leachate recirculation parameters on leachate quality could be analyzed. Although COD was the main leachate quality parameter analyzed, the program can be used for any other leachate quality parameter as well which follows the same pattern of variation over time as COD. The following sections discuss the methodology utilized in detail.

MASS BALANCE APPROACH

Single Cell

For a single recirculating active cell, shown schematically in Figure D-1, a mass balance can be applied to arrive at equations which determine the leachate organic strength. The biological degradation of the organic portion of the waste mass is thought to be carried out by anaerobic microorganisms and proceed in three phases. The first phase called the hydrolysis phase, involves the transformation of higher-molecular compounds into compounds suitable for energy source. The second phase is called acidogenesis phase and is characterized by the formation of lower-molecular organic acids by a group of microorganisms called 'acidogens' or 'acid formers'. During these two phases of degradation of organic waste mass, the leachate organic concentration increases. During the third phase called the methanogenesis phase, the leachate organic strength decreases due to the conversion of organic compounds into end products, mainly methane and carbon dioxide. Methanogens are the microorganisms responsible for this conversion to end products. In actuality, as the active cell is filled, the older waste might have already advanced to the next phase of stabilization (methanogenesis) while fresh waste is still being placed in the same cell/section of the landfill. Thus, even in the same active cell, not all waste is in the hydrolysis/acidogenesis phases and the active cell can be visualized as two cells: one in the hydrolysis/acidification phase and the other in the methanogenesis phase. Figure D-1 is a schematic diagram illustrating this concept. Assuming that the cells behave as CSTRs, application of mass balance on the hydrolysis/acidogenesis portion of the cell yields:

$$V_a \frac{dC}{dt} = Q_a C_a + Q_p C_p - C'_a Q'_a + k_a C'_a V_a \qquad \text{(D-1)}$$

Where V_a = Void volume hydrolysis/acidogenesis portion of the cell

C = Leachate parameter concentration of the hydrolysis/acidogenesis portion of the cell

t = Time

Q_a = Flow into the cell

C_a = Concentration of the leachate parameter into the cell

Q_p = Moisture infiltration

C_p = Concentration of the infiltrating moisture

Q'_a = Flow out of the cell

C'_a = Concentration out of the cell

k_a = Reaction rate constant for the hydrolysis/acidogenesis portion of the cell

Since C_p is zero, between times (t) and (t+1), Equation D-1 can be written as:

$$V_a \frac{(C'_{a(t+1)} - C_{a(t)})}{\Delta t} = Q_{a(t)} C_{a(t)} - Q'_{a(t+1)} C'_{a(t+1)} + k_a C'_{a(t+1)} V_a \qquad \text{(D-2)}$$

Where C'a(t+1) and Ca(t) are the concentrations at times (t+1) and (t) respectively. Thus,

$$C'_{a(t+1)} = \frac{C_{a(t)} (Q_{a(t)} + V_a)}{(V_a + Q'_{a(t+1)} - k_a V_a)}$$

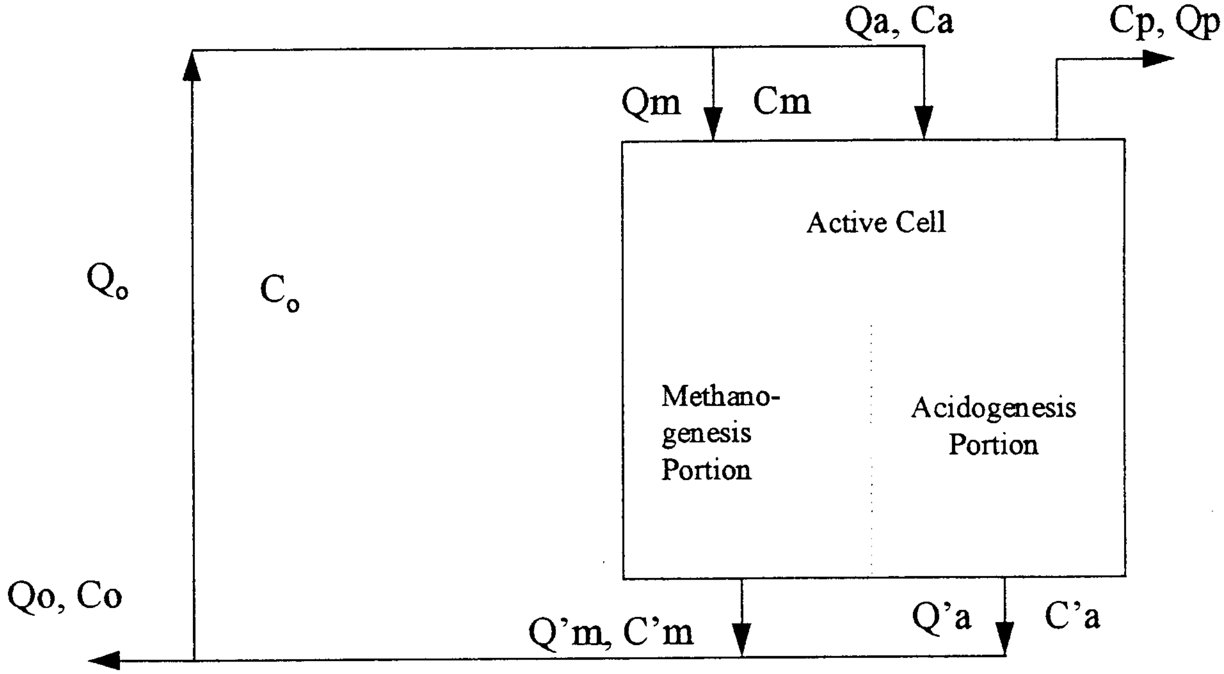

Figure E-1. Schematic Drawing of single recirculating active cell

Similarly, for the methanogenesis portion of the cell,

$$V_m \frac{dC}{dt} = Q_m C_m + Q_p C_p - Q'_m C'_m - k_m C'_m V_m \qquad \text{(D-4)}$$

Similarly, for the methanogenesis portion of the cell,

$$V_m \frac{dC}{dt} = Q_m C_m + Q_p C_p - Q'_m C'_m - k_m C'_m V_m \qquad \text{(D-5)}$$

Where
V_m = Void volume in the methanogenesis portion
C = Parameter concentration of the methanogenesis portion
t = Time
Q_m = Flow into the methanogenesis part
C_m = Concentration into the methanogenesis part
Q_p = Moisture infiltration
C_p = Concentration of the infiltrating moisture
Q'_m = Flow out of the methanogenesis part
C'_m = Concentration out of the methanogenesis part
k_m = Reaction rate constant of the methanogenesis part

The concentration of the infiltrating moisture is zero and thus Equation E-4 reduces to:

$$V_m \frac{dC}{dt} = Q_m C_m - Q'_m C'_m - k_m C'_m V_m \qquad \text{(D-5)}$$

Between times (t) and (t+1), Equation D-5 can be written as:

$$V_m \frac{(C'_{m(t+1)} - C_{m(t)})}{\Delta t} = Q_{m(t)} C_{m(t)} - Q'_{m(t+1)} C'_{m(t+1)} - k_m C'_{m(t+1)} V_m \qquad \text{(D-6)}$$

Where $C'_{m(t+1)}$ and $C_{m(t)}$ are the concentrations at times (t+1) and (t) respectively. Therefore,

$$C'_{m(t+1)} = \frac{C_{m(t)} (Q_{m(t)} + V_m)}{(V_m + Q'_{m(t+1)} + k_m V_i)} \qquad \text{(D-7)}$$

Equations D-3 and D-7 are used in the modified program to calculate the leachate parameter concentration over a time period using input parameters. The details are described in the following sections.

The equation used in the modified program to calculate the overall leachate parameter concentration is:

$$C_o = \frac{(C_m Q_m) + (C_a Q_a)}{(Q_m + Q_a)} \qquad \text{(D-8)}$$

where :
C_o = Overall leachate parameter concentration
C_m = Concentration out of methanogenesis portion of the active cell
C_a = Concentration out of hydrolysis/acidogenesis portion of the active cell
Q_m = Flow out of the methanogenesis portion of the active cell
Q_a = Flow out of the hydrolysis/acidogenesis portion of the active cell

Two Cells

Considering two landfill cells, one closed and inactive and the other active (receiving wastes), and applying mass balance on each cell, equations can be developed to calculate the concentration of a leachate quality parameter. Although, in reality, landfill cells are neither Continuous Stirred Tank Reactors (CSTRs) nor plug flow reactors, because of the use of the apparent reaction rate constant, it is assumed that the cells behave as CSTRs. Also, because the inactive cell has been completely filled with waste and closed, it is assumed that there is no infiltration of moisture to that cell from sources other than recirculation. However, the active cell is open and receiving waste, therefore moisture infiltration resulting from precipitation occurs. A schematic diagram of the cells is shown in Figure D-2.

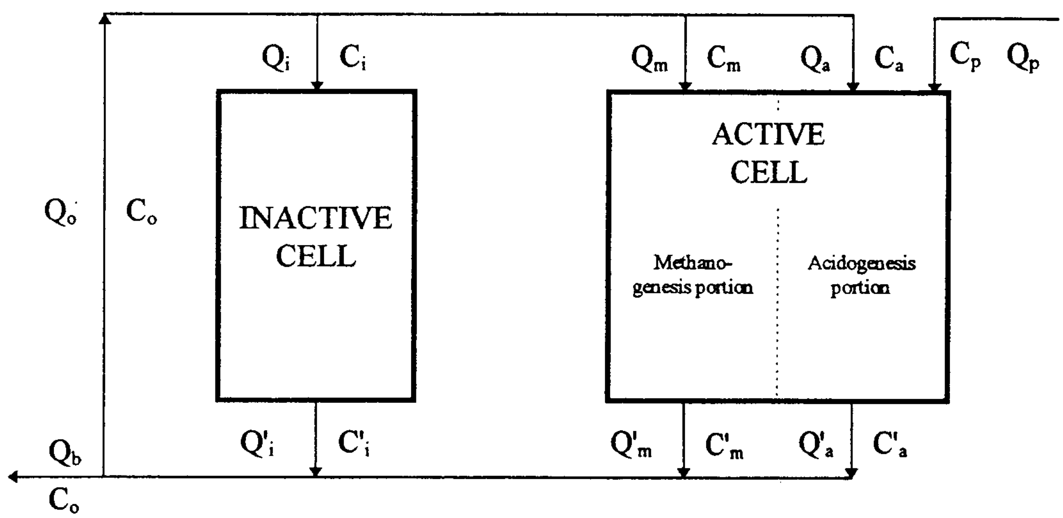

Figure D-2. Schematic diagram of two parts in the active cell

Applying mass balance to the inactive cell:

$$V_i \frac{dC}{dt} = Q_i C_i - Q'_i C'_i - k_i C'_i V_i \qquad \text{(D-9)}$$

Where: V_i = Void volume in the inactive cell

C = Parameter concentration of the inactive cell
t = Time
Q_i = Flow into the inactive cell
C_i = Concentration into the inactive cell
Q'_i = Flow out of the inactive cell
C'_i = Concentration out of the inactive cell
k_i = Reaction rate constant for the inactive cell

Since the cell is closed, there is no moisture infiltration into the inactive cell. Thus, flow into the inactive cell is equal to the flow out of the inactive cell. In other words, leachate flow out of the inactive cell is equal to the recirculation flow into the inactive cell. Also, since the cell is full, the volume V_i remains constant.

Over a time step, Equation D-9 can be approximated as:

$$V_i \frac{(C'_{i(t+1)} - C_{i(t)})}{\Delta t} = Q_{i(t)} C_{i(t)} - Q'_{i(t+1)} C'_{i(t+1)} - k_i C'_{i(t+1)} V_i \qquad \text{(D-10)}$$

Where $C'_{i(t+1)}$ = Concentration at time (t+1)
$C_{i(t)}$ = Concentration at time (t)
Δt = Time interval, assumed to be one day

Thus, concentration at time (t+1) reduces to:

$$C'_{i(t+1)} = \frac{C_{i(t)} (Q_{i(t)} + V_i)}{(V_i + Q'_{i(t+1)} + k_i V_i)} \qquad \text{(D-11)}$$

Similarly, applying mass balance to the methanogenesis portion of the active cell,

$$V_m \frac{dC}{dt} = Q_m C_m + Q_p C_p - Q'_m C'_m - k_m C'_m V_m \qquad \text{(D-12)}$$

Where V_m = Void volume in the methanogenesis portion
C = Parameter concentration of the methanogenesis portion
t = Time
Q_m = Flow into the methanogenesis part
C_m = Concentration into the methanogenesis part
Q_p = Moisture infiltration
C_p = Concentration of the infiltrating moisture
Q'_m = Flow out of the methanogenesis part
C'_m = Concentration out of the methanogenesis part
k_m = Reaction rate constant of the methanogenesis part

Since the active cell is subject to moisture infiltration, the terms Q_p and C_p are included in Equation D-12. Thus, the flow out of the portion of the landfill experiencing methanogenesis is greater than the recirculation flow by an amount equal to daily moisture infiltration. Initially, as the active cell fills, all the waste will be at the hydrolysis/acidogenesis phase, which implies that methanogenesis part will be absent. Only after the hydrolysis/acidogenesis portion of the active cells gets filled up completely, the methanogenesis portion starts filling. This implies that initially, the void volume of the methanogenesis portion of the active cell, V_m, remains zero until the hydrolysis/acidogenesis portion fills up. Then V_m starts increasing until the entire active cell fills. Eventually the entire cell reaches the methanogenic phase. The concentration of the infiltrating moisture is zero and thus Equation D-12 reduces to:

$$V_m \frac{dC}{dt} = Q_m C_m - Q'_m C'_m - k_m C'_m V_m \qquad \text{(D-13)}$$

Between times (t) and (t+1), Equation D-13 can be written as:

$$V_m \frac{(C'_{m(t+1)} - C_{m(t)})}{\Delta t} = Q_{m(t)} C_{m(t)} - Q'_{m(t+1)} C'_{m(t+1)} - k_m C'_{m(t+1)} V_m \qquad \text{(D-14)}$$

Where $C'_{m(t+1)}$ and $C_{m(t)}$ are the concentrations at times (t+1) and (t) respectively.

Therefore,

$$C'_{m(t+1)} = \frac{C_{m(t)} (Q_{m(t)} + V_m)}{(V_m + Q'_{m(t+1)} + k_m V_i)} \qquad \text{(D-15)}$$

Applying mass balance to the acidogenesis portion:

$$V_a \frac{dC}{dt} = Q_a C_a + Q_p C_p - Q'_a C'_a + k_a C'_a V_a \qquad \text{(D-16)}$$

Where
- V_a = Void volume in the acidogenesis part
- C = Parameter concentration of the hydrolysis/acidogenesis portion of the active cell
- t = Time
- Q_a = Flow into the acidognesis part
- C_a = Concentration into the acidogensis part
- Q_p = Moisture infiltration
- C_p = Concentration of the infiltrating moisture
- Q'_a = Flow out of the acidogenesis part
- C'_a = Concentration out of the acidogenesis part
- k_a = Decay rate constant for the acidogenesis part

Because the active cell is open, similar to the methanogenesis portion, moisture infiltration occurs in the hydrolysis/acidogenesis portion of the active cell. Thus, the flow out of the cell is greater than the recirculation flow into the cell. Since hydrolysis/acidogenesis acts to increase the leachate organic concentration, k has a positive value as opposed to negative value once methanogenesis starts. Initially, the hydrolysis/acidogenesis portion fills until the waste moves to the methanogenesis phase. From then on, the volume of the hydrolysis/acidogenesis part remains constant until the entire cell is filled. Thus, V_a initially increases and then remains constant until the entire cell is filled. Then V_a starts decreasing and eventually all the waste reaches the methanogenesis phase. Since C_p is zero, Equation D-16 reduces to:

$$V_a \frac{dC}{dt} = Q_a C_a - Q'_a C'_a + k_a C'_a V_a \qquad \text{(D-17)}$$

Between times (t) and (t+1), Equation D-17 can be written as:

$$V_a \frac{(C'_{a(t+1)} - C_{a(t)})}{\Delta t} = Q_{a(t)} C_{a(t)} - Q'_{a(t+1)} C'_{a(t+1)} + k_a C'_{a(t+1)} V_a \qquad \text{(D-18)}$$

Where C'a(t+1) and Ca(t) are the concentrations at times (t+1) and (t) respectively. Thus,

$$C'_{a(t+1)} = \frac{C_{a(t)} (Q_{a(t)} + V_a)}{(V_a + Q'_{a(t+1)} - k_a V_a)} \qquad \text{(D-19)}$$

Equations D-11, D-15 and D-19 are used in the program to calculate the leachate parameter concentration over a time period using input parameters. The details are described in the next section.

The equation used in the program to calculate the overall leachate parameter concentration is:

$$C_o = \frac{((C_i Q_i) + (C_m Q_m) + (C_a Q_a)}{(Q_i + Q_m + Q_a)} \qquad \text{(D-20)}$$

Where:
- C_o = Overall leachate parameter concentration
- C_i = Concentration out of inactive cell
- C_m = Concentration out of methanogenesis portion of the active cell
- C_a = Concentration out of hydrolysis/acidogenesis portion of the active cell
- Q_i = Flow out of the inactive cell
- Q_m = Flow out of the methanogenesis portion of the active cell
- Q_a = Flow out of the hydrolysis/acidogenesis portion of the active cell

PROGRAM INPUTS

Turbo C Version 2.01 was used to develop the program to iteratively calculate the leachate parameter concentration over a period of time. The program accepts a set of input parameters and calculates the leachate parameter concentration every day and upon successful completion, writes the concentration at the end of every month (30th day) onto a specified file in the same directory as the executable file. If no disk space is available the program will not write onto the file. If the specified file (an input to the program) already exists, the file will be overwritten.

Sample input screens are presented in the appendix. The program prompts for the input of the following parameters in the same order:

- length of the landfill cell in meters. This refers to the length of the cell or section of the landfill being analyzed.

- width of the landfill cell in meters. Together with the length, this determines the area receiving precipitation.
- depth of the landfill cell in meters. This refers to the average depth.
- density of the waste in Kg/m^3. This refers to the wet density of the waste as placed in the landfill cell. It is used with the waste placement rate to determine the volume of the waste being placed and in turn, determines when the cell gets completely filled.
- waste placement rate in Kg/day. The wet weight of waste being placed daily in the cell. This rate is assumed to be constant throughout the filling process.
- void volume of the waste as a percentage of the total volume which refers to the percentage volume of voids in the waste being placed. This, together with the saturation value, determines the actual volume available for leachate movement and reactions.
- moisture infiltration rate in m^3/day, the amount of moisture infiltrating the active cell which is determined by the product of average annual precipitation and the surface area of the active cell. It is assumed that this amount of moisture is added to the active cell every day.
- leachate bleeding rate as a percentage of the total leachate flow out of the two cells. This determines the amount of leachate going out of the system (wasted) and is calculated as a percentage of the total leachate flow from the two cells. It is assumed to be constant.
- time of inversion of 'k' in days, is the time required for the organic fraction of the waste to move from hydrolysis/acidogenesis phase (time at which the waste is placed) to the methanogenesis phase. This determines how long a batch of waste (daily cell) will be in the hydrolysis/acidogenesis phase (increasing the leachate organic strength) before changing to the methanogenesis phase (decreasing leachate organic strength).
- initial leachate concentration in mg/l is the leachate organic concentration in the leachate being recirculated for the first time. This is not zero because of the fact that the concentration of the leachate being recirculated for the first time will not be zero.
- initial leachate recirculation rate, in m^3/day, is the leachate recirculation rate at

the start of the process.

- positive k (day^{-1})value is the reaction rate constant for the hydrolysis/acidogenesis portion of the active cell.
- negative k (day^{-1}) value, the reaction rate constant for the methanogenesis portion of the active cell and the entire inactive cell.
- percent moisture saturation of the waste is the fraction of the void volume filled with moisture. This determines the leachate volume within the cell. This value, along with the void volume is used to determine the total reaction volume of the cells.
- name of the output file, the file containing the output upon successful completion of the program. If the disk is full, the file will not be created. If the specified file already exists, it will be overwritten.

ASSUMPTIONS MADE IN THE PROGRAM

Several assumptions are made within the program and are described in the following paragraphs. It is assumed that the landfill section is rectangular in geometry. The dimensions are used in the program to calculate the total volume of the cell or section and to determine when to stop filling the cell when it is completely filled. Also, it is assumed that the dimensions of the active cell (being filled and open) and inactive cell (filled and closed) are the same, i.e., their volume/capacities are the same.

It is assumed in the program that the hydrolysis/acidogenesis phase lasts for the number of days as specified by the time of inversion of k. This implies that the value of the reaction rate constant changes from a positive value to a negative value after a number of days equal to the time of inversion of k. Initially, the methanogenesis portion of the active cell is empty as the hydrolysis/acidogenesis portion is filling. After a time period equal to the time of inversion of k since placement, the waste shifts to methanogenesis and the volume of waste in the hydrolysis/acidogenesis portion declines until the hydrolysis/acidogenesis portion empties and all the waste in the cell will be in the methanogenesis phase.

The transition from hydrolysis/acidogenesis and methanogenesis is assumed to be sudden and not gradual. This implies that the k value suddenly reverses from positive to negative after a period equal to time of inversion.

The amount of cover material in both the active and inactive cells are assumed to take up ten percent of the total volume of each cell. The actual volume available for waste mass is ninety percent of the total volume of the cell. Also, settlement of waste mass over time is not taken into account in any of the cells and the volume of the waste mass is assumed to remain constant.

The hydraulic aspects of the leachate movement have not been considered in the program.

It is assumed that the flow of leachate through the waste mass in both the cells is smooth and unhindered. This implies that the leachate parameter concentration is the same at all points within the cells. The leachate from both the cells are mixed. A portion of the leachate is then wasted for external treatment and disposal. The quantity of leachate after bleeding is recirculated and distributed between the two cells proportional to the volume of waste in the two cells. The two conceptual cells of hydrolysis/acidogenesis and methanogenesis are assumed to be separated hydraulically and the leachates from these two portions are mixed only after exiting from the cells. The scheme of leachate recirculation is assumed to be as shown in Figure D-2. The wasting rate is assumed to be the total flow from the active and inactive cells minus the flow into the active and inactive cells.

The amount of moisture infiltration is based on the average daily precipitation falling within the active area of the landfill. This parameter is a user input. This amount is added to the active cell every day (every iteration in the program). The amount of infiltrating moisture is assumed to be distributed between the methanogenesis and hydrolysis/acidogenesis parts of the active cell in proportion to the volume of the waste in the respective parts.

The details about the working of the program are described in the next section. Initially, as the active cell is filled, there is no waste in the methanogenesis portion of the active cell. As the cell fills, oldest waste moves from the hydrolysis/acidogenesis phase to the methanogenesis phase. From this point on, the methanogenesis portion grows as the active cell fills and the active volume (in the hydrolysis/acidogenesis phase) remains constant for a period (until the entire active cell fills) and then begins to decline. Once there is no more input to the active cell, the waste in the hydrolysis/acidogenesis phase shifts to the methanogenesis phase. In an actual landfill, as one cell fills, the next section is opened and so on, until the entire landfill area is completed.

PROGRAM EXECUTION

The program execution is started by typing the program name "Recirc", which is an executable file, at the DOS prompt. The program begins and clears the screen and displays a brief message. Upon pressing any key, it clears the screen and displays an input screen. The return/enter key has to be pressed after typing in each input parameter. After the first input screen, the second input screen is displayed. After accepting all the inputs, the program starts execution. The output is displayed on the screen. Then the output is written onto the specified file in the same directory in which the executable program resides. The output file is not created if there is no disk space or if the specified file already exists. After successful completion of the program and creating the specified output file, the program prompts for another run of the program.

Since the range of values for each of the input parameter is very wide, no validation of the input parameters is performed within the program. Also, since it is used to analyze the effect of various parameters on leachate quality parameter, restricting the range for input parameter is not desirable.

The first step of the program is to determine the void volume in the inactive cell based on the input dimensions of the cell. The inactive cell is "created" and assumed to have the same dimensions as that of the active cell. The void volume of the daily cell is also determined. Then the initial flow rate with initial leachate parameter concentration is assumed to flow into the cells after the waste is "placed" in the hydrolysis/acidogenesis portion of the active cell. Initially, as the hydrolysis/acidogenesis portion fills, the methanogenesis portion of the active cell is empty. Thus, there is no flow into the methanogenesis portion of the active cell when there is no waste present. Also, since the flow from the both active and inactive cells is mixed, as shown in Figure D-2, the input concentration into both the cells will be the same.

The time at which the first batch of waste (daily cell) is placed in the active cell is considered to be day one. All further time references are with respect to this point. There is a counter in the program to keep track of time so that the program knows when to shift the waste from the hydrolysis/acidogenesis phase to the methanogenesis phase based on the time of inversion of k.

All the calculations are performed on a daily basis and the concentration of the leachate constituent parameter is recorded once every thirty days. At every increment of time (a day), the program performs the following calculations and routines:

- If the active cell is not completely full, waste is placed in the hydrolysis/acidogenesis portion of the active cell. The waste capacity of the active cell is determined by the dimensions (volume) of the active cell. If the time elapsed since placing the first daily cell is more than time of inversion of k, then the waste is shifted to the methanogenesis phase. The shifted quantity of waste is equal to the daily placement rate (daily cell). From this point on until the active cell fills, the hydrolysis/acidogenesis portion can be visualized to have the same volume of waste. However, this may not be the case if the waste placement rate is very high where the active cell fills within a time period of time of inversion of k.
- If the active cell is full and more than the time of inversion has passed, then the waste from the hydrolysis/acidogenesis phase is shifted to methanogenesis. This means that the hydrolysis/acidogenesis volume starts decreasing and eventually reaches zero while all the waste shifts to methanogenesis phase. The hydrolysis/acidogenesis portion of the active cell ceases to exist once the volume in this portion reaches zero.
- The leachate flow into the cells are calculated based on the input parameters. Since the inactive cell is closed, it is assumed that there is no moisture infiltration and the leachate flow out of the inactive cell is the same as the inflow. However, since the active cell is open and moisture infiltrates, the flow out of the active cell is greater than the recirculation flow into the cell. The flow out of the active cell is greater than the inflow by an amount equal to the average daily infiltration. It is assumed that the average daily infiltration is distributed between the hydrolysis/acidogenesis and the methanogenesis portions proportional to their respective waste volumes. The

hydrolysis/acidogenesis and methanogenesis portions of the active cell are assumed to be hydraulically separated.

- The concentrations of the leachate quality parameter is calculated next. First the output concentration of the inactive cell is calculated using Equation D-11. The output concentration of the methanogenesis portion of the active cell is calculated using the Equation D-16 and that of hydrolysis/acidogenesis portion using Equation D-19. Once the output concentrations are calculated, the flows are mixed before wasting. The new average concentration is calculated using Equation D-20, which becomes the input concentration for the cells for the next time step. Depending on the input, a certain amount of leachate is bled out of the system. The remaining quantity is recirculated into the cells and is distributed between the active and inactive cells proportionally to the amount of waste present in each cell. The quantity of leachate flowing into the active cell is again in turn distributed between the hydrolysis/acidogenesis part and methanogenesis part proportionally to the volume of wastes in the respective parts. There will be no recirculation flow into the any part of the cell which is empty. Thus, there will be no flow into the methanogenesis portion initially and there will be no flow into the hydrolysis/acidogenesis portion towards the end.
- The above procedure is repeated thirty times (thirty days). The output concentrations from the inactive cell, the hydrolysis/acidogenesis and methanogenesis portions of the active cell are stored in a table within the program. Then the program continues for another thirty days before storing the output concentrations again. This procedure is repeated until the concentrations are recorded (within the internal memory and not on the disk)for a specified time period of approximately twenty years. The concentrations are not written to the file directly because it is more efficient to store the values of concentrations internally within the program and write on to the file once all the concentrations are calculated and stored. The program checks for disk space before creating the output file. If there is no sufficient disk space or if the disk is write protected, the output file is not created. The output format of the program is detailed in the following section.
- After the successful completion of one run of the program for a certain set of input parameters, the program prompts for another run. If the user enters 'y' (for yes), then the program starts all over again from the message screen. The process is repeated until the user enters 'n' when the program prompts for another run. If the user enters 'n' (for no), the program terminates normally and returns to the DOS prompt.