The greenhouse effect and US landfill methane

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The author estimates likely greenhouse contributions of methane emissions from solid waste landfills In the USA. These emissions appear significant: their effect, evaluated over the short term (< 10 years), Is to add the order of 1% to the total annual Increase of radiative forcing due to bulld-up of all greenhouse gases In Earth's atmosphere. Costs to mitigate landfill methane emissions were also estimated. Such costs appear quite low compared to those of most carbon dioxide mitigation approaches giving comparable benefit. This work, while prellmlnary, suggests landfill methane abatement Is one of the more cost-effective measures that can be taken to address a component of the greenhouse problem.

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The 'greenhouse effect' has recently been receiving a great deal of scientific and popular attention. The term refers to a cause-and-effect relationship in which 'heat blanketing' of the earth, due to trace gas increases in the atmosphere, is expected to result in global warming. The trace gases are increasing as a result of human activities. Carbon dioxide (CO_2) is the trace gas contributing most importantly to the heat blanketing and currently receives most attention. Less widely recognized has been the high importance of methane (CH_4). Methane's contribution to the increased heat blanketing occumng since 1980 is estimated to be over a third as much as that of carbon dioxide. Gas from landfills has in turn been recognized to be a source of methane in the atmospheric build-up.' However, the magnitude of the landfill methane contribution, and the overall significance of landfill methane to the greenhouse phenomenon, has been uncertain and the subject of some debate.

This article first briefly reviews mechanisms and possible implications of the greenhouse effect. It then presents an estimate of methane emissions from the US landfills and attempts to evaluate the net contribution and significance of these emissions to the atmospheric methane build-up and greenhouse phenomenon. Finally, it examines the possible cost-effectiveness of mitigating landfill gas emissions, relative to other approaches for greenhouse gas abatement. It must be noted at the outset that uncertainties remain in a number of areas. However, it appears that methane from US landfills makes an important net contribution to the greenhouse phenomenon. Measures to reduce landfill methane emissions could be among the more economical steps which could be taken to address a component of this problem.

The greenhouse effect

The greenhouse effect occurs because human activities are causing the concentration of several atmospheric trace gases to increase. The principal gases, in order of importance, are carbon dioxide, methane, the chlorofluorocarbons, and nitrous oxide. The importance of these gases lies in their radiative properties: their transparency to incoming solar radiation, but relative opacity to infrared radiation in wavelengths (>2.8 microns) at which Earth radiates heat back out to space.[2] Their

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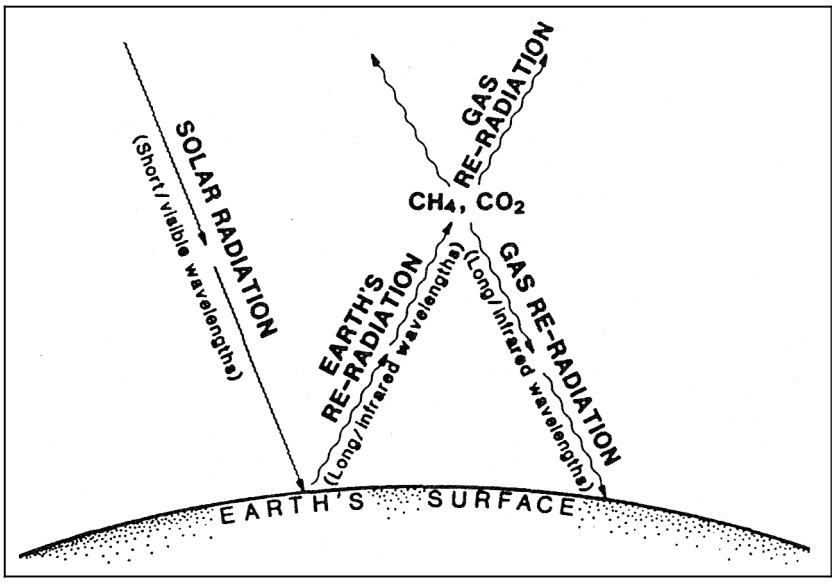

Figure 1. How greenhouse gases act.

The schematic shows radiation flow that establishes Earth's surface temperature. Although greenhouse gases interfere very little with the incoming solar spectrum, they intercept radiation (infrared) re-emitted from Earth's surface and re-radiate some of this back to Earth. They can thereby cause warming.

net effect as they build up is to cause heat entrapment, and it is expected that with increasing concentration of these gases in the atmosphere, Earth's surface will ultimately warm.

Figure 1 shows schematically the flow of radiational energy which establishes Earth's surface temperature, and illustrates how greenhouse gases can cause warming: they do so by absorbing radiation emitted by Earth's surface and emitting some of the absorbed radiation back toward the surface. They can be considered, in effect, as radiational 'heat blankets' for Earth (the technical term for this action is 'radiative forcing').

The effectiveness of greenhouse gases in causing warming is a function of many parameters – the wavelengths or 'windows' at which they absorb, the absorption efficiency per molecule of gas, the temperature at which gases receive and re-radiate energy, and several other factors. Because of interactions among variables, the effectiveness of the various gases must be expressed for specific sets of conditions. It is convenient to refer to relative effectiveness of added increments of the individual gases under existing atmospheric trace gas compositions and conditions, averaged over Earth's surface as a whole. The gases' potencies are commonly compared to carbon dioxide. Under atmospheric conditions the effect of a given concentration rise of methane from current levels is about 25 times that of the same concentration rise of carbon dioxide in blocking radiative heat loss from Earth.[3] That is, added methane is 25 times as effective as carbon dioxide, molecule for molecule, or volume for volume, in its greenhouse impact. This is the key to the importance of methane.

Figure 2 shows the recent historical rises for carbon dioxide and methane,[4] the two gases of greatest importance (the remarkable speed and size of the rises in Figure 2 will be seen below from the perspective of changes over geological time). Causes of the carbon dioxide rise include increased fossil fuel use starting with the industrial revolution, and deforestation. The methane rise is qualitatively similar to that of carbon dioxide (though changes are of different magnitude). It is due to a mix of causes, not all well characterized. These include emissions from

[1] H.G. Bingemer and P.J. Crutzen, 'The production of methane from solid wastes', Journal of Geophysical Research, Vol 92, No D2, 1987, pp 2181–2187.

[2] R.A. Houghton and G.M. Woodwell, 'Global climatic change', Scientific American, Vol 260, No 4, April 1989, pp 36-44 (this article presents a good general overview of greenhouse effect mechanisms and possible consequences); V. Ramanathan, P.J. Cicerone, H.B. Singh. and T.J. Kiehl, 'Trace gas trends and their role in climate change', Journal of *Geophysical* Research, Vol 90, No D3, 1985, p 5547; A.J. Lacis, J.P. Hansen, P. Lee, T. Mitchell and S. Lebedeff, 'Greenhouse effects of trace gases', Geophysical Research Letters, Vol 8, 1981, p 1035.

[3] H. Rodhe, 'A comparison of the contribution of various gases to the greenhouse effect', Science, Vol 1248, No 4960. June 1990, pp 1217–1219; Ramanathan et al, op *cit*, Ref 2.

[4] Houghton and Woodwell, op *cit*, Ref 2.

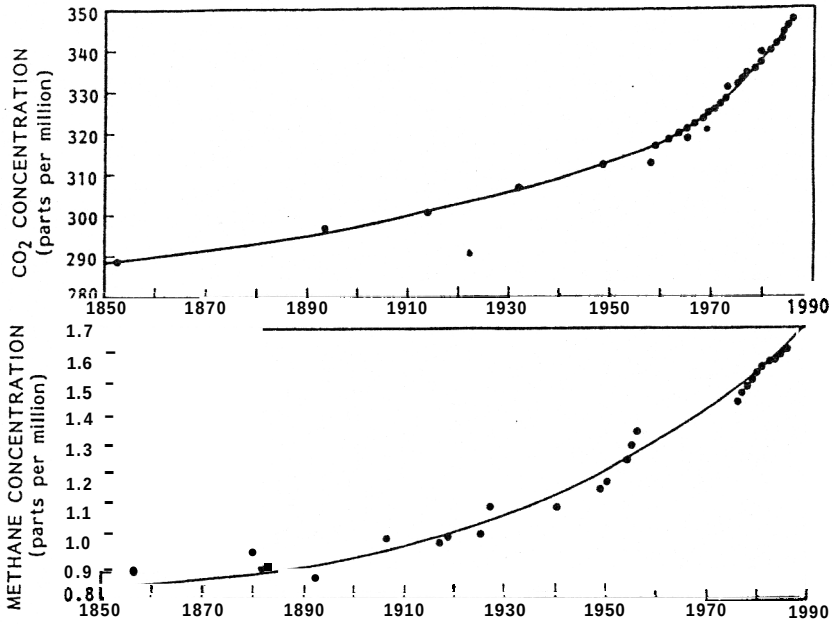

Figure 2. Recent atmospheric profiles of the greenhouse gases carbon dioxide and methane.

Atmospheric concentration of both gases has been increasing rapidly in the timespan shown.
Source: **Adapted from R.A. Houghton and G.M. Woodwell, 'Global climatic change',** *Scientific American,* Vol 261, No 3, April 1989, pp 36-44.

Table 1. Contribution of increasing greenhouse gases to the increased radiative forcing in the 1980s.

Gas	Radiative forcing contribution (percentage of total)
CO_2	49
CH_4	18
N_2O	6
CFCs	14
Other	13

Source: J. Hansen, A. Lacis and M. Prather, 'Greenhouse effects of chlorofluorocarbons and other trace gases', *Journal .of Geophysical Research.* Vol 94, No D3, 1988, pp 16417–16421.

[5]Bingemer and Crutzen, *op cit*, Ref 1.
[6]S.H. Schneider, 'The changing climate', *Scientific American,* Vol 261, No 3, September 1989, pp 70–79.
[7]J. Hansen. A. Lacis and M. Prather, 'Greenhouse effects of chlorofluorocarbons and other trace gases', *Journal of Geophysical Research,* Vol 94, No D3, 1989, pp 16417–16421.
[8]J. Hansen, J.I. Fung, A. Lacis, D. Rind, S. Lebedeff, R. Ruedy and G. Russell, 'Global climate change as forecast by the Goddard Institute for Space Studies three-dimensional model', *Journal of Geophysical Research,* Vol 93, No D8, 1988, p 9341; Policy *Implications of Greenhouse Warming,* National Academy Press, Washington, DC, 1991 (a discussion of climate models is given on pages 17–19).
[9]To cite only one example of a possible impact in monetary terms, a $500/acre drop in the value of half of US farmland due to climate-related losses in its produc-

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coal mining, combustion processes, ruminant animals, rice paddies, landfills, and from many other sources.[5] Changes in atmospheric chemistry may also contribute, as rises in other reactive species like carbon monoxide (CO) may be interfering with methane destruction in the atmosphere.[6] For all important greenhouse gases, rise rates have been greatest recently, with timescale depending on the gas. The estimated relative contribution of the various gases to increased heat blanketing was calculated for the 1980s by Hansen *et al* and is shown in Table 1.[7] The notable aspect of Table 1 is that methane has been responsible for over a third as much of the recent heat blanketing increase as carbon dioxide.

What could happen to Earth's climate because of greenhouse gas build-up? Climate modelling projections to date' all indicate significant warming as well as other effects; the other effects are less certain and depend on which of the various models and assumptions are used. Impacts could be major, though it is difficult to identify clearly potential winners and losers. Warming and consequent increased agricultural productivity could benefit those living in higher latitudes. On the other hand, the higher temperatures and increased evaporative soil drying projected for the American Midwest (in some forecasts) could easily cost tens or hundreds of billions of dollars in lost farm value and farm productivity.' Projected sea level rises of 10 or more feet as polar icecaps melt after the year 2050, in the 'worst case' projections, could displace low-lying and coastal populations of hundreds of millions of people.[10]

Yet, for perspective on all such projected consequences – dire or good – it must be recognized that this climate modelling is, simply, weather forecasting of a complex and different sort. It is difficult enough. to forecast tomorrow's weather, let alone the next century's. The climate models are acknowledged to be uncertain;'' in terms of current evidence, the temperature record of the past few decades is suggestive of changes, but moderate change would also be compatible with short-term 'noise' in the climate which can occur normally and independently

of greenhouse gas changes. Arguments can be made on the basis of model imprecisions that greenhouse effects could turn out to be relatively insignificant. The question then, is whether there is any basis other than the model predictions on which they may be expected.

Probably the best evidence for correlations between global temperature and greenhouse gas levels comes from ice-core work. The first work was done by a Russian and French team on the Vostok core, removed from the Antarctic icecap.[12] Isotope and trapped gas measurements of this core, which was laid down as a result of the last 160 000 years' snowfall, indicate Earth's temperature and atmospheric trace gas compositions over that period. Figure **3** shows the correlation between greenhouse gas concentrations (from gas bubbles trapped in the core) and temperature (determined from isotope ratio measurements). Temperature over the last 160 000 years, until the very recent past, has varied in virtual lock-step with atmospheric carbon dioxide and methane concentrations. There is, additionally, abundant supporting evidence from the geologic record for corresponding climatic changes **of** great magnitude. There is no question that ice sheets advanced as far south as the American Midwest; then retreated, and sea levels rose and fell by hundreds of feet, as Earth's temperature changed. This record **is** construed as strong evidence linking greenhouse gas levels and climate change in the expected way.

Perhaps the most striking features of Figure **3** to consider are the recent sharp rises of both methane and carbon dioxide. These are the rises shown in Figure 2, but seen in the longer-term context of the typical concentrations of these gases over the last 160 000 years. In an 'instant', geologically speaking – represented approximately by the width of the line on the Figure – carbon dioxide has increased to a level **20%** higher than at any time over the last 160 000 years. Even more impressively, human activities have caused atmospheric methane concentrations to rise to two-and-a-half times their previous maximum in that period (120 000 years ago). We are perturbing the atmospheric and climatic system significantly; the perturbations are, incidentally, so rapid that temperature responses to them may be far from complete (because of factors such as lags in oceanic warming).[13]

To summarize very briefly, recent temperature evidence for greenhouse warming might be considered tenuous. However the climate models, and ice-core and geologic records, support it. The preponderance of evidence suggests that major changes due to the recent sharp greenhouse gas build-up should be expected *if* these gases continue increasing in keeping with current trends. The consensus in the scientific community **is** that greenhouse effects will occur, although the timing and magnitude of changes is uncertain. That is the reason for current concern.

Clearly, landfill methane makes some contribution to the greenhouse effect. **An** issue of interest to many – including those dealing with the greenhouse effect, and also those in the solid waste industry – is, what is its significance? And, if landfill methane is significant, what approaches might be appropriate to address it? In the following sections of this article answers to the following questions are attempted:

- What are methane emissions from **US** landfills?
- What **is** the significance of these emissions to the atmospheric build-up, and thus to the greenhouse effect?
- How do the economics of mitigating landfill methane emissions

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tivity would representa loss of about $250 billion.
[10]Woodwell and Houghton, *op cit*, Ref 2.
[11]Hansen *et al*, *op cit*, Ref 7.
[12]Woodwell and Houghton, *op cit*, Ref 2.
[13]Schneider, *op cit*, Ref 5.

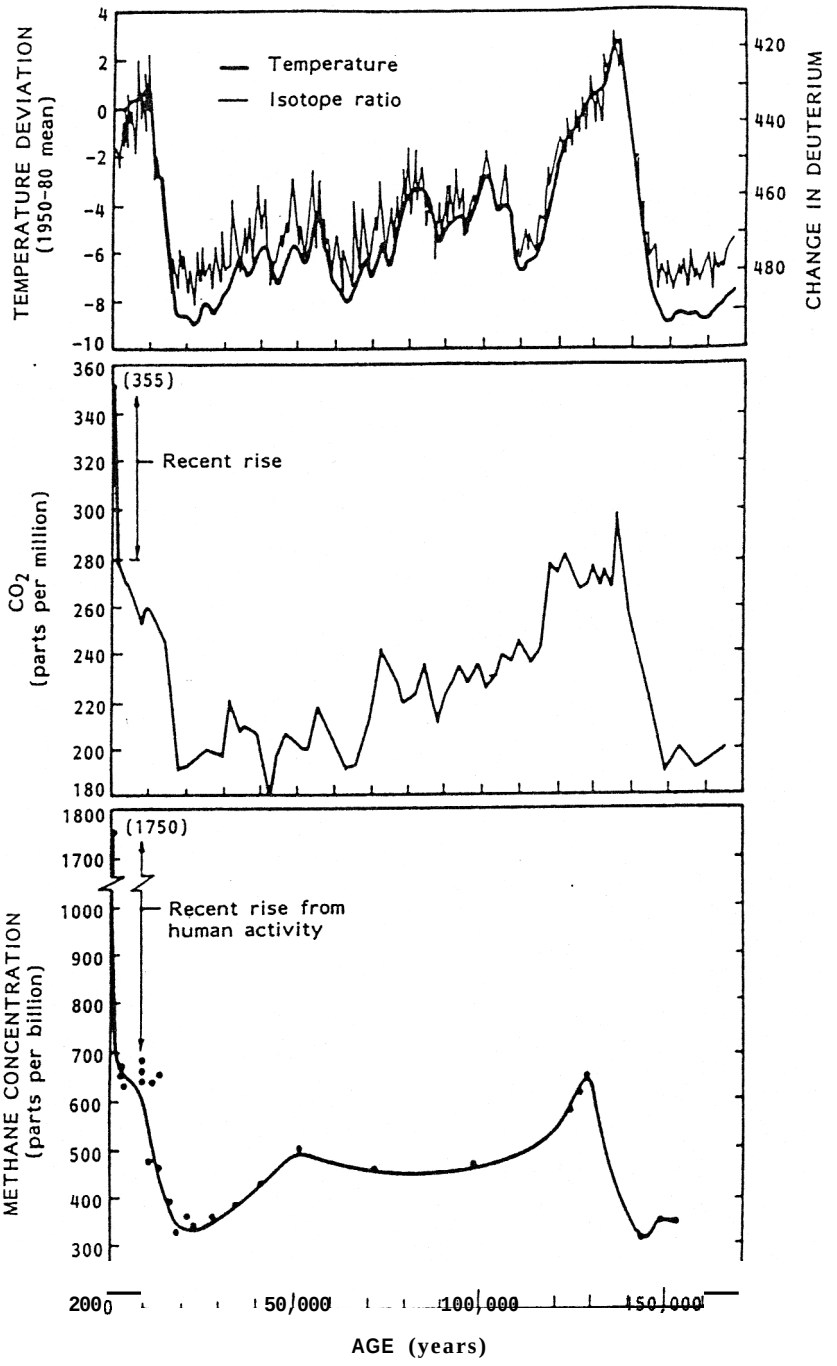

Figure 3. Temperature, and the atmospheric concentrations of carbon dioxide and methane over recent geological time (past 160 000 years to present) based on ice-core results.

Source: Adapted from R.A. Houghton and G.M. Woodwell, 'Global climatic change', *Scientific American,* Vol 261, No 3, April 1989, pp 36–44; combines data of Figure 2 with longer-term ice-core data as published in that reference.

compare with the costs of other approaches to the greenhouse problem?

Emissions estimate for US landfill methane

The estimate of US landfill emissions is developed using a gas generation model, developed by EMCON Associates, in conjunction with data developed by others on rates of waste placement into US solid waste landfills. The model and the landfilling data are discussed in turn.

Table 2. EMCON MGM gas generation model parameters used to project methane generation by the total of US landfilled waste.

	waste category (inerts omitted)	% by weight (dry)	Methane yield (ft^3/lb)	Lag time (yrs)	Time constant
CASE I	Readiiy decomposable	4.0	4.5	0.2	3
Ultimate yield	Moderately decomposable	45.0	3.55	1.5	10
1.8ft^3/lb (dry)	Slowly decomposable	52	0.5	5	20
CASE II	Readily decomposable	4.0	2.75	0.3	4
Ultimate yield	Moderately decomposable	45.0	1.95	2	20
1.0ft^3/lb (dry)	Slowly decomposable	52	*0.29*	*5*	40

This model is currently used commercially to project gas generation/emission by landfills.
Sources: D. Augenstein and J. Pacey. 'Landfill methane models'. *Proceedings from Technical Sessions of SWANA's 29th* Annual *International Solid* Waste *Exposition*, SWANA, Silver Spring, MD, August 1991, pp 111-87–III-111; R. Van Heuit, 'Estimating landfill gas yields', *proceedings of the GRCDA 9th* International *Landfill Gas Symposium*, SWANA. Silver Spring, MD. 1986, pp 92–120.

Gas *generation model*

Conditions in solid waste landfills, including the conditions that influence gas generation, are seldom well defined.[14] Correlations developed under more controlled conditions are not applicable and it has been necessary to develop empirical models to predict gas generation.[15] The process of modelling gas generation begins with assumptions about kinetics of gas generation, and at least ideally, follows this with refinement of the model with field extraction results. Several models have been developed to various stages of refinement using this approach. The one used here is that developed and used commercially by EMCON, termed the MGM (ie 'methane generation model').[16]

The MGM's fundamental assumptions are that waste is composed of rapidly, moderately and slowly decomposable fractions, each marked by its own lag time, time constant and yield." The model is used to project methane generation from individual landfills, with parameters depending on waste and the individual landfill site characteristics (approaches to parameter selection for the individual site applications are proprietary to EMCON); it can also be applied, however, to estimate generation from the total of landfilled waste in the USA. The parameters selected for application of this model to US landfilled waste as a whole are shown in Table 2.

There are uncertainties with all extant gas generation models, including the MGM. With proper selection of parameters, this model is a useful tool for estimating generation. However, it has been tested against gas recovery for less than the expected total generation period of landfills.[18] Efficiencies for fractional gas recovery have been assumed in its derivation which are actually uncertain." Finally, parameters would actually vary by site across the USA when it is applied to total US waste. To reflect the uncertainties, 'high-limit' and 'low-limit' assumptions were selected, shown as Cases I and II in Table 2. These assumptions for those two cases are considered to provide reasonable bases for upper and lower bound projections of methane generation by US landfills.

Solid *waste landfilling data*

The solid waste landfilling statistics used are those developed by Franklin Associates for the US EPA.[20] Landfilling rates were estimated by Franklin Associates based on a number of databases. These included US primary production of various materials, with allowances for factors such as imports and exports. Other databases used included waste stream composition data and wastes incinerated and composted. Resulting waste landfilling and other data are shown (as published by Franklin, in US tons per year) in Figure 4.

[14] D. Augenstein and J. Pacey. 'Landfill methane models', Proceedings *from* Technical Sessions *of SWANA's 29th* Annual International Solid Waste Exposition, SWANA, Silver Spring, MD, August 1991, pp 111-87-111-111.
[15] R. Van Heuit, 'Estimating landfill gas yields', Proceedings *of* the GRCDA *9th* International Landfill *Gas Symposium.* SWANA, Silver Spring, MD, 1986, pp 92–120; Augenstein and Pacey, op *cit*, Ref 14.
[16] "Augenstein and Pacey, op *cit*, Ref 14.
[17] "The lag time is the interval assumed between waste placement in the landfill and the time methane generation starts. Generation then declines exponentially over time from a peak rate with a characteristic time constant; the yield is the total methane that can be generated from a mass or fraction of waste. The yield is based on dry waste.
[18] Augenstein and Pacey, *op cit*, Ref 14.
[19] *Ibid.*
[20] M.A. Franklin, N.S. Artz, J.E. Beachey, V.R. Sellers and K.L. Totten, *Characterization of* Municipal Solid Wastes in the *United* States *1960–2000* (Update *1988)*, US EPA Document 530-SW-88-033, prepared by Franklin Associates, Prairie Village, KS, 1988.

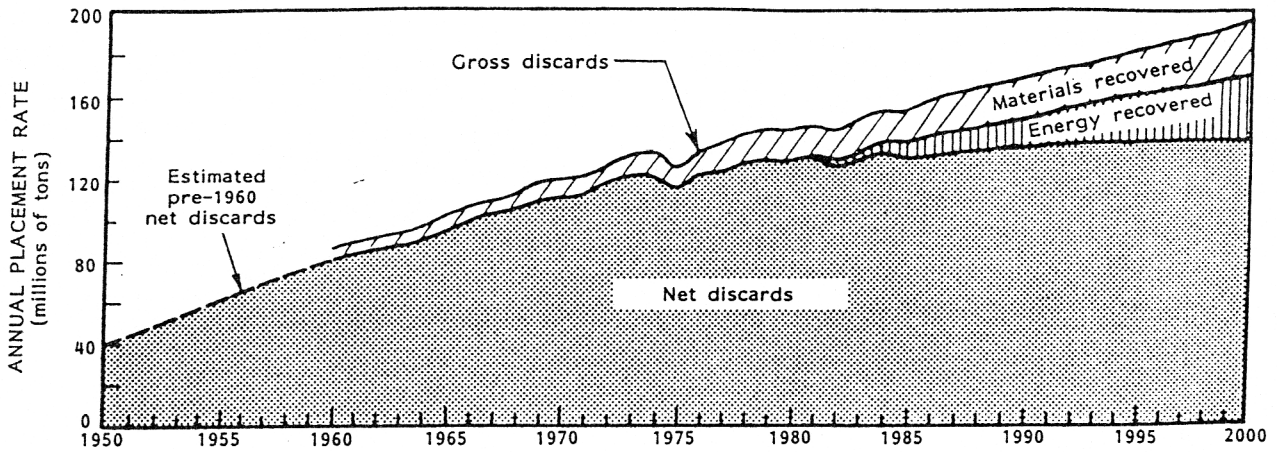

Figure 4. US EPA solid waste landfilling data used in calculating methane emissions from US landfilled waste – showing past and projected estimates of waste placement in landfills (net discards) from 1950 to 2000.

Source: Adapted from M.A. Franklin, **N.S.** Artz. J.E. Beachey, **V.R.** Sellers and K.L. Totten, ***Characterization*** of ***Municipal Solid Waste in the United States 1960–2000 (Update 1988),*** US EPA document 503-SW-88-033. Prepared by Franklin Associates. Prairie Village, KS, 1988.

It should be noted that other and higher estimates of annual US landfill placement than those used here can be found;[21] however, the other statistics indicating higher waste placement rates are for single years rather than continuous over time, as is required for this analysis. In addition, the higher placement increments over that of Figure **4** appear to be largely non-biodegradable and thus would contribute rather little to methane production.[22]

The Franklin Associates statistics began in 1960; the dashed line seen in Figure **4** is the author's estimate of the pre-1960 wastes subject to anaerobic decomposition. The assumed pre-1960 values are uncertain, but likely to be nearer the true situation than the value **of** zero which would otherwise be implicit.

The assumed composition of the landfilled waste stream for the **USA** as a whole **is** based on the EMCON MGM default values and is shown in Table **3.**

Methane emission estimate

Figure **5** shows the emissions calculated on the basis of information given in Tables 2 and **3,** and Figure 4.[23] **A** range for net methane emission rate into the atmosphere of **3** to 8 million tonneslyear or 3 to 8 Tg was obtained for the year 1990. Figure **5** shows both gross genera-

[21] J. Glenn and **D.** Riggle, 'Where does the waste go?', *Biocycle*, April 1989, p **34;** also ***National Study*** of ***Solid Waste Landfill Facilities,*** US Environmental Protection Agency, Washington, **DC,** September 1988.

[22] *Ibid.*

[23] All methane estimates to follow in this article are in metric units: 1 tonne = 1.102 US tons; 1 million tonnes = 1 teragram (Tg).

Table 3. Assumed composition of US **refuse used with gas generation model.**

Component	Percentage in refuse (wet)	Percentage of moisture In component
Food waste	10	60
Garden waste	10	*50*
Paper waste	50	20
Plastics/rubber	2	10
Textiles	2	15
Wood	2	15
Ash/dirt/rock	8	0
Metal	8	0
Glass/ceramics	8	0

Average moisture content = 21.8%.

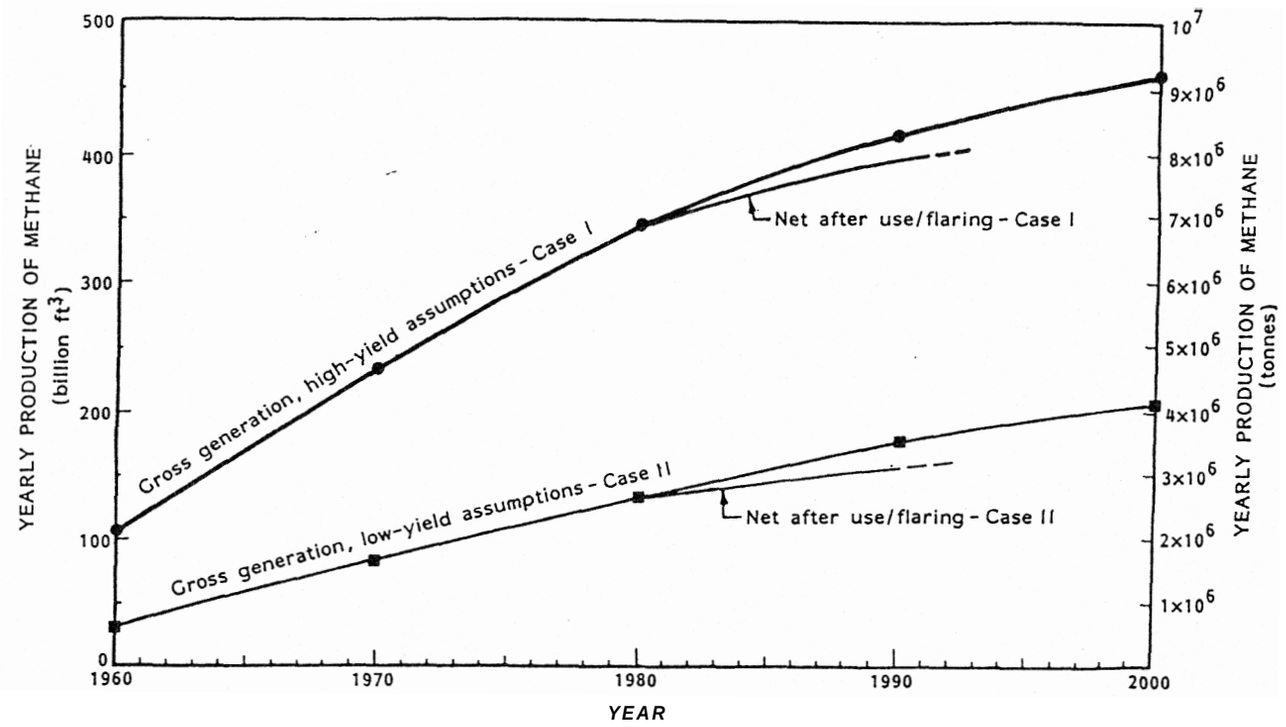

Figure 5. Landfill methane emission estimates.

The parameters of Tables *2* and **3** and waste data of Figure 5 were used to obtain upper- and lower-bound generation estimates as described in the text. Estimated net emissions after flaring/use are also shown.

[24]Information is sparse on the degree to which emissions of methane may be reduced by microbial oxidation in the cover soils of typical landfills, but it is considered likely that under 10% may be oxidized; information indicating unchanging CO_2/CH_4 ratios with landfill cover soil depth, suggesting little oxidation, is cited by Bingemer and Crutzen, op *cit,* Ref 1, from G. Rettenberger and O. Tabarasan, *Untersuchungen zur* Entstehen, *Ausbreitung,* und *Ableitung* von *Zersetzungsgasen* in Abfallablagerungen, Rep 103,02,207, Umweltbesamt, Berlin, 1980.

[25]Bingemer and Crutzen, *op cit,* Ref 1.

[26]Bingemer and Crutzen assumed substantially higher yields (over 200 l/Kg, to be compared to our assumed yield of 62–110 l/Kg of dry waste). This factor alone increased their emissions projection. compared to that in this article, by over a factor of two. They also assumed somewhat higher landfill placements, and rapid or 'instant' conversion of waste components to methane, both of which have the effect of increasing projected emissions somewhat further.

[27]R.L. Peer, D.L. Epperson, D.L. Campbell, and P. Von Brook, Development of an *Empirical* Model of Methane Emissions from Landfills, Report EPA-600/R-92-307, US Environmental Protection Agency, Washington, DC.

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tion, and emissions net of the adjustment for energy use and flaring (taken as increasing to 7% of the averaged high and low projections in 1990). Losses to bacterial oxidation in landfill cover soils have been presumed insignificant.[24]

These calculated US landfill methane emissions are quite low compared to those that can be inferred from one widely cited reference. Bingemer and Crutzen have estimated worldwide landfill methane emission rates of 30 to 70 million tonnes/year;[25] pro-rating those workers' calculations on the basis of the ratio of US to worldwide landfilling placements would lead to annual US emissions (based on their data) of about 11 to 21 Tg methane per year, well above the estimates in this article. Their higher estimate is primarily attributable to higher yield assumptions, although other factors contribute.[26] Relating to US emissions, however, other very recent work based on field measurements suggests lower values. Landfill gas recovery rate data have been obtained and validated for 21 sites across the USA.[27] From these data a model ('regression model') has been developed.[28] As used, the regression model's methane generation projections depend on model assumptions about key variables such as placement rates, generation time, and recovery efficiency. For one example case, where placement of 100 Tg/year along with other parameters considered reasonable were used, an emissions estimate of 2-6 Tg/year was obtained.[29] The workers who have developed the regression model have been careful to point out dependence of generation/emission estimates on the various assumptions, as well as the model's uncertainties. However, it can be noted that over a likely range of parameters,

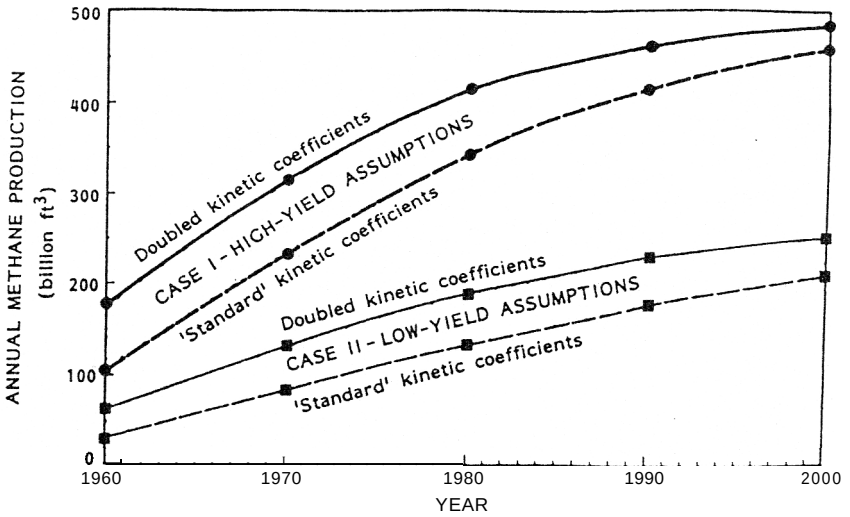

Figure 6. Example **of** effect ***of*** varying kinetic coefficients.

In this case doubling all rate coefficients (ie halving all lag times and time constants) leads to only modest increases in projected methane generation. In general, as stated in the text, varying such assumptions would lead to only modest changes in methane generation projections.

projections of the regression model would tend to be consistent with those in this article.

As further comment on the EMCON MGM-based emissions estimate of this article, it is noted that it depends directly on the ultimate methane yields assumed per pound of dry waste. The ultimate yield assumed in the EMCON MGM is 1 to 1.8 ft^3 of methane/lb (60 to 110 Ykg), much lower than would be obtained from the complete stoichiometric conversion of waste organics to methane, and well under that assumed by Bingemer and Crutzen. Nonetheless the assumption of this yield in the MGM is observed by **EMCON** to give results in line with EMCON's own field measurements to the extent validations have been made.[30] In addition, the methane yield assumed in the MGM model is very much in line with reported municipal waste results obtained by investigators under ideal laboratory conditions.[31] Such laboratory results can be considered to represent limits on yield attainable. This supports the fact that such low yields assumed in the model, and the methane emission figures assumed in this article may be realistic.

Sensitivity to kinetic parameters

Figure 5 showed methane emission estimates based on what might be termed 'best judgment' for high- and low-limit kinetic parameters to apply to US waste as a whole. Other emission estimates (not shown) were made to reflect greater variance in kinetic parameters which in fact might occur over 'wet', 'medium' and 'dry' regions of the **USA;** these emission estimates did not vary greatly from the base case. The difference resulting when the rate constants were doubled and lag times halved (a major change) relative to the base case is shown in Figure **6,** which illustrates only modest sensitivity to choice of kinetic parameters.

The emissions estimate of Figure 5 **is** preliminary. However, despite uncertainties, the estimate gives a reasonable basis for the discussion which follows of its probable significance.

Greenhouse significance of US landfill methane emissions

The net build-up of methane in Earth's atmosphere is the consequence of an enormous aggregate of worldwide emissions from a wide range of

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[28]R.L. Peer, S.A. Thomeloe, and D.L. Epperson, 'A comparison of methods for estimating global methane emissions from landfills', ***Chemosphere,*** in press, 1992.

[29]***Ibid.***

[30]Bingemer and Crutzen, *op cit,* Ref 1.

[31]For example, see **D.C.** Augenstein, D.L. Wise, and C.L. Cooney, 'Packed bed digestion of solid wastes', ***Resource Recovery and Conservation,*** Vol 2, 1976, pp 257–262; M.A. Barlaz, 'The use of mass balances for calculation of the methane potential of fresh and anaerobically decomposed refuse', ***Proceedings from the GRCDA 73th International Landfill Gas Symposium, Lancashire, Illinois,*** SWANA, Silver Spring, MD, March 1990; D.C. Augenstein, D.L. Wise, R.L. Wentworth, and C.L. Cooney, 'Fuel gas recovery from controlled landfilling of municipal wastes', ***Resource Recovery and Conservation,*** Vol 2, 1976, pp 103–117.

Table 4. Global sources and sinks of methane.

Source/sink	Methane (million tonnes/year)
Sinks	
Tropospheric reactions with OH	290–350
Stratospheric reactions with OH	25–35
Uptake on aerobic soils	10–30
Annual growth (≈1.1%/yr)	50–60
TOTAL REQUIRED SOURCES (sum of above)	375–475
Sources	
Domestic animals	70–80
Natural gas leaks	≤35
Coal mining	35
Landfills	30–70
Biomass burning	30–100
Wild ruminants	2–6
Other fauna (eg insects)	<30
Decay of animal wastes	?
Rice fields and natural wetlands	>44–228

This table shows some of the global sources and sinks, and overall methane budget, as estimated by one set of workers. These have been used to determine parameters of a simple first-order atmospheric model, presented in the text. *Source*: Adapted from H.G. Bingemer and P.J. Crutzen, 'The production of methane from solid wastes', *Journal of Geophysical Research*, Vol 92, No D2. 1987. pp 2181–2187.

sources, and a slightly smaller but still enormous consumption. Consumption is due mostly to chemical processes in the atmosphere. The estimated emission and consumption rates for various sources and sinks as estimated by one set of investigators is shown in Table 4.[32] It should be pointed out that there are large uncertainties in many of the inputs and outputs, although the atmospheric rise rate is known with considerable accuracy. It should also be noted that Table 4 is adapted from Bingemer and Crutzen's work, and the landfill methane figure is not that of this work, but the larger one they derive from worldwide emissions.

The basic question here is how the landfill methane emissions (or other emissions of comparable 'small' magnitude €or that matter) affect the atmospheric rise rate. Does emitted landfill methane cause a corresponding additive increase in the rise rate, or is it, as some have argued,[33] insignificant because US landfill methane is only a small fraction, 1–2%, of the total methane entering Earth's atmosphere? One possible, but perhaps simplified, view of the impact of landfill methane would be that of a roughly 5 Tg/year input to the atmosphere, if additive to the atmospheric build-up, could be accounting for about 10% of a roughly 50 Tg/year atmospheric methane build-up. This atmospheric methane build-up accounts in turn for about 18% of the increased 'radiative forcing' by greenhouse gases in Earth's atmosphere since 1980 (refer to Table 1). Simple multiplication suggests significant effect – US landfill methane emissions (if 5 Tg/year) might have been responsible for adding about 1.8% to the increase in the radiative forcing resulting from atmospheric build-up of all greenhouse gases together since 1980. The question is, is this interpretation correct?

Modelling small source contributions

It was initially thought that the above question could be answered straightforwardly based on knowledge of the mechanisms of removal of methane from Earth's atmosphere. However, processes which remove methane from Earth's atmosphere are highly complex, as may be inferred from Figure 7 which shows some (nor all) of the various reactions involved. The mechanisms of atmospheric oxidation, the major pathway for consumption,[34] can depend on levels of nitrogen oxides (NO,) present in the atmosphere: two different reaction chains are possible, represented by the inner loop of Figure 7 involving

[32] Bingemer and Crutzen, *op cit*, Ref 1.
[33] For example, see E. Repa, 'Landfills and global warming', Waste Age, June 1989, p 28. Also, audience comment at GRCDA/SWANA Landfill Gas Symposium, Lincolnshire, IL, March 1990. The argument that landfill methane is inconsequential because it is only a small fraction of worldwide generation has been expressed repeatedly.
[34] R.J. Cicerone and R.S. Oremland, 'Biogeochemical aspects of atmospheric methane', *Global Biogeochemical Cycles*. Vol 2, December 1988, p 299.

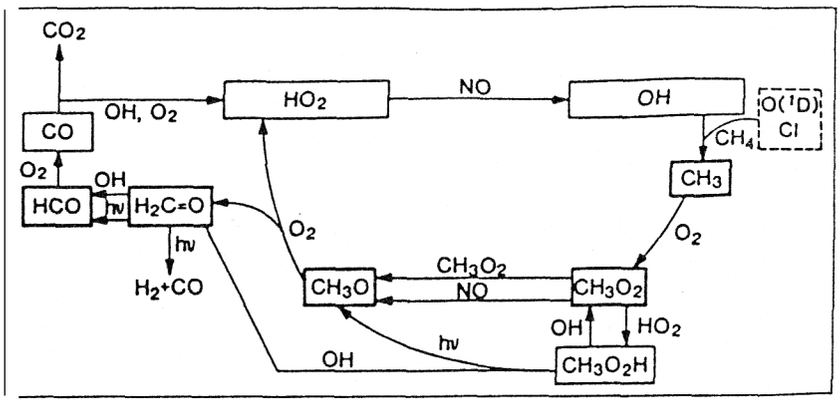

Figure 7. Atmospheric chemistry of methane degradation, shown, is complex. Uncertainties in reaction **order,** and consequent uncertainties in methane's atmospheric residence time must **be** recognized (see text).

Source: R.J. Cicerone and R.S. Oremland, 'Biogeochemical aspects of atmospheric methane', ***Global Biogeochemical Cycles,*** Vol 2, December 1988, p 299.

nitrogen oxides, and the outer reaction pathway which does not involve them. Both reaction chains start with methane's initial reaction with hydroxyl radical, which is consumed in the reaction. The methane destruction routes not involving NO, have methane competing (with itself, and other reactants such as CO and other hydrocarbons, not shown) for reaction with available hydroxyi radical. Methane destruction by this pathway (termed 'Case **A'** here) would be expected in chemical kinetic terms to exhibit a reaction order with respect to methane which is less than one. The methane destruction pathways involving NO, create more hydroxyl radical which in turn can react with more methane; such a reaction scheme (termed here 'Case B') would be expected to show a higher order in methane than pathways where hydroxyl radical is not regenerated.[35]

An exact analytical expression for methane destruction is not possible at this point, because of unknowns. What can be done for purposes of estimation, though, is to assume a model for methane destruction which is first-order in methane (and which is expected to be close to the actual case) and perturbations in the reaction order to reflect the two Cases **A** and B. The perturbations would be downward from first-order in methane for Case **A,** and upward to (perhaps) slightly more than first-order for Case B.

A basic first-order reaction model developed directly from the information presented previously in Table **4** is

$$dC/dt = I - kC$$

where

I = atmospheric input (130 ppb/year in 1980)
C = atmospheric concentration (1600 **ppb** in 1980)
k = first-order rate constant 0.072 per year^{-1} (derived from data in Table **4)**
t = time, years.

The above parameters are such that the model explains the material balance of Table **4.** That is, if atmospheric destruction is really first-order in methane, the kinetic coefficients shown above are what are necessary to account for the atmospheric build-up of methane as actually observed, with existing atmospheric concentration, and sources of the size shown in Table **4.** (However, the approximate nature of the model and the data on which it is based is emphasized.[36])

[35] In this discussion of models and chemical reaction order for atmospheric methane disappearance, disappearance is assumed characterized by a classical chemical equation of the form $dC/dt = kC^x$. Concentration is C; the exponent x is reaction order and t is time. For a first-order reaction, x = 1; for Case A, **xis** less than 1 (for example, it might be 0.9. and *for* Case **B,** x might be 1.05).

[36] Dana Hartley (Department of Earth and Planetary Sciences, Massachusetts Institute of Technology) has kindly reviewed an earlier draft of this article. Her comment on the model derivation is that the total magnitude **of** methane emissions in Table 4, on which the derivation is based, may be somewhat low; with the derivation approach that leads to a rate constant somewhat lower than the actual. To reflect this possibility a higher rate constant (by about 30%) as derived by other workers is also cited in the text and is included in Figure 9.

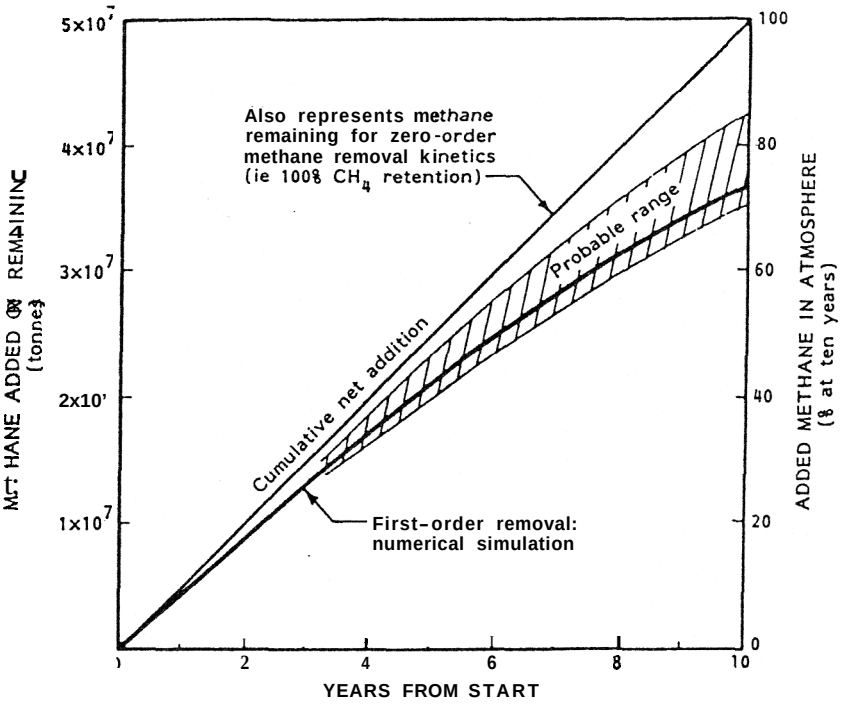

Figure 8. Atmospheric retention of a 'small Source' incremental methane input.

An input (landfill or other) *of* 5 million tonnes per year (5 Tg per year) *is* assumed (cumulative input is represented by the straight 45-degree line rising from the origin). The estimated fraction of this cumulative input remaining in the atmosphere is shown as the hatched area, with the projection of the text's first-order model shown as the solid line within the hatched area. In general, with rate constant and order assumptions considered reasonable (upper and lower bounds are estimates based *on* judgment). the atmosphere will still contain most of such emissions into it after 10 years.

Impact of landfill methane on atmospheric build-up

The effect of landfill or other 'small source' methane emissions on the atmospheric build-up can be expressed in various ways. The landfill methane emissions to the atmosphere do not vary substantially over short intervals. For analytical purposes they can be regarded with little error as 'ramp functions' (ie constant-rate emissions into the atmosphere over time). One way to express the contribution of a small methane source to the atmospheric inventory is as the fraction of total emitted methane which remains in the atmosphere at a given time after start of the emissions. This can be estimated using the model developed above, and perturbations on it, to account for reaction orders from below to slightly above first-order in methane to account for Cases **A** and B.

Figure 8 shows results for a hypothetical **US** landfill methane emission of 5 million tonnes/year (5 Tg/year) of methane entering the atmosphere continuously over ten years. The 45-degree line rising from the origin represents the cumulative additional input of landfill methane to the atmosphere over ten years; the estimated methane remaining in the atmosphere as a result of this input is shown below the cumulative input line.[37] The preliminary estimate is that between 70% and 90% of **a** constant rate or 'ramp function' input of methane may remain in the atmosphere after ten years. Thus one important conclusion is that 'incremental source' atmospheric inputs such as landfill methane do make a difference *to* the atmospheric inventory closely proportional to their total input over the ten year interval which was examined. It is also important to note that where destruction is (as expected) first-order in methane, the methane input adds to the atmospheric build-up in this way (that is, it makes a difference to the atmospheric inventory) independently of other sources, sinks, and perturbations.

Figure 9 shows similar information to that in Figure 8, but over a

[37]Note that Figure 8 shows only the *added* methane and the fraction of it remaining for comparison. Baseline or pre-existing levels are not shown.

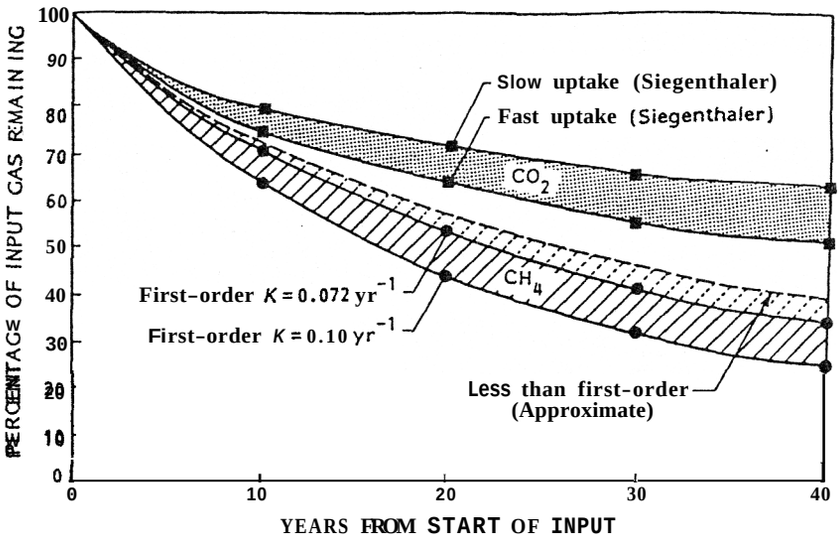

Figure 9. Atmospheric retention of ramp functions of CO_2 and CH_4 *over* time.

A constant-rate or ramp function emission of these gases begins at time zero: the fraction of cumulated input of each gas remaining in the atmosphere is shown in terms of an estimated range. These data in turn allow estimation of relative radiative forcing potency and greenhouse equivalences of ramp function emissions of the two gases over time as discussed in the text.

Sources: Calculations based on data found in R.D. Prinn, R. Cunnold, R. Rasmussen, P. Simmonds, F. Alyea. A. Crawford, P. Fraser. and R. Rosen, 'Atmospheric trends in methylchloroformand the global average for the hydroxyl radical', Science, Vol 238, No 945, 1987; U. Siegenthaler, 'Uptake of excess CO_2 by an outcrop-diffusion model of the ocean', Journal of Geophysical Research, Vol 88, No C6, 1983, pp 3599 (cases 1 and 4 data from Figure 5 of this reference were used to compute the atmospheric response to ramp functions of CO_2).

longer term. Shown is the fraction of a constant rate (or ramp) input of methane which remains in the atmosphere for a longer period of 40 years. Two sets of parameters were used in this case: those derived above and the case where the first-order rate constant for atmospheric destruction is $k = 0.1\ year^{-1}$ after work of Prinn.[38] Even after 40 years' input, about 25–40% of such a ramp input function remains. Also shown for comparison is an estimated range for fraction of CO_2 remaining in the atmosphere, as the result of an identical rate of ramp input. While methane is destroyed by reactions in the atmosphere, carbon dioxide is largely taken up by absorption into the ocean: kinetics of its absorption are marked by different time constants for its equilibration with shallow and deep ocean layers. These have been calculated by Siegenthaler (among others) for various model cases for oceanic absorption and the CO_2 information in Figure 9 is adapted from Siegenthaler's work.[39] Based on data in Figure 9, greenhouse effectiveness of abating constant-rate methane emissions into the atmosphere (by combustion) may be compared to abating equal rates of CO_2 emission. Such comparison can be based on a 25-fold greater greenhouse potency of atmospheric methane relative to CO_2, and after accounting for product CO_2 from methane combustion. Using radiative forcing at a 40-year endpoint as the index, the effect of abating a ramp input of methane is equal to abating a 40-year ramp output of CO_2 roughly 15 times as great on a volume basis. This result is generally consistent with other recent work and is referred to below.[40]

The effects of the presence or absence of US landfill methane emissions can be seen as significant. Over the short term, analysis suggests US landfill methane could be causing a 5–15% difference in the rate of atmospheric methane build-up (implied by a 3–8 Tg/year component in a roughly 50-60 Tg/year build-up). Similarly, the short to medium, say 40 years, difference made in radiative forcing increase centres on 1% (within, roughly, a factor of 2, depending on actual emissions and term considered). Yet this does *nor* quite enable us to assign straightforwardly responsibility for 5–15% of the global atmospheric methane rise to US landfills. The total of worldwide sources at 375–475 million tonnes/year adds up to about 600–1000% of the 50-60

[38] R.D. Prinn, R. Cunnold. R. Rasmussen, P. Simmonds, F. Alyea, A. Crawford, P. Fraser, and R. Rosen, 'Atmospheric trends in methylchloroform and the global average for the hydroxyl radical', Science, Vol 238,1987, p 945.

[39] U. Siegenthaler, 'Uptake of excess CO_2 by an outcrop-diffusion model of the ocean', Journal of Geophysical Research, Vol 88, No C6, 1983, p 3599. (Case 1 and 4 data from Figure 5 of this reference were used to compute the atmospheric response to ramp functions of CO_2.)

[40] All of this preceding calculation was presented at the SWANA meeting, Lincolnshire, IL, March 1990. Analysis along analogous lines to the approach of this article, but in terms of the time-averaged radiative forcing consequences of pulse inputs of CO, and CH_4 relative to one another over a 100-year period were published subsequently by Rodhe, *op cit*, Ref 3. With allowance for the differences in input and evaluation methods (ramp function, 40 years, this work, with evaluation at the 40-year endpoint, as opposed to pulse function, time-averaged radiative forcing over 100 years by Rodhe) our two analyses are consistent – and, interestingly, both analyses relied on data of Prinn *et al*, *op cit*, Ref 38, and Siegenthaler, *op cit*, Ref 39.

Table 5. Equivalences of reducing US landfill methane emissions by half: summary list.

Immediate effects
Reducing US fossil CO_2 emissions by 1.8–4.5%.
Reducing fossil CO_2 emissions of US electric utilities by 5–13%.

Effect over 40 years (approximate)
Reducing US fossil CO_2 emissions by 1–3%.
Reducing US electric utility CO_2 emissions by 3–8%.

Very long-term effects (estimate by first-order model)
Reducing atmospheric methane inventory by 15–60 million tonnes (greenhouse equivalent to 1–4 months of current global atmospheric CO_2 rise)

These effects may be considered large.
Source: Information on US and US utility fossil CO_2 emissions was based on figures compiled and kindly supplied by Douglas Leadenham, Electric Power Research Institute. *Palo Alto*, CA, personal communications. March 1990.

million tonne atmospheric rise (values from Table 4). Because of the kinetics of methane's destruction, *all* of the sources together are necessary to cause the atmospheric rise rate observed, and US landfills are only about 1–2% of the total source. There are many, many other sources ('responsible parties') which would make the same difference – perhaps the sheep of New Zealand, or if not those, then bogs of the Arctic, or cows of India, or swamps of Africa . . . the list goes on. What the analysis ***does*** importantly indicate is that reductions in 'small source' methane emissions such as from US landfills (or landfills worldwide, or a host of other sources) can make a significant difference to the greenhouse problem. The differences such reductions can make are illustrated below.

With information above about the relative radiative forcing effects of CH_4 versus CO_2 over time, it is possible to make some comparisons to illustrate the impact of landfill methane emissions into the atmosphere in terms of various known fossil CO_2 emissions. The comparative effects depend on the timespan examined, and to a certain limited degree on whether methane is used for energy. (If the methane is used for energy then the displacement of fossil CO_2 which would otherwise need to be emitted elsewhere makes the volumetric equivalence somewhat greater depending on the fossil fuel displaced.)

It will certainly not be cost-effective or practical to capture all US landfill methane, but it might be reasonable at some point in the future to abate as much as half of it. The effects which would be obtained by reducing **US** landfill methane emissions by even half are large, as shown in Table 5. Effects are equivalent to reducing total US fossil CO_2 emissions by between 1% and 5%,[41] or reducing CO_2 emissions from US electric power generation by 3% to 13%. (There is a wide range in equivalent CO_2 removal; this is in part due to methane emission and other uncertainties, and in part reflects the difference in moving between 'instant' and 40-year timeframes.) Lest it be considered that 1% of fossil CO_2 emissions by the **USA** is a small number, it is equivalent to CO_2 emissions by about 10 million average automobiles operating on US highways.[42]

Cost-effectiveness of landfill methane mitigation

Mitigation of landfill methane emissions can clearly benefit the global warming situation to some degree. It is of interest to compare economics of its abatement to those of other approaches which can be taken. Landfill gas is collected at many US landfills using current technology (largely vertical well extraction)[43] whose cost is well established.[44] The equivalence of methane emissions to fossil CO_2 emissions, developed

[41] Total US electric utility fossil CO_2 emissions were taken as 1.95 billion tonnes; total US fossil CO_2 emissions from all sources were taken as 5.6 billion tonnes (all values based on 1988 estimates). Much of the information on fossil CO_2 emissions was based on figures compiled and kindly supplied by Doug Leadenham of the Electric Power Research Institute.

[42] Assuming a typical automobile goes 12 000 miles per year, gets 20 miles per gallon, and emits 5000 kg CO_2 per year.

[43] EMCON Associates, *Methane Generation and Recovery from Landfills*, Ann Arbor Science, Ann Arbor, MI, 1982.

[44] Cost estimates in this work are based on EMCON experience; EMCON has consulted on over 100 landfill gas extraction systems, on components including design, costing. and other aspects over the past 20 years.

Table 6. Landfill methane and fossil CO_2 mitigation cost comparison.

Landfill gas System	Dollars per tonne C, carbon, or equivalent
Landfill gas, 50% CH 1000 cfm	$1.50–4.00
Landfill gas. 50% CH_4: 250 cfm	$5.00–12.00
Membranes: incremental cost	$9.00–50.00
Equivalent alternative to landfill system	
Nuclear for coal	$150–300
Photovoltaic for coal	$150–250
Nordhaus: 10th percentile CO_2 carbon	$10–30
Nordhaus: 50th percentile CO_2 carbon	$100–200

Basis of cost comparison: mitigation of one tonne (lob g) carbon in CO_2, or one tonne carbon equivalent (1/15 tonne carbon in methane).
This table offers a cost-effectiveness comparison of landfill methane abatement versus various carbon dioxide abatement approaches as defined in the text. Landfill gas mitigation should be relatively inexpensive compared to CO_2 abatement alternatives giving comparable benefit.
Sources: Landfill gas abatement options, EMCON Associates estimates: coal-fired power costs estimated at $0.06/kWh. Nuclear power cost is based on $3500/kW, 20%/yr capital recovery factor, 65% service factor, and costs other than capital at $0.018/kWh for a total power cost of $0.14/kWh. Costs shown are the net of nuclear costs over coal-fired power costs per tonne of coal CO_2 abated: costs for photovoltaic are from J. Schaefer (Project Manager, Solar Power Systems Program, Electric Power Research Institute. Palo Alto, CA), 'Review of photovoltaic power plant performance and economics', text of paper presented at IEEE/PES 1990 Winter Meeting, February 1990. Also, personal communications, March 1990. Other CO_2 carbon abatement costs are from W.D. Nordhaus. 'The cost of slowing climatic change', *Energy Journal*, Vol 12. No 1, 1991, pp 37-64.

earlier, can be used in conjunction with cost estimates for methane abatement to make such comparisons. Costs to prevent emission of either a tonne of carbon in fossil CO_2 or its 'greenhouse equivalent' in methane can be compared as shown in Table 6. For comparison, a tonne of methane carbon is taken to have a 'greenhouse potency' 15 times that of a tonne of carbon in CO_2, as was estimated above.

The landfill gas abatement cases selected for cost comparisons are the EMCON-estimated costs for collecting and abating landfill gas by flaring for three situations.[45] Costs are based on US experience. The first of the situations assumes the collection of 1000 CFM of methane from a single large landfill, and its flaring.[46] The second cost estimate is for the collection and flaring of gas from a smaller landfill at 250 CFM. (The 250 CFM system costs are included to give perspective on a recovery rate smaller than is normally economic for energy recovery.) The last case is the *incremental* cost to collect an extra 1000 CFM of methane using surface membranes to capture the estimated fraction (10–60%) of generation which is not extracted but escapes through the surface when conventional well systems are used.[47] Flaring and piping costs were considered already covered for the last case. The range of costs shown reflects variations which can exist in landfill configuration, operating and maintenance *costs,* assumed capital recovery, and other factors.

Two approaches which can be taken to reduce emission of fossil carbon in CO_2, whose costs can be estimated with some confidence, are the substitution of nuclear for coal in electric power generation,[48] and the substitution of photovoltaics for coal.[49] These are shown in Table 6. Other published costs for preventing emission of fossil carbon in CO_2 can also serve for comparison: these have been published by many and estimates are typically presented as marginal costs, since they depend strongly on the percentile of fossil CO_2 carbon emission reduced. (Reduction of the first few percent of CO_2 carbon emission may be at low or even zero cost if benefits such as conservation are realized. At higher fractional reductions, marginal costs to reduce each tonne of

[45]The author wishes to express appreciation to members of the EMCON gas group, particularly Kurt Bungert, in helping to develop these figures.
[46]See Ref 45.
[47]Cost estimates for surface liners to capture methane were developed in discussions with EMCON's liner group, March 1990.
[48]The cost differential is assumed reflected by differences experienced in electric power costs. The cost for nuclear power is assumed based on a cost of $3500/kW, 20%/year capital recovery factor, 65% service factor, and costs other than capital at $0.018/kWh for a total power cost of $0.14/kWh. Costs of coal-fired power are estimated at $0.06/kWh.
[49]J. Schaefer (Project Manager, Solar Power Systems Program, Electric Power Research Institute, Palo Alto, CA), 'Review of photovoltaic power plant performance and economics', text of paper presented at IEEE/PES 1990 Winter Meeting, February 1990. Also, personal communications, March 1990.

carbon emission escalate sharply.) A compilation of such marginal removal costs as published from many sources has been made by Nordhaus:[50] low-range costs to prevent the 10th percentile of carbon emission and mid-range cost (marginal cost to remove a tonne of carbon when reduction is already 50% from baseline) are shown. Although it must be noted that the quoted cost estimates within this article and elsewhere are approximate and dependent on timescales and a host of other assumptions, the cost of landfill gas abatement would, again, appear very low compared to other possible greenhouse gas amelioration strategies. Even allowing for cost variation (as likely outside the USA) and overlap, the landfill gas abatement approaches would appear to have costs in large part at a tenth or less of most of the possible greenhouse equivalent fossil CO_2 abatement approaches.

From landfill operators' down-to-earth perspectives,[51] the costs of installing a landfill gas extraction system will certainly seem high. However, the costs appear economical in the context of other approaches which can be taken to address the greenhouse problem. As an additional comment on costs, it does appear, based on these preliminary estimates, that it may be economically feasible (given reasonable system capture efficiencies) to abate up to half of the current landfill emissions at the lower costs.

Facilitating methane mitigation

Increasing landfill methane mitigation is potentially a relatively cost-effective way of addressing a component of the greenhouse problem. Regulatory and other driving forces[52] can be complemented by technical efforts in areas such as improving collection efficiencies, technology transfer efforts, and by various incentives.

For those landfills with controls, current approaches (in the USA and elsewhere) recover methane with efficiencies estimated to lie for the most part between 40% and 90%.[53] Routes can be identified to improve these efficiencies: their investigation appears warranted.[54] Controls can be expanded to encompass more sites. While statistics and indices are far from perfect," it is likely that in the USA only a moderate fraction of generated methane (well under half) from waste currently reposing in landfills is in landfills subject to control at all (though this will be increasing in response to regulatory and other factors). In addition control, where practised, is at the fractional efficiencies discussed above, which can be considered modest. In some cases lack of basic information is part of the barrier to mitigation: technology transfer efforts, such as those supported by the US Environmental Protection Agency (EPA),[56] will help facilitate mitigation. Such technology transfer, although supported on the basis of US needs and benefits, has obvious applicability, and transferability, worldwide. In fact, some EPA efforts (including, in one case, on emissions data, and, in another, on energy uses) are being conducted with international cooperation and encouragement.[57] Other approaches, including regulation and incentives, can also help abate emissions, as discussed below.

Regulations can obviously result in mitigation.[58] However, regulatory approaches or mandates also have some limits in terms of what they can accomplish.[59] Costs, though favourable from the perspective of greenhouse gas mitigation, can still be barriers. For these and related reasons, various modifications to regulatory approaches, and incentives, have been recommended recently by expert groups.[60] Suggestions that have

[50] W.D. Nordhaus, 'The cost of slowing climatic change', ***Energy Journal***, Vol 12, No 1, 1991, pp 37-64.

[51] It was impossible to resist using this terminology.

[52] For example, the incentives from energy sales (in that fraction of cases where they are economic).

[53] Augenstein and Pacey, *op* ***cit***, Ref 14.

[54] Such work could indude,. for example. more work on optimization of extraction system design and operation. Issues to be addressed indude well depth, spacing, containment of waste and thus gas, recovery control strategies, energy uses, and the like. Use of membranes to improve capture is addressed in the text: also, see S. Thorneloe, 'EPA's Global Climate Change Program – Program Plan for Methane Emissions from Solid Waste and Other Waste Disposal Facilities', ***Proceedings from GRCDA/SWANA's 14th Annual International Landfill Gas Symposium, San Diego, CA, March 1991,*** SWANA, Silverspring, MD. Also, D. Maunder, 'Using landfill gas in the UK, ***Proceedings of SWANA's 15th Annual Landfill Gas Symposium, Arlington, VA, March 1992,*** SWANA, Silverspring, MD: and personal communications, March 1992.

[55] For example, some US data are available on tonnage of emplaced waste subject to control but these are incomplete. Also, extrapolation of generation from these will not reflect biases such as from variable generation over time.

[56] Thorneloe, *op* ***cit***, Ref 54.

[57] S. Thorneloe and R. Peer, 'EPA's Global Climate Change Program – global landfill methane', ***Proceedings of the Air and Waste Management Association Annual Meeting,*** Vancouver, BC, June 1991; personal communications, S. Thomeloe, 1991 and 1992; Thomeloe, ***op cit,*** Ref 54.

[58] For example, the new US regulatory requirements proposed for landfill gas control. See 'Standards of performance for new sources and guidelines for control of existing sources: Municipal waste landfills', ***Federal Register,*** Vol 56, No 104, 30 May 1991. Although initiated primarily to address emissions of other components (non-methane organic compounds) in landfill gas, these will be effective in reducing methane emissions.

[59] There appear to be no means that are very accurate for measuring fugitive methane emissions from landfill surfaces; these tend to be a normal focus of regulations. Also, for example, enforceability can diminish with intricacy, particularly when implementationis up to those who may have non-technical backgrounds and who may have little incentive to optimize recovery.

[60] For example, see Environment Agency of Japan, US Agency for International Development, and US Environmental Protection Agency/Japan Environmental Agency, ***International Workshop on Methane Emissions from Natural Gas Systems, Coal Mining and Waste Management System,*** US Environmental Protection Agency, Washington, DC, April 1990.

been or may be considered for US (and worldwide) application include the use of environmental balance sheets, offset allowances, and, with regard to the gas's energy uses, various levies on use of the alternative fossil fuels that emit radiatively forcing gases; a number of these are discussed elsewhere.[61]

As far as possible incentives go, it would appear that those providing rewards or funds proportional to methane collection – to whatever entity may collect – have advantages.[62] They allow latitude to select the more effective approaches for collection from among the alternatives, and to avoid less workable approaches that can sometimes be 'hard-wired' in by mandates. They should result in mitigating the least-cost methane first, which represents an optimum use of funds (hopefully for society, as well as mitigators). Such approaches can also provide for, as well as minimize the burden on those responsible for, closed waste landfill systems emitting significant amounts of methane in situations where there is no other continuing revenue. (This situation is common in the **USA** and likely to obtain in many places elsewhere in the world.) Current **US** tax credits provide benefit proportional to methane recovery in this fashion,[63] and other incentive approaches may be considered.[64] The diligence with which landfill gas collection is practised now in the **USA,** where there can be energy related revenue (that is proportional to collected gas), suggests the likely efficiency of such incentives.

Landfill gas energy uses are also desirable, relative to simply flaring, because of increased greenhouse benefit: they increase benefit by offsetting the use of 'swing' fuels, nearly all fossil, elsewhere. However, energy use economics are currently unattractive for much of the generated methane that may be additionally recoverable across the USA.[65] Further ,incentives to facilitate the energy uses, rather than simply flaring, may be considered.[66] **A** further possibility is to combine enhancing of landfill methane generation with its high efficiency capture, and such energy uses.[67]

Whether or not the approaches listed or others may be most desirable, those dealing with landfill methane mitigation should be considering these issues. Those responsible for waste landfill facilities should recognize that controls are likely, and make known which approaches would be preferable from their standpoinrs.

Conclusions

This has been a preliminary analysis. The uncertainties should be evident from qualifying statements, and the ranges given to various estimates. Despite the uncertainties it is possible to state some important conclusions with reasonable confidence.

First, methane emissions from landfills in the **USA** add significantly to the atmospheric methane build-up and thus are contributing to the greenhouse effect. By analyses presented here, their presence or absence in the short term (<10 years) probably makes a difference of 1–2% in the annual rate of increase in radiative forcing due to atmospheric build-up of all greenhouse gases.

Second, an equivalence of landfill methane emissions to fossil CO_2 emissions from various sources can be defined based on radiational properties and atmospheric residence times of the two gases. The equivalence depends on the timespan and type of CO_2 and CH_4 input

[61] For example, see D. Augenstein and J. Pacey, ***Landfill Gas Energy Utilization: Technology Options and Case Studies,*** Report EPA-600/R-92-116, US Environmental Protection Agency, Washington, DC, June 1992. Incentives as they apply to energy uses, including some from ***op cit,*** Ref ***60,*** are discussed in Section 6, pp 77–78.

[62] While measuring emissions from landfill surfaces presents problems, methane recovery (and subsequent destruction) is much easier to measure accurately and its benefit is clear. Emissions will be reduced by whatever amount is collected and destroyed. Thus incentives that result in maximizing recovery fulfil the objective of minimizing emissions.

[63] R. Hatch, 'The federal tax credit for nonconventional fuels: Its status and role in the landfill gas industry', ***Proceedings from GRCDA/SWANA's 14th Annual International Landfill Gas Symposium, San Diego, CA, March 1991,*** pp 37-45.

[64] Imposing a 'methane tax' on decomposable waste that is landfilled. This could provide a pool of funding towards methane abatement, and might be preferentially collectible if the methane were abated through energy use.

[65] Augenstein and Pacey, ***op cit,*** Ref 59.

[66] For example, through a fossil carbon tax as referred to in Nordhaus, ***op cit,*** Ref 50, or through supporting landfill gas energy use with a levy on fossil fuel use (reflecting emission consequences of fossil fuel use) similar to the UK non-fossil fuel obligation. as discussed in Maunder, ***op cit,*** Ref 54.

[67] D. Augenstein, D.L. Wise, R.L. Wentworth and C.L. Cooney, 'Fuel gas recovery from controlled landfilling of municipal wastes', ***Resource Recovery and Conservation,*** Vol 2, 1976, pp 103–117.

function assumed. For ramp function inputs, and radiative forcing impacts defined at endpoints of up to 40 years, US landfill methane emissions are equivalent in their greenhouse impact to between **2%** and 10% of total **US** fossil CO_2 emissions.

Finally, preliminary estimates are that capture and flaring or delivery to energy application of the easily collectable fraction of US landfill methane may be achievable at a cost well below, possibly less than one tenth that, of most greenhouse-equivalent CO_2 carbon abatement alternatives. Increasing effort **is** being made to mitigate landfill methane emissions in the USA. Incentives and other routes are available and can be implemented to further mitigation, not only in the USA, but also worldwide.