WASTE TO ENERGY AND ABSORPTION CHILLER: A CASE STUDY

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All measured performance characteristics corresponded well to manufacturer's specifications or were within the expected range for this type of incinerator. The simplified economic analysis showed a payback of period 4.5 years. An optimized payback calculation based on a set of possible improvements to the waste-to-energy system showed a payback period of 3.8 years.

SYSTEM DESIGN AND OPERATION

The Compaq incinerator is a well operated state-of-the-art system. It has many advanced control features with respect to design, operation, and usage. The waste-to-energy systems consists of two major equipment groups: the energy production components and the energy application components.

The energy production components of the system consist of all those parts that prepare solid waste to be used as fuel and generate thermal energy. These include the (a)waste handling equipment, (b)incinerator and thermal reactor, (c)stack, and (d)500 horsepower boiler. The energy application components convert thermal energy (in the form of steam) to useful end products such as hot water or chilled water. The energy application components include a heat exchanger and absorption chiller, to produce hot water and chilled water, respectively. The hot and chilled water are used for space heating and cooling.

Because the energy production components can supply energy for both application components, there are multiple operational modes to be considered. These operational modes are: (1)to produce hot water, (2)to produce chilled water, (3)to produce hot and chilled water simultaneously, and (4)to incinerate waste only, without producing hot or chilled water.

Hot water production requires the following components to be on-line: (a)waste handling, (b)incinerator, (c)stack, (d)500 hp boiler, and (e)heat exchanger. Chilled water production requires the following components be on-line: (a)waste handling, (b)incinerator, (c)stack, (d)500 hp boiler, and (e) absorption chiller. Waste incineration only requires the following components be on-line: (a)waste handling, (b)incinerator, and (c)stack.

The incinerator cannot produce enough thermal energy to drive both the hot water exchanger and the absorption chiller at the same time. To operate both energy application components simultaneously, the system can operate under a (natural) gas fire mode to assist or replace the waste-to-energy fire mode.

MEASUREMENTS

A total of more than 800 individual measurements were made during a one-week period to determine the performance characteristics of the waste-to-energy systems. The monitoring approach had two purposes: establish the performance characteristics of individual components, and determine the overall energy balance of the system.

Although the incinerator is the waste-to-energy conversion plant, the 500 hp boiler is really the key component of the system. This boiler can be operated in three ways: (1)to provide steam to generate chilled water in the absorption chiller, (2)to provide steam to generate hot water in the heat exchanger, and (3)to provide heating and cooling energy simultaneously.

The boiler can operate using natural gas, solid waste, or a combination of the two, and operational measurements were taken with each fuel separately. Since the operational characteristics with either, or both, fuels should be approximately identical under identical operating conditions, and the energy characteristics of natural gas are well known, it was possible to ascertain many of the energy characteristics of the solid waste. Information obtained in this manner was compared to measured values as means of checking the data.

However, there are two major differences in boiler operation when burning solid waste as opposed to burning natural gas. First, the overall system efficiency decreases because of the addition of another component (the incinerator) during solid fuel usage. Second, in a solid waste only operation there is insufficient thermal energy produced to operate both the heat exchanger and the absorption chiller as noted above.

The real impact of the incinerator can best be measured in terms of natural gas avoidance in the boiler. In other words, the impact of the incinerator can be gauged by measuring the amount of natural gas that is not needed in the boiler to generate thermal energy. By measuring the boiler operation under gas only operation, solid waste only operation, and combined fuel operation, it was possible to determine the real energy, energy cost, and impact of the waste-to-energy components of the system.

Gas only boiler efficiency was measured in two ways: (1)through flue gas analysis, and (2)from the enthalpy differential between the water entering the boiler and the steam leaving the boiler. The results of these two measurement techniques were found to be similar, and combustion efficiencies are shown in Table 1.

Proceedings of the Seventh Symposium on Improving Building Systems in Hot and Humid Climates, Fort Worth, TX, October 9-10, 1990

The net efficiency of the 500 hp boiler in gas only hot water generation mode was found to be 60.8%.

For gas fired operation, an ideal excess air quantity would be in the 20%-25% range. However, Table 1 shows excess air quantities well over the optimum. Reducing excess air would provide the opportunity for improved heat exchange in the boiler and could improve efficiency by 3-4%.

The efficiency and energy use of the absorption chiller were measured in two ways: (1)by measuring a Coefficient of Performance (COP) based upon chilled and condenser water temperature differentials, and (2)by measuring the energy into the system and the cooling tons out and calculating the COP.

The measured COP of the absorber based on temperature differential was 1.36 which compares well with the factory provided design COP of 1.3. Under typical operating conditions the absorber requires 9.9 pounds of steam per ton of cooling. At an average absorber output of 456 Tons, or approximately 5.3 MBtuh, the steam requirement would be 4513 pounds. The energy input to the absorber is based upon the energy that can be removed from the steam as it condenses, about 4.0 MBtuh for 4513 pounds of steam. The ratio of the cooling energy output from the absorption chiller divided by the heat input of the condensing steam should approximately equal the COP. Thus 5.3/4.0=1.33, which compares well with the 1.36 COP based upon temperature differential.

The incinerator requires between 4 and 5 hours to burn a 40 cubic yard container of solid waste. During our test run, it required 4.25 hours. The container had 3440 pounds of solid waste, therefore the average usage was 809 pounds per hour. At an average weight of 52 pounds per burn-load, this would equal 15.6 loads per hour, allowing for stoking and burn-down time. The 15.6 loads per hour is 3 minutes and 50 seconds per load. Based on operator log, the average load time ranges from 3 to 8 minutes. The efficiency of the incinerator was measured at 60.1% which compares well with the 59% efficiency calculated by the incinerator's designers.

Table 2 shows the results of efficiency tests conducted when the incinerator was applied to the absorption chiller only. Of the 5.4 MBtuh input into the boiler, 4.2 MBtuh comes from the waste incinerator and 1.2 MBtuh is provided by two 800,000 Btuh gas burners. Under typical operation modes one burner is running 92% of the time and the other 58% of the time. Under these conditions, 4.1 MBtuh is output from the boiler and nearly all of that is available as input at the chiller. With a chiller COP of 1.36, chiller output is 5.6 MBtuh, giving an overall system efficiency of 62.4%, which is well within the 60%-67% efficiency range one would expect from this type of system.

Table 3 shows the net performance when both the absorber and heat exchanger are being operated while solid waste is being burned. Under this operation mode, gas must always be burned in the boiler and the net systems efficiency is 49.7%. While this may seem like a low overall efficiency, it is important to note that of the 16.1 MBtuh of energy input, only 7.1MBtuh must be purchased gas. This represents a gas savings of 5.5 MBtuh when compared to the 12.6 MBtuh required to run both application components in natural gas only mode as shown in Table 1. Energy from the incinerated waste makes possible a 43.75% reduction in natural gas usage. To achieve this level of savings, it is necessary for the incinerator to operate at full capacity (1040-1060 pounds per hour). If the incinerator is operating at 76% capacity, then the savings add up to 4.3 MBtuh.

ASH ANALYSIS

To determine an energy balance for the system, it was necessary to define the following parameters: (a)the composition of the solid waste entering the system, (b)the energy content of the solid waste, (c)the composition and content of the remaining ash, and (d)the composition of stack residue. All analysis procedures followed the EPA SW-846 methods.

Since the solid waste source varies from load to load, waste composition varies accordingly. The sample used for burn and chemical analysis consisted of 8 different types of waste shown in Table 4. The average energy content per load placed in the incinerator varies with the mix of plastics and wood products, and at no time did the plastic content exceed 40%. Typical wood/plastic ratios were in the 70/30 to 80/20 range. Our run samples had a ratio of 70/30. Table 5 shows the energy content of a pound of solid waste for various ratios of wood/plastic. These values represent the energy available in the solid waste, not the output energy exiting the incinerator.

Inorganic matter is not destroyed during combustion. Most of this material leaves the incinerator as bottom ash, but some is entrained in the stack gas as particulate matter (PM). PM is emitted as a result of incomplete combustion and by the entrainment of noncombustibles in the flue gas stream. PM may exist as a solid or an aerosol, and may contain heavy metals or polycyclic organics.

Analysis of the flyash from the incinerator has shown that particulate emissions are largely inorganic in nature and are from one-third to one half soluble in water. The water soluble phase is principally chloride, phosphate, and sulfide salts of sodium and calcium. The insoluble phase is comprised of oxides, silica, and phosphate salts of aluminum, lead, and iron along with potassium, cadmium, and magnesium. The amount of trace metals in the flue gas is directly related to the quantity of trace metals in the waste stream.

The primary sources of trace metals found in the waste stream are foil wrappers, plastics, nails, cans, and printer's ink. In addition, cadmium and lead are found in inks and paints. Plastic products made with polyvinyl chloride (PVC) contain cadmium heat stabilizing compounds.

PVC is normally found in the waste stream at Compaq, although it was not found in all of our samples. PVC is a low energy plastic (9,754 Btu/lb) that results in a very high chloride content in the flue gas, with the remainder appearing in the ash. Chloride is the focus of a number of problems associated with waste-to-energy systems and should be avoided.

Fortunately, two-step incinerators of the design used at Compaq do not produce large amounts of PM, and our observations were consistent with this. These low levels are desirable since heavy metal enrichment can occur with PM. Of special interest is the possibility that PM could serve as nucleation sites for undesirable large organic molecules, a process which may be further promoted by the presence of chlorine.

Thermodynamic equilibrium considerations indicate that under proper excess air conditions and proper temperatures, emissions of organic species should be so low that they can be considered to be zero. There may, however, be mixing or kinetic barriers to achieving this. To meet these conditions good combustion practices must be followed at all times. Such practices would include careful control of excess air, temperature, turndown restrictions (part load operation), start-up/shut-down procedures, and some related operational considerations. These conditions were being met during the week we observed operation of this system.

ENERGY BALANCE

The total output energy, Q_{out} is equal to :

$$Q_{out} = Q_{in} - [Q_{ash} + Q_{losses}] \qquad [1]$$

The input energy for a 70/30, wood/plastic mix is 10,009 Btu/lb. The unused energy left in the ash is 1095 Btu/lb. The moisture content of the solid waste was 13% by weight. The energy required to remove this moisture is ≈ 250Btu/lb, but varies with environmental conditions. Other energy losses can add up to another 200Btu/lb and may be caused by the following factors: (a)humidity/moisture in the air used for combustion, (b)water spray used to control burning in the pyrolysis chamber, (c)heat remaining in the ash, and (d)heat consumed to bring the solid waste to combustion temperature. Therefore, the output energy should be approximately:

$$Q_{out} = 10{,}009 - [1{,}095 + 450] = 8{,}464\text{Btu/lb}$$

In independent field measurements the energy content of the solid waste was found to be 8.606Btu/lb, which is close enough to the above value obtained from laboratory tests to be within the allowable measurement error range for this analysis.

ECONOMIC ANALYSIS

Economic analysis was based on the simple payback principle by which the net cost savings generated by the system were divided into the total first costs. Net savings were calculated by taking the total amount of savings and subtracting out the cost of operating and maintaining the energy producing portions of the waste-to-energy system. Cost savings include utility cost savings, in KWh and reduced kVA, as well as reduced waste disposal costs (tipping fees).

The ideal operation of the incinerator system is to provide steam to drive the absorption chiller. Such operation reduces both energy usage and peak demand. Therefore, energy savings were based upon a dynamic simulation of the electrical and peak demand savings achieved by using the absorption chiller on a continuous basis. Savings from energy as well as trash hauling avoidance are shown in Table 6.

Operating costs include the personnel and maintenance required to keep the energy producing portions of the system working, and the cost of natural gas in the thermal reactor. Natural gas is currently used during start-up and to augment the operation of the thermal reactor.

Simple payback was based on the ratio of total construction costs to net savings for the first year of operation. A second "optimized" calculation was made by assuming that many of the recommendations outlined below were addressed, or a taken into account in the design of a new system. The results of the payback calculations are also in Table 6.

CONCLUSIONS

In general, the Compaq incinerator is a well operated state-of-the-art system with many advanced control features. As with any mechanical system, there can always be improvements or corrections to make the operation easier, more efficient, and more economical. Following are conclusions regarding how designers of similar waste-to-energy systems could enhance system performance:

Sorting. We would recommend sorting out all PVC from the waste stream to eliminate the major sources of chlorides in both ash and flue gas. Sorting should occur where the waste stream is generated rather than the central plant.

Storage. When the mix of refuse reaching the incinerator varies, the energy content of the refuse varies accordingly. A better strategy would be to shred incoming waste and mix it with a one day quantity stored on site. This approach is common in municipal waste-to-energy systems and ensures a more homogenous fuel.

Cold Start-Up. Typically, cold start-up is a key time when organics are produced. To avoid this problem, the thermal reactor should be fired using natural gas until it approaches its normal operating temperature. When this temperature is reached, solid waste can then safely be used for fuel. Such strategy usually adds only about $20.00 per week in additional natural gas costs.

Over-Feeding. We have observed that it is sometimes perceived by incinerator operators that over-feeding is good operation, but this is not true. Over-feeding increases the likelihood of incomplete combustion of fuels. The products of incomplete combustion include organics and chloride compounds, both of which should be avoided. Over-feeding the incinerator during start-up is also a primary reason that large plastic "clinkers" may be found in the system during cleanout. These plastic clinkers settle on the bottom where they clog the air ports and reduce air intake, further increasing the likelihood of organics formation. Although there is a considerable amount of 'art' involved in establishing and maintaining proper feeding cycles, charging an incinerator more frequently than every 15 seconds should be avoided.

Combustion Air. To achieve proper operation, combustion air must be closely controlled. With too little air, the furnace will be oxygen-starved either throughout the furnace or in localized zones. On the other hand, flame temperatures are hottest at zero percent excess oxygen conditions and fall off with increasing excess air due to the dilution of furnace gases with air that must be heated. The range of excess air can be assessed by monitoring O_2 and CO in the flue gas, and should be maintained between 40-100%.

Temperature. Most of the organic emissions of concern are unstable above 1300F, with some potential precursors stable to 1500F. These characteristics, and the existence of temperature gradients across the thermal reactor, indicate that a mean exit temperature of 1800F should be maintained at all times. Significantly higher temperatures should be avoided due to the increase of NO_x with increasing temperatures.

Slow-Burn Operation. Slow-burn is the procedure employed when there is insufficient refuse to operate for a complete 24 hour cycle. Lower firing rates result in lower temperatures and poorer mixing, which may result in two undesirable conditions: (a)Excessive use of natural gas and (b)increased products of incomplete combustion. It would be better to shut a system down that to operate it at slow-burn, especially since this condition most often occurs at night when the system has a minimum impact upon energy cost and peak demand.

Additional Monitoring. Three continuous monitoring schemes may be used to insure that a system operates correctly and stays in EPA compliance. These include: (1)minimum flue gas CO concentration monitoring (corrected of O_2 concentration), (2)maximum and minimum levels of flue gas oxygen concentration, and (3)minimum furnace temperature. Flue gas measurements can be used to insure that excess air conditions and starved air conditions are controlled, and therefore, organics and chlorides are controlled.

TABLE 1
500 HP BOILER OPERATION GAS ONLY

Operation Mode	Input Energy (MBtuh)	Fraction of Full Load (%)	Combustion Efficiency (%)	Excess Air (%)
Heat Exchanger Only	7.4	32.2	77.0	115.5
Absorption Chiller Only	5.4	24.8	76.8	119.7
HX And Chiller	12.6	60.0	79.1	62.5

TABLE 2
INCINERATOR-BOILER-ABSORBER SYSTEM EFFICIENCY

Component	Input Energy (MBtuh)	Measured Efficiency (%)	Output Energy (MBtuh)
Incinerator	6.9	60.1	4.2
Thermal Reactor	1.2	NA	5.4
Boiler	0	76.8	4.1
Pipe (interconnecting)	4.1	99.5	4.1
Absorber	4.1	136.0	5.6
NET EFFICIENCY		62.4	497 Tons

Component	Input Energy (MBtuh)	Measured Efficiency (%)	Output Energy (MBtuh)
Incinerator	9.0	60.1	5.4
Thermal Reactor	1.2	NA	6.6
Boiler	12.5	77.0	9.6
Absorber	4.0	136.0	5.4
Heat Exchanger	5.6	79.0	4.4
NET EFFICIENCY, system		49.7	

Table 3 Incinerator-Boiler-Absorber-Heat Exchanger System Efficiency

Solid Waste	Energy (Btu/lb)	Chloride (%)	Sulfur (%)
Blue Foam	19,080	0.09	---
Cardboard/paper coat	3,304	0.11	---
White Foam	10,633	0.09	---
Polyethlene	19,221	<0.01	---
Translucent Foam	16,873	<0.01	---
Packing Bubbles	18,565	<0.01	---
Wood Pieces/Pallets	7,782	<0.01	0.13
Computer paper	6,718	0.04	0.15
Cardboard	6,695	0.02	0.03

Table 4 Sample Waste Stream

Ratio Wood to Plastic	Wood & Paper (Btu/lb)	Plastics (Btu/lb)	Total (Btu/lb)
80/20	5,650	3,375	9,025
75/25	5,297	4,219	9,517
70/30	4,944	5,063	10,009
65/35	4,591	5,907	10,498
60/40	4,238	6,751	10,989

Table 5 Average Energy Content, per lb., various W/P ratio's

TABLE 6
ECONOMIC ANALYSIS

Category	*Cost* *($ x 1000)*
	Utility Cost Savings
$/kWh/yr	133.6
$/kVA/yr	21.9
Total Utility Savings	155.5
	Waste Disposal Savings
Fee/yr	289.6
	TOTAL SAVINGS PER YEAR
Utility + Disposal	445.1
	Operation and Maintenance Costs
Gas Costs/yr	33.3
O&M Costs/yr	183.9
	TOTAL COSTS PER YEAR
Gas + O&M	217.2
NET SAVINGS	227.9
FIRST COSTS	1,029.2
SIMPLE PAYBACK	4.5 yr
OPTIMIZED PAYBACK	3.8 yr

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