INCINERATION AS A METHANE ABATEMENT OPTION - USING INCINERATION TO MEET THE KYOTO OBJECTIVES

A. John Chandler,
A.J. Chandler & Associates Ltd.,
Willowdale, ON Canada

Steven E. Sawell,
Compass Environmental Inc.,
Burlington, ON, Canada

Shin-ichi Sakai,
Environmental Preservation Center,
Kyoto University, Japan

Maggie Thurgood,
Consultant
England

Dr. Jurgen Vehlow,
Forschungszentrum Karlsruhe,
Karlsruhe, Germany

ABSTRACT

Incineration is generally considered a CO_2 neutral means of managing MSW. A thorough evaluation of the environmental effects of MSW incineration should consider the potential for greenhouse gas effects from the methane emissions of managed landfills sites. While emitted at a similar rate to CO_2, the global warming potential for methane is said to be in excess of 15 times greater than that of CO_2. Thus, reducing the potential for methane emissions from MSW management options through the use of incineration would make a positive contribution to greenhouse gas control. Based upon this premise, a study was undertaken to evaluate the potential costs and benefits of applying this technology in various parts of the world.

This paper describes the development of an MSW facility capital and operating cost model for different countries based upon North American contract information and assumptions about the capability of the country's industry. All the data are compared on the basis of 1996 purchasing power parity corrected US dollars. The capital costing model was compared with German and Japanese data and shows general applicability in countries that have the ability to manufacture the major components of the systems. North American operating cost data was combined with country specific waste, landfill and utility information to derived a net cost of methane abatement through the application of MSW incineration.

There will be opportunities for increased incineration capacity in many countries, both now in developing countries whose waste currently might not support autogenous combustion and the developed countries. In developing economies the time to start thinking about these opportunities is now so capabilities will match improved waste characteristics. Developed countries, with a greater potential to release methane from landfills, should be seeking to increase the use of incineration to meet their Kyoto commitments.

INTRODUCTION

While considerable emphasis has been placed on the greenhouse gas effects attributable to carbon dioxide releases to the atmosphere from anthropogenic sources, incineration is generally considered a CO_2 neutral means of managing municipal solid waste [MSW]. However, CO_2 is only one of the greenhouse gases of concern. The global warming potential for methane is said to be in excess of 15 times greater than that of CO_2 and methane and carbon dioxide are produced in almost equal proportions in MSW landfill sites. Indeed, the Intergovernmental Panel on Climate Change [IPCC] estimate that land disposal of wastes contributes between 5 and 20 percent of the annual anthropogenic methane emissions of 360 Tg [1]. Thus, the waste management sector has the potential to select disposal methods that may contribute to achieving the objectives of the Kyoto Agreement on reducing greenhouse gas emissions.

At the regional and national level, governments are beginning to realize the importance of landfills in the global warming context. Measures are being implemented to reduce methane emissions by improving the capture and use of landfill gas. Another way to reduce these greenhouse gas emissions is to minimize the amount of organic carbon entering the landfill. By implication this will increase incineration and that is forecasted to happen in jurisdictions such as The Netherlands, Switzerland and Germany where the organic content of landfilled material has been limited to 5%. Indeed, the EU Directive on landfilling waste, currently in draft, will introduce decreasing limits on organic waste sent to landfills in Europe.

The US EPA [2] notes that incineration might not be the most effective way to reduce the release of carbon to the atmosphere. After comparing the energy conversion efficiency of older municipal waste combustors [MWC] with that of fossil fuelled generating stations, they say that it may be more beneficial to sequester carbon in the form of plastic in landfills where it will stay indefinitely. This conclusion ignores the optimized energy production performance of more recently constructed MWC units and should be reevaluated.

Regardless of those conclusions, reducing the potential for methane emissions from MSW management options through the use of incineration could make a positive contribution to greenhouse gas control. The question is, how do the costs compare with other potential control measures?

This paper describes the development of an MSW facility capital cost model for six countries based upon North American contract information and assumptions about the industrial capability in those countries. By combining typical North American operating cost data with information obtained about the quality of waste, the types of landfills, and utility costs, the net cost of methane abatement through the application of MSW incineration was determined for each location. These costs compare favourably with disposal costs at landfills equipped with methane management measures.

CAPITAL COST ESTIMATES

Facility pricing information obtained from suppliers in the United States, and actual costs of two Canadian facilities were combined to form the basis for the Capital Cost Model. U.S. prices were normalized to 1996 based upon: changes in the Gross Domestic Product per capita [GDP] from the year when construction started; and employment costs for the particular part of the United States where the facility was built. Canadian costs were adjusted to U.S. dollars based upon prevailing exchange rate for the year construction started and then these prices were normalized using the U.S. GDP correction factors.

Figure 1 shows the base data for 29 facilities initially included in the study. They represent different types of combustion equipment, mass burn refractory wall [RW] and mass burn water wall [MBWW] furnaces as well as refuse derived fuel [RDF] fired units of different capacities. Air pollution control [APC] equipment also varies from electrostatic precipitators [ESP] to dry scrubber fabric filter [DSFF] units and various add ons for NO_x control [DSFFNOx] or mercury and Dioxin and Furan control [DSFFPAC].

Generally the economies of scale are evident in the inverse relationship between price per Mg/day of capacity and the size of the facility. However, limited data indicates that facilities equipped for steam sales [/steam] are less expensive than those equipped for producing electricity. Also, improving the APC system tends to increase the price for the same size facility. The smaller factory manufactured refractory walled systems appear to be less costly. These are designated RWDSFF. All other units plotted in Figure 1 are water wall furnaces simply labelled DSFF.

RDF facilities are found towards the high capacity end of chart, but their costs do not appear to be sensitive to size. This could be a function of the facilities included in the list. Each have different APC systems the cost of which may mask economies of scale for the furnaces and material handling equipment. Furthermore, one was a retrofit of a power plant and as such was likely more costly than a green field development would be. Given these factors, and the relatively costly processing equipment required to produce RDF, these systems were excluded from further study.

Three other facilities were eliminated from consideration in the final model. One was a steam facility equipped with a completely redundant fossil fuel fired steam generating system. This was considered to be a non-standard application and thus excluded. The second facility, NE Maryland, includes the cost of a railway unloading facility used to deliver waste to the EFW and remove bottom ash from the site. Without being able to subtract the cost of this feature, the costs were considered to be biased high. Like NE Maryland, the third facility was equipped with NO_x control and powdered activated carbon [PAC] to control Hg and PCDD/PCDF. Both these facilities were out of line with the other two facilities with similar APC configurations. It was thought that the costs of the smaller of these may have been influenced by extensive litigation during the approval process. During the analysis it was found that removing these facilities improved the fit of the model.

The remaining data were analysed using ANOVA techniques to determine the coefficients of various factors that could be introduced into the pricing formula. Appendix 1 provides the details of this calculation. The only

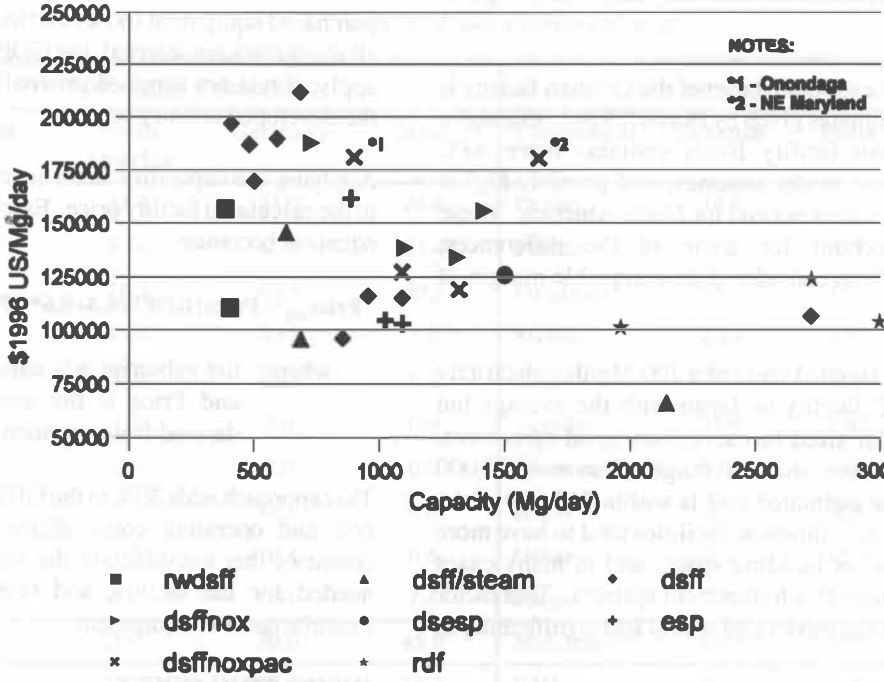


Figure 1 MWC Capital Cost versus Capacity

significant factors influencing price were:

- the capacity of the facility;
- the presence of electrical generating equipment; and,
- the type of furnace.

While there were differences in the prices for the various configurations of the APC, removing the anomalies discussed above reduced this factor to insignificant. However, this price equation includes the cost of various APC systems even though the variations were not of themselves significant. The base case was a MBRW facility with DSFF and electricity generation. The cost equation developed is:

$$LN(Price[\$/Mg/d]) = 14.662 - 0.481\ LN(Capacity[Mg/d]) - 0.316\ COGEN - 0.502\ STEAM + 0.626\ MBWW \quad [1]$$

Refractory wall furnaces are cheaper than water wall systems, so the water wall is an add to the price. Electricity is the most expensive energy options and cogeneration or steam generation involve a reduction in the overall cost from the base case.

The model provides a reasonable fit for North American situations, allowing for regional cost differences and inflation but it cannot be uniformly applied to any country in the world. To do that, one needs to account for the differences in costs between countries.

For this study, a cost ratio factor based upon Gross Domestic Product [GDP] values for the countries. The GDP purchasing power parity [PPP] based values were taken from the World Factbook [3]. These values compare the cost of the same basket of goods and services in the various countries. The values were:

- United States - $28,600
- Germany - $23,100
- Japan - $22,700
- Lebanon - $ 3,400
- India - $ 1,600
- South Korea - $14,200

The factor, labelled the GDPF, was simply the Country's PPP GDP divided by the US's PPP GDP. Using these values avoids fluctuating exchange rates and better reflects the comparative costs in the different countries. The implication of applying the cost correction factor is that products manufactured in a country with a PPP corrected GDP that is lower than the U.S. would be less costly than they would be in the U.S.

The results were checked against cost data for the other two developed countries considered in the study: Germany and Japan.

In U.S. dollars, the estimated cost of the German facility is 12% under the estimates given by Horch [4], \$142,000/Mg/d. That base German facility likely contains more APC equipment than the model assumes, and possibly higher cost steam turbines than normal for North America. These factors could account for some of the differences. Regardless, 12% was considered an acceptable margin of error.

Comparing the estimated costs of a 200 Mg/day electricity generating MWC facility in Japan with the average bid values from similar sized furnaces show good agreement. The 1997 bid values show a range of over \$100,000 difference, but the estimated cost is within \$10,000 of the minimum bid price [5]. Japanese facilities tend to have more amenities in terms of building space, and in many cases newer facilities include ash treatment systems. This factor is not included in the model and would add significantly to the price.

The model has a second limitation when applied to countries with developing economies. Some means had to be incorporated to allow for the differences in price attributable to purchasing equipment made outside the country. Applying a country's cost correction factor to materials that were manufactured in another country would be misleading and thus, if the country is not considered capable of producing all the equipment for the facility internally, the US costs for equipment should be reflected in the overall capital cost of the facility.

Any facility contains a substantial portion of proprietary equipment. Typically, the vendor would have this equipment fabricated to his specifications. It was assumed that a country capable of such fabrication would not pay a premium for equipment based upon the need to manufacturer it in another country, and ship it to site. A second portion of the facility equipment cost is industrial equipment commonly used in process and manufacturing industries: pumps, fans, controls, switchgear etc. In most industrialized countries such equipment is probably manufactured internally. A country deemed to have the capability to manufacture such equipment was given a capability factor of 0.5. If neither of these were deemed possible, a lower capability factor was applied. The capability factors used for the study were:

- Japan, Germany and the United States - 1.0
- Korea - 0.5
- Lebanon and India - 0.0

The construction price of a facility is a combination of purchased equipment (60%) and installation costs (40%). If all these costs are internal, the GDP correction factor should apply; if it is not supplied internally, the costs must reflect the developed country cost.

Applying the capability factor involved adding a multiplier to the calculated facility price. Essentially the modified price equation becomes:

$$\mathbf{Price_{adj} = Price\{GDPF(0.4+0.6*CF)+0.6(1.0-CF)\}} \qquad [3]$$

where: the subscript adj stands for the adjusted price and Price is the antilog of the capital cost derived from equation 2

This approach adds 30% to the GDP corrected facility capital cost and operating costs related to the capital cost for countries that manufacture the non-proprietary equipment needed for the facility, and 60% if the country cannot manufacture the equipment.

OPERATING COSTS

Estimates of operating revenue and operating costs were also developed. Factors such as labour costs for operating the facility, maintenance costs, consumables, residue management, insurance, capital replacement, and debt retirement were included in the cost side. Operating costs purposely excluded NO_x control costs because it was not considered appropriate to saddle the comparison with APC technology that might not be warranted in all locations.

Revenues were based upon steam sales or electricity sales with conversion from steam to electricity being based upon industry accepted factors. Electricity sales were assumed to be at a rate discounted 15% from the readily available purchase price for power and furthermore were discounted for the parasitic load of the facility assumed to be 16%.

The energy production is tied directly to the quality of the waste received at the facility. Waste composition data was obtained, Table 1, and an analysis was completed to define the energy available based upon the ultimate fuel analysis. This was calculated using von Dracek's equation [6] which has been shown to be more representative of measured higher heating value [HHV] numbers for MSW than formulae used for estimating the heating value for coal and other combustible materials:

$$\mathbf{As\ Fired\ MJ/Mg = 2326\ \{\ C(160.5 - 0.112C_l) + 486\ (H - O/10\ ) + 45\ S\}} \qquad [3]$$

Table 1 Estimated Waste Composition for Case Studies (as a % of wet as received mass)

Developed Countries				Developing Countries			
Component	**North America**	**Germany**	**Japan**	**Component**	**Lebanon**	**India**	**South Korea**
Paper	43.4	28.9	24.0	**Paper**	17.5	5.3	18
Plastic	9.76	4.75	11.4	**Plastic**	8.2	1.3	7.8
Organics	26.3	48.5	50.8	**Organics**	56.8	45.1	60
Metals	4.46	3.13	1.6	**Metals**	2.44	1.52	2
Glass	2.01	4.65	4.2	**Glass**	7.87	0.7	2.6
C&D	1.7	0.0	0.0	**Textiles**	3.09	2.42	5.6
Appliances	0.37	0.0	0.0	**Footwear**	0.01	0.06	0.1
HHW	2.1	0.0	0.0	**HHW**	0.0	0.0	0.0
Other	1.5	10.1	0.6	**Other**	2.1	25.9	1.4
Fines	8.6	0.0	7.4	**Fines**	0.0	17.7	2.5
Moisture	23.87	30.0	45.0	**Moisture**	46.5	60.0	59.0
HHV [MJ/kg]	14.0	12.0	10.7	**HHV [MJ/kg]**	9.7	4.3	7.8

Where: C = as fired carbon content in %

C_1 = as fired carbon on an ash and moisture free basis %

H = as fired hydrogen content in %

O = as fired oxygen content in %

S = as fired sulphur content in %

The net cost resulting from combining the operating costs with the revenues represents the potential tipping fee for a facility, Table 2. The estimate does not include an allowance for site purchase and development, a component that is too difficult to predict in a general way, nor does it contain any element of profit that might be expected to be required for any commercial service provider. When the calculated tipping fee in specific countries is compared to the fee normally quoted for that country, it is evident that the excluded profit could be a significant source of error in the overall cost equation.

In most cases it is difficult to explain discrepancies between published tipping fees and the numbers shown in Table 2. Financing arrangements for North American facilities can be handled differently than the model assumes removing the need to carry the debt retirement in the operating costs. Furthermore, the facility pricing model assumes average 1996 costs for the facility. Since these costs are used as the basis for some operating cost segments, they might bias those estimates high for facilities that were constructed in the late 1980s or early 1990s. Similarly, the existing tipping fee contracts may not have been escalated at the same rate as the model estimates.

For Germany, neither of the break-even tipping fees approach the level quoted by Horch, $120 US/Mg however, this is explainable. Horch notes that an extra $48,000,000, over the cost of the base facility, should be added to cover the ancillary items required to build a turnkey facility. In addition, he specifically notes that the contribution of profit/return on investment is included in his costs. With an anticipated return on investment of 15% of the capital cost including development costs and construction costs including the ancillary items, the return on investment would add on the order of $85/Mg to the break even cost. This would raise the cost at the gate to $110/Mg for the electrical option, very close to the average German tipping fee. Furthermore, it has been reported that the actual electrical sale price paid to the MWC facilities may be lower than that estimated in the model. In 1999 the rates are reported to be as low as those for North America.

Table 2 Comparative Results for Facility Costing

Cost Item	North America	Germany	Japan	Japan	Lebanon	India	South Korea
Size [Mg/d]	1000	1000	750	200	500	750	750
HHV [MJ/kg]	14.0	12.0	10.7	10.7	9.66	4.25	7.84
Steam Capital [$1,000/Mg/d]	94.8	76.6	86.5	163.3	85.7	52.3	70.6
Elec. Capital [$1,000/Mg/d]	156.7	126.6	142.8	269.8	141.7	86.5	116.6
Steam Ops. [$$10^6$/annum]	22.5	22.7	19.1	7.63	9.04	6.8	11.8
Elec. Ops. [$$10^6$/annum]	28.5	23.0	19.2	9.3	11.6	10.6	15.2
Steam Sales [$$10^6$/annum]	10.1	6.8	4.3	1.1	0.37	0.23	2.5
Elec. Sales [$$10^6$/annum]	26.5	20.5	19.2	4.5	4.5	1.6	6.9
Steam Net [$/Mg]	70.37	70.15	82.63	134.74	57.92	42.33	80.29
Elec. Net [$/Mg]	84.89	27.12	30.25	108.96	47.77	52.49	75.87
Methane Potential [kg/Mg]	112	100	92	92	85	40	70
Control Costs Steam [$/Mg]	630	700	900	1460	680	1050	1150
Control Costs Elec. [$/Mg]	760	270	330	1180	560	1300	1090

METHANE OFFSET

To compare the cost of using incineration as a means of controlling methane emissions with other options it is necessary to take the break even cost of incineration and divide it by the methane emission reduction. This value can then be converted to a cost per tonne of methane avoided. The starting point is to determine the amount of methane produced by the garbage burned in the incinerator as outlined in Appendix 2.

The net methane emissions from incineration can be assumed to be negligible because typical CH_4 levels in flue gas streams are less than 5 ppm_v.

As illustrated by the equation in Appendix 2, the reduction afforded by incineration will change with changes in the mix of the waste because the degradable organic carbon [DOC] will change. The DOC fractions had to be adjusted to reflect the lack of specific information on the putresibles. The food and yard waste DOC values were averaged to 0.16 and applied to all the organic fraction. The paper fraction was assumed to have a 0.4 factor and the balance of the stream was multiplied by 0.01.

The variation in methane generation rate as a function of changes in the waste stream are illustrated in Figure 2. Clearly, paper has a significant effect on the methane generation rate from landfills, implying the need to increase the diversion of paper from landfill if significant reductions in methane emissions are to be realized.

THE COST OF LANDFILL

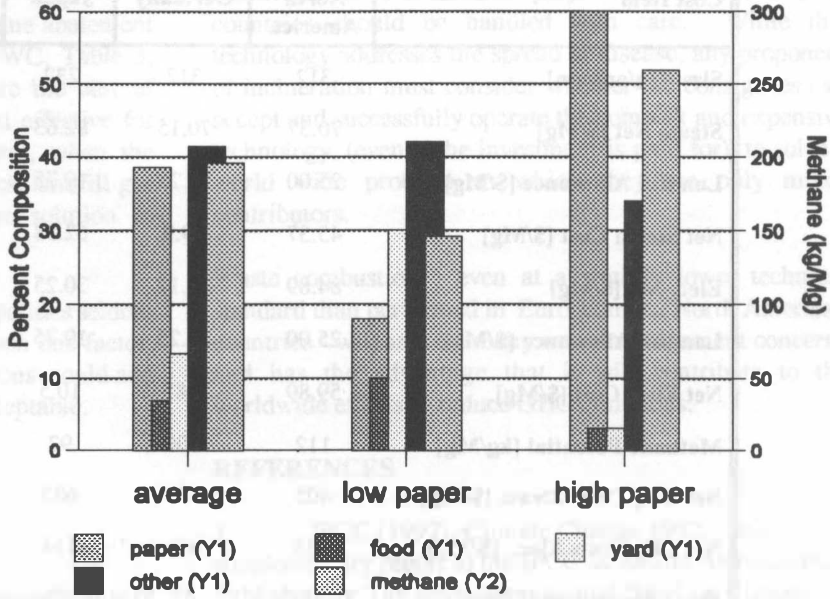
The cost of methane control, in $/Mg methane reduction, calculated as suggested in the previous section put an undue burden on the MWC approach. The tipping fee that forms the basis for the cost of control includes the capital cost recovery of the incinerator price. Incinerators provide many societal benefits such as:

- energy recovery,
- disposal volume reduction,
- control of vectors that can spread disease,
- reduced leaching and contamination of groundwater, and,
- reduced risk of explosions, vegetative damage, and odour generation.
-

These benefits are not captured in the methane control costs.

Similarly, the cost for installing methane control systems as an add-on at landfill sites cannot be viewed in isolation. Such costs do not account for the developing and operating costs of the landfill. To address this discrepancy between the two cost bases we have included in the MWC methane control cost a factor to address the offset the MWC provides for landfill. This is basically an adjusted landfill cost per tonne disposed.

Figure 2 Variation in Methane Generation with Composition



The cost to build a landfill must include the purchase of land, a precious commodity in some countries. While it might appear that land costs were excluded from the incinerator costing model that is true for the facility itself, but residue disposal requires extensive space and was factored into the operating cost for the MWC. Even accounting for the space for residue disposal, the MWC is unlikely to require 15% of the land required by a landfill designed to dispose of the equivalent amount of waste. Overall, the land costs for incineration are likely captured within the model error; but clearly when costing a landfill some allowance must be included for land costs.

Landfills have economies of scale but vary in cost according to location [7]. To address these factors both a low and high cost estimate are provided. At the low end, facilities over 7 Tg capacity can cost only 10% of those designed to dispose of less than 0.5 Tg. At the high end, the difference caused by size is only a factor of 3. A similar trend is evident in the annual operating costs. Perpetual care costs are more uniform differing by a factor of 3 between high and low estimates as the size changes. The estimated costs of landfills range from a low of $8 US/Mg to a high of $25 US/Mg, with the average being $20 US/Mg. None of these costs include gas control systems such as those discussed in Meadows et al.[8]. Others [9] provide additional insights into the cost of landfilling suggesting that in the Toronto area the cost of landfills should be anticipated to run from $34 to $51 US/Mg, although there is a component for landfill gas utilization included in these costs.

These prices reflect the relative ease of locating a landfill site in Canada. The majority of Canada's population lives within 400 kilometers of the U.S. border and the population density in this region is similar to the average for the U.S. or about 1 million people every 35 square kilometers. In Europe, Japan, and the other countries in this study the norm is 8 to 9 times greater. It would stand to reason that land would be more costly in these countries a fact corroborated by another Canadian government report [10]. A comparison of business costs between Canada, the U.S.A. and Europe included the cost of the land required for a building to house 100 software workers. The Canadian costs were 40% greater than U.S. costs but the German costs were nearly 8 times more than the Canadian costs. All the European countries had land costs that were over twice those of the U.S. with the German costs being the highest.

As was suggested in the methane generation discussion, incineration is most practical in large cities with high population densities. Since land would be harder to find in these areas, and costs would be anticipated to reflect the higher end of the scale, the upper end of the Canadian costs for larger facilities, $25 US/Mg, was selected as the starting point for estimating landfill costs. The landfill cost was then deducted from the break even MWC costs, after the GDP ratio was factored in, to arrive at net costs of disposal shown in Table 3.

This was considered a conservative estimating approach. In the extreme the Canadian costs could be factored for the cost of land assuming it was directly related to population

Table 3 Comparison of Methane Abatement Costs

Cost Item	North America	Germany	Japan	Japan	Lebanon	India	South Korea
Size [Gg/annum]	312	312	232	62	155	232	232
Steam Net [$/Mg]	70.37	70.15	82.63	134.74	57.92	42.33	80.29
Landfill Allowance [$/Mg]	25.00	20.25	19.75	19.75	3.00	1.50	12.50
Net Steam Cost [$/Mg]	45.37	49.9	62.88	114.99	54.92	40.83	67.79
Elec. Net [$/Mg]	84.89	27.12	30.25	108.96	47.77	52.49	75.87
Landfill Allowance [$/Mg]	25.00	20.25	19.75	19.75	3.00	1.50	12.50
Net Elec. Cost [$/Mg]	59.89	6.87	10.5	89.21	44.77	50.99	63.37
Methane Potential [kg/Mg]	112	100	92	92	85	40	70
Net CH_4 Costs Steam [$/Mg]	405	499	683	1250	646	1021	968
Net CH_4 Costs Elec. [$/Mg]	535	69	114	970	527	1275	905
Flare Abatement [$/Mg]	53	43	42	42	6	3	27
SI Engine/Turb. Abate [$/Mg]	124	100	98	98	80	60	81
Steam Cycle Abate [$/Mg]	138	112	109	109	90	67	90

density. That is, German landfills would be 8 times those of Canadian facilities, before allowing for GDP differences. Such a correction would result in incineration being cheaper than landfill in Japan, Germany, and South Korea. This might explain, at least in part, why incineration is chosen in Japan and Germany.

COMPARING METHANE ABATEMENT COSTS

To complete the comparison between landfill and incineration, it is necessary to identify the costs of various landfill gas control alternatives outlined by Meadows:

- collection and gas flares estimated at $0.15 to $0.30/Mg for capital and $0.03 to $0.045/Mg for operations with no revenues and a 70% collection efficiency (methane abatement costs $31 - $53/Mg methane);

- adding spark ignition engines to generate electricity for sales would raise the costs to $0.75 - $1.50/Mg for capital and operating costs to $0.22 - $0.33/Mg; however, at the energy sales rates used for the incinerator study energy revenues could pay for the project at the low end of the cost scale. Estimated methane abatement cost $124/Mg methane. Note gas turbines are in the same abatement cost range.

- steam cycle electricity generation causes a marginal increase in abatement costs to $138/Mg methane.

Other schemes are possible including using the gas as a replacement for natural gas or in vehicles. Natural gas replacement provides revenue and the abatement cost is about equal to the cost of collection and flaring. Vehicle use of the gas could end up paying more money to the project than it costs and the abatement income would be $18/Mg methane.

To incorporate these data into Table 3, allowance has to be made for the GDP cost ratio, and, in the case of the developing countries, the capability factor. The following assumptions were applied:

- all flare systems are built locally with locally manufactured materials, only the GDP cost ratio need by applied;

- all other systems include 40% of the cost that is attributable to local construction issues and pro-rated by the GDP ratio and the 60% related to equipment is subject to a capability factor for local versus imported equipment.

Comparisons between the landfill gas methane abatement costs and the methane abatement using MWC, Table 3, indicate that in Germany and Japan, where the cost of electricity is the highest, EFW is more cost effective for methane abatement than landfill gas control, when the energy will be utilized. In the other countries, landfill gas control likely offers a more cost effective solution to methane abatement.

Such comparisons are arbitrary since municipalities seldom make waste management decisions based upon one factor, methane abatement in this case. Such decisions would add cost and may make projects politically unacceptable.

CONCLUSIONS

The study showed that:

- even after diversion activities, the heating value of residual waste in developed countries will ensure autogenous combustion;
- in developing countries additional fossil fuel is required to ensure the wet organic based waste is burned under appropriate operating conditions.

The nature of waste management decisions in a community requires a broad consideration of many factors. These issues cannot be avoided.

The sustainability (both technical and economic) of any given management option is influenced by the waste disposed over the long term. Thus, careful consideration must be given to future changes in the waste composition. As economies develop, the volume/mass of waste they generate increases and incineration facilities built to meet today's requirements will remain fully utilised for the foreseeable future. This suggests that, in preparation for the eventual improvement in waste quality, future incineration capacity should be a definite consideration in developing countries. This may allow incineration technology to be installed when it is most effective for methane mitigation.

Methane generation potential is greater from landfills in developed countries suggesting that MWC technology should be encouraged in these countries. Economic measures to encourage the application of incineration in the developed countries needs to be expanded to realise the benefits offered by MWC in terms of reducing methane emissions, and overall GHG emissions reduction.

Developing countries have more urgent concerns than reducing GHG emissions. Support by the developed countries for incineration projects in the developing countries should be handled with care. While this technology addresses the spread of disease, any proponent of incineration must consider whether the consignees can accept and successfully operate the complex and expensive technology, (even if the investment is paid for), to solve a world wide problem to which they are only minor contributors.

Waste combustion - even at a slightly lower technical standard than performed in European and North American countries - will address many waste management concerns and has the advantage that it will contribute to the worldwide efforts to reduce GHG emissions.

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Appendix 1 Capital Cost Pricing Model

The natural logarithm values of both the price and capacity data discussed in the body of the paper were included in a multiple linear regression equation based upon the logarithm of the continuously varying factors and the blocking factors. The logarithmic form of the price versus capacity equation linearizes the effect of size on pricing.

The blocking factors were essentially a series of defined dummy variables:

- power conversion; STEAM = 1 for steam and = 0 if not;
- power conversion; COGEN = 1 for cogen and = 0 if not;
- power conversion; ELECTRIC = 1 for electricity only;
- DSESP = 1 for dry scrubber ESP equipped facilities and = 0 if not;
- ESP = 1 for ESP equipped facilities and = 0 if not;
- DSFF = 1 for dry scrubber FF equipped facilities and = 0 if not;
- $DSFFNO_x$ = 1 for DSFF with NO_x equipped facilities and = 0 if not;
- $DSFFNO_xPAC$ = 1 for $DSFFNO_x$ and PAC equipped facilities and = 0 if not;
- MBRW = 1 for Mass Burn refractory walled furnaces and = 0 if not;
- MBWW = 1 for Mass Burn waterwall furnaces and = 0 if not;
- RDF = 1 for RDF furnaces and = 0 if not;
- type of fabrication FAB1 = 1 if <400 Mg/d and = 0 if >400 Mg/d; and
- type of fabrication FAB2 = 1 if modular shop built or = 0 if not.

The resulting equation took the form:

$$\begin{aligned}\mathrm{LN(Price)} = {} & a + b\,\mathrm{LN(Capacity)} + c\,\mathrm{STEAM} + d\,\mathrm{DSESP} \\ & + e\,\mathrm{ESP} + f\,\mathrm{DSFF} + g\,\mathrm{DSFFNO_x} + h\,\mathrm{DSFFNO_x} \\ & + i\,\mathrm{DSFFNO_xPAC} + k\,\mathrm{COGEN} + l\,\mathrm{MBRW} \\ & + m\,\mathrm{MBWW} + n\,\mathrm{ELECTRIC} + o\,\mathrm{FAB1} \\ & + p\mathrm{FAB2} + error \qquad [1]\end{aligned}$$

If the regression yields a statistically significant coefficient c for STEAM, then the absence of a turbine generator set can be said to influence the price. The magnitude and the sign of the coefficient are also of interest. If the value of c were -0.5 it indicates that use of steam only (i.e., when STEAM = 1) produces values of LN(Price) that are, on the average, 0.5 units lower than the baseline condition of electricity generation. If the value of c is not statistically significant, it can be concluded that the energy conversion alternative has no effect on price over the range of conditions tested.

The significant factors influencing price were:

- the capacity of the facility;
- the presence of electrical generating equipment; and,
- the type of furnace.

While there were differences in the prices for the various configurations of the APC, removing the anomalies discussed above reduced this factor to insignificant. While the factory fabrication of smaller MBWW systems appeared to have an influence in reducing the cost, it was only significant at the 60% level and was excluded. All the factors in the equation are significant at better than 95%. The model fit produced an R of 0.906 and the base case was a MBRW facility with DSFF and electricity generation. The cost equation developed is:

$$\begin{aligned}\mathrm{LN(Price[\$/Mg/d])} = {} & 14.662 - 0.481\,\mathrm{LN(Capacity[Mg/d])} \\ & - 0.316\,\mathrm{COGEN} - 0.502\,\mathrm{STEAM} \\ & + 0.626\,\mathrm{MBWW} \qquad [2]\end{aligned}$$

The factors appear to be intuitively obvious, refractory wall furnaces are cheaper than water wall systems and electricity is the most expensive energy options due to the cost of the power island. This cost equation includes the cost of various APC systems even though the variations were not of themselves significant. To determine the cost for the base facility set all the dummy variables to zero (0) and the price in $/Mg/d simply is the anti-log of {14.662 - 0.481 Ln(capacity in Mg/d)}. To find any other alternative's price point, set the appropriate dummy variables to 1 and sum the right hand side of the equation before taking the anti-log.

Appendix 2 Methane Generation Model Discussion

The IPCC method was used for estimating the amount of landfill methane emissions:

$$MR = 1330\,(MCF) \cdot (DOC) \cdot (DOC_F) \cdot (F) \qquad [4]$$

Where:

- MR = Methane Reduction from incineration (kg CH_4/Mg waste)
- MCF = Methane correction factor for landfill type
- DOC = degradable organic carbon (%) = 0.4 (paper) + 0.17 (yard) + 0.15 (food) +0.01 (other) where the values in parentheses represent the fraction of the component in the waste stream
- DOC_F = fraction of DOC converted to LFG (default = 0.77)
- F = proportion of methane in LFG (g C as CH_4/g C as biogas = 0.5)
- 1330 = constant converting C in biogas as CH_4 to kg of CH_4

The methane correction factor addresses variations in methane production due to the nature of the landfill. In shallow landfills oxygen can readily penetrate the waste and the microbial species necessary to produce the gas are not supported. The IPCC recommend reducing the methane production rate for unmanaged and shallow landfills as follows:

- managed landfills – 1.0;
- unmanaged and > 5m deep – 0.8;
- unmanaged and < 5m deep – 0.4; and,
- indeterminant – 0.6.

For the study, the methane proportion was assumed to be 50% and the landfill characteristics were defined in terms of the landfill correction factor. Since incineration is likely most effective when used in large scale applications, it was assumed that the landfills being replaced would be large reasonably managed facilities and for all but India and Korea, where a 0.8 factor was applied, the correction factor was 1.0. The result of the calculation is given as methane potential in kg/Mg of waste.