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Ecological Research Series

A CASE STUDY OF THE LOS ANGELES COUNTY PALOS VERDES LANDFILL GAS DEVELOPMENT PROJECT

Municipal Environmental Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Cincinnati, Ohio 45268

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A CASE STUDY OF THE LOS ANGELES COUNTY PALOS VERDES LANDFILL GAS DEVELOPMENT PROJECT

by

Frank R. Bowerman
Naresh K. Rohatgi
Kenneth Y. Chen
and
R. A. Lockwood
CDM Inc. Environmental Engineers
Pasadena, California 91101

Contract No. 68-03-2143

Project Officer

Charles J. Rogers
Solid and Hazaradous Waste Research Division
Municipal Environmental Research Laboratory
Cincinnati, Ohio 45268

MUNICIPAL ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

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FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research; a most vital communications link between the researcher and the user community.

This report documents the first-ever-attempt to capture sanitary landfill gases and beneficiate them to natural gas pipeline quality--or very nearly so.

Francis T. Mayo, Director
Municipal Environmental Research
Laboratory

ABSTRACT

Life teaches many lessons, some through success and some through a failure to succeed. This report documents the first-ever-attempt to capture sanitary landfill gases and beneficiate them to natural gas pipeline quality - or very nearly so. For this reason the authors must credit the entrepreneurs for a successful first full-scale demonstration of a technology that produces very nearly pure methane and wish to compliment the Los Angeles County Sanitation Districts for the willingness, cooperation, and technical assistance that made the demonstration possible. Herein lies an excellent example of local government and industry working together to produce results that may have ultimate benefits for people throughout the nation and the world.

That this demonstration failed to show an economic viability during the twelve-month study period only suggests to the authors that further consideration should be given to improving the dependability of the molecular sieve process for landfill gas beneficiation, to the study of alternative beneficiation processes, and/or alternative uses for less modified landfill gases. Experiences since the completion of the data collecting period, July 1976, indicates that the process has worked with but little interruption for as much as 90 days. This is encouraging, but the economics are still not favorable for molecular sieve beneficiation, in the opinion of the authors.

Perhaps more serious consideration should be given to the use of landfill gas with little or no modification, except perhaps moisture removal. Reciprocating piston engines, rotary turbines, steam generators, air heaters, and a host of other devices can be fueled successfully with mixtures of methane, carbon dioxide, and small amounts of other gases, provided the heat content is not below certain critical levels. Such uses date back to the constantly-heated coffee pot warmed by the flame from a pipe stuck into the landfill by the operators. Much more sophisticated, but economically viable uses can be hypothesized; the authors are convinced that some of them will prove to be practical and economical in use. Landfill gases present an energy resource - modest as it is - that should be developed and utilized wherever and whenever possible.

This report was submitted in fulfillment of Contract No. 68-03-2143 by CDM Inc. Environmental Engineers under the sponsorship of the U.S. Environmental Protection Agency. This report covers the period October 1974 to July 1976.

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CHAPTER I

INTRODUCTION

A. History of Palos Verdes Landfill Gas Migration and Recovery

The landfill site lies in coastal hills within the corporate limits of the city of Rolling Hills Estates, Los Angeles County. A private company mined diatomaceous earth from the site until about 1950. The Sanitation Districts of Los Angeles County acquired the site in 1956 and since May 15, 1957, have operated a 289 acre sanitary landfill there. To date, the Districts have deposited close to 15 million tons of solid wastes and liquid industrial wastes within the Palos Verdes sanitary landfill.

The initial permit, for Class II (essentially household refuse) landfill operation, was issued to the County Sanitation Districts on April 17, 1957. Filling proceeded at a rate of about 20,000 cubic yards per month until one portion was completed in 1966 when the total weight of material deposited was 4.1 million tons. At present this site is developed as the South Coast Botanical Garden (Section A in Figure 2), a very attractive arboretum.

The present operating landfill lies between the section completed in 1966 and Hawthorne Boulevard (Figures 1, 2). As a result of favorable geohydrological conditions at the current site, the Los Angeles Regional Water Quality Control Board (LARWQCB) has adopted resolutions for waste discharge requirements permitting the Districts to operate this sanitary landfill as a Class I (virtually unrestricted) disposal site. An average of 4810 tons per day or 1.46×10^6 tons per year household, commercial, industrial, and liquid wastes, including hazardous and toxic wastes, are now being deposited. The presence of a large organic fraction and added moisture in the waste makes the Palos Verdes landfill ideal for methane gas generation by anaerobic decomposition.

The Palos Verdes landfill has been the scene for recent experimentation with both a gas migration control system and a gas recovery system. A few years after the start of landfill operations it was determined that refuse-generated gas had migrated across a public street which had been constructed over a portion of the uncompacted mine tailings outside of the site's boundary. The problem was remedied by the construction of a gravel-filled cut-off trench to provide venting for the migrating gases.

Another problem arose in 1971 when a strong odor indicated that gas had begun seeping through a crack in the concrete floor of a Sunday School Church auditorium located about 150 feet outside of the landfill property line. The District's gas survey and monitoring program indicated that landfill gases were seeping through another area of loosely compacted mine tailings to a maximum distance of 250 feet from the fill (Ref. 1). This problem was solved by constructing a gas-collecting, well-withdrawal system along the property line. Eighteen wells were constructed varying in depth from 25-45 feet. The wells were connected by a collection pipeline which terminates in a suction blower and gas burner station. This system has operated successfully for over three years.

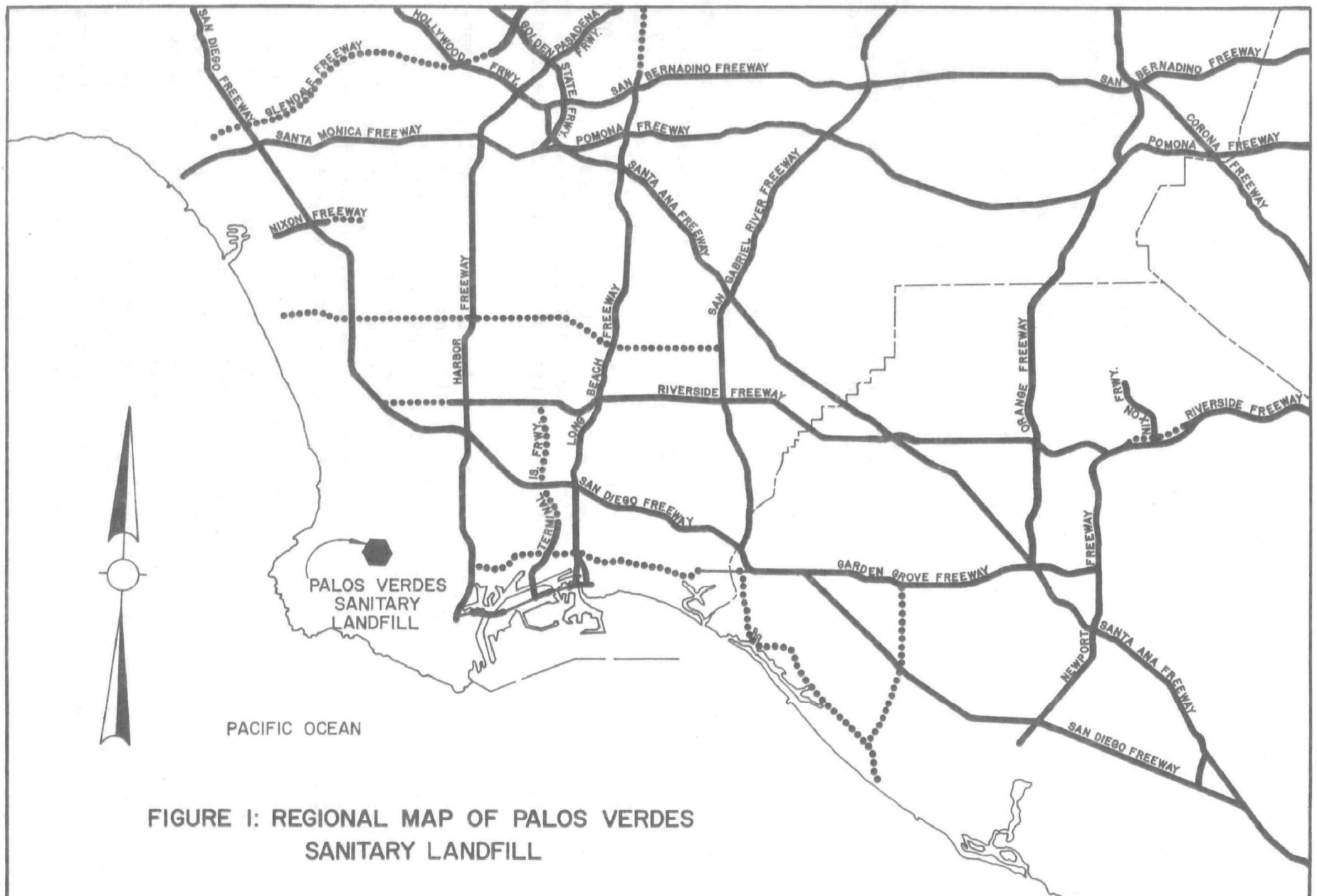

FIGURE I: REGIONAL MAP OF PALOS VERDES SANITARY LANDFILL

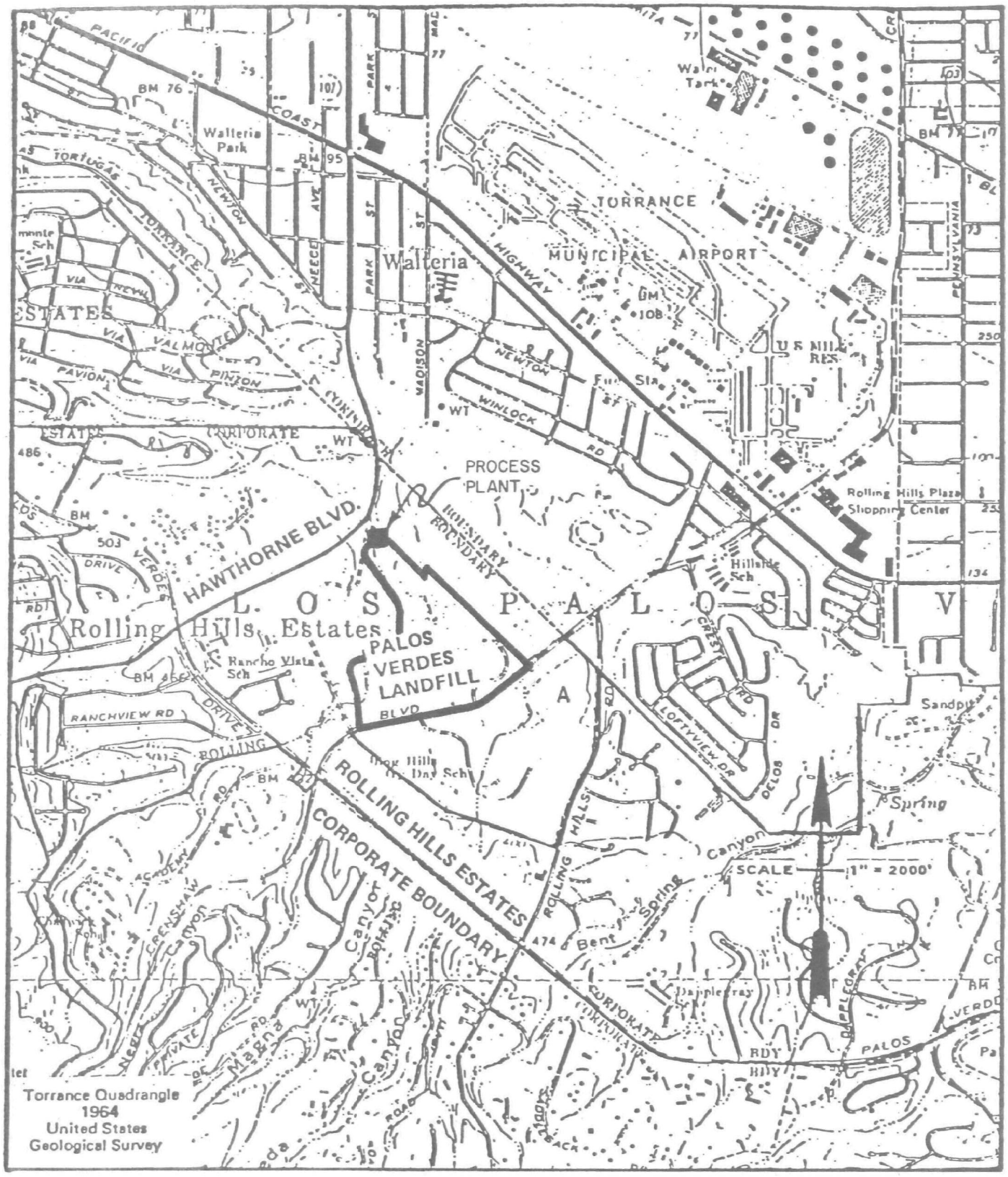

FIGURE 2: SITE LOCATION MAP

As a result of the energy shortage and increasing prices for natural gas, the Districts have instituted a Research Program aimed at recovering gases for useful purposes. In early 1972, a 30-inch diameter experimental gas well (which has since been backfilled) was dug in the refuse to an approximate depth of 110 feet. A steel pipe was used for the well casing with the bottom 80 feet perforated. This well became operative on December 8, 1972. Several parameters were evaluated to design a landfill gas collection system. Initial testing of the system was performed by withdrawing approximately 300 SCFM of the refuse-generated gases using a one horsepower centrifugal vacuum blower. Gas composition during this period was approximately 53 percent methane and 45 percent carbon dioxide with a heating value of 535 Btu/scf.

The Southern California Gas Company, a subsidiary of Pacific Lighting Service Company, indicated a definite interest in the gas if it could be economically purified to meet pipeline standards of 1000 Btu per standard cubic feet. During this time, the Districts contacted the Reserve Synthetic Fuels, Inc. (RSF), previously known as NRG Technology, Inc., Newport Beach, California to discuss possible acquisition of the gas rights. RSF has developed a process for carbon dioxide removal by an adsorption process based on the molecular sieve.

The inability of the Sanitation Districts to guarantee the volume of gas production for a long term basis led to the current contract made with RSF, dated October 31, 1973. The contract requires the Districts to drill a sufficient number of wells so as to provide 1000 SCFM of unprocessed gas to RSF. Under the terms of the contract, RSF shall at no cost to the Districts design and construct all necessary facilities to receive and purify the wellhead gas. The initial program is designed for research and development. If at any point in the program the process proves infeasible, RSF has the right to cancel upon a 30-day notice. The research and development program was set for a 12-month period; afterwards, if the process proves feasible, both parties have agreed to negotiate in good faith for an expanded operation. Should the experiment prove feasible for production of commercial quantities of acceptably high Btu gas, the Southern California Gas Company has indicated it will buy the gas from RSF and feed it into existing nearby pipelines serving peninsula residents. If the negotiations fail to produce an expanded program, the Districts have agreed to permit RSF to continue the 1000 SCFM withdrawal system for an additional four year period in order to recover part of their initial research investment. During this extended four year period, the Districts would share in the royalties received from the sale of the gas, based on 12-1/2 percent of the gross income.

B. Energy Shortage

Total energy consumption in the United States rose from 45 quadrillion (10^{15}) Btu in 1960 to over 60* quadrillion Btu in 1970 and it

*During 1970, the total energy consumption in the United States was approximately 67.5 quadrillion (10^{15}) Btu (Ref. 5).

was predicted in 1970 that usage would top the 90 quadrillion Btu mark in 1980. By the year 2000, the energy demand was predicted to reach 200 quadrillion Btu, Figure 3 (Ref. 2). The natural gas share of the total energy market in the U.S. reached 31 percent in 1968, up from 14 percent in 1947 (Ref. 3). This total energy demand will exhaust the available natural gas resources in the foreseeable future. Therefore, efforts should be made to conserve energy and develop other sources of gas.

Gains in production of natural gas between 1947 and 1968 averaged more than 6 percent a year or from 5.6 to 19.3 trillion (10^{12}) cubic feet. During the same period, reserves increased an average of 2.5 percent annually or from 165 to 282 trillion cubic feet. The reserves-to-production ratio has declined from 29.5 to 14.6 years. By the end of 1969 the reserves were down to 275.1 trillion cubic feet while production rose seven percent to 20.7 trillion cubic feet (Ref. 4). It is estimated that production of gas in 48 contiguous states will be limited to about 27 trillion cubic feet a year from 1974 to 1990. With gas from Alaska, U.S. production could reach more than 35 trillion cubic feet a year by 1990 and hold at this level for nearly 10 more years (Figure 4) before resource depletion would seriously affect production rates of natural gas.

C. Possible Significance of Sanitary Landfill Gas Recovery

The 77 incorporated cities, together with the unincorporated portions of Los Angeles County, have a combined population of approximately 7 million people (at the time of the 1970 census). An average of 30,000 tons of refuse are generated each day and disposed of entirely by landfill methods (Table 1). These landfills are operated by county sanitation districts and by municipal and private authorities (Figure 5).

It is probable that sanitary landfill gas can be collected and used as an energy source by installing a properly engineered gas control and processing system. Each year 10,119,000 tons of refuse are deposited in the Districts' landfills. It is calculated that a sustained yield of 5.12 x 10^9 cubic feet per year of recoverable gases are produced, based on generation capacity of 0.23 cubic feet of gas per year for each pound of refuse (Ref. 6, 7). Since the gas is approximately 50 percent methane, the total generation capacity for methane is approximately 2.5 x 10^9 cubic feet per year or 2.5 x 10^{12} Btu per year. Using a value of $1.00 per million Btu, this amount of energy has a gross value of $2.5 x 10^6 per year.

The total natural gas consumption in the Los Angeles County area is approximately 0.5 x 10^{12} cubic feet per year (Ref. 8). Despite the fact that the energy derived from landfill gas is considerable, the amount is only approximately 0.5 percent of the total natural gas consumption in the Los Angeles County area; this energy derived from solid waste is not a very significant amount to the energy industry. On the other hand, it is a great opportunity for landfill operators to convert a definite liability into a financial asset.

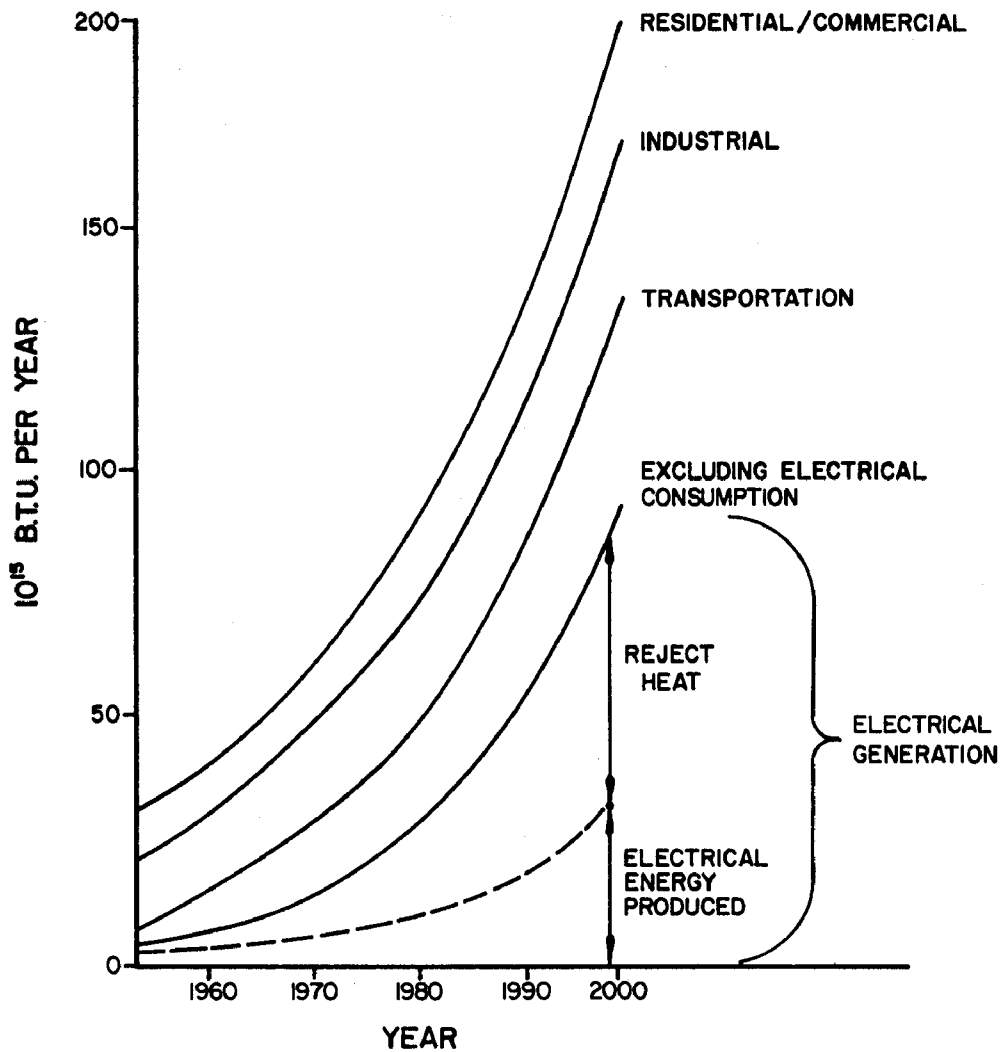

FIGURE 3: FUTURE TOTAL U.S. ENERGY DEMAND (Ref. 2)

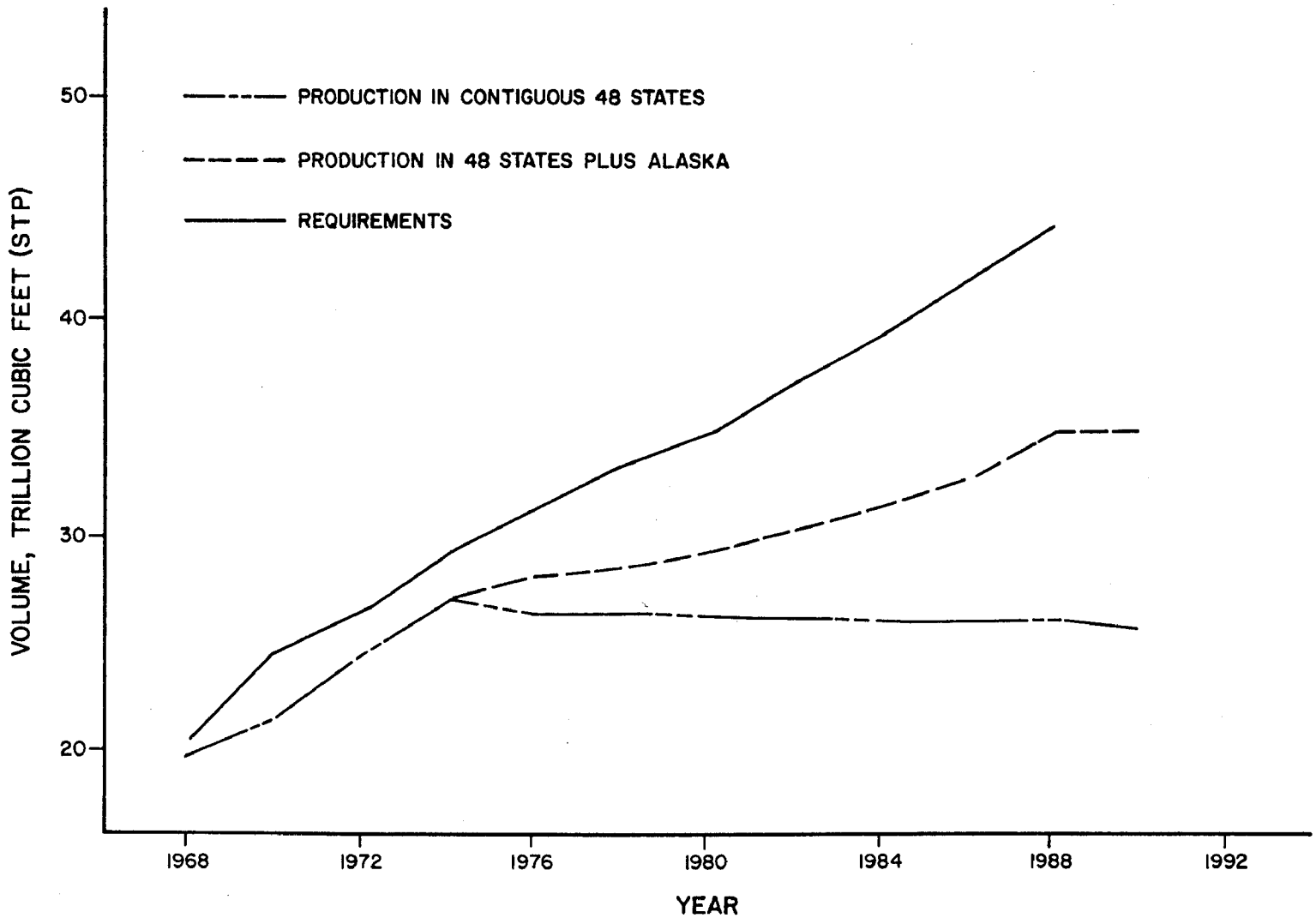

FIGURE 4: FUTURE NATURAL GAS SUPPLIES AND REQUIREMENTS (Ref. 3)

FIGURE 5: EXISTING LANDFILLS IN LOS ANGELES COUNTY

TABLE 1

EXISTING LANDFILLS

LOS ANGELES COUNTY AS OF JUNE, 1973 (Ref. 9)

NO	SITE	TONS/DAY SOLID WASTE	TONS/DAY LIQUID WASTE	TOTAL* TONS/YR	PREDICTED YEAR OF COMPLETION
1	Palos Verdes Landfill	4096	617	1,461,000	1978
2	Sparda Landfill	639	29	207,000	1998
3	Mission Canyon Landfill	4381		1,358,000	2002
4	Scholl Canyon Landfill	1452		450,000	2015
5	Calabasas Landfill	984	90	333,000	2080
6	Puente Hills Landfill	4281	74	1,350,000	2090
7	Sheldon-Arleta Pit	2613**		682,000	1974
8	Toyon Canyon Landfill	2299**		600,000	1976
9	Burbank City Landfill	252		78,000	2001
10	City of Whittier Landfill	352		109,000	1983
11	North Valley Refuse Center	900		279,000	2008
12	Bradley Avenue Dump	1152		357,000	1975
13	Hewitt Pit	1300		403,000	1977
14	Penrose Pit (Replaced Tuxford Pit, Tujunga Pit)	971		301,000	1979
15	Azusa Rock & Sand	1139		353,000	1994
16	Owl Park	200		62,000	1979
17	B.K.K. Co.	1081	719	558,000	2176
18	Operating Industries	2361	339	837,000	1975
19	ASCON	961	139	341,000	1975
	Total***			10,119,000	

* Based on 310 operating days per year (6-day week)

** Based on 261 operating days per year (5-day week)

*** Does not include 131,000 tons per year of solid waste disposed of in minor sites in Los Angeles County

D. Project Objectives

Various types of field investigations are required to evaluate the operation of a landfill gas extraction system and determine the potential quality of gas which can be used as a new energy source. In this project, the Palos Verdes landfill gas recovery and purification system is evaluated with emphasis on the following objectives (presented in this report as separate chapters):

1. Develop a landfill evaluation system based on landfill physical and operating parameters that are significant in gas generation and recovery.

2. Evaluate the physical parameters important in Palos Verdes landfill gas generation and recovery.

3. Evaluate the operating conditions for gas withdrawal such as, drilling of wells, collection system, withdrawal rate, amount of vacuum required to produce gas at a given withdrawal rate, gas composition, radius of influence (spherical, to determine the number of wells required at a particular landfill site), and total energy production capacity. The discussion will be totally based on the Los Angeles County Sanitation Districts' experimental findings.

4. Evaluate the basis for selection of techniques for gas beneficiation. General techniques for gas beneficiation will be discussed. The criteria for the design of the adsorption system will also be discussed.

5. RSF's commercial experience in landfill gas extraction and purification to boost the heating value to pipeline standards (1000 Btu/scf). The discussion is limited by the information provided by RSF, Inc., Newport Beach, California.

6. General discussion on the safety precautions required against fire and explosion in operating a landfill gas recovery and purification system.

A discussion on cost analysis for a gas recovery and purification system is not included in this report because of the unavailability of critical information which concerned organizations thought to be proprietary. Readers interested in this topic may find a paper prepared by Pacific Gas and Electric Company (Ref. 10) of real value.

CHAPTER II

LANDFILL EVALUATION SYSTEM FOR METHANE RECOVERY

Sanitary landfilling is the most popular method utilized for disposal of both inorganic and organic solid waste. The organic waste disposed of in this manner undergoes decomposition. Initially, as decomposition proceeds, the organic matter is utilized in the metabolism of aerobic microorganism. Carbon dioxide and water are formed through consumption of the oxygen trapped in the fill. After the atmospheric oxygen is used up, anerobic decomposition of the waste results from fermatative reactions that produce methane and carbon dioxide. The amount and composition of these gases of decomposition depends upon the physical conditions existing in the landfill.

The recovery of methane for useful purposes requires development of a landfill evaluation system. The purpose of this system is to evaluate the following:

1. Gas generation, both total and time-dependent.

2. The percentage of the total gas generated that is actually recoverable.

3. Operating parameters for a gas recovery system to extract a high percentage of methane from a landfill without reducing the overall production rate.

4. The variation in gas compositions and production rate.

5. The actual life of a well, operating under forced withdrawal conditions.

It is the purpose of this chapter to establish and discuss parameters important in a landfill evaluation system for methane gas recovery. A procedure is developed that can be followed to evaluate the potential recovery of landfill methane gas.

A. Refuse Characterization

The total gas generation depends on the types and amount of waste deposited in the fill. An estimate of methane gas production requires the characterization of waste in terms of total organic carbon and volatile solids. The presence of a high proportion of organic carbon and volatile solids in the waste increases the volume of gas generation. The bacteria responsible for organic waste decomposition also requires a certain amount of nitrogen and phosphorous to obtain growth and methane production.

The solid waste composition is not only hetrogeneous, but also varies with regard to seasonal and climatic changes. The precise and accurate characterization of waste in terms of the above parameters requires a proper selection of sampling and sample preparation procedure. Klee and Carruth (Ref. 11) have developed a statistical method that may represent the weight and composition of waste with a minimum degree of variance. Their technique is based on the concept of random sampling.

Figure 6 illustrates a sample preparation procedure that may be used for refuse characterization. Three different groups* of samples are collected from a truck load of solid waste. The desired weight of samples are obtained from different waste pile locations. Initially, samples are dried at 70° C. The selection of a low temperature is to prevent possible loss of volatile organics. Each group of samples is separately ground and pulverized until all of the particles can be passed through a No. 60 sieve. It is assumed that after this process all samples are homogeneous. Each group of samples are further subdivided into three groups and analyzed for different parameters.

B. Solid Waste Processing

It is a general landfill practice to deposit wastes in whatever condition they are collected. These wastes may consist of a variety of materials ranging from organic waste residues to a wrecked car or dead animals. In the interest of recovering methane gas from a landfill, it may prove cost-effective to remove metalic, refractory organic (plastic, tires, etc.), and inorganic wastes before filling.

In order to enhance the rate of gas generation and possibly the in-place density, it may prove cost-effective to grind the solid waste before filling. The rate of waste decomposition is a function of the surface area of the particles; a large surface area will most likely increase the rate of gas generation.

C. Fill Characterization

The fill characterization is performed to generate information such as the degree of waste decomposition, moisture content, and level of nitrogen and phosphorous present to support bacterial growth. The samples are collected at various fill depths during well drilling. Fill characterization is determined by analysis of sample taken according to the sample preparation scheme described in Figure 7.

D. Potential Total Gas Production

An estimation of potential total methane gas production may be made from the characterization of waste in terms of volatile solids content. However, a theoretical estimate may be made from the total organic carbon content in the solid waste. A small portion of the total organic carbon will be

*The number of samples selected here is arbitrary. According to Klee (Ref. 11) this parameter should be estimated based on the standard deviation of a system. His findings on solid wastes indicated that sixteen number of samples of 200 pounds each will provide reliable results.

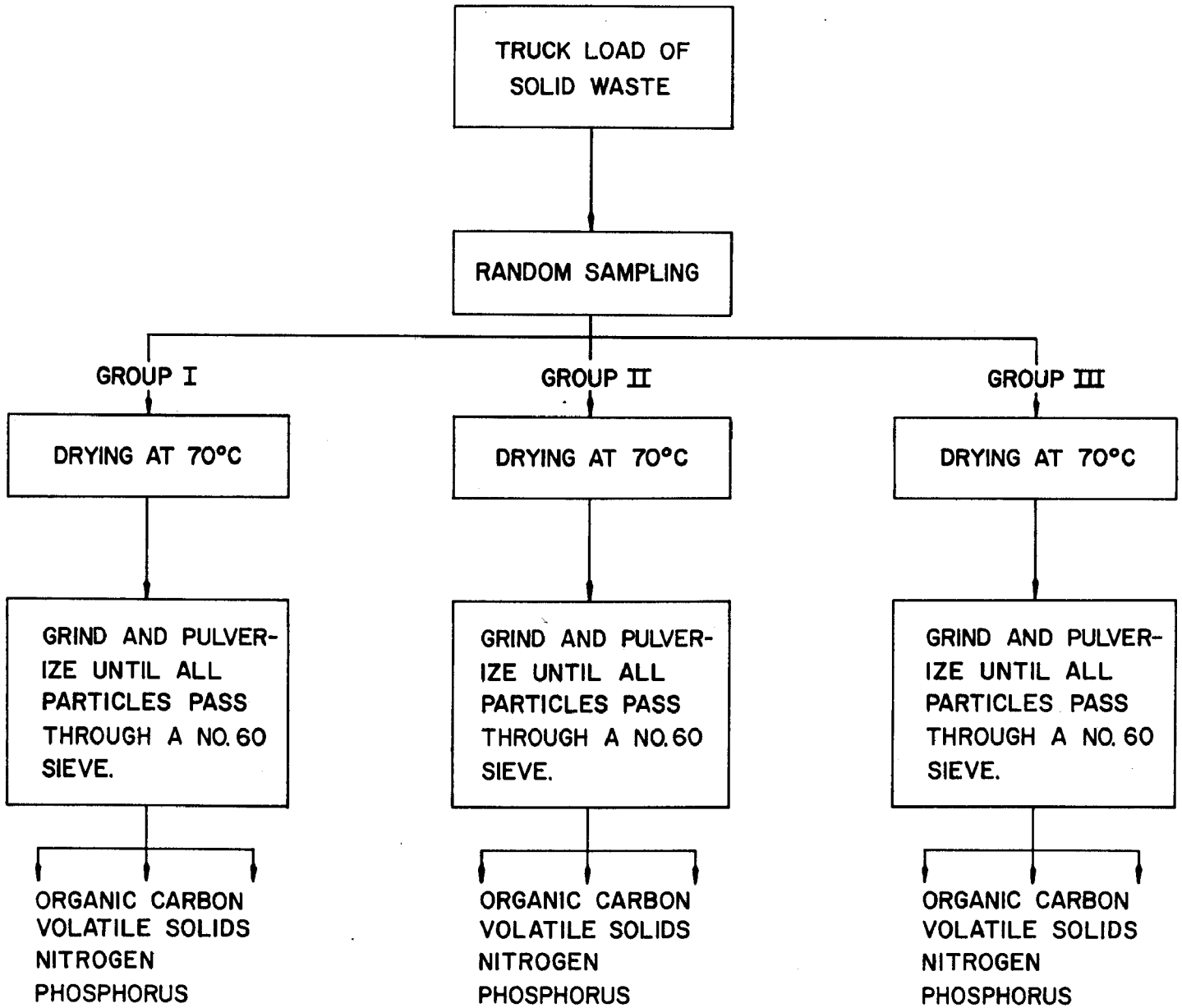

FIGURE 6: SAMPLE PREPARATION SCHEME FOR "AS RECEIVED" SOLID WASTE CHARACTERIZATION

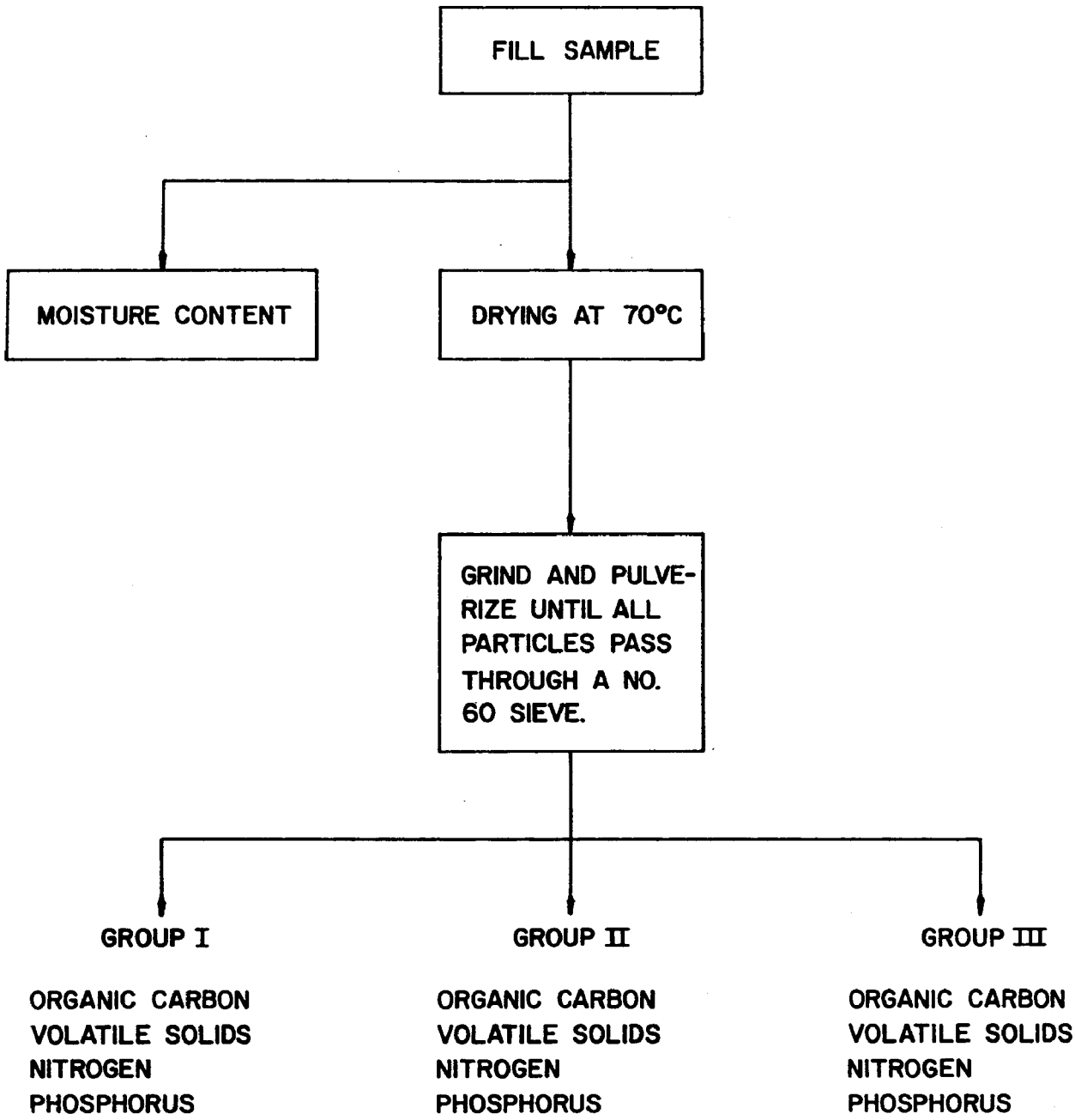

FIGURE 7: SAMPLE PREPARATION

SCHEME FOR FILL CHARACTERIZATION

used for bacterial cell formation, but most will be converted into methane and carbon dioxide. The balance between the two depends upon the environmental conditions. Under landfill conditions this parameter has yet to be determined; therefore, the loss of carbon to bacterial cell formation will not be included in the following calculations. Table 2 illustrates the typical organic carbon, nitrogen, and hydrogen content in different solid waste categories (Ref. 12). That reference determined that each pound of particular sample of dry refuse contained approximately 0.25 pounds of organic carbon.

Theoretically one mole of organic carbon will produce one mole of methane and carbon dioxide mixture. Therefore, gas generation by decomposition of one pound of organic carbon will be as follows:

$$= \frac{nRT/p}{1 \text{ mole} \times 12 \frac{\text{Pound}}{\text{mole}}} = \frac{(1.31)\ (298)}{12} = 32.5 \frac{\text{Cubic feet of } CH_4 \text{ and } CO_2}{\text{Pound of Carbon}}$$

where,

n = Moles of methane and carbon dioxide mixture

R = Gas constant

T = Absolute temperature, ^{o}K

p = Pressure, Atm.

or, $(0.25)\ (32.5) = 8.1 \frac{\text{Cubic feet of } CH_4 \text{ and } CO_2}{\text{Pound of Dry Refuse}}$

The gas production is time-dependent. The rate of gas generation depends on refuse characteristics; the decomposition of refractory organic carbon compounds will be extremely slow and decomposition might take 100 years or more. Therefore, actual gas production rates should be estimated based on the kinetics of gas generation.

E. Kinetics of Gas Generation

The rate of gas generation is a dynamic process responding to various physical parameters such as the concentration of oxygen present, moisture contact of the fill, temperature, and surrounding pH. The landfill gas production life may range from a few years to hundreds of years, depending upon these environmental conditions and the characteristics of the fill material.

TABLE 2

AVERAGE REFUSE COMPOSITION - HEMPSTEAD, NEW YORK

Category	% by Weight (wet)	Amount of dry weight	% by Weight (dry)	% Carbon (dry basis)	% Nitrogen (dry basis)	% Hydrogen (dry basis)
Cardboard	5.33	0.8316	4.43	2.02	0.0071	0.324
Newspaper	13.81	0.765	10.56	5.11	0.015	0.85
Misc. Paper	24.16	0.7365	17.79	7.83	0.076	1.485
Plastic	2.83	0.8512	2.41	1.62	0.029	0.275
Garbage	11.13	0.3644	4.06	1.69	0.11	0.64
Grass	17.94	0.6206	11.13	4.03	0.23	0.852
Textiles	3.2	0.7621	2.44	1.13	0.053	0.205
Wood	3.24	0.8558	2.77	1.34	0.008	0.193
Mineral	9.73	0.9704	9.44	0	0	0
Metallic	8.63	0.934	8.06	0	0	0
	100		73.09	24.77	0.528	4.82

Source: "Municipal Refuse Disposal" American Public Works Association (Ref. 12)

The actual kinetics of landfill gas generation is as yet unknown. A theoretical concept may be developed, based on the assumption that a typical solid waste falls in three categories such as readily decomposable (food, grass etc.), moderately decomposable (paper, wood, textile etc.), and refractory materials (plastic, rubber etc.). The metallic and mineral wastes do not enter into the gas generation. With an assumption that half-lives, the time required to produce 50 percent of the total estimated gas for categories such as readily decomposable, moderately decomposable, and refractory materials are 1, 2, and 20 years respectively, by the end of 3-1/2, 6, and 60 years, 99 percent of the total estimated gas will be produced.

Mathematical formulation is based on an assumed concept of two-stage gas generation (Ref. 13). It is represented by a discontinuous unimolecular reaction (first order) defined as constant rate of increase followed by a discontinuous equation of constant rate of decrease. The first stage is characterized by the following equation:

$$\frac{dG}{dt} = K_1 G, \quad \text{or} \quad \ln G = K_1 t + \ln C_1 \qquad (1)$$

and second stage by:

$$\frac{dG_t}{dt} = -K_2 G_t, \quad \text{or} \quad \ln G_t = -K_2 t + \ln C_2 \qquad (2)$$

where,

G = Amount of gas produced in time t

G_t = Amount of gas remaining to be produced after decomposition has proceeded for time t

L = Total amount of gas to be produced

K_1 & K_2 = Gas generation rate constants

C_1 & C_2 = Constants of integration

At the point of inflection ($t = t_t$) when half of the total estimated gas production has been reached ($G = G_t = L/2$), the equation number 1 and 2 are reduced to form:

$$\ln \frac{L}{2} = K_1 t_t + \ln C_1 \qquad (1a)$$

$$\ln \frac{L}{2} = -K_2 t_t + \ln C_2 \qquad (2a)$$

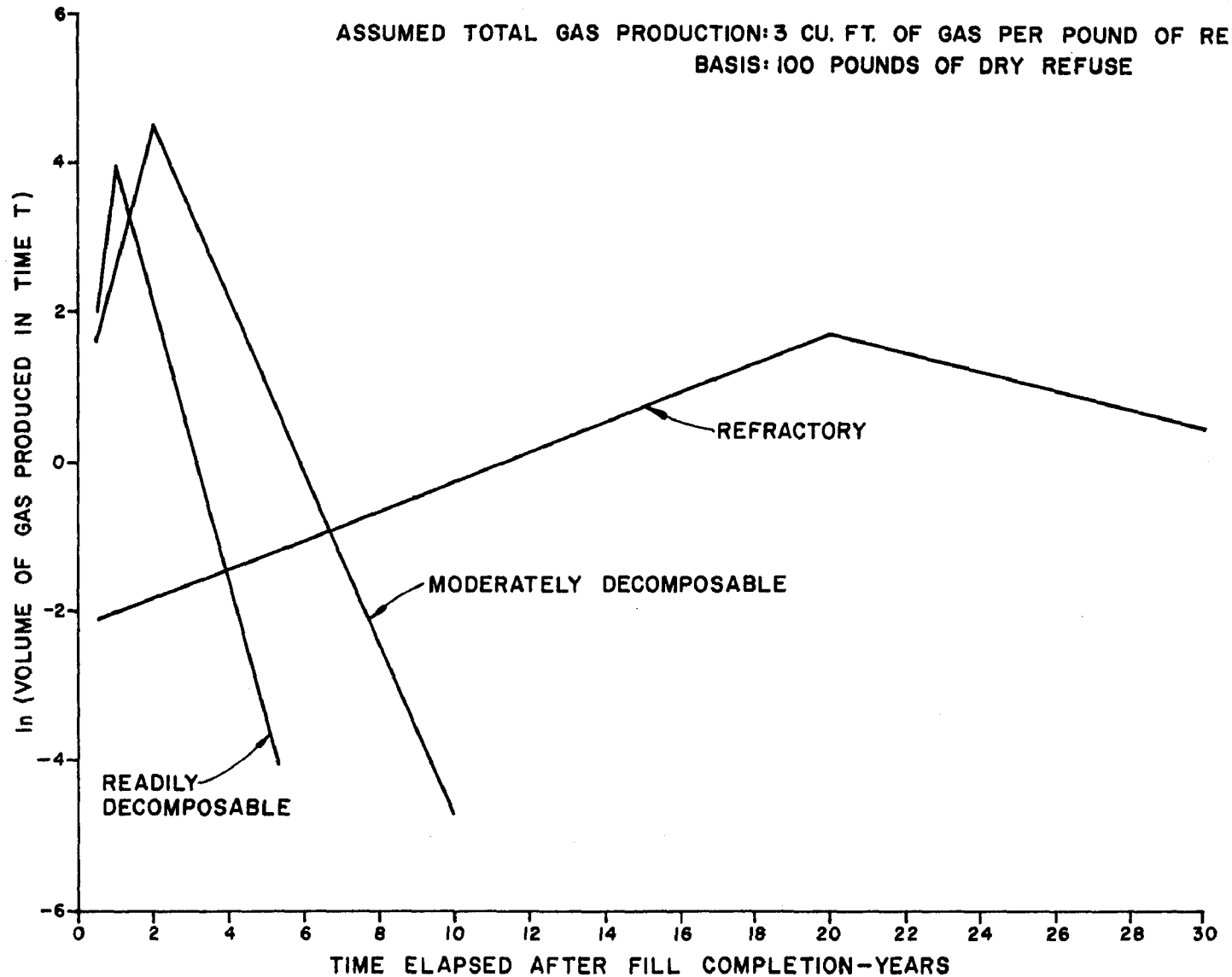

FIGURE 8: PLOTS OF THEORETICAL TWO-STAGE GAS GENERATION FROM DIFFERENT CATEGORIES OF SOLID WASTE

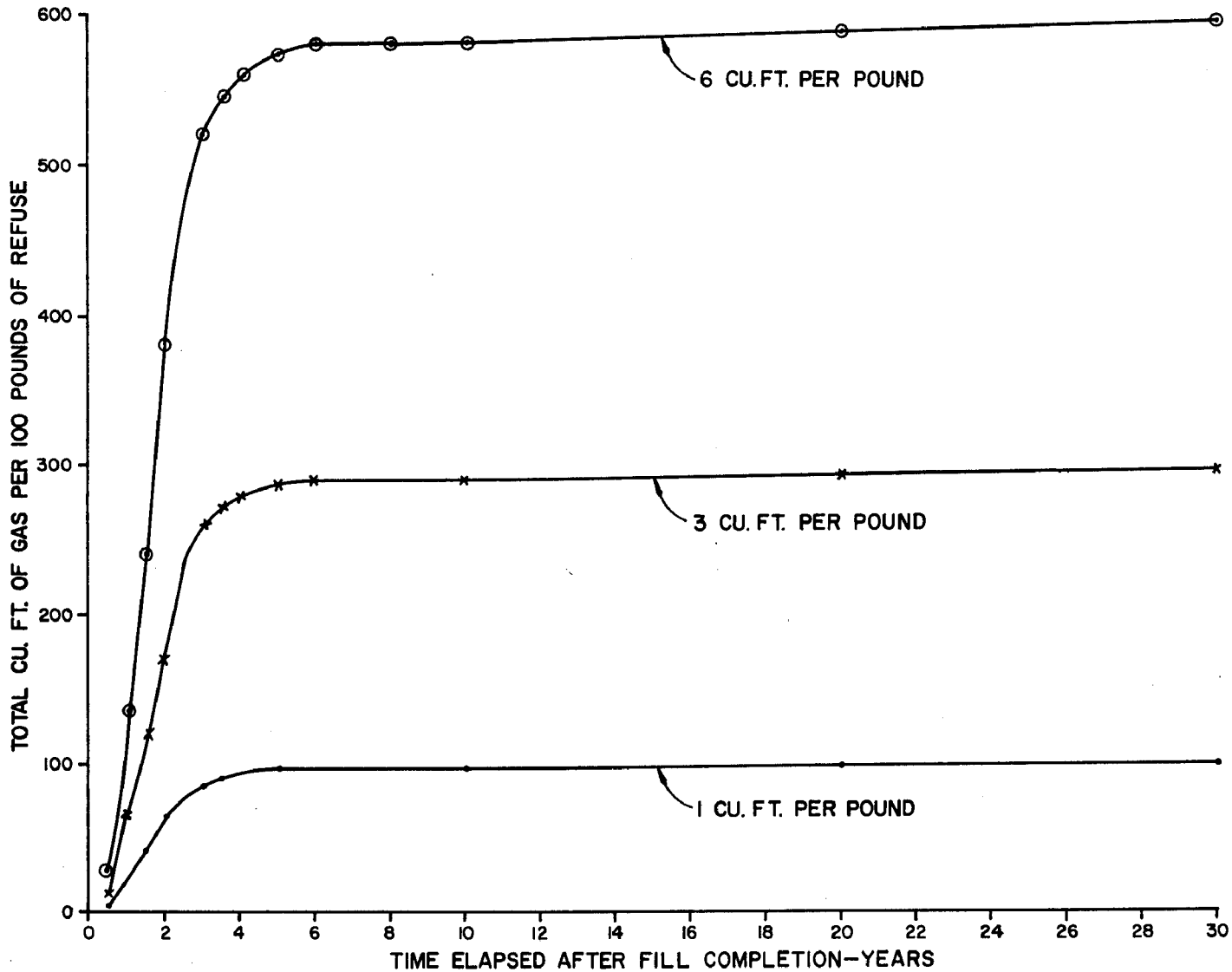

FIGURE 9: PLOTS OF THEORETICAL COMMULATIVE GAS GENERATION

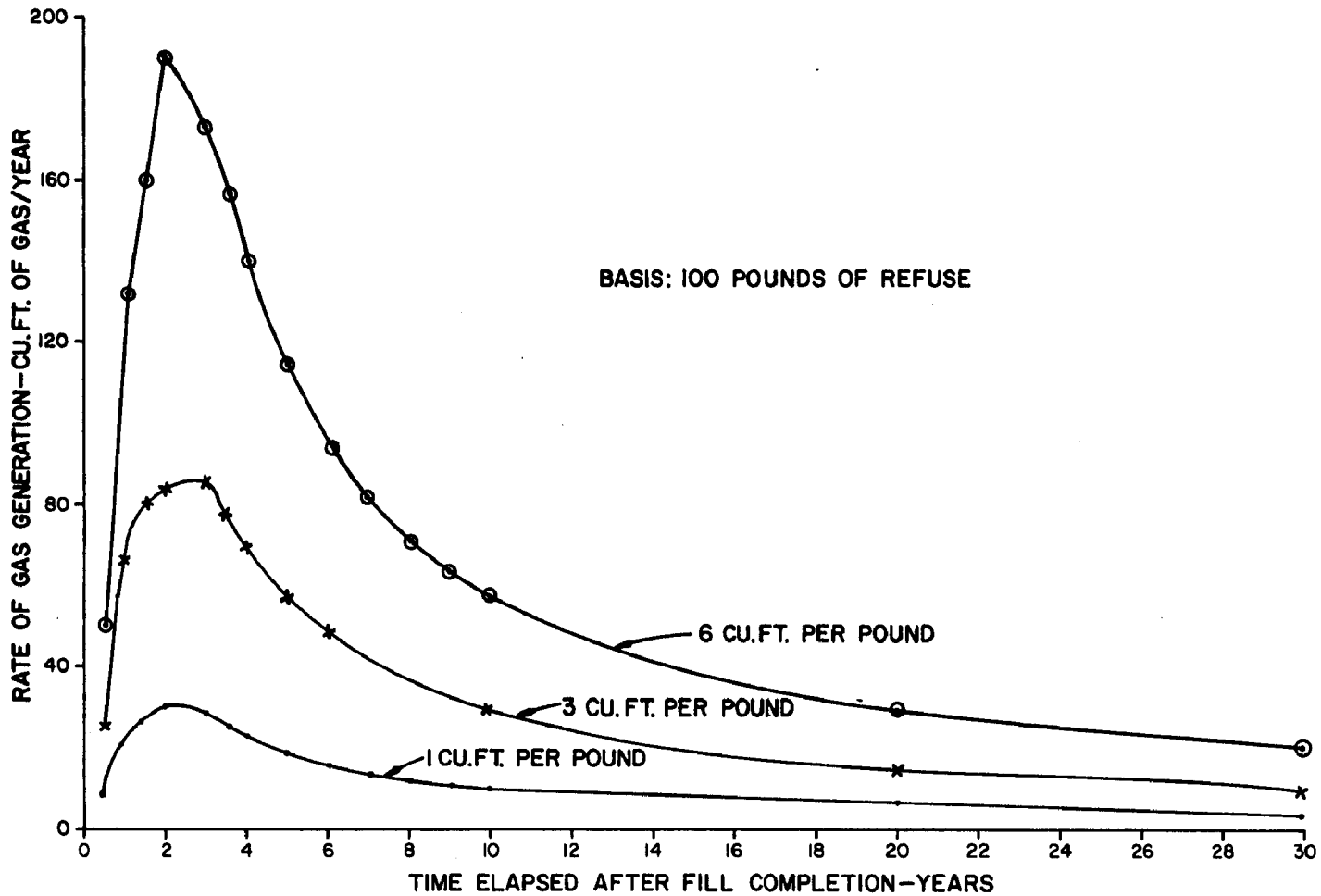

FIGURE 10: PLOTS OF THEORETICAL RATES OF LANDFILL GAS GENERATION

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The combination of 1 with 1a and 2 with 2a provides the following equations:

$$\ln G = \ln\frac{L}{2} - K_1 (t_t - t) \qquad (3)$$

$$\ln G_t = \ln\frac{L}{2} - K_2 (t - t_t) \qquad (4)$$

A sample solid waste composition is shown in Table 3. It does not include mineral and metallic content in the solid waste. Based on total gas production and composition, the maximum possible gas generation by anaerobic decomposition of each category of solid waste was estimated. First order rate constants were calculated based on half-lives and maximum time required to produce total estimated gas.

Equations 3 and 4 are plotted as a straight line, lnG vs. t. For purposes of illustration, the calculations are made for an assumed total gas production of three cubic feet of gas per pound of dry refuse. As shown in Figure 8, the gas production becomes discontinuous at the point of intersection or at the half-life. The constants of the equation K_1 and $\ln C_1$ for both first and second stages are given, respectively, by the slope of the line and its intercepts on the Y-axis at t = 0.

The gas production with respect to time at selected total gas production capacities of 1, 3, and 6 standard cubic feet of gas per pound of dry refuse is shown in Figure 9. Within six years after the refuse placement, approximately 95 percent of the total gas is produced. After that, gas production capacity tails off and economical considerations will not permit the continuation of gas recovery operation.

Figure 10 shows the rate of gas generation with respect to time, calculated at various assumed gas production capacities. As expected, the production will start with a small, but recognizable generation rate. The theoretical curves indicate that approximately one percent of the total expected gas production is generated during filling operation. After the landfill has become completely anaerobic, methane is produced at an increased generation rate until it reaches a maximum. Theoretical calculations indicate that within two to three years after the fill completion, the methane generation rate reaches its peak. At this point approximately half of the total estimated gas has been produced. The remaining gas is produced at a decreasing generation rate.

The kinetics of gas generation is theoretically estimated and cannot be reasonably extrapolated to all possible landfill conditions. However, a landfill with an optimal moisture content (50-60 percent on wet weight basis is often reported in the literature) will probably not show significant discrepancies from the theoretically predicted kinetics.

TABLE 3

MATHEMATICAL FORMULATION OF LANDFILL GAS GENERATION
(Ref. 12 for Solid Waste Composition)

Solid Waste Characteristic	Solid Waste Composition (Percentage)	Half-Lives (Years)	Rate Constants $(Year)^{-1}$	$\ln G = \ln\frac{L}{2} - K_1 (t_t - t)$ $\ln G_t = \ln\frac{L}{2} - K_2 (t - t_t)$
Readily Decomposable	35.4	$t_t = 1$ $[t_{max} = 3\text{-}1/2]$	$K_1 = 3.9$ $K_2 = 1.84$	$\ln G = 0.07 + 3.9t$ $\ln G_t = 5.81 - 1.84t$
Moderately Decomposable	61.0	$t_t = 2$ $[t_{max} = 6]$	$K_1 = 1.96$ $K_2 = 1.15$	$\ln G = 0.6 + 1.96t$ $\ln G_t = 6.82 - 1.15t$
Refractory	3.6	$t_t = 20$ $[t_{max} = 60]$	$K_1 = 0.196$ $K_2 = 0.115$	$\ln G = 0.196t - 2.21$ $\ln G_t = 4.01 - 0.115t$

t_t = Half-life, time required to produce 50 percent of the total estimated gas.

t_{max} = Maximum time required to produce 99 percent of the total estimated gas.

Basis: 100 pounds of dry refuse

3 standard cubic feet of gas per pound of dry refuse (assumed).

Total Estimated Gas = 300 cubic feet.

F. Gas Recoverability

The actual recovery of predicted methane gas production is of particular concern in a landfill evaluation. The gas recoverability depends on the following parameters:

1. The loss of gas prior to recovery operations.

2. The loss of gas caused by migration through the cover material and sides.

3. The amount of gas which is not recovered as a result of poor economics in continuing recovery operation after the production rate tails off in later years.

The loss of landfill decomposed gases to the surrounding environment occurs by the following two basic processes: convective flow in response to pressure gradient; molecular diffusion, migration from high gas concentration to low gas concentration regions (Ref. 14, 15, 16). In a landfill where the compacted solid waste and surrounding soil are of high permeability, the gas migration is as a result of pressure gradient. The methane lost by this process not only creates fire hazard problems in near-by properties, but CO_2 also enters groundwaters and creates a weak carbonic acid. The quantitative determination of gas migration requires an investigation to determine permeabilities of cover soil and side and bottom soil.

To study potential gas generation, the landfill must be considered as a closed system (Figure 11). An impermeable liner is theoretically used to cover top, sides, and bottom of the fill. The gases generated inside the fill by waste decomposition are withdrawn at the rate of their generation. Under these circumstances the only possible loss is as a result of molecular diffusion of gases. This loss is very small compared to the convective migration.

G. Evaluation of Operating Parameters for Landfill Gas Extraction

The maximization of potential gas and energy production requires the evaluation of several operating parameters. A thorough field investigation is required to determine optimal conditions for landfill gas extraction without degrading the quality of the gas. The method utilized for gas recovery is by pumping from extraction well. This will establish a pressure gradient on a landfill, causing the gases produced in a region to flow into the well. At the same time it may also create enough negative pressure to allow atmospheric gases to flow into the fill through the cover soil. Aerobic oxidation in the presence of atmospheric oxygen will increase the carbon dioxide content resulting in low quality landfill gases. An effective gas withdrawal system requires development of an evaluation system addressing the number, size, and depth of wells that can be located at certain portions of the landfill with maximum system efficiency. The development of such a landfill gas extraction system requires experimental evaluation of the following parameters:

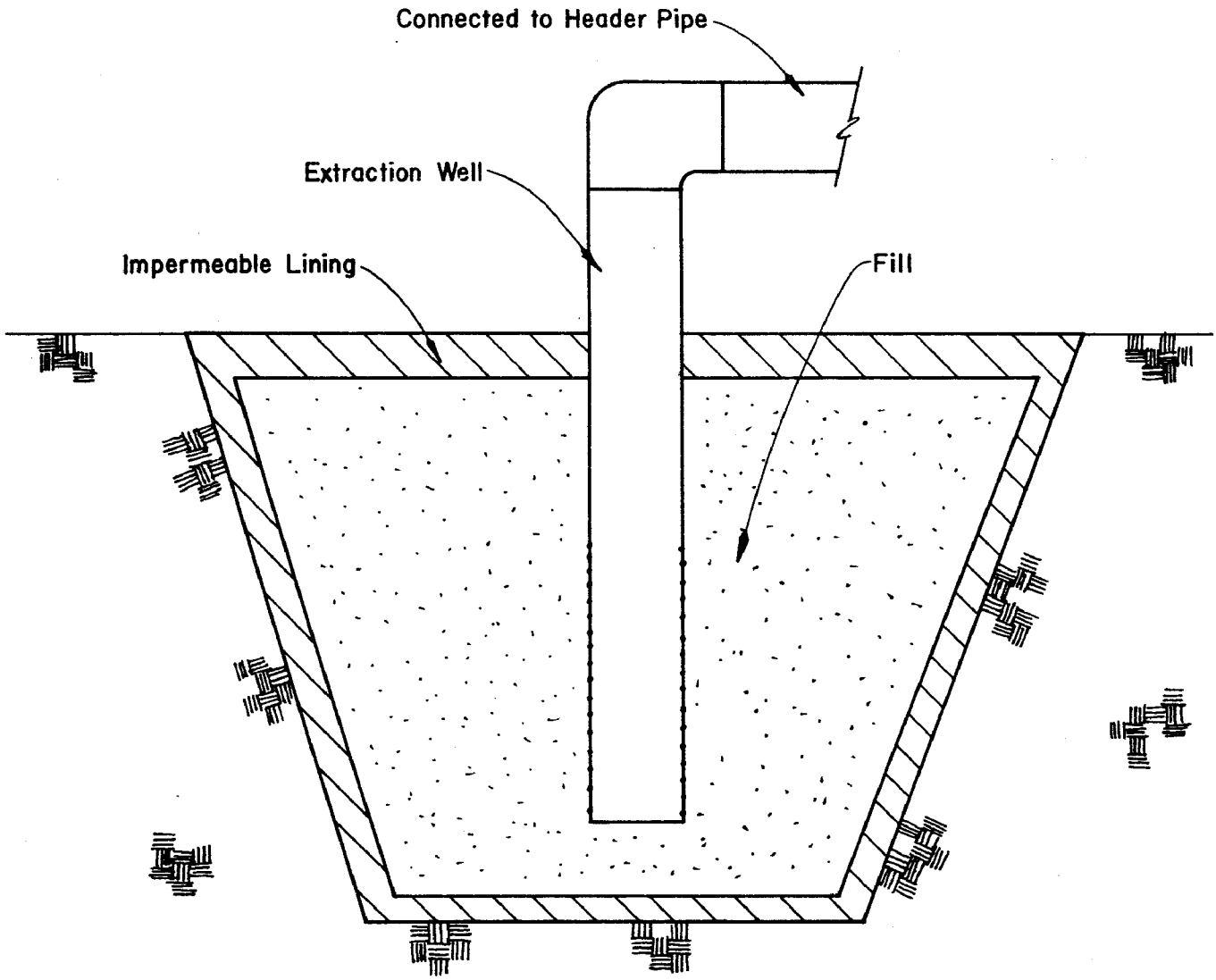


FIGURE II:
SCHEMATIC DRAWING OF HYPOTHETICALLY IDEAL
LANDFILL GAS RECOVERY SYSTEM

1. Selection of a "safe" withdrawal rate that can extract landfill gases with maximum heating values.

2. Establish a differential pressure gradient to assure scavenging of the landfill gases without interfering with the adjacent wells. This will determine the radius of influence.

3. Optimization of energy required to operate a landfill gas withdrawal system.

4. Determination of number of withdrawal wells that can be located at a certain landfill configuration.

5. Total possible energy production from a gas withdrawal system.

The evaluation of these parameters requires a thorough field investigation. An experimental well should be constructed at a portion of the landfill not older than one year, preferably within an age of six months to one year. This selection is based on the assumption that a well-compacted and covered landfill becomes completely anaerobic within six months of completion. The bottom three-fourths of the experimental well should be perforated. Materials of construction should be resistant to carbonic acid. The well should be provided with a sampling device so that gases can be extracted at various well depths. The experimental well should also be equipped with various instruments to measure temperature, flow rate, and absolute pressure. Around experimental well, various monitoring wells are constructed to determine the pressure distribution at various landfill locations (Figure 12).

Table 4 describes the schedule for operating parameter evaluation. The described order of performance should be used to conduct the evaluation tests. Prior to and after gas extraction, gas composition and landfill pressure distribution are determined. This static test is performed to determine the change caused in landfill gas quality parameters by gas extraction (if any).

The purpose of the short-run test is to establish the initial data on gas composition, landfill pressure distribution, and radius of influence at various withdrawal rates and well depths. As indicated earlier, gas composition is a function of withdrawal rate. The optimal situation would appear to be to extract the gases at the rate of generation. Under this circumstance not enough gradient would be developed between cover soil and fill to allow atmospheric gases to penetrate. Experimentally, this value may be determined by conducting a test for about 7 to 15 days at each of several selected withdrawal rates. During this test gas composition and heating values are determined. The maximum withdrawal rate that produces gases with suitable constant heating value should be selected for a long-run test. This test should also be conducted at various well depths to minimize the total energy required to operate the gas withdrawal system. The recovery of the greatest practical amount of gas in a landfill requires construction of a number of extraction wells. The well spacing at a

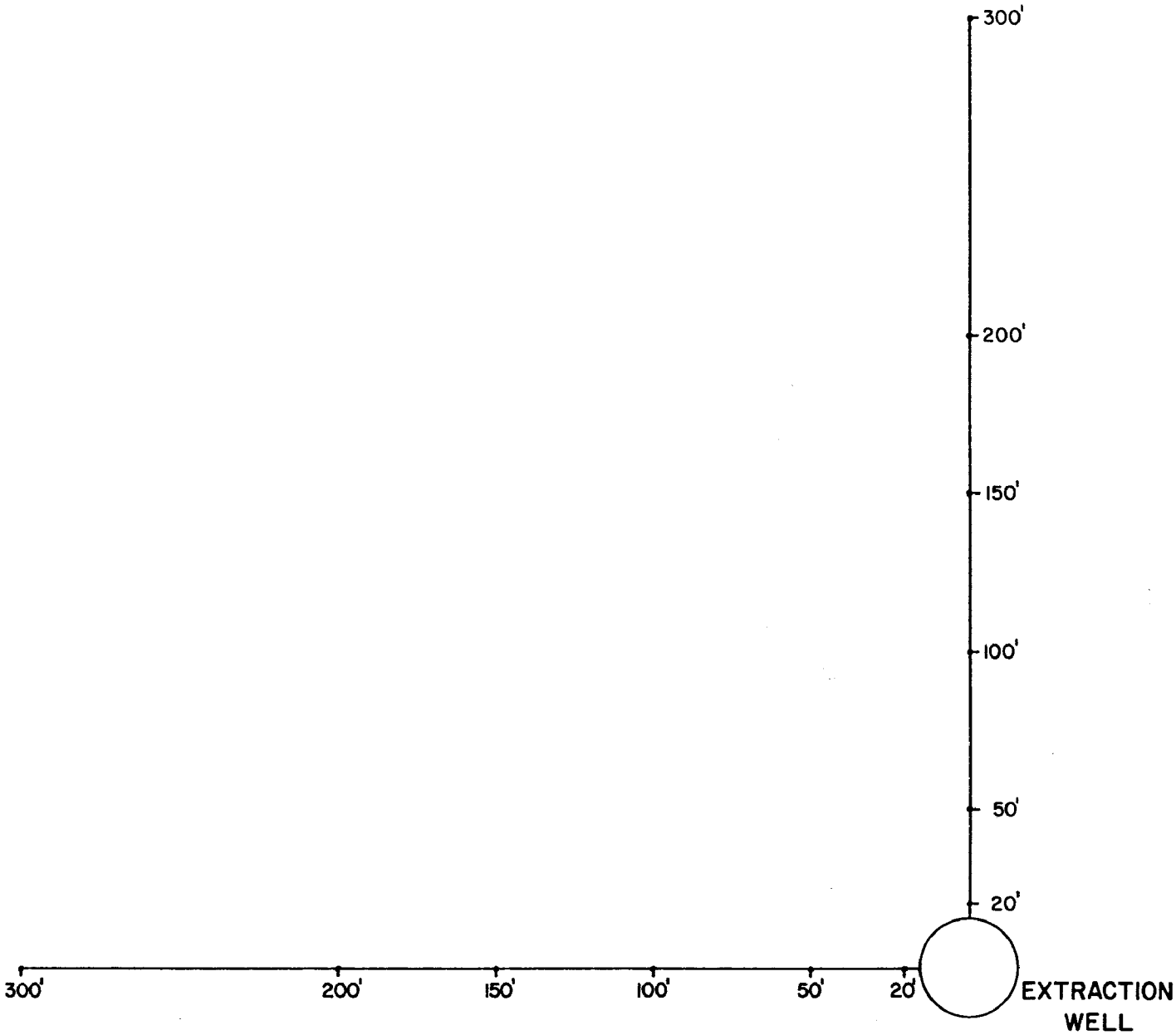


FIGURE 12: EXTRACTION AND MONITORING WELLS LOCATIONS AT A SELECTED PORTION OF THE LANDFILL

TABLE 4

SCHEDULE FOR OPERATING PARAMETERS EVALUATION

CODE	MODE OF TEST	PARAMETERS	DAYS REQUIRED
A	Static	Landfill pressure profile and gas composition prior to initial extraction	7*
B	Short-run	At different withdrawal rate and well depths, evaluate: (1) Extraction well and monitoring wells pressure distribution, (2) Gas composition	Each withdrawal rate and selected well depth will take approximately 7 to 15 days
C	Static	Same parameters as in "A"	7
D	Long-run	At the selected withdrawal rate: (1) Gas composition, (2) Heating values, (3) Stability of withdrawal rate	150 to 180 days
E	Static	Same parameters as in "A"	7
F	Life of a well	Same parameters as in "D"	

*The time schedule selected for operating parameter evaluation is arbitrary. It may vary from landfill to landfill depending upon fill depth, and chemical characteristics of waste deposited.

particular landfill configuration is determined by obtaining the pressure distribution data at a given withdrawal rate. The distance at which there is no pressure effect from gas extraction (pressure gradient is approximately zero) is called the neutral point and the distance between the well and this point is called the radius of influence.

The long-term test is conducted by continuous extraction of gases from a well at its production rate for a long period of time. This evaluation test will provide information such as reliability and quality and quantity of gas production from a well located at a particular landfill site. The satisfactory performance of a landfill gas recovery system depends on the following factors:

1. Minimize variations in gas composition during entire extraction period.

2. Practical life of a well operating under forced withdrawal conditions.

From the point of view of meeting a total energy requirement, as well as designing a purification plant, it is important to have an idea about variation in gas composition extracted from a landfill. The economic feasibility of a gas recovery system can be determined, based on the life of a well during which a selected desirable withdrawal rate can be sustained.

CHAPTER III

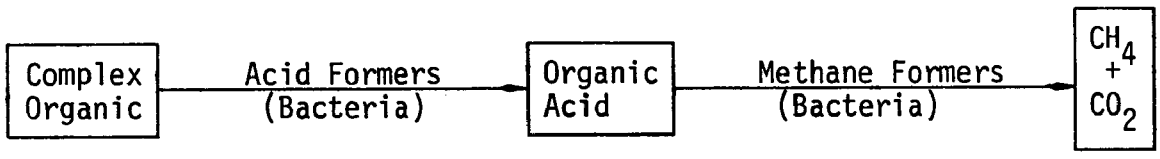
EVALUATION OF PHYSICAL PARAMETERS AT PALOS VERDES LANDFILL

Initially, as decomposition proceeds, the organic matter is utilized in the activity of aerobic micro-organisms. Carbon dioxide and water are formed during the consumption of the oxygen initially trapped in the fill. Following are the typical oxidation reactions for carbohydrates and fatty materials (stearic acid):

$$C_6H_{12}O_6 + 6\ O_2 = 6\ CO_2 + 6\ H_2O$$

$$C_{18}H_{36}O_2 + 26\ O_2 = 18\ CO_2 + H_2O$$

After all atmospheric oxygen is used up, anaerobic decomposition of the waste results from fermentative reactions that produce methane and carbon dioxide gases. The overall anaerobic decomposition of complex organic materials can be represented by the following two-step process:



In the first step, both facultative and anaerobic bacteria, known as the "acid formers", act upon complex organic material such as fats, proteins, cellulose, and carbohydrates and convert them to short chain organic acids. This step is an essential prerequisite for the second step in which the formation of methane occurs.

In the second step, short chain organic acids are decomposed by a strictly anaerobic group of bacteria, known as the "methane formers", and converted to gaseous methane and carbon dioxide end products.

Under optimum operating conditions, a proper balance between the two steps can be established to produce the maximum methane formation. The important operating parameters are generalized below:

<u>Strict Anaerobic Conditions</u> The methane generating bacteria are obligate anaerobes and even small amounts of free oxygen can be quite detrimental to them. At Palos Verdes landfill where waste deposits are up to 125 feet deep, the existence of anaerobic conditions can be assumed.

Temperature Two optimum temperature levels have been established for methane formation. The mesophilic temperature ranges from 26° to 37.5° C; thermophilic temperatures range from 50 to 55 C (Ref. 17).

Moisture Content Volume of gas production is related to the moisture content of the refuse deposit. Merz (Ref. 7) has indicated the effect of moisture content in gas production by conducting an experiment containing 15 tons of refuse in a 10,000 gallon underground storage tank. About 39.3 cubic feet of gas were produced during the first three days after sealing. However, gas production was negligible by the end of 60 days and continued so until about the 230th day. Thereafter, production was resumed by addition of 450 gallons of water to a moisture content of 69.9 percent, dry weight basis. A total of 2025 cubic feet of gas were produced during the period of 230 to 530 days after initiation.

pH Anaerobic decomposition can proceed quite well with a pH varying from about 6.6 to 7.6 with an optimum range of about 7 to 7.2. At a pH of 6.2 and lower, the acid conditions become toxic to the methane formers. This will result in a drop in methane production, if not death of the methanogens.

Nutrient Availability The bacteria responsible for waste decomposition require nitrogen, phosphorus, and all trace quantities of other materials for growth. In cases where nutrients are lacking or inadequate in quantity they must be supplemented in the fill to obtain growth and methane production.

The rate of gas production in landfills depends upon the type of waste, age of landfill, and the operating parameters. General observations in the landfills indicate that generation rates would range between 0.06 to 0.23 cubic feet per pound per year (Ref. 6). RSF (Reserve Synthetic Fuels) also estimated the recoverable gas from any sanitary landfill as a function of fill volume, so that the potential gas generation rate can be related to the fill area and depth as shown in Figure 13. Under real conditions, the generation rate starts out at its maximum value and decreases with time. The actual kinetics of waste decomposition (or gas generation) with age of the fill is an unknown factor. Landfills excavated 25 years after placing have indicated that many materials, particularly cellulose, remain virtually unchanged. Therefore, continuous production of gas at a certain flow rate cannot easily be predicted.

The total volume of decomposition gases available under Palos Verdes landfill conditions can be approximated by assuming that 1500 cubic feet of gases will be produced by the decomposition of each ton of as received refuse (Ref. 18). For example, consider parcel three in Figures 14 and 15; RSF is using this area for gas withdrawal at Palos Verdes landfill. The landfill surface area is approximately 1.91×10^6 square feet or 44 acres. Fill depth ranges from 53 to 140 feet. With the help of topographic maps prepared June 20, 1957 and February 19, 1975, the volume of refuse deposited is estimated to be approximately 1.6×10^8 cubic feet, with an average depth of 100 feet. Based on an average in-place refuse density of 1300 pounds per cubic yard (determined by the Districts), a total of 7.6×10^9 pounds (3.8×10^6 tons) of solid waste will be producing gas.

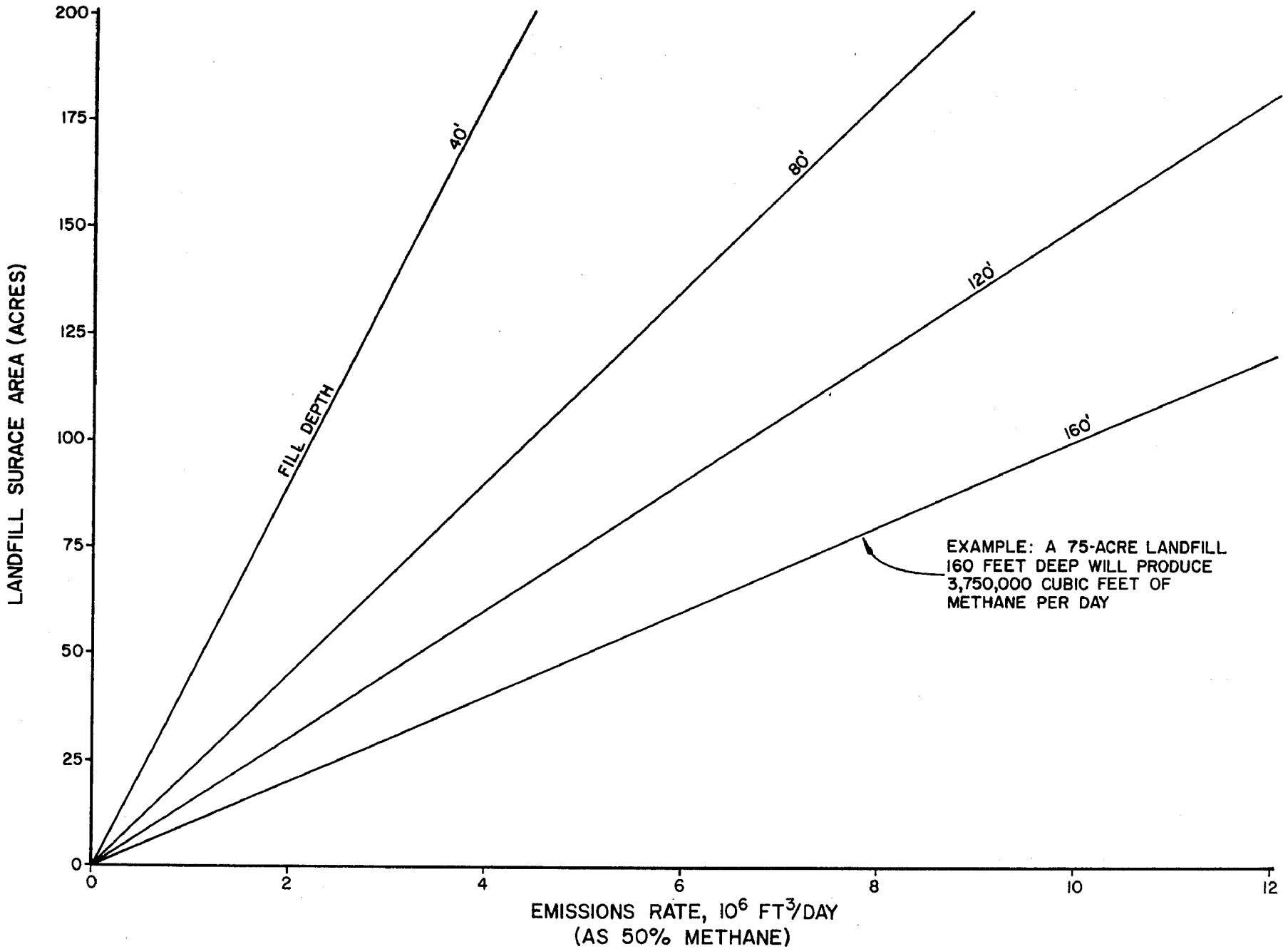


FIGURE 13: LANDFILL METHANE EMISSIONS RATE

Source: Reserve Synthetic Fuels Inc.

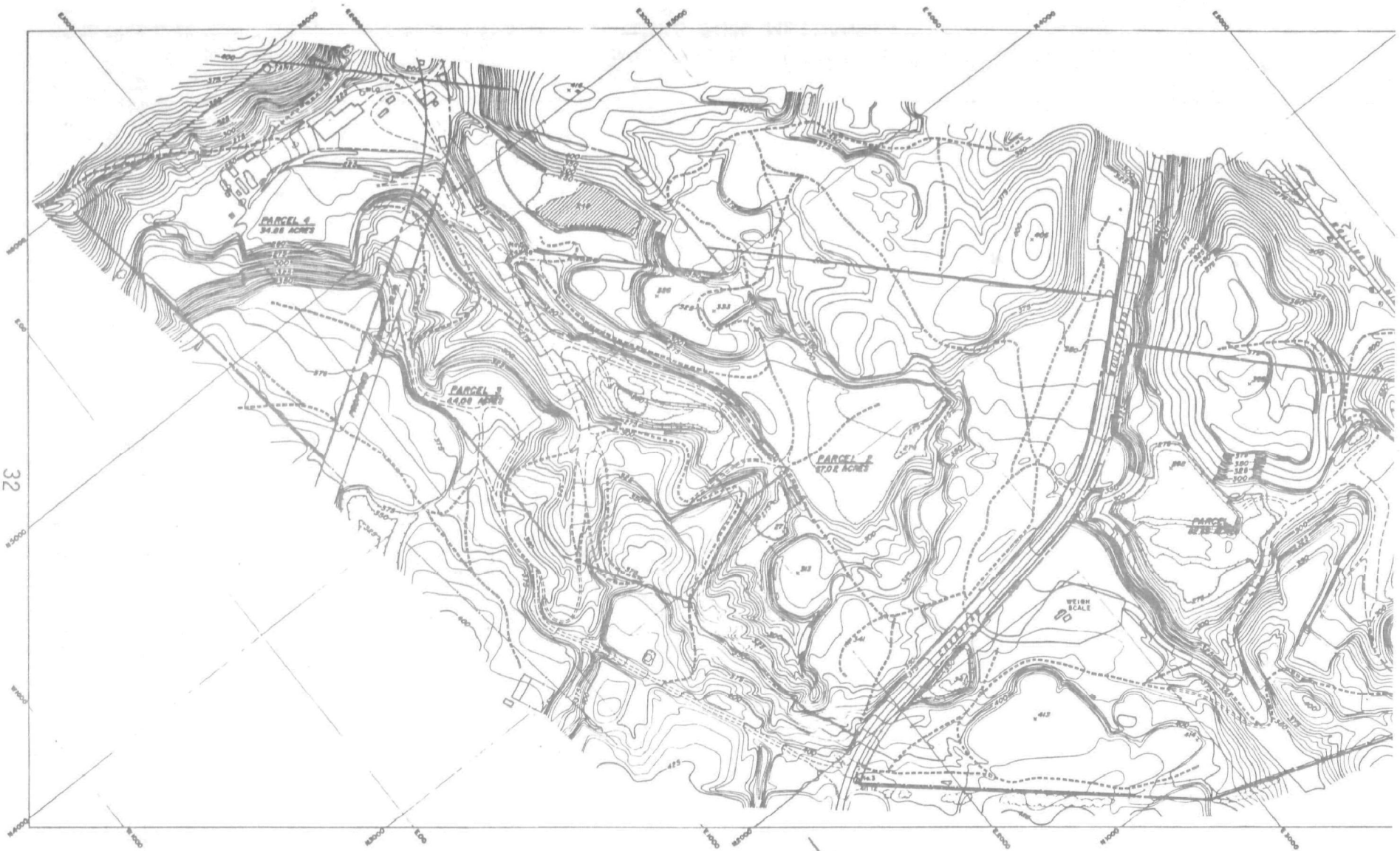


FIGURE 14: TOPOGRAPHIC MAP OF PALOS VERDES LANDFILL

SCALE 1"=665' ± CONTOUR INTERVAL 5'

PHOTOGRAPHY DATED JUNE 20, 1957

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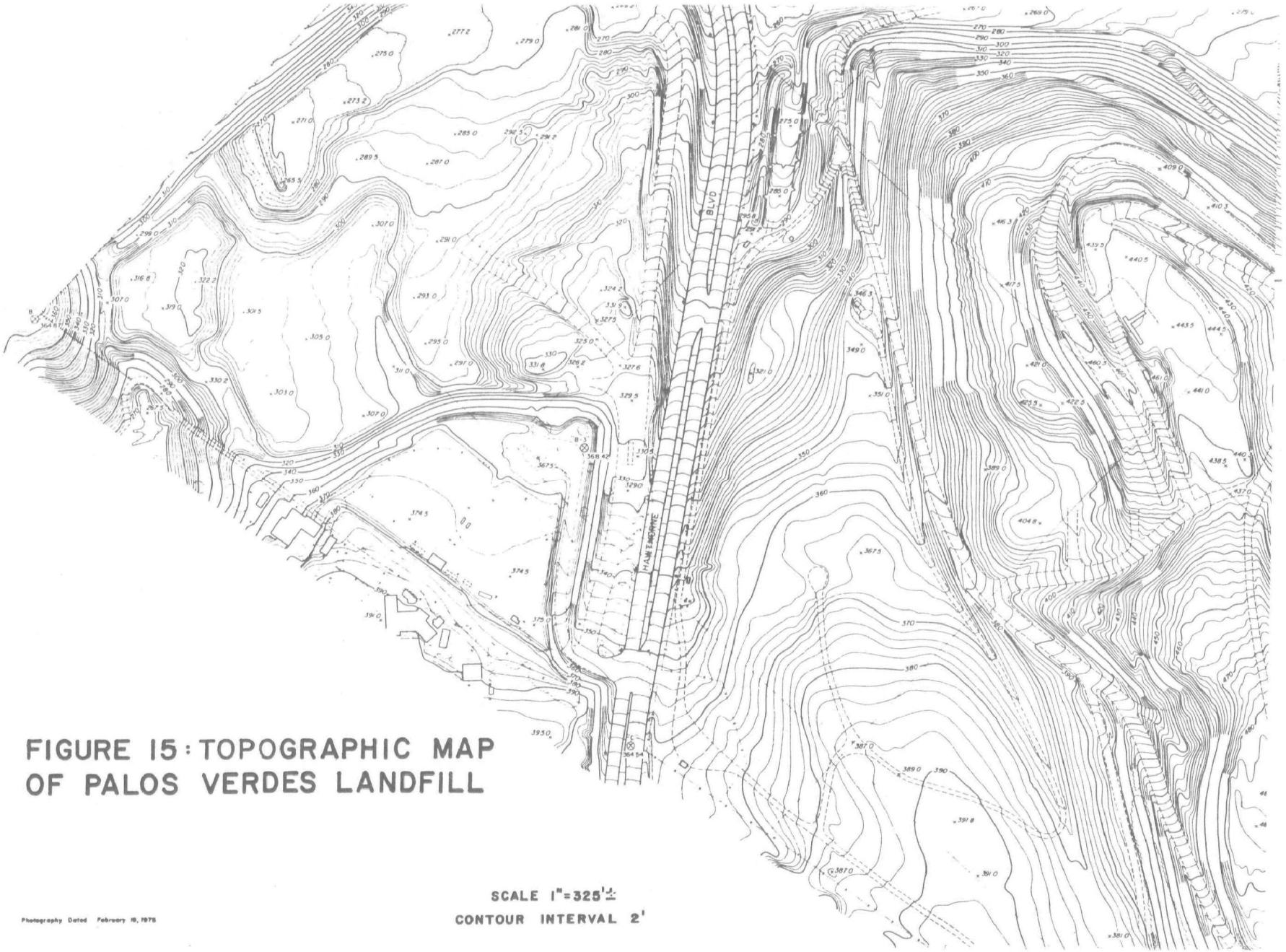


FIGURE 15: TOPOGRAPHIC MAP OF PALOS VERDES LANDFILL

SCALE 1"=325'±

CONTOUR INTERVAL 2'

Photography Dated February 19, 1975

A total of 4.5×10^9 cubic feet of gases will be produced based on the assumption that one ton of as received refuse produces 1500 cubic feet of gases. From a withdrawal well system of 31.5 acres of surface area and 100 feet deep, approximately 2×10^6 cubic feet per day of gases can be extracted (Figure 6). At this production rate, flows could be sustained for only six years. However, these calculations are estimates and may not represent the actual conditions in the landfill.

After a landfill is completed, the rate and volume of gas generation depends upon the types of waste deposited, age of landfill, mode of operation, and climatic conditions. The amount of this potential production which is actually recoverable depends upon the permeability of the soil beneath the fill material, the permeability of the cover material, and the permeability of the actual fill material. At a completed landfill site, such as Palos Verdes, the only real control is on the permeability of cover material. Since local earth is being used as a cover material, it is important to study both the geological characteristics of the Palos Verdes soil and its permeability for methane gas movement. In this chapter, those physical parameters pertinent to Palos Verdes landfill conditions will be discussed.

A. Refuse Types

The amounts and types of waste disposed of at Palos Verdes landfill by the Districts are illustrated in Table 5. The data were complied by the Districts during a month-long survey in March 1974, and show an average daily input of 4810 tons of household and commercial waste. These categories comprise about 50 percent; liquid waste comprises about 19 percent of the total. The presence of a high proportion of organic material in these types of waste enhances the potential in the Palos Verdes landfill for methane gas generation.

B. Mode of Operation

The basic tool for placing and compacting the refuse is a crawler tractor of about 65,000 pounds gross weight. The refuse is placed at the bottom of the working face and compacted to the in-place density ranging from 1000 to 1700 pounds per cubic yard. A maximum degree of compaction can be achieved by the addition of water. This will not only help in regulating the gas migration, but also enhances the rate of gas generation. At Palos Verdes landfill since both liquid and solid waste are deposited, the addition of water is not required.

The moisture content in the completed fill was analyzed at the San Jose Creek Water Quality Laboratory of the County Sanitation Districts of Los Angeles County. Grab samples at various depths ranging from 5 to 110 feet were collected by 30-inch bucket auger rigs. Table 6 shows the moisture contents in well numbers 1 to 7 which RSF is operating for gas extraction. It shows that on an average about 30 percent (wet weight basis) of moisture is present in the fill except in the case of well number 7 which taps a region used for dumping greater amounts of liquid waste. The distribution of moisture content with respect to depth shows no clear pattern.

TABLE 5

REFUSE SURVEY - TYPES AND
QUANTITIES OF REFUSE RECEIVED

TYPE	AMOUNT (Tons per Day)	PERCENTAGE OF TOTAL (%)
Household	1198.1	24.9
Commercial	1238.5	25.7
Solid Fill	598.8	12.4
Small Wood & Logs	87.6	1.8
Large Wood & Logs	106.4	2.2
Demolition Waste	254.1	5.3
Garden Wastes	153.9	3.2
State Park Wastes	97.2	2.0
Industrial Wastes	48.6	1.0
Bulky Items	51.8	1.1
Rubber Tires	28.9	0.6
Liquid Wastes	900.4	18.7
Agricultural Wastes	46.1	1.0
Daily Average	4810.4	100.0

Period: March 4 through March 30, 1974

Source: County Sanitation Districts of Los Angeles County

TABLE 6

PERCENTAGE MOISTURE CONTENT IN REFUSE DEPOSITS
(Wet Weight Basis)

DEPTH (Ft.)	WELL NUMBERS								
	1	2	3	4	5	6	6A*	7	9*
5**	31	26	54	-	26	20	19	25	16
10	32	32	26	-	28	32	19	20	21
15	-	-	-	-	23	34	-	45	-
20	40	32	30	-	38	33	29	36	34
25	-	-	-	-	30	34	-	31	-
30	23	23	-	-	28	40	23	25	45
35	-	-	-	-	28	39	-	25	-
40	26	15	37	-	37	33	14	23	40
45	-	-	-	-	41	30	-	34	-
50	33	19	39	35	22	30	37	47	43
55	-	-	-	30	25	29	34	36	-
60	34	30	29	26	33	31	-	28	-
65	-	-	-	20	25	31	-	29	-
70	25	37	26	28	23	32	34	33	56
75	-	-	-	33	26	38**	-	37	-
80	29	25	30	30	22	-	62	62	33
85	-	-	-	13	22	-	57	64	-
90	54**	36	22	27	36	-	-	56	32
95	-	-	-	31	30	-	-	50	-
100	54**	34	29	30	22	-	44	51	32
105	-	-	-	51**	-	-	-	65	-
110	45**	44**	51**	-	-	-	-	63	-

Source: Los Angeles County Sanitation Districts

* Analyses were conducted at the University of Southern California, Los Angeles
** Soil

In addition to the application of water to achieve desired moisture content, compaction and dust control, it is also necessary to cover the fill with soil to reduce the loss of methane. At Palos Verdes landfill all final surfaces of the fill are covered with a minimum of 3 feet of clean earth.

C. Fill Characterization

Only two wells (Wells 6A and 9) were used for fill characterization. These wells were more recently drilled by the Districts to increase the gas withdrawal capacity. The samples were collected at various fill depths during drilling operation. The analyses for total volatile solids, total organic carbon, ammonia nitrogen, and total phosphorous were conducted at the Environmental Engineering Laboratory of the University of Southern California, Los Angeles, under the direction of Dr. Kenneth Y. Chen.

In order to perform statistical analyses of heterogenous refuse deposits, each sample was divided into three groups weighing 500 grams per subsample. Samples were dried at 70° C for 24 hours and ground to smaller particle size by mortar. Once the moisture content of the sample was determined, the dried and ground samples were used for conducting other analyses.

The total volatile solids were determined by igniting the dried samples in a 550° C muffle furnace for one hour. The loss in weight was designated as volatile solids. The total organic carbon was determined by the LECO-12 automatic carbon analyzer. Approximately 0.1 to 0.2 gram of acid-treated, dried, ground sample was weighed into a LECO crucible. Iron and copper catalysts were added to increase the rate of organic carbon oxidation. The concentration was determined by comparing it with a standard curve.

The procedures used for ammonia nitrogen (Kjeldahl method) and total phosphorous are described in "Standard Methods for the Examination of Water and Wastewater" (Ref. 19).

The total organic carbon in the refuse deposit does not follow any pattern with respect to depth, Table 7. In the top 20 feet of refuse deposits the organic carbon content is comparatively smaller. This is probably because of two reasons: (1) The presence of natural soil used as covering material. (2) The existance of aerobic conditions as a result of the infiltration of atmospheric oxygen and the resulting faster oxidation of organic carbon. The organic carbon content ranges from as high as 14.0 percent to as low as 0.4 percent on a dry weight basis. Since this fill is approximately 4 to 5 years old, the organic portion of the fill has already been partially decomposed, showing a relatively smaller concentration of carbon content.

The volatile solids content range from 3.5 percent to 56 percent on a dry weight basis (Table 8). The total volatile solids profile seems to follow the same pattern as in the case of total organic carbon.

TABLE 7

PERCENTAGE TOTAL ORGANIC CARBON CONTENT IN REFUSE DEPOSITS
(Dry Weight Basis)

WELL NUMBER	DEPTH (FEET)	NO. OF SAMPLES	MEAN	STANDARD DEVIATION	COEFFICIENT OF VARIATION
6A	5	3	2.3	0.2	8.7
6A	10	3	1.86	0.26	14.0
6A	20	3	2.9	1.5	51.7
6A	30	3	3.2	0.3	9.4
6A	40	3	7.9	1.1	13.9
6A	50	3	14.0	2.4	17.1
6A	55	3	5.87	1.31	22.3
6A	70	3	5.4	0.5	9.3
6A	80	3	7.9	2.4	30.4
6A	85	3	9.0	0.8	8.9
6A	100	3	4.0	0.6	15.0
9	5	3	0.4	0.1	25.0
9	10	3	2.7	0.4	14.8
9	20	3	0.6	0.06	10.0
9	30	3	7.6	0.4	5.3
9	40	3	8.8	2.5	28.4
9	50	3	3.5	0.5	14.3
9	70	3	5.5	1.3	23.6
9	80	3	3.5	0.6	17.1
9	90	3	2.4	0.2	8.3
9	100	3	0.8	0.3	37.5

TABLE 8

PERCENTAGE TOTAL VOLATILE SOLIDS CONTENT IN REFUSE DEPOSITS
(Dry Weight Basis)

WELL NUMBER	DEPTH (FEET)	NO. OF SAMPLES	MEAN	STANDARD DEVIATION	COEFFICIENT OF VARIATION
6A	5	3	7.6	0.65	8.6
6A	10	3	10.6	1.58	14.9
6A	20	3	12.7	6.7	52.8
6A	30	3	11.8	1.4	11.9
6A	40	3	50.9	6.7	13.2
6A	50	3	43.8	4.2	9.6
6A	55	3	21.23	4.25	20.0
6A	70	3	29.0	1.3	4.5
6A	80	3	44.2	6.9	15.6
6A	85	3	32.1	1.8	5.6
6A	100	3	16.5	1.6	9.7
9	5	3	3.5	0.15	4.3
9	10	3	10.4	0.7	6.7
9	20	3	6.3	1.2	19.0
9	30	3	44.5	3.6	8.1
9	40	3	40.2	1.9	4.7
9	50	3	42.7	1.6	3.7
9	70	3	55.9	4.6	8.2
9	80	3	32.8	0.6	1.8
9	90	3	32.3	4.6	14.2
9	100	3	32.3	0.55	1.7

Tables 9 and 10 show the total phosphorous and Kjeldhal ammonia nitrogen content in the refuse. In anaerobic decomposition, a portion of the organic waste is converted to biological cells, while the remainder is stabilized by conversion to methane and carbon dioxide. The biological growth resulting from anaerobic decomposition is an unknown factor, especially in the case of sanitary landfills. However, growth rate is predicated on the basis of waste strength and composition. Fatty acids produce lowest biological growth compared to the carbohydrates. It is estimated that approximately 0.1 Kg of biological solids are produced per Kg of BOD as a result of methane fermentation (based on carbohydrates). In order to produce a certain amount of biological growth, inorganic nutients such as nitrogen and phosphorous are required. The requirements for nitrogen may be determined from the cell growth and the fraction of nitrogen in the cells. Based on an average chemical formulation of biological cells of $C_5H_9O_3N$, the nitrogen requirment is approximately 11 percent of the cell weight. The phosphorous requirement is approximately one-fifth that of nitrogen or about 2 percent of the biological solids weight. Based on the assumption that the ultimate biological oxygen demand is the same as the average total organic carbon, 5 Kg per 100 Kg of dry refuse, approximately 0.5 Kg of biological cells per 100 Kg of dry refuse are formed. The nitrogen and phosphorous requirement would be 0.05 and 0.01 Kg per 100 Kg of dry refuse respectively. Since the nitrogen and phosphorous contents in refuse deposits are much higher than required, it is believed an additional supply of nutrients will not be needed.

D. Climatic Conditions

Meteorological data are reported for the Long Beach Airport, approximately 11 miles to the east of the landfill site. These are the bases for estimating the climatological situation at the Palos Verdes landfill. However, the climate at the landfill site may be influenced by local topographic irregularities and climatological depictions should reflect this orographic effect.

Precipitation is sparse during the summer months, with only an average of about 0.35 inches falling between the months of May and October (see Figure 16). With an annual average rainfall of nearly ten inches, it is apparent that almost all of the rainfall occurs during the winter months. Topography plays an important role in these precipitation totals. The Palos Verdes Hills, in which the landfill lies, are sufficiently high to create appreciable orographic precipitations, adding to the totals as recorded at Long Beach. Occasionally heavy rains occur on the slopes of these hills; in some instances flood damage has occurred.

In the winter months, maximum temperatures range in the middle and high sixties, while the minimum temperatures usually range in the middle and high forties (see Figure 17). In the summer months, maximum temperatures in the high seventies are common, while low temperatures vary between the high fifties and middle sixties. The mean annual temperature is approximately 63° F.

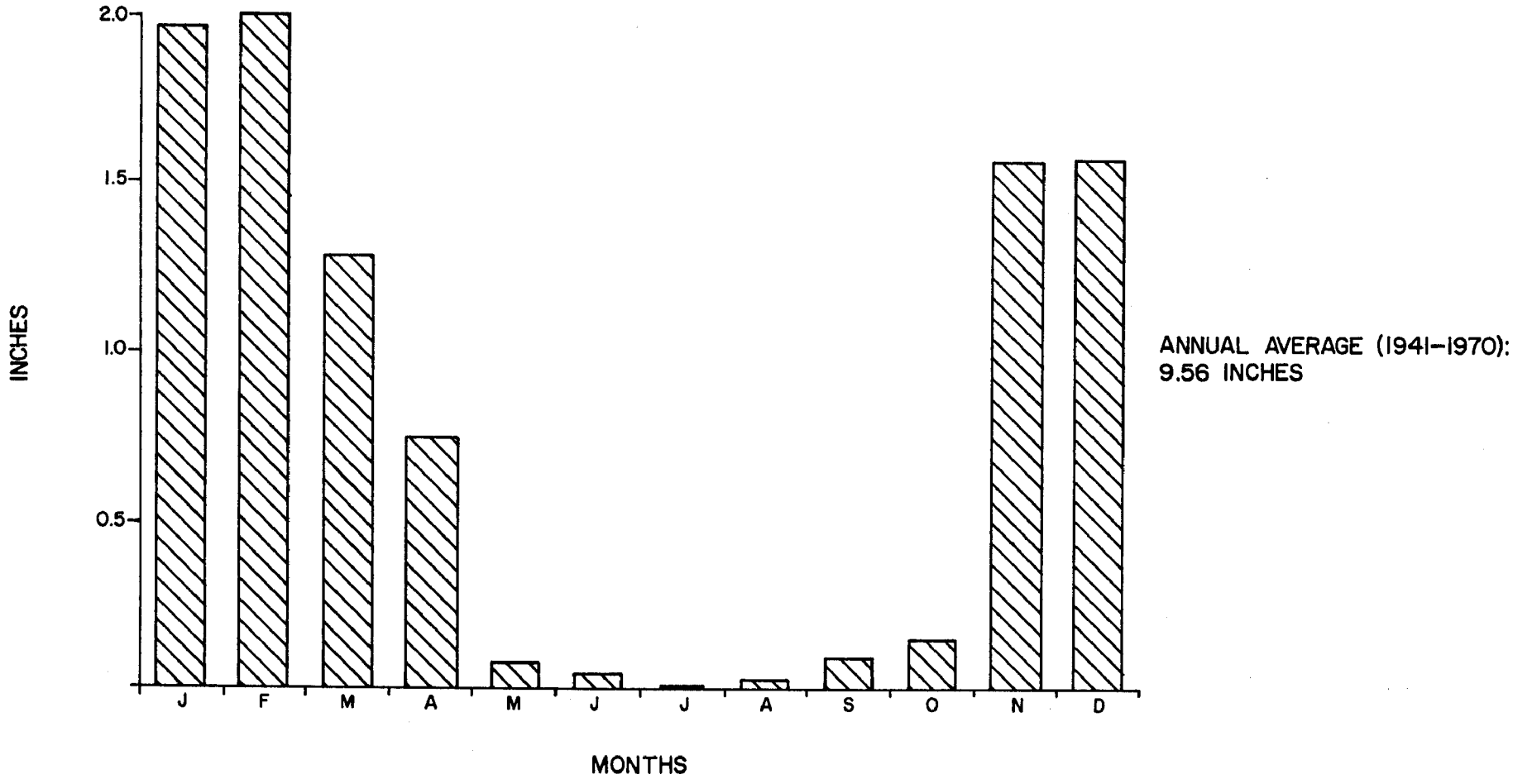


FIGURE 16: PRECIPITATION BY MONTH, LONG BEACH, CALIFORNIA

Source: U.S. Weather Bureau

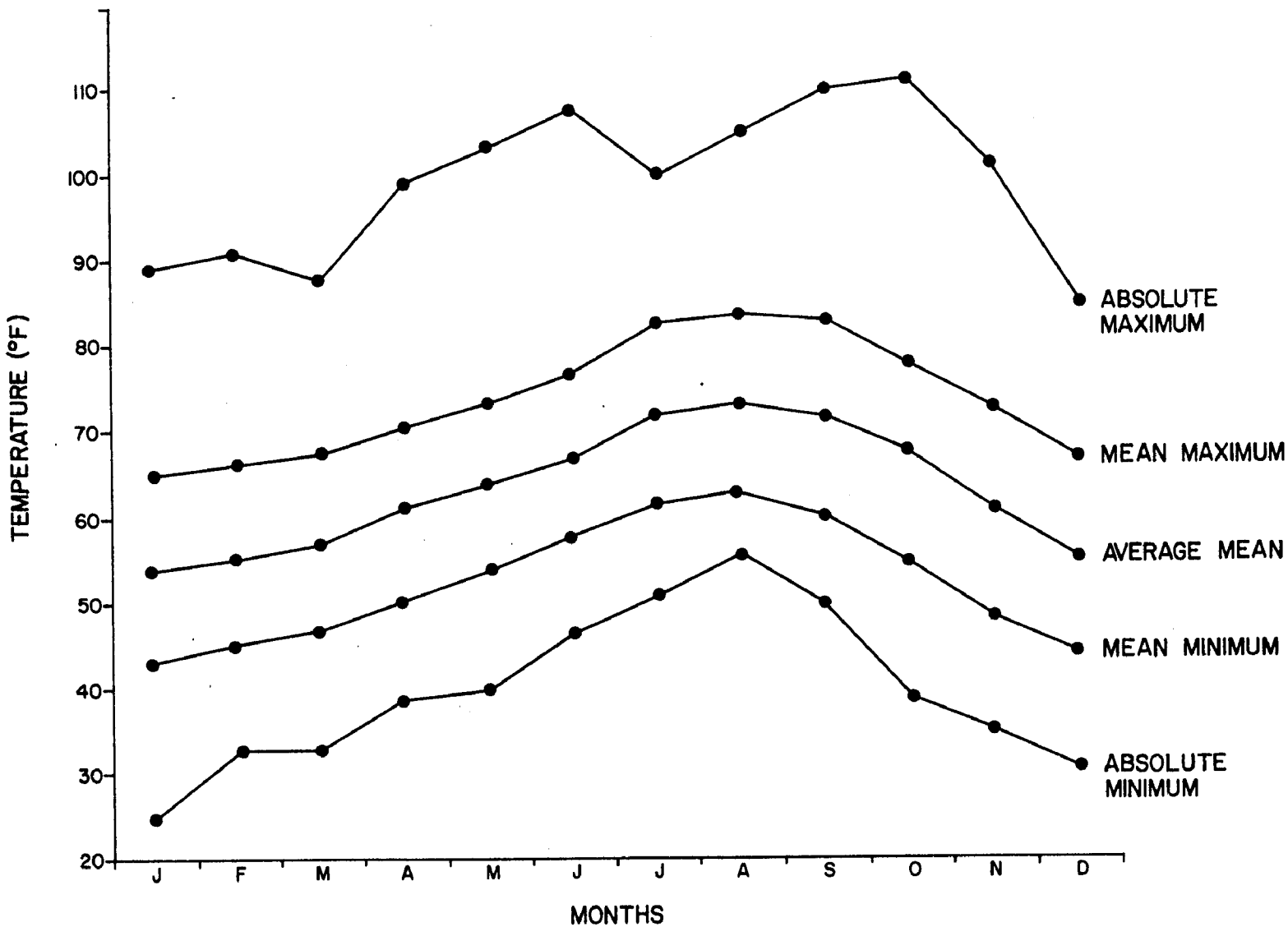


FIGURE 17: TEMPERATURE BY MONTH, LONG BEACH, CALIFORNIA

Source: U.S. Weather Bureau

TABLE 9

PERCENTAGE TOTAL PHOSPHOROUS CONTENT IN REFUSE DEPOSITS
(Dry Weight Basis)

WELL NUMBER	DEPTH (FEET)	NO. OF SAMPLES	MEAN	STANDARD DEVIATION	COEFFICIENT OF VARIATION
6A	5	3	0.333	0.02	6.0
6A	10	3	0.246	0.05	20.3
6A	20	3	0.145	0.04	27.6
6A	30	3	0.314	0.012	3.8
6A	40	3	0.202	0.011	5.4
6A	50	3	0.182	0.007	3.8
6A	55	3	0.33	0.03	9.1
6A	70	3	0.387	0.066	17.0
6A	80	3	0.136	0.02	14.7
6A	85	3	0.244	0.027	11.1
6A	100	3	0.283	0.038	13.4
9	5	3	0.293	0.032	10.9
9	10	3	0.295	0.03	10.2
9	20	3	0.296	0.0016	0.5
9	30	3	0.180	0.033	18.3
9	40	3	0.208	0.019	9.1
9	50	3	0.306	0.012	3.9
9	70	3	0.295	0.05	16.9
9	80	3	0.706	0.18	25.5
9	90	3	0.485	0.055	11.3
9	100	3	0.181	0.026	14.4

TABLE 10

PERCENTAGE KJELDHAL NITROGEN CONTENT AS N_2 IN REFUSE DEPOSIT
(Dry Weight Basis)

WELL NUMBER	DEPTH (FEET)	NO. OF SAMPLES	MEAN	STANDARD DEVIATION	COEFFICIENT OF VARIATION
6A	5	3	0.28	0.029	10.4
6A	10	3	0.25	0.01	4.0
6A	20	3	0.25	0.014	5.6
6A	30	3	0.26	0.028	10.8
6A	40	3	0.38	0.035	9.2
6A	50	3	0.29	0.027	9.3
6A	55	3	0.29	0.011	3.8
6A	70	3	0.24	0.028	11.7
6A	80	3	0.25	0.02	8.0
6A	85	3	0.23	0.044	19.1
6A	100	3	0.35	0.003	0.9
9	5	3	0.1	0.0006	0.6
9	10	3	0.21	0.011	5.2
9	20	3	0.11	0.007	6.4
9	30	3	0.25	0.01	4.0
9	40	3	0.3	0.014	4.7
9	50	3	0.21	0.008	3.8
9	70	3	0.23	0.019	8.3
9	80	3	0.17	0.019	11.2
9	90	3	0.23	0.035	15.2
9	100	3	0.18	0.026	14.4

E. Geology

The main geologic unit comprising the Palos Verdes Hills is the Monterey Shale formation of middle and upper Miocene age (18 to 11 million years old), which lies upon highly altered Catalina Schist basement rocks of early Mesozoic age (about 190 million years old). The Monterey formation consists of three members, the Altamira shale member, Valmonte diatomite member, and the Malaga mud-stone member, from oldest to youngest. At the northeast edge of the hills, Lower Pliocene age Repetlo siltstone (6 to 11 million years old) are unconformably overlain by lower Pleistocene age (less than 2 or 3 million years old), exposed in the syncline. These latter are the Lomita marl, Timms point silt, and San Pedro sand (Ref. 20).

At the landfill site, only the Valmonte member of the Monterey shale is found. This unit is composed of grey-brown to white diatomite, diatomaceous claystone, siltstone, and thin beds of altered ash underlie the entire property. The diatomite phases are composed of siliceous, very fine grained, gritty, clay-like material with a porous texture. Because of its relatively poor permeability and good stability, the Valmonte diatomite is a satisfactory base for the present Class I sanitary landfill.

At the Palos Verdes Sanitary landfill, all final surfaces of the landfill are covered with a minimum of three feet of clean earth consisting partly of diatomaceous earth. The extent of migration of methane gas through the cover soil depends upon the soil porosity and particle size. Figure 18 shows that approximately 60 percent (by weight) of diatomaceous soil particles are finer than 10 mm size. This cover soil is quite impermeable to gas migration if compacted to the optimum moisture content and maximum density.

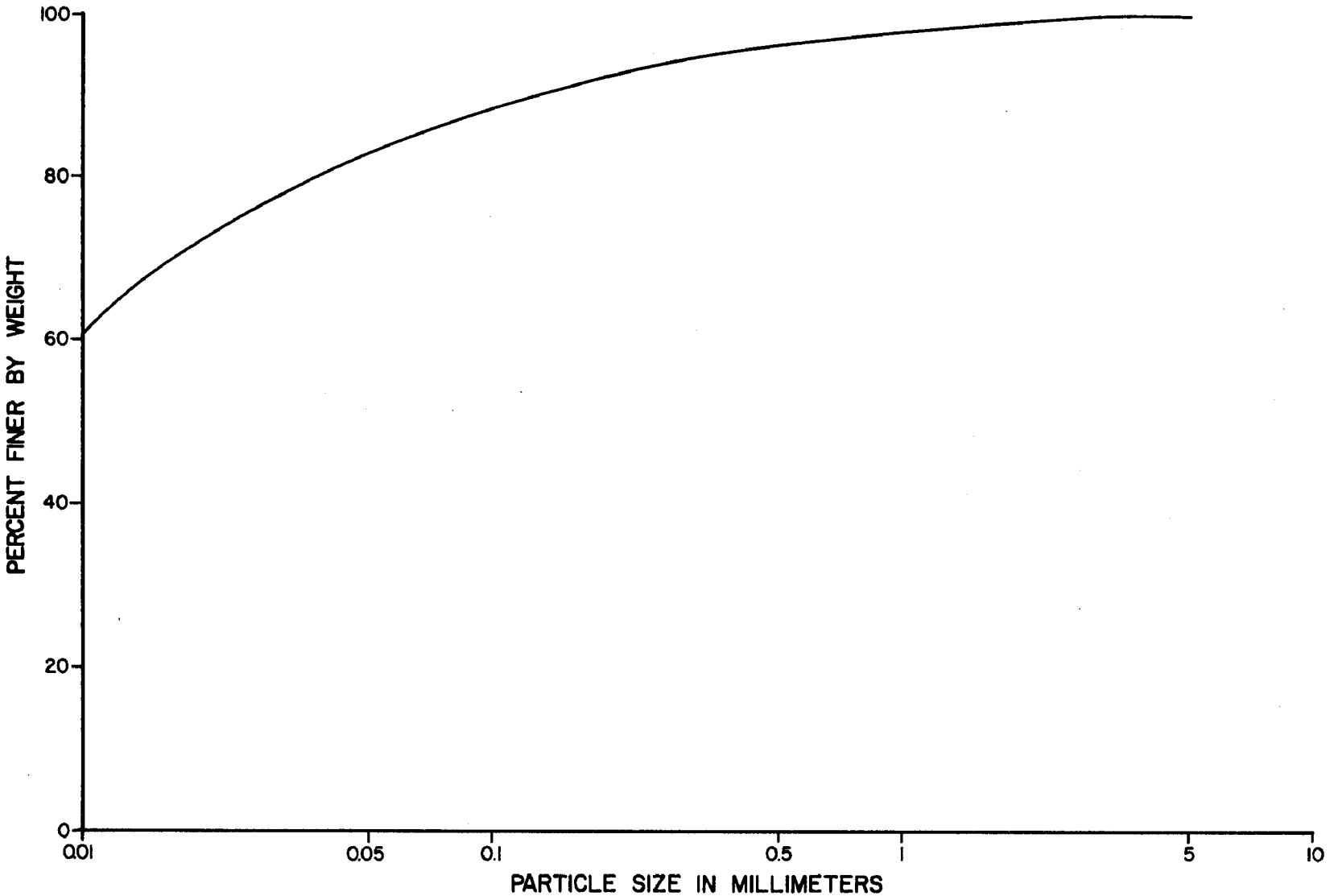


FIGURE 18: PARTICLE SIZE DISTRIBUTION OF DIATOMACEOUS COVER SOIL (REF. 14)

CHAPTER IV

EVALUATION OF OPERATING CONDITIONS FOR GAS WITHDRAWAL

During 1972 to 1973, the Districts constructed well number 8 to conduct an experiemental investigation. This well is approximately 110 feet deep. The bottom 80 feet is perforated and lies within the fill of the Class I portion of the landfill. Based on the experimental findings, the Districts have constructed seven extraction wells at the Palos Verdes landfill (Figure 19 showing wells numbered 1 to 7). These wells are constructed in the same way as the experimental well number 8. Each of these wells is approximately 110 feet deep, spaced on 500 foot centers. During the past year RSF operated only wells numbered 1, 2, 3, 4, 5, and 7 to meet a demand of 1000 SCFM.

Figure 20 shows the wells and header pipe locations. Each well utilizes alternate six-inch and four-inch diameter, 20-foot long polyvinyl chloride pipe, coupled by burlap-wrapped joints. The well heads themselves are buried. A buried concrete vault encloses a butterfly valve to adjust flow rate and instrumentation consisting of a thermometer, a pressure tap, and a pitot tube device for measuring the flow rate.

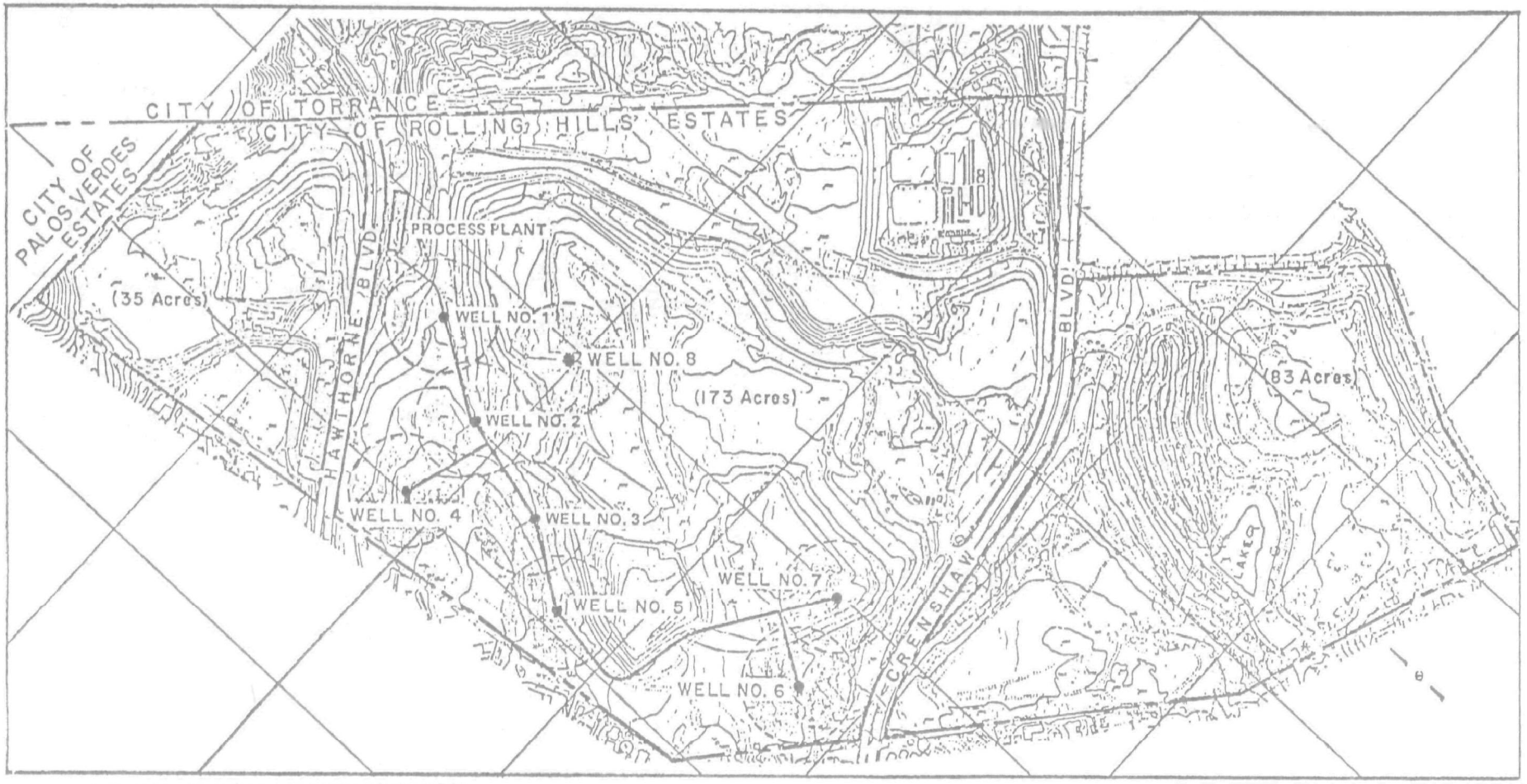
The collection manifold connecting these wells is a 10-inch diameter polyethylene pipe fabricated from 40-foot lengths fused together. This manifold is buried approximately 35 inches below ground level. The polyethylene pipe is flexible and will withstand differential settlement of the landfill as well as seismic activity.

Experimental well number 8 was used for evaluating the operating conditions for gas withdrawal. The findings reported in this chapter were experimentally determined by Districts during 1973. These results were determined for a short duration (maximum of four weeks) and they cannot be reasonably extrapolated to continuous long-term operation.

A. Gas Composition

The landfill gas composition obtained from a depth of up to 110 feet is shown in Tables 11 and 12. Both the results obtained by Districts and by the Reserve Synthetic Fuels, Inc. indicate that for a well producing 320 SCFM, the methane content in the landfill gases is approximately 53 percent. Carbon dioxide is the major impurity (approximately 45 percent). However, operation of well number 8 indicated that composition depends upon withdrawal rate. It was determined for the particular configuration that a withdrawal rate of 320 SCFM will produce gases of heating value of approximately 500 Btu per SCF.

The high carbon dioxide concentration in landfill gases reduces by dilution the heat of combustion compared to pipeline standards. Carbon dioxide in conjunction with water, also makes landfill gases highly corrosive. It is therefore important to remove both water and carbon dioxide before its use in commercial gas distribution systems.



SOURCE: LOS ANGELES COUNTY SANITATION DISTRICTS

FIGURE 19: GAS WELL LOCATIONS AT PALOS VERDES LANDFILL

0 250 500 750 1000
SCALE-FEET

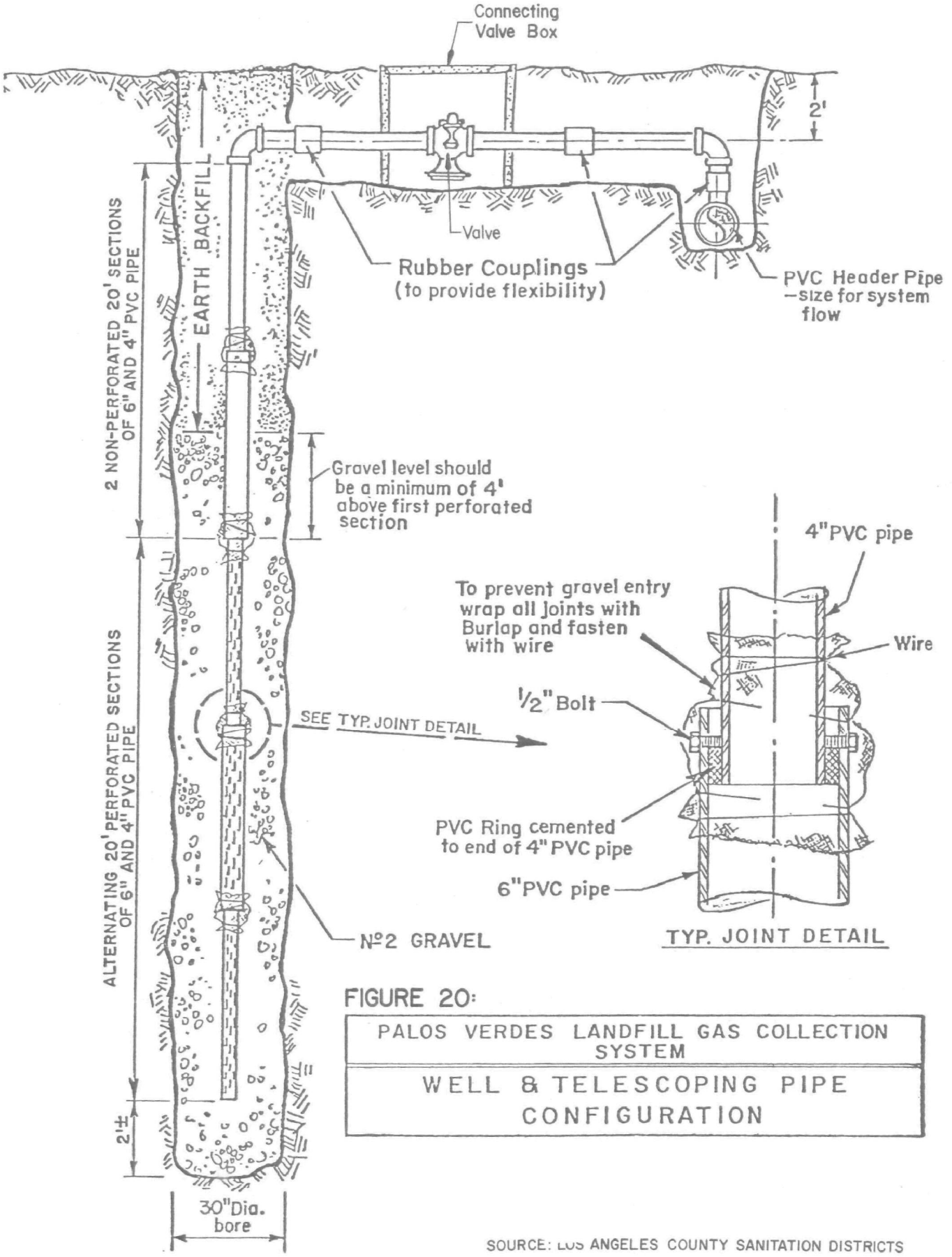


FIGURE 20:

PALOS VERDES LANDFILL GAS COLLECTION SYSTEM
WELL & TELESCOPING PIPE CONFIGURATION

SOURCE: LOS ANGELES COUNTY SANITATION DISTRICTS

TABLE 11

GAS ANALYSIS*

PALOS VERDES SANITARY LANDFILL
(January 31, 1973)

GAS	VOLUME(%)
Methane (CH_4)	52.6
Carbon Dioxide (CO_2)	43.5
Hydrogen (H_2)	0.05
Nitrogen (N_2)	2.92
Oxygen (O_2)	0.29
Argon (A)	0.05
Hydrocarbon (Heptane, C_7H_{16})	0.45
Benzene	0.11
Toluene	0.05
Heat of Combustion (Btu/ft^3)	585

Source: Los Angeles County Sanitation Districts

* Withdrawal Rate 320 SCFM

TABLE 12

GAS ANALYSIS*

PALOS VERDES SANITARY LANDFILL
(June 8, 1974)

GAS	VOLUME (%)
Oxygen	0.070
Nitrogen	0.272
Carbon Dioxide	45.588
Hydrogen	0.056
Hydrogen Sulfide	0.0017
Methane	53.283
Ethane	0.000
Propane	0.007
Iso. Butane	0.004
N. Butane	0.006
Iso. Pentane	0.010
N. Pentane	0.014
Hexane	0.128
Heptane	0.292
Octane	0.206
Nonane	0.064
Heat of Combustion (Btu/ft^3)	580
Specific Gravity (gram per cubic centimeter)	1.017

Source: Reference 18

* Withdrawal Rate 320 SCFM

B. The Effects of Withdrawal Rates on Gas Composition

The withdrawal of gases at higher flow rates may cause the migration of air through the porous cover layer, resulting in the change in gas composition. The extent of air migration depends upon the permeability of the soil used in final cover and also the inches of vacuum required to withdraw gases at a certain flow rate. The increase in air concentration in landfill gases will oxidize methane, resulting in higher carbon dioxide and nitrogen content and in a reduction in the heating value. The purpose of this test is to determine a withdrawal rate at which CH_4/CO_2 ratio is maximum and also remains constant throughout the gas extraction.

In order to determine this parameter, Los Angeles County Sanitation Districts conducted an experiment at the increased withdrawal rate from 320 to 600 SCFM. The experiment was conducted for a relatively short time (four weeks). Figure 21 shows the influence of withdrawal rate upon gas composition and heating values with respect to time. After operating continuously for a three-week period at the withdrawal rate of 600 SCFM, the methane to carbon dioxide ratio of the gas decreased about 15 percent from 1.1 to 0.94.

In attempts to determine a withdrawal rate which would yield a stable methane to carbon dioxide ratio and maximum heating value, the withdrawal rate was reduced to 400 SCFM. After four weeks of continuous operation at 400 SCFM withdrawal rate, the Btu value of the extracted gases began to decline as the percentage of CO_2 began to rise. Therefore, composition data would seem to indicate that a withdrawal rate of approximately 320 to 350 SCFM will permit the gases to be collected with maximum heating values.

C. Effects of Gas Withdrawal Rates on Well Pressure and Gas Pressure in Surrounding Fill Regions

The purpose of this test is to determine the amount of pressure drop required to withdraw gases at certain flow rates. This parameter depends upon the porosity and permeability of the fill. A 30-inch diameter experimental well number 8 dug to 110 feet below the surface elevation was used for this test (Figure 22). This experimental well is prototype for all extraction wells on site. It was connected to a positive displacement blower equipped with a nine-foot kittel muffler on the blower discharge.

The gas pressures in the surrounding landfill regions were determined from a remote well. This well is also 30 inches in diameter, dug to 125 feet below the surface elevation at a distance of 110 feet from an experimental extraction well. This well is tightly caped to eliminate the emission of gases to the atmosphere.

Gauge pressure readings (with respect to atmospheric pressure) were determined with a U-tube barometer filled with water. Results were obtained up to a 0.01 inch accuracy (water column).

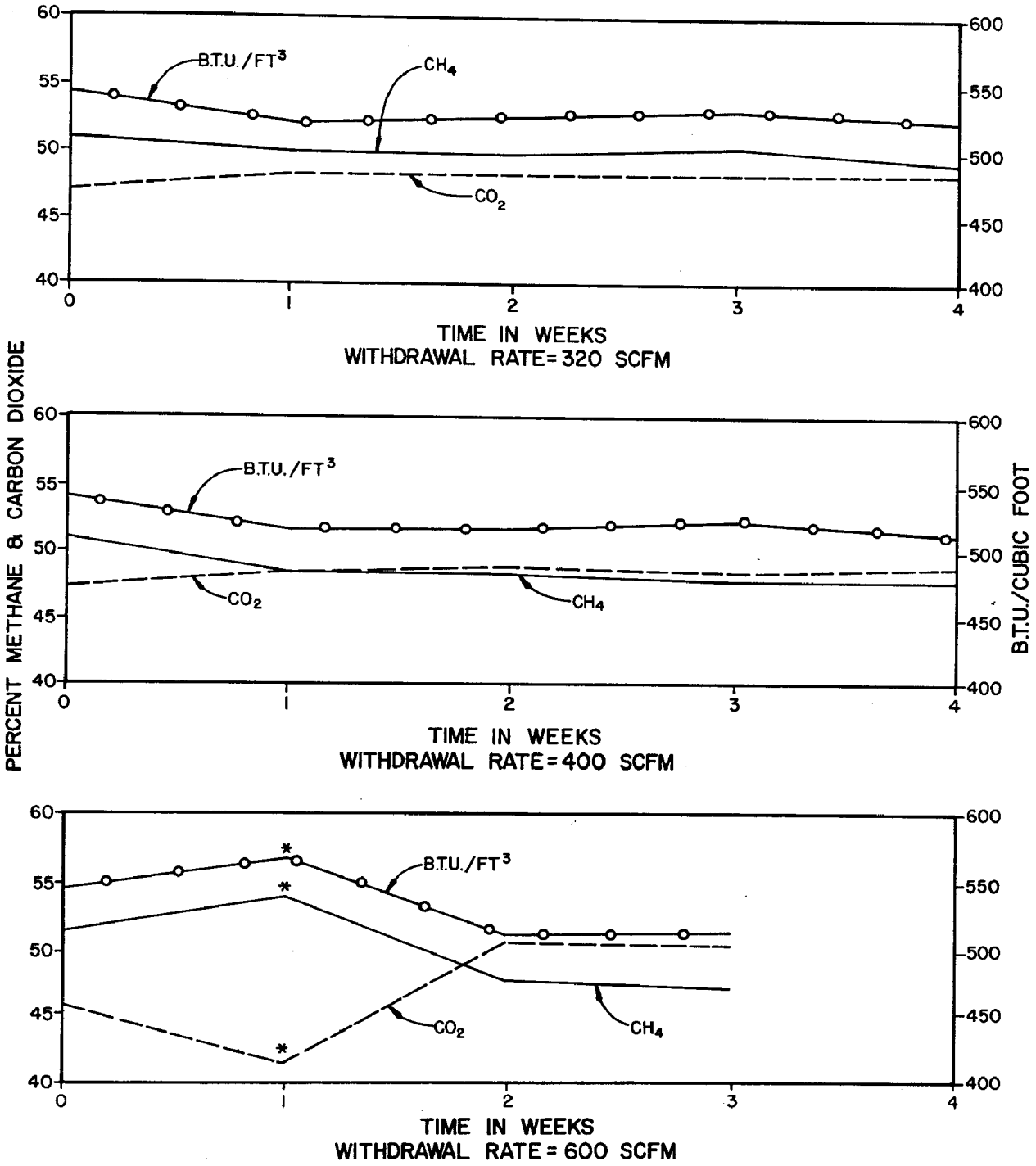


FIGURE 21: THE EFFECTS OF WITHDRAWAL RATES ON GAS COMPOSITION AND HEATING VALUES

SOURCE: LOS ANGELES COUNTY SANITATION DISTRICTS

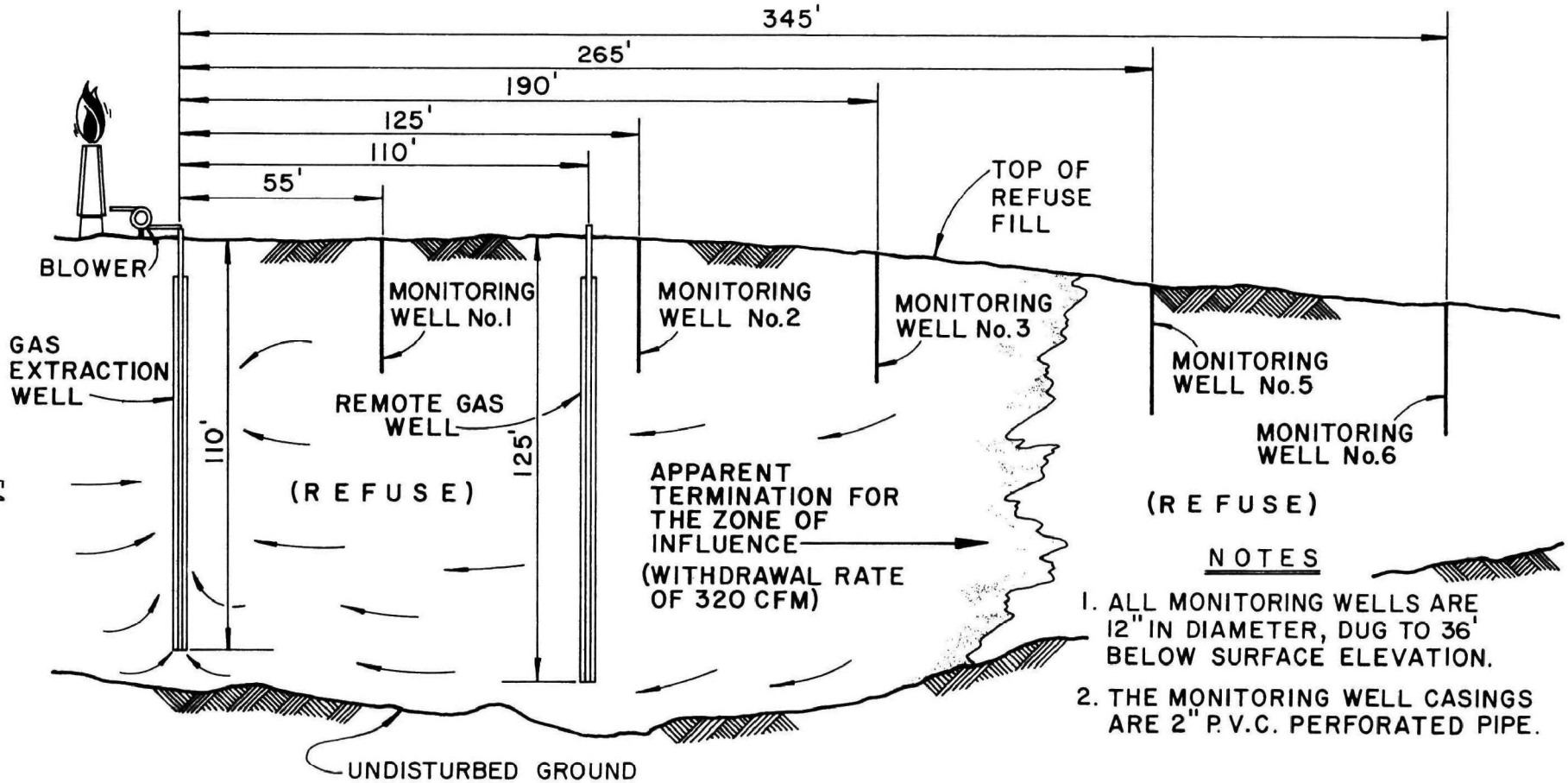


FIGURE 22: INFLUENCE AREA STUDY

MONITORING WELL LOCATIONS AT PALOS VERDES LANDFILL

SOURCE: LOS ANGELES COUNTY SANITATION DISTRICTS

Figure 23 shows the change in pressure with respect to time at shutdown and restart of the blower, both in the case of experimental gas extraction and remote wells. At 8:24 AM when the blower was shutdown, pressure in the gas extraction and the remote well was increased to 0.6 and 0.9 inches of water respectively, in approximately 90 minutes. The remote well follows a time-lag of approximately six minutes compared to the extraction well located at a distance of 110 feet. The increase in pressure is a result of the accumulation of gases in the well.

On restart of the blower to withdraw gases at 320 SCFM, a velocity head of 0.94 inches of water will be required. The pressure in the experimental gas extraction well will drop by 3.3 percent of the atmospheric pressure, whereas in the case of the remote well the reduction in pressure is only 0.12 percent. The latter reduction in pressure is clearly due to the influence of gas withdrawal from the extraction well.

D. Radius of Influence at a Selected Withdrawal Rate (320 SCFM)

In order to design an economical gas recovery system, it is important to know the number of extraction wells that should be located in a particular landfill configuration to extract the gases at their production rate. The number of wells can be correlated with the radius of influence (or sphere of influence), which depends upon withdrawal rate, depth, and volume of refuse deposits. Los Angeles County Sanitation Districts did an extensive survey at the Palos Verdes landfill to evaluate these parameters. The following discussion is based on their results.

Figure 22 shows the schematic diagram indicating the number and location of monitoring wells. All monitoring wells are 12 inches in diameter and dug to 36 feet below the surface elevation. The monitoring well casings are 2-inch PVC perforated pipe. Monitoring wells, numbers 1, 2, 3, 5, and 6, are located at a distance of 55, 125, 190, 265, and 345 feet respectively from the extraction well. The extraction well was continuously operated for three days at a withdrawal rate of 320 SCFM. The pressure changes in monitoring wells, numbers 1, 3, and 5, were determined with respect to time (Figure 24).

Pressure readings were first taken in the monitoring wells while the suction blower was not operating. Those initial readings indicated positive pressures for all wells to be approximately 0.25 inches of water column. The blower was then started up and continuous hourly readings were recorded over a 32-hour period after which hourly readings were made during the regular working day. Within 12 hours after the start of the blower, pressures in the monitoring wells, numbers 1, 3, and 5, were reduced by 0.31, 0.21, and 0.19 inches of water column respectively. Variation in the gas pressures in the monitoring wells were observed to have a definite daily cycle. These variations are not clearly understood at this moment because it does not follow diurnal atmospheric pressure fluctuations. Maximum pressure variation in wells 1, 3, and 5 is approximately 0.08 inches of water. The data appear to show a measurable pressure influence up to 265 feet in distance from the withdrawal well.

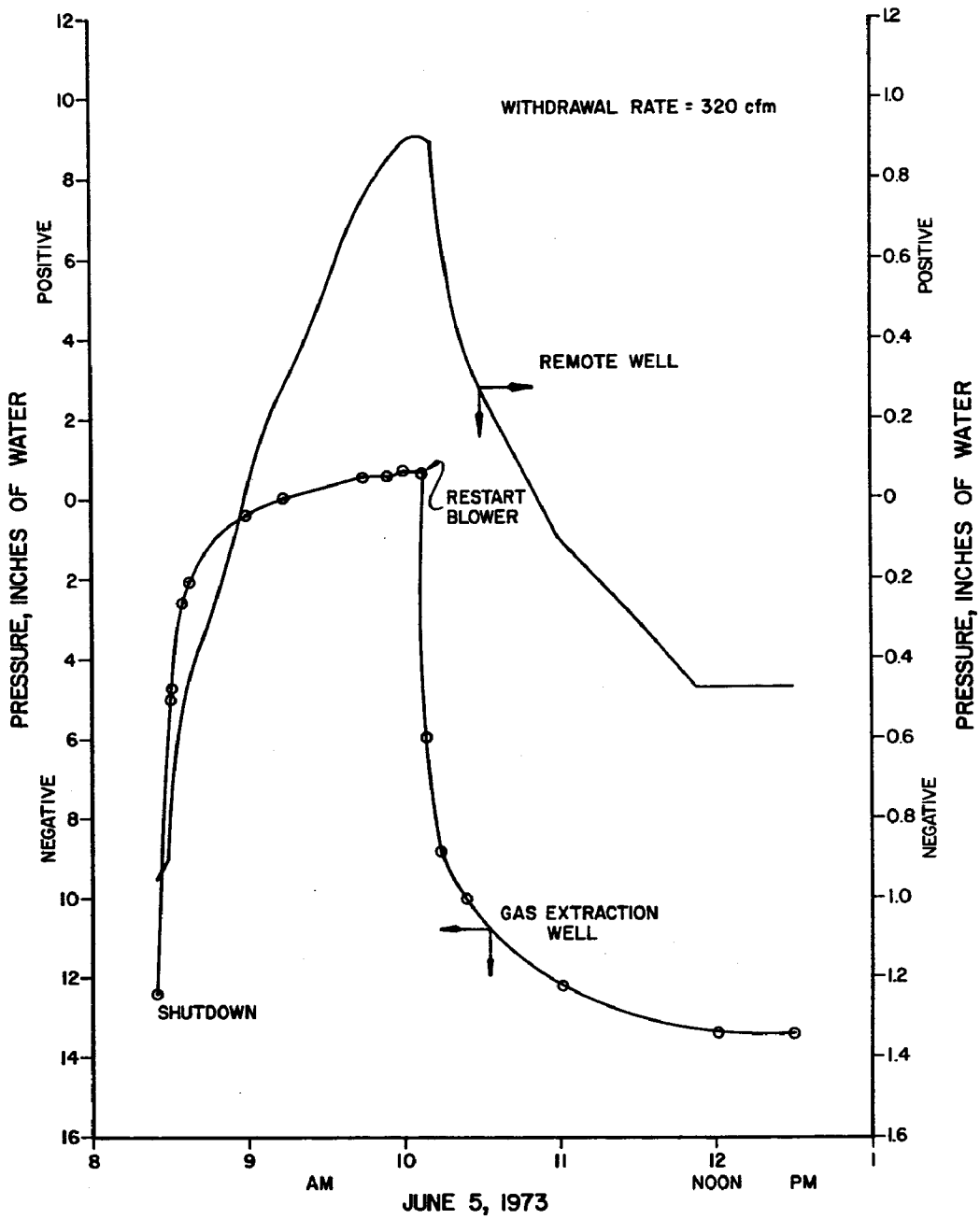


FIGURE 23: EFFECTS OF GAS WITHDRAWAL RATES ON WELL PRESSURE

SOURCE: LOS ANGELES COUNTY SANITATION DISTRICTS

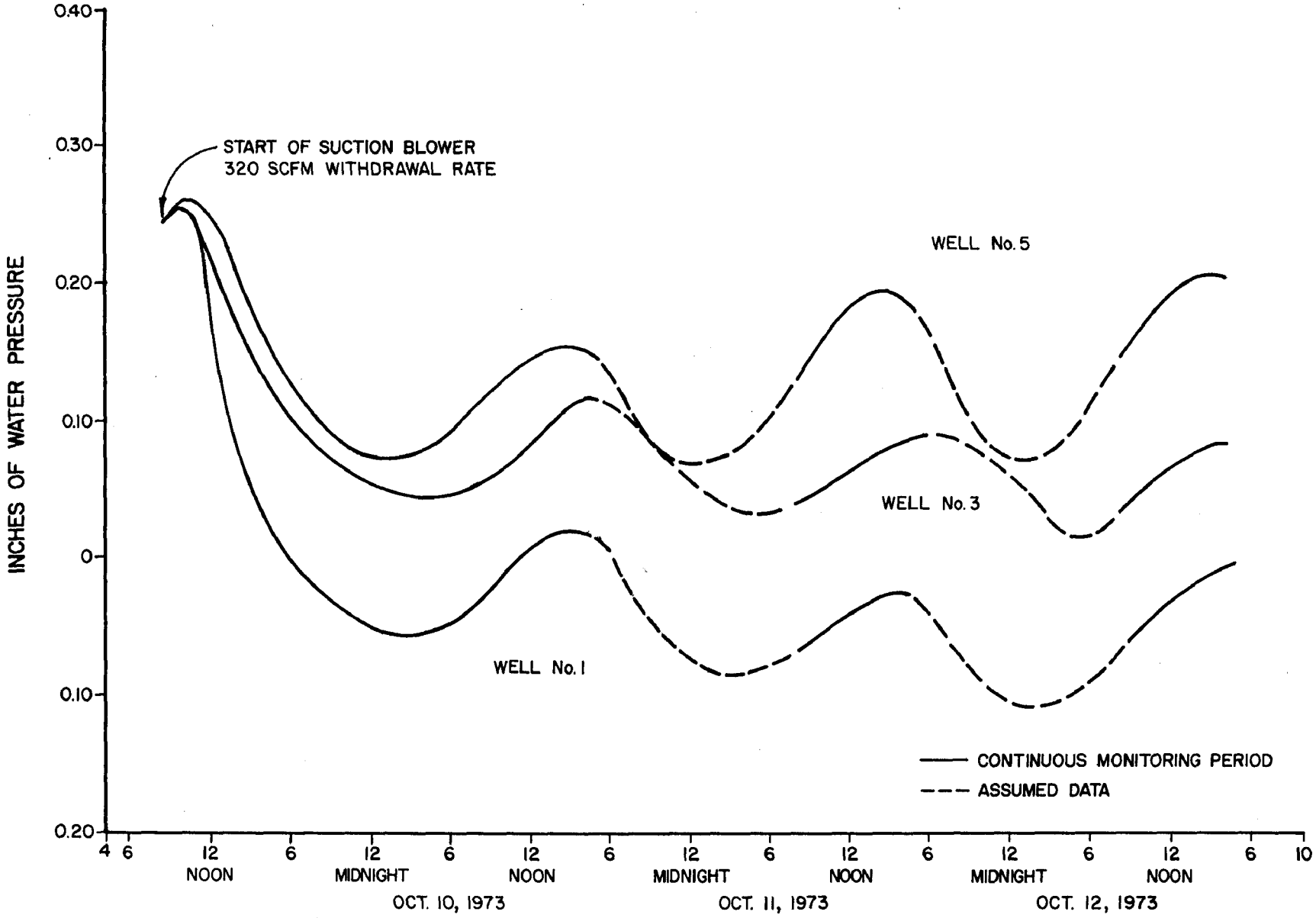


FIGURE 24: MONITORING WELLS

PRESSURE VARIATION VERSUS TIME

SOURCE: LOS ANGELES COUNTY SANITATION DISTRICTS

From the data obtained in this study, a withdrawal rate of 320 SCFM would appear to produce a radius of influence of approximately 250 feet. These values correspond to the Palos Verdes landfill site containing an extraction well of 110 feet deep.

E. Total Energy Production

The gas quality evaluation test is conducted by continuously extracting gases from a well at its production rate for a long period of time. The purpose of this test is to determine:

1. The total energy production from a well.

2. The actual life of a well operating under forced withdrawal.

The results reported here were obtained from a short run (one week) and they do not satisfy any of the above purposes. However, it is shown that at the withdrawal rate maintained within a range of 300 to 350 SCFM, gases with an average heating value of 500 Btu per cubic feet can be extracted (Figure 25). This will produce gases of approximately 1.5×10^9 Btu by the end of one week of operation.

F. Permeability of Refuse Deposit

A laboratory measurement of the permeability of porous refuse deposit medium with suitable apparatus and with the proper technique will undoubtedly give the most accurate results in a determination of this permeability constant (K). Theoretically this constant may be defined with the help of Darcy's law (Ref. 21). For a radial flow (Vr) into a well, Darcy's law can be written as:

$$Vr = -\frac{K}{\mu}\frac{\delta P}{\delta r} \; ; \; ft/_{sec} \qquad (1)$$

Considering Q as volumetric flow rate in cc/sec and h and r are the depth and radius of well respectively, we may calculate

$$Vr = \frac{Q}{2\pi rh} \qquad (2)$$

and,

$$\frac{Q}{2\pi rh} = -\frac{K}{\mu}\frac{\delta P}{\delta r}$$

The radial flow system may be characterized by the conditions:

$r = rw$ (radius of well); $\delta P = \Delta P$

$r = re$ (radius of influence); $\delta P = 0$

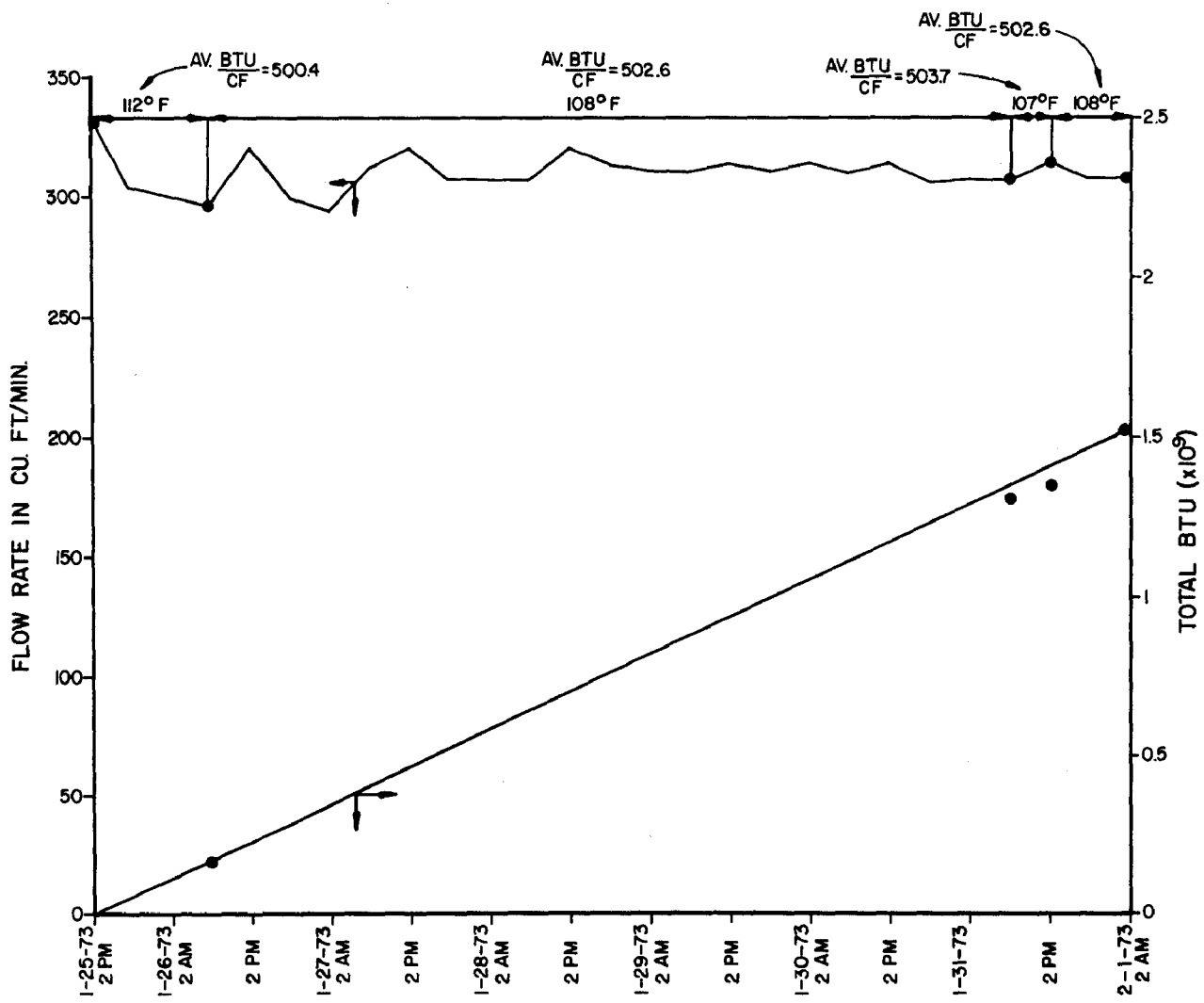


FIGURE 25: ENERGY PRODUCTION FROM A WELL

SOURCE: LOS ANGELES COUNTY SANITATION DISTRICTS

Whence, equation 2 may be written as:

$$K = \frac{Q \mu \ln \frac{re}{rw}}{2 h \pi (\Delta P)} \qquad (3)$$

In equation 3 the resultant value for permeability constant (K) will be in terms of Darcy's if μ is expressed in centipoises, Q in cubic centimeters per second, h in centimeters, and ΔP in atmosphere.

With the help of experimental data discussed earlier, we may determine the permeability constant of Palos Verdes landfill refuse deposits. A 110 foot deep experimental well withdrawing gases at a rate of 320 CFM produces a 250-foot long radius of influence and 13.5 inches of pressure drop. Assuming that this gas is composed of 50 percent of methane and 50 percent of carbon dioxide, we may calculate the average viscosity of landfill gas at standard temperature and pressure

$$\mu_{ag} = 0.011(0.5) + 0.0153(0.5) = 0.01315 \text{ centipoise}$$

By substituting these values in equation 3 we may calculate the permeability of refuse deposits:

$$K = \frac{(0.01315) \quad (320 \times 472) \quad \ln \frac{250}{0.25}}{(2\pi) \quad (110 \times 12 \times 2.54) \quad (13.5 \times 0.00245)}$$

$$K = 20 \text{ Darcys}$$

G. Theoretical Correlation of Operating Parameters for Landfill Gas Extraction

For the flow of ideal gases through landfill refuse deposits, the operating parameters such as flow rate, pressure drop and radius of influence may be theoretically correlated. Under steady conditions where the generation rate is equal to the withdrawal rate, the following equation may be written:

$$Q = \pi (Re^2 - Rw^2) \; Fg \quad D \; h \times \frac{1}{(365) \; (24) \; (60)}, \text{ CFM}$$

Where,

Re is radius of influence, ft.

Rw is radius of a withdrawal well, ft.

Fg is generation rate, $\frac{\text{cu. ft.}}{(\text{Yr}) \; (\text{lb})}$

D is in-place density of refuse, lb/cu.ft.

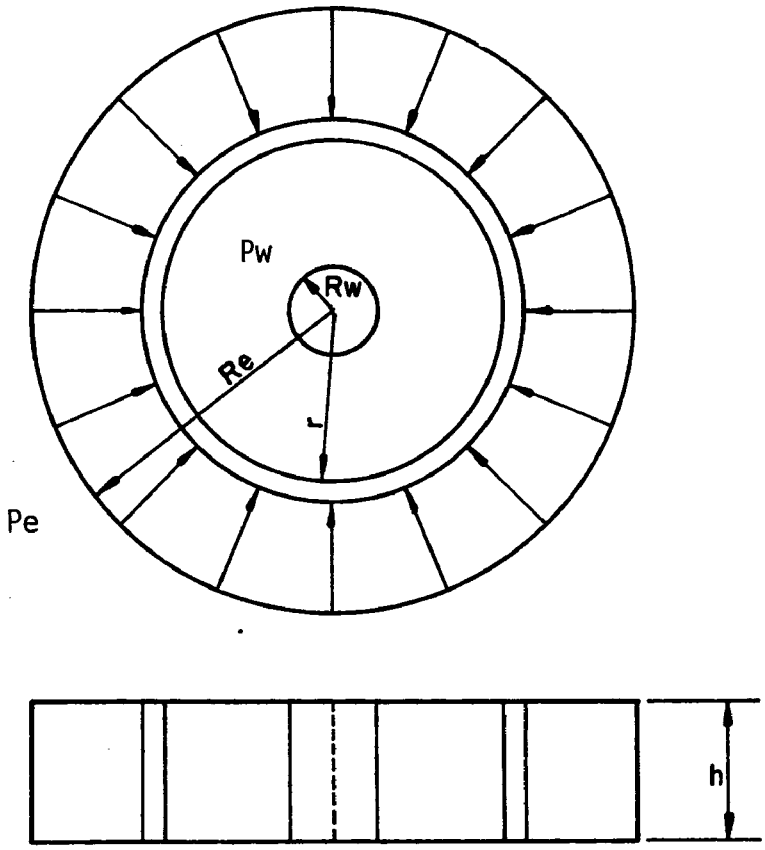
h is depth of a well, ft.

The above equation may be reduced to:

$$\frac{Q}{C_1} = 5.97 \times 10^{-6} \left(R_e^2 - R_w^2\right) \quad Fg \qquad (4)$$

$C_1 = h\ D$, Assuming constant depth and in-place density

With the help of equation 4 volumetric flow rate may be correlated to the radius of influence and generation rate. The forced withdrawal of gas will produce a pressure drop of (Pw-Pe). This value may be calculated by making a mass-balance across a ring of radius r and depth h.



The volume of refuse outside the ring is, $\pi(Re^2-r^2)h$ and volume of gas generated in this segment in unit time, $\pi(Re^2-r^2)h$ Fg. D.

Whence velocity at radius r is, $Vr = \dfrac{\pi(Re^2-r^2)h\ Fg.\ D}{2\pi rh}$

For radial flow into a well, Darcy's law may be written as:

$$Vr = -\frac{K}{\mu}\frac{\delta P}{\delta r} = \frac{(Re^2-r^2)\ Fg.\ D}{2r}$$

or,

$$-\int \delta P = \frac{\mu}{2K} Fg.\ D \int \left[\frac{Re^2}{r} - r\right] \delta r$$

The above equation can be solved for the conditions:

r = Rw (radius of well); P = Pw

r = Re (radius of influence); P = Pe

Whence,

$$-(Pe - Pw) = -\Delta P = \frac{\mu}{2K}\ Fg.D \left[Re^2 \ln\frac{Re}{Rw} - \frac{1}{2}(Re^2 - Rw^2)\right]$$

Where,

K is permeability of fill, Darcy, $\dfrac{cc/Sec}{(cm^2)\ (^{atm}/cm)}$

μ is viscosity of gas, centipoise

$$-\Delta P = \frac{1}{2} \times \frac{1}{(365)\ (24)\ (60)\ (60)} \times 929\ \frac{\mu}{K}\ Fg.D \left[Re^2 \ln\frac{Re}{Rw} - \frac{1}{2}(Re^2-Rw^2)\right] \text{, atm.}$$

or,

$$-\Delta P = 6\times10^{-3}\ Fg\ \frac{\mu D}{K} \left[Re^2 \ln\frac{Re}{Rw} - \frac{1}{2}(Re^2-Rw^2)\right] \text{, inches of water}$$

$$\left.\begin{aligned} -\frac{\Delta P}{C_2} &= 6\times10^{-3}\ Fg \left[Re^2 \ln\frac{Re}{Rw} - \frac{1}{2}(Re^2 - Rw^2)\right] \\ C_2 &= \frac{\mu D}{K} \end{aligned}\right\} \qquad (5)$$

Equation 4 and 5 were solved for volumetric flow rate (Q) and pressure drop ($-\Delta P$) as a function of constants C_1 and C_2, generation rate, and radius of influence (Appendix A). In the case of a completed landfill, constants C_1 and C_2 can be calculated from average in-place density, depth, and permeability of the fill; and viscosity of fill decomposed gases. If rate of gas generation is known for a particular landfill site, Figure 26 can be used for operating parameters evaluation under steady-state conditions.

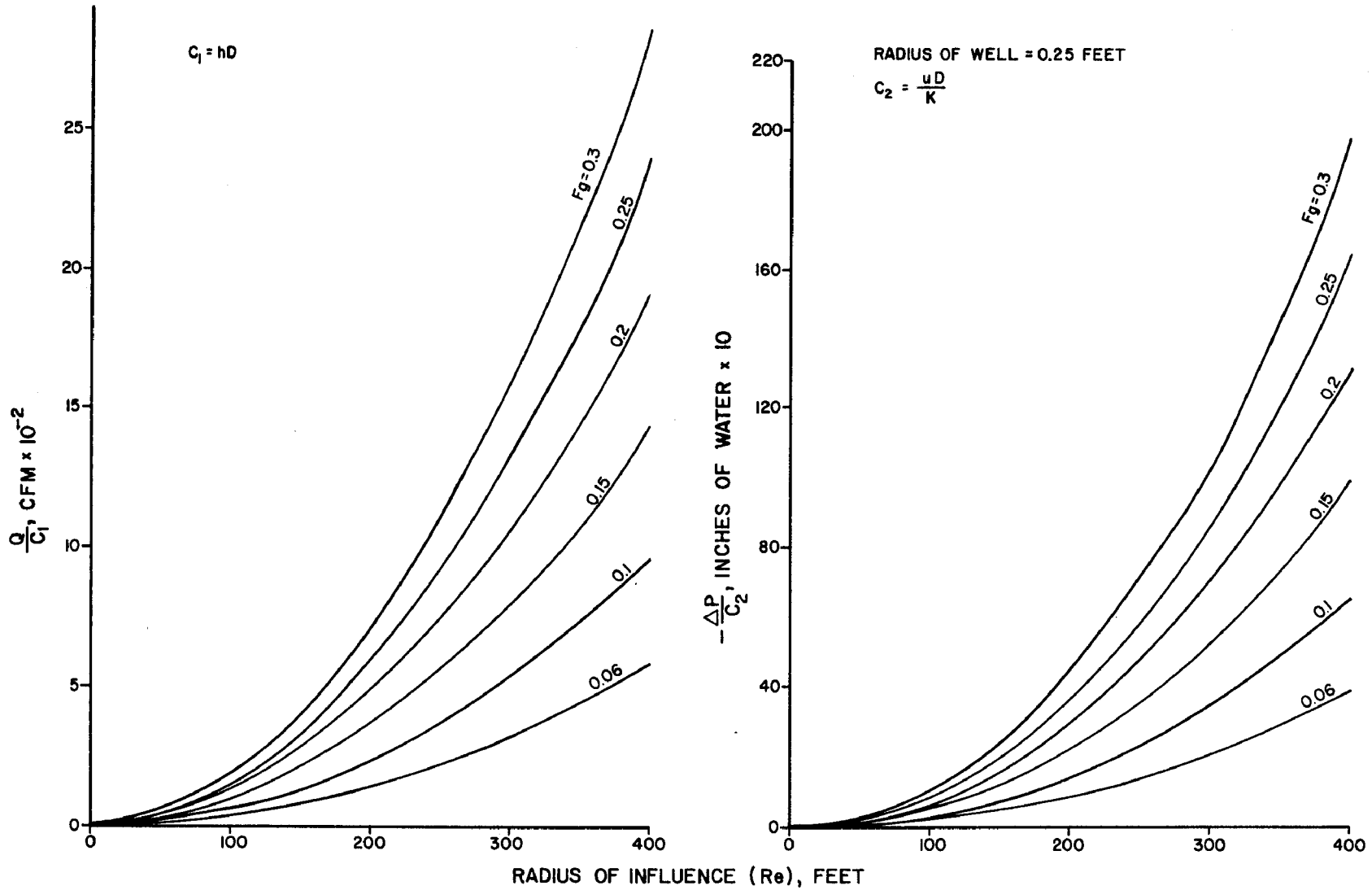


FIGURE 26: THEORETICAL CORRELATION OF OPERATING PARAMETERS FOR LANDFILL GAS EXTRACTION

+BIND

CHAPTER V

SELECTION OF TECHNIQUES FOR GAS BENEFICIATION

The fermentation process that is responsible for the decomposition of combustible waste produces a mixture of gases. Methane gas withdrawn from sanitary landfill deposits under slight vacuum is mainly contaminated with carbon dioxide, with smaller fractions of nitrogen, water, hydrogen sulfide, and other decomposition products. The methane is thus diluted with incombustibles that lower the heating value. The acid gases are also corrosive in the presence of water.

The low Btu raw gas from landfill sources cannot be mixed with pipeline gas because of its degraded performance in burners adjusted to the current pipeline gas standard. Gas metering is performed on a volume basis, but the heating value of 1000 Btu/SCF is guaranteed. Therefore, landfill gases should be purified to meet the pipeline standard.

The raw landfill gases have higher specific gravity and lower heating value compared to methane. Therefore, for its on-site efficient combustion, a proper modification in burner design is required (Ref. 22).

Dehydration to reduce the corrosion problem may enhance the utility of landfill gas where they can be used on site. Glycol and molecular sieve dehydration processes are generally used. On the other hand, these gases may also be processed to 99 percent methane purity to meet the pipeline standard, thus upgrading the gas to a commercial product. Process selection obviously will depend on the nature of the final product requirements as they relate to the actual composition of the raw gas. The first requirements of a processing system are that the impurities of the raw gas may be removed to meet commercial standards. Among the processes meeting these requirements the most attractive economic choice may be made giving due consideration to any environmental impacts involved. A number of gas purification processes are commercially available and have had long use in the petroleum and the energy production industry (Ref. 23, 24, 25). A review of the operation of some of the most important techniques is given here, followed by a section on the design procedure for an adsorption column.

A. Gas Purification Techniques

Generally absorption, liquefaction, and adsorption processes are used for bulk removal of carbon dioxide and hydrogen sulfide impurities.

1. Absorption

The ethanolamine absorption process is widely used for CO_2 and H_2S removal. Monoethanolamine (MEA) and diethanolamine (DEA) are the most widely used solvents, but particularly the former (Ref. 26, 27, 28, 29).

Figure 27 shows the simple process scheme where lean solvent (ethanolamine) enters the top of the absorber at approximately 100° F and contaminated landfill gas flows upward. Purified gas leaves the tower at its top. The gas must be dehydrated before being fed into the distribution pipeline. Since aqueous amine has very little affinity for the hydrocarbon constituents of the gas to be purified, this process can be successfully used for methane gas purification.

Ethanolamine solution is regenerated by stripping at a temperature of approximately 230 to 240° F. The released gases and traces of solvent are burnt in the flair burner and discharged to the atmosphere. The reactions involved in absorption-regeneration processes are very complex, but may be summarized by the following reversible reaction equations.

$$HO - CH_2 - CH_2 - NH_2 + H_2S \underset{240^\circ F}{\overset{100^\circ F}{\rightleftharpoons}} (HO - CH_2 - CH_2 - NH_3)\ HS$$

MEA hydrogen sulfide

$$HO - CH_2 - CH_2 - NH_2 + CO_2 + H_2O \underset{300^\circ F}{\overset{120^\circ F}{\rightleftharpoons}} (HO - CH_2 - CH_2 - NH_3)\ HCO_3$$

MEA hydrogen carbonate

The presence of carbon dioxide and water together causes the corrosion problem in the operation of ethanolamine plant. It is necessary to add corrosion inhibitors to reduce the effect. It is also recommended to use 304 and 316 stainless steel at critical points (points of maximum stress), which will, of course increase the total initial capital investment of the plant.

The sulfinol (known as tetrahydrothiophenedioxide) process was developed by Shell Oil Company (Ref.30, 31). This process works on the principle of absorption of acid gases (CO_2 and H_2S) at high pressure and solvent generation by reduction in pressure without heat application.

The diglycolamine (DGA) gas purification process was developed by Fluor Corporation. Its primary advantages versus MEA are: lower utility costs due to lower circulation rates, low freezing points, and ability to remove mercaptans (Ref. 32, 33).

The hot potassium carbonate process was developed by the U.S. Bureau of Mines at Bruceton, Pennsylvania (Ref. 34, 35, 36). Its primary use is for bulk H_2S and CO_2 removal at higher pressure since both H_2S and CO_2 must be physically absorbed before they can react in the following reversible manner:

$$K_2CO_3 + CO_2 + H_2O \rightleftharpoons 2KHCO_3$$

$$K_2CO_3 + H_2S \rightleftharpoons KHCO_3 + KHS$$

Although this process requires an inexpensive chemical, it cannot produce gases of pipeline standards.

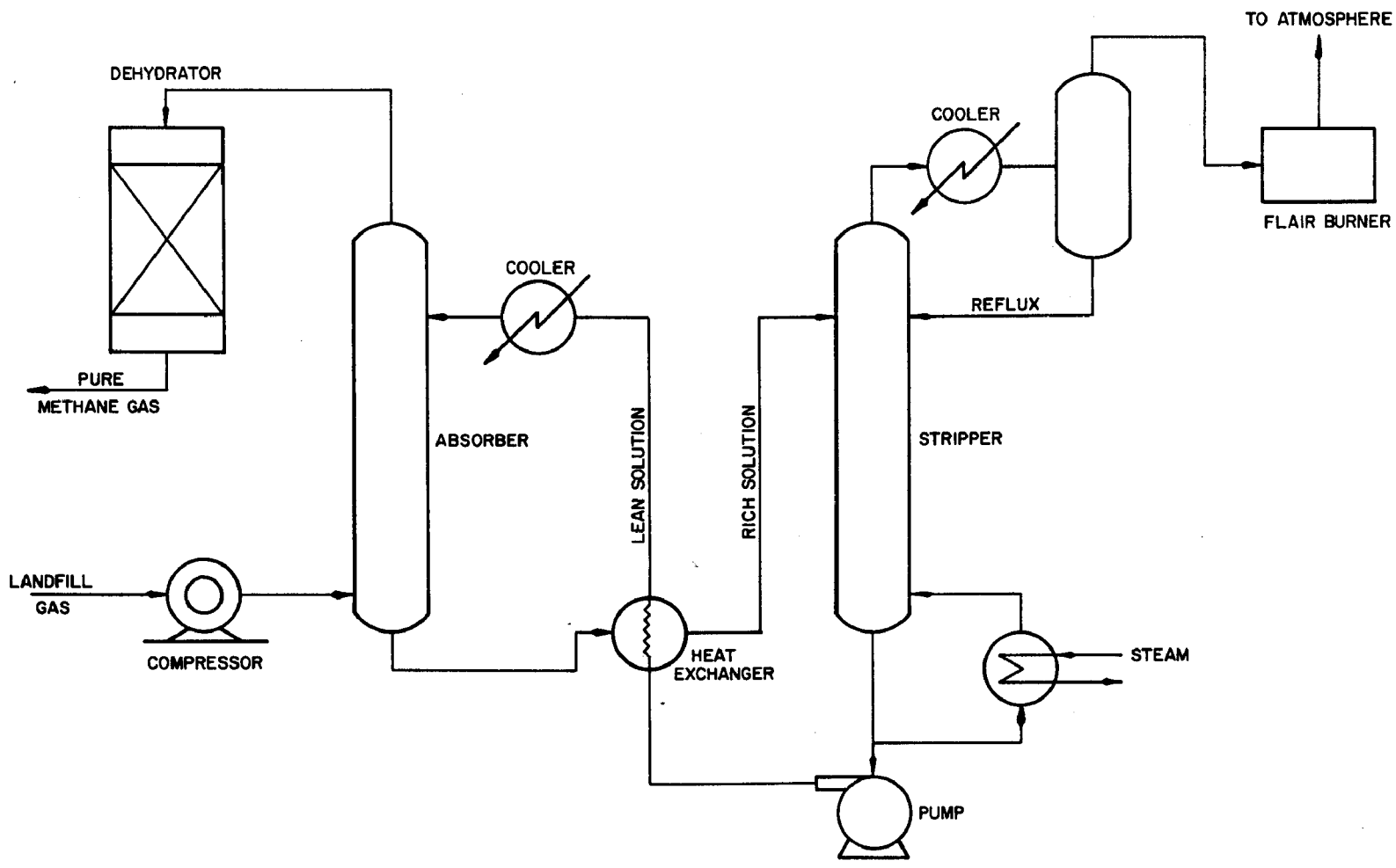


FIGURE 27: ETHANOLAMINE ABSORPTION PROCESS FOR CO_2 AND H_2S REMOVAL

2. Liquefaction of Carbon Dioxide

Purification of landfill gases containing 50-50 percent of CO_2 and CH_4 can be achieved by liquefaction. Figure 28 shows the phase diagram for the CH_4-CO_2 system (Ref. 37). In order to produce methane of 90 percent purity, it is necessary to operate the plant at 730-750 psia with temperature no lower than -100° F. Methane (boiling point -259° F) vapor under these conditions has a heating value of 900 Btu per SCF and contains 10 percent CO_2. This does not meet pipeline standards; a second stage of purification would be required.

Figure 29 illustrates the simplified process scheme for treating the low Btu sanitary landfill gases containing about 50 volume percent of CO_2. Water removal is accomplished by passing the gases through an adsorption tower (dehydrator) containing either molecular sieve or activated carbon. Gas is cooled to the desired temperature and purified in the demethaniser, a standard distillation type separator. CO_2 and CH_4 are separately passed through a heat pump cycle to recover energy which can be used in cooling the feed gas.

The additional purification of landfill gas to boost the heating value to acceptable pipeline standard can be achieved by one of the following methods:

A second stage of liquefaction treatment involving freezing close to the solid CO_2 vapor region, which will require an additional refrigeration system. This process can be competitive only when a source of low cost refrigeration is available.

Absorption of CO_2 into liquid: this process has the disadvantage of re-introducing water back into the gas, thus requiring an additional drying stage before entering the distribution pipeline.

Adsorption of CO_2 on solids: this process has the advantage of removing the remaining 10 percent of CO_2 while keeping the gas dry.

3. Fixed-Bed Adsorption

Gas purification by adsorption process is based upon the physical properties of specially prepared granular solids, the adsorbent. An adsorbent will selectively attract and retain gases on its surfaces.

Adsorbents generally used for gas purification are molecular sieves, activated carbon, silica gel, and activated alumina. Among all these adsorbents, molecular sieves are being most successfully used to purify gases containing CO_2 and H_2S (Ref. 38, 39, 40). They are particularly attractive with gases containing relatively large quantities of CO_2 with small quantities of H_2S (Ref. 41).

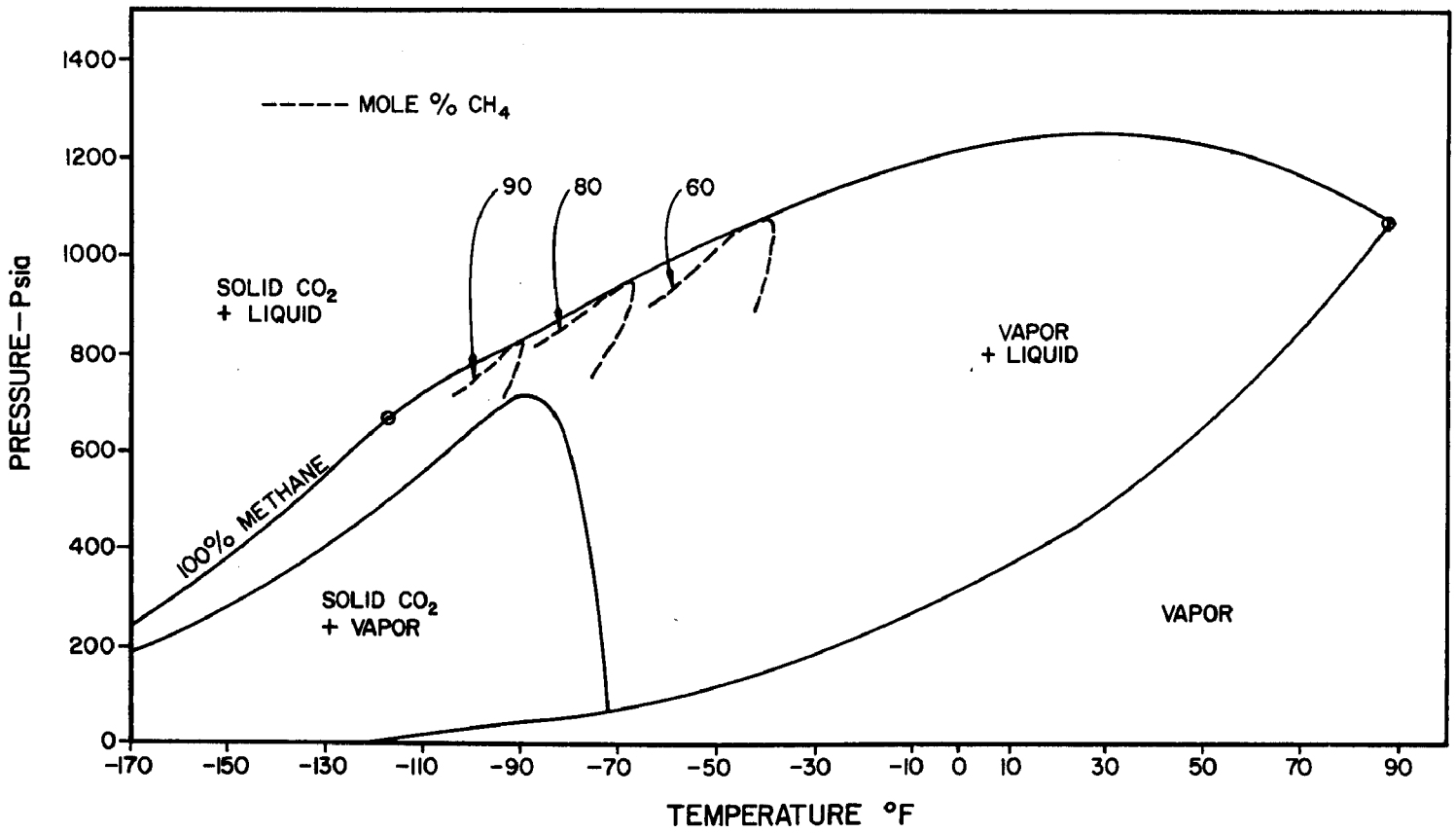


FIGURE 28: PHASE DIAGRAM FOR $CO_2 - CH_4$ SYSTEM

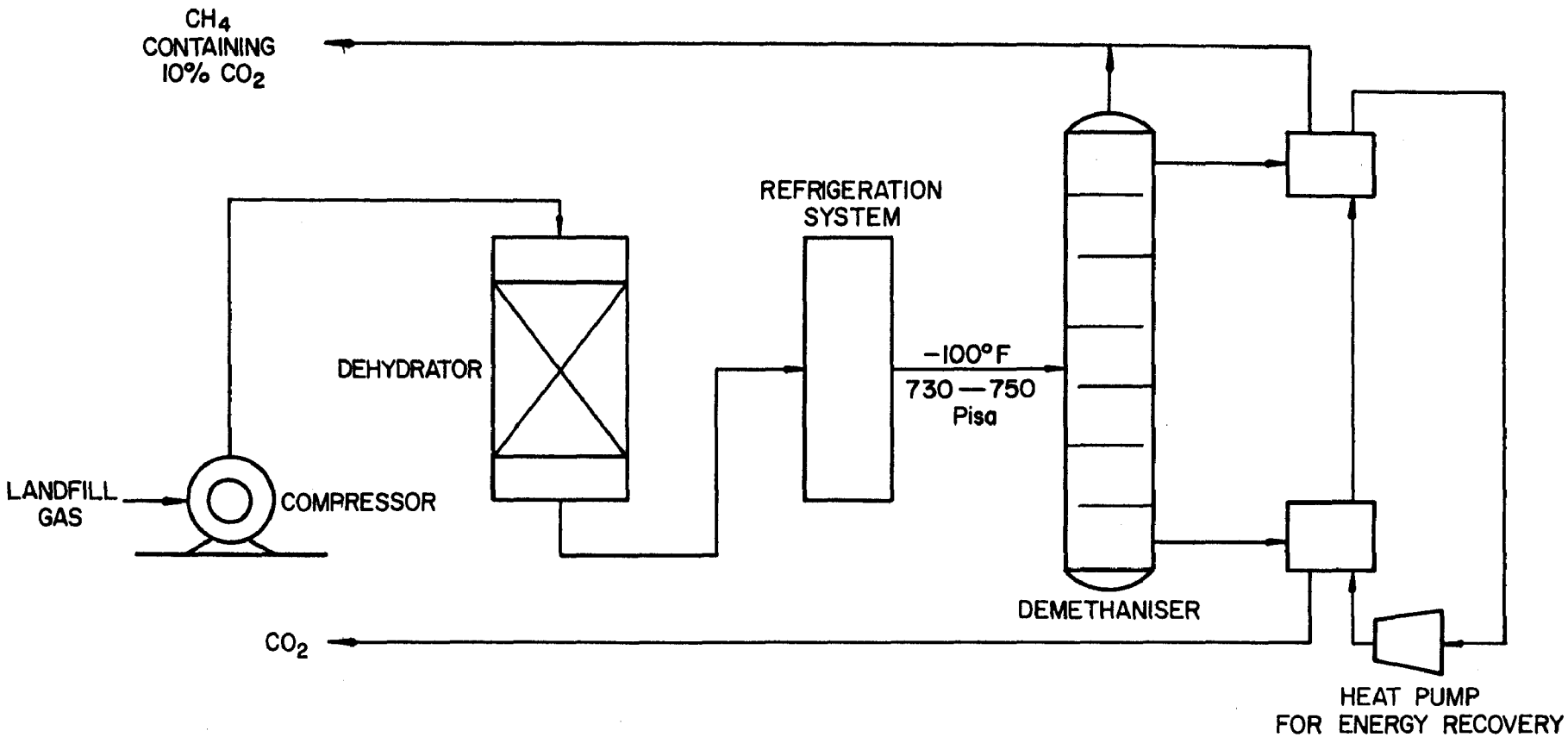


FIGURE 29: LIQUEFACTION OF CARBON DIOXIDE FROM LANDFILL GASES

Figure 30 illustrates the simplified process scheme for gas purification by the molecular sieve adsorption process working on the thermal-swing regeneration cycle. Compressed landfill gas passes through filteration and dehydration unit to remove dust and water respectively. The dried gases enter at the top of one of the triple-beds unit. One bed is adsorbing contaminants while the other two are at one of the two stages of regeneration (heating and cooling). In a properly designed adsorption column, adsorption time is always the same as the regeneration time so that this process can be continuously operated. The gases produced by this process are of 99 percent purity and they meet the pipeline standards.

Among all the process discussed earlier, the molecular sieve adsorption technique is considered to be one of the most economical for bulk landfill gas purification. The economic feasibility of this process depends upon designing a proper purification system. Therefore, in the next section, the criteria for adsorption column design are established.

B. Design of an Adsorption Column for Sanitary Landfill Gas Purification

The design of an adsorption column requires a detailed investigation of the following items.

1. Selection of an Adsorbent

A number of commercially available adsorbents should be selected which have the best adsorption properties for the gases to be removed. Generally, molecular sieve, activated alumina, or silica gel are used to remove water, carbon dioxide, and hydrogen sulfide by selective adsorption.

2. Static Adsorption Test

One of the important basis for adsorbent selection is its adsorptive capacity. This is determined by running a series of static test to determine the pounds of impurity that can be removed at equilibrium by each pound of adsorbent. The extent of adsorption is highly temperature and pressure dependent and it is usually represented by isotherms - gas phase concentration versus specific adsorption on the solid at a given temperature (Figure 31 and 32).

Generally, molecular sieve type 5A and 13X is used for removal of smaller molecules such as H_2O, CO_2 and H_2S. Figure 22 shows that molecular sieve 13X has almost five times the drying capacity of either alumina or silica-type adsorbents when water is present in extremely low concentrations. This is why exceptionally low dew points can be obtained with molecular sieves in gas purification.

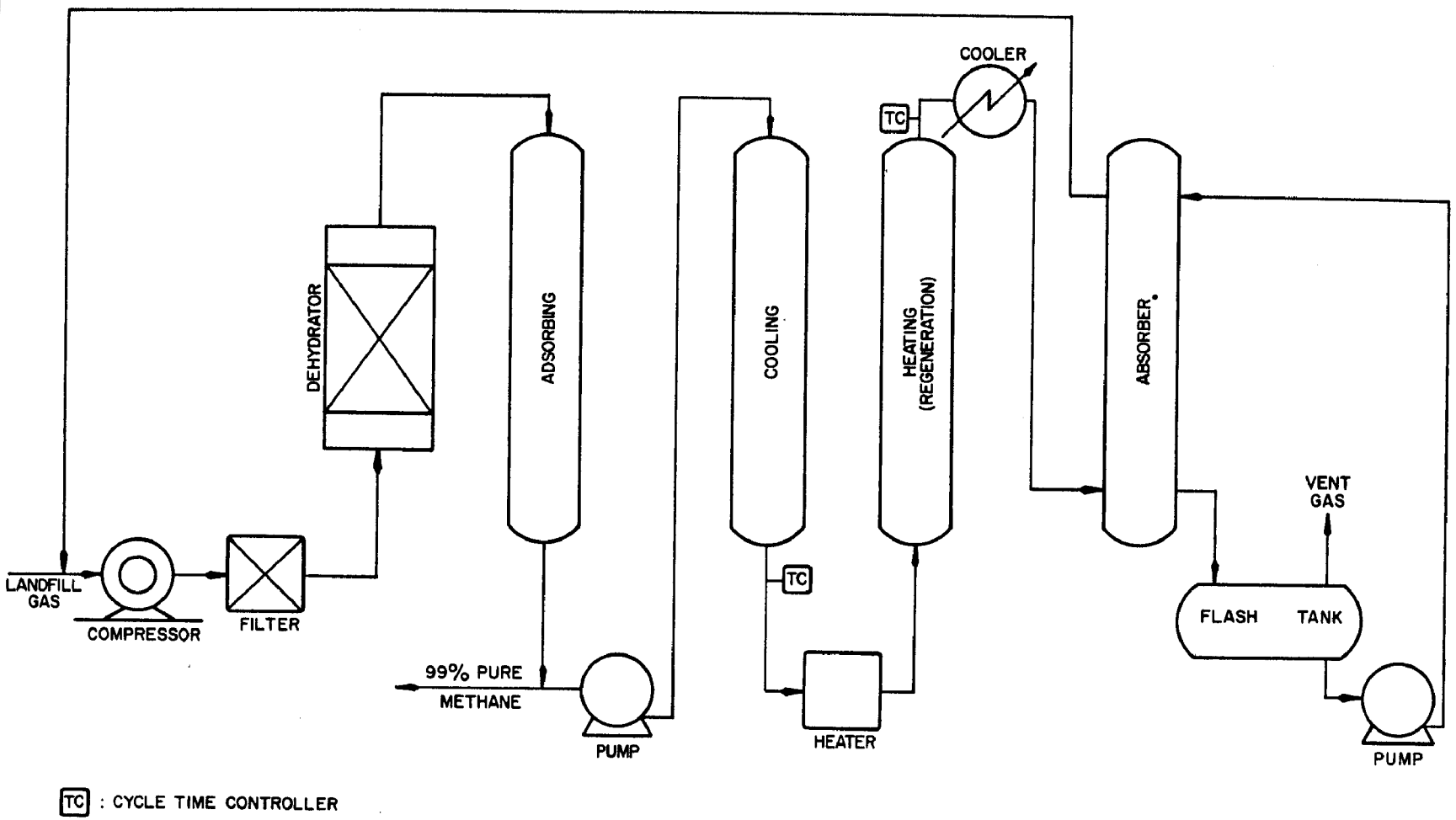


FIGURE 30: A CLOSED CYCLE MOLECULAR SIEVE ADSORPTION PROCESS

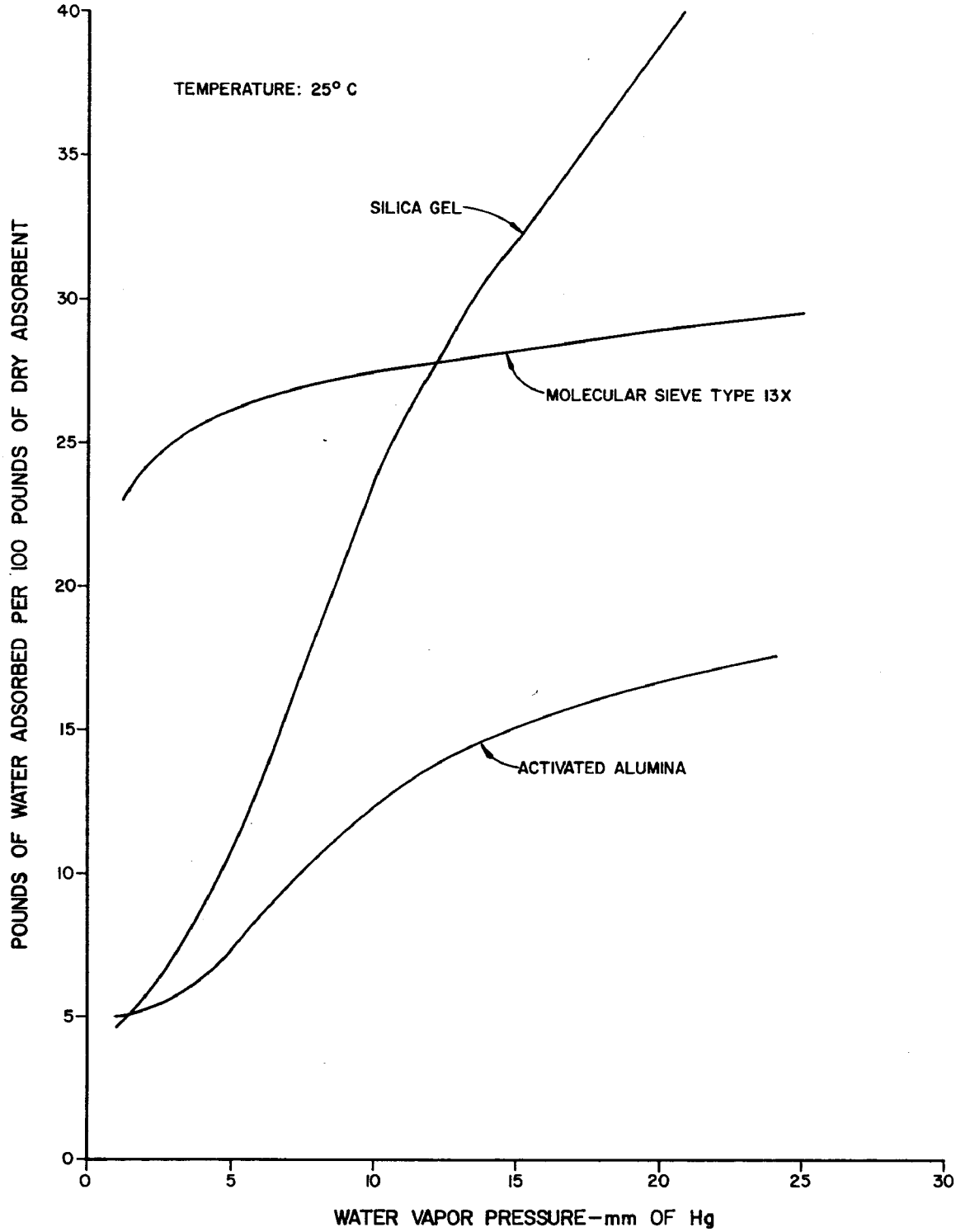


FIGURE 31: ISOTHERMS FOR WATER ADSORPTION (REF. 42)

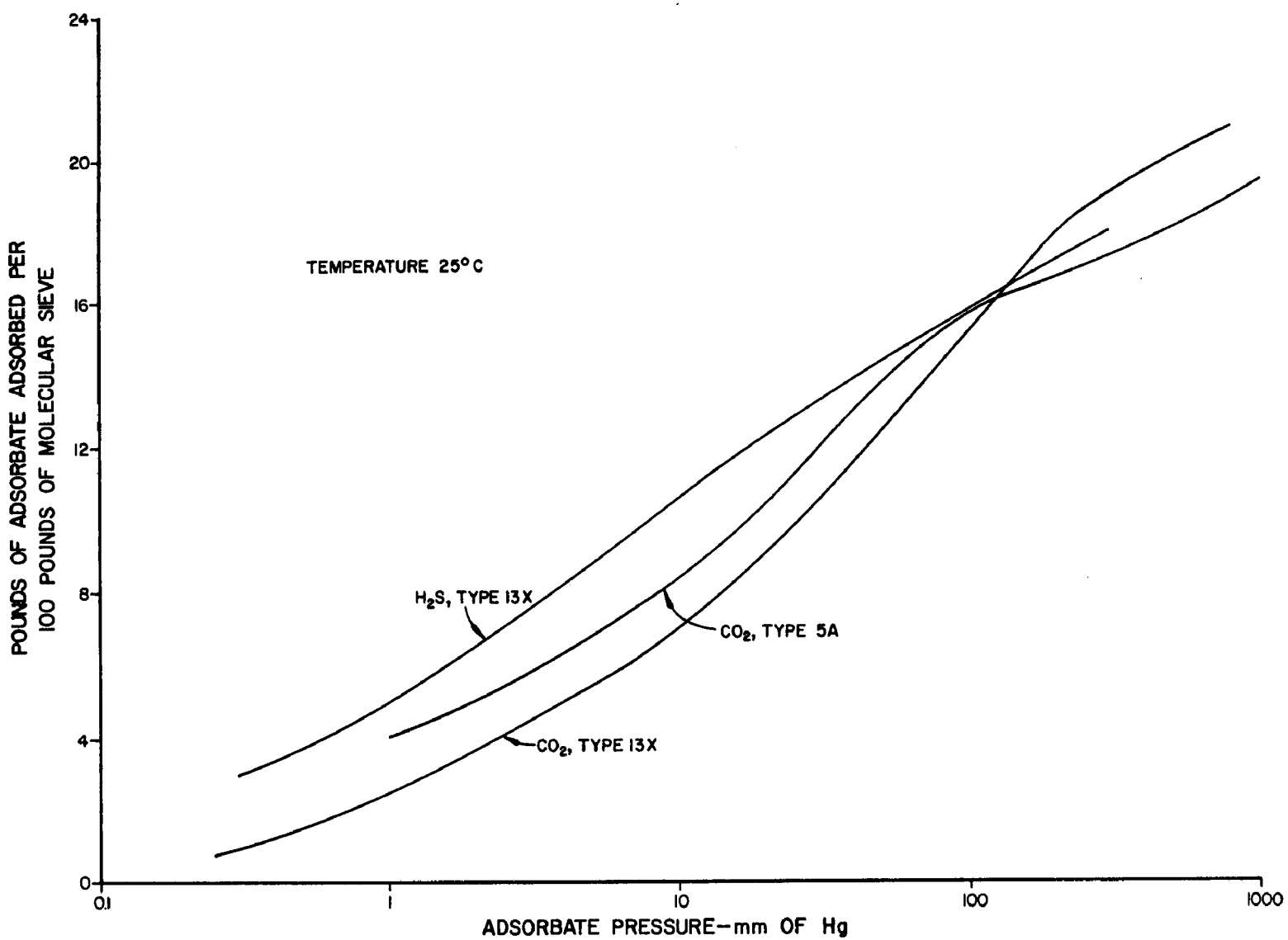


FIGURE 32: ISOTHERMS FOR CARBON-DIOXIDE AND HYDROGEN SULFIDE ADSORPTION (REF. 42)

3. Dynamic Adsorption Test

In a gas purification process, the results obtained under static adsorption only show the maximum loading attainable. The rate of attainment of any fraction of the equilibrium loading of the adsorbent under dynamic adsorption conditions remains to be determined. The purpose of this test is to find the breakthrough time and capacity to reduce the adsorbate from one concentration to another.

As the gas enters an activated adsorbent bed, the sorbable component is attracted to and adsorbed on the adsorbent. Figure 33 shows the adsorbate loading with respect to length of the bed (X-L) and concentration of sorbable component in effluent with respect to time (Y-O). The portion of the bed in which adsorbate loading is equal to equilibrium loading is defined as the equilibrium zone (Area h a b k h). The portion of bed in which the adsorbate concentration transition occurs is defined as the mass-transfer zone (MTZ). The point at which adsorbent capacity is exhaused to produce certain allowable concentration of effluent, is called breakthrough point. This point advances through the column with time.

For a particular landfill gas, (X-L) and (Y-O) plots are experimentally determined in the dynamic adsorption test. From this plot one can determine the ratio of the weight of equilibrium bed (Area h k c f h) to weight of unused bed (Area c d e f e), and breakthrough time (Ob) required to reduce the adsorbate concentration to a desired level.

4. Gas Flow Rate

The superficial flow rate is fixed by the diameter of the column. The pressure drop across the adsorbent bed becomes the limiting factor. Since the cost of a pressure vessel tends to increase dramatically with the diameter, the minimum diameter of an adsorption column is set by pressure drop limitation. Generally, a superficial flow rate from 0.5 to 2 feet per second is selected for a downward gas flow.

5. Heat of Adsorption

As the adsorption progresses the adsorbent is heated by the exothermic heat of adsorption, and this heat is carried ahead of the adsorption zone by the gas. The effect of increase in temperature lowers the capacity of the adsorbent. Therefore, gas flow rate should be controlled to prevent over-heating.

6. Adsorbent Bed Arrangement

Generally adsorption-regeneration systems are dual-bed units, or multiples of dual-bed units. In this arrangement one bed is adsorbing while the other is regenerating.

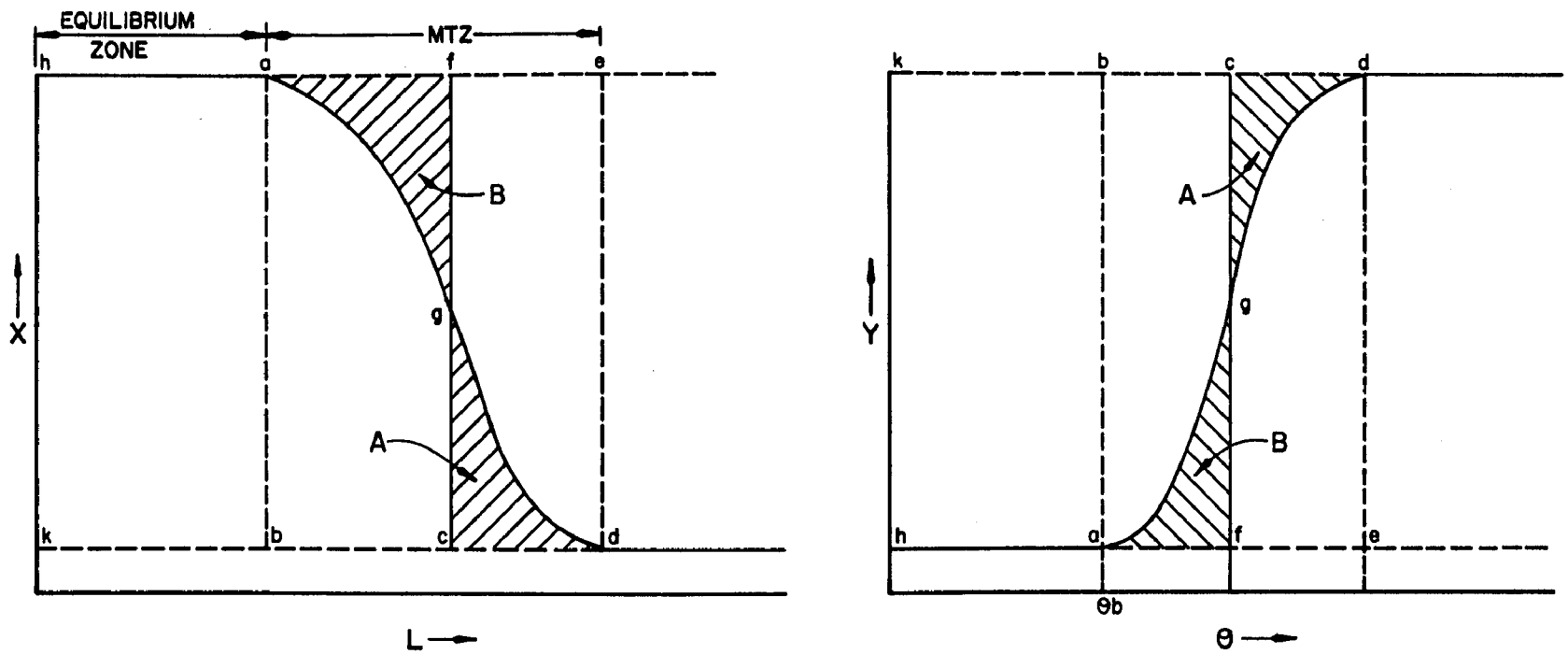


FIGURE 33: DETERMINATION OF MASS-TRANSFER FRONTS BY DYNAMIC ADSORPTION TEST

In thermal-swing cycles, three-bed units are used with one adsorbing while the other two are either heating or cooling. A bed spends a third of its cycle time in each of the three positions.

7. Selection of a Regeneration Procedure

A procedure is selected on the basis of residual loading and adsorption-regeneration cycle time. The following regeneration cycles are used in gas purification:

Thermal-Swing Cycle Broadly defined as one in which desorption takes place at a temperature higher than that of the adsorption step. Raising the temperature of the adsorbent increases the equilibrium pressure of the adsorbate. Cooling is required after regeneration before the adsorbent is ready for a subsequent adsorption step. The long regeneration time makes this technique unattractive for use in bulk separation processes such as CO_2 removal from landfill gases.

Pressure-Swing Cycle Desorption is carried out at a pressure lower than that of the adsorption step. Here, the partial pressure of the sorbate in the gas is lowered instead of raising the equilibrium pressure on the adsorbent as in the temperature swing cycle. The main advantage of this technique is that desorbed materials can be recovered as high purity products. The technique is very useful for bulk separation where short cycles and low residual loadings are required.

Purge-Gas-Stripping Cycle In this case a reduction of partial pressure of sorbable component in fluid phase is achieved by dilution with an inert gas to cause desorption. The purge gas may be heated to improve efficiency and shorten the purge time required - the effects of thermal swing may be enlisted.

CHAPTER VI

RSF'S COMMERCIAL EXPERIENCE IN PALOS VERDES LANDFILL GAS EXTRACTION AND PURIFICATION

As a result of the uncertainty on the part of the Los Angeles County Sanitation Districts to guarantee a continuous supply of raw landfill gases to RSF's gas purification plant, a mutual agreement was reached to extract and process 1.0 MMSCF per day of gases on an experimental basis. It was decided that the District would only construct the withdrawal wells required by RSF to meet the desired methane gas production; it would then be the responsibility of RSF to operate and maintain a gas withdrawal and purification system. On June 1, 1975 this sophisticated gas collection system became operative to extract landfill gases under vacuum. These gases are automatically routed to the purification plant or by-passed to the waste burners. Carbon dioxide and hydrogen sulfide are removed by a process based on the molecular sieve adsorption technique.

A. Landfill Gas Extraction

During the operation, an irregular supply of raw landfill gas at variable withdrawal rates was experienced. Between June 1, 1975 and February 12, 1976, on four different occasions gas extraction was stopped as a result of mechanical and/or technical problems. Those problems were mostly caused by the presence of corrosive carbonic acid. It was felt that selection of a construction material resistant to carbonic acid would partially solve this problem.

Table 13 indicates the total quantity of raw landfill gas withdrawn to the end of December 1975. The extraction rate was acceptable only during the months of November and December. A total of 91,239.2 MSCF of raw landfill gas was extracted which is only 42.6 percent of the predicted amount (based on a withdrawal rate of 1 MMSCF per day for 214 days).

During the month of December 1975 and part of January 1976, the gas composition and flow rates of extraction wells numbered 1, 2, 3, 4, 5 and 7 were investigated (Table 14). These wells were pumped to supply approximately 1000 SCFM of raw landfill gas. Generally, the flow rate of an individual well ranged from as low as 75 SCFM to 310 SCFM. The methane content in the raw landfill gas was always over 50 percent by volume. At increased withdrawal rates, these gases contained substantial percentages of nitrogen. An air leak can be the result of three possible causes: (1) a broken header or branch header pipe, (2) a faulty connection at one of the wells, and/or (3) an infiltration of air through the top cover of the landfill.

B. Gas Purification

The purification of raw landfill gases require the following five basic operations: initial and final compression, water removal, H_2S and water removal, carbon dioxide removal, and burning of contaminants to form non-polluting products (Figure 34). The facilities to accomplish this were built by RSF, costing approximately one million dollars.

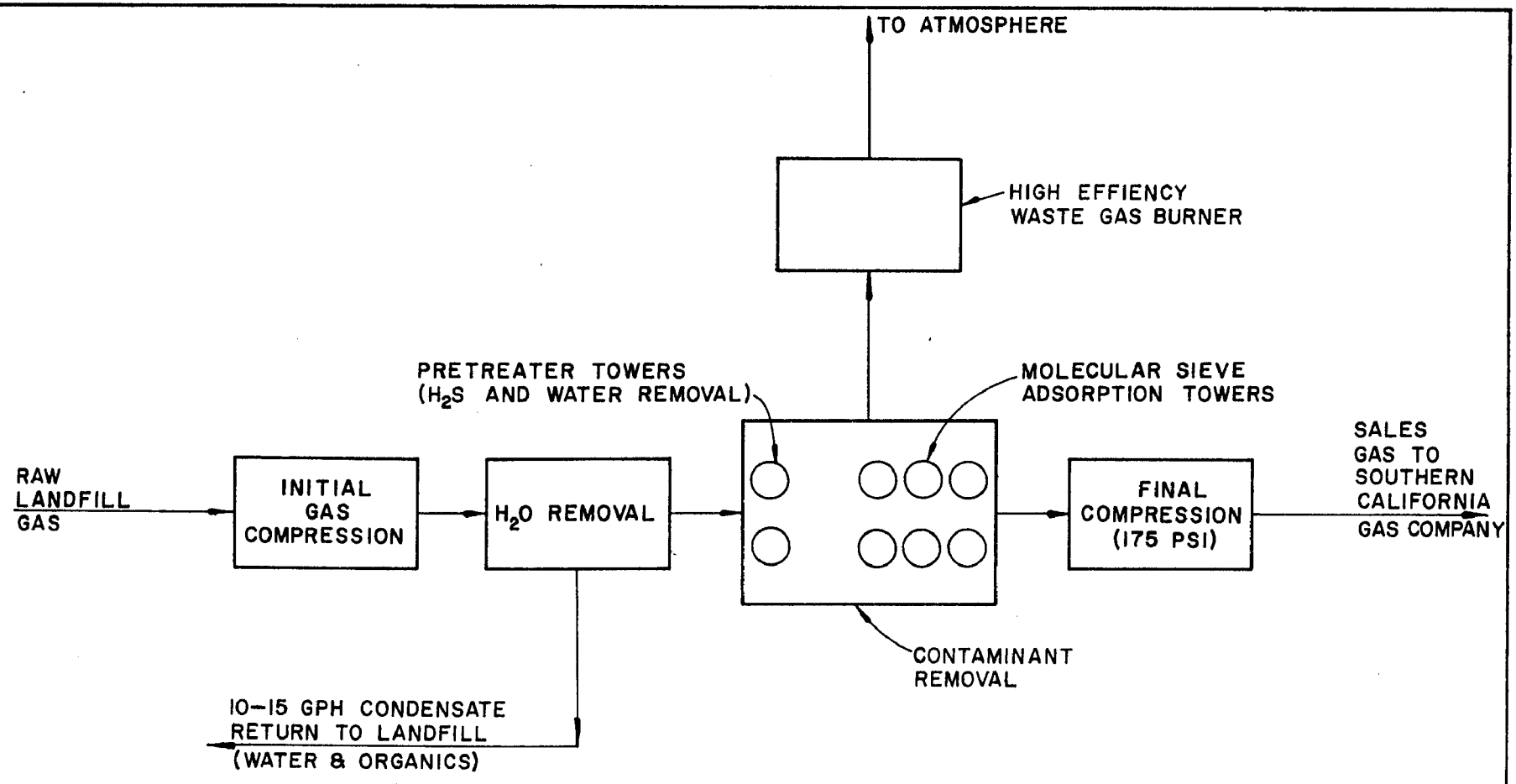


FIGURE 34: SCHEMATIC DIAGRAM OF
PALOS VERDES LANDFILL GAS PURIFICATION PROCESS

SOURCE: RESERVE SYNTHETIC FUELS, INC.

TABLE 13

PALOS VERDES LANDFILL GAS EXTRACTION
AND PURIFICATION OPERATION

	RAW LANDFILL GAS MSCF(A)*	AMOUNT OF METHANE PRODUCED MSCF(B)**	$\frac{B}{A}$	AMOUNT OF METHANE CONSUMED MSCF(C)**	$\frac{C}{B}$	NET AMOUNT OF METHANE GAS SOLD TO SOUTHERN CAL. GAS CO., MSCF
June, 1975	6,165	3,242	0.53	3,274.8	1.01	- 32.8****
July, 1975	11,669	4,838	0.42	5,558	1.15	-720
August, 1975	11,333	6,490	0.57	2,561	0.39	3,929
September, 1975	11,035	4,576	0.42	1,879	0.41	2,697
October, 1975	4,317	495	0.12	896	1.81	-401
November, 1975	20,738	5,504	0.27	1,309	0.24	4,195
December, 1975	25,982.2	4,108	0.16	2,716	0.66	1,392
January, 1976	-	2,273	-	1,202	0.53	1,071
February 12, 1976	-	314	-	490	1.56	-176
	91,239.2***	31,840	-	19,885.8	0.62	11,954.2

* Source: Los Angeles County Sanitation Districts

** Source: Southern California Gas Company, Los Angeles

*** The total quantity of gas withdrawn to the end of December, 1975

**** The negative sign indicates that methane consumption rate is higher compared to the production rate.

Note: Readings were corrected for pressure. The heating values ranged from 968 to 1,030 Btu/SCF.

TABLE 14

COMPOSITION AND FLOW RATES OF RAW GAS OBTAINED FROM EXTRACTION WELLS LOCATED AT PALOS VERDES LANDFILL

DATE	WELL NO.	PERCENTAGE (VOLUME) CO_2	CH_4	N_2	O_2	WELL FLOW RATE SCFM	TOTAL FLOW RATE FROM ALL WELLS SCFM
12/5/75	1	40.6	59.4	Trace	0	200	
	2	38.7	61.3	0	0	160	
	3	40.5	57.1	2.4	0	200	960
	4	33.9	56.2	8.1	1.8	190	
	5	34.6	62.4	3.0	0	210	
12/8/75	1	49.0	49.1	1.9	0	200	
	2	45.1	54.9	Trace	0	310	
	3	-	-	-	-	Shut Down	1070
	4	38.9	57.4	3.7	0	280	
	5	41.4	58.6	0	0	280	
12/9/75	1	40.1	57.7	2.2	0	310	
	2	40.8	59.2	Trace	0	280	
	3	-	-	-	-	Shut Down	1150
	4	39.8	60.2	Trace	0	280	
	5	39.7	56.7	3.6	0	280	
12/10/75	1	42.2	57.8	0	0	100	
	2	42.4	57.6	0	0	280	
	3	34.4	65.6	0	0	130	940
	4	39.4	60.6	0	0	250	
	5	35.9	58.4	5.7	0	180	
12/11/75	1	47.8	50.8	1.4	0	75	
	2	43.8	56.2	Trace	0	300	
	3	41.0	59.0	Trace	0	95	835
	4	43.9	56.1	0	0	175	
	5	39.5	57.1	3.4	0	190	

TABLE 14 (continued)

DATE	WELL NO.	PERCENTAGE (VOLUME) CO_2	CH_4	N_2	O_2	WELL FLOW RATE SCFM	TOTAL FLOW RATE FROM ALL WELLS SCFM
12/12/76	1	42.1	56.9	1.0	0	75	
	2	36.3	63.0	0.7	0.05	250	
	3	41.0	58.4	0.5	0.2	95	820
	4	39.1	60.7	0.2	0.05	200	
	5	36.4	58.0	5.6	0	200	
12/13/75	1	38.3	58.2	3.2	0.28	95	
	2	38.8	60.4	0.8	0.06	290	
	3	40.3	58.9	0.6	0.2	95	900
	4	38.1	61.6	0.3	0.04	200	
	5	43.5	52.1	4.4	Trace	220	
12/16/75	1	41.7	55.9	2.4	0.1	75	
	2	40.4	59.2	0.4	0.03	250	
	3	44.1	55.4	0.5	0.08	110	825
	4	44.3	55.5	0.2	0.04	180	
	5	40.6	53.8	5.4	Trace	210	
12/17/75	1	37.3	59.4	3.1	0.15	75	
	2	38.9	60.6	0.5	Trace	250	
	3	38.2	61.1	0.6	0.1	95	845
	4	44.1	55.7	0.2	Trace	175	
	5	38.8	56.2	5.0	Trace	250	
12/18/76	1	39.4	57.1	3.3	0.15	75	
	2	40.7	58.8	0.5	Trace	270	
	3	42.4	57.1	0.4	0.08	95	830
	4	38.4	61.4	0.2	0.03	180	
	5	41.3	53.3	5.4	Trace	210	

TABLE 14 (continued)

DATE	WELL NO.	PERCENTAGE (VOLUME) CO_2	CH_4	N_2	O_2	WELL FLOW RATE SCFM	TOTAL FLOW RATE FROM ALL WELLS SCFM
12/22/75	1	43.8	55.4	0.8	0.04	110	
	2	44.7	55.0	0.3	0.02	280	
	3	45.0	54.9	0.1	0.02	160	980
	4	41.8	58.1	0.1	Trace	200	
	5	44.3	54.2	1.5	Trace	230	
12/23/75	1	-	-	-	-	Shut Down	
	2	44.2	55.1	0.7	0.05	360	
	3	45.9	53.5	0.5	0.1	330	1000
	4	42.8	55.2	1.8	0.2	310	
	5	-	-	-	-	Shut Down	
12/24/75	1	-	-	-	-	Shut Down	
	2	38.4	57.7	3.4	0.5	260	
	3	43.7	53.0	2.5	0.8	250	820
	4	44.1	50.6	4.7	0.6	310	
	5	-	-	-	-	Shut Down	
12/26/75	1	-	-	-	-	Shut Down	
	2	44.2	53.2	2.3	0.3	310	
	3	42.0	55.8	1.8	0.4	290	950
	4	39.5	52.4	7.7	0.4	350	
	5	-	-	-	-	Shut Down	
12/30/75	1	-	-	-	-	Shut Down	
	2	37.5	52.9	7.1	2.5	290	
	3	41.2	51.2	5.8	1.8	265	955
	4	44.4	52.6	2.5	0.5	310	
	5	43.8	52.2	3.3	0.6	90	

TABLE 14 (continued)

DATE	WELL NO.	PERCENTAGE (VOLUME) CO_2	CH_4	N_2	O_2	WELL FLOW RATE SCFM	TOTAL FLOW RATE FROM ALL WELLS SCFM
12/31/75	1	-	-	-	-	Shut Down	
	2	41.6	53.3	3.5	1.6	290	
	3	41.4	54.6	3.1	0.8	290	1040
	4	41.8	52.2	2.7	0.4	310	
	5	42.0	53.3	2.8	1.9	75	
	7	42.5	56.2	1.0	0.3	75	
1/10/76	1	46.0	51.1	2.3	0.6	58	
	2	45.6	52.7	1.5	0.2	250	
	3	39.2	51.1	7.6	2.1	95	925
	4	45.1	52.9	1.6	0.3	172	
	5	42.9	54.5	2.2	0.4	90	
1/11/76	1	45.8	53.1	0.9	0.2	75	
	2	38.3	61.1	0.5	0.1	240	
	3	-	-	-	-	Shut Down	639
	4	41.8	57.1	0.9	0.2	165	
	5	42.7	55.4	1.7	0.18	84	
	7	42.5	56.5	0.8	0.15	75	

Source: Los Angeles County Sanitation Districts

Water removal is accomplished by cooling the gases below the dew point of water. This causes the water vapor to condense and separate from the gas stream. This process has two advantages: (1) the load on the adsorbent bed is reduced as a result of the water vapor being removed by condensation in the cooler, and (2) the capacity of the adsorbent is slightly increased because of the lower temperature. The water removed in this fashion is collected and injected back into the landfill at depths well below the ground level via an underground piping system. The quantity of water will vary from 10 to 15 gallons per hour depending upon climatic conditions and the volumetric flow rate of raw landfill gas.

The gas leaving the water removal operation then passes through two pretreater towers which remove the adorous compound H_2S and free water vapor. The adsorbent used in the pretreater towers is a molecular sieve. The regeneration of the adsorbent bed is accomplished by thermal-swing cycle. In this process a heated gas stream is recirculated through the towers, heating the beds to the temperature required to release the adsorbed contaminants. Maximum energy saving is accomplished by using the contaminated effluent from the pretreater and adsorption towers as fuel to heat the regeneration system. The remaining contaminated gas stream is incinerated in the waste gas burner, where the sulfur-bearing compounds are oxidized to SO_2.

The purification plant also consists of six molecular sieve adsorption towers to remove carbon dioxide. The molecular sieve adsorption beds undergo an adsorption-desorption cycle on an intermittent basis to provide continuous production of gas. On the desorption cycle the vessel is depressurized to release the CO_2. The CO_2, which contains four percent methane, is then routed to the waste gas burner, where methane is oxidized to CO_2 and water. The composition of the combusted exhaust gas is given in Table 15. Upon completion of the desorption cycle the vessel is pressurized and put back on stream.

The product gas undergoes the final stage of compression to 175 psi required by the Southern California Gas Company. The product gas composition is given in Table 15.

C. Methane Gas Production and Consumption

Table 13 indicates the total amount of methane gas produced, the amount of methane gas consumed (gas sold back to RSF to operate their facilities), and the net amount of methane gas delivered to Southern California Gas Company's pipeline (see Figure 35). During the months of June, July, and October 1975 and part of February 1976, the methane consumption rate was higher than the production rate. Out of a total of 31,840 MSCF of methane gas produced, approximately 19,886 MSCF (62 percent) was consumed to operate the purification plant.

During the initial four months, approximately 50 percent by volume of the total raw landfill gas extracted was produced as pure methane gas. After that, this ratio dropped, ranging from 12 to 27 percent. The loss in production capacity was blamed on an infiltration of air at an increased

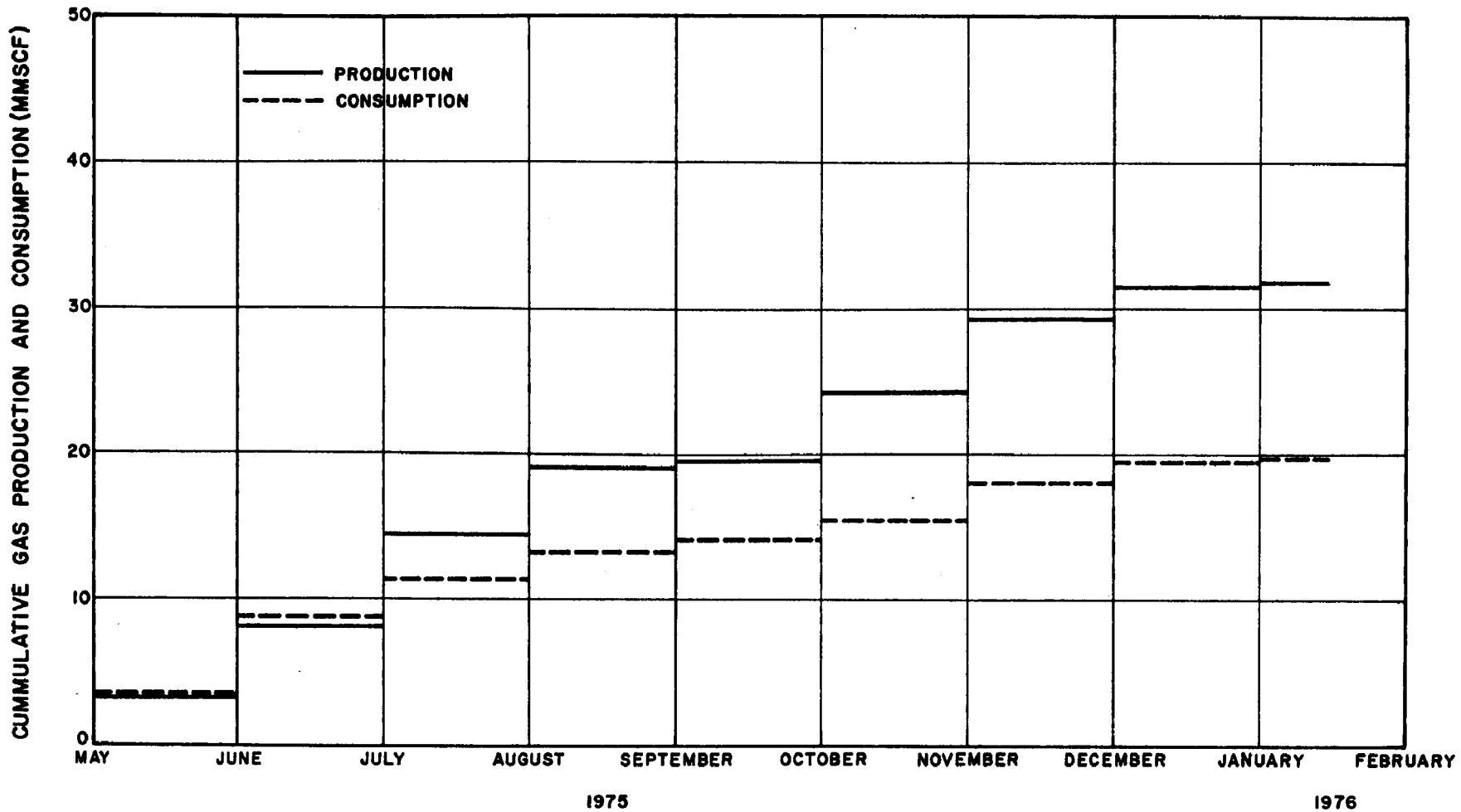


FIGURE 35: PALOS VERDES LANDFILL–
CUMMULATIVE METHANE PRODUCTION AND CONSUMPTION

SOURCE: SOUTHERN CALIFORNIA GAS CO., LOS ANGELES

TABLE 15

SALES AND COMBUSTION GAS STREAM
(Volume Percentage)

	SALES GAS (IN %)	COMBUSTED GAS (IN %)
Hydrogen (H_2)	0.1047	-
Oxygen (O_2)	0.1299	-
Nitrogen (N_2)	0.5072	-
Carbon Dioxide (CO_2)	-	75.0
Hydrogen Sulfide (H_2S)	-	-
Methane (CH_4)	99.2458	-
Carbon Compounds	0.0124	-
Water (H_2O)	-	6.999986
Sulfur Dioxide (SO_2)	-	0.000014
Free Air (by Difference)	-	18.0
	100.0000	100.00000

Source: Reserve Synthetic Fuels, Inc.

withdrawal rate causing an increase in nitrogen content in the landfill gas. Since the existing RSF gas purification plant does not remove nitrogen, the product methane gas is lower in heating value. As a result of this problem, RSF was unable to sell a significant amount of product gas to the Southern California Gas Company.

During the time span of 264 working days, the gas extraction and purification system was under operation for only 204 days. A total of approximately 31,840 MSCF of 99 percent methane gas was produced. The purification plant was operating at 16.6 percent of its suggested production capacity. The total saleable energy production during this period was approximately 31.84 x 10^9 Btu based on the average heating value of 1000 Btu/SCF.

D. Economic Evaluation

The discussion on this gas purification system would be incomplete without conducting an economic evaluation. According to the contract, the Los Angeles County Sanitation District is to receive the royalty after RSF has extracted 525,600 MSCF of raw gas or 12 months from the date of plant completion (June 1, 1975). Therefore, at this stage, the Sanitation Districts are not yet earning any profit on the investment they have made to drill and construct extraction wells. Based on the net energy production (11.95 x 10^9 Btu) and maximum control price of $2.50 per million Btu, the following conclusions can be drawn as of February 12, 1976:

Gross Income	$29,886
Los Angeles County Sanitation District's Royalty	0
Interest on one million dollars for 264 days (based on 7.5 percent annual rate)	54,246
Deficit	$24,360

These calculations do not include operational, engineering, and administrative expenses. It appears that RSF is not producing a net profit at this stage of the operation. However, looking at the complexity of the gas recovery and purification system it is advisable to wait another year before a meaningful and rational economic evaluation can be made.

CHAPTER VII

FIRE HAZARD AND SAFETY

The combustion and ignition of methane in air depends upon lower and upper methane inflammability limits, pressure, and temperature (Ref. 43, 44). Based on these parameters, the possibility of fire and explosion at various landfill locations may be evaluated. Therefore, in this section, the mechanism of methane oxidation and ignition will be discussed.

The ignition of flame (such as of methane) is always a result of the progressive auto acceleration of reaction, which becomes possible only under definite thermal conditions brought about by an external source such as the presence of flame, adiabatic compression, and possible spark from impact (flint and steel). The rate of any chemical reaction increases with temperature according to the Arrhenius equation:

$$k_1 = k_0 \exp(-E/RT)$$

Where, E, the activation energy, is the energy required for the internal reorientation of the reacting molecules.

And T, is the absolute temperature of the reacting mixture.

In the case of exothermic reaction, which includes all reactions of fuel combustion, there is always some temperature at which the rate of heat evolution due to the reaction begins to exceed the rate of heat removal from the reacting gas mixture. This will cause the increase in temperature, reaction rate and uncontrollable rate of heat evolution which is characterized as ignition - at the ignition temperature. The ignition temperature is a function of pressure and the concentration of methane in the air stream. Figure 36 illustrates the effect of pressure on the ignition temperature in an air mixture containing 13 percent methane. At one atmosphere pressure, the ignition temperature lies within the range of 800-900° C. At low methane concentration (about 3 percent and less) the ignition temperature also depends on formation of intermediate products such as carbon monoxide and formaldehyde. Sokolik (Ref. 45) reported that the ignition process is retarded by the formation of formaldehyde. The lower and upper inflammability limits of methane and air mixture are between 5-15 percent at one atmosphere and 25° C.

In the landfill gas recovery and purification processes where the methane concentration is very high, as well as temperature and pressure above ambient conditions, the possibility of a fire hazard exists. Air leaks on the suction side at landfill wells, pipeline, and suction blower may result in the formation of an explosive mixture. At these locations, an oxygen analyzer may be used to detect the oxygen content of the gas coming into the plant. This is done to prevent the possibility of an explosive mixture of air and gas being generated. In the case of excessive oxygen concentration, the compressor should be shut down, thereby stopping all the processes.

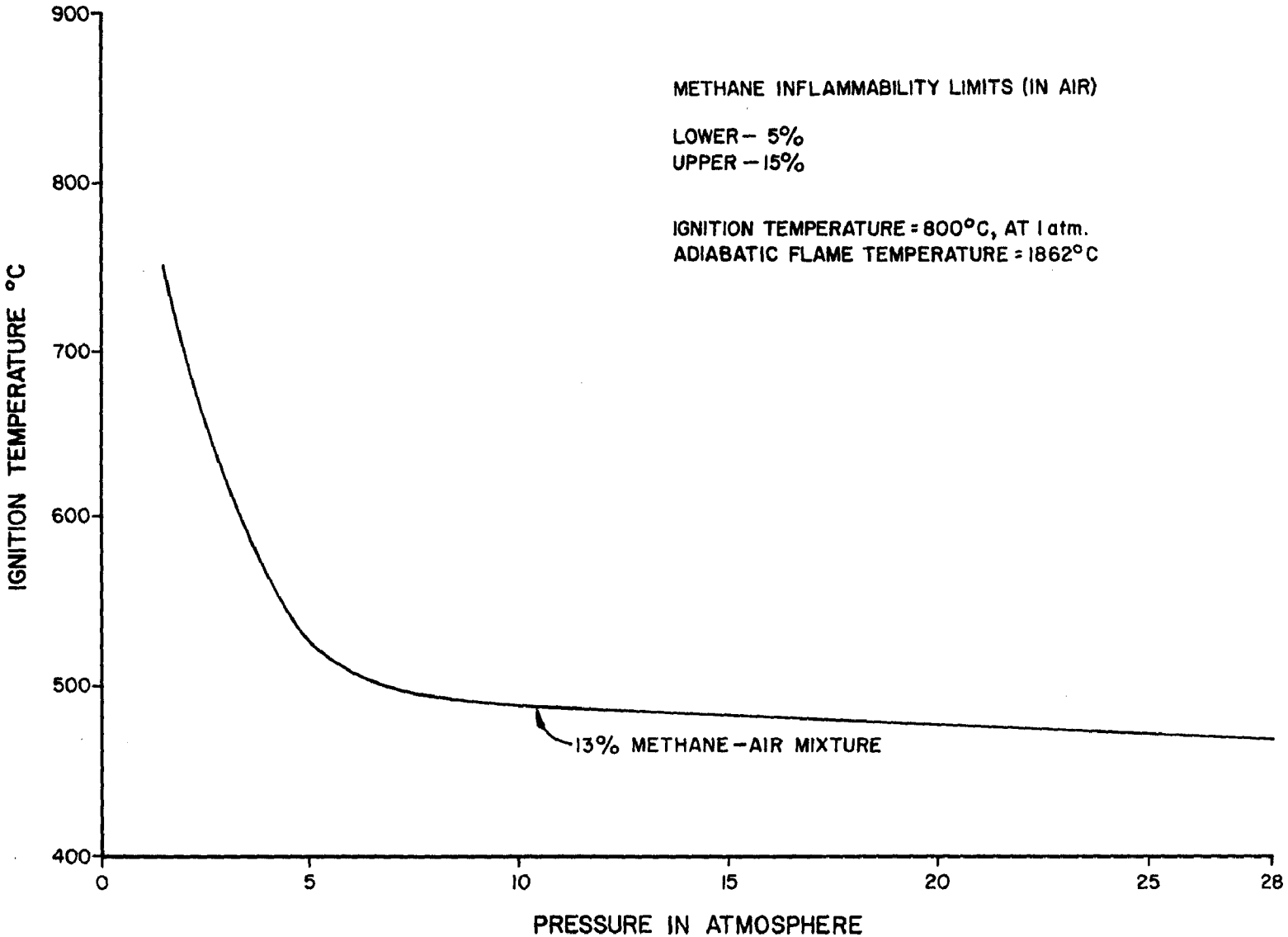


FIGURE 36: IGNITION TEMPERATURE OF METHANE–AIR MIXTURE

Gas leaks on the purification plant side at the compressor, pipeline, and different processing units into the atmosphere may also result in fire and explosion. Various safety methods used at the Palos Verdes gas purification plant are discussed in the EIR (Ref. 18).

CHAPTER VIII

CONCLUSIONS

(1) The potential total energy that could be derived from sanitary landfills in Los Angeles County represents approximately 0.5 percent of the total natural gas consumption in Los Angeles County.

(2) The generation and recovery of landfill methane gas requires evaluation of both physical and operating parameters. The solid waste and fill materials should be characterized in terms of organic carbon, volatile solid, moisture, ammonia nitrogen, and phosphorus. The amount and kinetics of gas generation is believed to be governed by these physical parameters, including pH and temperature of the fill.

(3) A typical solid waste consists of 0.25 pound of organic carbon per pound of dry refuse.

(4) Theoretically, the gas generation rate reaches its maximum after two to three years from fill completion, and within six years approximately 95 percent of the total estimated gas is produced.

(5) The operating parameters are evaluated to determine gas withdrawal rate, gas composition, radius of influence (to determine number of wells that can be located at a certain landfill configuration), energy required to operate the gas withdrawal system, and total possible energy production.

(6) An average of 4810 tons per day of waste is disposed of at the Palos Verdes landfill. Household and commercial waste categories comprise about 50 percent and liquid wastes comprise about 19 percent of the total. The wastes are compacted to an in-place density ranging from 1000 to 1700 pounds per cubic yard. Refuse deposits contain an average of 30 percent (wet weight basis) of moisture.

(7) The nitrogen and phosphorus content in Palos Verdes fill deposits are sufficient enough to meet biological growth.

(8) At the Palos Verdes landfill, the migration of gas is reduced by covering the final surfaces with a minimum of three feet of clean diatomaceous earth. This cover soil is quite impermeable to gas migration if compacted to the optimum moisture content and maximum density.

(9) From the parcel "three" located at the Palos Verdes landfill, an estimated total of 5.2×10^9 cubic feet of gases will be produced. At a gas withdrawal rate of 2.25×10^6 cubic feet per day, flows could be sustained for approximately six years.

(10) At a withdrawal rate of 320 CFM at an experimental well, the methane and carbon dioxide content in landfill gases are approximately 53 percent and 45 percent respectively.

(11) A withdrawal rate of 320 SCFM will produce a radius of influence of approximately 250 feet in a 110-foot well.

(12) From a well dug to 110 feet below the surface elevation, a pressure drop of -13.5 inches of water will be required to extract gases at 320 SCFM.

(13) Dehydration to reduce the corrosion problem may enhance the utility of low Btu landfill gases where they can be used on site. However, their efficient combustion may require a proper modification in burner design.

(14) The low Btu landfill gases may also be processed to 99 percent methane purity to meet the pipeline standards, thus up-grading the gas to a commercial product. The molecular sieve adsorption technique with pressure-swing regeneration cycle appears to be well-suited to bulk gas purification.

(15) The gas withdrawal system which RSF is operating at Palos Verdes landfill has pumped approximately 91,239.2 MSCF of raw landfill gas starting from June 1, 1975 to the end of December 1975. This amount is about 42.6 percent of the predicted (based on a withdrawal rate of 1 MMSCF per day for 214 days).

(16) At increased withdrawal rates, the landfill gases contained substantial percentages of nitrogen resulting from air leaks. This is the main problem which RSF is facing at the Palos Verdes gas recovery operation. Since the removal of nitrogen from landfill gases is a very expensive process, the final product may not meet the pipeline standards. For that reason, a significant amount of purified gas was not bought by the Southern California Gas Company (statement by RSF).

(17) During the months of June, July, and October 1975 and part of February 1976, the methane consumption rate was higher than the production rate. Out of a total of 31,840 MSCF of methane gas produced, approximately 19,886 MSCF (62 percent) was consumed to operate RSF's purification plant.

(18) Economic evaluation indicates that RSF is not producing a net profit at this stage of the operation. However, these evaluations are too immature to predict any long-term profits.

CHAPTER IX

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APPENDIX

THEORETICAL CORRELATION OF OPERATING PARAMETERS FOR LANDFILL GAS EXTRACTION

```
 1   1   FORMAT ('1','    FG    RE     Q/C1         -DELTA P/C2 '/)
 2   2   FORMAT ('  ' F10.3, F 10.2, F14.5, F14.5)
 3       DIMENSION  RE(10)
 4       WRITE (6,1)
 5       RW = 0.25
 6       READ, (RE(N), N=1.9)
 7       READ, FG
 8   5   DO 20 I=1,9
 9       R = RE(I) *RE(I)
10       P = RW *RW
11       Q = 5.97* (R-P) *FG* 0.000001
12       DP = 0.006 *FG* (R*ALOG(RE(I)/RW)-0.5* (R-P)
13  20   WRITE (6,2) FG, RE(I), Q,DP
14       READ, FG
15       IF (FG.NE.0.0) GO TO 5
16       WRITE (6,1)
17       STOP
18       END

     ENTRY
```

TABLE 16

THEORETICAL CORRELATION OF OPERATING PARAMETERS
FOR LANDFILL GAS EXTRACTION

Fg	Re	Q/C1	-DELTA P/C2
0.060	0.25	0.00000	0.00000
0.060	50.00	0.00090	4.31849
0.060	100.00	0.00358	19.76927
0.060	150.00	0.00806	47.76511
0.060	200.00	0.01433	89.05838
0.060	250.00	0.02239	144.17440
0.060	300.00	0.03224	213.51840
0.060	350.00	0.04388	297.42010
0.060	400.00	0.05731	396.15860
0.100	0.25	0.00000	0.00000
0.100	50.00	0.00149	7.19749
0.100	100.00	0.00597	32.94879
0.100	150.00	0.01343	79.60854
0.100	200.00	0.02388	148.43060
0.100	250.00	0.03731	240.29080
0.100	300.00	0.05373	355.86400
0.100	350.00	0.07313	495.70060
0.100	400.00	0.09552	660.26460
0.150	0.25	0.00000	0.00000
0.150	50.00	0.00224	10.79624
0.150	100.00	0.00895	49.42319
0.150	150.00	0.02015	119.41270
0.150	200.00	0.03582	222.64590
0.150	250.00	0.05597	360.43600
0.150	300.00	0.08059	533.79580
0.150	350.00	0.10970	743.55070
0.150	400.00	0.14328	990.39670
0.200	0.25	0.00000	0.00000
0.200	50.00	0.00298	14.39498
0.200	100.00	0.01194	65.89760
0.200	150.00	0.02686	159.21700
0.200	200.00	0.04776	296.86130
0.200	250.00	0.07462	480.58150
0.200	300.00	0.10746	711.72820
0.200	350.00	0.14626	991.40130
0.200	400.00	0.19104	1320.52900
0.250	0.25	0.00000	0.00000
0.250	50.00	0.00373	17.99373
0.250	100.00	0.01492	82.37201
0.250	150.00	0.03358	199.02130
0.250	200.00	0.05970	371.07660
0.250	250.00	0.09328	600.72680
0.250	300.00	0.13432	889.66040
0.250	350.00	0.18283	1239.25100
0.250	400.00	0.23880	1650.66100
0.300	0.25	0.00000	0.00000
0.300	50.00	0.00448	21.59247
0.300	100.00	0.01791	98.84641
0.300	150.00	0.04030	238.82550
0.300	200.00	0.07164	445.29190
0.300	250.00	0.11194	720.87230
0.300	300.00	0.16119	1067.59200
0.300	350.00	0.21940	1487.10200
0.300	400.00	0.28656	1980.79300

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(Please read Instructions on the reverse before completing)

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15. SUPPLEMENTARY NOTES

Project Officer: Charles J. Rogers

16. ABSTRACT

This report documents the first-ever-attempt to capture sanitary landfill gases and beneficiate them to natural gas pipeline quality--or very nearly so. For this reason the authors must credit the entrepreneurs for a successful first full-scale demonstration of a technology that produces very nearly pure methane and wish to compliment the Los Angeles County Sanitation Districts for the willingness, cooperation, and technical assistance that made the demonstration possible. Herein lies an excellent example of local government and industry working together to produce results that may have ultimate benefits for people throughout the nation and the world.

That this demonstration failed to show an economic viability during the twelve-month study period only suggests that further consideration should be given to improving the dependability of the molecular sieve process for landfill gas beneficiation, to the study of alternative beneficiation processes, and/or alternative uses for less modified landfill gases. Perhaps more serious consideration should be given to the use of landfill gas with little or no modification, except perhaps moisture removal. Reciprocating piston engines, rotary turbines, steam generators, air heaters, and a host of other devices can be fueled successfully with mixtures of methane, carbon dioxide, and small amounts of other gases, provided the heat content is not below certain critical levels. Landfill gases present an energy resource - modest as it is - that should be developed and utilized wherever and whenever possible.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Methane, Carbon Dioxide Anaerobic processes Materials recovery Cellulose Decomposition	Gas benefication Municipal solid waste Methane production	13B

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