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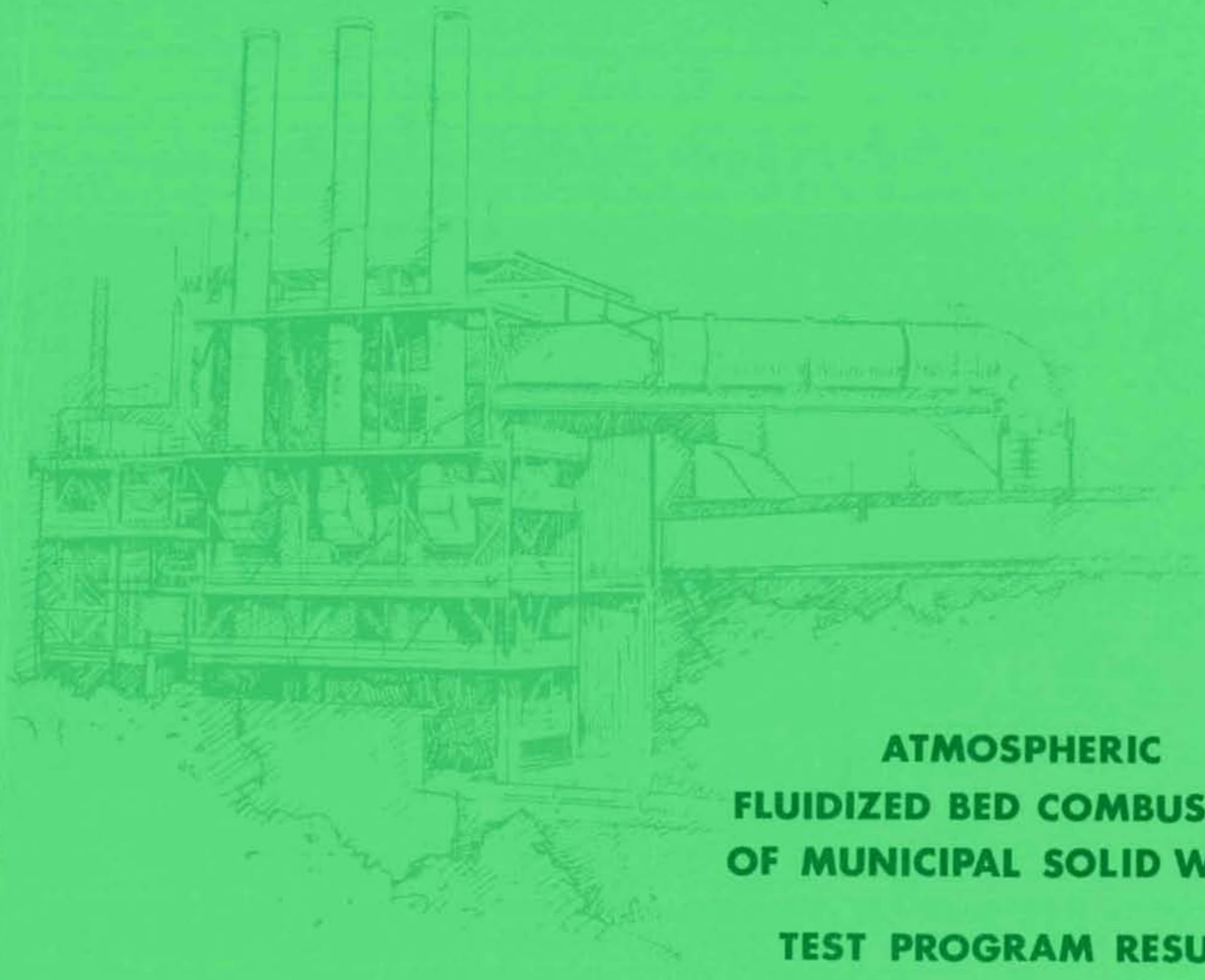

ATMOSPHERIC FLUIDIZED BED COMBUSTION OF MUNICIPAL SOLID WASTE:

TEST PROGRAM RESULTS

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Combustion Power Company Inc.
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MENLO PARK, CALIFORNIA

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BY

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ABSTRACT

Air classified Municipal Solid Waste (MSW) was fired in an Atmospheric Fluidized Bed Combustor at low excess air to simulate boiler conditions. The 7 sq. ft. combustor at Combustion Power Company's energy laboratory in Menlo Park, CA, incorporates water tubes for heat extraction and recycles elutriated particles to the bed. System operation was stable while firing processed MSW for the duration of a 300-hour test. Low excess air, low exhaust gas emissions, and constant bed temperature demonstrated feasibility of steam generation from fluidized bed combustion of MSW.

During the 300-hour test combustion efficiency averaged 99%. Excess air was typically 44% while an average bed temperature of 1400 ^{o}F and an average superficial gas velocity of 4.6 ft/sec were maintained. Typical exhaust emission levels were 30 ppm SO_2, 160 ppm NO_x, 200 ppm CO, and 25 ppm hydrocarbons. No agglomeration of bed material or detrimental change in fluidization properties was experienced.

A conceptual design study of a full scale plant to be located at Stanford University was based on process conditions from the 300-hour test. The plant would produce 250,000 lb/hr steam at the maximum firing rate of 1000 tons per day (TPD) processed MSW. The average 800 TPD firing rate would utilize approximately 1200 TPD raw MSW from surrounding communities. The Stanford Solid Waste energy Program was aimed at development of a MSW fired fluidized bed boiler and cogeneration plant to supply most of the energy needs of Stanford University.

ATMOSPHERIC FLUIDIZED BED COMBUSTION OF MUNICIPAL SOLID WASTE: TEST PROGRAM RESULTS

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Menlo Park, California

INTRODUCTION

Disposal of solid waste has historically been an economic cost to municipalities and industry. The least expensive means of disposal in this country has traditionally been landfill. Rapidly decreasing availability of space for landfill and rapidly increasing need for recovery of energy value of solid waste have generated considerable interest in the development of solid waste combustion technology. Mass burning incinerators, both with and without water walls for energy recovery, have seen the greatest use in combustion of municipal solid waste. Drawbacks of mass burning are low process efficiency and high emissions levels. Alternative processes include atmospheric fluidized bed (AFB) boilers, semi-suspension fired boilers, and pyrolysis processes.

AFB boilers offer the advantage of low NO_x emissions and high combustion efficiency in relatively compact equipment for the firing of municipal solid waste (MSW). Prior to the present tests, however, MSW combustion in an AFB boiler had not been demonstrated. An experimental program was designed to investigate the favorable operating regimes for a bed with steam-raising tubes, to determine the combustion efficiency, to measure the gaseous pollutants, to determine the erosion or corrosion of the tubes, and to investigate the fouling of the tubes or system internals caused by the combustion of municipal solid waste. Two 50-hour preliminary experiments were run to shake down the equipment and to identify the most favorable operating regime for a subsequent 300-hour test. This paper will describe the results of the experimental program and relate those results to the economics of a full scale cogeneration facility being considered for Stanford University.

EQUIPMENT DESCRIPTION

Testing was conducted in a 7 sq ft atmospheric fluidized bed combustor at Combustion Power Company's energy laboratory. The refractory-lined combustor is cylindrical with an inside diameter of 3 ft and an inside height of 16 ft. A view port permits observation of the bed during operation. Figure 1 diagrams the combustor facility as arranged for combustion of processed municipal solid waste (MSW). Figure 2 shows the combustor.

The combustor permits several arrangements of in-bed heat exchanger tubes so that heat extraction can be adjusted to suit desired test conditions. Primary heat extraction is through two, three, or four horizontal water tube bundles. These stainless steel tubes operate at low temperature to assure test reliability. Typically, 150 psig water is heated from 100 F to 300 F. This water is flashed to atmospheric pressure and makeup water reduces the feedwater temperature to 200 F. The water tube wall temperatures are lower than those of typical boiler tubes so that temperature-related corrosion does not occur. For the long duration test, air-cooled sample tubes were installed in the fluid bed and in the freeboard above the bed. These tubes were designed to duplicate boiler and superheater tube-wall temperatures for study of erosion and corrosion. Figure 3 shows the bed heat exchanger arrangement for the 300-hour test.

The combustor may be operated with or without recycle of elutriated bed material. During the first parametric test, the exhaust cyclone at the combustor was arranged to discharge into a collection barrel rather than returning collected particles to the bed. During the second parametric test and the 300-hour test, elutriated particles were recycled back to the bed from the cyclone. Discharge piping from the stainless steel recycle cyclone permits sampling of recycle material during operation.

Exhaust gas from the recycle cyclone passes through a spray cooler before

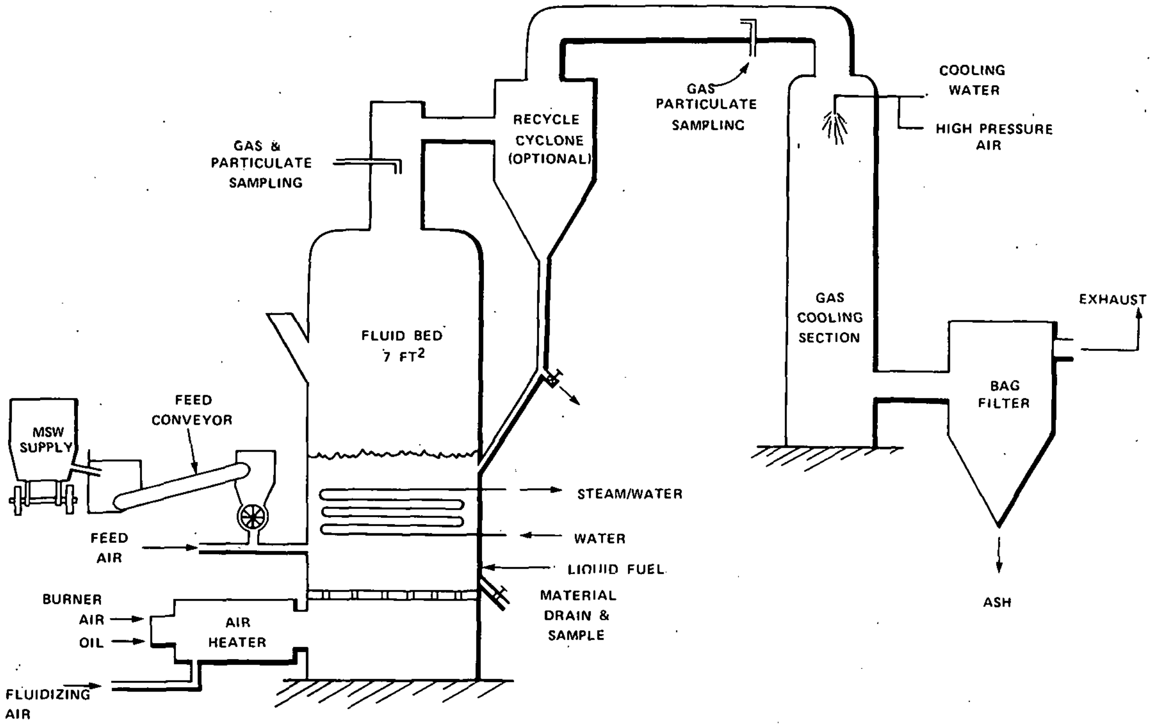

Figure 1 Fluid Bed Boiler Test Facility

final particulate cleanup in a baghouse. Stack discharge from the baghouse meets all applicable emissions regulations. Sampling ports are provided before and after the recycle cyclone, and also in the discharge stack from the baghouse.

Solid Waste Processing and Feed

Municipal solid waste is received in conventional packer trucks, each containing 3 to 6 tons of refuse. The trucks dump their contents on a covered concrete pad from which the refuse is pushed to shredder input conveyors as shown in Figure 4. The 100 hp Eidal mini-mill shredder has a nominal capacity of 5 tons per hour. Shredded solid waste is air-classified and the light fraction pneumatically transported to a storage shed to await transport to the combustor facility.

At the combustor, a live bottom bin provides short term storage and variable outfeed capability. Processed MSW is carried from the bin by the feed conveyor which is designed to provide uniform volumetric flow of the fuel. The combustor bed temperature control loop adjusts the speed of the feed conveyor, which discharges into a constant-speed rotary airlock. From the airlock, fuel is fed pneumatically through a 3-inch feed pipe to the fluid bed combustor.

Instrumentation

During combustion of processed MSW, temperatures in the system are monitored at 37 points. Data is collected for pressure and flow of combustion air, exhaust gas, cooling air and water, and fuel and oil. Exhaust gas composition is continuously monitored and concentrations

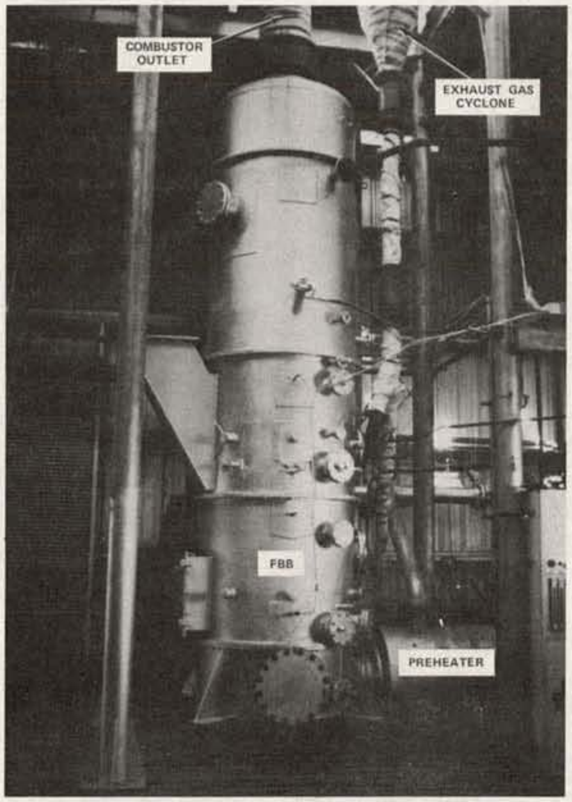

Figure 2 Fluidized Bed Combustor at Combustion Power Co.

of O_2, CO, NO_x, and hydrocarbons are recorded. Gas analysis is supplemented by Orsat testing at frequent intervals. Samples are taken daily for determination of HCl concentration and particulate loading. Material samples for analysis are taken daily from the bed and from the baghouse.

PARAMETRIC TESTS

Two 50-hour parametric tests were conducted to accomplish operational checkout of the system, explore the range of allowable process parameters, and identify the most desirable conditions for longer duration steady-state operation. Both parametric tests were planned to explore the same range of parameters. The first test, however, was run without recycle while in the second parametric test, elutriated material was recycled back to the bed. The first test ran 48 hours before being shut down by high pressures caused by slag buildup in the combustor freeboard and exhaust duct.

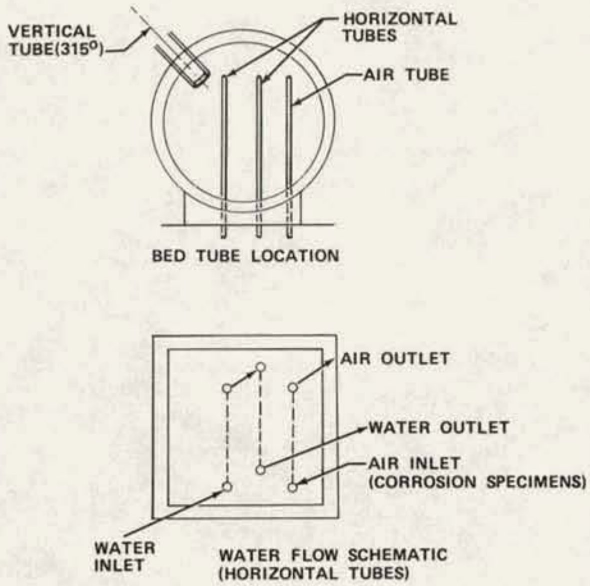

Figure 3 SSWEP 300-hour Test Bed Heat Exchanger Arrangement

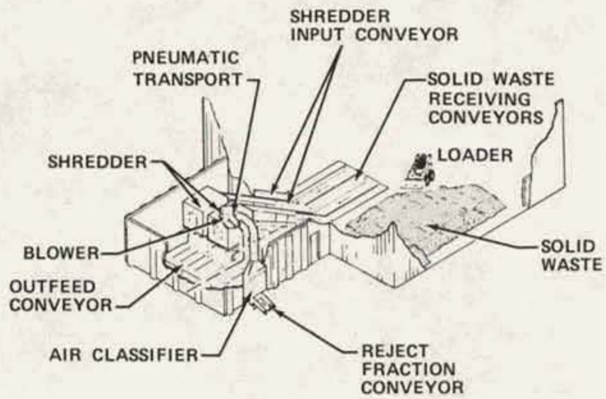

Figure 4 Solid Waste Processing Station

The second parametric test was terminated after 73 hours of operation.

Parametric Test Results

Parametric testing began with the bed depth maintained at 2.5 ft (slumped), but freeboard combustion appeared decreased when bed depth was increased to 3.5 ft (slumped). Deeper beds were used for all subsequent testing. Stable combustion was maintained within the ranges of:

Bed Temperature	1300-1410 F
Superficial Velocity	4.1-6.8 ft/sec
Excess Air[1]	50%-74%

Combustion efficiency[2] averaged 98.9%. Operation outside these ranges, particularly with excess air below 40%, resulted in undesirable freeboard afterburning and slag deposits in the combustor freeboard and exhaust ducting.

Slag deposits which formed during parametric tests were subjected to fusion-temperature analysis and found to have initial deformation temperatures of 1990 F and above. Differential thermal analysis confirmed the fusion test results. Since slag formation thus appeared to be related to high freeboard temperatures, one process condition set for the 300-hour test was a freeboard high temperature limit of 1600 F. The slag samples analyzed were, in general, calcium-rich alumina silicates.

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[1] Excess air is calculated from:

$$EA = \frac{2.67C}{2.67C+8H+S-0} \times \frac{0_2}{CO_2+CO} \times 100\%$$

where:

EA = excess air
C, H, S, 0 = respective elemental dry weight %
0_2, CO_2, CO = respective gaseous dry volume %

[2] Combustion efficiency is based on unburned carbon in the flue gas and ash:

$$\eta = \frac{\frac{12}{44}\, a(\Delta H_{CO_2}) + \frac{12}{28}\, b(\Delta H_{CO}) + \frac{24}{30} c(\Delta H_{HC})}{\frac{12}{44}\, a + \frac{12}{28}\, b + \frac{24}{30}\, c + dH_{CO_2}}$$

where: a,b,c = respective weight concentration of CO_2,CO,HC in flue gas
and d = weight ratio of C to flue gas.

The 3-inch diameter fuel feed line was found to be very susceptible to plugging problems caused by round plastic lids of approximately 4-inch diameter. These lids were resilient enough to pass through the shredder, light enough to pass through the air classifier, but just stiff enough to cause blockage of the pneumatic feed line. Adjustment of the air classifier eliminated most of the lids and the problem with feedline plugging, but also resulted in rejection of a larger portion (near 50%) of the shredded MSW than had been desired. Larger diameter feedlines or improved shredding of the MSW would eliminate this problem in large scale equipment.

300-HOUR TEST

Operating conditions for the 300-hour test were based on results of the two parametric tests. Test objectives were to:

- Demonstrate the feasibility of burning municipal solid waste in an atmospheric fluid bed combustor with energy extraction from the bed.
- Evaluate the fluid bed media and fluidization characteristics over a 300-hour time period.
- Characterize exhaust gas emissions.
- Measure bed heat transfer coefficients.
- Gather data on erosion and corrosion of typical boiler and superheater materials at representative tube wall temperatures.

The 310 hours of operation included 298 hours of firing MSW at test conditions. The test was completed without any significant combustion-related problems, and operating conditions remained substantially constant. Upsets were caused by feedline plugs which occurred 35 times during the test. These blockages, caused by plastic lids which did not shred during fuel processing, were cleared within two to five minutes while combustor operation was maintained on oil. No material deposition or agglomeration was observed; at test conclusion the combustor and freeboard were virtually free of slag.

Fuel Analysis

Samples of the processed MSW were analyzed daily. Fuel properties were reasonably consistent throughout the test. Results of proximate and ultimate analysis on the fuel are:

PROXIMATE ANALYSIS (As Received)	Average	Range
Moisture Fraction (%)	23.6	17-26
Ash Fraction (%)	10.6	9-13
Volatiles (%)	57.6	54-64
Fixed Carbon (%)	8.2	8-9.7
Higher Heating Value (Btu/lb)	5572	5250-6050

ULTIMATE ANALYSIS (Dry Weight %)	Average	Range
Carbon	44.46	43.9-45.2
Hydrogen	5.96	5.8- 6.1
Oxygen	34.32	32.2-35.6
Nitrogen	0.67	0.63-0.80
Chlorine	0.49	0.40-0.67
Sulfur	0.13	0.09-0.17
Ash	13.97	12.0-16.0
Higher Heating Value (Btu/lb)	7352	6900- 7700

Operating Conditions

Operating conditions remained substantially constant throughout the 300 hours of test operation. Some parameters, however, changed due to a gradual decrease in bed particle size that occurred during the first half of the test. At typical steady state operating conditions, data from the last 144 hours of the test were averaged:

Bed Temp.	1392 F
Freeboard Temp.	1487 F
Superficial Velocity	4.6 ft/sec
Excess Air	44%
Bed Depth (slumped, nominal)	3.5 ft
Fluidizing Air Flow	43.0 lb/min
Fuel Feed Rate	8.2 lb/min
Combustion Efficiency	99.0%
Exhaust Material Recycle Rate	16 lb/min
Baghouse Ash collection Rate	0.9 lb/min
Bed Material Letdown Rate	4.9 lb/hr

Figure 5 shows the temperature recorder chart for a portion of the twelfth day of operation (260 through 264 hours into the test) as representative of general test conditions. Bed temperature remains constant, despite fluctuations in freeboard and exhaust temperatures caused by variations in heating value of processed MSW fuel.

Flue Gas Emissions

Emissions levels in the flue gas were considered very important to the basic program objective of demonstrating the feasibility of steam generation by firing MSW in an AFB boiler. Actual emission levels verified the potential of AFB combustion for low flue gas emission levels. Average emissions levels for the last 144 hours of test operation were:

Flue Gas Emissions	
O_2	6.7%
CO_2	13.5%
CO	200 ppm
SO_2	29 ppm
NO_x	160 ppm
Hydrocarbons (as CH_4)	40 ppm
HCl	100 ppm

Generally, each of the gaseous emissions monitored tended to exhibit constant variation. Occasional very high spikes of SO_2, CO, and hydrocarbons occurred independently of each other or any other parameter recorded. These spikes were probably due to particular constituents of the MSW fuel.

Emissions of SO_2 and NO_x are of particular concern in light of the tight regulations regarding these pollutants. Actual emissions levels were well under 1979 EPA promulgated New Source Performance Standards (NSPS) for boilers but would require emissions offset consideration to

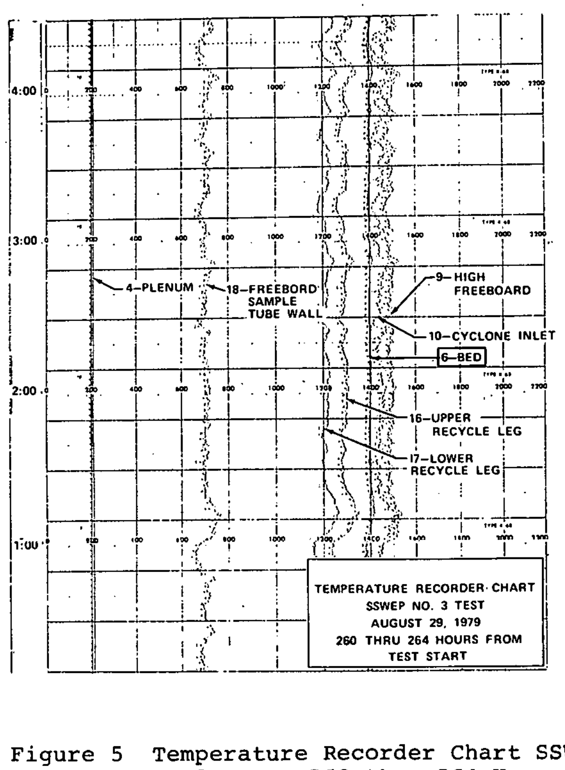


Figure 5 Temperature Recorder Chart SSWEP No.3 Test, 260 thru 264 Hours

be approved by California and local authorities. The indicated exhaust concentrations translate to approximately 0.06 lb/MMBtu fuel input for SO_2 and 0.25 lb/MMBtu for NO_x average for the last 144 hours of operation.

Bed Material

The original bed material was Monterey 16-mesh sand with an average particle size[3] between 1.0 and 1.1 mm. Daily samples were taken of bed material and of material returning to the bed from the recycle cyclone. Figure 6 shows the rapid drop in bed particle size at the beginning of the test, followed by a more gradual decline to nearly constant particle size at the end of the test. Also shown is the recycled material size which appeared unaffected by the changing bed material size. Some pieces of glass could be observed in the material samples and a few (less than 1%) pieces of agglomerated particles up to 1/4" size.

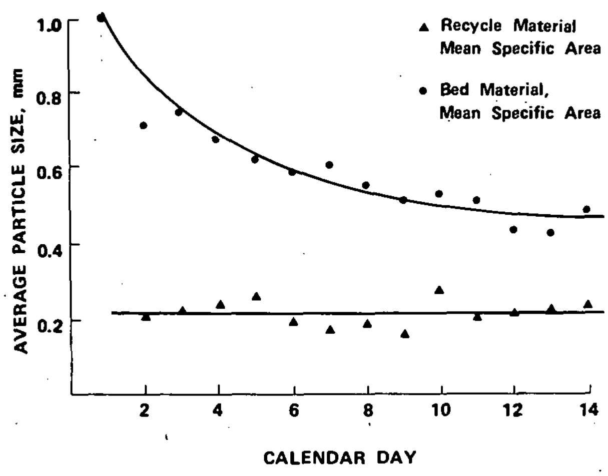


Figure 6 Bed Particle Size

Daily bed material samples were analyzed for cations and metals content by means of the emission spectroscopy scan method. The concentrations of the major constituents of the bed material were found to remain essentially constant. A number of elemental concentrations, however, increased throughout the test and accumulation of these materials appeared to be continuing up to the time the test was terminated. This accumulation of elements was the only observed phenomena which had not reached a steady state equilibrium before the end of the test. Longer test duration will be necessary to observe the effects of this accumulation.

Elements which accumulated were Ca, Fe, Mg, Ti, Na, Cu, Mn, P, Zn, and possibly Pb. Concentrations of these elements are shown for samples taken early in the test and at the end of the test. (Trace elements are not shown).

Element	Concentration Weight % 3rd Day	12th Day
Si	37.0	33.8
Al	4.0	3.8
Ca	1.8	5.5
K	2.8	2.7
Na	1.9	4.0
Fe	0.48	1.2
Mg	0.17	0.69
Ti	0.068	0.28
Ba	0.11	0.10

Heat Transfer

Water inlet and outlet temperatures as well as flow through the main heat exchanger were monitored throughout the test. That heat exchanger consisted of two four-pass, horizontal tubes arranged in bed as shown in Figure 3. Early in the test, the overall heat transfer coefficient averaged 46 Btu/hr-ft^2-F. By the end of the test, the heat transfer coefficient had increased to 58 Btu/hr-ft^2-F. The increase in heat transfer coefficient is attributed to the decrease in bed material particle size. The influence of particle size on outside wall heat transfer coefficient is predicted by Bashakov (2) or Locke (3).

Corrosion and Erosion

In addition to the stainless steel (TP316) water cooled tubes in the bed which were the primary means of heat extraction, air cooled sample tubes were installed in the bed and in the freeboard to duplicate wall temperatures of superheater tubes. No significant corrosion or erosion was observed on the water cooled tubes in the bed. Mechanical failure of the air cooled tube in the bed invalidated the sample exposure.

The freeboard air cooled sample tube was installed transverse to gas flow in the exhaust ductwork from the combustor. The tube was fabricated from sample sections of six different tube materials. The samples were exposed to 1500 F to 1600 F flue gases heavily laden with particulate (40-50 gr/acf) at a gas velocity of about 35 fps. The sample tube

[3] Particle size is calculated by the "Mean Specific Surface" method (1)

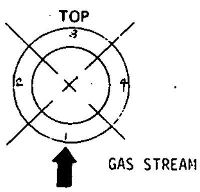
wall temperature was about 720 F. Combined corrosion and erosion resulted in substantial metal wastage of carbon steel specimens, with less wastage apparent as the alloy content increased.

As shown in Table I, metal wastage was greatest for carbon steel coupons, approximately 50%-60% of the wall facing the gas side, while wastage of the sides and tops was less than 5%. Wastage was considerably less for the low alloy steels in the same orientation. On the side facing the gas flow, the wastage was 13%-17% while elsewhere it was less than 3%. The metal wastage of the austenitic specimens (SS304, SS316, and Incoloy 825) was the lowest, being less than 6% on the side facing the gas flow and less than 1% elsewhere. Scaling and deposits were also orientation dependent, with bottoms of the coupons relatively free of scale and deposits compared to the sides and top. As expected, scale formation was thickest on the carbon steels, and the chrome-containing austenitic steels were resistant to scaling.

Residual corrosion penetration was very low on the bottoms of the carbon steel and low alloy specimens. Apparently, corroded areas and scale were removed by erosion as they formed, i.e., corrosion-erosion was a major factor in the metal wastage. Corrosion penetration on the low alloy specimens was comparatively low on the tops and sides at 5 to 10 microns. With respect to corrosion

TABLE I

PIPE THICKNESS AND MICROGRAPH MEASUREMENTS



SSWEP: 300 HR TEST COUPONS
LOCATION: CTU FREEBOARD

Specimen Identification	Pipe Orientation	Pipe Thickness (Inch) Unexposed*	Exposed	% Wastage	(Residual Maximum) Micrograph Measurements Scale	Penetration M	Comments
1A1	1. Bottom	.115	.060	47.8	None(a)	6	(a) Corrosion-erosion
(Carbon Steel)	2. Left Side	.112	.113	-.9	15	10	
(SA-106B)	3. Top	.110	.116	-5.5	16	60	
(SA-210A1)	4. Right Side	.113	.110	2.7	(b)	14	(b) Spalled
3A3	1.	.116	.100	13.8	3	<2	
(1¼Cr-½ Mo-Si)	2.	.115	.116	-.9	60	10	
(SA-335P11)	3.	.118	.124	-5.1	15	10	
(SA-213T11)	4.	.120	.117	2.5	250(a)	10	(a) Scale and ash deposit
4A4	1.	.135	.113	16.3	80	<2	
(2¼Cr-1 Mo)	2.	.130	.129	.8	a.	5	a. Spalled
(SA-335P22)	3	.129	.131	-1.6	b.	10	b. Spalled
(SA-213T22)	4.	.132	.132	0	c.	5	c. Spalled
5A5	1.	.105	.100	4.8	-	35	.005" wastage
(18Cr-8Ni)	2.	.105	.105	0	100(a)	50	(a) Scale and ash deposit
(SA-312-TP304H)	3.	.105	.106	-1.0	(b)	10	(b) Spalled
(SA-213-TP-304H)	4.	.104	.104	0	200(c)	10	(c) Scale and ash deposit
6A6	1	.107	.101	5.6	8	-	.006" wastage
(16Cr-12Ni-2Mo)	2	.118	.118	0	30	10	
(SA-312-TP316H)	3	.107	.107	0	a.	-	a. Spalled
(AS-213-TP-316H)	4	.106	.106	0	b.	5	b. Spalled
7A7	1	.112	.109	2.7	20	30	.003" wastage
(Ni-Fe-Cr-Mo-Cu)	2	.113	.113	0	a.	30	a. Spalled ?
(INCO 825)	3	.117	.117	0	b.	4	b. Spalled ?
(Sb-163)	4	.118	.119	-.8	c.	25	c. Ash deposit

* Unexposed pipe remnant measurements.

under the exposure conditions, the low alloy specimens compared well with the type SS316 that showed only 5 to 10 microns of corrosion penetration, while the metal wastage of the low alloy specimens was greater. The SS304 and Incoloy 825 showed corrosion penetrations ranging from 10 to 50 microns. Apparently, corrosion was by oxidation and sulfidation as sulfur was found in most corroded regions of all coupons.

CONCEPTUAL DESIGN STUDY

An economic study was undertaken to determine the promise of the AFB boiler system as defined by results of the experiments. The complete cogeneration system was envisaged for application to the Stanford University campus with the sizing and performance of the MSW fired AFB boiler based on test results.

Proposed System

The AFB system for study was designed to meet an existing situation in which the local municipality is faced with unavailability of landfill disposal area while Stanford University is seeking to control energy costs. Municipal solid waste would be processed at a central collection location and the MSW fuel trucked to the campus boiler plant. Size of the system is set by the 800 tons per day of processed MSW derived from 1200 tons per day of raw municipal solid waste estimated to be available in 1983. The modular AFB boilers would produce 600 psia, 750 F steam for a turbine with extraction at a pressure of approximately 170 psia. The extraction steam would condense in a heat exchanger to provide heating steam for the campus. Steam not needed for campus services would flow through the condensing stage of the turbine. Thermodynamic and process studies provided estimates that the proposed system would supply all of the university steam demand and approximately 50% of the electricity needs.

A flow diagram of the proposed system is shown in Figure 7. No attempt was made to investigate the processing of the MSW; study was limited entirely to conversion of the processed MSW to thermal energy and to electricity. All ancillary equipment necessary for energy production from MSW fuel was included.

Plant Design and Cost Estimating

The plant design was broken down into 12 major cost components listed in Table II.

For each of these systems, sufficient design work was done to define a concept and to specify the necessary size of the equipment. Wherever possible, standard components were used and cost estimates obtained from vendors. A plant plan, Figure 8, and layout drawings were made and necessary buildings included to enclose turbine, boiler, and fuel receiving areas so as to be compatible with the campus site. No cost was included for the value of the land. An artist's rendition of what the plant might look like is shown in Figure 9. General performance figures for the plant are shown below.

Plant Performance

- Design firing rate for processed MSW fuel:
  Average - 800 tons/day
  Maximum - 1000 tons/day
- Yearly average plant output:
  Steam at 125 psi, 110,800 lb/hr
  Electricity - 6.7 MW
- Boiler output:
  Average - 200,000 lb/hr
  Maximum - 250,000 lb/hr
- Maximum electrical output (net): 13.8 MW
  Concurrent 125 psi steam output 91,200 lb/hr
- Fuel Storage:
  Normal - 200 tons (6 hr avg output)
  Maximum - 500 tons (15 hr avg output)
- Reserve Fuel:
  Low grade bunker oil - 35 gpm at max. output
- Reserve fuel storage: 126,000 gal, 3 days.

Environmental Considerations

Emissions data collected during the 300-hour test were converted to a pounds-per-hour basis using the flow rate of combustion products for an 800 tons-per-day plant. Below are the data reported in this form, together with the "offset" that Stanford is permitted to take if it shuts down its present oil-fired heating plant.

Emissions	Projected 800-TPD Plant	Offset from Existing plant
SO_2	2.9 lb/hr	24.1 lb/hr
NO_x	7.7	23.1
CO	8.9	5.2
Hydrocarbons	0.7	1.1

Only CO would exceed the offset available from the existing boiler. The present

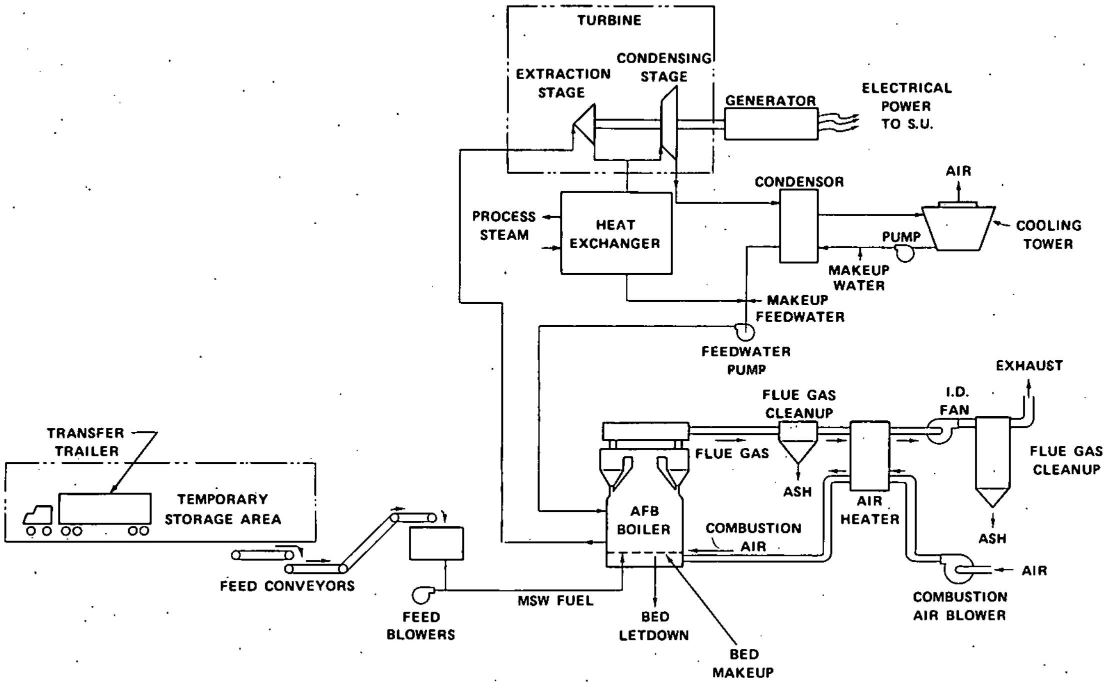


Figure 7 MSW Fired Cogeneration Plant Diagram

TABLE II

PLANT DESIGN - LIST OF MAJOR EQUIPMENT

1. Boiler System
   - Modules w/tubes & plenums (6)
   - Recycle cyclones (24)
   - Exhaust manifolds (2)
   - Evaporators (2)
   - Economizers (2)
   - Attemporators (2)
   - Supports & lagging
   - Sootblowers (6)

2. Startup System
   - Duct burner assembly
   - Booster fan
   - Fuel-oil pumps (dual)
   - Fuel-oil storage tank
   - Bed injectors (36)
   - Air manifold & dampers

3. Combustion Air System
   - F.D. fans & motors (2)
   - Intake silencers (2)
   - Tubular air preheaters (2)
   - Ductwork

4. Flue-Gas System
   - Multiclones (2)
   - Electrostatic granular filter
   - I.D. fan & motor
   - Ductwork

5. Bed Maintenance Systems
   - Slide gates (6)
   - Water-cooled conveyors (3)
   - Blowers w/filter silencers (3)
   - Airlock feeders (3)

5. Bed Maintenance Systems (Cont.)
   - Sand storage bin
   - Bin discharger
   - Fabric filter
   - Transport piping
   - Discharge diverter valves (7)

6. Flyash Disposal System
   - Airlocks (6)
   - Screw conveyors (2)
   - Feeders (2)
   - Transport piping
   - Ash silo
   - Fabric filter
   - Blower w/filter/silencer (2)
   - Silo discharger
   - Discharge conveyor

7. Fuel-Feed System
   - Main conveyor
   - Distribution conveyor
   - Feed bins (6)
   - Metering conveyors (6)
   - Conditioners (6)
   - Airlocks (36)
   - Blowers w/filter silencers (2)
   - Transport piping

8. Fuel Receiving & Storage
   - Apron
   - Conditioners
   - Live storage bin
   - Fabric filter w/blower
   - Dust collection ductwork
   - Front-end loader

9. Main Steam System
   - Turbine & assoc. equipment
   - Condensor
   - Condensate pumps
   - Condensor vacuum pumps
   - Condensate polishing
   - Cooling towers
   - Cooling water pumps
   - Process heat exchangers

10. Feedwater System
    - Boiler feed pumps (motor) (2)
    - Feedwater heater
    - Deaerating feedwater heater
    - Boiler feedwater transfer pump
    - Deaerated feedwater storage tank
    - Boiler feed pumps (turb.) (2)
    - Feedwater piping valves

11. Electrical & Control Systems
    - Generator & controls
    - Switchgear
    - Transformers
    - Motor control center
    - Instrumentation & controls

12. Buildings & Site
    - Grading & roads, landscaping
    - Foundations
    - Structures
    - Enclosures
    - Maintenance & administration
    - Heating, ventilation, A.C.
    - Fire safety equipment
    - Utilities

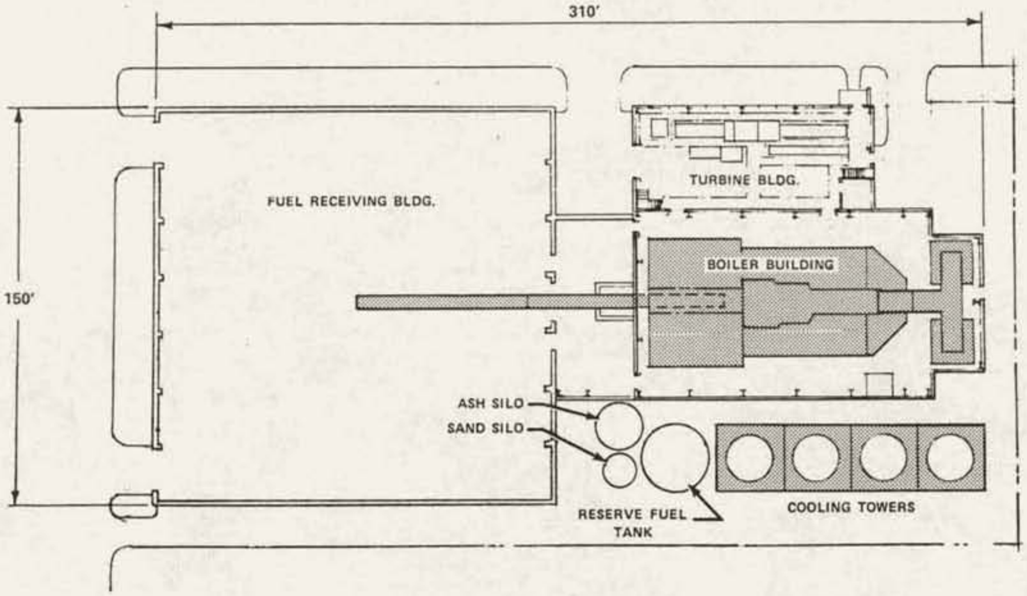


Figure 8 Solid Waste Energy Plant Plan

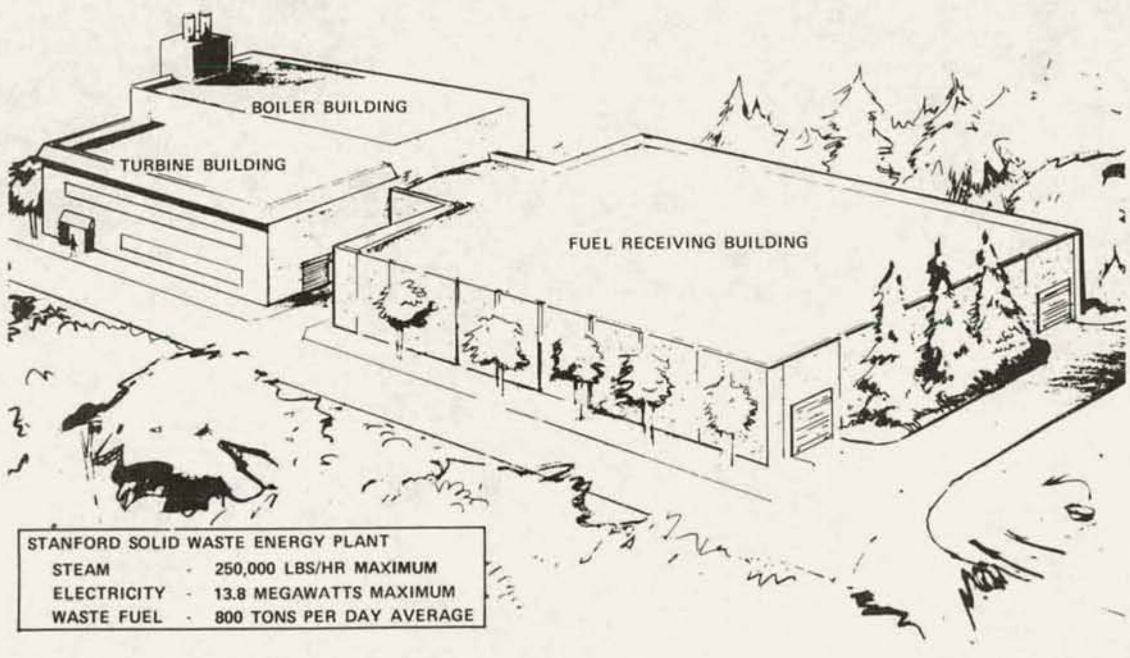


Figure 9 Artist's Rendition

Environmental Considerations (Continued)

boiler figures are based on steam generation at the rate of 80,000 lb/hr whereas the AFB plant figures are based on 800 tons per day fuel corresponding to 110,000 lb/hr of steam plus an average of 6.7 MW of electrical power. Thus the AFB boiler is nearly 40% larger than the present boiler and the emission levels are very similar. It appears that fluidized bed combustion of MSW is a sufficiently clean process that there would be little difficulty in meeting the stringent requirements of the San Francisco Bay Area Air Pollution Control District when the offset from the present boiler is considered.

Economic Summary

Cost estimates for the proposed full scale system are summarized in Table III. Each major subsystem is shown, along with the additional costs which are recommended for a construction project such as this by the standards of Electrical Power Research Institute. These figures should be compared to plants which handle 1200 tons per day of raw municipal solid waste and produce both steam and electrical power. The costs presented do not include processing or transporting the processed MSW to the point of use. For purposes of comparison, if the entire boiler steam output were converted to electricity, the plant would generate approximately 20 MW_e and capital cost would be approximately $1150/kW.

TABLE III

STANFORD SOLID WASTE ENERGY PLANT

Total Plant Investment

1.	Boiler system	$ 2,239,700
2.	Startup system	155,200
3.	Combustion air system	798,900
4.	Flue gas system	2,382,000
5.	Bed maintenance system	84,100
6.	Flyash disposal system	79,200
7.	Fule feed system	457,800
8.	Fuel receiving bldg. equip.	252,400
9.	Main steam system	5,421,000
10.	Feedwater system	1,942,600
11.	Electrical/controls/mis.	1,204,100
12.	Building, sitework, construction, A&E	1,645,000
	Total Direct Costs	16,662,000
	Undistributed Costs (6%)	999,700
	Process Capital	17,661,700
	Engrg. & Home Office Fees	1,666,200
	Subtotal	19,327,900
	Project Contingency (Subtotal x 15%)	2,899,200
	Process Contingency (Item 1 x 5%)	112,000
	Sales Tax	777,300
	Total Plant Investment	$23,116,400

CONCLUSIONS

Successful completion of the 300-hour test demonstrated the feasibility of fluidized bed combustion of municipal solid waste to generate steam. Necessary conditions for steam generation were met:

1. Operation at reasonably low excess air (44%) for process efficiency.

2. Constant bed temperature (±20 F) for controllable system output.

3. Freedom from slag and its associated problems.

4. Low exhaust gas emissions for environmental acceptability.

These conditions were met in a long-duration test designed to reveal any process problems likely to develop.

Early in the 300-hour test the average bed particle size decreased significantly although it subsequently appeared to reach equilibrium. The elemental composition of the bed was still changing after 300 hours. Neither situation caused any detrimental change in bed fluidization properties nor were emissions affected. It was concluded that the overall heat transfer coefficient for the bed tubes increased due to the decrease in bed material size.

Sample tubes exposed to high velocity flue gas stream with high particulate loading experienced substantial metal wastage. Alloy steels would be suitable for service if protected from abrasion but none of the samples tested would be suitable for long term service under test conditions.

Conveying air in the fuel feedline constitutes a significant (30%) portion of the total combustion and fluidizing air. This air enters the bed as a point source and is not easily distributed throughout the bed. While a larger feedline is desirable to avoid feedline plugging and permit firing of less-processed fuel, greater spacing between larger feedlines may create air distribution problems in the bed. Investigation of alternate fuel feed technology is warranted.

Based on data from 300 hours of testing, projected emissions from an AFB boiler firing municipal solid waste would be low compared to an existing conventional oil fired boiler. Total plant investment for a cogeneration plant burning 800 tons per day of processed MSW fuel would be $23,116,000 corresponding to approximatley $1,150/kW if the entire steam output were converted to electricity.

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