feces to spatter during heating present a significant cavity sanitation problem. The major problem is the continual deposition of noxious substances and probable growth of viable bacteria which in the cavity, could escape to the cabin atmosphere during loading or other functions requiring crew-cavity contact.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

On the basis of the incineration and microwave drying tests conducted during this program the following conclusions have been reached.

- a. Complete oxidation of human fecal matter with oxygen in a flow-type incineration system is feasible, but requires continuous temperature and oxygen concentration monitoring coupled with controlled, programmed oxygen flow.
- b. The fecal incineration process takes place in three phases:
 - 1.) drying of feces from ambient to the boiling-point of water,
 - 2.) thermal decomposition of feces, in the absence of oxygen, i.e., pyrolysis, from 150° to 550°C, with simultaneous but separate oxidation of the pyrolysis products, typically at 480°C over a catalyst, and
 - 3.) final direct oxidation of solids remaining after pyrolysis, from 550° to 700°C.
- c. The ignition temperature of dried feces is approximately 200°C. Direct oxidation above this temperature is very rapid, highly exothermic, dependent on oxygen feed rate, and virtually uncontrollable once initiated, resulting in an explosion if conducted in a confined volume. Direct oxidation of the dry fecal sample in the incineration system during the pyrolysis phase, 150° to 550°C, results in detonations, highly accelerated temperature rise, and incomplete combustion. Dried feces constitute a serious fire or explosion hazard if stored in an oxygen atmosphere where high

temperatures might occur.

- d. The oxygen demand, which changes as much as fifteen-fold during the incineration process, can be supplied automatically without prior fecal sample analysis, so that samples that vary widely in composition and oxygen requirement can be accommodated and completely oxidized, using between only 1 and 5% excess oxygen. The maximum oxygen demand rate approaches 1500 cc/min and lasts for as long as three minutes for a 100 gm. fecal sample.
- e. Neither the chemical oxygen demand, COD, nor the total carbon content, TC, served as reliable indicators of the actual amount of oxygen needed for complete combustion of fecal material.
- f. There was no significant difference in operating requirements or products formed in incineration at 10 psia versus 20 psia, or at 1-10% versus 30-40% excess oxygen.
- g. The power required for the incineration process was a function primarily of the main and catalytic reactor masses, and of the time required to heat the main reactor through the necessary temperature levels for the separate phases of the incineration process.
- h. The gaseous products of complete combustion are CO_2 and N_2 , containing trace (<0.1%) amounts of CH_4 , CO , NO , and NO_2 . After incomplete combustion the main products again were CO_2 and N_2 , but CH_4 , CO and H_2 were present in the 0.3 to 20% range, with trace amounts of H_2S , NO and NO_2 .

- i. The composition of condensate water from either complete or incomplete combustion did not vary significantly, and contained amounts of NH_4^+ , SO_4^{2-} , Cl^- , carbon, and solids ranging from 10 to 10,000 mg/l. The pH of the condensate generally ranged from 1 to 4 for complete combustion, and 6 to 8 for incomplete combustion. In the seventeen significant incineration tests at 10 and 20 psia the condensate was sterile in all but two tests, at 10 psia. In-leakage at the reactor exit was the probable cause of non-sterility, since the gases were exposed to 480°C , for at least 15 seconds.
- j. The solid residue remaining after incineration is a grey-white ash, odorless, and sterile, approximating 2 to 3% of the initial sample weight. The residue after pyrolysis alone, i.e. without any oxidation of the sample, is a black soot-like material, odorless, but not always sterile, approximating 5 to 6% of the initial weight.
- k. The palladium on alumina catalyst used for catalytic oxidation was still effective for the complete oxidation of gases and vapor after 300 cumulative hours of testing.
- l. The reaction products of incineration are highly corrosive and stainless steel was required for all metal components in contact with these products.
- m. Drying feces with microwave energy is feasible, but dependent on reactor cavity design, power input, and operating pressure.
- n. The time for drying the fecal sample varied inversely with microwave power input, the primary controlling variable. On a comparable power basis microwave drying required approximately one-tenth the

time for thermal drying, not corrected for the weight of the reactor (50 x sample wt.) which required heating in thermal drying.

- o. Reactor design and sample location are critical to effective power utilization. In the cylindrical reactor cavity input microwave power utilization approximated 80% with the sample in the direct path of the microwave beam, but only 55% with the sample below the beam.
- p. Pressure did not exert a significant effect on drying rate or duration, except to the extent that boil-off occurred at a lower temperature when the pressure was lower.
- q. The boil-off temperature affected gas product composition. The highest value for product gases occurred at higher boiling temperatures and higher power input levels. The gaseous products consisted of CO_2 , CO , CH_4 , SO_2 , and H_2S besides the oxygen and nitrogen originally in the reactor cavity. No nitrogen oxides were formed. The presence of these gases indicates that some degree of distillation or pyrolysis was effected by the microwave energy.
- r. The microwave drying process was capable of producing sterile but not potable condensate water for all pressures and power levels tested. However, the potentially injurious environment of the dry ice-acetone condenser may have aided in producing sterile condensate. Water which condensed on the unheated reactor walls was contaminated by bits of fecal matter spattered from the dish during boil off and consequently was not sterile.
- s. Condensate water produced was similar to the condensate produced

in the incineration process. However, the total solids content and $\text{SO}_4^{=}$ concentration were considerably lower, indicating that these are possibly generated only when the sample is exposed to temperatures considerably above the water boiling-point.

- t. Bacteria survival in the cavity condensate appeared unrelated to microwave power level but related to thermal effects, specifically the length of time and temperature level of the boil-off period.
- u. The length of time of boiling affected the sterility of the solid residue remaining after drying. At the longest boiling time the solid residues were sterile; for all other residues bacterial growth was evident, and increased with decreased drying time.
- v. Microwave drying of a fecal sample in an open sample dish allowed spattering which contaminated the reactor cavity.

Recommendations

Based on the observations and conclusions drawn from the complete program the following recommendations are made concerning the use, operation, evaluation and future testing of incineration and microwave treatment of human fecal matter.

- a.. To insure complete oxidation of fecal material an oxygen feed control system should consist of an oxygen sensor in the effluent gas line from the catalytic reactor, an automatic controller, and a rapid response control valve to meter oxygen flow and a switch valve to direct flow to either the main or catalytic reactor for

the specific incineration phases determined from sample and reactor temperature.

For cycled incineration, i.e. where the main reactor is heated and cooled for each loading, the reactor configuration should be designed to allow rapid heating through typical incineration temperatures at minimum power input; this would require a minimum weight and volume configuration, with the weight including heaters and insulation, being ideally equal to or less than the feces weight, and with the geometry of the reactor cavity providing maximum heat transfer contact area for zero-gravity operation.

- c. For non-cycled incineration, i.e., where the main reactor continually remains at an elevated temperature of approximating 500°C, suitable for pyrolysis, the main reactor design should include a transfer system for insertion of the fecal sample and removal of ash residue, in zero-gravity.
- d. The incineration system should be constructed of materials which are corrosion resistant, e.g., stainless steel, to withstand the attack of typical incineration products. Specific materials would probably require cycling and duration testing, particularly in light of the temperatures involved.
- e. Additional evaluation of catalyst for pyrolysis gas oxidation should be conducted to demonstrate feasibility during extended continuous operation.
- f. The highly combustible nature of dried fecal material should be evaluated to determine the characteristics of sustained incineration

slightly above ignition temperature, controlled primarily by oxygen input rather than power input to the reactor. If feasible, incineration in this manner would minimize and possibly eliminate the need for external power input.

- g. If gaseous products other than CO_2 or N_2 , are desired, e.g. CH_4 , CO or H_2 , incineration should be conducted with zero oxygen feed, i.e. pyrolysis, or with less than stoichiometric amounts, in a system utilizing continuous monitoring of CO_2 , CH_4 , or CO leaving the catalytic reactor.
- h. The technique and equipment used for fecal incineration and microwave drying should be evaluated for possible application to other waste material such as urine distillate solids or unconsumed feed residues, alone or combined with fecal material.
- i. In microwave drying the main reactor cavity should be designed according to the requirements of microwave theory to maximize absorption of energy by the fecal sample.
- j. Methods and equipment for removal or control of undesirable trace gases such as CO , H_2S and NO_2 in product gases, should be developed and integrated into the overall incineration system.

APPENDIX

Test No.	Dried Wt. Gm	Filter Paper No.	Temp. °C	Drying Time Hr	Total Time Hr	Sieve Residue	Oxygen Feed Gas			Effluent Gas			Color	Conc. mg/l	Product Water			Apparatus	Solid Residue Wt. Gm								
							Let Stage	2nd Stage	Con- sumed Liter	O ₂ %	CO %	H ₂ %			CH ₄ %	Total mg/l	Solid Cx. mg/l			SO ₄ mg/l	Cl ⁻ mg/l	pH					
1.	200	600	700	0.9	3.0	20	0	9.9	MA*	MA	MA	MA	MA	MA	16.2	Dark Strg. Brown H ₂	.034	9336	515	4620	34	35	7.9	Clay	5.9	Grey	None
2	250	600	550	1.1	3.3	20	0	11.5	MA	MA	MA	MA	MA	MA	177	Brown Strg. Black H ₂	.008	2380	5050	8300	691	148	8.7	Clay	17.1	Black	None
3	250	600	500	1.2	2.1	20	0	7.2	MA	MA	MA	MA	MA	MA	207	Brown Strg. Black H ₂	.020	1360	5220	7500	310	177	8.7	Clay	16.7	Black	None
4	250	600	570	1.2	3.6	20	10.0	10.0	20.0	MA	MA	MA	MA	MA	221	Grn Strg. H ₂	.020	648	4600	11K	76	103	9.0	Foggy	10.8	Black	None
5	250	600	600	1.2	3.0	20	0	8.5	MA	MA	MA	MA	MA	MA	206	Grn Strg. H ₂	.013	1796	1900	6700	1000	88	7.7	Foggy	10.7	Black	None
6	250	600	550	1.2	3.3	20	0	11.4	11.4	MA	MA	MA	MA	MA	175	Brown Strg. H ₂	.018	1152	3700	10K	725	82	8.9	Clay	18.0	Black	Silt
7	250	600	590	1.2	4.0	20	0	13.7	13.7	MA	MA	MA	MA	MA	210	Brown Strg. H ₂	.034	3164	6350	2K	2679	275	8.5	Clay	16.1	Grey	None
8	250	600	590	1.3	3.3	20	0	13.8	13.8	MA	MA	MA	MA	MA	199	Brown Strg. H ₂	.030	1908	6020	14K	922	1.7	8.0	Clay	17.7	Black	None
9	250	600	660	1.1	4.8	20	0	16.0	16.0	MA	MA	MA	MA	MA	206	Black Strg. H ₂	.036	3412	7600	16K	2000	269	8.0	Clay	9.7	Wet	None
10	250	600	560	1.3	5.3	20	0	19.8	19.8	MA	MA	MA	MA	MA	212	Brown Strg. H ₂	.050	3028	7100	16K	1943	106	8.1	Clay	6.7	Wet	Silt
11	250	600	580	0.9	5.9	20	0	24.5	24.5	MA	MA	MA	MA	MA	MA	Brown Strg. H ₂	.025	1746	3060	13K	1170	64	9.1	Clay	MA	Wet	None

* MA - Not Analyzed

Test No.	Power Plant		Total Inlet Press Time Hr	Total Inlet Press Hr	Chemical Feed Gas			Dry Gas			Wet Gas			Present Water			Solid Residue													
	Wt. On	Input Watts			Temp °C	1st Stage	2nd Stage	Total L	CO ₂ %	O ₂ %	N ₂ %	Total Liter	CO ₂ %	O ₂ %	N ₂ %	Wt. On	Color	Wt. On	Color											
12	250	600	685	1.2	5.4	20	19.2	19.0	38.7	NA*	NA	NA	.01	.01	NA	NA	NA	NA	NA	Black Strg. NI ₃	.017	1544	6730	8300	667	87	8.8	Clay	15.0	Gray None Yel
13	250	600	690	1.1	3.3	20	22.7	72.3	154.5	NA	NA	NA	.01	.01	NA	NA	NA	NA	NA	Black Strg. NI ₃	.016	1840	5800	6900	849	70	8.6	Clay	6.8	Gray None
14	172	600	600	1.0	3.2	20	NA	NA	NA	NA	NA	NA	.01	.01	NA	NA	NA	NA	NA	Brown Strg. NI ₃	.013	2160	3270	4400	764	99	8.2	Clay	6.5	Gray None
15	250	650	690	0.8	4.3	20	55.1	44.4	109.5	NA	NA	NA	0	.01	NA	NA	NA	NA	NA	Yel Strg. NI ₃	.018	2244	4210	670	449	44	1.5	Clear	NA	Gray None
16	250	650	655	1.0	4.7	20	51.5	48.1	99.6	NA	NA	NA	.01	.01	NA	NA	NA	NA	NA	Yel Strg. C ₂ H ₁₈	.030	6192	99	520	3870	9	1.1	Clear	7.3	Gray None
17	250	650	NA	1.0	3.3	20	70.6	88.1	158.7	53.0	106	29	0	0	5	66	NA	NA	NA	Yel Strg. C ₂ H ₁₈	.025	1500	165	1940	907	24	1.6	Clear	5.5	Whit None Yel
18	300	600	NA	NA	4.0	20	NA	NA	NA	NA	NA	NA	.01	.01	NA	NA	NA	NA	NA	Yel Strg. C ₂ H ₁₈	.009	972	172	1070	131	12	2.0	Clear	2.6	Gray Very Silt
19	300	600	NA	NA	3.7	20	70.1	25.1	95.2	NA	76	NA	0	0	NA	NA	NA	NA	NA	Yel Strg.	.002	1368	98	570	674	15	1.5	Clear	3.2	Whit Very Silt
20	300	600	670	0.9	2.6	20	38.2	17.6	49.8	24.2	26	30	.01	0	1.5	59	NA	45	NA	Yel Strg.	.011	176	43	270	42	15	1.8	Clear	2.5	Whit None Yel
21	300	600	580	0.8	3.7	20	59.9	27.3	87.2	NA	44	NA	0	0	NA	NA	NA	NA	NA	Gray None	.012	248	52	570	85	26	1.7	Foggy	2.3	Whit Silt Yel
22	300	600	640	0.6	2.3	20	36.6	26.3	42.9	NA	NA	NA	0	.01	NA	NA	NA	NA	NA	Black Silt	.006	1436	383	2340	697	104	8.5	Clay	2.2	Gray None

* NA - Not Analyzed

Test No.	Feed No.	Plant No.	Temp. Input	Temp. Inlet	Dry-Ing Time	Total Inclin. Time	Eys. Press	Crown Feed Gas			Effluent Gas					Wt. Color	Color	Wt. Color	Wt. Color																
								Let Stage	Mid Stage	End Stage	CO ₂	O ₂	H ₂	SO ₂	SO ₃					SO _x	SO ₂	SO ₃	SO _x	SO ₂	SO ₃	SO _x									
23	100	800	680	0.6	1.9	20	18.6	28.9	47.5	18.0	29	32	0	.03	10	58	MP	51	81	Grey Blt	.008	2236	130	70	1360	6	2.2	Feeds	2.2	Grey	None	Wht			
24	100	800	640	0.6	2.1	20	30.1	25.7	55.7	30.0	26	38	0	0	6	56	..	46	79	Black Shrp	.008	2840	128	1700	1523	58	6.8	Clay	2.1	Grey	None	Wht			
25	100	800	640	0.5	2.5	20	19.4	23.5	48.9	23.0	20	47	0	1	9	43	NA	46	78	Yel Moth	.003	2788	71	1040	1395	12	1.6	Feeds	2.4	Grey	None	None			
26	100	800	640	0.5	2.0	20	6.5	19.7	26.3	11.6	15	38	.01	.01	19	43	NA	34	83	Black Moth	.006	2884	126	2470	1765	97	6.5	Clay	1.8	Grey	None	Yel			
27	100	800	630	0.5	2.4	15	4.9	22.7	27.6	12.3	15	39	0	0	8	53	NA	29	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	1.4	Wht	None	Yel		
28	100	800	670	NA	1.9	15	36.2	20.5	56.7	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	4.0	Grey	None	None			
29	100	800	530	NA	2.5	15	25.5	15.5	41.0	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA		
30	100	800	570	NA	1.9	15	11.9	20.7	32.6	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	
31	100	800	670	NA	2.4	15	16.9	33.5	50.4	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
32	100	800	650	0.5	2.2	20	13.7	30.3	42.8	30.9	12.9	54	0	0.1	12	36	NA	44	75	Black Shrp	.011	2410	22	210	1411	25	1.9	Clay	3.0	Grey	None	Wht			
33	100	800	650	0.5	2.3	20	10.7	30.4	43.1	29.2	11.9	57	0	0.1	4	38	.01	41	84	Black Moth	.007	2984	26	1400	1932	17	2.2	Clay	3.1	Grey	None	Wht	Black		

* NA - Not Analyzed

Test No.	Power Plant Status		Total Incin Press Time Hr	Dry- ing Time Hr		Total Syn. Press PRTA	Current Feed Gas			Effluent Gas			Product Water			Solid Residue																
	Wt. Gm	Input Watts		°C	1st Stage		2nd Stage	Total L.	CO ₂ %	CH ₄ %	O ₂ %	NO ₂ %	Total mg/L	Wt. Gm	Color	Odor	Total mg/L	Total mg/L	Total mg/L	Wt. Gm	Color	Odor										
34	100	800	560	0.7	2.1	20	13.9	22.9	36.8	29.7	6.6	61.1	7.7	5	28	.01	34.7	69	Black	Moth Ball	1000	1192	266	7.5	Clay	2.6	Gray	None	Whit			
35	100	800	630	0.5	1.8	20	15.1	29.9	45.0	34.7	10.3	56	.01	3	4	36	.04	31.1	83	Black	Moth Ball	2380	2550	85	2.2	Clay	2.7	Gray	None	Whit		
36	100	800	560	0.6	1.8	20	0	19.7	19.7	15.2	4.5	57	.08	3	6	50	.08	22	79	Black	Moth Ball	720	872	12	2.0	Clay	5.7	Black	None	None		
37	100	800	610	0.6	1.8	20	0	38.3	38.3	28.8	7.0	40	0	.1	8	27	.08	26	79	Black	Moth Ball	2200	2727	56	2.5	Clay	4.7	Black	None	None		
38	100	800	600	0.5	1.8	12	26.2	36.2	62.4	NA	NA	27	0	0	46	29	.12	NA	87	Yel	Moth Ball	1740	217	79	2.2	Clay	4.5	Gray	None	Whit		
39	100	800	600	0.6	2.2	10	23.5	17.1	40.6	NA	NA	NA	0	0	NA	13	.09	NA	89	Black	Slt	2060	2180	27	1.7	Clay	3.3	Gray	None	Whit		
40	100	800	640	0.6	2.7	10	26.3	23.6	49.9	40.6	9.3	41	0	.1	7	NA	.10	24	91	Black	Slt	200	1284	24	1.8	Clay	4.0	Gray	None	Whit		
41	100	800	640	0.5	2.1	10	27.3	32.1	59.3	42.4	11.3	73	0	0	10	36	.14	34	88	Black	Very Slt	480	56	342	48	1.8	Clay	3.8	Gray	None	Whit	
42	100	800	610	0.6	1.8	10	14.8	26.3	41.1	36.0	5.3	41	.01	1	28	28	.17	30	90	Black	Moth Ball	4428	173	960	3020	91	1.8	Clay	3.5	Gray	None	Whit
43	100	800	650	0.5	1.9	10	22.7	26.2	48.9	33.0	14.5	60	.3	.1	9	26	.01	63	89	Black	Slt	2852	76	980	1924	32	1.9	Clay	4.0	Gray	None	Whit
44	100	800	650	0.6	2.0	10	37.7	11.5	49.3	43.2	6.0	56	0	0	11	31	.37	30	90	Black	Slt	308	77	48	42	24	1.9	Clay	3.8	Gray	None	Whit

*NA - Not Analyzed

