United States
Environmental Protection
Agency

EPA-600/7-91-002

January 1991

EPA

Research and Development

APPROACH FOR ESTIMATING GLOBAL LANDFILL METHANE EMISSIONS

Prepared for

Office of Air and Radiation

Prepared by

Air and Energy Engineering Research
Laboratory
Research Triangle Park NC 27711

EPA-600/7-91-002
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APPROACH FOR ESTIMATING
GLOBAL LANDFILL METHANE EMISSIONS

By:

Rebecca L. Peer, Ann E. Leininger, Barbara B. Emmel, and Susan K. Lynch
Radian Corporation
3200 Progress Center
Post Office Box 13000
Research Triangle Park, North Carolina 27709

EPA Contract 68-02-4288
Work Assignment 48

Project Officer: Susan A. Thorneloe
U.S. Environmental Protection Agency
Air and Energy Engineering Research Laboratory
Research Triangle Park, North Carolina 27711

Prepared for:

U. S. Environmental Protection Agency
Office of Research and Development
Washington, DC 20460

ABSTRACT

In response to concerns about global warming, the U.S. Environmental Protection Agency's (EPA) Office of Research and Development (ORD) has initiated a program to characterize the effects of global change, including identifying and quantifying emission sources. EPA's Air and Energy Engineering Research Laboratory (AEERL) is part of this effort, and is particularly concerned with quantifying emissions sources both in the United States and globally.

This report provides an overview of the available country-specific data and modeling approaches for estimating global landfill methane. The current estimates of global landfill methane indicate that landfills account for between 4 and 15% of the global methane budget. The report provides an approach for using country-specific data and field test data to develop a less uncertain estimate of global landfill methane. The development of enhanced emissions factors for landfills and other major sources of methane will improve the understanding of atmospheric chemistry and feedback effects, will target mitigation opportunities, and will ensure cost-effective mitigation strategies.

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1.0 INTRODUCTION

In response to concerns about global warming, the U.S. Environmental Protection Agency's (EPA) Office of Research and Development (ORD) has initiated a program to characterize the effects of global change, including identifying and quantifying emission sources. EPA's Air and Energy Engineering Research Laboratory (AEERL) is part of this effort, and is particularly concerned with quantifying emissions sources both in the United States and globally.

Considerable effort has been expended studying carbon dioxide (CO_2) emissions since CO_2 is responsible for most of the global warming. Methane (CH_4), is of particular concern since its radiative forcing potential has been estimated to be 20 to 30 times that of CO_2 on a mole basis; furthermore, atmospheric methane is increasing at a faster rate than any of the other greenhouse gases except for CFCs (Rodhe, 1990). Although the major sources of methane are known qualitatively, considerable uncertainty exists about the quantitative emissions from each source. One of the goals of AEERL's global climate research program is to develop better models and inventories for methane sources.

This report summarizes the current state of knowledge with respect to one important methane source--landfills. The objectives of this study are:

- to evaluate the approaches currently available for estimating landfill methane emissions, and
- to determine the best available approach for estimating global methane emissions from landfills.

These objectives were met by reviewing the current literature on methanogenesis in landfills, collecting and evaluating methane emissions models, and interviewing experts in this field.

The "best" approach is obviously determined by a variety of factors including the desired level of accuracy, desired resolution, data limitations, and budget and time constraints. The level of accuracy is largely determined by the needs of the users of the model outputs. Policymakers need quantitative measures of landfill emissions in order to develop mitigation strategies and to assign priorities to mitigation programs. However, they may need only one number, such as average annual global methane emissions from a given source; the finest resolution they may need is likely to be at the country-specific level. At the other end of the spectrum, AEERL's model may be needed to supply information to regional and global atmospheric models. If so, the resolution of the data will need to be finer. Spatially, the emissions may be needed for grid cells as large as $10° \times 10°$ or as small as $1° \times 1°$. Temporally, time periods smaller than a year may be desirable.

At this time, AEERL can only recognize that these divergent needs exist, but can not say for certain that the needs of all users can be met. The limitations to meeting all these needs are partly related to the costs of model development. Even more critical, however, is the large amount of *uncertainty associated with modeling methanogenesis. Cost considerations aside, the data required as* inputs for a mechanistic model of methane production may not exist.

The conclusions and recommendations are summarized in Section 2.0. Section 3.0 discusses several different modeling approaches that are currently available, and discusses data needs and availability. Section 4.0 presents a conceptual scheme for a global landfills model, and outlines a program to develop that model further.

2.0 CONCLUSIONS

The purpose of this project was to determine the preferred approach for estimating global landfill methane. This effort is part of a larger effort in which field test data are being collected to develop enhanced emission factors for major sources of methane including coal mines, natural gas production/distribution systems, and waste disposal facilities such as landfills. The development of enhanced emission factors will improve the understanding of atmospheric chemistry and feedback effects, will target mitigation opportunities, and will ensure cost-effective mitigation strategies.

This report provides an overview of the approach to develop enhanced emission factors for global landfill methane. The approach was developed considering the availability and quality of country-specific information such as the amount of waste being landfilled, the composition of landfilled waste, and other landfill characteristics that affect landfill methane emissions. The approach was also developed considering the needs of policymakers and atmospheric chemistry modelers.

Provided below are conclusions from this project for developing an approach to more reliably estimate global landfill methane:

1. An analysis of available models was conducted (Section 3.1) and the conclusion is that several current models exist which could be modified for use with country-specific data. The models were evaluated considering availability of required inputs. In future work, field test data are to be collected to evaluate how the available models compare to gas production data at landfill sites where methane is being collected and controlled/utilized. The results of this future work will be used to define the algorithm for estimating global landfill methane.

2. A review of available country-specific data was conducted (Section 3.2). It was found that data on waste composition and waste management for most countries are adequate. However, some regions are not covered as well as others, so extrapolation from similar countries or use of surrogates is needed to develop inputs for those countries. Also important are the country-specific waste generation rates because methane production is directly proportional to the amount of degradable waste landfilled. Data are available for a large number of countries. It was also found that gross national product (GNP) is a good predictor of waste generation rate. Future work will need to determine whether to use estimates of waste generation rates or to use the gross national product approach developed by Keith Richards of the United Kingdom Department of Energy.

3. The results of enhanced emission estimates for global landfill methane will be used as input to other models. Policymakers are generally concerned with total and country-specific estimates. Atmospheric chemistry modelers generally require finer resolution. A sensitivity analysis of three allocation schemes was conducted to test the relative performance of each scheme using a range of grid sizes: 1° X 1°, 5° x 5°, and 10° x 10°. The allocation schemes range from the very simple to the very detailed. The conclusion of this analysis is that a "Population Centroid" methodology previously developed for a global VOC

inventory study is reasonably accurate and cost-effective for a 10° x 10° grid. If maximum flexibility is desirable or if a 1° X 1° grid cell is required, then a new methodology is required (Section 4.1). Future work will need to determine the user needs of enhanced emission estimates for global landfill methane.

4. A review was conducted of the functional relationships between methane production and the various factors known or suspected to affect the rate of gas production. It was found that moisture appears to be the greatest factor affecting gas production. The other factors such as waste age, composition, quantity and quality of nutrients, and ambient temperature may also affect gas production. However, the results of studies reported in the literature are sometimes contradictory, and it is unclear how the results would be extrapolated to actual landfills. Future work where field testing data are to be collected will help in determining the functional relationships for the factors affecting gas production. In addition, work being conducted in the United Kingdom, Sweden, the Netherlands, and India will also provide data needed to help determine the functional relationships. The results of this work need to be collected for developing the inputs for estimating global landfill methane.

3.0 REVIEW AND ASSESSMENT OF LANDFILL MODELS AND DATA AVAILABILITY

Currently available models are reviewed below in Section 3.1. Data gaps and knowledge gaps that limit development of a global model are identified in Section 3.2.

3.1 EVALUATION OF AVAILABLE MODELS

Three different types of models dealing with landfill methane were identified. The first are global landfill methane emissions estimation models. These are simplistic models which do not take into account time-dependent variations in methane production. In general, the refuse generated annually is assumed to be converted to methane and carbon dioxide based on the degradable carbon content in the same year that the waste is landfilled. Spatial variation is, at best, limited to the scale of individual countries.

The second group of models are theoretical first-order kinetic models of methane gas production. They are based on the methanogenic processes of bacterial populations and include a time component. These models are generally applied to individual landfills, although they could be applied to entire countries or regions.

The third group of models are not concerned with methane production, but model the movement of gases through a landfill. While these models are capable of providing the most detailed emissions data with respect to temporal resolution, they are far too detailed for global applications. These models are not discussed any further in this report. The first two types of models are described in more detail below.

3.1.1 Global Emissions Models

Two examples of global models were found. The simplest was developed by Richards (1989) and is based on using Gross Domestic Product (GDP).[1] Using estimates of annual refuse production and GDP for the U.S. and western Europe, Richards calculated that these two industrialized regions (which account for 65% of the world GDP) produce 492 million metric tons of refuse per year. Making some other gross assumptions about gas generated per ton of refuse and percent landfilled, he estimates that, globally, 39.2×10^9 m^3 landfill gas are produced each year. This number includes all landfill gases, so the amount of methane was extracted using an assumed CO_2/CH_4 ratio. Richards estimates that 9.8-18.3 million metric tons of methane are emitted from uncontrolled landfills globally.

[1] Gross Domestic Product is the Gross National Product excluding payments on foreign investments.

Another example of a method for estimating global landfill emissions is provided by Bingemer and Crutzen (1987). In this methodology, 80 percent of the degradable organic carbon (DOC) in landfill waste is assumed to be converted into landfill gas that is 50 percent methane by volume. The authors then used existing studies to develop estimates of annual refuse generation rates and waste composition for different countries. Data are not available for all countries, so estimates had to be made for the USSR and eastern Europe and for some developing countries. Based on these assumptions the authors estimate global landfill emissions of 30-70 million metric tons annually.

These two methods produce quite different estimates, reflecting the problem with an approach that uses such gross simplifications. Bingemer and Crutzen (1987) assume a rather high conversion rate (80%) which is not likely to apply to all climates and landfill types. They also assume a relatively high percentage of waste is landfilled (80% globally). In fact, the percentage of the waste deposited in sanitary landfills where anaerobic conditions are likely to occur may be much lower than 80 percent. In developed countries, alternative forms of waste management, such as incineration, recycling, and composting, are becoming increasingly important (Richards, 1989; Swartz, 1989). In the developing and undeveloped countries, very little waste is deposited in sanitary landfills. Most of it ends up in dumps (i.e., deposited on the surface) where aerobic conditions prevail (Bhide et al., 1990).

Although consideration of all these variables suggests that Bingemer and Crutzen's estimates are on the high side, Richards' estimates are based on a few broad assumptions and must be regarded as crude approximations. Both of these approaches have merit and the techniques used may be incorporated into more detailed models. However, at this time, both methods yield only rough approximations of present-day emissions; they have even less credibility for projecting emissions in the future.

3.1.2 Methane Gas Production Models

Methane emissions from individual landfills may be estimated using theoretical first-order kinetic models of methane production. Specific models are discussed and evaluated in Emcon (1982). These and other models were reviewed for EPA's Office of Air Quality Planning and Standards (OAQPS) by

Radian Corporation.[2,3] The Scholl Canyon model has been modified for use in estimating landfill VOC emissions in the United States.

The original form of the Scholl Canyon model is

$$Q_{CH_4} = L_0 R(e^{-kc} - e^{-kt})$$

where:

Q_{CH_4} = methane generation rate at time t, ft^3/yr

L_0 = potential methane generation capacity of the refuse, ft^3/Mg refuse

R = average annual refuse acceptance rate during active life of landfill, Mg/yr

k = methane generation rate constant, 1/yr

c = time since landfill closure, year (c=0 for an active landfill)

t = time since the initial refuse placement, year

For a given landfill, R, c, and t are usually available. Values for L_0 and k are not so easy to find, in part because they are defined ambiguously. The potential methane generation capacity of refuse, L_0, is generally treated as a function of the moisture content and organic content of the refuse. The rate constant, k, is a function of many factors, including moisture, pH, temperature, and other environmental factors, as well as landfill operating characteristics.

Unfortunately, no explicit functional relationships are available that can be used to estimate the kinetics of methane production. Both L_0 and k must be estimated; the OAQPS method is to use measured methane emissions from several landfills to calculate both k and L_0 for different climates within the United States. Another approach is to estimate L_0 for a given landfill from refuse composition; then, using measured methane generation rates, k can be calculated for that landfill.

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[2] Memorandum to S.A. Thorneloe, EPA, from Y.C. McGuinn, Radian Corporation. "Use of a Landfill Gas Generation Model to Estimate VOC Emissions from Landfills." June 21, 1988. II-B-14, U.S. EPA Standards of Performance for New Stationary Sources and Guidelines for Control of Existing Sources: Municipal Solid Waste Landfill Docket, Docket No. A-88-09.

[3] Memorandum to S.A. Thorneloe, EPA, from Y.C. McGuinn, Radian Corporation. "Sensitivity Analysis of Landfill Gas Generation Model." June 21, 1988. II-B-15, U.S. EPA Standards of Performance for New Stationary Sources and Guidelines for Control of Existing Sources: Municipal Solid Waste Landfill Docket, Docket No. A-88-09.

Similar models are described in Emcon Associates (1982). They will not be discussed here since the limitations of the Scholl Canyon model for global modeling apply to all of these kinetic models. A sensitivity analysis of the Scholl Canyon Model[4] found that emission rate was a direct linear function of L_0 and R, and a negative exponential function of k. The sensitivity of emission rate to k depends partly on the year (t) and partly on the magnitude of k. Furthermore, greater uncertainty is associated with k. In the U.S., k appears to be affected somewhat by climate in that estimated k values tended to be higher in states with higher precipitation. However, a wide range of k values were found within both "dry" and "wet" states.

These models would have to be modified for use on a global scale for many reasons. One problem is that the model requires information on landfill age and time since closure. It would be impossible to get this kind of information for every landfill within a country. An alternative would be to model the average landfill within each country and multiply model emissions by the number of landfills. However, this still requires fairly detailed country-specific data.

An even more important problem is that k must be estimated from empirical data on methane generation rates. While this is a reasonable approach for the United States, it is probably not feasible on a global scale because sufficient data on methane generation rates are not likely to be available to estimate k values for individual countries or regions. If functional relationships between k and the factors believed to affect k (e.g., moisture) were available, kinetic models such as these might have more potential. Even if these relationships could be determined, unless a rather large data set covering a wide range of refuse types (for estimating L_0) and moisture regimes (assumed to partially determine k) is available, this approach is unlikely to be any more reliable or accurate than the methods discussed in Section 3.1.1.

3.2 DATA NEEDS AND AVAILABILITY

Data necessary to develop global models for methane emissions from landfills include refuse generation, waste composition, landfill size, aerobic vs. anaerobic processes, age of refuse, pH, temperature, moisture content, and available nutrients. Researcher's opinions vary concerning which parameters are most important in determining methane emissions from the landfill. For example, while many studies conclude that a certain pH range combined with moisture and refuse content will result in maximum methane generation, one study found that lack of soil moisture actually increased methane generation from the landfill (Jones and Nedwell, 1990). Conclusive data concerning these parameters

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[4] See footnote 3.

are important in developing modeling approaches. Data may be collected by initiating sampling of landfills or bench scale research.

Availability of data concerning landfill methane emissions was assessed through database and library searches using keywords such as: landfill, municipal solid waste, biomass, alternative energy, methane, and anaerobic decomposition. Information was evaluated to establish relevance to this project. The results of these searches reveal that there is a great deal of information concerning waste composition and, to a lesser extent, waste generation rates. Information concerning factors that affect the generation of methane from landfills is generally not available, or, where available, is not conclusive.

Information concerning waste composition and generation as well as disposal methods was found for both developed and developing countries. Composting is becoming a popular program for reducing the amount of waste sent to landfills in some countries. Tables summarizing this information can be found in Appendices A and B.

3.2.1 Essential Data Requirements

In order to develop a modeling approach to estimate global landfill methane emissions, inputs for parameters affecting methane generation are necessary to develop estimates. The major data types required are discussed below. The first two, waste composition and refuse generation rate, affect potential methane production. The environmental variables affect the rate of production.

3.2.1.1 Waste Composition and Refuse Generation Rate--

Waste composition and refuse generation is a major determinant of both gas quality and rate of production. Both organic content of the waste as well as the size of the particles of waste influence gas generation quantity. Waste having a high percentage of biodegradable organic material (food and garden waste, paper, wood) and small particle size (25-250 mm) has been found to increase gas production from landfills, although other factors, such as the pH, affect the concentration of methane as opposed to carbon dioxide (Senior, 1990).

Refuse generation rates affect the amount of waste being delivered to a landfill and therefore the amount of waste available for decomposition. Waste decays at different rates. According to one source (Rovers et al., 1977), food and garden waste decompose within 1-5 years, paper breaks down in 5-20 years, and wood may take 20-100 years to decay. Refuse generation rates in past years will affect the amount of material degrading in the landfill at any given time. Refuse generation rates can also be used to estimate the amount of biodegradable carbon in a landfill given annual generation rate, composition of waste, and size of the landfill.

Industrialized countries tend to have high generation rates, with paper and cardboard as the most significant contributors to degradable carbon. Waste in developing countries, by contrast is generally comprised of vegetable and garden refuse, but the total volume of waste generated is lower. Some data on waste generation rates in different countries are also available (e.g., World Resources Institute, 1988). See Appendix A for a summary of refuse composition in developed and developing countries.

3.2.1.2 Environmental Variables--

Several environmental parameters influence methane production from landfills: pH, moisture content, refuse generation, waste composition, temperature, aerobic vs. anaerobic processes, landfill size and type. Data are needed to quantify relationships between these variables and how they affect the methane generation rate. Much of the recent research on landfills has focused on optimizing methane production for collection and utilization as an energy source.

Moisture--In landfills, moisture determines the mixing, dilution, and flushing of refuse components and nutrients. Moisture has been found to increase methane production in landfills; however, in some instances, decreased moisture values have increased methane production, possibly because it decreases the activity of methanotrophic soil microorganisms which consume methane (Jones and Nedwell, 1990).

It is generally accepted that controlling water conditions can increase methane generation rates; however, introducing controls may also introduce problems (Senior, 1990). Presence of high water content should enhance availability of nutrients and, therefore, stimulate bacterial growth. However, there is a distinction between moisture volume and infiltration. One study performed with three cells filled with different amount of refuse found that rapid infiltration could impede methane generation (Rovers and Farquhar, 1973). Another study (Klink and Ham, 1982) found that methane production could increase 25-50 percent with infiltration even when total moisture content of the refuse remained constant. This increased production rate of methane may be due to an increase in uniform distribution of nutrients and pH (Klink and Ham, 1982).

No definitive answer has been found concerning the necessary moisture content for maximum methane generation. Laboratory studies (deWalle et al., 1978) have found that maximum rates result from water-saturated refuse; while other studies found that moisture contents of 60-80 percent produce maximum methane generation (Farquhar and Rovers, 1973). Researchers hypothesize that large water additions may introduce oxygen which delays the initiation of methanogenesis, and in some instances, may introduce acidogenesis which retards methane production. Conversely, the ratio between methane and carbon dioxide may increase in favor of methane production, in the presence of elevated moisture contents (Senior, 1990).

In a study conducted by EPA's Office of Solid Waste (OSW), landfill gas generation rates between 0.34 and 15.28 cubic meters of landfill gas per cubic year of refuse per year are reported. These data are provided in Table 1 (SCS Engineers, 1986). Assuming a refuse density of 593.24 kilograms per cubic meter, this corresponds to a landfill gas generation rate of 0.75 to 34 liters of landfill gas per kilogram of refuse annually. One important finding of this study was the correlation between landfill gas generation rate and moisture content. Based on these data obtained from 12 landfills in "wet" States and 8 landfills in Southern California, emissions from "wet" landfills are approximately 2.6 times greater for the "wet" States as for the "dry" ones. The field data supporting this factor is presented in Table 2. The factor of 2.6 is obtained when the mean or median value (7.78 or 7.67) of wet region gas generation rate is divided by the dry region gas generation rate (3.04 or 3.00). The "wet" States are defined as the States with annual precipitation of 23 inches (58.4 centimeters) of annual precipitation. All States except the following receive greater than 23 inches of precipitation annually: Arizona, California, Colorado, Hawaii, Idaho, Montana, Nevada, New Mexico, North Dakota, South Dakota, Utah, and Wyoming.

Temperature--An optimum temperature range exists in which the methanogenic bacteria function best. It is the temperature of the anaerobic zone that regulates the optimum methane production. Research has found that at 35° C almost 80 percent of the degradable organic carbon (DOC) may be dissimilated. It is assumed that 80 percent of the DOC is converted into biogas containing 50 percent by volume of methane (Bingemer and Crutzen, 1987). Verstraete et al. (1984) obtained a 70 percent increase in gas production with a temperature elevation from 22 to 33° C.

Temperature in the landfill is determined by microbial metabolism, dry density of refuse, specific surface area, refuse composition, and water content. Landfill temperature changes in response to air temperature changes have been reported (Rovers and Farquhar, 1972). For example, a landfill in Canada exhibited seasonal temperature fluctuations between 2 and 21° C at a depth of 1.22 m.

Temperature can also affect gas composition. Temperature increases can affect the fermentation balance, resulting in increased acid generation while inhibiting methanogenesis (Kasali, 1986).

TABLE 1. LANDFILL GAS GENERATION RATES AND REFUSE MOISTURE CONTENT

Landfill Location	Gas Generation Rate (m^3/m^3-yr)[a]	Refuse Moisture Content (wt %)	Methane Content (vol %)
WET REGIONS			
Michigan	2.67	33	52
Maryland	3.41	34	49
Wisconsin	5.33	50	52
New York State	7.04	53	57
Washington, DC Area	7.18	-	47
Maryland	7.37	-	56
Florida	8.15	29	55
Ohio	8.29	33	53
Florida	9.26	24	50
New York State	9.26	30	51
Ohio	9.59	37	55
Florida	20.00	42	58
DRY REGIONS			
Southern California	0.44	17	56
Southern California	1.78	12	52
Southern California	2.22	18	55
Southern California	2.30	16	50
Southern California	3.67	27	54
Southern California	3.92	18	56
Southern California	4.67	22	54
Southern California	5.30	22	51

[a]Cubic meters of landfill gas/cubic meters of refuse per year.

TABLE 2. EFFECT OF MOISTURE CONTENT ON LANDFILL GAS GENERATION RATE

Landfill Location	Gas Generation Rate (m^3/m^3-yr)[a]	Refuse Moisture Content (wt %)	Methane Content (vol %)
WET REGIONS			
Michigan	2.67	33	52
Maryland	3.41	34	49
Wisconsin	5.33	50	52
New York State	7.04	53	57
Washington, DC Area	7.18	–	47
Maryland	7.37	–	56
Florida	8.15	29	55
Ohio	8.29	33	53
Florida	9.26	24	50
New York State	9.26	30	51
Ohio	9.59	37	55
Florida	20.00	42	58
Mean	7.78	37	53
Median	7.76	34	53
Standard Deviation	4.52	9	3
DRY REGIONS			
Southern California	0.44	17	56
Southern California	1.78	12	52
Southern California	2.22	18	55
Southern California	2.30	16	50
Southern California	3.67	27	54
Southern California	3.92	18	56
Southern California	4.67	22	54
Southern California	5.30	22	51
Mean	3.04	19	54
Median	3.00	18	54
Standard Deviation	1.63	5	2

[a] Cubic meters of landfill gas/cubic meters of refuse per year.

pH–The pH value in a landfill can vary at different depths and cells of the landfill. Ranges of pH have been reported as 4.4-6.9 (Bookter and Ham, 1982); however, the optimum for methanogenesis seems to be around 7.0 (Emcon Associates, 1982). Low pH values and high concentrations of carboxylic acids can inhibit methanogenesis. While the methanogenic bacteria necessary for production of methane are most active at certain pH values, this is a parameter that would be difficult to measure in the field as it is highly variable in space and time.

Aerobic vs. Anaerobic Conditions–During aerobic processes in the landfill, bacteria decompose refuse by consuming oxygen, while producing carbon dioxide and water. Anaerobic processes result in the production of methane. The aerobic decomposition of waste generally lasts only a few weeks while the anaerobic process can continue for 10-30 years after the filling has been completed (Bogardus, 1987). Some methane produced through anaerobic processes in the landfill may be oxidized by methylotrophic bacteria present in the top cover of the landfill (Jones and Nedwell, 1990).

Waste disposal practices dictate the presence of aerobic vs. anaerobic processes. Landfilling wastes encourages the presence of anaerobic processes while composting and surface disposal, prevalent in developing countries, result in aerobic processes of decomposition.

Size and Type of Landfill–Landfills may include municipal solid waste, industrial waste, hazardous waste, or in some cases, a combination of refuse. Because it is important to have waste with a high percentage of organic material for methane production, municipal solid waste landfills are the obvious source of methane emissions. Hazardous and industrial waste landfills may contain compounds that will result in a low pH atmosphere toxic to the methanogenic bacteria.

Larger landfills will generally provide greater mass of organic material. However, no information was found to describe the functional relationship between landfill size and methane production. The depth and surface area are probably more important factors to consider than size alone. For example, a large shallow landfill is likely to produce more CO_2 than a deep landfill of comparable size because of its greater surface area.

4.0 DEVELOPMENT OF A GLOBAL LANDFILLS MODEL

Ideally, the global landfill methane emissions model used by AEERL should meet two criteria. The first is that it provides reliable country- or region-specific estimates of methane currently produced by landfills. The second is that it be capable of projecting emissions into the future. The reliability of these projections will depend on the ease with which the model's parameters can be changed to reflect various world scenarios; for example, country-specific trends in waste management could affect the amount of waste landfilled as opposed to incinerated or composted. Increasing affluence of developing countries may increase the amount of waste generated annually. Finally, changes in the earth's climate–particularly in precipitation–could affect the rate of methane production.

4.1 CONCEPTUAL SCHEME FOR A GLOBAL LANDFILLS METHANE EMISSIONS MODEL

Based on the review of the currently available models, the needs of AEERL and other model users, and the current state of understanding of methane production, a general scheme for a global landfills model can be described. This scheme is presented solely for the purpose of synthesizing the current state of the science. It provides a framework for discussion, and helps identify both data needs and potential modeling methodology requirements. The actual form of the model that is developed may be quite different.

Figure 1 shows a flow diagram of the conceptual model. Three modules are delineated that reflect the two major steps required to generate annual methane emissions per country plus a third step that allocates those emissions to a global output format. A brief summary of each step is:

(1) Determine the methane potential of landfill waste, taking into account refuse composition, level of development of the country, and other pertinent factors;

(2) Calculate methane generation rate on an annual basis, taking into account the factors that affect the rate of production, annual waste generation rate, and methane potential of the waste; and

(3) Allocate methane emissions to a spatial grid for input into other models and data bases (such as atmospheric models or mapping programs).

Note that only steps 1 and 2 are required to get country-specific and total global methane emissions. The third step is necessary only if the data are to be useful to atmospheric modelers or if a spatial data base is used for the inventory. These steps are discussed in more detail below.

4.1.1 Calculating Methane Potential

The organic content of the waste primarily determines the landfill gas potential of the waste. However, the relative amount of methane in that gas is determined by the disposal method. If wastes are incinerated or composted, only CO_2 will be produced. Wastes that are "dumped" (i.e., surface disposal in relatively shallow heaps) will decompose primarily under aerobic conditions, producing CO_2. In addition, these trash heaps are open to scavenging animals that will remove a good portion of the

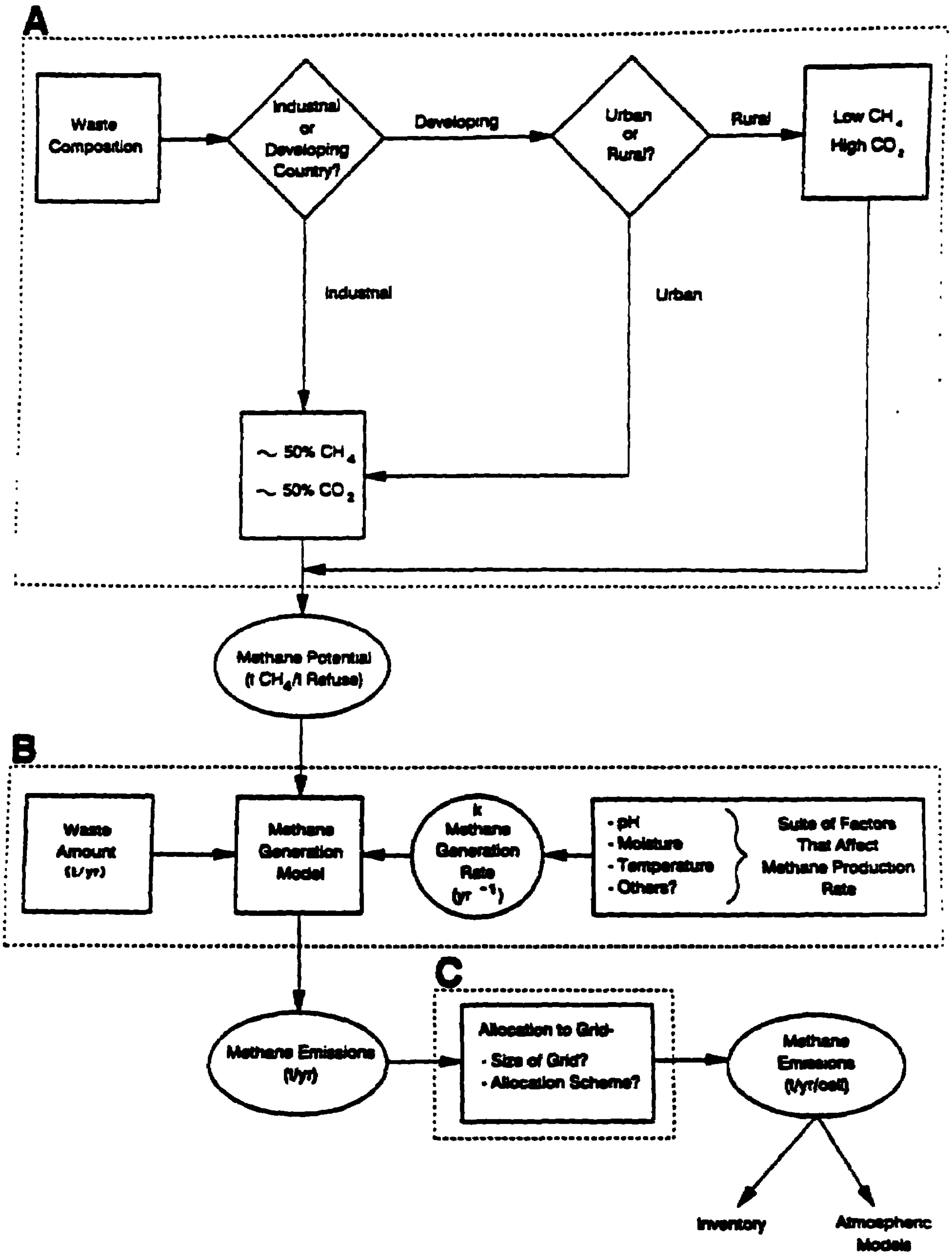

Figure 1. Conceptual Scheme for a Global Landfills Methane Model.

biodegradable wastes. Only wastes that are deposited in sanitary landfills (i.e., excavated pits that are filled and covered with some sort of cap) are likely to produce significant amounts of methane.

In industrial countries, it is probably safe to assume that landfill wastes are going to sanitary landfills where anaerobic conditions prevail. The relative percentage of potential methane will depend on the organic content of the refuse, and the amount of waste that is anaerobically gasified.

Various methods have been proposed for estimating methane potential. Theoretical estimates range from 47 to 270 L CH_4/kg wet composite refuse, although 31-94 L CH_4/kg wet composite refuse is thought to be a more realistic range for most sanitary landfills (Emcon Associates, 1982). Relative amounts of landfill gas constituents are generally predicted to be 54 percent methane and 46 percent carbon dioxide. In fact, landfill gas is typically 50-70 percent methane and 30-50 percent carbon dioxide with traces of other gases (Emcon Associates, 1982).

Module A of Figure 1 diagrams a series of categorizations the model would have to make to determine methane potential of the waste for a given country. The fraction of biodegradable material must be supplied as input data. The percentage of material that will be converted to CH_4 is determined by a set of criteria. If the country is an industrialized one, then waste that is not incinerated, composted, or recycled is assumed to go to sanitary landfills. In this case, the relative methane content of the landfill gas is likely to be around 50 percent. If the country is not a developed one, then sanitary landfills are likely to be found only in large cities. In the rural areas, open dumping is likely to occur. Moreover, refuse composition may vary between rural and urban areas; in India, the organic content of refuse in rural areas is lower than in large urban areas (Bhide et al., 1990). Therefore, for these countries, two estimates of methane potential may be needed: one estimate for urban wastes and one for rural wastes.

4.1.2 Calculating Annual Methane Emissions

Module B requires the following country-specific input data: average amount of waste landfilled each year, the methane potential of that refuse (generated by Module A), and the methane generation rate, k. The exact form of the methane generation algorithm is not specified. It could resemble one of the methods described in Section 3.1, or it could be entirely different. A hybrid approach that uses elements of Bingemer and Crutzen's methodology and of the kinetics model would be to model annual methane production within a country as though it were all being generated by one landfill. Waste generated each year can vary as can k, the rate of methane production.

This approach does not require variables such as the age of the landfill. For estimating emissions from an individual site, the age is very important. However, for global emissions calculations, this information is probably not important. A global model deals with a population of landfills; therefore, for estimating current emissions, the population average is sufficient. If a steady-state can be assumed, then using current average waste production to calculate current emissions should give a reasonable estimate (even though today's emissions probably come from waste deposited years ago). However, if the number of new landfills is increasing at a rapid rate, then the average age of the landfills is decreasing. Since landfill emissions tend to lag behind actual deposition of the waste, younger landfills produce gas at a slower rate than older ones.

In fact, landfilling is likely to decline in developed countries as space becomes limiting and incineration becomes more popular. On the other hand, sanitary landfills may become more common in developing countries, especially around cities. These two trends may cancel each other out. This issue needs to be recognized, but is probably not the most important issue in the short-term (i.e., the next 20-30 years). It is more important for doing projections into the future, and can probably be dealt with in the model by use of a lag time. Other variables, such as refuse acceptance rate and time since closure, are easily dealt with at this scale. Refuse acceptance rate is simply all of the waste sent to landfills each year. That amount can be allowed to change by modeling it as a function of population or economic growth. Time since closure is no longer relevant, unless changes in waste management practices are foreseen such that all landfills within a country are to be closed.

One critical piece of information is still needed: the functional relationship between k and the suite of factors that determine k. As was stated previously, a variety of factors such as moisture affect k, but the functional relationships are unknown. Globally, landfills may be found in a wide range of climates. Since both moisture and, to a lesser extent temperature, are known to affect methane production rates, developing a better understanding of the functional relationship between k and these two variables will increase the reliability of methane emissions estimates in several ways. First, for modeling current emissions, geographic variability in emissions will be more accurate. It may even be possible to increase the temporal resolution to a seasonal scale for those countries with pronounced wet and dry seasons. Second, the model can be used to do projections into the future for alternative climate scenarios. The possibility of feedback effects where climate changes accelerate the release of RITGs is one that concerns scientists and policymakers. To the extent that landfill methane production is affected by climate, feedback effects are potentially important.

Unfortunately, as was discussed in Section 3.2.1.2, insufficient data are available to develop the needed functional relationships. An intensive research effort is needed to gather data that can be used to develop this component of the model. Section 4.2.3 discusses the proposed research in more detail.

4.1.3 Allocation to a Grid

The results of the emissions model will be needed as input to other models, particularly atmospheric models. These models are typically spatial with resolutions from 1° x 1° up to 10° x 10°. In order to be compatible with these models, the methane emissions model will need to convert the country-specific emissions output to emissions per grid cell. This poses several problems: how will emissions be allocated to the spatial grid, how small will the grid cells need to be, and what effect will choice of grid cell size have on the validity of the allocation scheme?

At this time, the desired grid cell size is unknown. In fact, it is likely that methane emission model estimates will be needed for input into several different models with different resolutions. Most general circulation models (GCMs) are relatively coarse with resolutions of 10° x 10° or 5° x 5°. Regional models may require data at a finer resolution, such as 1° x 1°. Clearly, developing an allocation scheme for a 1° x 1° grid will be extremely labor intensive, and should not be done unless really needed. On the other hand, if a 10° x 10° grid is used initially, is there some way to design an allocation scheme that can be adapted to a finer resolution if the need should arise in the future? In other words, can a flexible allocation scheme be devised that allows for different grid resolutions, but is also not too costly to develop?

If the exact location of every landfill in the world were known, then an allocation scheme would not be needed. However, the acquisition of information this detailed is not feasible. Several possible schemes can be envisioned. The simplest would be to allocate emissions uniformly within a country; the relative area of the country included within a particular cell would be used to weight the emissions from that country assigned to that cell. For example, if 25 percent of a country is located within a given grid cell, then 25 percent of that country's emissions are allocated to that cell.

Another approach is to use population centroids. The problem with this approach is that the number of centroids used is often dependent on the grid cell size. This method was used in a global VOC inventory[5] which allocated VOC emissions to a 10° x 10° grid. Population centroids were developed for each cell, but the number of centroids varied. Every cell had at least one centroid unless there were obviously no emission sources within the cell (e.g., a cell that had only open ocean). Over populated areas, the number of centroids depended less on the size of the population than on its distribution geographically. For example, a cell with a large population that was concentrated in one corner of the grid would have fewer centroids than one with a smaller but more evenly dispersed population.

Many other possible schemes exist. The problem for this particular model is in trying to identify a scheme that will be flexible but also not too costly to implement.

4.2 FILLING THE GAPS

The review of models and data in Section 3.0 and the discussion of a conceptual model above have identified strengths and weaknesses of currently available models and data. The remainder of this report addresses remedies for three of the issues identified:

(1) the use of economic indicators to predict refuse generation rates (as in Richards' model);

(2) the relative merits of emission allocation schemes as a function of grid cell size; and

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[5]Details on the development of this inventory will be available in a forthcoming EPA report.

(3) the acquisition of data that will allow development of a predictive methane production model.

Each of these are addressed in more detail below.

Some other areas not considered in more detail at this time are still important. Refuse composition by country is an important input variable, but one for which considerable data exist (see Appendix A). Although data are not available for many countries, reasonable extrapolations from existing data can be made. Another issue is that of determining the proportions of waste going to different types of treatments. Although some data have been found (Appendix B), it covers a small number of countries. Little is know about developing countries in particular. Furthermore, future trends in waste management will make current data obsolete. Since the development data for individual countries is beyond the scope of this program, currently available sources will have to be relied on. For most countries, the percent of waste landfilled will have to be estimated based on information for similar countries.

4.2.1 Predicting Waste Generation Rates from GNP

Richards' (1989) used gross domestic product (GDP) to predict waste generation rates in his global estimation of landfill gas production. The basic concept is that increasing affluence will be accompanied by increasing waste production. Since economic indicators such as gross national product (GNP) are widely available for most countries, this could provide a readily available surrogate for waste generation rates.

To test this idea, a small sample (12) of countries representing a broad range of economic levels was selected from a data set of waste generation rates (World Resources Institute, 1988). GNPs for those countries were also given in the same source. The data are shown in Table 3; waste generation rates and GNPs are not necessarily from the same years, but all are from the time period between 1980 and 1986.

A linear regression was used to test the relationship between waste per year and GNP. The regression was significant with $R^2 = 0.97$. The regression model is,

$$\text{WASTE(1000 Mg/yr)} = 0.0399 \cdot \text{GNP (million US \$)}. \quad (1)$$

This looks like an excellent model even with such a small sample size. As a further test, the GNP of India was used to estimate that country's annual waste generation; this was converted to a per capita

TABLE 3. DATA USED FOR REGRESSION OF WASTE GENERATION RATE ON GNP

Country	GNP (million US $)	Waste Generation Rate (1000 Mg/yr)
Canada	361,720	16,000
Costa Rica	3,790	534
Federal Republic of Germany	735,940	27,544
France	595,180	14,000
Ireland	18,190	1,270
Israel	26,730	1,400
Japan	1,559,720	41,095
Korea	98,370	15,746
Singapore	19,160	1,498
Spain	188,030	10,600
United Kingdom	504,850	16,398
United States	4,221,750	178,000

per day basis and compared to an independent estimate.[6] The model prediction fell in the middle of the range of the other estimate (0.2 to 0.5 kg/capita/day).

However, both the U.S. GNP and waste generation rate are so much higher than the second largest (Japan) that this data point appears to exert undue influence on the model. The regression was rerun without the U.S. data. Although the regression was still significant, the R^2 dropped to 0.86. The regression model without the U.S. data is

$$\text{WASTE}(1000/\text{Mg/yr}) = 3902 + 0.0251 \cdot \text{GNP (million US \$)}. \qquad (2)$$

The intercept term in this model was not significant although it was very close (0.06). Again, the model's prediction for India fell within the range of the independent estimate.

This approach appears to be very promising but further research is needed. The best strategy may be a mixed one, using different equations for different countries. The next phase of analysis should include:

(1) Increased sample size (more data observations are available);

(2) Separate analyses for different regions (e.g., continents); and

(3) Separate analyses for industrialized versus developing countries.

Other economic indicators should be considered, such as per capita income. However, these indicators need to be readily available for a large number of countries if this method is to be useful.

4.2.2 Allocation of Emissions to a Grid

A sensitivity analysis of three allocation schemes was conducted to test the relative performance of each scheme using a range of grid sizes: 1° x 1°, 5° x 5°, and 10° x 10°. The allocation schemes range from the very simple to the very detailed.

The simplest scheme, "Uniform," assumes emissions are uniformly distributed throughout a country. Within a grid cell, emissions are calculated by determining what proportion of the country is included in that cell, multiplying that proportion by total emissions for the country, and summing for all countries within the cell.

The "Population Centroid" scheme uses an existing data base that was developed for EPA's Global VOC Inventory. The population within a country is subdivided into several groups based on the

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[6] Personal communication from A.D. Bhide, National Environmental Engineering Research Institute, Nagpur-20, India, to D.L. Campbell, Radian Corporation. April 13, 1990.

The advantage of using the existing centroid data base is that it could be implemented at very little cost, since the bulk of the development work has been done. The population data needs to be updated, but this will not require a great deal of effort. One potential problem with this scheme is that it was developed for a 10° x 10° grid. The analysis performed in this study evaluates the performance of the data set for finer resolutions.

The third scheme, "Urban/Rural," is a composite of the first two. The population within a country is divided into two groups. The urban population is the proportion of people residing in cities of 200,000 or more. The rest of the population is considered rural. Each city of 200,000 or more is treated as a population centroid. The populations of the centroids were summed and the total was subtracted from the country's total population. The remaining population was assumed to be uniformly distributed throughout the country.

The Urban/Rural scheme was considered to be the most accurate of the three schemes used in this analysis. Its outputs are used to evaluate the relative accuracy of the other two schemes. The relative merits of all three schemes with respect to ease of implementation, flexibility, and performance with differing resolutions were analyzed qualitatively.

Two 10° x 10° grid cells were chosen for analysis. The India cell lies between 70° and 80° E longitude and 20° and 30° N latitude. Part of Pakistan is also included in the cell. This cell was chosen because it represents two cell "types": it is simple (only two countries included), and it includes only developing nations. The second cell was chosen to represent the other extremes: it includes eight countries, all of them industrialized. This European cell is bounded by 0° to 10° E longitude and 40° to 50° N latitude. Characteristics of each cell are summarized in Tables 4 and 5. Each cell was subdivided into four 5° x 5° grids; one of these cells was further subdivided into 1° x 1° grids. Figure 2 shows the lettering and numbering conventions used to identify each cell.

For the India cell, a waste generation rate of 0.125 Mg waste/yr/capita was used for India, and 0.017 for Pakistan. These waste generation rates were estimated using GNP values from World Resources Institute (1988) in the equation given in Section 4.2.1. Methane was assumed to be produced at the rate of 30 m^3 CH_4/Mg waste. A second analysis for the Urban/Rural scheme only was run using 30 m^3 CH_4/Mg waste for urban populations and 10 m^3 CH_4/Mg waste for rural populations (designated by (b) in Table 6). This is done to reflect the fact that sanitary landfills are relatively rare in developing countries, and are only found in large urban areas. The methane potential used for rural area was chosen arbitrarily as no estimates were found in the literature. The results of each allocation scheme for 10° x 10° and 5° x 5° grids are shown in Table 6; results for two sets of the 1° x 1° grids are shown in Figures 3 and 4.

In the European cell, the proportion of waste landfilled in each country was included in the analysis. Table 7 shows the waste generation rates and proportion landfilled for each country. A methane generation rate of 30 m^3 CH_4/Mg waste was used for all countries. The results for 10° x 10°

TABLE 4. CHARACTERISTICS OF THE INDIAN CELL

Country	Total Population	Proportion of Country in 10° x 10° cell
India	683,810,051	0.33
Pakistan	83,782,000	0.10

TABLE 5. CHARACTERISTICS OF THE EUROPEAN CELL

Country	Total Population	Proportion of Country in 10° x 10° cell
Austria	7,507,000	0.02
Belgium	9,855,110	0.14
Federal Republic of Germany	61,658,000	0.25
France and Corsica	54,077,842	0.80
Italy and Sardinia	58,613,800	0.25
Luxembourg	364,000	1.00
Spain	37,430,000	0.06
Switzerland and Liechtenstein	6,391,180	1.00

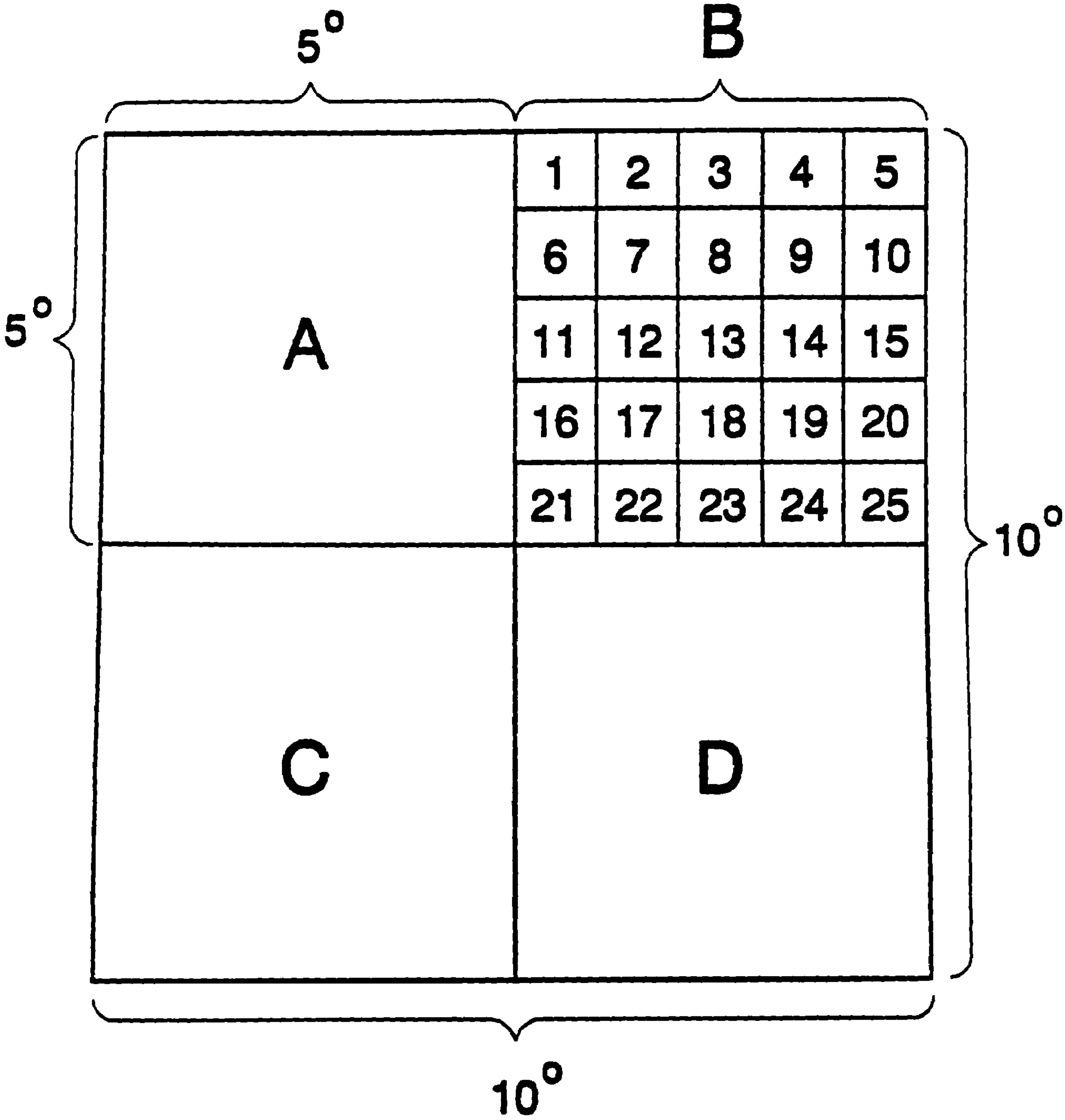

Figure 2. Lettering and Numbering Conventions for Grid Cells.

TABLE 6. RESULTS OF ALLOCATION ANALYSIS FOR INDIAN CELL

Allocation Scheme	Emissions from 10° x 10° cell (10^3 m^3 CH_4/yr)		Emissions from 5° x 5° cell (10^3 m^3 CH_4/yr)	Percent of 10° x 10°
Uniform	850,488			
		A	192,210	22.6
		B	234,735	27.6
		C	188,808	22.2
		D	234,735	27.6
Centroid	621,838			
		A	6,409	1.0
		B	384,643	61.9
		C	230,786	37.1
		D	0	0
Urban/Rural (a)	710,460			
		A	90,538	12.7
		B	282,639	39.8
		C	158,651	22.3
		D	178,633	25.1
Urban/Rural (b)	296,004			
		A	32,624	11.0
		B	125,084	42.3
		C	67,844	22.9
		D	70,452	23.8

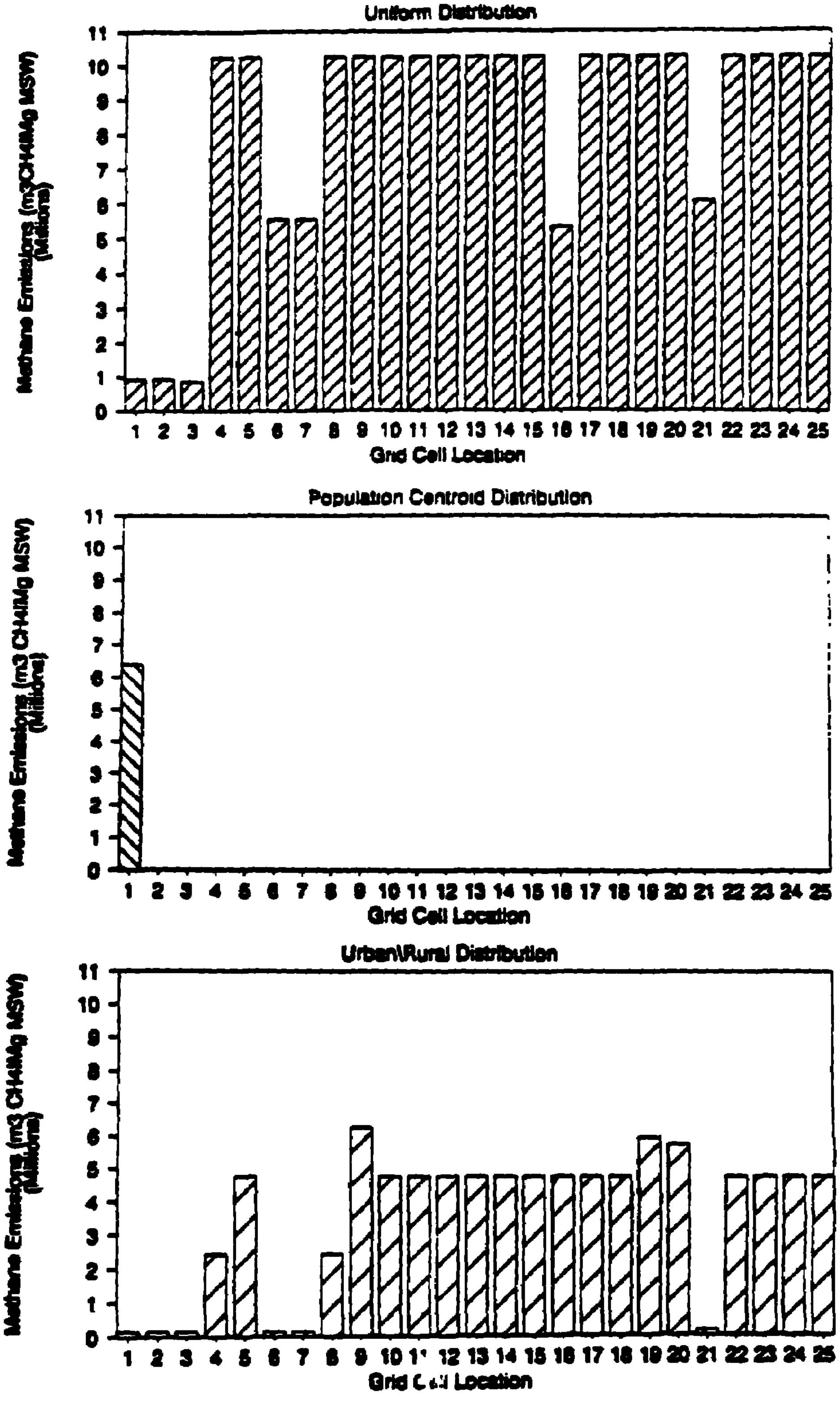

Figure 3. Indian Cell Landfill Methane Emission, Quadrant A, 1° x 1°.

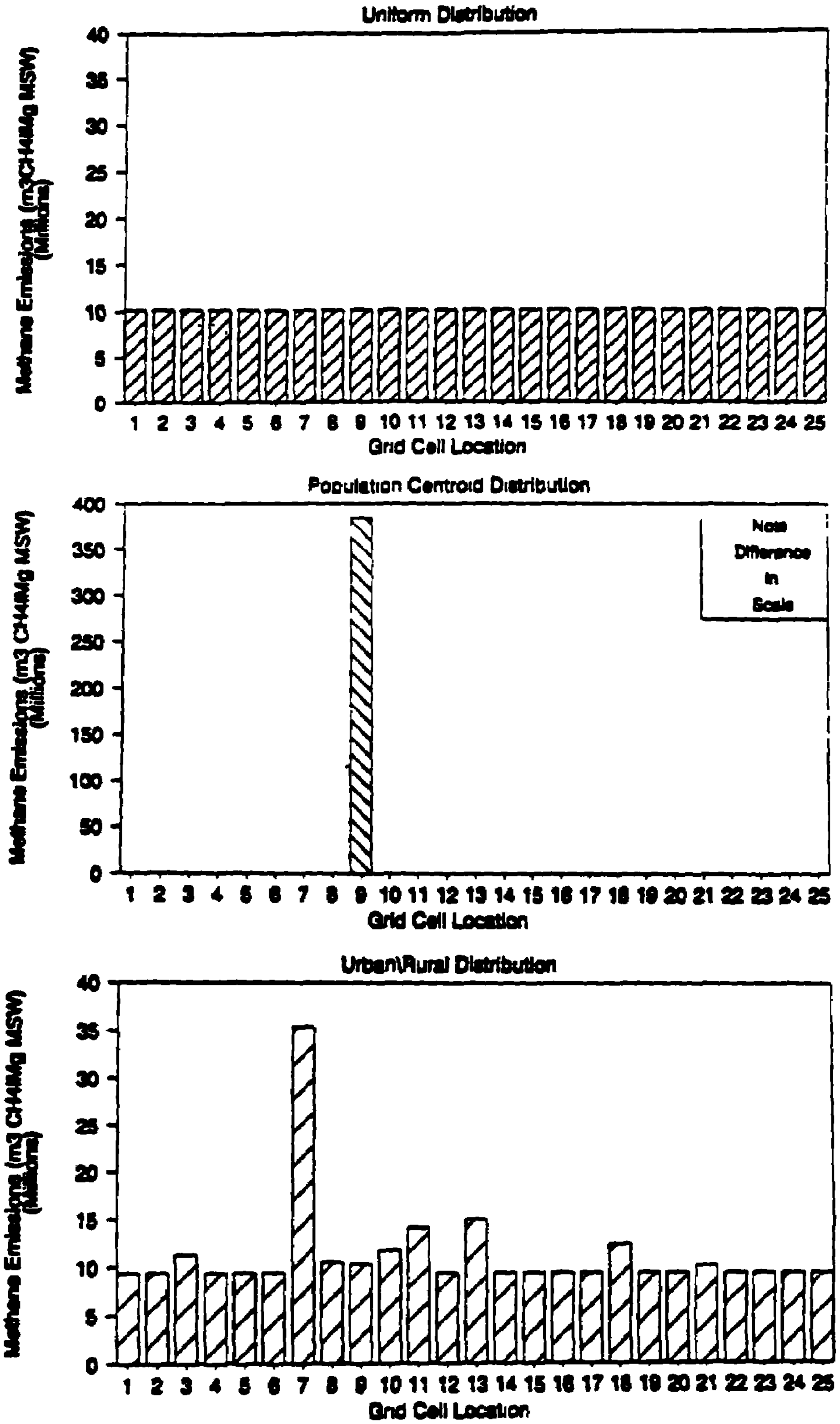

Figure 4. Indian Cell Landfill Methane Emission, Quadrant B, 1° x 1°.

TABLE 7. INPUT DATA FOR EUROPEAN CELL

Country	Waste Generation Rate (Mg waste/yr/capita)	Proportion Waste Landfilled[a]
Austria	0.21	0.70
Belgium	0.31	0.45
France	0.26	0.35
Italy	0.25	0.85
Luxembourg	0.52	0.90
Spain	0.28	0.70
Switzerland	0.34	0.90
W. Germany	0.45	0.70

[a]Derived from Richards (1989). When specific data not available, proportion was estimated.

and 5° x 5° grids are shown in Table 8; the results for two sets of the 1° x 1° grid are shown in Figures 5 and 6.

The results for the 10° x 10° cell show that, if the Urban/Rural method is closest to the true emissions, then the Population Centroid method is the second best. Although it underestimates emissions in both cells somewhat, the Uniform method overestimates it; furthermore, the magnitude of the error is greater for the Uniform method. However, the three methods produce much more similar estimates for "Europe" cell than for "India" cell. This is partly due to the fact that the Europe cell encloses all or large parts of several densely settled countries. Since these countries are small relative to the grid, they become, in effect, centroids. Therefore, less difference between the Uniform and Population Centroid methods occurs in this cell than in one like India that encompasses part of a large country. Finally, the Urban/Rural (b) method shows that total estimated emissions are significantly reduced if a distinction between urban and rural methane generation rates is made. Although these results show higher emissions for India than for Europe, the methane generation rate used is probably much too low. A rate four times as high is more likely (Orlich, 1990), making Europe's emissions more than double India's. However, these numbers are for model comparisons only and should not be treated as true predictions.

When a 5° x 5° grid is used, considerable disparity can be seen between the three methods, particularly for India. The Population Centroid method in India produces a very skewed distribution of emissions in comparison to the Urban/Rural method. For both Europe and India, the Uniform method comes closes to matching the Urban/Rural method. .This is partly due to the "small country" effect described above. However, it is also due to the fact that this particular Population Centroid scheme was designed for a 10° x 10° grid. The formation of centroids is based partly on subjective decisions which are determined in part by scale considerations. Therefore, it is not surprising that centroids developed at the 10° x 10° scale should be too coarse for finer resolutions.

At the 1° x 1° level, these disparities are even more apparent. The Population Centroid method is clearly inappropriate at this scale since the relatively few centroids available leave most of the cells blank. The Uniform method performs somewhat better in that some emissions are allocated to each cell that is supposed to have emissions. However, the pattern of emissions from the 1° x 1° cells does not match the Urban/Rural emissions pattern very well.

Based on these results, if it is known that a 10° x 10° grid is all that is required, using the existing Population Centroid methodology is reasonably accurate and very cost-effective. If maximum flexibility is desirable or, if a 1° x 1° grid cell is required, then some new methodology is required. The Urban/Rural scheme here could be simplified by using larger metropolitan areas as centroids. A similar approach would be to develop new population centroids, but more of them, and to allocate rural emissions uniformly.

TABLE 8. RESULTS OF ALLOCATION ANALYSIS FOR EUROPEAN CELL

Allocation Scheme	Emissions from 10° x 10° Cell (10^3 m^3 CH_4/yr)		Emissions from 5° x 5° Cell (10^3 m^3 CH_4/yr)	Percent of 10° x 10°
Uniform	438,520			
		A	59,881	13.7
		B	293,601	67.0
		C	42,557	9.7
		D	42,482	9.7
Centroid	410,475			
		A	51,394	12.5
		B	302,350	73.7
		C	20,020	4.9
		D	36,710	8.9
Urban/Rural	413,835			
		A	60,239	14.6
		B	258,769	62.5
		C	47,484	11.5
		D	47,343	11.4

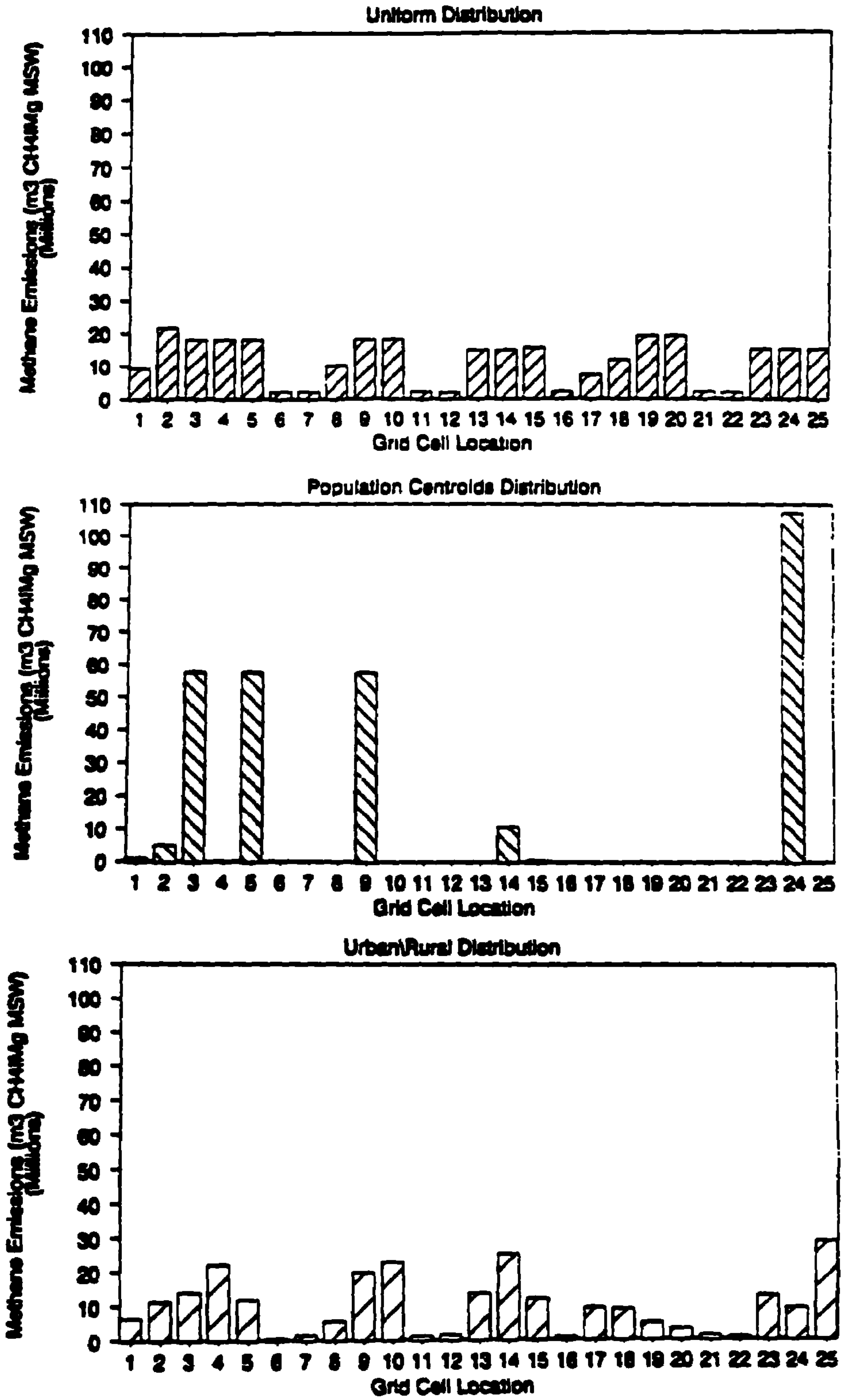

Figure 5. European Cell Landfill Methane Emission, Quadrant B, 1° x 1°.

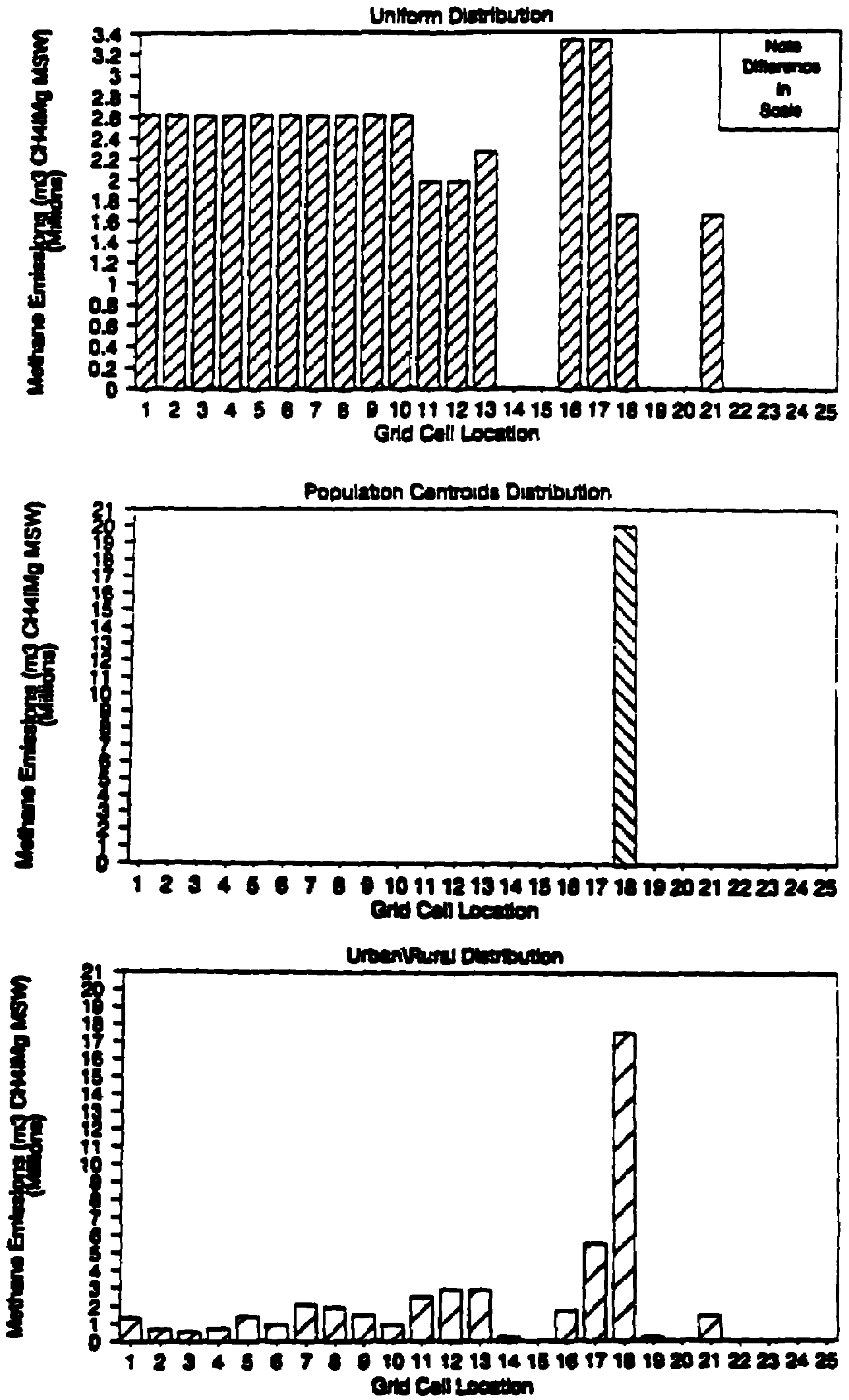

Figure 6. European Cell Landfill Methane Emission, Quadrant C, 1° x 1°.

4.2.3 Landfills Sampling Program

The greatest gap identified is the lack of sufficient quantitative data to develop a reliable model of methane production. A large number of laboratory studies have been conducted on the microbiological processes that occur in landfills, but the results are difficult to extrapolate to the field (Senior, 1990). It is also not clear that the theoretical models, which are based on microbial population kinetics models, are useful for projections at the global scale.

A new approach is needed for the development of a global model. The following pieces of information are known:

(1) landfill emissions vary widely;

(2) methane emissions seem to be higher in wetter climates within the temperate zone;

(3) in the temperate zone, air temperature probably does not affect methanogenesis, but in extreme climates, it may;

(4) the greater the organic content and moisture content of the waste, the greater the methane potential; and

(5) site and operating characteristics, such as age and depth of landfill, and size of cells, may affect methane emissions in some way; but, the relative importance or even direction of the effects are not known.

AEERL is planning a testing program that will begin to try to define some of these relationships in a functional way. Although the scope of the program may eventually become global, in the near future, a pilot study within the U.S. is planned. The focus of this study will be to determine whether some readily available data are sufficient to develop a predictive model. It is desirable that elaborate models requiring very detailed data be avoided due to the expense.

The approach to be used in the pilot study is to select only landfills where methane is already being recovered. Methane content and flow rate will be sampled, analyzed, and the results will be compared to measurements made by continuous monitors at each site. This will allow standardization of data sets from different sites. Physical characteristics, operating conditions, refuse composition, refuse acceptance rate, age of landfill, and other pertinent information will be collected by interviewing landfill operators.

Climate data from the National Climatic Data Center will be obtained and used with the monitoring data to determine if any relationship between climate and methane emissions can be found. This weather data is collected at airports in major cities; the landfills to be tested will be chosen from those located near a source of weather data. Sites will also be selected so that a range of climates are represented; for example, sites from the southwest, the southeast, and the northeast might be chosen to represent temperature and precipitation extremes within the contiguous United States.

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APPENDIX A

WASTE COMPOSITION DATA

The following tables were compiled from a variety of sources that are referenced in the footnotes. Categories of waste have been combined to standardize the data as much as possible. Data are reported for 22 countries, but multiple sources were found for several of these. In general, the industrialized countries are well-represented with data for 9 European countries as well as the United States and Canada. Less data were found for developing nations, particularly South America, the Middle East, Turkey, Greece, and Indonesia.

WASTE COMPOSITION IN DEVELOPING COUNTRIES (WEIGHT PERCENT)

CITY, COUNTRY	Indonesia	Jakarta, Indonesia	India	Middle East	Egypt	Egypt
DATA SOURCE	A	C	A	A	B	C
YEAR	1984					
WASTE MATERIAL						
Paper/Cardboard	14	8.24	2	20	9 2 - 25 0	13.0
Organic Household Waste	74					
Vegetables/Putrescibles		93 68	75	50	37.1 - 65.6	60 0
Plastics	2	5.52			1.9 - 4 5	1 5
Textiles		3.16				2 5
Plastics & Textiles			4	7		
Glass	1	1.78	0	4	1.1 - 2.0	2 5
Metals	1	2.08	0	9	2.3 - 3.8	3.0
Cloth					2.1 - 3 0	
Combustibles					0 - 9.6	
Fines	4					
Rubber/Wood/Leather/Cloth						
Bones					0.2 - 1.3	
Inert below 10mm			12	10		
Other/Unclassified	4	5.34	7	0	13 7 - 28 0	17 5

A) CRC Press. 1980. Microbiology of Landfill Sites.

B) El-Halwagi, W.W., et al. 1988. Municipal Solid-Waste Management in Egypt. In: ISWA Proceedings of the 5th International Solid Wastes Conference.

C) Curi, K. 1988. Comparison of Solid Waste Management in Touristic Areas of Developed and Developing Countries. In: ISWA Proceedings of the 5th International Solid Wastes Conference.

D) Papachristou, E. 1988. Solid Wastes Management in Rhodos. In: ISWA Proceedings of the 5th International Solid Wastes Conference.

WASTE COMPOSITION IN DEVELOPING COUNTRIES (WEIGHT PERCENT)

CITY, COUNTRY	Istanbul, Turkey	Rhodos, Greece	Monaco	South America	Rio de Janeiro Brazil
DATA SOURCE	C	D	C	A	C
YEAR					
WASTE MATERIAL					
Paper/Cardboard	11.98	11.5 - 18.0	38.40	15	38.92
Organic Household Waste		32.0 - 48.0			
Vegetables/Putrescibles	44.62		35 - 15	55	36 75
Plastics	11.87	10.0 - 13 0	1 25		6 83
Textiles	4.28		1.90		3 07
Plastics & Textiles				10	
Glass	3.42	10.0 - 22.0	6 47	4	3.79
Metals	2.28	8.5 - 15.0	2 47	6	3.84
Cloth					
Combustibles					
Fines	14.12		3.38		
Rubber/Wood/Leather/Cloth		1.8 - 8.4			
Bones					
Inert below 10mm					
Other/Unclassified	7.49	0.7 - 2.0	1.53	10	6.80

A) CRC Press. 1990. Microbiology of Landfill Sites.

B) El-Halwasi, W.W., et al. 1988. Municipal Solid-Waste Management in Egypt. In: ISWA Proceedings of the 5th International Solid Wastes Conference.

C) Curl, K. 1988. Comparison of Solid Waste Management in Touristic Areas of Developed and Developing Countries. In: ISWA Proceedings of the 5th International Solid Wastes Conference.

D) Papachristou, E. 1988. Solid Wastes Management in Rhodos. In: ISWA Proceedings of the 5th International Solid Wastes Conference.

WASTE COMPOSITION IN DEVELOPED COUNTRIES (WEIGHT PERCENT)

CITY, COUNTRY	West Germany	West Germany	West Germany	France	France	Vendargues France
DATA SOURCE	A	B	D	B	D	E
YEAR	1977	1985		1985		
WASTE MATERIAL						
Paper & Cardboard	27	18	28	28	11	20 - 35
Food & Yard Wastes			2			
Organic Household Waste	35				34	
Vegetables & Putrescibles			16			
Fermentables						15 - 35
Textiles & Wood			5			1 - 6
Plastics, Rubber, Glass, Leather & Textiles	14	15	23	12	9 6	8 - 70
Metals	5	3	5	6	3.6	5 - 8
Fines, Dirt, Sand, Ash & Ceramics	19		21		31	10 - 20
Bones						
Screenings						
Other, Unclassified		64		54	10 8	0 - 100
Moisture			25 - 40		30	

A) CRC Press. 1990. *Microbiology of Landfill Sites.*

B) Swartz, N. 1989. *Overview of International Solid Waste Management Method. State Government Technical Brief.* The American Society of Mechanical Engineers, November.

C) Lawson, P.S. 1988. The UK Department of Energy R&D (biofuels) Programme for Landfill Gas. Department of Energy, Energy Technology Support Unit, Didcot, England.

D) Abert, J.G. 1985. *Integrated Resource Recovery, Municipal Waste Processing in Europe: A Status Report on Selected Materials and Energy Recovery Projects.* The World Bank, Washington, DC.

E) Cayrol, F.C., et al. 1988. Anaerobic Digestion of Municipal Solid Waste by the Valorga Process. In. ISWA Proceedings of the 5th International Solid Wastes Conference.

WASTE COMPOSITION IN DEVELOPED COUNTRIES (WEIGHT PERCENT)

CITY, COUNTRY	London, England	England	United Kingdom	Tyne & Wear, England	Sweden	Sweden
DATA SOURCE	A	B	C	D	B	D (*)
YEAR	1979	1980	1987		1980	
WASTE MATERIAL						
Paper & Cardboard	37.3	29	33	30 - 40	43	50
Food & Yard Wastes						20
Organic Household Waste						
Vegetables & Putrescibles	23.0		24	15 - 25		
Fermentables						
Textiles & Wood	3 5			4 - 7		
Plastics, Rubber, Glass, Leather & Textiles	15 8	17	15	12 - 18	15	8
Metals	7.2	8	8	9 - 12	6	5
Fines, Dirt, Sand, Ash & Ceramics			10			
Bones						
Screenings	6.3			10 - 15		
Other, Unclassified	6.9	46	10	3 - 5	36	17
Moisture				20 - 30		22

A) CRC Press. 1990. Microbiology of Landfill Sites.

B) Swartz, N. 1989. Overview of International Solid Waste Management Method. State Government Technical Brief. The American Society of Mechanical Engineers, November.

C) Lawson, P.S. 1988. The UK Department of Energy R&D (biofuels) Programme for Landfill Gas. Department of Energy, Energy Technology Support Unit, Didcot, England.

D) Abert, J.G. 1985. Integrated Resource Recovery, Municipal Waste Processing in Europe: A Status Report on Selected Materials and Energy Recovery Projects. The World Bank, Washington, DC.

E) Cayrol, F.C., et al. 1988. Anaerobic Digestion of Municipal Solid Waste by the Valorga Process. In· ISWA Proceedings of the 5th International Solid Wastes Conference.

(*) Percent Wet Weight.

WASTE COMPOSITION IN DEVELOPED COUNTRIES (WEIGHT PERCENT)

CITY, COUNTRY	United States	United States	Tokyo, Japan	Japan	Spain	Madrid, Spain
DATA SOURCE	A	B	A	B	B	D
YEAR	1978	1987	1980	1986	1985	
WASTE MATERIAL						
Paper & Cardboard	48	37	31.4	38	15	19 1
Food & Yard Wastes	23	25	32.6			
Organic Household Waste						53.6
Vegetables & Putrescibles						
Fermentables						
Textiles & Wood	3		3 9			
Plastics, Rubber, Glass, Leather & Textiles	12	17	22	10	12	2 74
Metals	9	10	7.8	2	3	2 24
Fines, Dirt, Sand, Ash & Ceramics	5		2.3			
Bones						
Screenings						
Other, Unclassified		11		50	70	22.32
Moisture						48

A) CRC Press. 1990. Microbiology of Landfill Sites.

B) Swartz, N. 1989. Overview of International Solid Waste Management Method. *State Government Technical Brief* The American Society of Mechanical Engineers, November.

C) Lawson, P.S. 1988. The UK Department of Energy R&D (biofuels) Programme for Landfill Gas. Department of Energy, Energy Technology Support Unit, Didcot, England.

D) Abert, J.G. 1985. Integrated Resource Recovery, *Municipal Waste Processing in Europe: A Status Report on Selected Materials and Energy Recovery Projects*. The World Bank, Washington, DC.

E) Cayrol, F.C., et al. 1988. Anaerobic Digestion of Municipal Solid Waste by the Valorga Process. In: ISWA Proceedings of the 5th International Solid Wastes Conference.

WASTE COMPOSITION IN DEVELOPED COUNTRIES (WEIGHT PERCENT)

CITY, COUNTRY	Rome, Italy	Italy	Rome, Italy	Switzerland	Vienna, Austria	Netherlands
DATA SOURCE	A	B	D	B	D	B
YEAR	1977	1985		1980		1985
WASTE MATERIAL						
Paper & Cardboard	17	22	25	30	39 48	23
Food & Yard Wastes	53					
Organic Household Waste			50			
Vegetables & Putrescibles					21 82	
Fermentables						
Textiles & Wood	2.5		3		8 36	
Plastics, Rubber, Glass, Leather & Textiles	16.5	13	19	22	17 05	14
Metals	3	3	2.5	6	5 13	3
Fines, Dirt, Sand, Ash & Ceramics					7 07	
Bones					1 09	
Screenings						
Other, Unclassified	8	62		42		60
Moisture			45 - 50			

A) CRC Press. 1990. Microbiology of Landfill Sites.

B) Swartz, N. 1989. Overview of International Solid Waste Management Method. State Government Technical Brief The American Society of Mechanical Engineers, November.

C) Lawson, P.S. 1988. The UK Department of Energy R&D (biofuels) Programme for Landfill Gas Department of Energy, Energy Technology Support Unit, Didcot, England.

D) Abert, J.G. 1985. Integrated Resource Recovery, Municipal Waste Processing in Europe: A Status Report on Selected Materials and Energy Recovery Projects. The World Bank, Washington, DC.

E) Cayrol, F.C., et al. 1988. Anaerobic Digestion of Municipal Solid Waste by the Valorga Process In ISWA Proceedings of the 5th International Solid Wastes Conference

WASTE COMPOSITION IN DEVELOPED COUNTRIES (WEIGHT PERCENT)

CITY, COUNTRY	Canada	Israel	Hong Kong
DATA SOURCE	B	A	A
YEAR	1985	1979	1983
WASTE MATERIAL			
Paper & Cardboard	36	30.3	5
Food & Yard Wastes		57.8	
Organic Household Waste			
Vegetables & Putrescibles			2 6
Fermentables			
Textiles & Wood			72 2
Plastics, Rubber, Glass, Leather & Textiles	12	7.4	10
Metals	7	3.1	2.9
Fines, Dirt, Sand, Ash & Ceramics			1.2
Bones			
Screenings			
Other, Unclassified	45	1.4	6.1
Moisture			

A) CRC Press. 1990. Microbiology of Landfill Sites.

B) Swartz, N. 1989. Overview of International Solid Waste Management Method. State Government Technical Brief. The American Society of Mechanical Engineers, November.

C) Lawson, P.S. 1988. The UK Department of Energy R&D (biofuels) Programme for Landfill Gas. Department of Energy, Energy Technology Support Unit, Didcot, England.

D) Abert, J.G. 1985. Integrated Resource Recovery, Municipal Waste Processing in Europe: A Status Report on Selected Materials and Energy Recovery Projects. The World Bank, Washington, DC.

E) Cayrol, F.C., et al. 1988. Anaerobic Digestion of Municipal Solid Waste by the Valorga Process. In· ISWA Proceedings of the 5th International Solid Wastes Conference.

APPENDIX B

SOLID WASTE MANAGEMENT METHODS IN ELEVEN COUNTRIES

The following data were compiled from a report from the American Society of Mechanical Engineers.[1] Only industrialized nations were included in this report. Other sources of data on this particular aspect of global waste management do exist, however, and more research is probably warranted.

[1] Swartz, A. 1989. Overview of International Solid Waste Management Methods. In: State Government Technical Brief. Paper No. 98-89-M1-2.

DISPOSAL METHODS OF WASTE IN DEVELOPED COUNTRIES (WEIGHT PERCENT)

COUNTRY	West Germany	France	England	Sweden	United States	Japan
YEAR	1985	1985	1980	1980	1987	1986
DISPOSAL METHODS						
Incineration	28	36	8	53	10	72
Recycling					10	
Landfilling	69	47	88	41	80	24.6
Composting	2	8		6		.1
Sorting						
Other	1	9	4			3.3

COUNTRY	Spain	Italy	Switzerland	Netherlands	Canada
YEAR	1985	1985	1980	1985	1985
DISPOSAL METHODS					
Incineration	5	19	80	36	4
Recycling					2
Landfilling	76	35	18	55	90
Composting	19	5	2	5	
Sorting		3		1	
Other		30		3	4

Reference: "Overview Of International Solid Waste Management Methods", State Government Technical Brief, Allan Swartz, The American Society of Mechanical Engineers, November, 1989.

APPENDIX C

SAMPLE PRELIMINARY LANDFILL SURVEY FORM

Date: ____________ Person making call: ____

Landfill facility: ____

Name and address: ____
____
____
____

Contact at landfill: __________________________________ Telephone: ______________

Methane recovery system in place? _____ Yes _____ No

Active landfill? _____ Yes _____ No Refuse acceptance rate: ______________________

Date landfill opened: _______________ Closure date: _____________________________

Describe landfill structure (depth, cell size, etc.): _____________________________________
____
____

If the answer to any of the following questions is "Yes," get a copy of test results if available.

Refuse composition known: _____ Yes _____ No

Results available? _____

Moisture tests run on landfill: _____ Yes _____ No

Results available? _____

Moisture tests run on refuse? _____ Yes _____ No

Results available? _____

Are there perimeter wells or has surface testing of landfill been done? _____ Yes _____ No

Results available? _____

Comments:

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/7-91-002	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE Approach for Estimating Global Landfill Methane Emissions		5. REPORT DATE January 1991
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Rebecca L. Peer, Ann E. Leininger, Barbara B. Emmel, and Susan K. Lynch		8. PERFORMING ORGANIZATION REPORT NO. DCN 90-239-005-48-09
9. PERFORMING ORGANIZATION NAME AND ADDRESS Radian Corporation P. O. Box 13000 Research Triangle Park, North Carolina 27709		10. PROGRAM ELEMENT NO.
		11. CONTRACT/GRANT NO. 68-02-4288, Task 48
12. SPONSORING AGENCY NAME AND ADDRESS EPA, Office of Research and Development Air and Energy Engineering Research Laboratory Research Triangle Park, North Carolina 27711		13. TYPE OF REPORT AND PERIOD COVERED Task final; 4-9/90
		14. SPONSORING AGENCY CODE EPA/600/13

15. SUPPLEMENTARY NOTES AEERL project officer is Susan A. Thorneloe, Mail Drop 63, 919/541-2709.

16. ABSTRACT The report is an overview of available country-specific data and modeling approaches for estimating global landfill methane. Current estimates of global landfill methane indicate that landfills account for between 4 and 15% of the global methane ɔudget. The report describes an approach for using country-specific and field test lata to develop a less uncertain estimate of global landfill methane. Development of ·nhanced emissions factors for landfills and other major sources of methane will mprove the understanding of atmospheric chemistry and feedback effects, will target ıitigation opportunities, and will ensure cost-effective mitigation strategies. EPS's rogram to characterize the effects of global change, including identifying and quanfying emission sources, responds to concerns about global warming and is particu-ɹrly concerned with quantifying emissions sources both in the U. S. and globally.

17. KEY WORDS AND DOCUMENT ANALYSIS

DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
·llution	Pollution Control	13B
thane	Stationary Sources	07C
ission		14G
·th Fills		13C
imating		
ıte Disposal		15E

TRIBUTION STATEMENT ɜase to Public	19. SECURITY CLASS *(This Report)* Unclassified	21. NO. OF PAGES 53
	20. SECURITY CLASS *(This page)* Unclassified	22. PRICE

m 2220-1 (9-73)