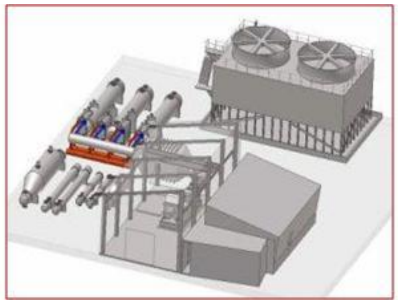
Generate Electric Power from Waste Heat



Prepared for California Energy Commission (CEC)

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Disclaimer

Executive Summary

This technical Guide describes a calculator tool that will allow a user to estimate annual energy savings and associated money (US Dollars) savings and reduction in CO_2 emission through use of waste heat to generate electrical power in industrial plants. Waste heat is available from several sources such as industrial heating systems including steam generators, gas turbines, reciprocating engines etc. The calculator allows users to select different types of possible methods of power generation. It offers flexibility to select any available technology for which sufficient operating data is available. The user is required to obtain the required data for the selected technology. The calculator estimates expected power generation for a given quantity of waste heat. The calculator also gives reduction in CO_2 emission resulting from reduction of electricity production at a power generation facility and associated reduction in fuel used.

Primary objective of the calculator is to promote energy savings in industrial heating operations and allow a user to calculate potential savings that can be used to make a go/no go decision on additional detailed engineering and economics analysis. The user is required to give data or values for several operating parameters, which can be measured or estimated during the normal operating conditions from available records or actual measurements. The data should be collected at typical or average operating conditions.

The calculation results should be considered preliminary and a starting point for detail technical and economic analysis. It should be used as a starting for making a go- no go decision for further analysis. Accuracy of the results is expected to be within plus or minus 5 percent.

TABLE OF CONTENTS

LIST OF EXHIBITS

1. Description of the topic or subject area

This technical guide describes a calculator tool that will allow the user estimate annual energy (electricity) savings, reduction in CO_2 emission and energy cost savings ($/year) by using waste heat to produce electricity. The source of waste heat, typically in the form of hot exhaust gases, can be any process heating system (furnaces, heaters, kilns etc.), boiler, gas turbine, or engine. At this time, several options are available for the heat recovery and power generation with technological improvements occurring constantly. Hence, the tool allows user to select any type of power generation system that uses waste heat for electricity production for a given a particular waste heat source. Selection of the type of power generation system depends on the characteristics of the waste heat. Some of the important characteristic parameters are: temperature of the waste heat stream, mass flow of the waste heat stream, presence of contaminants (such as particulates or corrosive gases), and variations in flow rates.

At this time two types of systems are available and used in the industry. They are: (i) steam generation and use of steam in a steam turbine – generator set to generate power, and (ii) Organic Rankin Cycle (ORC) systems that use organic liquids as a working medium. Recently there are new developments that use non-organic liquids however their working cycle is same as the ORC. Newer systems are under development and it is necessary to get detailed information about their design and performance when this tool is used for estimating electric power generated with use of waste heat.

A schematic of a waste heat steam system generation is shown in Exhibit 1. Here the heat from the waste heat stream (hot gases) is used to produce steam which is used in a steam turbine – generator set to produce electricity. For technical and economic reasons this system is used for higher temperature (>600 °F) flue gases and for large mass flows (usually >10,000 lbs/hour) of flue gases.

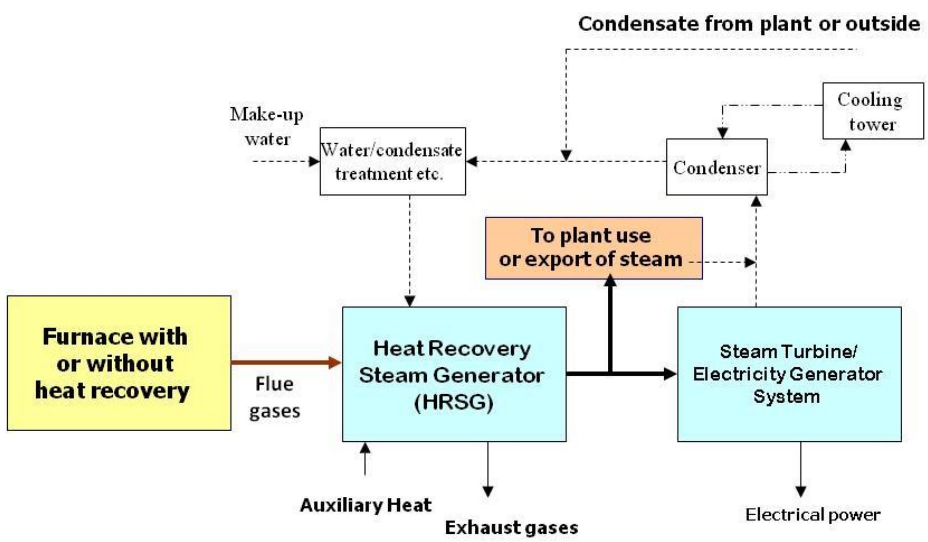
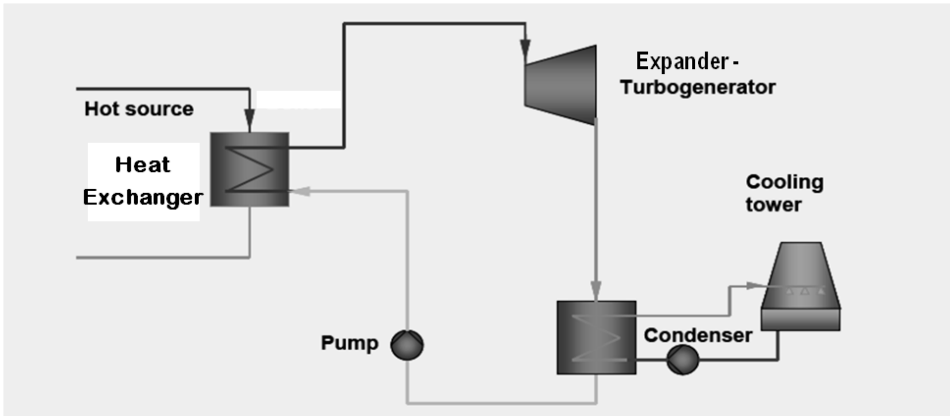


Exhibit 1: Steam system for electrical power generation from waste heat

A schematic of the ORC system is shown in Exhibit 2. In this case heat from the waste heat stream (flue gases) is used within a heat exchanger to vaporize a high pressure organic liquid that acts in a similar manner to steam. The high pressure vapor enters an expander that is connected to a generator that produces electricity. A wide variety of liquids are used as working fluids.

These systems claim to be used with waste streams at as low as 400 °F. The upper temperature limit depends on a particular liquid's properties.



Several other variations of ORC system have been developed to improve its efficiency

Exhibit 2: ORC system for electrical power generation from waste heat

The calculator requires certain measured data and information on performance of the selected power generation system.

2. Impact of the energy saving step (activity) on energy savings, CO_2 reduction, and water consumption reduction, if any.

The calculator estimates the expected annual energy savings when waste heat is used for electrical power generation using one of the systems described above. It is necessary to provide information on the amount and the "quality'" of the waste heat. This can be estimated when operating conditions are known for the process equipment from which waste heat is derived. The calculator allows the user to make this estimate. It also allows the user to provide a value of waste heat and proceed with necessary calculations.

The energy savings also result in reduction of CO_2 emission. The amount of CO_2 emissions reduced is directly proportional to the on-site production of electricity using waste heat. According to the U.S. Environmental Protection Agency (EPA) estimates (Reference 5), for US an average value for CO_2 reduction is 1.34 lbs. per kWh. In this calculator the CO_2 emission reduction is estimated using this value.

The actual savings in electricity produced and associated energy costs depend on the following parameters:

- Amount of waste heat supplied (in terms of MMBtu/hour)
- Type of system used and its conversion efficiency as defined as a ratio of thermal value of electricity generated (3,412 Btu/kWh) to the amount of waste heat supplied to the system. This value is provided by the system supplier, by average firing rate, or fuel used per hour
- Number of operating hours per year

- Cost of electricity in terms of $/kWh.
- Other charges such as peal demand charges in terms of $/kW reduction in peak demand.

Annual energy cost savings depend on the cost of purchased electricity and other associated costs (such as peak demand rates) and electricity production estimated using the calculator.

3. Discussion on the technical approach and the calculations.

The energy savings and associated CO_2 emission reduction are calculated for a system in which heat from exhaust gases is used to preheat combustion air as shown in Exhibits 1 and 2 shown in Section 1.

The calculations are divided in two sections. The first section allows user to calculate the amount of waste heat that is discharged and available for use from a heating process (provided process operating parameters are known). The second section allows for an estimate of electricity production by using a selected waste heat source to power a conversion system. It is necessary to know the conversion efficiency (as defined below) for the selected process. The conversion efficiency value can either be obtained from the system supplier or the user may use the default value given in the calculator. The calculator allows gives preliminary guidance on application feasibility that is based on the waste heat stream temperature.

The waste heat discharged from the heating system or other system is calculated by using the process design and operating parameters.

Where

= waste heat discharged from the system expressed as Btu/hour or MMBtu/hour.

= available heat (expressed as percentage) for the heating process from which waste heat is to be used.

= Heat input to the process or equipment from which waste heat is discharged.

The available heat expressed in terms of percentage or depends on the following variables:

- Fuel composition
- Exhaust gas temperature
- Combustion air temperature
- Percent Oxygen (dry) in the exhaust gases.

Available heat can be calculated by using combustion calculations for a given fuel. For this calculator tool, such calculations use a typical natural gas composition as found in California.

The gas composition used for the calculations in this tool is given below.

Fuel Gas Analysis (See note below)		
Gas composition	**By volume**	**Adjusted by volume**
CH4	**94.00%**	**94.009%**
C2H6	**2.07%**	**2.070%**
N2 and other inert	**1.50%**	**1.500%**
H2	**0.01%**	**0.010%**
C3H8	**0.42%**	**0.420%**
C4H10 + CnH2n	**0.28%**	**0.280%**
H2O	**0.00%**	**0.000%**
CO	**1.00%**	**1.000%**
CO2	**0.71%**	**0.710%**
SO2	**0.00%**	**0.000%**
O2	**0.00%**	**0.000%**
Total of fuel components	**99.99%**	**100.000%**
Difference	**0.01%**	**0.00%**

Note: The fuel gas composition is in volume %. The higher hydrocarbons in fuel are treated as same as C4H10 and all other inert gases are treated as N2.

Exhibit 3: Composition of natural gas used for calculations

For this calculator the higher heating value (or gross heating value) for the fuel is used. The higher heating value for natural gas with the composition shown in Exhibit 3 is 1,011 Btu/scf. The heating value of natural gas may vary between 970 Btu/scf and 1200 Btu/scf. However 1,000 Btu/scf is considered a “normal” heating value of natural gas.

It is recognized that the natural gas composition may vary somewhat during the year or from location to location. However, a series of calculations show that the variation in natural gas composition has very small effect on available heat (expressed as percentage of the heating value). Hence, available heat changes are within a narrow range and error in its value is relatively small. The error for the available heat value is within ±5%. Similarly, the accuracy of the estimate will be in the same order of magnitude (i.e. ±5%) with use of this calculator. A separate calculator is available to calculate the exact value of available heat when the fuel composition is known or when natural gas composition is significantly different from that stated in Exhibit 4.

Further discussion on available heat and effect of fuel is discussed in References 1 and 2.

The second section of the calculator is used to calculate electrical power produced using waste heat. In this section the user is given an option of selecting up to three different methods of waste heat recovery to power conversion. The first option is for using steam generation followed by use of a steam turbine and generator set to produce electricity. This option should be used when the heat source temperature is at a minimum of 600 °F. The second option is use of ORC which is most suitable to use when the waste heat stream temperature is higher than 400 °F. The third option is for any other system that the user may want to use. It is assumed that these systems will be for a low temperature waste heat stream and its application feasibility is considered good when the temperature is higher than 300 °F.

In each case it is necessary to get a practical value of conversion efficiency ( ). Conversion efficiency is defined as:

The value must include all losses related to electricity generation including the efficiency of the turbine and generator plus other losses associated with electricity generation. This should be discussed in detail with the system supplier so that there is clear understanding for the definition of conversion efficiency.

Value of is calculated using the method described in Section 1 above or any other method acceptable to the supplier and used for calculation of the conversion efficiency. For example in some cases the supplier may use heat content calculations based on mass flow, temperature, and specific heat of the waste heat stream. It is necessary to clarify the definition of waste heat content or basis on which the conversion efficiency is stated.

Actual electricity generated can be calculated as

The net savings depend on following factors:

i. Demand charges credit

ii. Additional credits for on-site power generation if any.

iii. Expenses related to power generation. These may include maintenance cost, cost for supplies, labor cost, and other related costs.

The CO_2 savings can be calculated by using the annual power generated and CO_2 emission factors suggested by the US EPA. At this time the suggested value is 1.34 lbs. of CO_2 per kWh power generated. It is likely that the local value could be slightly different. Reference 5 gives details of US EPA guidelines.

4. Instruction on use of each calculator

The following list summarizes the user inputs that are required. The user should collect this information before use of this calculator-tool.

- Company name, plant location and address
- Customer name and contact information
- Heating equipment description (where the energy saving measure is applied)
- Equipment type (furnace, oven, kiln, heater, boiler)
- Equipment use (e.g., textile drying, aluminum melting, food processing.)

Note that some of this information may be optional for the web based calculators due to user's concerns about privacy.

- Firing rate for the process from where waste heat is available (MMBtu/hr)
- Exhaust (flue) gas temperature (°F)
- Percent oxygen (O_2) in flue gases
- Combustion air temperature (°F)
- Heat in exhaust gases (MMBtu/hour) – optional input
- Conversion efficiency (%)
- Demand (peak) charge reduction credit if any ($/kW)
- Electricity cost ($/kWh)
- Annual operating hours (hours/year)
- Additional credits ($/year)
- Other expenses - power generation ($/kWh)
- Expected cost for the power generation system ($/kW)
- Lower temperature limit for the exhaust gas temperature (°F) specified by the supplier. This is required only if the user selects "Other system"

The calculator gives following results:

- Available heat (%)
- Heat in exhaust gases (MM Btu/hour)
- Heat – power equivalent. (MM Btu/hr)

- Equivalent power generation (kW)
- Electricity Cost savings ($/year)
- Electricity Cost savings ($/year)
- Other expenses - power generation ($/year)
- Net energy cost saving ($/year)
- Cost saving based on power generated ($/kW)
- Simple payback period (years)
- CO_2 emission reduction (Tons/year)

The waste heat to power calculator requires following input parameters to describe the user and to estimate the savings. Exhibit 4 shows the user information screen and Exhibit 5 shows the calculator screen.

The first section requires information for the user, the equipment, process etc.

Generate Electrical Power Using Waste Heat					
1	Company name	ABC Corporation			
2	Plant name or designation	LA Plant			
3	Plant address	12345 Main Street, Gabriel, CA 90878			
4	Contact name	Bob Smith			
5	Contact address	54321 First Street, North Warren, CA 90878			
6	Contact phone number and e-mail	Phone:	916-756-9923	E-mail:	b.smith@abccorp.com
7	Date (format mm/date/year)	May 12, 2010			
Heating equipment description (where the energy saving measure is applied)					
8	Equipment type (e.g. furnace, oven, kiln, heater, boiler)	A furnace using a recuperator			
9	Equipment use (e.g., textile drying, aluminum melting)	Gas fired furnace used continuously			
10	Other comments if any	This is a preliminary evaluation for possible heat recovery and power generation using heat of exhaust gases.			

Exhibit 4: Required information for the calculator user

Line 1 – <u>Give name of the company</u>

Line 2 – <u>Give name or known designation such as “main plant” or “secondary plant” if applicable</u>

Line 3 – <u>Give plant address</u>

Line 4 – <u>Give contact name for the plant</u> – This is the individual who is main contact and responsible for collecting and providing the required data or information.

Line 5 – <u>Address for the contact person</u>

Line 6 – <u>Contact phone number and e-mail to be used for all future communications</u>

Line 7 – <u>Date when the calculations are carried out</u>

Line 8 – <u>Type of heating equipment</u> – This can be an oven, a furnace, a boiler, heater or other heating equipment where data is collected and the given energy saving measure is to be applied.

Line 9 – <u>Process or function for which the heating equipment is used</u> – This can be name of the process such as drying, melting, water heating etc.

Line 10 – Any additional information that can be useful in application of the results

The main calculator section is used for collecting the necessary data and reporting the estimated savings.

Electric Power Generation Using Waste Heat Higher Temperature (>800 deg. F.) Heat Source				
11	Firing rate for the process generating waste heat (MM Btu/hr)	100		
12	Exhaust (flue) gas temperature (°F)	550		
13	O2 (dry) content in exhaust gases (%)	12		
14	Combustion air temperature (°F)	90		
15	Available heat (NG as fuel) (%)	69.2%		
16	Heat in exhaust gases - estimated based on natural gas as fuel (MM Btu/hr)	30.82		
	Typical power generation systems	Steam turbine - generator	ORC based	Other system*
	Application feasibility	Poor	Good	Good
17	Heat in exhaust gases (MM Btu/hr) *(User Defined if necessary)*	30.82	30.82	30.82
18	Conversion efficiency **	27.5%	12.0%	18.0%
19	Heat - power equivalent (MM Btu/hr)	8.48	3.70	5.55
20	Equivalent power generation (kW)	2,484.05	1,083.95	1,625.92
21	Demand (peak) charge reduction credit if any ($/kW)	$ 10.00	$ 10.00	$ 10.00
22	Electricity cost savings ($/kWh)	$ 0.06	$ 0.06	$ 0.06
23	Annual operating hours (per year)	8,000	8,000	8,000
24	Electricity cost savings ($/year)	$ 1,217,184	$ 531,135	$ 796,702
25	Additional credits ($/year)	$ -	$ -	$ -
26	Other expenses - power generation ($/kWh)	$ 0.010	$ 0.010	$ 0.010
27	Other expenses - power generation ($/year)	$ 198,724	$ 86,716	$ 130,074
28	**Net energy savings ($/year)**	**$ 1,018,460**	**$ 444,419**	**$ 666,629**
29	Savings ($/kW)	$ 410.00	$ 410.00	$ 410.00
30	Expected cost for the package ($/kW)	$ 2,500	$ 3,500	$ 2,500
31	**CO2 savings for equivalent electricity (Tons/year)**	**13,315**	**5,810**	**8,715**
32	**Simple payback period (years)**	**6.10**	**8.54**	**6.10**
33	Lower temperature limit for the exhaust gas temperature (°F) specified by the supplier *		300.0	

* Define the lower temperature practical limit for the system applicability
** The conversion efficiency value must be obtained from the system supplier. This value depends on the system design and operating conditions such as the heat exchanger efficiency, cooling water (or air) temperature for the condenser, ambient conditions etc.

Exhibit 5: Example of calculator inputs and results

Line 11 – Firing rate for the process from where waste heat is available (MMBtu/hr) – This is the value of current fuel consumption expressed in terms of MMBtu/hour. This should be an average value based on fuel usage measurements over a period of time at "average" operating conditions. Fuel consumption data that is available for a certain period of time (monthly, annual etc.) for the furnace being considered can be used to determine the average value. Note that if meter data is used to determine the average firing rate the meter must be corrected for pressure and temperature at the meter. Additionally, the heat input of the fuel should be accounted for and determined using the Available Heat Tool included in the CEC tool package. For most commonly used or average quality natural gas a heating value of 1,020 Btu per standard cubic foot (scf) will be a sufficient approximation. .

Line 12 – Exhaust (flue) gas temperature (°F) – The exhaust or flue gas temperature is measured by using flue gas analysis where an appropriate type thermocouple is used to measure flue gases coming out of the heating system. If the system uses any type of heat recovery device such as a combustion air preheater or economizer, it is necessary to measure the temperature downstream of this device.

Line 13 – Percent oxygen (O_2) in flue gases – This value is obtained from a flue gas analysis using commonly available flue gas analyzers. These analyzers give measurements of flue gas components on dry basis in addition to other. The gas analysis sample should be taken when the furnace is operating at normal operating conditions. Readings taken at non-average production or operating conditions can give unreliable results. It is necessary to make sure that the flue gases are not mixed with cold air before the temperature is measured. Care should be taken to locate the sampling probe in the middle of the stack or area from where the flue gases are discharged.

Line 14 – Combustion air temperature (°F) – The temperature of combustion air entering the burners. In many cases it is not feasible to obtain exact air temperatures at the burner. A common practice is to use air temperature entering the combustion air blower or ambient temperature as the combustion air temperature if no air preheater is installed. If an air preheater is installed, use the air temperature exiting the recuperator or entering the burner.

Line 15 – Available heat (%) – This is a calculated value based on the data given above. The calculation uses “Available Heat“ tool developed as part of the tool set and natural gas as fuel The natural gas composition used for this calculation is same as given in Exhibit 3 above.

Line 16 – Heat in exhaust gases (MMBtu/hour) – This is a calculated value based on data given in lines 11 and 15.

Line 17 – Heat in exhaust gases (MMBtu/hour) – This could be same as in line 16 or it can be given by the user if it is available from other sources or the user does not have sufficient data to calculate value given in line 16.

Line 18 – Conversion efficiency (%) – This value is to be obtained from the waste heat to power system supplier. The efficiency must include all losses related to electricity generation including the efficiency of the turbine and generator. This should be discussed in detail with the system supplier so that there is clear understanding for the definition of conversion efficiency.

Line 19 – Heat – power equivalent (MMBtu/hr) – This is a calculated value which is based on data given in Lines 17 and 18 and it gives equivalent of possible power generation expressed in terms of MMBtu/hr.

Line 20 – Equivalent power generation (kW) – This is a calculated value and represents value of electric power by dividing number in Line 19 by a conversion factor of 3,412 Btu/kWh. It is the power that can be produced by using the selected system and air temperature.

Line 21 – Demand (peak) charge reduction credit if any ($/kW) – This is user input and its value can be obtained from current electric bill or from the electricity supplier.

Line 22 - Electricity cost savings ($/kWh) – This represents marginal or average cost of purchased electricity. It must include all charges related to the electricity cost billed by the supplier.

Line 23 – Annual operating hours (hours/year) – Give number of hours per year for which the system will be operated.

Line 24 – Electricity Cost savings ($/year) – This is a calculated value based on data given in Lines 20, 22 and 23.

Line 25 – Additional credits ($/year) – Give value of additional credit if available for the energy saving project. If it a lump sum then deduct this amount from the expected cost for the package.

Line 26 – Other expenses - power generation ($/kWh) – Give value of other expenses related to power generation system. These items may include maintenance, labor, supplies, and miscellaneous expenses. If this value is not available on per kWh basis then use value of total expenses and divide it by the kWh generated per year. This requires use of data given in Lines 20 and 23.

Line 27 – Other expenses - power generation ($/year) – This is a calculated value using data given in Lines 20, 23, and 26.

Line 28 – Net energy cost saving ($/year) – This is a calculated value using data given in Lines 24, 25 and 27.

Line 29 **–** Cost saving ($/kW) – This is a calculated value using data given in Lines 28 and 20.

Line 30 **–** Expected cost for the power generation system ($/kW) – This cost is obtained from the system supplier. It should include all costs including cost for hardware, auxiliary equipment such as added cost for cooling tower (if the current capacity is not adequate or does not exist), installation cost, and permitting cost. The calculator gives default values which are based on the best available data at the time when this calculator was developed. It must be validated and changed if necessary.

Line 31 – CO_2 emission reduction (Tons/year) – This calculated value shows CO_2 emission reduction related to reduction in purchased power production. Reduction in CO_2 emission is directly proportional to the on-site production of electricity using waste heat. According to the U.S. Environmental Protection Agency (EPA) estimates (Reference 5) for US an average value for CO_2 reduction is 1.34 lbs. per kWh. In this calculator the CO_2 emission reduction is estimated using this value.

Line 32 – Simple payback period (years) – This is a calculated value based on the data given in Lines 28, 20 and 30.

Line 33 – Lower temperature limit for the exhaust gas temperature (°F) specified by the supplier – This data is required when the user selects 'Other system' as an option. It should be obtained from the system supplier.

5. References

1. *North American Combustion Handbook*, Third Edition, 1986. Published by North American Mfg. Company, Cleveland, OH.
2. *Combustion Technology Manual*, Fifth Edition, 1994. Published by Industrial Heating Equipment Association, Cincinnati, OH.
3. *Improving Process Heating System Performance: A Sourcebook for Industry*, U.S. Department of Energy and Industrial Heating Equipment Association. Available on-line at www.eere,eenrgy.gov/industry.
4. *Tip sheets and Technical Briefs,* published by The U.S. Department of Energy. Available on-line at www.eere,eenrgy.gov/industry.
5. *Unit Conversions, Emission Factors and Other Reference Data, published by the U.S. EPA, November 2004. Available on-line at http://www.epa.gove/cpd/pdf/brochure.pdf*