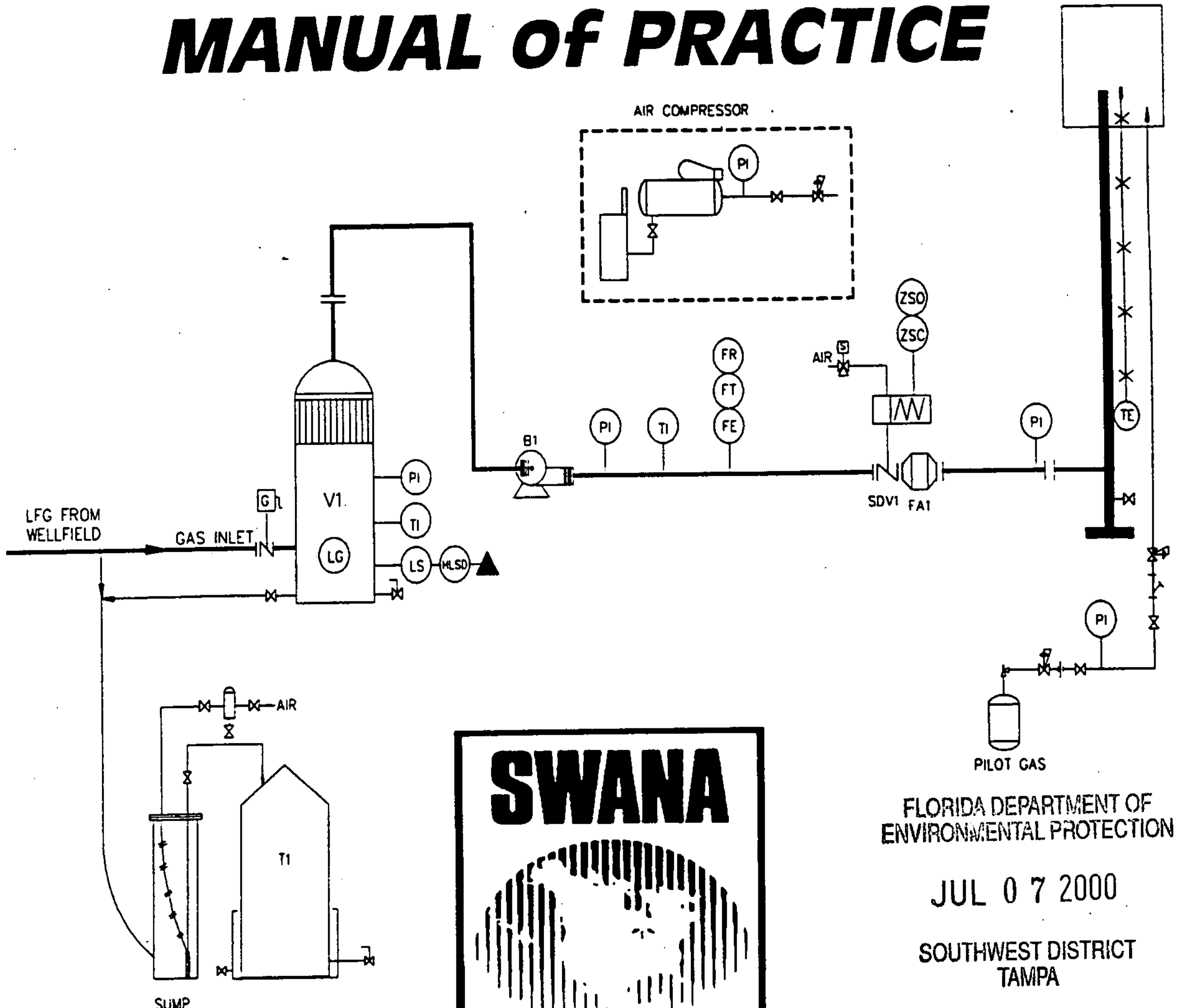
LANDFILL GAS OPERATION & MAINTENANCE *MANUAL of PRACTICE*



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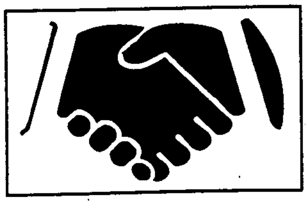

ACKNOWLEDGMENTS

Development of this LFG Manual of Practice was sponsored by the National Renewable Energy Laboratory (NREL). The work was managed by Charlotte Frola and Dianne De Roze of the Solid Waste Association of North America (SWANA). Gas Control Engineering, Inc. prepared this document. We thank Mr. Alex Roqueta, of Landfill Control Technologies (LANDTEC), for his advocacy for the development of an industry LFG Manual of Practice over the years and his encouragement of this project. We are grateful to the companies mentioned who provided information and photographs for inclusion in this manual. We also wish to acknowledge the helpful suggestions and guidance of the peer review staff assembled by SWANA for preparation of this Manual.

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These advisors participated as individuals, not as official representatives of their organizations or institutions. We are grateful for their assistance and their insights; however, SWANA is solely responsible for the overall conduct of the study.

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1. INTRODUCTION

1.1 PREFACE

1.1.1 Disclaimer

The naming of specific manufacturers or brand names is not meant to be a specific endorsement of that brand, or of one brand over another. Where, for a specific purpose, a brand has established itself as such an industry standard so that its name may commonly be used as a description of a generic type, that brand name is used here with the recognition that a comparable, competing item may be available and equally suitable. No specific endorsement of items or equipment is made or implied.

1.1.2 Purpose of Manual

This Manual of Practice (manual) is intended to be a source of information, practices and procedures for the operation of landfill gas (LFG) collection and control systems for both inexperienced and experienced operators..

1.1.3 Objectives of This Manual

This manual has the following objectives:

1) Compile and present key portions of the general body of knowledge about operating and maintaining LFG control systems.

2) Present information in an easy to understand format useful for hands-on practical use in the field.

3) Present accepted practices and procedures for LFG control practices.

4) Highlight key points, common mistakes and lessons learned from more than 20 years of industry experience. Point out areas of controversy and indicate alternative practices where applicable.

5) Compile key reference information.

6) Provide theory and discussion needed to develop a deeper understanding of LFG control and recovery.

1.2 INTRODUCTION

Included in the broad term "LFG system" is any method used to control or collect LFG. This can include active and passive systems which may encompass perimeter migration control, general gas collection, surface emissions control, or ground water protection.

This manual is not intended to be a manual on theory, modeling, testing, or design of LFG systems. However, some aspects of these issues are discussed because they are related to or support LFG operational practices. Reasoning, scientific thinking and mechanical aptitude are important skills needed for LFG operational.

Since LFG field of practice is diverse, there is not yet complete standardization or agreement on all terms or practices. This manual attempts to use generally accepted and simple terminology. The manual contains a **Glossary** of terms that serves also as a compendium of certain LFG fundamentals.

1.3 NOTICE AND WARNINGS

1.3.1 General Warnings

Operating a LFG collection and control system can be inherently hazardous. Before operating a LFG collection and control system and related process equipment, individuals should be properly trained in the potential hazards and proper operating techniques and procedures for such operation. This manual is a general guide and not intended to be a substitute for proper training in general process operations, specialized regulatory requirements, or special safety activities and training, which may be required by various local, state, or Federal regulations. It is the responsibility of the landfill owner, operator or other party actively or passively interactive with the LFG collection and control system to ensure that these requirements are met.

The reader should become familiar with the following types of related hazards and the appropriate and safe procedures to identify and avoid them:

- Fire and explosion hazards
- Confined space, toxic exposure, and asphyxiation hazards
- Drilling and excavation hazards
- Process (rotating, fired, and pressurized) equipment hazards

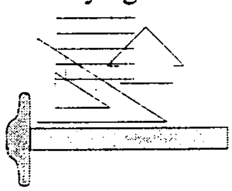
A brief summary of LFG health and safety issues is available in Chapter 19, Safety. For more detailed information on LFG health and safety issues refer to the Health and Safety Section of the SWANA "Landfill Gas Field and Laboratory Practices and Procedures" Manual.

1.4 PROJECT TEAM

The development of this manual was a collaboration of a project team which included Mr. Jim Wheeler of James H. Wheeler Environmental Management (t) as principal author, Mr. Alan Janechek of Gas Control Engineering (GCE) as project manager and contributing author, Messers. Fredrick C. Rice of F.C. Rice and Co. Inc. and Mr. John Pacey of FHC as principal reviewers, and Mr. Richard Prosser of GCE as a principal reviewer. Additional staff who were instrumental in preparing this manual were Ms. Cheryl Wood (GCE) for word processing and layout, Ms. Denise Manchego (GCE) for Computer Aided Drafting, Ms. Monica Zuberbuehler (GCE) for graphic arts and layout, Mr. Kirk Hein (GCE) and the National Renewable Energy Laboratory (NREL) for technical editing/review.

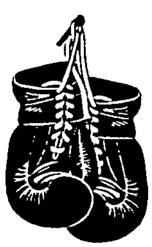
1.5 MANUAL HELPS - INFORMATION IDENTIFYING ICONS

Throughout this manual key information is identified by icon symbols to aid the reader in identifying certain classes of information and key points. The identification is as follows:



Engineering Calculations

Tables and Charts

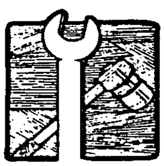


Point of Controversy or Controversial Topic

Key Point of Information

Checklist

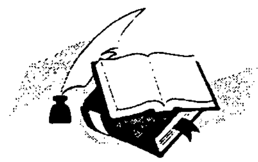
Safety



Maintenance

Warning! or Caution!

2. LFG FUNDAMENTALS

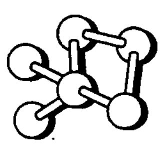


2.1 REVIEW OF SCIENTIFIC FUNDAMENTALS FOR LFG SYSTEM OPERATION

There are a number of areas of science, engineering and management that apply to the multi-disciplinary understanding that is necessary for LFG practice. These areas may include:

- Biology
- Chemistry
- Physics
- Mechanical engineering
- Fluid mechanics
- Process operations and production management
- Maintenance management
- Civil engineering
- Geology and hydrogeology

Comprehensive knowledge in these areas is not essential to be a good LFG system operator. Nevertheless, it is helpful for operating staff to be observant and to have good general scientific and mechanical aptitude and problem solving skills.



2.2 COMPOSITION, CHARACTERISTICS, AND HAZARDS OF LFG

The most significant characteristics of LFG are as follows:

- Consists primarily of methane (about 55 %) and carbon dioxide (about 45%).
- LFG is wet; cooling almost always results in condensate water formation.
- LFG is flammable (i.e., potentially explosive).
- LFG may migrate through surrounding soils, within open conduits, permeable trench backfill.
- LFG may accumulate in confined spaces.
- The weight (specific density) of LFG is usually close to the weight of air.
- Typical temperature range is 16 to 52° C. (60 to 125° F.) within the landfill.
- Component gases (methane, carbon dioxide, water vapor and others) tend to stay together but may separate through soil and liquid contact.

- Secondary constituents (trace gases) may cause nuisance odors, environmental pollution and may create a health risk.

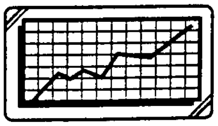


Table 2.1 General Range of LFG Characteristics

Component	**Percent Volume (All are stated on a dry basis except moisture.)**
Methane (CH_4)	45 to 58 %
Carbon dioxide (CO_2)	32 to 45 %
Oxygen (O_2)	less than 1 %
Nitrogen (N_2)	0 to 3 percent
Hydrogen (H_2)	trace to 5 % plus; generally less than 1 %
Carbon monoxide (CO)	trace; CO is an indicator of the possible presence of a subsurface fire
Hydrogen sulfide (H_2S) and other sulfur compounds	varies by landfill (nominally 10-200 PPM)
Moisture	up to 14% (increases with gas temperature)
Volatile organic compounds (VOCs)	Less than 2 percent; typically ¼ to ½ %

Note: This table represents typical characteristics. A difference in characteristics does not necessarily mean there is a problem. However a large disparity should be looked at closely.

LFG is produced by anaerobic bacteria which consume organic matter in the refuse. LFG is chiefly composed of methane, and carbon dioxide. In addition to methane and CO_2 other major gases that may be present include oxygen, nitrogen, and water vapor. LFG usually contains traces of hydrogen, ethane, and many other trace gases including volatile organic compounds (VOCs). Oxygen and nitrogen are usually present because of air in the landfill (air is approximately 21% oxygen and 79% nitrogen), either during placement of refuse, from atmospheric weather effects, because of LFG system operations, or by diffusion of air into the landfill.

Characteristics of Landfill Gas

Methane is a colorless, odorless, flammable and potentially explosive gas that as landfill gas together with other volatile trace gases may be emitted into the atmosphere; LFG that contains other gases may migrate through the soil into surrounding areas or contact groundwater. These other gases may adversely impact the environment. LFG may travel long distances under ground. It may accumulate underneath and in structures and confined or enclosed spaces creating a potential explosion hazard. Methane and carbon dioxide are simple asphyxiates. Carbon dioxide is colorless, odorless, and non-combustible.

The flammable range of methane is approximately 5 to 15 percent (by volume) in air. The lower limit of 5 percent is referred to as the Lower Explosive Limit (LEL); the upper limit of 15 percent is referred to as the Upper Explosive Limit (UEL). Walking across a carpet in leather shoes creates a static charge sufficient to ignite methane. The auto-ignition temperature of methane is 540° C (1004° F). The specific density of methane and carbon dioxide are 0.55 and 1.52 respectively, however, the specific density of LFG is close to that of air. For structure protection, it should not be assumed that methane gas will rise. The landfill gas mixture may be lighter or heavier than air and its behavior will be dictated by its overall composition.

LFG has its own characteristic odor due to trace compounds in the gas. Some of the most significant examples of the classes of odor causing trace constituents include esters, phenols, organic acids, solvents, and sulfur compounds (including mercaptans). However, LFG may not always exhibit an identifiable odor since the odor carrying trace components may be stripped off as a result of movement through cover or adjacent soil.

The methane in LFG is the same gas that is the main component found in commercial natural gas. Since methane by itself is odorless, commercial natural gas is odorized, usually with mercaptans (a class of sulfur compounds), to identify or "tag" the odorless methane for safety purposes.

2.3 MOVEMENT OF LFG

The movement of LFG through and beyond refuse and into native soil is known as LFG migration. There are several mechanisms that drive migration of LFG. The two primary mechanisms are by convection or pressure gradient (i.e., movement from an area of higher pressure to an area of lower pressure) and molecular diffusion or concentration gradient, (i.e., movement from an area of higher concentration to an area of lower concentration). Figure 2.1 depicts these principal modes of LFG transport. Typically convection causes most LFG migration; however, in the absence of a pressure gradient, diffusion may dominate.

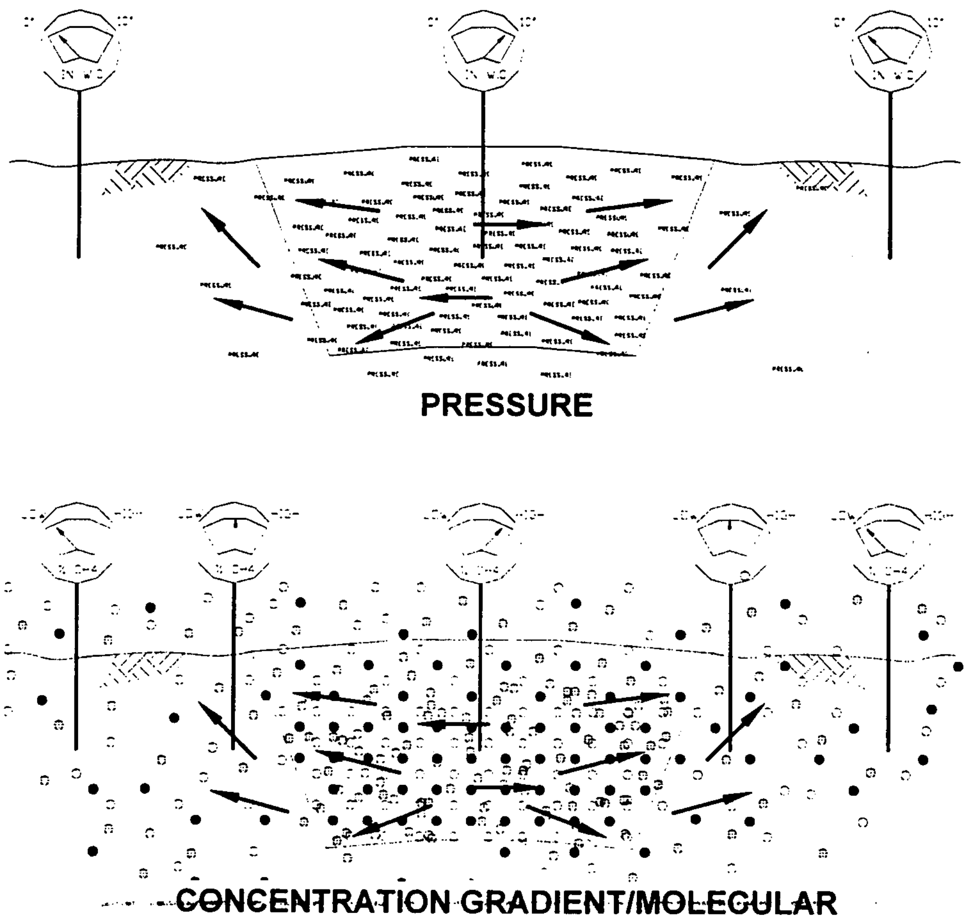


Figure 2.1

Principles of LFG Movement

The movement of LFG can also be affected by atmospheric pressure changes. These changes can occur as a result of:

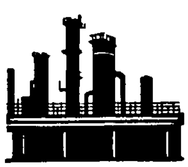
1) Daily (or diurnal) cyclical fluctuation of atmospheric pressure and

2) Barometric changes brought on by weather changes (e.g., storm front movement).

The movement of LFG can also be affected by changes in soil pressure due to ground water fluctuations from recharge (e.g., after a heavy storm) or pumping and tidal fluctuations at sites near the ocean.

LFG May Migrate Offsite Developing Potentially Dangerous Accumulations

Under certain conditions, LFG can migrate laterally long distances from the landfill. An often used rule-of-thumb is LFG can migrate up to 1000 feet. Structures within this distance may require additional precautions to protect them from LFG accumulation. In some dramatic instances landfill gas containing methane above the LEL has been known to migrate for one-half mile or more into soils below surrounding communities. There are instances of lateral subsurface gas migration from landfills which fueled explosions with recorded fatalities and damage to structures. LFG will potentially migrate along all possible pathways, favoring those that present the least resistance.



2.4 BENEFITS OF LFG

LFG can provide an energy benefit when its significant methane content is put to beneficial use. For this reason it is considered a renewable resource. The viability of recovering LFG for its energy benefit has been well demonstrated as there are approximately 150 and 450 LFG energy recovery projects in the U. S. and Europe respectively. The general energy uses for LFG are shown in Figure 2.2.

Landfill methane may be used to fuel boilers, furnaces, engines and vehicles. LFG can also be used as a feedstock for chemical processes.

Recovering LFG for its energy benefit provides a side benefit of reducing liabilities associated with LFG.

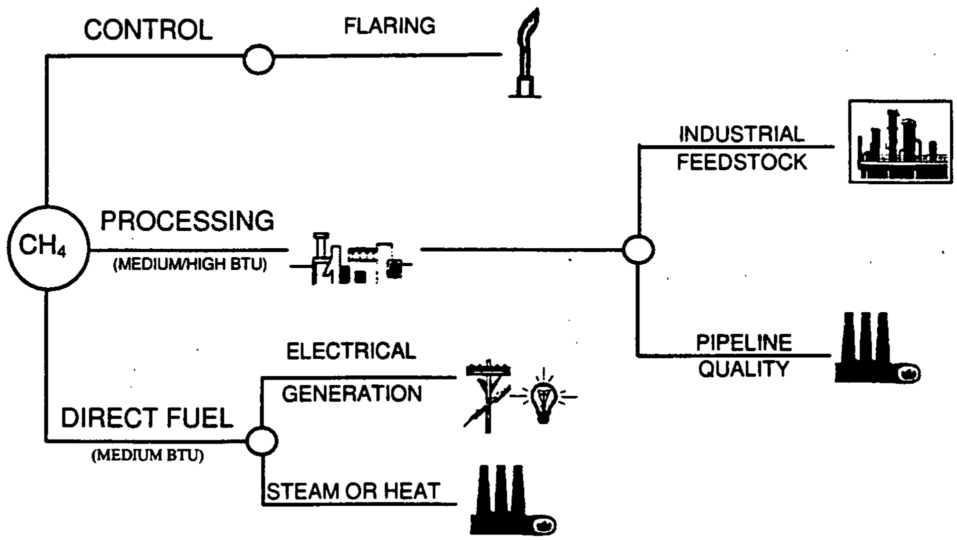


Figure 2.2

General Uses for LFG
Source: California Air Resources Board

2.5 GENERATION OF LFG

A general understanding of the processes of anaerobic decomposition of refuse and generation of LFG is necessary as a foundation to understand the operation and adjustment of LFG wellfields and collection systems. LFG is produced by the process of anaerobic decomposition of organic waste. Basically, anaerobic bacteria cause the breakdown of complex organic material (vegetable and plant matter, wood and paper products, etc.) into simpler forms such as organic acids and ultimately to methane and carbon dioxide. The latter part of this process is known as methanogenesis.

The complex process that results in LFG production may be simply represented by the following reaction formula:

$$C_nH_nO \xrightarrow{\text{Bacteria}} CH_4 + CO_2$$

where C_nH_nO represents the decomposable fraction in the refuse (normally cellulose and sugar).

It is believed that LFG generation rate and yield are affected by many factors, which include:

- Refuse Composition,

- The placement history (refuse age and quantity),
- Conditions of the waste mass (nutrient substrate) present in the landfill that is available for the anaerobic bacteria,
- Moisture content of the refuse,
- pH of the refuse,
- Temperature of the refuse,
- Maintenance of the anaerobic environment (i.e., little oxygen present in the refuse).

Most of the factors associated with LFG generation cannot be easily changed or improved. Of the above factors, other than composition, volume and age of refuse, moisture and temperature are the most important factors in controlling the rate of LFG generation and the volume of LFG generated. Usually, most of these factors are naturally limited and less than that required for optimum LFG generation, but may often be sufficient for generation of significant volumes of LFG.

2.5.1 Conditions for LFG Generation

When municipal solid waste (MSW) is placed in a landfill, the void volume (the volume not occupied by solids or liquids) within the MSW is filled with air from the surrounding atmosphere. Through natural aerobic processes, the oxygen from the air is quickly consumed and an anaerobic environment is soon established within the landfill. This anaerobic environment is one of several conditions necessary for the formation of methane.

Introducing Oxygen into the Landfill

If oxygen is reintroduced into the landfill, those portions into which the oxygen are introduced are returned to an aerobic state and the methane producing bacteria are inhibited. If the introduction of oxygen is stopped, some time must pass before the oxygen is depleted. The affected refuse mass then gradually returns to an anaerobic condition and LFG is again produced. This process impacts the rate of LFG generation. For an energy recovery project this may have dire consequences. For a migration control project the introduction of small quantities of air is typically not significant. However, introduction of large amounts of air can result in erratic production of LFG and a site that is difficult to control.

2.6  LFG GENERATION AND YIELD MODELS AND TESTING

2.6.1 LFG Generation and Yield Models

Although a thorough discussion of LFG generation and yield modeling is beyond the scope of this manual, it is desirable to have a basic understanding of why and how LFG generation models are used and their limitations.

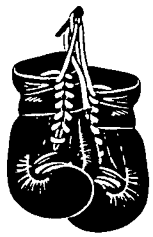
LFG generation models are mathematical models that are used to predict the potential of LFG that may be generated from a landfill. Models may also include some prediction of the amount of gas that can be captured from a landfill. This information is useful to designers for the design of the LFG collection system components and equipment. Models may also be used for regulatory purposes to estimate emissions from a landfill.

There are numerous theories, approaches and divergent opinions on LFG generation and yield modeling. They are not discussed in detail since it is not the intent here to provide engineering advice for modeling purposes. However, it should be recognized that LFG generation is difficult to predict because many of the contributing factors are difficult to quantify. The LFG generation models, therefore, tend to have a high degree of uncertainty. Hence the necessity of subjectivity and application of experienced judgment in modeling LFG generation.

Once a gas system is designed and constructed the model plays only a small part in the continued system operation. Well adjustments need to be based on the quality of the LFG collected from the wells regardless of what the model predicts.

2.6.2 LFG Testing

LFG testing includes those activities and assessments made in an attempt to determine or validate key design parameters in a generation model and to attempt to evaluate and support gas generation and yield model predictions. The behavior of landfill gas, site specific landfill factors, atmospheric pressure effects, and extraction and control procedures are key elements of this study area. Testing experience usually develops a deeper understanding of LFG issues. To the observant operator, studying and practicing LFG testing theory and case studies may help to develop such understanding.



Effectiveness of Testing

The usefulness and validity of LFG testing is controversial and most experienced LFG practitioners tend to discount its value. It has been used in the past primarily to support development of energy recovery facilities. Regardless of the value of testing programs, understanding testing theories, techniques, and procedures can provide a better understanding of how to better operate a LFG collection and control system. A detailed discussion of LFG testing is beyond the basic scope of this manual. Appendix A of the NSPS for MSW Landfills (See Chapter 5, LFG Regulatory Requirements) includes a procedure for performing field testing.

2.6.3 Basis of Design of the LFG Control System

A LFG collection system is sized based upon current and future municipal solid waste intake, corresponding LFG generation and yield potential, rules-of-thumb, designer experience and observations, and any field testing performed. LFG generation will normally peak shortly after site closure and will continue for decades. For some sites, a formal basis-of-design document is prepared as part of the design process. Operating staff should become familiar with the Basis-of-Design which should be integrated into the operating documentation.

The basis-of-design document should state the assumptions and conclusions that provided the basis for the design of the system including:

- Sizing of system components
- Materials of construction
- System layout
- Method of operation

3. SOLID WASTE LANDFILLING PRACTICES

3.1. About Landfills

A sanitary landfill is a land depository of waste. The primary purpose of a landfill is to provide a safe, sanitary and environmentally secure depository for municipal solid waste (MSW). This is designed to eliminate the spread of disease, pollution, and fires that occur with uncontrolled waste heaps and dumps. Landfills, when poorly designed or controlled, are often referred to as "dumps" or "open dumps," signifying a less than environmentally secure status.

Many of the problems brought on by the practices of the past have been recognized and an evolution of sanitary landfilling practices and standards has occurred. The current regulatory practice for new landfills is to require an engineered waste containment unit which will prevent surface water infiltration, leachate leakage and LFG containment management. It is standard practice to provide for leachate and LFG control and treatment.

3.1.1. Landfilling Methods

A landfill may be filled as a pit, mound, canyon fill, or a combination. Filling methods include the trench or cut and cover method, the area method, and the ramp method. There are various methods for operating landfills and types of landfills that result. A modern landfill is filled according to a plan that takes into consideration such factors as filling rate, types of wastes taken in, seasonal climatic conditions, available space, cover material availability and cost, among others.

3.1.2. Cover Material Practices

MSW placed in the landfill is commonly covered daily with soil or a suitable soil alternative. The purpose of cover was originally to prevent fire, blowing debris, odors and disease carrying vectors (birds, rodents, insects, etc.) from breeding on the landfill. The use of soil cover has evolved to prevent infiltration of water and prevent windblown debris.

Cover material for daily cover may be obtained on site if a sufficient amount is available and if it meets requirements specified by the landfill design and regulations. Otherwise, cover material must be imported from off site or an alternative cover used. The type and thickness of cover material affects the permeability of the internal cells, landfill cover and the performance of the LFG control system.

3.1.3. Geomembrane Liner and Cover

Landfill engineering is being advanced to provide more secure repositories for MSW by incorporating a geomembrane liner and cover into modern landfill designs. The operator is faced with challenges to control the effects of LFG pressure build up beneath the membrane which may damage it and to address the effect membrane placement may have on control. Placement of the membrane will usually increase the extent of extraction influence but may redirect emissions or air intrusion where the membrane terminates or at unsealed penetrations. It is important to realize that landfills are rarely sealed completely by this practice.

Several issues that must be addressed in this regard are:

1. Identifying, designing, installing and maintaining those portions of the LFG control system above and below the membrane

2. Effectively sealing and maintaining penetrations through the membrane

3. The need to collect LFG beneath the membrane to reduce pressure that may cause the membrane to balloon or have an impact on final slope cap stability.

4. Considerations for control and wellfield balancing given that effects of air intrusion or LFG venting may be more locally emphasized where a membrane terminates

5. Increased rates of venting at point sources, e.g., static vents

6. Potential increase in lateral subsurface migration of LFG where the cover permeability of the landfill is substantiality reduced by the use of a membrane.

3.1.4. Landfill Geometry

A knowledge of the geometry of the landfill, surrounding terrain and elevations, ground water levels and fluctuation, and geology and hydrogeology, etc., in relationship to the LFG control system is helpful in understanding gas migration and emissions phenomena. The LFG control system operator can assess these and other factors to determine what affect they have on system performance and the ability to control LFG migration and emissions. As an example, the operator should be able to relate well depths, age of the waste, and perched or standing liquid zones, to the overall performance of the well. In the case of migration control, the location and depth of the monitoring probes and intervening geologic conditions must be considered as well. The filling of areas with thin lenses and narrow fingers of waste material sometimes creates special problems for LFG control.

3.1.5. Leachate Formation and Behavior

Despite efforts to prevent liquids from being introduced, some of these inevitably find their way into modern landfills. In the past, practices for controlling receipt of liquids and household hazardous wastes were not as strict as they are now. Precipitation may also infiltrate through the landfill soil cover. In addition, many wastes, such as green waste (plant, lawn and garden waste), have a naturally high moisture content.

Liquid accumulating in and leaving a landfill is known as leachate. This name refers to the tendency of liquids to move through the waste and leach contaminants from the waste. The character of leachate is determined by the waste it passes through and the amount of liquid passing through the waste. Like LFG, the character of leachate will vary with time, climate conditions, landfill design and operating status, landfill conditions and other conditions. In the absence of testing, leachate should be assumed to be inappropriate for discharge into either groundwater or surface water.

Water Balance

The degree to which a landfill tends to either give up or accumulate moisture is known as water balance. A water balance is a means to estimate the amount of leachate exiting the landfill. The water balance can be expressed as the sum of all inflows, outflows and changes in storage as equal to zero. A simplified water balance can be written as follows:

Precipitation
\+ Surface Water Inflow
\- Evapotranspiration
\- Surface Water Outflow
\+ Changes in Storage
\- <u>Leachate Leaving the Landfill</u>
0

Landfills in an area with a lot of concentrated rainfall such as the Northeast may experience a net positive water balance. At such sites leachate may have to be regularly pumped from the landfill. Landfills in arid parts of the country, such as the Southwest may have a net negative balance and in fact may have little to no leachate. In such instances, LFG may play a much more important role in ground water contamination than leachate.

Modern landfill operating standards require that the allowed infiltration of precipitation be limited by design standards. Operating standards specified by Subtitle "D" may also limit the standing head of leachate that may be allowed to accumulate above the landfill bottom liner.

4. THE LFG CONTROL FUNCTION - AN OVERVIEW

4.1. PURPOSES OF COLLECTION AND CONTROL

LFG control is a term that encompasses all methods for controlling movement of LFG, including active collection, barriers, passive control and monitoring. When there is more than one purpose to collection and control of LFG, additional complexity may be added to the control task. Some of these purposes include:

- Control subsurface LFG migration
- Control surface emissions and nuisance odors
- Protect ground water from VOCs
- Control an existing fire in the landfill waste mass
- Collect LFG for its energy benefit.
- Protect structures
- Reduce vegetative stress

4.2. OVERVIEW OF THE LFG COLLECTION AND CONTROL ACTIVITIES

The LFG control process consists of a number of activities. The purpose of this chapter is to provide an overview of these activities. They will be discussed in greater detail later in the manual. Collection and control activities may include the following:

- Monitoring perimeter probes
- Monitoring LFG extraction wells
- Monitoring ground water wells
- Measuring liquid levels in LFG extraction wells
- Monitoring for gas emissions from the landfill surface
- Checking the gas collection piping network
- Adjusting the LFG wellfield
- Checking condensate water systems
- Keeping records of system performance and data
- Monitoring the operation and performance of LFG disposal or treatment/energy recovery equipment
- Maintenance, repair, and logistical activities
- Compliance reporting (e.g., to regulatory agencies as required).
- Non-routine and emergency activities

4.3. Modes and Methods of Controlling LFG

4.3.1. Passive Control Mode

Passive collection is defined as allowing the LFG to move without mechanical assistance, primarily by the pressure developed within the landfill, to a system of individual vents, which may or may not include connecting piping. The gas is allowed to simply escape into the atmosphere with little or no treatment. Additional treatment could consist of granular activated carbon to remove VOCs or flaring at each vent.

In the past it was common to passively vent LFG. This practice still occurs at older landfills or landfills with liners and geomembrane covers. Passive venting is becoming less common and in some locations is no longer allowed. However, passive features such as cut off walls still have a place in LFG control. Figure 4.1 shows a typical LFG vent well.

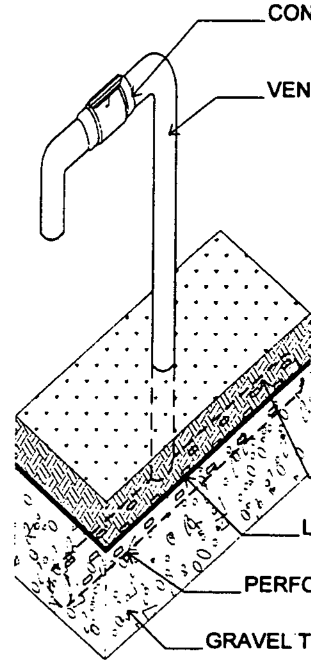


Figure 4.1
Typical Passive Vent Well

Sometimes, passive venting is sufficient to control LFG adequately to prevent migration. However, it has been demonstrated that passive systems are not the most effective way to control LFG.

4.3.2. Active Control Mode

The other control mode option is active control. This mode is widely accepted as the most effective way of controlling LFG because it provides a greater degree of control and flexibility. Active control is defined as using mechanical means (i.e., blower) to actively remove LFG from the landfill under vacuum. Procedures for operating active control systems are discussed in Chapter 9.

Sometimes, through operation of a passive LFG control system, it is recognized that the existing passive system is inadequate to meet control requirements (i.e., gas migration may still occur beyond the property boundary). In such cases, it may be decided to convert a passive system to an active collection system. It may be desirable to salvage as much of the existing passive system as possible. However it should be realized that the two types of systems are very different. Design criteria, objectives and approaches for passive systems are different from those of active systems. As a result, passive systems converted to active systems may not perform as well as a system designed as an active system from the outset.

4.4. THE LFG MONITORING AND PERIMETER CONTROL SYSTEM

It is common to install a LFG collection system to control off site migration because LFG tends to migrate off site through soil surrounding landfills. Such a system typically consists of LFG extraction wells located near the landfill's perimeter. Wells may be in the MSW or outside the MSW depending on the designer's objectives. A system of monitoring probes is commonly placed around the landfill perimeter at the property boundary or near the refuse boundary (point of regulatory compliance). Figure 4.2 shows a typical cross section of a perimeter monitoring and control layout. Probes may also be placed at other locations for specific monitoring purposes, i.e., structure monitoring, specific migration monitoring, etc. Monitoring probes are discussed in greater detail in Section 6.

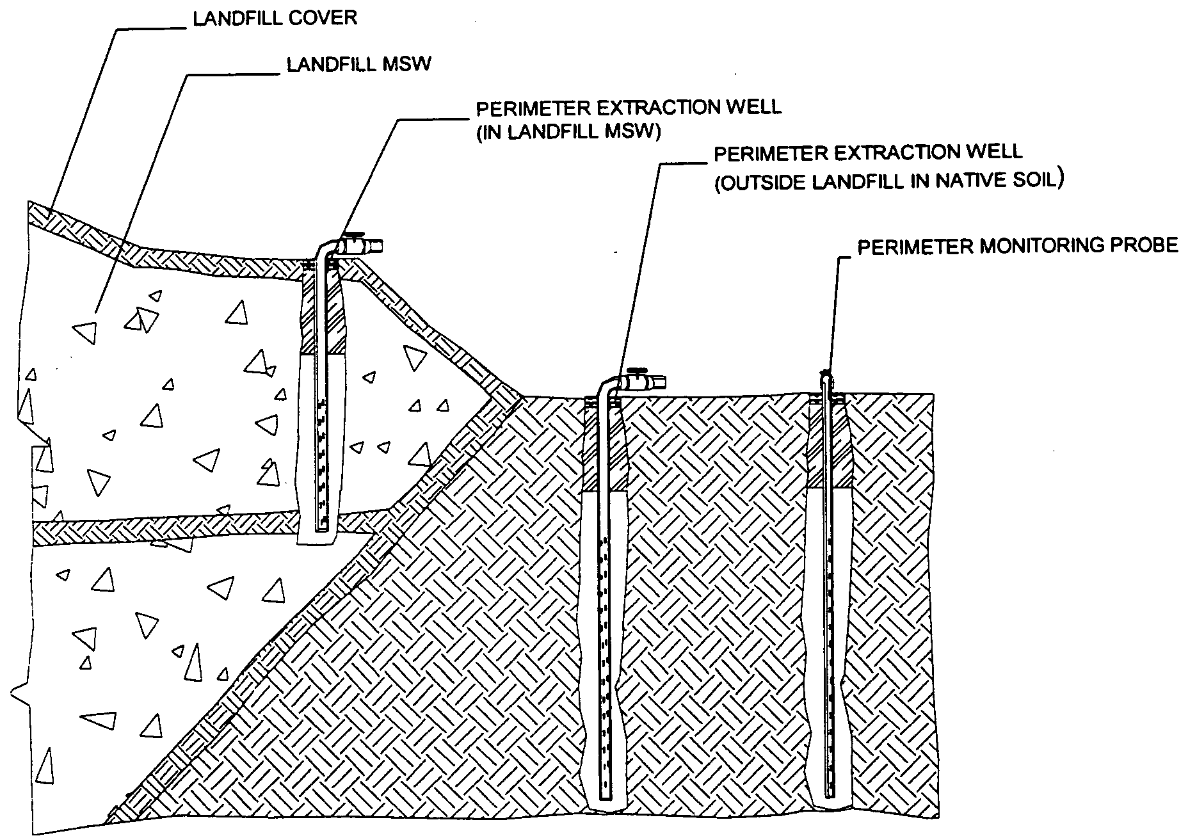


Figure 4.2
Typical Relationship of Extraction Wells and Migration Monitoring Probes

It is common practice and a regulatory requirement to routinely monitor perimeter probes in accordance with the Federal RCRA landfill operating standard. This operating standard prohibits gas migration at the landfill property boundary in excess of 5 percent methane by volume.

There are many types of configurations, both passive and active for controlling off site LFG migration. Types of perimeter migration control devices are:

- Passive vertical wells
- Passive barrier and vent trenches
- Active vertical extraction wells
- Active horizontal collector trenches
- Air injection systems
- Clay, geomembrane and hydraulic barriers
- Soil well extraction systems.

The most common form of a perimeter control system is a perimeter vertical well system combined with perimeter monitoring probes. It is also widely held that for migration control to be effective, perimeter gas collection should be supported with interior gas collection in order to relieve the pressure of interior LFG.

An increasingly common engineering practice and regulatory requirement is to install probes to the maximum depth of the waste in the vicinity of the probe, and that some probes extend to a depth equal to the deepest part of the waste mass. For deeper landfills, installation of multi-depth probes is becoming more common and a regulatory requirement. The preferred method is to design monitoring probes which can be used to detect the earliest occurrence of migration, taking into account site specific geologic conditions and migration pathways. Whether or not multi-depth probes are used or even necessary depends upon site specific conditions.

4.5. THE LFG WELLFIELD AND COLLECTION SYSTEM

The LFG wellfield and collection system consists of a network of LFG extraction wells and collection piping to transport the LFG to a treatment or disposal facility.

The major components of the LFG wellfield and collection system include:

- Vertical and/or horizontal extraction wells
- Well monitoring and control assembly to monitor and control the gas extraction
- Collection piping
- Condensate water traps, sumps and knockouts

- Surface collectors (use in conjunction with geomembrane cover systems)
- Landfill cover cap (if installed).

Figure 4.3 is a representation of a typical LFG collection system layout. A typical layout will show the location of the above mentioned components.

In later chapters the individual components, their features and application will be discussed in detail followed by a discussion of their operation, maintenance, and troubleshooting.

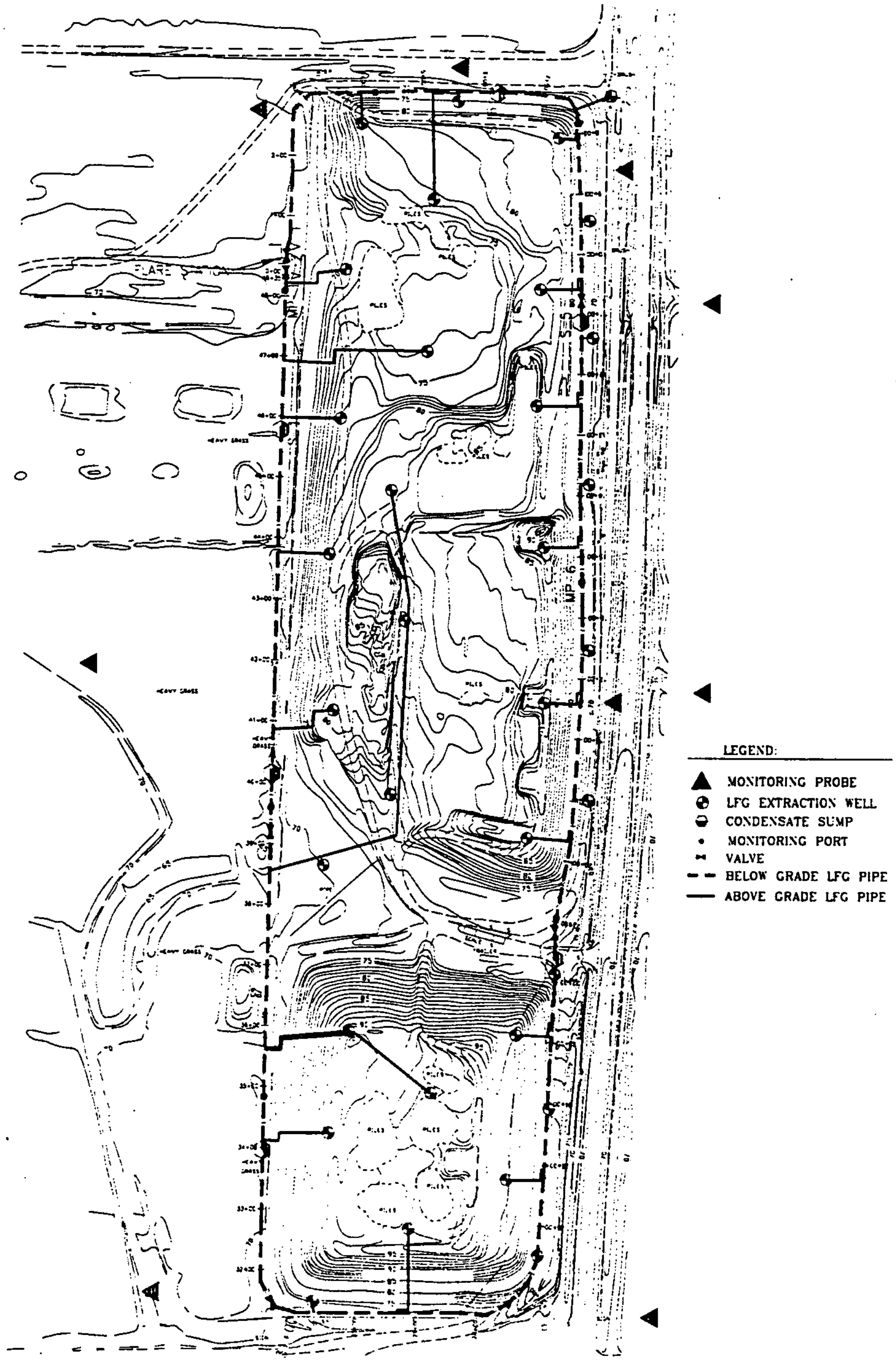


Figure 4.3
Sample LFG Collection System Wellfield Layout
Source: University of California-Davis, Davis, CA and GCE

4.5.1. The LFG Wellfield

LFG is collected by means of wells or collectors installed in the landfill. The system of wells and collectors is referred to as the wellfield. Generally, in referring to a LFG wellfield, we mean an active extraction wellfield.

The term "balance" or "balancing the wellfield" is frequently used to indicate the process of adjusting the wells to achieve smooth, steady state system operation and effective LFG recovery and control.

4.5.2. The LFG Collection System

The active LFG collection system consists of piping for collection and transport of the extracted LFG to a blower-flare facility or other treatment and disposal, or energy recovery equipment. The collection piping system may be either placed above grade or buried. High density polyethylene (HDPE) and polyvinyl chloride (PVC) are the most common types of materials used for collection piping.

Condensate is removed from the LFG collection piping system by the LFG condensate handling system. The condensate handling system consists of one or more of the following components: traps, drains, sump and pump units, knockouts, storage tanks, and treatment equipment. If allowed by regulation, condensate may be returned to the landfill, otherwise it must be removed and disposed of.

4.5.3. The LFG Treatment and Disposal Facility

The most common type of treatment or disposal facility is the blower-flare facility. However, there are a number of other options available that are commonly employed. The commonly available treatment and disposal options include:

- Free venting to atmosphere (generally not recommended)
- Venting through granular activated carbon
- Destruction by combustion in a flare
- Treatment or destruction in an energy recovery facility

4.5.3.1. Free Venting to the Atmosphere

This is the simplest process. All LFG is directly vented to the air without treatment. This process is most commonly used on a passive gas well system. Disadvantages of free venting include nuisance odors emission of untreated VOCs and release of methane.

4.5.3.2. *Venting Through Activated Carbon*

Carbon is commonly used to treat dilute LFG/air streams. Carbon is effective in removing most VOC and non-methane organic compounds (NMOCs). Carbon has a limited absorption capacity and periodically must be replaced or regenerated to maintain removal efficiency.

4.5.3.3. *Description of the Blower-Flare Facility*

The major mechanical components of the blower-flare facility are the blower(s) and flare(s). Figure 4.4 shows a typical blower/flare facility using an enclosed flare. The LFG blower (or compressor) provides vacuum by which the LFG is extracted and pulled to the blower and also provides the pressure to push the LFG to a flare or other treatment equipment. The LFG flare burns the landfill gas by means of an open flame (enclosed ground flares are considered an open flame in this case).

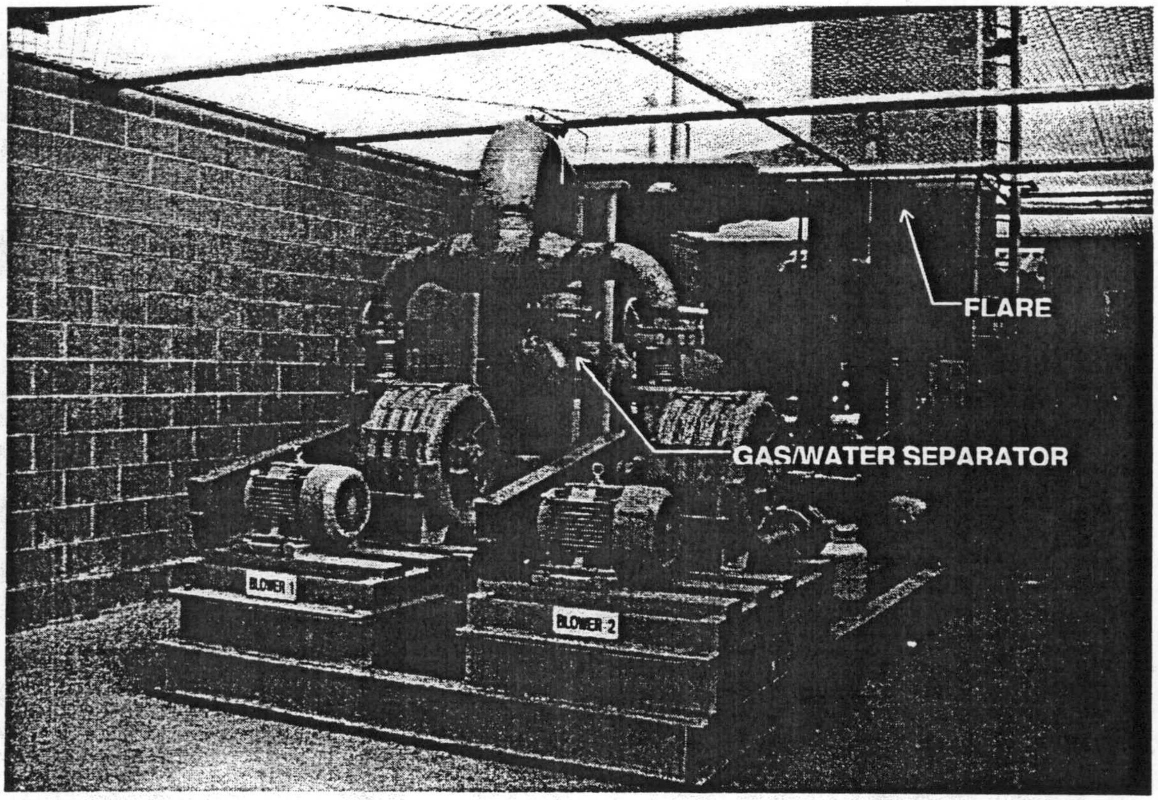


Figure 4.4

Typical Blower/Flare Station (Enclosed Flare)

Source: Riverside County Waste Resources Management District, Riverside CA

The other components of the blower-flare facility include process piping and valves, an inlet scrubber vessel, and associated electrical controls and instrumentation. Normally a flame arrester and an automated block valve are located between the blowers and the flare.

LFG commonly enters the blower-flare facility through a liquid knockout or inlet scrubber vessel. The scrubber vessel removes excessive moisture and particulate matter in the gas. The scrubber vessel may also be designed to remove other components of the gas stream (i.e., hydrogen sulfide), however moisture removal for protection of the blower is usually its primary purpose.

One of two types of LFG flares, enclosed ground flares, are controlled to burn at a predetermined temperature range. The other type, candlestick flares, are not temperature controlled. Control of the flare facility process is discussed in detail in Chapter 10.

4.5.3.4. Treatment or Destruction in an Energy Recovery Facility

Most energy recovery facilities use combustion as the primary method of energy use. These processes are typically able to destroy a large part of the VOCs and NMOCs in the LFG.

5. LFG REGULATORY REQUIREMENTS (SUMMARY)

5.1. REGULATORY PRACTICE AND INTERPRETATION

In understanding regulations and how to comply with them, it is helpful to understand the framework of regulatory application and development. Agencies such as EPA develop regulations to support laws. An example is the Clean Air Act. States usually develop and administer their own programs with approval from EPA. The preamble to a rule promulgation will contain important information as to the reasoning behind the development of a regulation, its intent, and interpretation.

Key terms are usually defined in the first section of a law. Words have specific meanings in the law. A regulation is usually understood in the context of its own definitions defined within. In regulations, definitions are often explicitly spelled out and usually strictly limited to the application of the regulation for which they are specific. Therefore, refer to and read definitions carefully when applying a particular regulation.

5.2. RESOURCE CONVERSATION AND RECOVERY ACT (RCRA) SUBTITLE D

The Resource Conservation and Recovery Act (RCRA) was originally passed in 1974. The Act and its regulatory guidelines (rules) have been updated and modified several times. In the most recent rule update, October 1991, additions were made to the portion of the regulation which addresses LFG control. RCRA Part 257 originally provided for what are known as Minimum Operating Standards for sanitary landfills. There are a number of these Standards which address daily cover, vector control, proximity to airports, geologic and hydrogeologic conditions, leachate, ground water protection, and explosive gas (LFG) control. People in the LFG practice often refer to the explosive gas portion of the regulation Part 257.3-8 as the RCRA standard because it is the portion of RCRA we are concerned with. In fact it is only one of several minimum operating requirements for landfills under Subtitle D. Subtitle D, Parts 257 and 258, is the principal regulatory standard that drives LFG collection and control.

As part of the updating of RCRA, USEPA has added a new section to RCRA, Part 258 which applies only to recently closed (since October 1993) and currently operating landfills. This Standard adds additional gas control requirements to some landfills.

5.3. THE RCRA LFG SAFETY STANDARD

40 Code of Federal Regulations (CFR) Part 257.3-8 Safety, (Resource Conservation and Recovery Act (RCRA) LFG Safety Standard), specifies that:

1) Landfill gases may not exceed an accumulation of 25 percent of the lower explosive limit (LEL) for methane within structures in or near the facility. Structures, as originally defined and explained in the original rule promulgation, includes items such as drain culverts and vaults, etc., as well as buildings. Structures associated with LFG recovery equipment are exempt.

2) Migrating LFG may not exceed the LEL (5 percent methane gas by volume) at the property boundary. For this reason the property boundary becomes the point of regulatory compliance for most landfills.

3) For landfills receiving waste on or after October 9, 1993, additional gas control requirements apply. These requirements are spelled out verbatim in Appendix F.1.

RCRA also specifies liquid restrictions and mandates compliance with the Clean Air Act (CAA).

The requirements and clarification on LFG condensate disposal is in Chapter 12, LFG Condensate Handling System. Generally, liquids can only be returned to MSW landfills that have a Subtitle D approved liner and leachate collection system.

The requirements of the CAA as they apply to landfills are spelled out in the "New Source Performance Standard (NSPS) for Municipal Solid Waste (MSW) Landfills" described in the following Section.

5.4. EPA MSW NSPS NEW SOURCE PERFORMANCE STANDARDS (NSPS)

5.4.1. General - Application of the NSPS/Emission Guidelines

A new LFG control regulation was promulgated by USEPA, effective on March 12, 1996. The regulation is known as the "New Source Performance Standard (NSPS)/Emission Guidelines for Municipal Solid Waste (MSW) Landfills." This rule is directed at controlling emissions from landfills of non-methane organic compounds (NMOCs) found in LFG at MSW landfills. The rule was published in the Federal Register (Federal Register Vol. 61, No. 49, on March 12, 1996) as "40 CFR Parts 51, 52 and 60; Performance Standards for New Stationary Sources and Guidelines for Control of Existing Sources: Municipal Solid Waste

Section 111(b) and (d) of the CAA Amendments. The Rule, subdivided into NSPS and Emission Guidelines, is summarized as follows:

New Source Performance Standard (NSPS)

1) Applies to all "new" landfills. A new landfill is defined as each MSW landfill that started construction (including reconstruction) or modification, or began initial waste acceptance on or after May 30, 1991.

2) Within 30 months after a MSW landfill with a calculated a non-methane organic compound emission rate ≥50 megagrams (Mg) per year, the provisions of this rule require installation and start-up of a LFG control system (LFGCS) at the landfill.

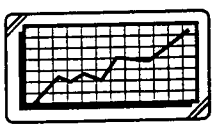


Table 5.1 Summary of NSPS Requirements

Item	Requirement
Affected MSW Landfills	Landfills with a maximum design capacity ≥2.5 million Mg (approx. 2.75 million tons) or 2.5 million cubic meters (approx. 3.27 million cubic yds.)
Exemptions	MSW landfills with design capacity less than 2.5 million Mg or annual emissions less than 50 Mg (approx. 55 tons) NMOCs
Disposal Areas Requiring Control	Active areas where the first waste deposited in the area has reached an age of 5 years or more <u>or</u> areas closed or at final grade where the first waste in the area has reached an age of 2 years or more
Surface Monitoring	Quarterly monitoring for surface emissions, concentrations which are not to exceed 500 ppm methane
Emission Control Requirements	Installing a gas collection system and utilization or disposal system that has a 98 percent destruction efficiency.
Implementation Schedule	• Capacity and Emission Reports due within 90 days of the NSPS effective date by 6/12/96. • Design Plan within one year of the NMOC Emission Report, by 6/12/97. • Start-up within 18 months of Design Plan.

Emission Guidelines (EG)

Emission Guidelines apply to all "existing" MSW landfills that satisfy two conditions:

1) The construction, modification, or reconstruction of the landfill began before the proposal date of May 30, 1991; and

2) The landfill received waste on or after November 8, 1987 or has additional capacity which may be filled in the future.

The requirements of the EG are almost identical to those of the NSPS. The main ways the EG differ from the NSPS are as follows:

1) Applicability criteria are for "existing" landfills;

2) There is flexibility for a state-implemented emission standard;

3) States need to develop a plan to implement the requirements of an EG; and

4) There are different landfill compliance schedules for state-implemented emission standard. A state has up to 9 months to address EG requirements within its state plan. The EPA has 6 months to review the plan changes. The EG becomes effective upon the EPA's final action on the plan.

5) The EG implementation schedule is similar to that of the NSPS:

   - Capacity and Emission Reports due within 90 days of the EG effective date
   - Design Plan within one year of the NMOC Emission Report
   - Start-up within 18 months of Design Plan.

5.5. STATE AND LOCAL REQUIREMENTS - GENERAL PRINCIPALS

LFG control regulations can vary depending upon the state. As a minimum, states must comply with the requirements of RCRA Subtitle D and the MSW NSPS. They may however have equivalent approved plans. Approximately two-thirds of the states have specific regulations pertaining to LFG control. Many duplicate the RCRA Minimum Standard of not exceeding the LEL (5 percent methane by volume) at the property boundary and 0.25 percent of the LEL (1.25 percent methane by volume) in facility structures. The LFG operator should be thoroughly familiar with the state and any applicable local regulations for LFG control for the site in question.

5.6. FACILITY PERMITS

Many states require facility permits to construct and operate a LFG facility. Facility permits may include specific operating requirements and restrictions. The facility permit may also require a source test for enclosed flares. This requirement may need to be repeated annually and additional permits may be required for LFG-to-electricity systems.. Operating requirements may include minimum flare operating temperature, maximum flow rate, emission controls and limits, etc. Often documentation of operation, e.g., recording of flare temperature and flow, is required. A copy of all facility permits should be made available to operating staff and posted at the facility.

The NSPS and other regulations include destruction and removal efficiency (DRE) requirements for the control device. The NSPS requires a DRE of 98%. Performance is verified by testing the inlet and exhaust stream from the control device. The total mass of VOCs or NMOCs should be reduced by 98% at the exhaust. Rules are also written to control criteria pollutants (i.e., NOx and CO, SOx) and particulates. NOx and CO emissions are a function of the design and the operating conditions (flow rate, gas composition, temperature).

5.7. LFG CODES AND STANDARDS

As yet, there is no established national engineering or building code for LFG control systems in the United States. Whatever national standards have been developed, have been developed through industry and by trade organization consensus documentation. SWANA has produced specifications for LFG system materials and components. In some areas, local building codes may address LFG and natural methane migration and structure protection. These are most likely to be present in areas of naturally occurring gas emissions from petroleum reserves. The American Society of Mechanical Engineers (ASME) has considered the development of a code for LFG installations.

Codes and Standards for classifying hazardous electrical locations and areas where hazardous atmospheres exist are discussed in the Subsection on Hazardous Locations. See Chapter 19, Safety.

In Canada, standards are developed in the form of "National Standards of Canada (NSC) Code for Digester Gas and Landfill Gas Installations," (CAN/CGA-B105-M93), dated January 1993. This code was developed by the Canadian Gas Association and approved by the Standards Council of Canada. The practices presented in these codes differs substantially from the common practices in the United States. The NSC Code apparently borrows heavily from technology taken from the wastewater treatment industry.

6. THE LFG MONITORING SYSTEM

6.1. MONITORING LFG MIGRATION

Most landfills are required by regulation and safety practices to monitor for lateral (subsurface) LFG migration. In areas with stringent air quality regulations, surface emissions monitoring is also required. The reasons for monitoring for LFG and methane are to:

1) Determine if a pattern of LFG migration exists

2) Determine the extent of any LFG migration

3) Determine if an explosive gas hazard is present

4) Provide feedback for LFG system operation

5) Fulfill and document regulatory compliance.

Figure 6.1
Monitoring LFG Probe
Source: LANDTEC®

As LFG is generated within the landfill, it migrates (or moves) from the landfill in all directions, escaping through the bottom, sides and top surfaces. The presence of methane in the ground near structures presents a threat of gas accumulation and explosion in that structure. Structures such as vaults, manholes, buildings (particularly basements of buildings), sumps, etc., provide the opportunity for methane accumulation and explosive conditions. If the right conditions are present, (i.e., the correct fuel (methane) to air mixture accumulating in a confined space and the introduction of a source of ignition) an explosion will occur.

6.2. LFG MONITORING PROBES

LFG monitoring probes (sometimes called monitoring wells) are used to indicate whether LFG has migrated beyond the landfill property or some other established boundary. Monitoring probes are normally located according to regulations.

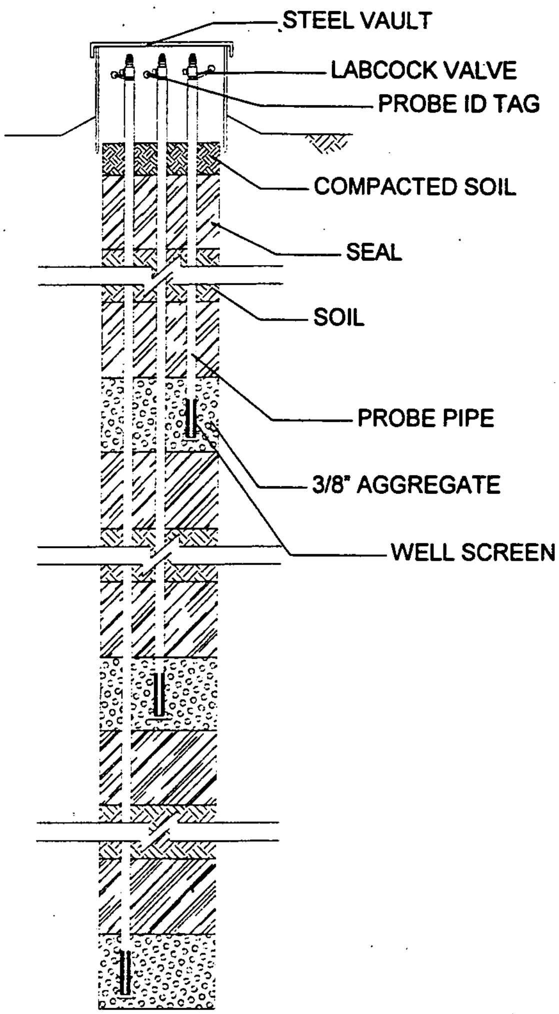


Figure 6.2
Typical Multi-Depth Monitoring Probe

Monitoring probes must be placed outside the waste mass, unless they are used as a means to collect samples of LFG. They are normally located at the property boundary because that is usually the point of regulatory compliance. Regulations often require a minimum spacing of the probes, however actual spacing should be based on site specific conditions, including the following:

- Adjacent land use
- Soil properties
- Migration potential
- Distance from structures.

Probe depths are generally based on the depth of the landfill in the vicinity of the probe. Probes may be single-depth or multi-depth. Multi-depth probes consist of several probe pipes installed at varying depths within a single borehole. The perforated length at the bottom of the probe varies, but is generally as long as practical so that gaps in the monitored zone are kept to a minimum. Figure 6.2 shows a typical detail of a multi-depth probe. If the required depth of the probe is less than 15 feet, the probe can be driven into the soil instead of installation in a borehole. Figure 6.3 shows a typical driven gas probe.

Probes should be accurately and permanently tagged. Identification of pipes within a multi-depth probe should be clear and understandable. Records of the identification, depths, and construction details should be maintained. Color coded pipe is sometimes used in multi-depth probes to prevent mislabeling of pipes.

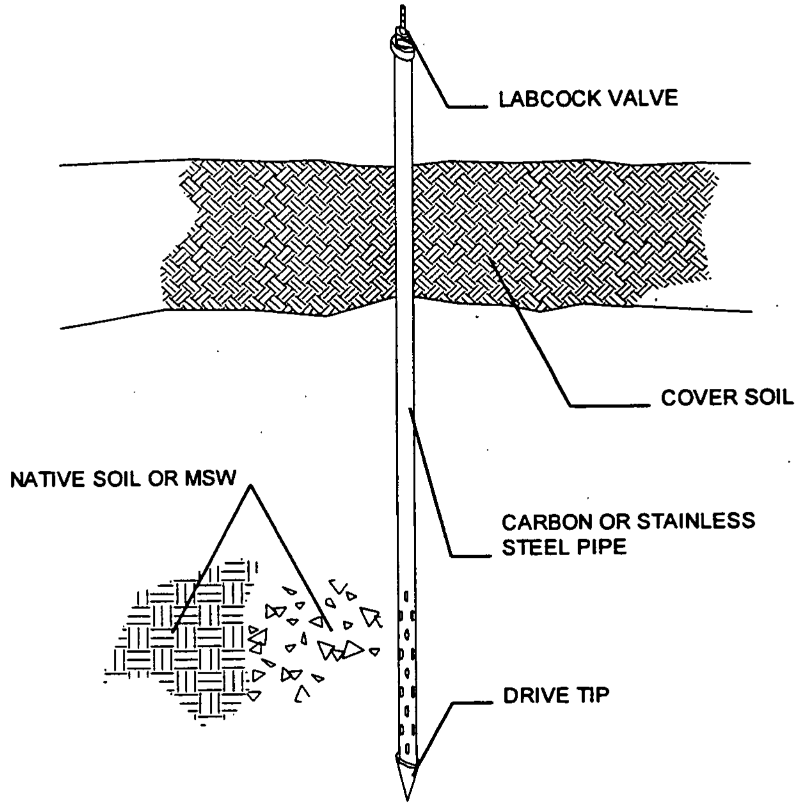


Figure 6.3
Typical Driven Gas Probe

6.3. Probe Monitoring Procedures

Prior to collection of probe monitoring data, the technician should obtain the following:

- A map showing probe locations and gas well locations
- Information on landfill depth
- As-built monitoring probe details
- As-built control well details
- Hydrologic/geologic reports
- A sample pump and knowledge of sample pump flow rate. Note sample pump may be integral to the monitoring instrument.

- Monitoring instruments:
  - Methane gas monitoring instrument (necessary)
  - Oxygen gas monitoring instrument (recommended)
  - CO2 gas monitoring instrument (optional)
  - Low range pressure gages. (e.g., 0-.25, 0-.50, 0-1.0, 0-5, 0-10 in. w.c. scale ranges) (recommended) See Figure 6.4
- Connecting tubing and fittings, etc.
- Data logger (optional)
- Barometric data (obtainable from nearby airport) or barograph (optional)
- Reading sheets, clipboard, pen, etc.

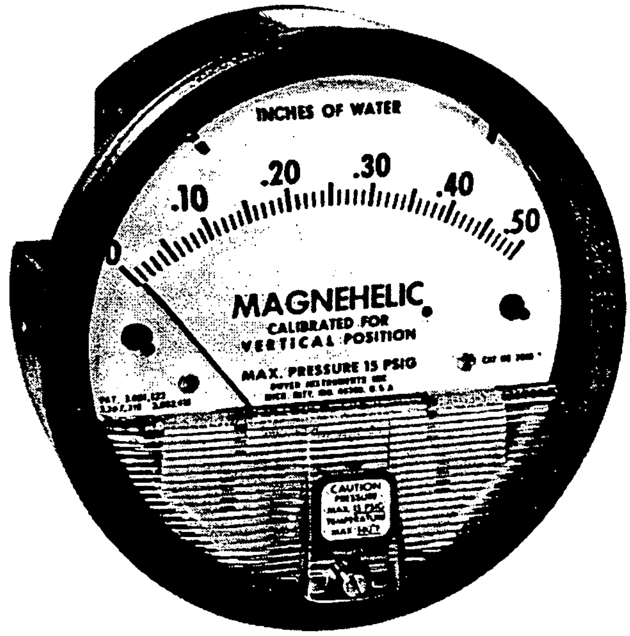


Figure 6.4

Typical Magnehelic™ Pressure Gage

Source: Dwyer Instruments

The steps in performing subsurface gas migration probe monitoring are as follows:

1) Measure and record the undisturbed probe pressure/vacuum. This requires connecting the pressure gauge to a labcock valve, quick connect, or other valve device and then opening the valve to measure the pressure.

2) Leak check the entire sample train. This is done by sealing the end of the monitoring hose and verifying that air does not leak into the sample train either through stoppage of the pump or maintaining a complete seal. Air infiltration must not be allowed while probe purging and monitoring.

3) Purge the probe casing (piping). It is desirable for evaluative purposes to note both maximum and stabilized readings. Normally the stabilized reading is used. (Note: the high value may reflect some gas separation by preferential solubalization of CO_2 in liquid.) During the purging process observe and record the maximum methane concentration. This may be different than the steady state value. Based on probe casing volume and sample pump flow rate, determine the pumping time to pump just over two probe volumes from the casing using the sample pump. The probe casing should be sealed during purging. The objective is to monitor soil gas from void spaces surrounding the probe screened interval.

4) Read and record concentration of measured gases (methane, oxygen, and if necessary, carbon dioxide).

5) If the methane reading is slowly increasing as the probe is pumped, the value at two probe volumes is recorded. The objective is to record the conditions of the gas around the probe and not gases that can be pulled to the probe via the purging process.

Limit Monitoring to the
Vapor Around the Probe Screened Interval

It is desirable to pump continually while monitoring to insure that steady state conditions are being monitored. To do this properly, the LFG technician should calculate the internal probe volume (see Appendix B.5). Apply the pump flow rate to determine the time required to evacuate two probe volumes.

High Methane Conditions May Give a False Negative

The technician should be particularly alert for temporary upscale meter needle deflection and return to zero or negative reading of the combustible gas indicator indicating an over scale or over range condition. Sufficient oxygen must be present to operate most combustible gas meters. Check the instrument operation manual for the required oxygen concentration and verify if the minimum concentration exists.

The following data should be recorded for each probe monitored:

- Name of person taking readings
- Date and time
- Ambient temperature
- Weather conditions
- Atmospheric pressure
- Probe identification and location
- Slot interval depth
- Probe pressure/vacuum
- Gas composition (methane, oxygen and CO_2).

Be careful to always note whether probe pressures are positive or negative, (i.e., pressure or vacuum). See Appendix C.2 for Sample Probe Monitoring Log. Pressures may be positive or negative due in part to factors such as barometric pressure swings and range in equilibration. It takes careful evaluation to determine if the readings are significant indicators of a problem.

Reseal the probe when finished monitoring. The probe should always remain sealed when not being monitored.

Some additional comments on probe sampling:

1) If gas samples are to be collected for trace constituent gas analysis, sample pump and all connecting tubing should be non-contaminating, (e.g., Teflon™ and stainless steel, etc.) Sampling flow rate should range from about 1/3 to 2-3 liters per minute (lpm), at or very near atmospheric pressure and ambient temperature.

2) Samples may also be collected into a sample container (e.g., a Tedlar™ bag or Summa™ canister), and then analyzed using portable direct reading instruments or by an analytical laboratory by gas chromatography or mass spectrometer.

3) Certain direct reading methane instruments require that a minimum oxygen concentration be present to operate properly. Knowledge of a given instrument's requirements and limitations is necessary. Instruments typically used are combustible gas analyzers (CGAs), organic vapor analyzers using a flame-ionization detector (OVA/FID), and infrared analyzers. These units are discussed in detail in Chapter 16, Instrumentation.

4) Almost all oxygen cells, which operate on a partial pressure principle, must be calibrated at the elevation at which they are to be used, prior to actual use. Otherwise readings will be inaccurate. These cells are also subject to pressure changes in the instrument samples stream, e.g., sample pump pressure.

5) Newly installed probes should be allowed to stand free for at least 24 hours to allow soil gases to equilibrate prior to sampling.

6) Many practitioners only monitor methane and pressure. By monitoring carbon dioxide and oxygen, and estimating nitrogen, rather than monitoring for just methane, a better idea of soil gas conditions can be obtained. This helps identify probes that are borderline, i.e., where methane is not present but its appearance is likely or occurs in a transient manner. This could be indicated by high carbon dioxide, low oxygen and sometimes low nitrogen appearing before the actual presence of methane. A more complete picture of soil gas also tends to confirm the accuracy of the monitoring data.

Trace Methane May Indicate a Larger Problem

As explained in previous sections, LFG tends to migrate away from the landfill and accumulate in confined spaces. The occurrence and accumulation of methane is sometimes transient. The presence of slight amounts of methane less than the LEL (5% UEL) is an indication that more may accumulate under other conditions if corrective action is not taken. If methane is detected in concentrations greater than 15 percent (the UEL) by volume, there is always the potential for an explosive methane-air "front" that could be formed nearby by dilution.

LFG Migration Can Deplete Oxygen

A second serious hazard is oxygen deficiency which may cause death by asphyxiation. As LFG builds up it displaces air, hence oxygen in the gas inhaled. The legal limit for oxygen deficiency may vary by state but 19.5 percent is a safe number to use (and is the most stringent). It is imperative that confined space regulations and procedures be followed before personnel enter any confined spaces or any location where oxygen deficiency could occur. Under certain circumstances special "permitted entry" requirements apply. Information on confined space entry regulations and procedures is in Chapter 19, Safety.

Methane and carbon dioxide are gases which may be present from sources other than the landfill. Field instruments cannot differentiate between the sources of these compounds.

6.4. LFG Monitoring Instrumentation

Pressure, methane, carbon dioxide,, and balance gas (indicating nitrogen) indicators are used to monitor LFG probes. A portable organic vapor analyzer/flame ionization detector (OVA/FID) is sometimes used to measure very low levels of combustible gas or volatile organic compounds. (The OVA/FID is also useful for monitoring surface emissions, identifying piping and equipment fugitive leaks or monitoring human exposure in specialized applications.) Table 6.1, "Typical Instrumentation Measurement Ranges", shows the measurement range for some monitoring instrumentation. Monitoring for methane in the parts per million range is not normally necessary for monitoring gas migration. It is necessary to have a thorough understanding of the principles of operation, operating procedures and maintenance of these instruments in order to perform accurate monitoring. The operator must also understand the operating limitations of the instruments. There is more discussion of LFG instrumentation in Chapter 16, Instrumentation.

TABLE 6.1 - Typical Instrumentation Measurement Ranges

INSTRUMENT	MEASUREMENT RANGE
Pressure (inches of water column)	0-0.25, 0-0.5, 0-1, 0-5, 0-10, 0-25, 0-60, 0-100, 0-150
Combustible Gas Indicator (Methane) (Note: In the LEL range, sufficient oxygen must be present in the sample stream to completely combust the methane to get an accurate reading.)	0-100% volume 0-100% LEL (0-5% volume)
Oxygen Meter	0-5% volume 0-25% volume
Carbon Dioxide Meter	0-60% volume 0-100% volume
OVA/FID (Methane or VOCs) (Note: Most OVAs require sufficient oxygen in the sample stream to operate properly)	0-10 ppm 0-100 ppm 0-1000 ppm 0-10,000 ppm

6.5. MONITORING STRUCTURES AND CONFINED SPACES

Federal and state regulations and good safety practices require that explosive concentrations of methane in structures on and off the landfill shall not exceed 25 percent of the lower explosive limit (LEL), or 1.25 percent by volume in air. It may be necessary to monitor on site structures to meet this requirement. Occupied on-site buildings especially should be monitored as frequently as good safety precautions dictate for a particular site. Monitoring daily is reasonable in some cases. In addition to buildings (both occupied and unoccupied) other types of structures including vaults, manholes and drainage culverts could contain an explosive concentration of landfill methane.

Note that structures that actually are a part of the LFG control system (e.g. piping, vaults) are excluded from this requirement. However, any structures that are part of the LFG system which also contain an electrical sparking device (motor starter, relay contact, etc.) should be monitored routinely. This is applicable regardless of electrical classification of the equipment or enclosures.

If LFG is detected around off site or on site structures, a thorough monitoring investigation should be conducted within the structure. Such work is usually performed by a regulatory agency or an independent evaluator. Such special monitoring must include detailed recording of monitoring results. Results should include locations, peak and stable readings, and time and date. Weather and atmospheric pressure conditions should be noted. Monitoring activities should include checking the following areas:

- Basements and substructures
- Wall space hollows and behind switch plates
- Locations of all fired equipment and pilot lights including:
  - Space and water heaters
  - Dryers
  - Ranges
  - Commercial fired equipment
- Foundation expansion joints and seams
- Below structure vents
- Elevator shafts, pits and seals
- Water wells
- Drains and plumbing penetrations
- Floor and wall penetrations
- Electrical conduit
- Vaults and other like structures and substructures
- Small rooms or non-vented areas
- Cracks, breaks or other imperfections in flooring
- Above and below building membrane protection systems if present
- Drilled monitoring probes (see "Warning" below)
- Bar punch probe holes (should be freshly punched or repunched)
- Driven probes (see "Warning" below).

For Safety - Always Monitor During Worst Case Conditions

Monitoring should be conducted under worst case atmospheric conditions, typically mid- to late-afternoon when the barometric pressure is decreasing and LFG is most likely to migrate and vent from the landfill. However, monitoring time of day may be varied to identify periods of highest migration.

Where the possibility of a natural gas leak exists, the likelihood of a source of methane other than the landfill should be evaluated. This can often be done by a utility company or through laboratory analysis. Laboratory analytical techniques can be used to differentiate sources of natural petroleum and other types of biogenic gases. These other sources should have a distinctly different analytical signature. However, natural gas can be oxidized, forming CO_2, which would cause it to have a composition similar to LFG.

Monitoring Probe Location Precautions

If permanent monitoring probes are to be installed around occupied buildings or residences, they should be installed so that people, especially children, cannot be injured by them. Options include a locking monitoring well cover or a locking vault box.

6.6. SURFACE EMISSION MONITORING PROCEDURES

Surface emissions monitoring has become more common in areas of the country with stringent air quality regulations.

There are several methods that are commonly used in conducting surface emissions monitoring. These are:

- Random instantaneous surface sweeps over the landfill surface
- Direct reading instantaneous surface sweeps over a defined area (grid)
- Integrated surface sampling (collection of a sample over time) over a defined area (grid)
- Ambient air sampling.

Random instantaneous surface sweeps over the landfill surface normally use an OVA/FID and a map of the site. Following a prescribed or random pattern over the landfill surface, instrument readings are observed and recorded. The technician pays particular attention to note and record peak readings and high readings due to thin or poor landfill cover or damage to the cap due to drying, cracking and settlement. Information obtained can be used to advise the landfill operator of areas where cover maintenance is needed and to assist in tuning the wellfield. This information can be quite valuable to the operation of the LFG control system.

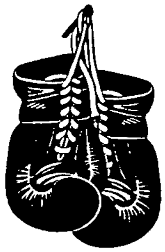
A direct reading instantaneous surface monitoring (ISM) over a defined area (a grid segment) is similar to the random walk technique, however in this case the LFG technician walks a predefined pattern within a grid segment at a defined speed and records the readings at a set time interval. A strip chart recorder or data logger may also be used with the OVA. It is helpful to have two persons for this technique. The OVA monitoring probe inlet is usually fitted with a funnel and held within 2 to 3 inches above the landfill surface. The typical grid consists of lanes 25 ft apart. Sampling is conducted at a slow pace, generally 1-2 mph. Figure 6.5 shows a typical grid patter across a landfill. High readings from cracks and fissures are also recorded as part of the monitoring. Steep landfill slopes are typically not monitored because of the risk to monitoring personnel.

Integrated surface sampling (ISS) consists of collecting a continuous sample over a defined grid pattern (usually over 50,000 square foot grids) at a set speed and sampling rate. The method is similar to the ISM method, however in this case, a sample is collected using a bag sampler. A combination non-contaminating sample pump bag sampler is used to collect the surface sample in a Tedlar™ or other non-contaminating sample bag. The methane concentration in the integrated sample can then be measured using an OVA to obtain an average reading over the grid pattern. The sample can also be analyzed for trace constituents using portable or laboratory instruments.

Before sampling is conducted, a topographic plan view map of the landfill should be used to lay out all the grids to be monitored or sampled. For some landfills, not all areas may be accessible. Those areas should be skipped or partially monitored by adjusting the monitoring or sample flow rate. In the field, the topography map is oriented using a compass and markers or grids are laid out prior to monitoring. On closed landfills, grids may be surveyed and marked.

Meteorological monitoring is usually conducted for wind speed (acceptable between 0 to 10 mph, with ideal speed between 2-5 mph) and direction (0 to 540 degrees) while instantaneous direct monitoring and integrated bag sampling is being conducted. (Note: the 0 to 540 degree range is necessary to accurately determine wind shifts through the 360 degree heading). Low threshold wind speed monitoring equipment mounted between 2 and 4 meters above the ground surface should be used. A data logger or recorder should be used to record the data.

Another type of emissions monitoring that is sometimes conducted is ambient air sampling. This type of monitoring is not needed for most landfills and requires special expertise. Ambient air sampling is usually focused on measuring total non-methane hydrocarbons (TNMHC) and individual species of trace priority pollutants which may be emitted from the landfill or another source in the ambient air at the landfill's property line. This sampling is usually conducted employing up-wind and down-wind integrated ambient air samplers. Samplers may employ Tedlar™ bag samplers or EPA Method TO-14 samplers which use Summa™ type electro-polished canisters. Ambient air sampling of various types has been conducted extensively at landfills in California and is required at some landfills in Illinois.



Limits to ISM and ISS Monitoring

Direct reading and integrated surface sampling results are subject to considerable variability due to wind and distance of the sample inlet from the surface of the landfill. The practice has many aspects that are problematic and debatable. It has been argued for example, that there are many mechanisms that mitigate trace constituents as they pass through cover soil. However, the practice is accepted as convenient and a practical approach. On a relative basis, the surface sampling results give at least a qualitative assessment of surface emissions.

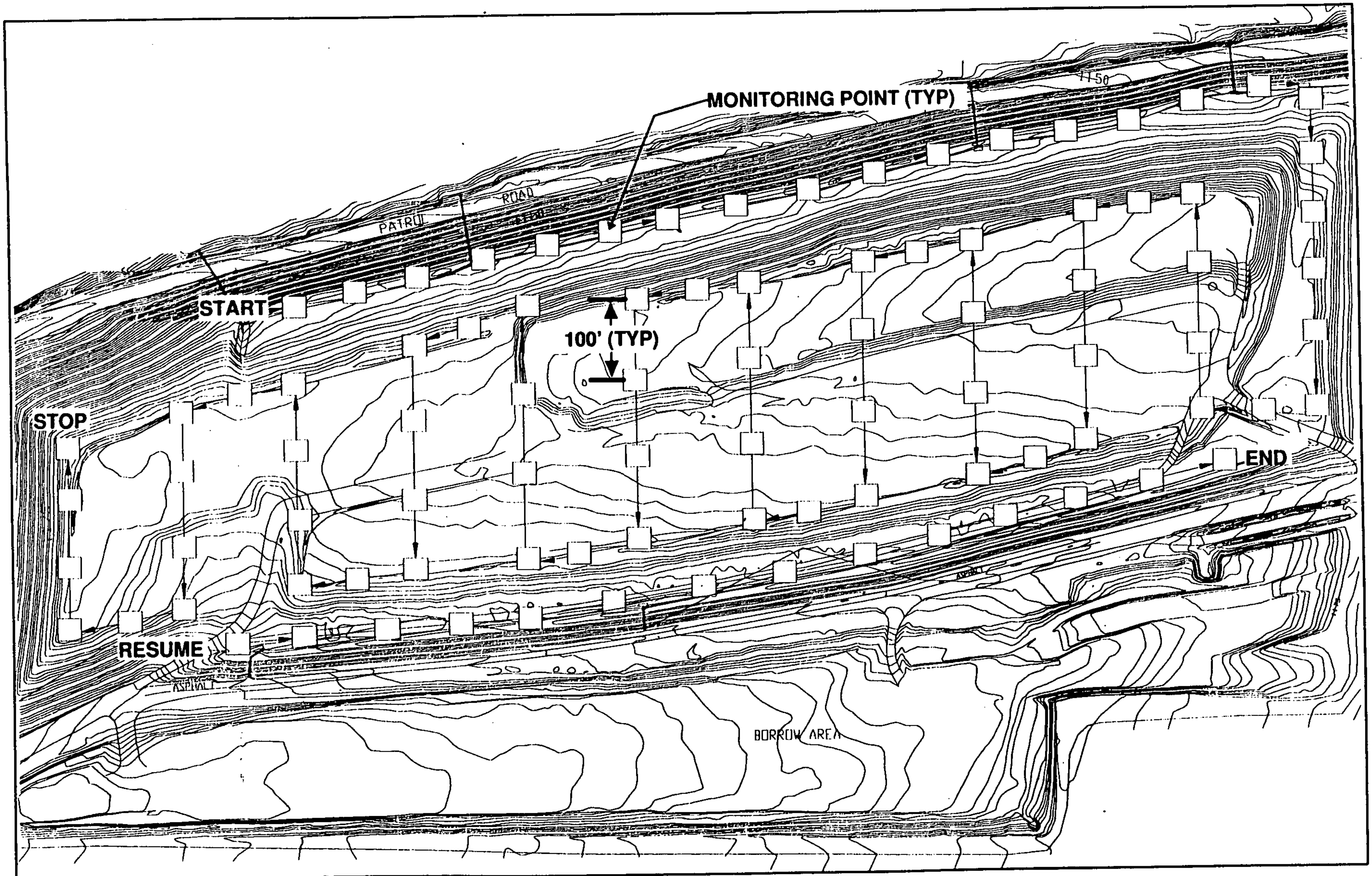


Figure 6.5
Sample Instantaneous Surface Monitoring Path
Source: City of Redlands, Redlands, CA and GCE

7. THE LFG WELLFIELD AND COLLECTION SYSTEM

7.1. EXTRACTION WELL AND COLLECTION SYSTEM CONFIGURATIONS

The LFG wellfield typically consists of the following components:

- LFG extraction wells, including:
  - flow control valves
  - monitoring ports
- LFG collection piping, including
  - condensate water collection points
  - isolation valves
  - monitoring ports

The most common practice is to install vertical extraction wells into the landfill waste mass. Vertical wells are installed along the perimeter of the landfill inside or outside the waste boundary for migration control and sometimes throughout the interior of the waste mass for control of LFG emissions. Vertical wells are installed within the landfill for emission control and energy recovery projects.

Common practice, particularly in landfills still actively filling, is the installation of horizontal wells, also referred to as trench collectors. These are typically very efficient collectors when installed sufficiently deep in the landfill or otherwise properly isolated from air intrusion. They are best suited for installation while a landfill is still being actively filled in areas where additional lifts of MSW will be placed over the well.

LFG is transported under vacuum to treatment and disposal equipment through a network of collection piping. The main pipe from the blower facility to the wellfield is called a header. The secondary pipes that connect the wells to the header(s) are called laterals. Sometimes sub-headers connect between the main header and smaller extraction unit lateral piping. The collection system may be placed on the surface of the landfill, buried beneath the surface cover, routed around the perimeter of the landfill on native soil, or some combination of these configurations. Header piping may be arranged in a branch, looped or matrix configuration.

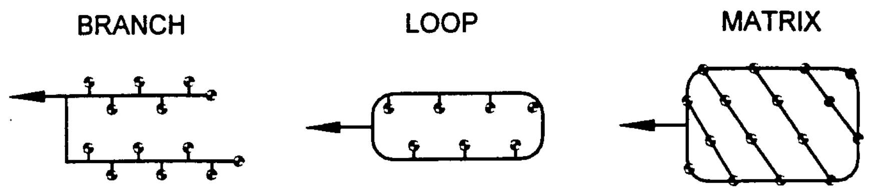


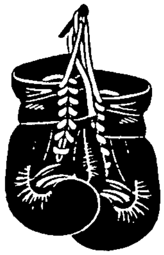
Figure 7.1
Header Routing Options

The routing of collection header piping is based on such factors as well placement, terrain, slope and drainage, and economically efficient routing. Effective drainage is the key to efficiently operating a LFG collection system.

Surface horizontal trench collectors placed in a lattice network are often used under a membrane cover. If a surface membrane is incorporated into final surface cover by design, surface collection is commonly used to prevent build up of pressure under the membrane.

A well variation commonly used in the United Kingdom is the rock trench and column approach. In this configuration, horizontal trenches and vertical columns of aggregate are placed in the landfill with collection piping inserted into the ends of the rock columns to apply a vacuum to the rock network.

Another approach is the installation of perimeter control "soil vapor" extraction wells outside the waste mass. This approach may be found at sites that are too wet for effective LFG recovery using the more common design approaches or areas of acute migration. The success of this approach is dependent on the surrounding geologic and hydrogeologic conditions. Extraction influence is usually much less in soil than in refuse, hence more wells are usually required, spaced closer together. These wells usually do not have the same performance restrictions as wells in refuse; air can be collected from soil wells with a limited risk of causing fires in the nearby refuse. The amount of air that can be collected is limited by the gas quality requirements of the system and potential for explosive mixtures in the collection pipe.



Air Injection

Another control variation is the reverse process from vacuum extraction, known as air injection. Air injection can be an effective vapor barrier by creating an air pressure curtain. Air injection can be effectively used if a sufficient buffer zone between the injection wells and the waste mass boundary is allowed. Air injection in the vicinity of the waste mass boundary should be avoided. Air injection as an approach has many negative connotations and is considered controversial by some because of the problems that have been caused by misapplication. Air injection wells have been known to contribute to landfill fires by introducing oxygen to the landfill and creating an aerobic environment.

Understanding LFG Extraction

An important concept in understanding active extraction of LFG is recognizing the nature of the landfill as an imperfect (i.e., unsealed) container. The landfill may be compared to a anaerobic sewage digester. However, instead of a controlled closed system (i.e., sealed) container as in the case of the digester, the landfill is a porous (constantly leaking) container. Ideally, we would like to collect all of the LFG (as it is generated) with little or no air intrusion. However, this is difficult because the landfill is porous, LFG continuously escapes, and air is continually pulled in. Even a completely membrane lined and covered landfill is likely to have venting or leaking. In fact, when a geo-membrane is used, air intrusion and LFG leakage may be magnified locations where this occurs. A completely gas tight sealed landfill presents considerable engineering design and economic challenges. For this reason we closely manage withdrawal of LFG by routinely balancing the wellfield, thus minimizing the introduction of air into the landfill through landfill cover and other pathways.

7.2. COLLECTION SYSTEM DRAWINGS

A set of design drawings of the LFG control system (LFGCS) should be readily available to the operating staff. Of particular importance are the following drawings:

- Extraction system site plan

- Header and lateral piping plan and profiles
- Detail drawings of components such as wells, wellheads, condensate traps and sumps
- Monitoring probe locations and boring logs .
- Well construction logs.

A handy drawing representative of the LFGCS should always be available. Engineering design plans do not always fill that need. It may be necessary to prepare a field map of the wellfield, LFG and condensate collection piping, traps, and sumps, access ports, and monitoring probes in an 8-1/2 x11 or 11x 17 inch plan view drawing format for use in inspecting, monitoring and operating the LFGCS. It is helpful to have copies on which to make notes and calculations and to record spatial and geologic relationships.

7.3. COLLECTION SYSTEM COMPONENTS

7.3.1. Wells

7.3.1.1. Vertical Extraction Wells

The vertical extraction well is probably the most standard and commonly used type of extraction well. The vertical well is best suited for installation in finished landfill areas. The well is usually constructed of PVC, HDPE, occasionally steel or other materials, with special considerations in each case. The bottom portion, approximately one-third to two-thirds of the casing, is slotted or perforated. The upper portion of the well is constructed of solid pipe casing. The slotted interval is typically surrounded in the boring with non-calcareous (i.e., non-chemically reactive) aggregate. The rock around the slotted interval of the well is sometimes referred to as a filter pack. A seal is often placed just above the filter pack. Native soil is placed and compacted above this seal. Another seal is normally placed near the surface of the boring.

The most common seal materials are bentonite, a bentonite and soil mixture, or a membrane well boot. Sometimes a slip joint (expansion joint) is installed in the well piping to allow the well to contract as the landfill settles. A wellhead is used to connect the extraction well to the collection system. The wellhead assembly may be located on the well casing or at the header. Well casing sizes of 3 to 8 inches are the most common. Figure 7.2 shows two typical LFG well configurations.

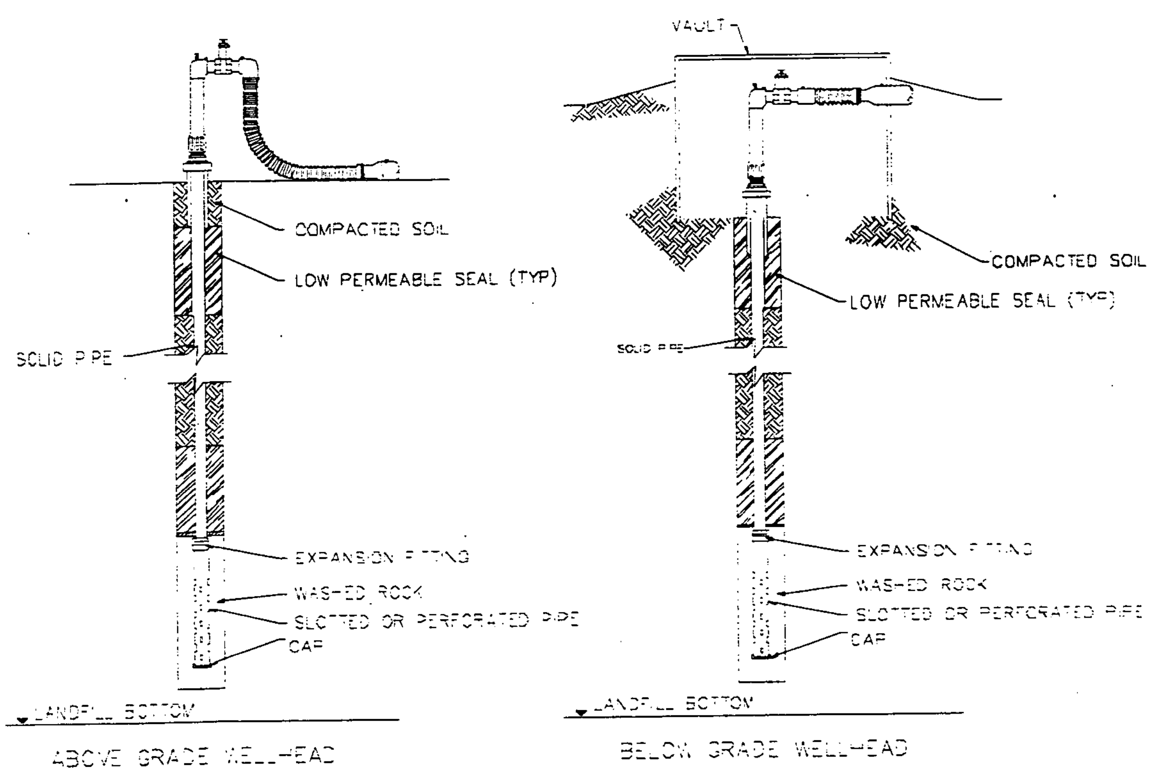


Figure 7.2
Typical LFG Extraction Wells with
Above & Below Grade Wellhead Configurations

Slip joints placed above the intermediate seal have a tendency to fail and leak, thus 'short circuiting' the well and allowing air leakage.

Experience has shown that some wells, particularly in wet conditions, will silt up or clog over time. Some believe that well performance is impacted adversely by returning (i.e., draining) LFG condensate back to the well. This practice is sometimes used in situations where condensate collection options are difficult or limited.

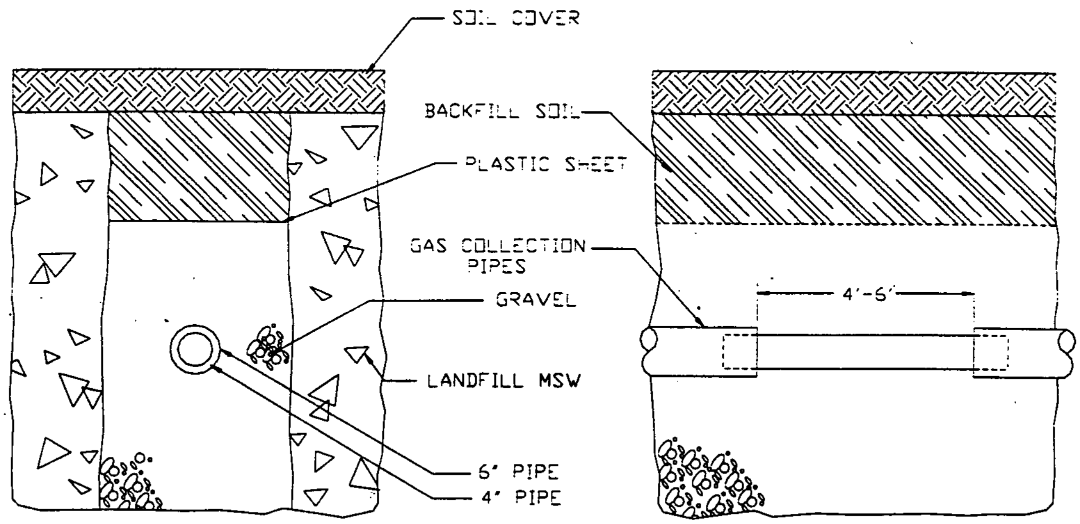


Figure 7.3
Typical Horizontal Well Detail, Front & Side Profiles

7.3.1.2. Trench Wells

Trench collector wells (or horizontal wells) are most often installed during the active landfilling phase. The horizontal trench collector is commonly constructed of continuously perforated pipe or interlaced pipe segments of two different diameters of pipe, (e.g., up to 15 inches nominal diameter). The horizontal well piping is surrounded with coarse aggregate. Figure 7.3 is an example of a horizontal well that uses interlaced pipe. The interlaced pipe provides openings for gas extraction similar to perforations. The aggregate is sometimes surrounded with a geofilter fabric. In very wet sites or where leachate will accumulate, an underdrain beneath the trench system has been used to drain accumulated water.

The effectiveness of a trench well is greatly limited when used in a shallow emplacement due to the potential for air intrusion especially if the landfill is not capped. Such wells usually must be operated at a very low vacuum. It is sometimes necessary to cover the trench well with geomembrane material to limit air intrusion. This is particularly true when the collector is within 20 to 30 ft of the surface of the landfill.

When intermediate or final landfill elevations are achieved, vertical wells may be added to enhance gas recovery and improve system performance.

7.3.1.3. Surface Collectors

A surface collector is a horizontal well near a landfill surface which is covered with an impermeable geo-membrane. This type of well is often used to relieve pressure build-up due to LFG and to prevent damage of the geomembrane. Surface collectors are usually placed just below the geo-membrane.

7.3.2. *The LFG Wellhead*

A wellhead is an assembly of pipe and fittings that usually provides for several functions including flow adjustment, gas monitoring, flow measurement, and sometimes water depth sounding and leachate extraction. The wellhead is usually mounted either at the extraction well or at a collection pipe to which the extraction well is connected by lateral header piping. When the wellhead is not mounted at the top of the well, it is commonly referred to as a monitoring and control assembly. The monitoring and control assembly is common on looped and buried systems and inactive sites where it is desirable to locate the header on native material. This places the controls at a location that may be more accessible. For purposes of this manual the term "wellhead" will be used as a generic term to refer to both wellheads and various monitoring and control assembly designs.

Wellheads may also be clustered together for ease of access. The primary purpose of the wellhead is to provide access to monitor well condition data parameters and to meter and control the rate of withdrawal of LFG from the landfill. Figure 7.4 shows a picture of a typical vertical wellhead. Figures 7.5, 7.6, and 7.7 show typical drawings of standardized wellhead configurations.

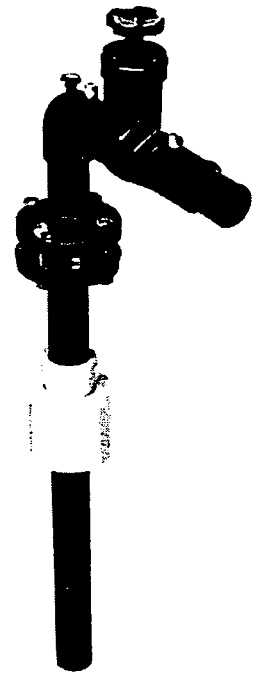


Figure 7.4
Typical Wellhead
Source: LFG&E[a]

7.3.3. *Components of the Wellhead*

A wellhead should include:

- A flow control valve
- Access ports for measuring pressure, temperature, and LFG composition
- Flex hose connecting wellhead to collection piping
- Flow element for flow measurement
- A removable cap for access, well sounding, internal inspection, liquid removal, etc.

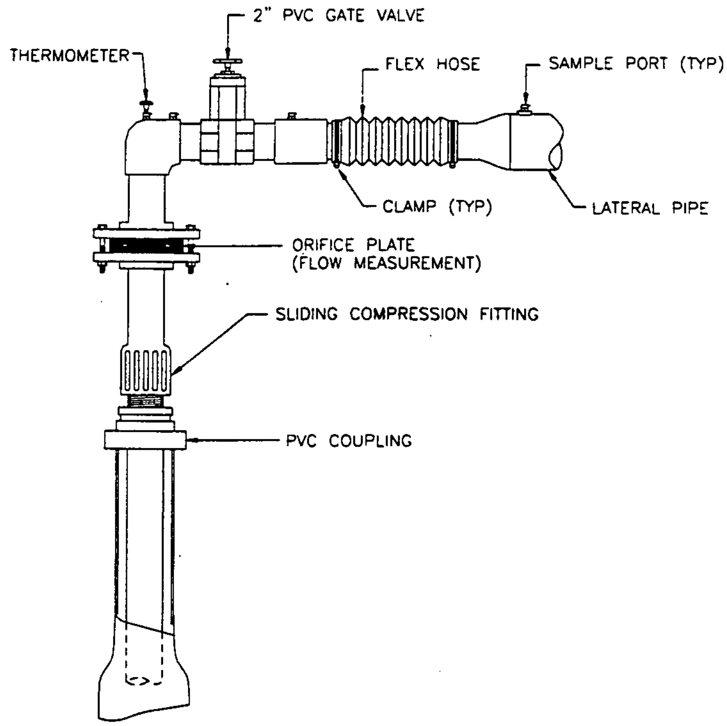


Figure 7.5
Typical Vertical Wellhead w/ Orifice Plate
Source: LFG&E®

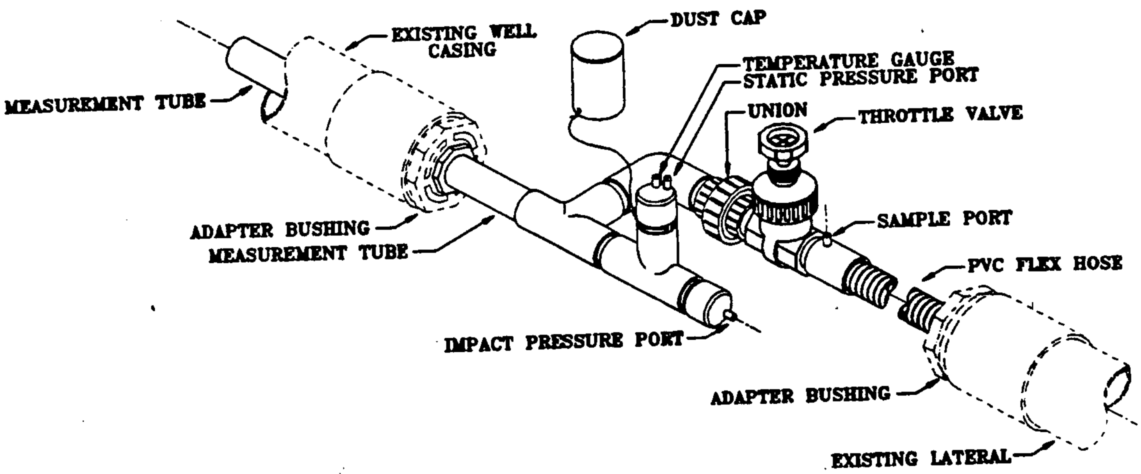


Figure 7.6
Typical Horizontal Wellhead
Source: LANDTEC[a]

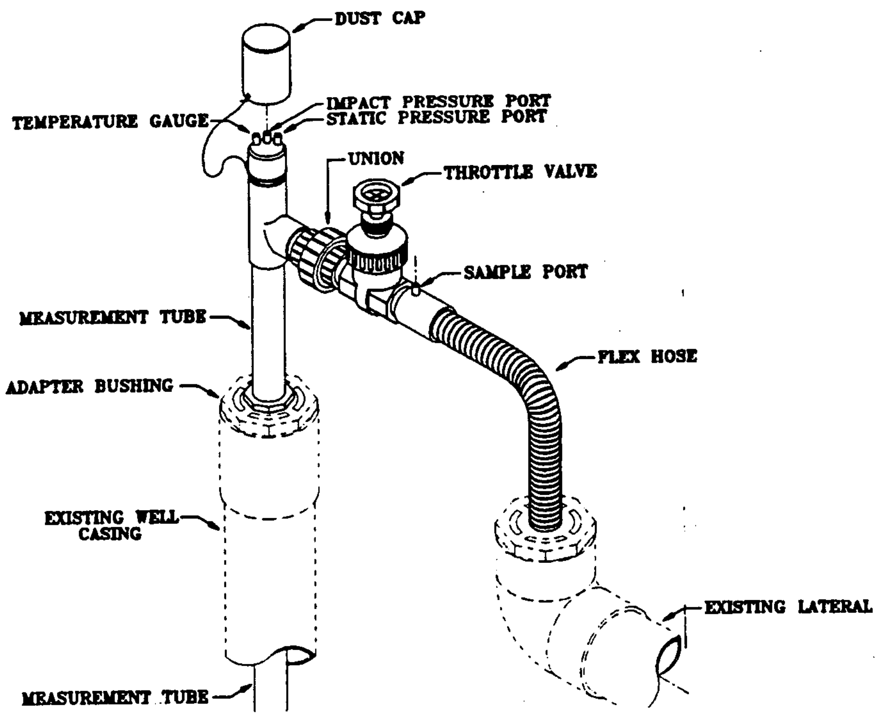


Figure 7.7
Typical Vertical Wellhead
Source: LANDTEC[a]

7.3.3.1. Wellhead flow element

A wellhead may be fitted with or without a flow element. Since wells should be adjusted based on a targeted flow rate (see well adjustment procedures), it is highly desirable to incorporate a flow element in the well head for both convenience and consistency of readings. Portable flow measuring instruments such as portable pitot tubes and anemometers may also be used. However, the setup takes time and a single instrument may not be applicable to the entire range of flows encountered.

Two types of flow elements are typically used for LFG wellheads; pitot tube and orifice plate. The pitot tube and typical orifice plates are shown below as Figures 7.8 and 7.9.

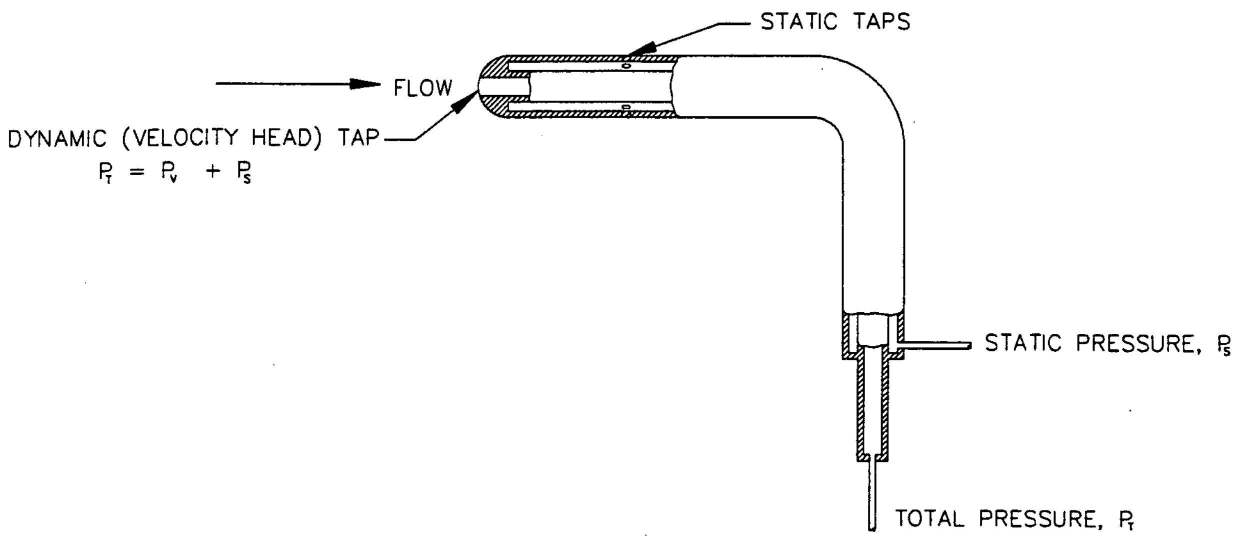


Figure 7.8
Typical Pitot Tube Configuration

From Bernoulli's Equation:

$$V = \sqrt{\frac{2(P_T - P_S)}{\rho}}$$

where:
- V = Fluid Velocity
- P_T = Total Pressure
- P_S = Static Pressure
- P_V = Dynamic Pressure, (velocity component) $P_V = P_T - P_S$
- ρ = Fluid Density

Assumption: (1) Fluid is treated as incompressible

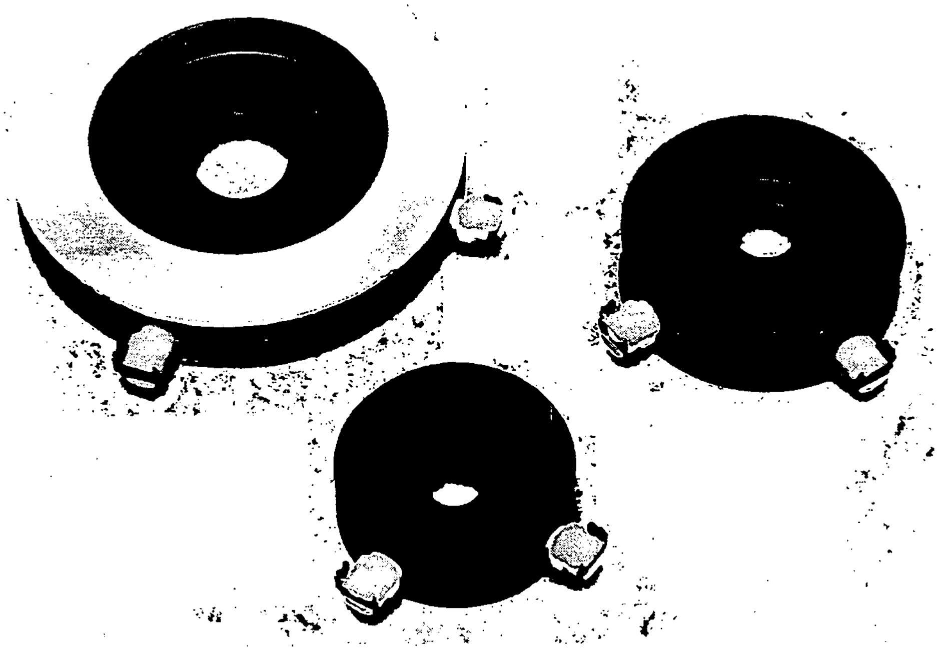


Figure 7.9
Standard Orifice Plates
Source: LFG&E*

7.3.3.2. Wellhead Valve

The wellhead valve is used for controlling well flow. Although many types of valves are available, gate valves are most commonly used in LFG well service. The different types of valves that may be used include:

- Gate valves
- Slide valves
- Butterfly valves
- Ball valves (both full and reduced port)
- Globe valves

A frequent error made in selecting a well control valve is using a valve that is too large. Generally the smallest valve that will satisfy the flow requirements should be selected. When using a valve that is oversized for the flow rate, small adjustments in flow are difficult. The advantages and disadvantages of various valves are discussed below.

Occasionally the valve must be replaced by operating staff. The wellhead valve should be selected or replaced with a thorough understanding of the control characteristics of the valve in mind. Plastic, cast iron, or ductile iron are suitable valve body materials for LFG service. Selection and replacement criteria include:

- Control requirements
- Material (body, packing, and seal)
- Acceptable pressure drop
- Ease of use and adjustment, ergonomics, etc.
- Valve position indicator or other options
- Cost.

Gate and Slide Valves

Slide valves are a form of gate valve which uses a slide mechanism instead of a turning mechanism. A gate valve is often used because of the large number of turns from full open to closed, which provides a higher degree of precision. An advantage of the gate valve is that in a fully open position it results in very little restriction in flow. For most fluid applications, it is commonly used for open or shut applications.

Globe Valves

Globe valves have more linear flow control characteristics for fluids applications. Globe valves are generally more expensive than gate valves. They also cause more restriction in flow.

Butterfly Valves

Butterfly valves are another common choice for wellhead control valves. The control characteristics of butterfly valves are that most of the flow control is in the first 30% open position. If the butterfly valve is oversized for the flow, control characteristics at low flow will be very poor. This may require reducing the size of the butterfly valve with respect to the pipe size. The butterfly valve provides poor control near the almost closed position.

Ball Valves

Ball valves are usually a poor choice for flow control. Thermoplastic ball valves are not designed for flow control, have poor flow characteristics, and are virtually impossible to obtain repeatability. A frequent complaint is that they are too difficult to operate and set, becoming too tight and freezing up, resulting in the handles being broken. Ball valves are a good choice for bleeder and drain valves and some instrument applications where an on and off service application is indicated. Valve handles should be properly oriented for fail open or fail closed operation depending upon the service.

The size range for valves used on vertical wells is typically 1-1/2 and 2 inches nominal. Valves used in conjunction with horizontal trench wells are often larger, commonly 3 inches, due to greater flow rates.

A common issue is how to determine valve position or the percent are the valve is open as a means of relating to flow. Many valves do not provide an accurate means to identify the percent of valve opening or to accurately relate the setting to flow rate. Nevertheless, it is desirable to record valve position as a means of recording valve position changes as part of monitoring data and its evaluation. It is also necessary to know if a valve is set fully open (maximum flow) or is closed (flow shut off) when evaluating well data. Some valves have position indicators that provide a means to estimate percent open. Some operating technicians record the number of notches open on a butterfly, others use the number of turns on a gate valve. While this may provide a rough indication, the valve setting frequently will not be repeatable due to valve hysteresis and changing conditions in general.

Some valves use an operating stem and yoke (OS&Y), also known as "rising stem," and non-rising stem configurations. The advantage of the rising stem type valve is that the condition of the valve (open or closed) can be ascertained by the height of valve operating stem. This is particularly helpful in a main pipeline valve.

In operating the valve, no more pressure should be applied than is necessary to open or close the valve. Many inexperienced operators tend to seat valves with excessive force. This is not necessary and may damage the valve. When evaluating well data, it is important to know the valve position before and after well adjustment. Without it, one cannot accurately interpret the well data.

7.3.3.3. Wellhead Flex Hoses

A flex hose is often incorporated in the wellhead assembly to connect the wellhead to the collection piping. The flex hose acts as an expansion joint to relieve the stress between the wellhead and the piping. This helps to protect the wellhead from stress due to movement of the piping. The flex hose should be stretched or supported so as not to allow a low spot where condensate will accumulate and block flow.

The most common flex hoses types are 1) reinforced semi-rigid PVC and 2) a high temperature and high vacuum service silicone and wire composite hose. Silicone hoses are resistant to high vacuum service, chemical and ultraviolet (UV) attack and high LFG temperature. Abrasion due to hose movement is a key performance issue.

PVC is also suitable for high vacuum service and is reasonably resistant to abrasion and chemical degradation. It is not as good at elevated temperatures and is not resistant to UV exposure.

7.3.3.4. Wellhead Access Ports

Wellhead and header piping access ports should be part of the design. In many cases they must be added by operating staff. This may not be practical on a buried system, in which case it may become a severe operating handicap. If access ports are to be installed for flow meter measurement, the port should be placed in as long and straight a pipe run; the general rule is 15 to 30 pipe diameters of straight pipe run length upstream and 5 to 15 pipe diameters of straight pipe run length downstream. Another way to state it as a rule is a two-thirds upstream and one-third down stream relationship of straight pipe before and after the flow element should be applied. Special circumstances may require even more pipe or other special consideration, (e.g., installation of flow straighteners).

A wellhead usually incorporates a 90 degree turn which can be accomplished using a 90 degree elbow or a tee. A tee in a vertical well affords the opportunity to use a removable cap so that the well may be measured for liquids. The cap may be slip or threaded and may be sealed with vacuum grease or Teflon® joint sealant.

7.3.3.5. Access Ports and Wellhead Instrumentation

Access ports provide a means for entry to the inside of the pipe for monitoring LFG parameters such as gas composition, pressure, differential pressure or flow, temperature, etc. Access ports should be planned as part of the system design and installed during initial construction of the collection system. The access port should be designed to accommodate the well monitoring equipment. Common sizes for access ports are 3/4, 1 and 2 inches. Normally a 3/4 or 1 inch port is adequate, a 2 inch port may be required when a standard pitot tube is used for flow monitoring. It is also a common practice to fit the header pipe or wellhead with a small sample valve sometimes known as a labcock or petcock valve. If the port is not properly sized to accommodate the monitoring equipment, an adapter should be fabricated or a new port installed.

There are many types of fittings used for access and measurement ports or taps. In selecting access or measurements ports, consideration should be given to instruments to be used. There a number of thermoplastic valves and fittings available. If using PVC plugs, it is preferable to use a tee or saddle fitting rather than directly threading into PVC pipe as PVC threads are easily stripped. Bronze or brass fittings should be avoided. Thermoplastic labcock fittings with a male hose barb end are commonly used as well as quick connect fittings. Stainless steel Schrader tire valve fittings with the internal valve removed have also been used.

7.3.4. LFG Collection Header Piping

7.3.4.1. Piping Configurations

Collection piping may be placed either on the surface or buried. Above ground systems are often used for piping within the refuse limits where adequate pipe slope is not available to accommodate landfill settlement. Above ground piping may need supports to create adequate slope. Cold weather climatic conditions and beneficial use of the landfill surface often dictate that a buried collection system be employed. Pipe is also frequently buried in areas outside the refuse limit where settlement is not a concern. Little maintenance is required for this type of buried pipe. Figure 7.10 shows a typical below grade header trench.

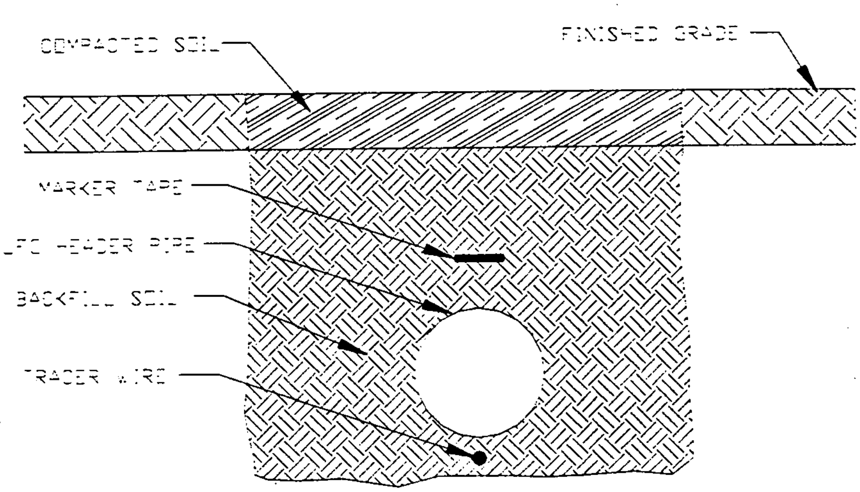


Figure 7.10
Typical Below Grade Header Trench

A new challenge in LFG collection system design is integration of the collection system with the final cap required by revisions to Subtitle D for newer landfills undergoing closure. Of specific importance here is the requirements for the repair of the cap in the event of a penetration such as construction or repair of the LFG system.

7.3.4.2. Types of Piping Layouts

One of the most common piping configurations is the branched piping layout which flows from individual wells composing branches that tie into larger lateral or subordinate header piping and then into one or several even larger main header pipes. Branches can be inter-tied or cross connected if there is some reason to do so for reasons of flexibility or maintenance.

Another common approach is to ring the site with a looped header, which may be located on or off the waste limit, and tie in individual or groups of wells with header lines that may be run laterally or radially across the landfill. In either case, the systems may be above or below grade. The looped system has the advantage of allowing operating personnel to pull from either direction, thus providing flexibility in situations of blockages or header repair. The looped system also provides for self-equalizing or balancing of the vacuum and flow.

7.3.4.3. Types of Piping

Two types of piping are commonly employed in LFG collection systems, PVC and HDPE. HDPE is not commonly used for above grade collection system applications because of the high rate of thermal expansion of HDPE. HDPE requires more specialized techniques for joining than PVC, however, it is very tough and resistant to stress. HDPE is also a good choice for condensate disposal lines and buried compressed air supply lines for pneumatic systems. Because of its high ductility, HDPE conforms to the shape of the ground surface which can cause condensate blockage at low points, if poorly constructed.

The other piping material in common use is PVC. PVC is easy to install, maintain and repair, but is subject to UV attack and should be protected with UV inhibitive paint. With age, unpainted PVC pipe will take a set (become oblately flattened or egg shaped) and brittle. PVC does not tolerate cold weather well and may shatter upon impact below 4 degrees C. (40 degrees F.). Because PVC is brittle , it is vulnerable to stress caused by differential settlement. PVC is easily joined or repaired with solvent cement and primer. Special cement and primer is also available for wet service application.

PVC is the most commonly used material for monitoring probes. Because solvent glue can sometimes register on gas analyzers, PVC probe casing and valves and fittings should be joined using threaded fittings. All joints must be air tight which is accomplished using Teflon™ tape or pipe compound at the joint or special piping which utilizes O-ring seals.

Other types of piping that have been used in LFG collection piping include fiberglass reinforced piping (FRP) and ABS pipe. FRP is not in common use because other materials have more desirable design characteristics, are more cost effective and are easier to work with.

Standard ABS used in drain piping is unsuitable due to its brittleness. However, there is a specialized formulation of ABS that can be useful in special circumstances. This material is ductile and will not shatter in cold weather. It is the only thermoplastic that is manufactured and specified specifically for compressed air service. (Standard thermoplastic materials are generally not code rated for compressed air service, and should never be used above grade. A manufacturer's applications engineer should be consulted if there is any question as to the suitability of plastic pipe.)

Carbon steel piping is typically not used in LFG piping that is buried in the landfill due to susceptibility to corrosion. The landfill is commonly an acidic environment that will rapidly attack and corrode buried carbon steel piping. This is especially dangerous in the case of pressurized service piping such as that used for natural gas or propane service. There has been at least one recorded fatality due to corrosion failure of steel natural gas piping buried in a landfill.

For buried pipeline transport of LFG off site, for example to a utility, the choices are HDPE, carbon steel (coated or wrapped), and FRP. The type and specification of pipe allowed will be dictated by local engineering, building, and U.S. Department of Transportation (USDOT) (pipeline) codes.

7.3.4.4. Collection System Piping Maintenance

Refer to the Collection System Inspection Checklist (See Appendix C) for information about identifying collection system deficiencies. The two principal types of problems that occur in operation of the collection system are LFG condensate blockages and air leaks.

Condensate blockages are most frequently caused by differential settlement. Likely locations for condensate blockage are in horizontal collectors themselves, at low points along the main gas collection headers and at buried road crossings. Often the operator can detect surging or "gurgling" noises in the piping, absence of flow, or fluctuations in pressure readings. With above ground system, it helps to place one's ear to the pipe to listen to the sound of gas flowing. Below grade systems can be listened to at access ports, condensate traps and road crossings. Blockages may be isolated by taking a pressure profile across the system by measuring and recording system vacuum at access ports throughout the system and bracketing to isolate the problem. An excessive pressure drop between any two access ports may indicate a potential problem.

Air leaks are usually detected by sound caused by the vacuum leak. Air leaks may also sometimes be detected when the system is down and residual pressure builds up in the pipe creating a "hissing" sound as the gas escapes at the location of the piping leak. Air leaks may be isolated by checking oxygen at access ports throughout the system and bracketing to isolate the problem. Sometimes there will be an excessive pressure drop as a result of the vacuum loss due to the air leak.

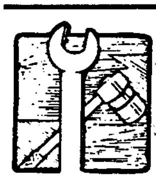
7.3.4.5. *Piping Settlement*

LFG collection piping is affected by landfill differential settlement. The LFG technician must check the system periodically for settlement that affects the integrity of the piping system, causes excess stress on piping, or creates condensate blockage. Long term monitoring has documented overall settlement exceeding 25% of initial fill depth. Settlement may occur at a rate of 1% per year.

The LFG technician should also check the collection system for strain and movement caused by thermal expansion and contraction. PVC expands and contracts at a rate approximately 5 to 6 times greater than steel. HDPE expands and contracts at a rate approximately 20 times greater than steel, or 3 to 4 times greater than that of PVC.

7.3.4.6. *Piping Supports Maintenance*

Piping supports are installed to structurally support the piping, anchor the pipe at key points to control the direction of thermal expansion, and in the case of thrust blocks, absorb and control piping thrust forces caused by expansion and contraction. Piping supports are sometimes required to support piping at minimum intervals to prevent sagging. Piping laid on the landfill cover surface or on berms may also require anchoring to minimize and control movement.



Pipe Support Adjustment

The LFG technician should periodically check piping supports to adjust piping alignment and correct sagging pipe and loose supports. Tires, although aesthetically unsightly, are sometimes used as a field expedient or temporary piping support.

7.3.5. *Condensate Collection; Traps, Sumps, Pumps, & Tanks*

See the LFG Condensate Handling System, Chapter 12.

8. OPERATING THE LFG CONTROL SYSTEM

The LFG control system consists of four basic components. Successful operation requires that each component function properly. Routine monitoring is necessary to verify performance of the complete system and to aid in identifying problems, should they exist. The four basic components of the control system are as follows:

- Migration monitoring system i.e., perimeter LFG monitoring probes
- LFG extraction system e.g., a combination of perimeter and interior LFG extraction wells and collection piping
- Condensate collection, pumping, storage, and treatment equipment
- LFG treatment, disposal or energy recovery equipment e.g., a blower-flare facility.

8.1. THE OPERATIONAL ROUTINE

Presented here is a general representation of the operational routine in operating a LFG control system. The specific tasks, frequency, routine and procedures can only be presented as general and generic. Many landfills will have site specific differences and needs.

8.1.1. Perimeter Probe Monitoring

For migration control systems the primary monitoring points are the perimeter migration probes. Monitoring the perimeter probes and landfill surface provides information on the performance of the LFG collection system. Procedures for this are discussed in Chapter 6, The LFG Monitoring System.

8.1.2. Condensate Water System

The condensate water system supports the operation of the LFG collection system by removing the water that condenses in the system. Monitoring consists of verifying the proper operation of the sumps and traps. LFG piping vacuum is also monitored to identify restrictions caused by condensate buildup.

8.1.3. Wellfield and Piping

Activities that would be part of the wellfield & collection piping operational routine would include:

- Monitoring and adjusting perimeter extraction control wells based upon perimeter probe, landfill surface, monitoring and extraction well monitoring data
- Monitoring and adjusting interior extraction wells
- Inspecting the wellfield components and header piping for performance, physical condition and needed maintenance
- Inspecting the surface of the landfill for cracks, openings, settlement, or damaged vegetation that may indicate areas where air intrusion or gas venting through the landfill surface may be occurring
- Calibrating and maintaining monitoring instrumentation.

The following miscellaneous tasks are equally important for a well operated and maintained system:

- Assessment and entering of field monitoring data
- Keeping such records and logs necessary to document the system performance and meet regulatory requirements
- Arranging services and supply deliveries with outside vendors that support the LFG control system operation.

Special conditions such as regulatory rules and compliance orders, the presence of off site LFG migration, or special waste site status or conditions (e.g., enforcement action or "Superfund" site status under CERCLA, etc.) may add additional requirements to the above routine.

8.1.4. LFG Disposal Facility

The frequency and type of monitoring at the LFG disposal facility will depend greatly on the type of design and components of the facility. An example of the daily routine and types of activities at a LFG blower-flare facility is as follows:

- Initial check for system status (running normally?) and general observation
- Perform blower-flare facility daily readings. Record readings on daily reading sheets. The following points should be addressed:
  - Check annunciator or alarm panel
  - Visual and audible inspection
  - Flare temperature (strip chart recorder, temperature indicator, or thermocouple voltage)
  - Facility flow
  - Flare inlet valve position
  - Flare firing condition - flame and secondary air dampers (visual observation)

- Blower suction and discharge pressures & temperatures and unusual vibration
- Gas quality: CH_4 & O_2
- Valve positions
- Instrument air operation
- Lubricant levels
- Tankage inventories/levels (condensate/lube oil/LPG/propane)
- Check for any unusual conditions

Note that this routine may be performed daily, on several days of the week, weekly or monthly, etc. depending on need.

If problems or a shutdown are observed:

- As part of troubleshooting, make "quick check" and evaluate all conditions.
- Note annunciator status (prior to resetting).
- Make notes in logbook.
- Make appropriate notations on recorder strip charts.
- Take corrective actions.

8.1.5. Administrative Procedures:

- Make appropriate entries in facility log book and on flare strip chart recorder.
- Based on scheduled items and results of "quick check" decide on course of action for day or shift.
- Conduct instrument maintenance activities. Record calibration results.
- Perform blower-flare facility readings. Record on daily blower-flare facility reading sheet. Readings should also be taken after any startup following a shutdown.
- Conduct a walking inspection of the landfill wellfield and landfill. Areas along buried header piping and the perimeter of the waste mass are particularly important. Log your observations. Sometimes at large sites a driving inspection is more practical on a frequent basis, however, a driving inspection should not be wholly substituted for regular performance of a detailed walking inspection conducted on foot over the system and landfill. It is not possible to see and hear all that is important from inside a vehicle.
- Conduct facility and well field routine or scheduled maintenance activities. Log maintenance activities. Non-routine maintenance is scheduled as required consistent with other priorities.

- Perform and record any final field instrument calibration. Record results.
- At end of shift/day make final checks and record logbook entries.
- A weekly/monthly maintenance reading sheet is used to monitor routine maintenance checks and service.
- Check status of supplies and parts orders. Order any supplies or repair parts needed.

9. MONITORING AND ADJUSTING THE LFG COLLECTION WELLFIELD AND COLLECTION SYSTEM

The LFG system is dynamic (i.e., continually changing) and its operation must account for this. Successful operation requires viewing the system as an integrated whole with many interrelated parts and influencing factors. The effects of continued withdrawal of LFG, air intrusion, state of the anaerobic environment and the factors that affect LFG generation, the influence of fluctuating atmospheric pressure, and the adjustment of the wellfield itself can impact the operation of the LFG control system. As a result, operating the LFG wellfield can be visualized as a balancing act to enhance certain objectives, perhaps at the expense of others. These objectives carry different weights, depending on the site and the operational goals, and are discussed in this chapter.

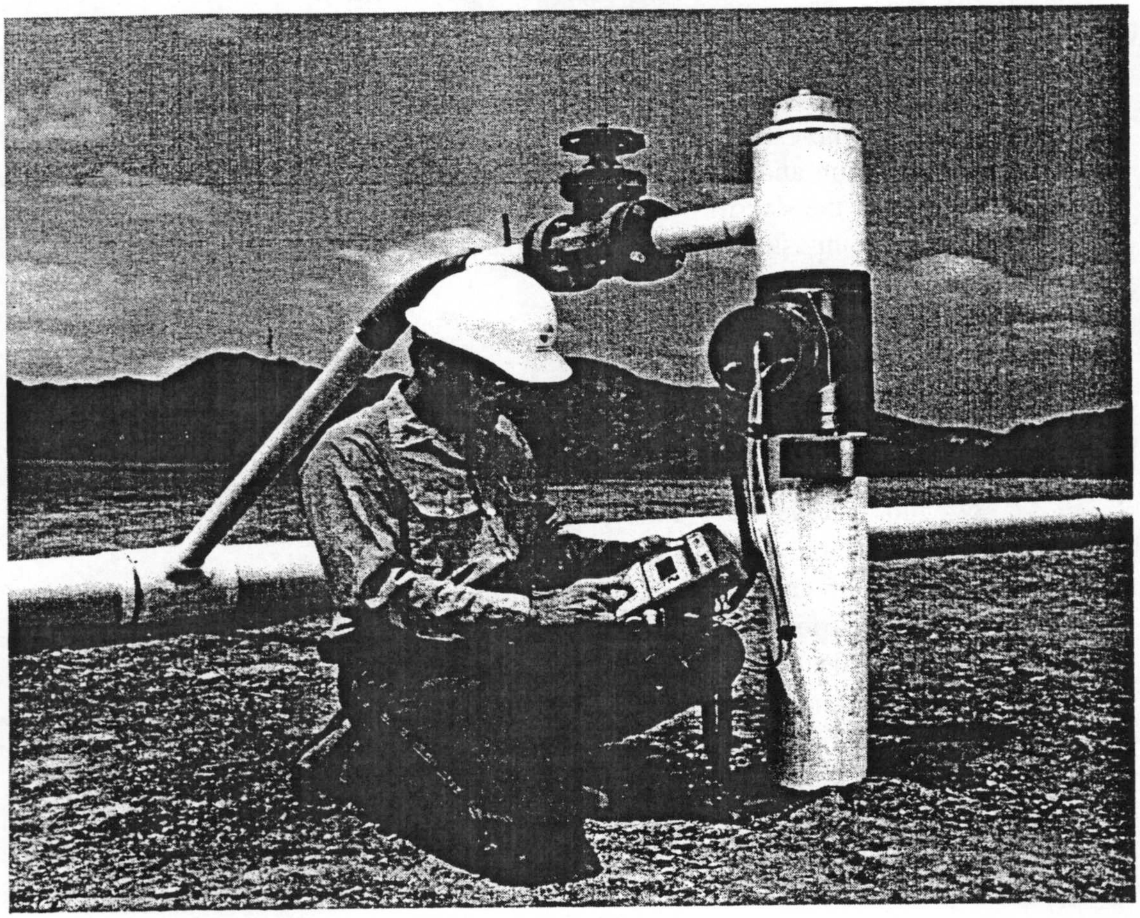


Figure 9.1
Well Monitoring
Source: LANDTEC®

9.1 SOME WELL PERFORMANCE THEORY

Thinking through the various effects of the many objectives of operating the wellfield is part of the subjective part of the routine thought process of a skilled LFG practitioner. This process is necessary because no easily manageable algorithm or "by the book" procedure can address all factors or situations adequately.

One example of this is in determining how much air is introduced into the landfill by active extraction. As has already been mentioned, air contains approximately 79 percent nitrogen and 21 percent oxygen. The ratio of nitrogen to oxygen is 3.8:1. The ratio of total air to oxygen is 4.8:1. This knowledge can be used (with some assumption) to estimate the amount of air attributed to surface or piping leakage with the remaining amount caused by air intrusion into the landfill. Because oxygen pulled into the landfill with air is often consumed by bacteria, the nitrogen in the air is used instead of oxygen to estimate the amount of air intrusion. Nitrogen and oxygen introduced by air leaks is subtracted leaving the remainder as an estimate of air intrusion.

Ideally, given a "perfectly sealed container" such as a sewage digester, we would like to extract LFG at the rate it is generated. What rate should that be? It is difficult to determine without some experimentation. The landfill more than likely has an irregular geometric configuration and virtually all factors associated with it vary to some degree. As has been said, the landfill is heterogeneous in many ways. Besides MSW characteristics and composition, factors that impact extracted LFG composition include:

- Rate of air intrusion*
- Atmospheric pressure *
- MSW moisture content*
- LFG containment efficiency of cover (permeability/porosity/cap)
- Site geometry
- Ground water levels*
- Landfill chemistry, pH, etc.*
- Bacteria population size and activity*
- Bacteria nutrient availability*
- Well field design
- Well adjustment* i.e., Extent of applied well vacuum
- Precipitation (rain, snow cover, etc.)
- Extraction system leaks.

*Note that many of the factors in the above list are dynamic and subject to change. The most dynamic ones in the above list that vary, depending on other factors, are marked with an asterisk (*). Here we are only talking about those that affect the landfill. There is another list (see the Well Adjustment Section) that includes some of the above factors and others that define extraction well performance.

9.2 WELLFIELD MONITORING

Periodically, the wellfield must be monitored to evaluate conditions within the landfill and adjust the collection system wells. This data must be collected with sufficient care, accuracy and frequency to provide for informed decisions about operating the collection and control system.

Monitoring Frequency

The frequency of LFG wellfield monitoring will vary depending upon field requirements and conditions. Monitoring frequency will typically vary from once a month to once a week. Wellfield monitoring should not be extended beyond one month. The importance of regular, timely monitoring cannot be overemphasized. Monitoring frequency should be based on the level of risk and the needs for collection efficiency at the site. For example, sites which are collecting gas for energy recovery, groundwater protection, or protection of residences adjacent to the landfill would typically require more frequent monitoring.

A complete set of wellfield readings consists of most of the following:

- Name of person taking readings
- Date/time of each reading
- Methane (CH_4) concentration
- Oxygen (O_2) concentration
- Carbon dioxide (CO_2) concentration
- Balance Gas (primarily nitrogen, N_2) concentration (normally a calculated number)
- Wellhead gas temperature (flowing)
- Ambient temperature
- Wellhead vacuum (P_s) before and after adjustment (from integrated instrument, digital manometer or Magnehelic™)
- Velocity head (ΔP or P_t) (from flow instrument or pitot tube and manometer)
- Wellhead gas flow before and after adjustment (from field or integrated instrument)

- Wellhead adjustment valve position (initial and adjusted)
- Observations/comments (e.g., maintenance issues).

The list of items to be monitored and frequency of monitoring will vary with the type of application and system requirements. Regulations may also sometimes dictate monitoring requirements. Not all readings are always needed.

Carbon monoxide (CO) or hydrogen sulfide (H_2S) readings may be collected if problems are suspected.

H_2S Can Be Lethal

Potentially lethal concentrations of H_2S may be present at landfills. Personnel must always be alert for the hazards presented by H_2S. High concentration levels may require the use of self-contained breathing apparatus (SCBA) or supplied air. If H_2S is detected or suspected, consult the site Health and Safety Officer, an industrial hygienist or other qualified person.

Supplementary monitoring once to several times a week may be performed using an abbreviated form of field readings.

An abbreviated form of field readings consist of a combination of some or all of the following:

- Name of person taking readings
- Date/time of each reading
- Methane (CH_4) concentration
- Oxygen (O_2) concentration
- Wellhead gas temperature (flowing) (Optional)
- Ambient temperature (Optional)
- Static pressure (P_s) (from integrated instrument, digital manometer or Magnehelic™)
- Velocity head (ΔP or P_t) (from flow instrument or pitot tube and manometer)
- Wellhead gas flow (from flow or integrated instrument, or pitot tube and manometer, or anemometer/velometer)
- Wellhead adjustment valve position (initial and adjusted)
- New wellhead vacuum and flow information after adjustment.
- Observations/comments.

The determination of which readings to include in an abbreviated set of wellfield readings is based on field monitoring needs but should be standardized for each site program and include as a minimum: methane, oxygen, static pressure at the well head, valve position and any adjustment made.

Line vacuums, gas flow and quality may be taken at key points along the main gas collection header and subordinate branches. This helps to identify sections of poor performance, excessive pressure drop, or leakage.

During monitoring, examine landfill and gas collection systems for needed maintenance or unusual conditions. Examples of unusual conditions are: severe settlement or subsidence, signs of subsurface fires, smoke, cracks and fissures, liquid ponding, condensate/leachate weeping from side slopes, surface emissions and liquid surging in the gas collection system.

9.3 Wellfield Adjustment - Purpose and Objectives

The objective of wellfield adjustment is to achieve steady state operation of the gas collection system by stabilizing the rate and quality of extracted LFG in order to achieve one or several goals. Typical reasons for recovery of LFG and close control of the wellfield are:

- Subsurface gas migration control.
- Surface gas emissions control.
- Protect groundwater.
- Assist with proper operation of control and recovery equipment.
- Avoidance of well overpull and maintenance of an anaerobic state within the landfill.
- Optimize LFG recovery for energy recovery purposes or equipment performance.
- Control nuisance LFG odors.
- Prevent or control subsurface LFG fires.
- Protect structures on and near the landfill.
- Meet environmental regulatory compliance requirements.

9.3.1 Approaches to Wellhead Adjustment

There are many approaches to adjusting extraction wells and controlling LFG extraction. These techniques can also be viewed as a set of complimentary tools that should be used together or selected as needed to adjust the LFG wellfield. In some situations, reliance on a single, or just a few, parameters such as methane and vacuum may work satisfactorily for some control projects, while in other cases collection of a more complete set of data parameters and a structured approach to data assessment and well adjustment is called for. Below is a discussion of the individual data parameters, the adjustment techniques that apply to them, how to use them and their limitations. The LFG operator should rely on all or at least most of the techniques and parameters available to him. Reliance on only a few of the techniques or parameters discussed can lead to misinterpretation of field data and improper operation of the wellfield.

There are two options in monitoring wells and making adjustments. One is to collect all monitoring data, analyze the data to establish the adjustments that should be made, then promptly return to the field to make the adjustments. This method is usually preferred, however it may not always be practical. The other method is to adjust the wellfield while the reading set is being taken. The method used will depend on monitoring objectives.

Effects of Well Adjustment

When one well is adjusted, all of the other wells are affected. This is even more true when a LFG disposal facility uses a constant rate of gas extraction (i.e., a positive displacement compressor or perhaps a gas engine. Adjustment on the fly will affect the entire well field including wells which have not yet been monitored. Normally, readings should commence at the furthest well from the blower-flare facility, then working towards the facility. For this case, recording all data prior to making adjustments may be more appropriate. Adjustment on the fly is more appropriate for systems that use centrifugal gas blowers on flare systems. For this case, well adjustments usually don't have a significant impact on the overall system.

Many systems are adjusted primarily based on methane quality rather than flow. This approach relies on small valve adjustments based upon observed methane levels. A multi-turn gate valve is ideally suited for this type of adjustment.

Sometimes wells are adjusted based on vacuums in lieu of flow data, however, this is not as good. Flow is generally not proportional to vacuum due to the non-homogenous nature of the landfill.

9.3.2 Extraction Well Adjustment Parameters

Before discussing the detail of well adjustment procedures and rationale, it is desirable to explain each well monitoring data parameter.

Importance of Collecting All Parameters

It should be understood that all of the foregoing parameters can, at times, provide useful information for well adjustment. It is recommended that the operator consider the effect of all parameters and use them as data "tools" to provide the fullest possible picture of what may be taking place within the landfill with respect to methane generation and collection.

Wellhead Valve Position—Some valves have a position indicator. The position of the valve position indicator does not provide sufficient information about the well flow or performance. It is, however, useful to note the relative position of the valve, to know which valves are fully open or closed. This information should be recorded on the wellfield monitoring data sheet.

LFG Temperature – LFG Temperature is an indicator of the state of anaerobic conditions at the well. Bacteria may be classified according to temperature as psychrophilic, mesophilic, and thermophilic. These ranges may be thought of on a simplistic and relative basis as cool, warm and hot environments, respectively in terms of the landfill environment and LFG temperatures.

These temperature environments are summarized in Table 9.1, Typical Temperature Ranges for Bacteria. The anaerobic methane producing bacteria are slightly exothermic (i.e., they produce heat). The anaerobic bacteria thrive in all three ranges. Temperatures of LFG at the wellhead typically range from 16 to 60 deg. C. (60 to 140 degrees F.). Because of the short residence time, the temperature of the flowing gas measured at the wellhead will usually be very close to that of the waste mass temperature.

TABLE 9.1 - Typical Temperature Ranges for Bacteria

	Range		Optimum	
Type	**Deg C.**	**Deg. F.**	**Deg C.**	**Deg F.**
Psychrophilic	-10 to 30	14 to 86	12 to 18	54 to 64
Mesophilic	20 to 50	68 to 122	25 to 40	77 to 104
Thermophilic	35 to 75	95 to 167	55 to 65	131 to 149

Data Source: Waste Water Engineering - Metcalf and Eddy; 3rd Ed.

Excessive localized overpull (drawing in air) encourages aerobic activity in the well's vicinity and will tend to increase the operating temperature of the well. When LFG temperature is elevated above about 60 Deg. C. (140 Deg F.), it could be an indication that aerobic conditions may be present and that the LFG flow should be reduced. This can be confirmed by evaluating the composition of the LFG. This is discussed later in this chapter.

Pipe Material Temperature Limits

Operating extraction wells at excessively high temperatures (greater than 63 Deg C. or 145 Deg F.) may weaken and ultimately cause collapse of thermoplastic well casings. The temperature limit for PVC is 74 deg. C (165 deg. F).

Wellhead Vacuum— Wellhead vacuum is a parameter that is often necessary to accurately calculate and determine flow. This technique relies on the relationship of well pressure/vacuum to flow for a given well. This relationship will be different for each well and will change with time. The technician may adjust the well judgmentally based directly upon the vacuum reading or may extrapolate flow from the vacuum. There is a square root relationship between pressure and flow. However, it is awkward to apply in practice. This technique of adjusting by pressure/vacuum can be used when flow measurement options are not available or for hasty balancing, but should not be relied upon for regular wellfield operation. The approach is imprecise, misleading and confusing. This is because the square root relationship between flow and pressure can be difficult to relate to while performing day-to-day wellfield adjustment. As conditions at the wellhead change, this method shows itself to be inadequate except for a hasty and cursory balancing effort. However, some have relied on this technique and found it satisfactory for their purposes.

Gas Composition—This technique uses gas composition as a basis for judgment about well adjustment. LFG composition parameters (methane, nitrogen (balance gas), oxygen and carbon dioxide) are measured at well heads using portable field instruments and sometimes analytical laboratory equipment. Methane, oxygen and nitrogen are the key parameters. It is usually necessary to measure carbon dioxide in order to determine nitrogen (balance gas). It is recommended that all gas composition parameters be checked whenever possible as this provides a check on the validity of all. It is also desirable to check carbon monoxide periodically, and when wellhead LFG temperature exceed 57°C (135°F) as an indicator of the possible presence of subsurface landfill fire.

Flow Rate—Methane flow rate is considered a key parameter for well adjustment. Wells are adjusted to a target flow rate determined empirically (i.e., by field trial and experience). Methane flow is calculated by multiplying the fraction of methane times the LFG flow in scfm. Flow is adjusted and determined based upon the other parameters. The target flow rate is validated when all other key parameters are within appropriate guide ranges. The well is often adjusted until the amount of methane or heat energy (BTUs) recovered is optimized for the long term to achieve smooth, steady state operation. How aggressively methane is recovered will depend upon the system objectives. Not all systems need to be optimized, however this generally is a good management practice. Adjusting the well to a target methane flow rate is a more meaningful and precise technique for determining and adjusting gas flow at individual wells.

Flow (of LFG and methane) in the wellfield is normally measured and recorded in volumetric terms actual or standard cubic feet per minute (ACFM or SCFM) as opposed to mass flow or heat rate (BTUs). Flow through the blower is also expressed in volumetric terms (SCFM). Flow at the flare is expressed as flow or heat energy (MMBTUs) to the flare. It is important to distinguish between the flow of LFG and the flow of methane. For purposes of well adjustment, it is the volume of methane collected that matters.

EXAMPLE 9.1 - Calculate Flow Rate from Velocity Measurement

Calculate the volumetric flow rate in cubic feet per minute ($ft.^3/min.$) from a well with a measured linear gas velocity of 1,000 ft./min. The velocity was measured in a 2" Schedule 80 PVC pipe.

$$Q = VA$$

where:

Q = Volumetric Flow Rate (ft^3/min)
V = Velocity (ft/min)
A = Cross-Sectional Area of Pipe (ft^2)

$$A = \frac{\pi\, d^2}{4} \times \frac{1ft^2}{144in^2}$$

where:

d = Inner Pipe Diameter (in.)
π = 3.14

$$Q = 1{,}000\ ft/min \times \pi \frac{(0.162ft)^2}{4} = 20.6\ ft^3/min$$

Flow at the wellhead is typically measured using a flow element and a pressure gauge or separate or integrated portable instrument. Examples of flow elements include orifice plates, and pitot tubes. Portable instruments used for flow measurement include the portable velometer or anemometer.

Mass flow rate is calculated by multiplying the unit mass of the substance (e.g. CH_4) by the flow rate. Mass flow may be cited in pounds of gas per hour (gas flow mass is not the normal unit used). It is important to realize that it is possible for the total volume of LFG extracted to increase while the total quantity of methane extracted decreases and vice-versa.

Heating Value—The heat value of the gas is another parameter of interest when considering the performance of fired combustion equipment such as a LFG flare, boiler or engines. While working in the wellfield or with the blower we think in terms of cfm of LFG and methane, with respect to the flare or and energy recovery device we tend to think in terms of heat flow rate in MMBTU's (millions of British Thermal Units, a standard measurement unit of heat energy). The following formula is used to calculate the heat flow rate. Since most all of the heat value in LFG is derived from methane, volumetric flow of methane and heating value are really two ways of saying the same thing.

EXAMPLE 9.2 - Calculating Heat Flow Rate

$$\text{Heat Flow Rate (in MMBTUs per hour)} = (\text{cfm LFG}) \times (\text{higher heat value per cu ft}) \times \left(\frac{(\text{percent methane})}{100}\right) \times 1012\ \text{BTUs/cf} \times \left(\frac{60\ \text{min/hour}}{10E+6}\right)$$

Heat rate is expressed two ways, in terms of higher heat value (HHV) and in terms of lower heat value (LHV). Heat energy in a laboratory analyses and the heat rate of LFG delivered to a flare is typically expressed in HHV. However, for engines that may operate on LFG heat rate is expressed in terms of LHV because this is the only portion of the heat energy that the engines can use. There are approximately 1012 BTUs per standard cubic foot (scf) of methane at the HHV and approximately 916 BTUs per scf of methane at the LHV. Hence, the usable energy available from the methane in LFG is about 90 percent of the HHV.

9.3.3 Wellfield Adjustment - Criteria

There are many criteria used in wellfield adjustment. The emphasis placed on various criteria will vary at each landfill site and individual extraction well along with varying control or recovery objectives. The primary criteria is methane quality. Methane quality at the wellhead is an indicator of the general anaerobic state of the landfill and the air intrusion impact on this condition, and thus operation of the LFG collection system. However, a decline in the as generated high quality state of the landfill is usually not immediately apparent from methane quality. This may depend on how well isolated the affected zone is from the external atmosphere. For this reason the wellfield is best controlled based on the flow rate of methane extracted from the landfill. Because of this we must consider numerous criteria.

The following criteria for wellfield adjustment should be considered:

- Objectives of the LFG control and collection system
- Methane concentration (ranging from 40 percent upwards)
- The degree to which conditions within the landfill favor methane production. Typical conditions include: pH, temperature, general cover/cap quality and condition, moisture conditions, waste stream characteristics, placement chronology, insulation characteristics, etc.
- Oxygen concentration (ranging below 1 percent, preferably less then ½ percent). Note: O_2 concentration may be higher if for emission control.
- Landfill cover porosity and depth in the proximity of the well
- Gas well construction factors including slotting depth and configuration, seal placement, and backfill material and compaction.
- Landfill construction factors including type of fill, size and shape of waste mass, depth of fill, compaction, leachate control methods
- Seasonal, climatic, geographical, or other considerations, including seasonally arid or wet conditions, precipitation, drainage, ground water elevations, etc.
- Surrounding topologic and geologic conditions
- Proximity of the well to side slopes (within 150 to 200 ft and less may require conservative operation of the well)
- Nitrogen concentration (typically 8 to 12 percent and less)
- Temperature (between ambient and about 135 degrees F). Note: Same as NSPS.
- LFG and methane flow from the wellhead
- The design criteria for the gas collection system
- Landfill perimeter gas migration and surface emission control, or energy recovery objectives
- Fluctuation in atmospheric (barometric) pressure.

9.3.4 Radius of Influence

The concept of radius of influence has been developed to aid in extraction well design and operation. This concept was originally derived from groundwater well drawdown theory. One definition of the radius of influence of a LFG extraction well can be defined as the distance from the well at which the pressure has been reduced by extraction without pulling excessive quantities of air into the landfill. In other words, the distance from which the well is collecting gas. The actual areal zone (3-dimensional) of influence of a well will be irregular in shape. The actual zone or prism influenced is not a cylinder at all. The areal area affected will be determined by LFG flow, refuse and cover soil permeabilities, locations of perched liquids, landfill cover and many other factors (for a list of factors, see 9.3.3 Well Adjustment Criteria). The radius of influence concept should only be used as a rough estimate of the area of collection of an extraction well.

9.4 WELL ADJUSTMENT PROCEDURES

There are numerous methods used to determine how to adjust the flow of a LFG extraction well. All of the methods assume that the objective is to manage the flow of LFG within safe operating parameters. While this may not always be true, most landfills require setting and controlling either LFG or methane flow either for energy recovery or migration or emission control. The control parameters (e.g., methane, oxygen, temperature, etc.) ,most emphasize during well adjustment , will depend on the site specific control or energy recovery and use requirements. An example is shown in Table 9.2 below.

TABLE 9.2 - Control Parameters Based on Control Objectives

Control Objective	Control Parameters
Energy use	Control by delivered Btus and well head temperature
Migration and emissions	Control by methane, and O_2 and well head temperature

The most common methods used for determining flow adjustments are based on methane flow. Alternative methods include using oxygen concentration (usually approximated by the concept of residual nitrogen), methane to carbon dioxide ratio, or "compost" indices to determine adjustment. The method to use will be based on landfill or well specific management criteria.

LFG is generated at about 55% to 60% CH_4 and as extracted its composition is generally 50% to 60% methane, and 35% to 40% CO_2. As the well flow is increased, eventually the extraction rate equals the landfill's generation rate within the area of influence of the well. This is the maximum rate at which LFG can be collected without pulling excessive amounts of air into the landfill. (Note: Since the landfill is not perfectly sealed, some air intrusion will almost always occur even while extracting at less than the generation rate.) Further increases cause excessive air to be drawn into the landfill to make up the difference between extraction and generation. This is represented by Figure 9.2 below. It should be noted that by introducing air into the landfill, anaerobic bacteria are inhibited and future methane generation will be reduced.

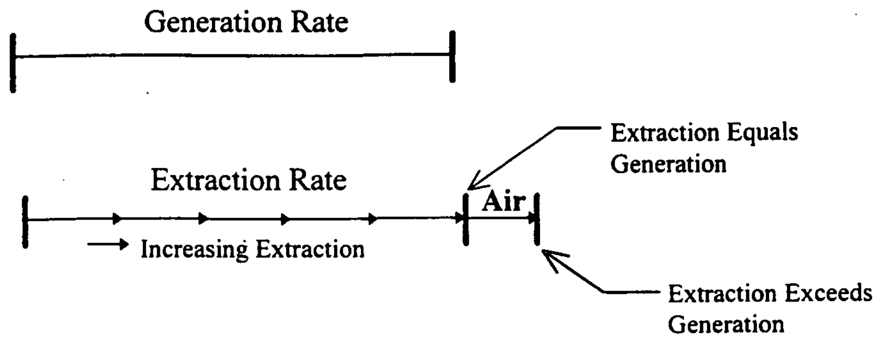


FIGURE 9.2 - Methane Generation vs. Extraction

Because of the non-uniform nature of extraction influence and the need to pull some air into the refuse to control surface emission, it is necessary to allow an amount of air to enter the landfill in order to collect as much LFG as needed to meet management objectives.

9.4.1 Methane Targeting - Flow Correlation

Because methane is the single most important environmental and energy relevant parameters, methane targeting is usually the preferred method of making well adjustments. The objective of this procedure is to adjust the LFG extraction rate so that the methane content of the extracted gas is equal to a predetermined target value. The procedure uses the actual well flow, methane concentration and the target methane concentration as the basis for the well adjustments.

Methane target values are generally as shown in Table 9.3 - Methane Target Values.

TABLE 9.3 - Example Methane Target Values

Target	Application
50-55%	Interior gas wells used for energy recovery
45-50%	Interior gas wells where environmental control is important.
40-45%	Aggressively trying to control LFG migration
30-40%	Interior gas wells where acute LFG emission problems are occurring (There may be an increased risk of landfill fires at some sites when operating in this range.)
>30% and less	Perimeter gas wells outside of refuse

From Figure 9.3 you can see that as air is pulled into the landfill, the methane concentration is reduced. The methane target method assumes that a constant flow of methane is available (worst case scenario) and that any increase in flow will be attributed to increased flow of air. The first step in the calculation is to calculate the measured methane flow. A calculation is then made for the new LFG flow assuming that the methane flow remains constant.

First, the methane flow is calculated

$$\text{Measured } CH_4 \text{ Flow} = \text{Measured LFG Flow} \times \text{Measured } CH_4 \qquad (1)$$

Next, the new flow is calculated based on the target methane concentration.

$$\text{New LFG Flow} = \frac{\text{Measured } CH_4 \text{ Flow}}{CH_4\,\%\ \text{Target}} \qquad (2)$$

Therefore, the new LFG flow is simply the measured flow times the ratio of the measured methane concentration to the target methane concentration.

EXAMPLE 9.3 - Methane/Flow Targeting

The measured LFG flow and methane concentration are 12 ACFM and 53%. If the target methane concentration is 45%, what is the new LFG flow?

Procedure

$$\text{New LFG Flow} = 12\ \text{ACFM} \times \left(\frac{53\%}{45\%}\right) = 14\ \text{ACFM}$$

It should be noted that this method is conservative and probably not able to reach the target methane flow in a single adjustment step. As the flow is increased, the well radius of influence will increase, hence, additional LFG and some air will be pulled into the well, whereas, the calculation assumes all increase is air. This procedure will need to be repeated several times before the target concentration is reached.

Depending on the rate of air infiltration, it may take weeks before the air reaches the well. If the above procedure were repeated every day during this period, by the time the air reached the well, the final steady state methane concentration might be well below the target value. Therefore, it is recommended that the flow adjustment be made in small increments and the well field be given time to respond to the adjustment. A good rule of thumb is to limit flow increases to 20% and flow decreases to 30% and to make adjustments a minimum one week apart.

A simplified approach to the above procedure is to use a 10% guideline for well flow changes. For example, if the target methane range is between 40 and 45% and actual methane is 48%, increase the well flow 10%. (The calculated flow increase would only be about 7%, but this approach would eliminate doing calculations in the field.)

9.4.2 Methane Target - Pressure Correlation

Methane targeting can also be used while measuring well vacuum. This procedure is more hit and miss than using flow as the adjustment criteria, but it can be successful if adjustment steps are kept small. This procedure should only be used if flow measuring devices are not available. The procedure is similar to methane target with flow correlation except that pressure is substituted for flow as the control variable. The equation for this is:

$$\text{New LFG Vacuum} = \text{Measured Well Vacuum} \times \left(\frac{CH_4\%\ \text{Measured}}{CH_4\%\ \text{Target}}\right)$$

This correlation would be valid if flow was proportional to the vacuum. Unfortunately, in landfills this is not usually true.

EXAMPLE 9.4 - Methane/Pressure Targeting

The measured well vacuum and methane concentration are 3 inches w.c. and 56% methane. The target methane concentration is 45%. What is the new vacuum?

Procedure

$$\text{New Vacuum} = \text{Measured Vacuum}\left(\frac{CH_4\%\ \text{Measured}}{CH_4\%\ \text{Target}}\right)$$

$$= 3\ \text{inches w.c.} \times \frac{56\%}{45\%}$$

$$= 3\ \text{inches w.c.} \times 1.22 \quad \text{Limiting the increase to 20\%}$$

Therefore:

$$\text{New Vacuum} = 3\ \text{inches w.c.} \times 1.2 = 3.6\ \text{inches w.c.}$$

The limits for increasing and decreasing flow for using flow correlation hold true for pressure correlation also. That is, increases should be limited to 20% and decreases to 30%.

9.4.3 Residual Nitrogen Target - Flow Correlation

Residual nitrogen targeting is usually used to balance perimeter gas wells where gas migration control is essential. As air is drawn into a landfill the oxygen is consumed along with methane by aerobic bacteria to form water and carbon dioxide. The nitrogen portion of air (~ 80% of air) that remains following removal of the oxygen by bacteria is called residual nitrogen. Residual nitrogen, therefore, is a measure of aerobic decomposition in the landfill and is typically the best indicator of air infiltration.

High Residual Nitrogen Levels May Indicate A Landfill Fire

High levels of residual nitrogen should be viewed with caution as an early indicator of conditions that can lead to landfill fires. (See Chapter 14, Landfill Fires.)

Air entering a landfill gas collection system that is not subject to aerobic consumption by bacteria is not of concern for refuse fires. If oxygen is not being consumed, it is likely that this air, commonly called leakage, is a result of short circuiting into the upper well casing or collection pipe. This air is unlikely to cause landfill problems, although it can cause other problems elsewhere in the system. For instance, if oxygen is sufficiently high (around 10% or greater), the LFG can be in the combustible range within the collection piping. Further, high air leakage can cause flare or combustion performance problems. The residual nitrogen concept differentiates between the nitrogen associated with air leakage (in a ratio of 3.76:1) and the nitrogen associated with aerobic activity (or residual nitrogen).

The procedure for calculating residual nitrogen requires knowledge of the methane, carbon dioxide, oxygen and water concentrations. Residual nitrogen (RN_2) may be estimated by assuming that residual nitrogen is the balance of gas remaining after subtracting the concentrations of air, methane, carbon dioxide and water. RN_2 is calculated by subtracting the concentration of all measured gases from 100 as follows:

$$RN_2 = 100 - CH_4\% - CO_2\% - H_2O\% - 4.76 \times O_2\%$$

The 4.76 constant is used to remove the amount of nitrogen associated with the oxygen which can be assumed to be leakage and not infiltration.

Once the residual nitrogen in the gas is known, the procedure for well adjustments is similar to methane targeting.

$$\text{New Flow} = \text{Old Flow} \times \left(\frac{(100 - RN_2\%\text{Actual})}{(100 - RN_2\%\text{ Target})} \right)$$

EXAMPLE 9.5 - Residual Nitrogen/Flow Targeting

Calculate the residual nitrogen and the recommended new gas flow for a well with the following operating conditions. Target RN_2 is 20%.

Ambient Temperature	75°F
CH_4	28%
CO_2	20%
O_2	3%
H_2O	3% (by calculation, see Appendix A.5)
Flow	90 ACFM

Procedure

$$RN_2 = 100 - CH_4\% - CO_2\% - H_2O\% - 4.76\ O_2\%$$

$$RN_2 = 100 - 28 - 20 - 3 - 3 \times 4.76 = 35\%$$

$$\text{New Flow} = \text{Old Flow} \times \left(\frac{(100 - 35)}{(100 - 20)}\right)$$

$$\text{New Flow} = 90 \times 0.81 = 73 \text{ ACFM}$$

9.4.4 Residual Nitrogen

Methane is an obvious indicator of anaerobic activity, but it is not the only indicator that should be examined. Nitrogen is also a key indicator of the anaerobic state of the landfill. The lower the nitrogen level in the LFG, the greater the indication of a fully anaerobic condition within the waste mass. As air is introduced into the landfill, the oxygen is converted to carbon dioxide and a nitrogen residual remains in the landfill.

While nitrogen cannot always be directly measured with the usual field portable instruments, it can usually be assumed as the balance after subtracting CH_4, CO_2, O_2 and H_2O. H_2O is also generally not measured directly, but looked up in tables based on assumed saturated conditions and temperature of the gas and ambient air. Other trace gases are usually ignored.

Interpretation of nitrogen residual is shown in Table 9.4 - Interpretation of Residual Nitrogen. Operating at levels which indicate overstressing of the landfill may lead to introducing or aggravating subsurface fires. In these instances, the well flow should usually be drastically reduced or shut off. Note that opinions vary as to how much nitrogen or residual nitrogen is "OK" or "too much."

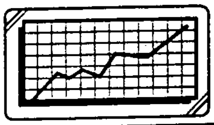
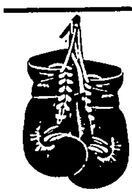


TABLE 9.4 - Interpretation of Nitrogen Residual in LFG

Residual Nitrogen %	Interpretation
0 to 6	Normal to understressed; typical for high BTU facility where low nitrogen is desirable
6 to 12	Normal desirable operating range without compromises for problem landfills
16 to 20	Excessive nitrogen, may be necessary for aggressive perimeter migration control, side slope emission control, or where other compromise is required.
Greater than 20 percent	Over-stressed, this level of nitrogen to be avoided if at all possible except for aggressive emission control.

Note that the residual nitrogen concentration shown in Table 9.3 does not allow for the nitrogen that may be contributed from piping air leaks.

A similar technique, though less direct and less useful is to use "carbon dioxide to methane ratios." The landfill operator will find that the direct observation of nitrogen is usually more appropriate and meaningful.



Carbon Dioxide Concentrations Are Used As A Check On Other Gas Constituents And To Determine Residual Nitrogen

Carbon dioxide is usually considered the floating variable in the LFG mixture and does not directly reflect the condition of the landfill. There is some evidence that the ratio of carbon dioxide to other gases may reflect the condition of the landfill, however, for operations purposes this should be neglected.

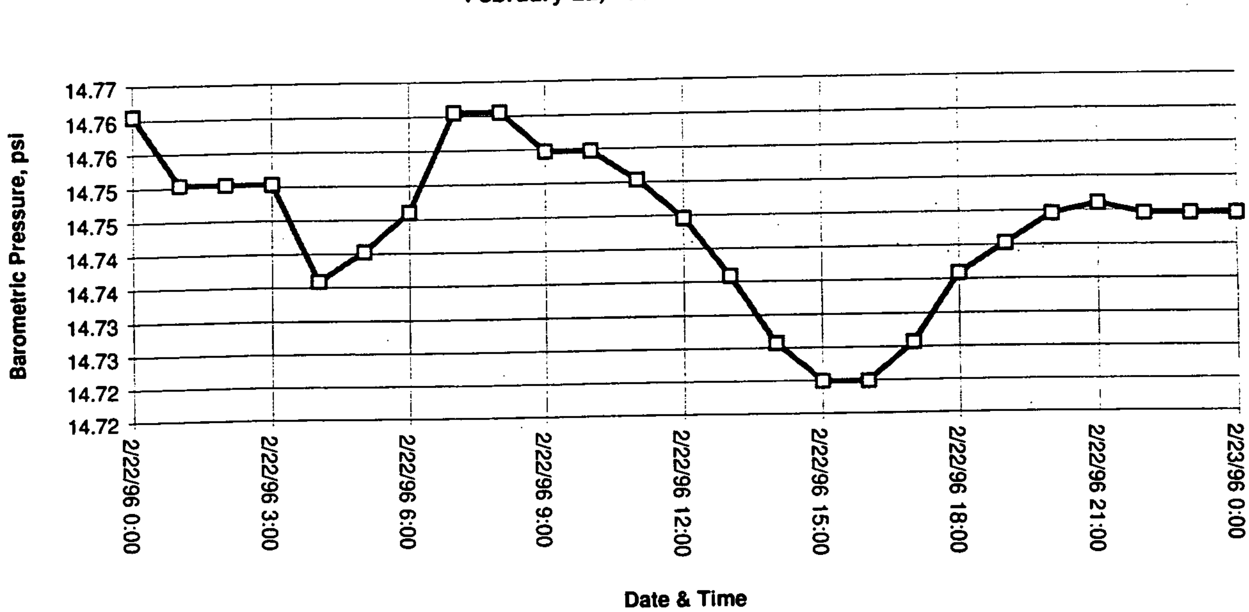
Residual nitrogen (discounting any sample or piping air leakage which may occur) provides a direct indication of air intrusion and the anaerobic state of the waste mass. Oxygen is not as direct and reliable an indicator, because, initially oxygen is converted aerobically to carbon dioxide in the surface layers of the landfill. Beyond the capacity of the surface soil for this conversion, oxygen will breakthrough and appear in LFG. When this occurs, it is an obvious indication of overpull and excessive air intrusion.

In evaluating residual nitrogen, allowances must be made if there has been any air leakage into the gas collection system or if there has been serious air intrusion. If enough air is drawn into the landfill, not all oxygen is converted into carbon dioxide and thus the oxygen is apparent in the sample. With careful analysis, one can usually deduce the approximate amount of oxygen contributed through air intrusion and what amount is due to air leakage in the piping. It is ideal to perform routine analysis of individual wells, as well as an overall wellfield composite sample by gas chromatography (GC). This can verify portable instrument calibration and help to prevent problems resulting from misconceptions caused by inaccurate data. A recommended frequency is monthly for most sites with active LFG control systems. A minimum frequency for GC analysis is quarterly.

9.5 Atmospheric Pressure Effects

One of the most important topics in understanding the behavior of LFG and LFG system operation is atmospheric pressure. An understanding of how fluctuation of atmospheric pressure affects LFG migration, collection and control is essential to perform these tasks. The fluctuation of atmospheric or barometric pressure is often diurnal. This means that the pressure of the atmosphere rises and falls generally on a daily cycle. The pattern of atmospheric pressure fluctuation typically shows a gradual rising in the early morning followed by a reversal and decline around noon to early afternoon followed by a continued gradual decline to a flattening out in the evening to early morning hours where the pressure again begins to rise. Figure 9.3 shows this typical pattern. Different regions may experience different atmospheric pressure patterns. Local weather effects (the movement of high and low pressure fronts) also play a role in atmospheric pressure.

February 22, 1996



Source: National Weather Service, Laguardia Airport, New York, NY

Figure 9.3
Time vs. Barometric Pressure

The diurnal pattern of rising and falling atmospheric pressure affects the venting of LFG from landfills and the natural intrusion of air into landfills. Most landfills under anaerobic conditions, without extraction of LFG, will build up a positive pressure. This pressure is one of the primary mechanisms causing LFG to vent and migrate from the landfill.

Atmospheric Pressure Effects and LFG Migration

During periods when atmospheric pressure exceeds landfill pressure, air is driven into the landfill. The most common time for this activity is early to late morning hours while barometric pressure is increased. This condition is indicated by negative landfill probe gage pressures.

Conversely, during periods when landfill pressure exceeds atmospheric pressure, LFG is driven out of the landfill. Therefore, for migration monitoring to be most meaningful, it should normally be performed in the early to mid-afternoon in correlation with falling atmospheric pressure. Atmospheric pressure should be monitored with other perimeter monitoring probe and wellfield data for a complete picture of LFG behavior. The pressure may differ from site to site and from day to day. As a result, migration monitoring should be done at various times so as not to systematically miss a possible migration event.

If atmospheric pressure is charted at hourly intervals the conditions described above can be seen as illustrated in Figure 9.2.

Although operation of a LFG control system effects landfill pressure, the principal of differential pressure between landfill and atmosphere, and the resulting direction of gas flow still holds true.

EXAMPLE 9.6 - Effects of Atmospheric Pressure

To illustrate the effects of barometric pressure, consider the following actual situation:

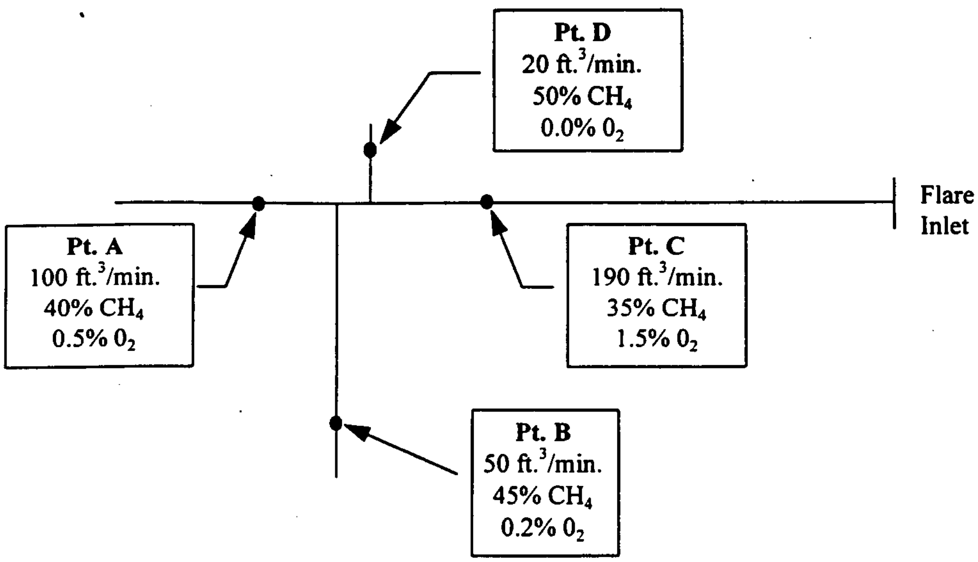
Landfill monitoring probes had been monitored first thing in the morning on a monthly basis for almost one year with non-detect methane readings. Monitoring was performed one afternoon and the result showed that the methane concentration in the probes was >30% (vol.). Monitoring was repeated the following morning and again monitoring pressure in the probes every thirty minutes. The recorded data showed that the methane concentration in the probes jumped rapidly as the barometric pressure started to decrease forcing gas to the probes.

9.5.1 Gas Concentration and Performing System Pressure Profiling

An important operational and troubleshooting technique that can be performed is gas concentration and pressure profiling of the header pipe. A pipe profile consists of collecting gas concentration pressure and flow at regular intervals along the pipe. Profiles can be compared with baseline profiles to identify problems due to air leaks and condensate blockages along the header piping.

EXAMPLE 9.7 - Determine Location of Air Leak in Collection Piping

After noting an increase in the oxygen concentration at the inlet to the flare station, the LFG technician collects the following data from sample ports along the collection header pipe.



Check using flow rate

Flow at Pt. C should equal the sum of the flows from all the pipes entering that point.

$$Q_C = Q_A + Q_B + Q_D$$
$$= 100 + 50 + 20$$
$$= 170 \text{ ft.}^3\text{/min.} < 190 \text{ ft.}^3\text{/min. measured}$$

Indicates a leak upstream of Pt. C, however velocity measurements are subject to error. Double check using O_2.

Flow of oxygen at Pt. C should equal the sum of the oxygen flows from all the pipes entering that point.

$$C_C Q_C = C_A Q_A + C_B Q_B + C_D Q_D$$
$$C_C = \frac{C_A Q_A + C_B Q_B + C_D Q_D}{Q_C}$$

$$= \frac{\left(100\ \text{ft.}^3/\text{min.}\ \times\ 0.05\right)+\left(50\ \text{ft.}^3/\text{min.}\ \times\ 0.002\right)+\left(20\ \text{ft.}^3/\text{min.}\ \times\ 0.0\right)}{190\text{ft.}^3}$$

$$= 0.3\%\ O_2 << 1.5\%\ O_2\ \text{measured}$$

Suspected leak is upstream of Pt. C and downstream of remaining points. If the collection pipe has isolation valves, the location of the leak can be further isolated by closing off valves.

Profiling using pressure in the system is sometimes easier than gas concentration profiling. If a significant pressure drop is noted between two points, that piping segment should be investigated for a problem. Potential problems could include liquid condensate blockage and piping air leakage causing vacuum loss.

9.5.2 Detecting and Repairing Air Leaks

Air leaks occur as a result of aging of the system, and damage or breakage due to settlement, piping expansion and contraction, components or access ports left open or uncovered, shock or fire. Air leaks can be detected by comparing oxygen readings taken at the wellhead with readings taken at access points throughout the piping system and at the blower flare station looking for increases in oxygen content as described in the previous example. Excessive vacuum loss may also be another indicator of large air leaks. The "sucking" sound of a vacuum leak or the "hissing" of gas pressure that has built up when the system is down can also often be heard on both above and below ground systems.

Air leaks are best repaired by replacing the damaged piping, fittings or joints. Small leaks and other minor repairs may sometimes be made using a silicone based caulking compound. Experience has shown that in situations where air leaks are ubiquitous due to the age or state of repair of the piping system, replacement of piping can be the most cost effective and practical approach.

On vertical well casings excessive oxygen may indicate the failure of a near surface coupling allowing air leakage as a result of short circuiting to the atmosphere.

A technique known as "bracketing" is used to most efficiently locate and identify a subsurface problem such as a leak where the location is unknown. This is discussed under collection system maintenance.

Don't Settle For Unexplained Problems

Good operators are creative in their investigations and troubleshooting abilities. They want to know why problems occur. The following actual example is given to emphasize this.

A landfill gas recovery system was experiencing shutdowns in the middle of the night. When the system was restarted the next morning, everything would check out O.K. This process was repeated for about a week until the problem was found. During the cold of the night, the PVC LFG pipe header would contract causing a coupling to pull apart. By the next morning, the air temperature would increase sufficiently so that the pipe would be pushed back into the coupling. Repairing the coupling was all that was needed to fix the problem.

9.5.3 Wellfield Adjustment for System Start-up

There are a number of methods to determine well settings at start-up. To determine the starting well flow rate use Method 1: the average flow rate per well or Method 2: proportion the flow based upon the predicted amount of LFG and methane levels at the well. Interior wells (deep landfill areas) should get more flow, perimeter wells less. Large horizontal trench wells will often produce more than vertical wells. Well with positive pressure can be initially set to equilibrate at zero gage pressure. If lacking other guidance or if unable to measure flow, set each valve to 5 to 25 percent (range of travel) open. Throttle overall flow at the blower-flare facility inlet. Read and adjust the wells as soon as possible following start-up and readjust by proportioning the flows based upon target versus actual methane values. Perform this procedure at least 3 times over the first 10 days. Regulate the overall LFG extraction flow rate by adjusting the blower-flare facility inlet throttling valve. These methods can also be used to rebalance a wellfield that is severely out of balance.

9.5.4 Poor Methane Quality - Emissions and Migration Control

As the MSW ages, methane generation, and hence deliverability will decline. Landfills located in arid environments may naturally have low methane generation rates. This can present problems in equipment operation. It may be necessary to operate extraction wells that yield poor quality gas. If methane and oxygen quality objectives cannot be maintained at a well (i.e., methane gas quality at a well is less than normal values before the well has been turned on), the best you can do is stabilize the well as closely as is practical, avoiding significant or rapid down trending of methane or up trending of oxygen.

It is not uncommon for perimeter migration control wells located outside the limits of the MSW mass to be operated at less than 40 percent methane or greater than 1 percent oxygen. These wells are likely in a zone where some aerobic action is being induced, and that there is some risk of introducing or enhancing the spread of a subsurface fire. Sometimes a reduction of methane quality objectives is necessary in perimeter wells. These wells should be monitored more frequently than high methane quality wells to verify that air is not being pulled through the refuse.

9.6 Operating for Surface Emissions Control

By regularly and systematically monitoring the surface of the landfill, surface emissions and relative operating efficiency can be monitored. Surface emissions monitoring data can be used along with other well adjustment parameters for surface emissions control. Surface emissions control requirements such as the NSPS may require more aggressive LFG extraction.

It is unusual to have a methane concentration of 500 ppm or greater at the surface of a landfill. At this level, LFG related odor should be noticeable. Any instantaneous reading above 100 to 200 ppm and integrated bag sample above 50 to 100 ppm should be cause for action. If surface emissions are a problem, cover should be improved or the extraction well flow rate should be increased.

LFG emissions are controlled by a combination of cover sealing and managed extraction.

9.7 Operating for Ground Water Protection

Recent work points to LFG as a contributor to VOC concentration in ground water. Protection of groundwater from LFG originated VOC contamination can be accomplished by several methods. These methods consist of removing VOC mass from the unsaturated zone, reducing the rate of migration of LFG outside the landfill boundary, or stripping VOC emissions at the source.

Most LFG collection systems have been designed to prevent migration caused by convective forces. As the role of LFG control in ground water protection becomes more recognized, LFG collection systems will increasingly be designed to also contain migration due to diffusive forces. Increasing the efficiency of current landfill gas collection practices will also be important.

9.8 Operating for Energy Recovery

The focus of LFG system operation for energy recovery purposes is to maximize BTU flow rate while accomodating emission goals. If extraction is too aggressive, the total available methane and heat value will decline and may remain depressed for some time. For these reasons it is desirable to control the wellfield conservatively, keep the methane concentration high (i.e., close to 50 to 55 percent and greater), and limit air intrusion to only that absolutely necessary.

Where high BTU cleanup of the LFG is conducted, nitrogen content of the gas must be strictly limited. Most processes rely on removal of carbon dioxide to upgrade the gas to a high BTU level, however, nitrogen cannot easily be removed. In this case, energy recovery and emission control systems may need to be designed separately.

Whenever the system is not operating (due to shutdown, etc.) some LFG escapes from the landfill and can never be recovered. The amount of energy that would have been recovered and hence the dollar value can be quantified. Shutdowns can also lead to severe odor releases. During shutdowns gas should be bypassed to a control device. This places a responsibility on operating staff to minimize downtime due to scheduled and unscheduled shutdowns. Required shutdown time should be consolidated and unnecessary shutdowns minimized. This can be enhanced by good planning and a proactive maintenance program.

9.9 Combined Control and Recovery

Combined control and recovery is difficult because the LFG operator must work with several objectives and these may be at cross-purposes to each other, requiring judgment and compromise to achieve acceptable results.

Common requirements are to recover LFG for energy benefit and to control LFG migration and emissions. In such cases, the common practice is to pull harder along the perimeter to control migration, and to pull easier on the interior taking what gas is available for energy recovery. Each case is site specific and operating objectives and the approach taken must be considered in light of this.

10. THE LFG TREATMENT AND DISPOSAL FACILITY

10.1. DESCRIPTION OF BLOWER-FLARE FACILITY

The main gas collection header connects the landfill wellfield to the blower-flare facility. The blower and controls may be outdoors or housed inside a building or enclosure for weather protection, protection from vandalism, or environmental noise control. Located at or near the blower-flare facility plot limit is usually an inlet block valve. This valve is used to throttle the overall LFG flow from the wellfield. It is also used to isolate the wellfield from the blower-flare facility during maintenance operations. Collected LFG typically passes through a liquid knockout vessel or "scrubber" which removes entrained liquid and particulate from the gas. Gas is then routed to one or more blowers or compressors. These blowers provide the vacuum needed to operate the wellfield and pressure to move the gas (under pressure) to the flare (or energy recovery equipment). LFG is then routed through check valves, an automatic block valve and flame arrester and into the flare. The equipment is operated by electrical controls located in a control panel nearby. The electrical service panel is usually also located in the vicinity.

LFG condensate is collected and stored or treated. Condensate may be collected from traps or sumps in the wellfield and pumped to the blower-flare facility. Additionally, it is common to collect condensate from an inlet knockout or scrubber located upstream of the blower-flare facility, and from the flame arrester. There may be other collection points within the blower-flare facility. Condensate is normally collected in a storage tank for treatment or disposal.

Equipment foundation pads are usually poured concrete. Individual equipment is usually bonded and electrically grounded to a ground network that may include a ground mat or rods and the facility fence system. The following subsections describe the major features of the blower-flare facility components.

10.2. BLOWER-FLARE FACILITY COMPONENTS

The major components of each blower-flare facility typically consists of one or more of the following components:

- Gas process piping and valves
- Inlet scrubber vessel or liquid knockout
- Gas compressor or blower
- Check valve
- Flow metering
- Automatic block valve

- Flame arrester
- Flare
- Instrumentation
- Electrical controls
- Electrical service
- Condensate handling and treatment equipment
- Facility utilities (LPG, air compressor, sewer, etc.).

See Figures 10.1 and 10.2 for typical Process and Instrument Diagrams (P&ID) of a typical blower flare station with both ground and candlestick type flares. Designs, features, and equipment arrangements often vary.

Start-up and control of each flare facility is accomplished by a control panel. The control panel will usually contain a start and stop button or switch, a number of other equipment or mode switches, status or indicator and annunciator lights or panel, and reset buttons. A detailed description of the process, and the start-up and operation of the flare facility should be provided in the site specific facility operation and maintenance manual.

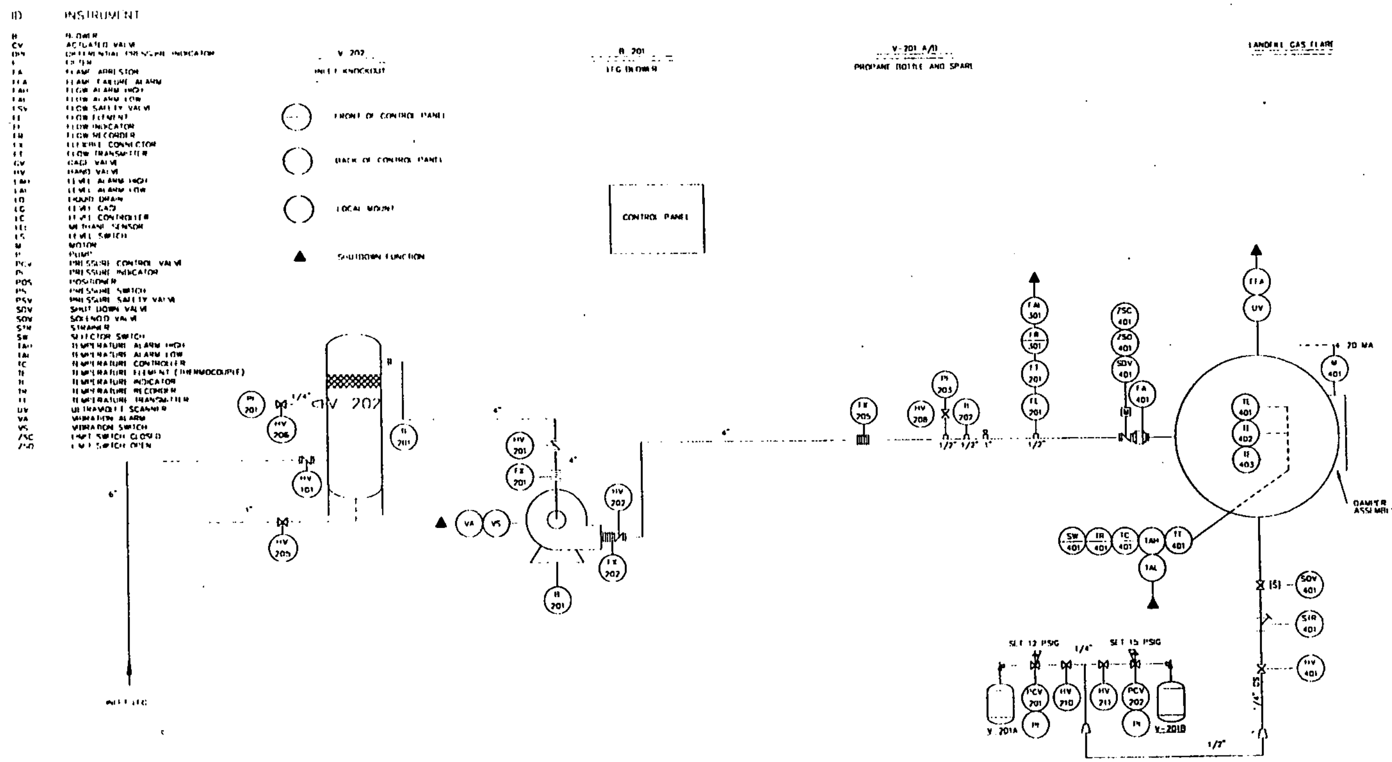


Figure 10.1
Typical P&ID for a Blower/Enclosed Ground Flare Station

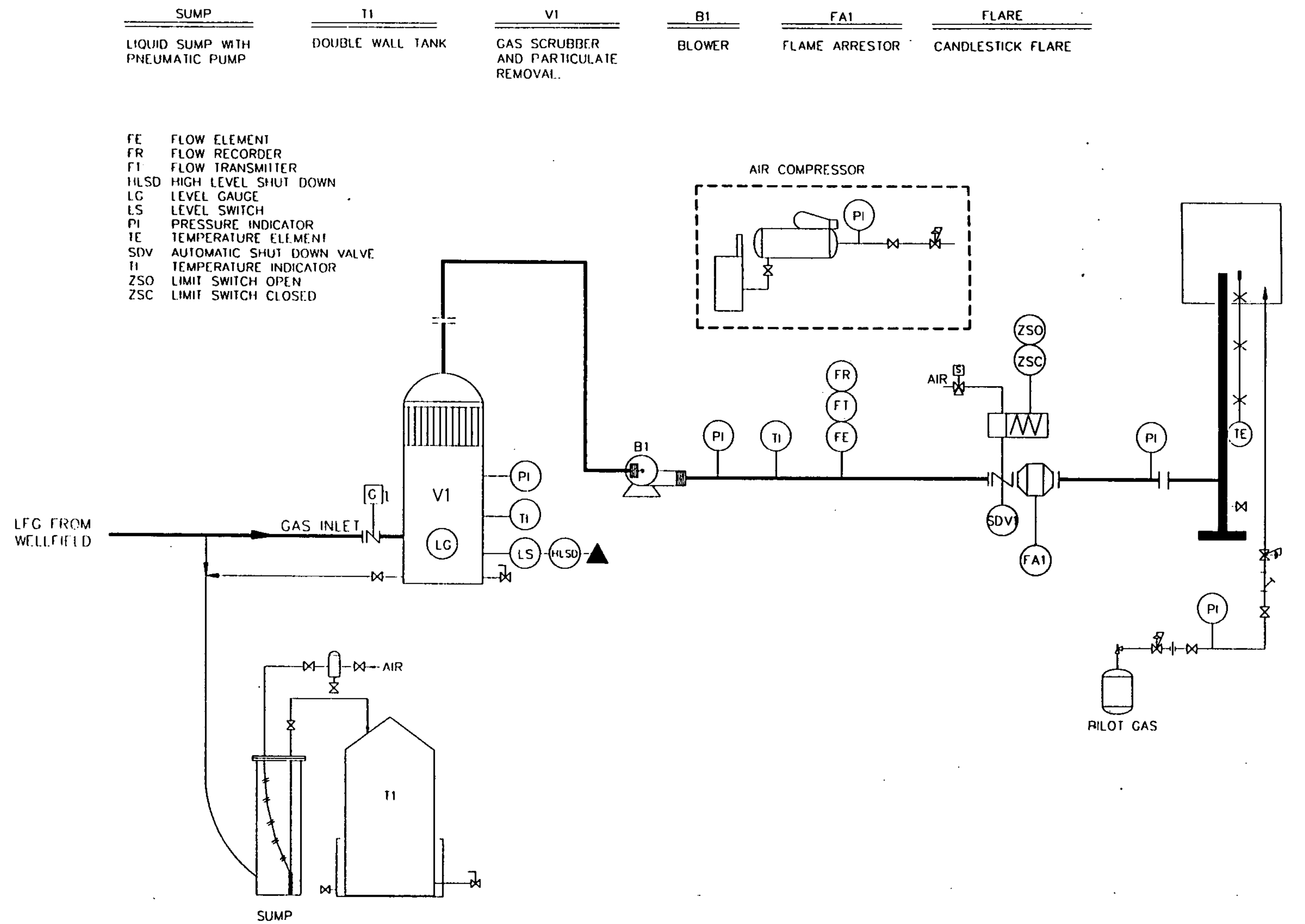


Figure 10.2
Typical P&ID for a Blower/Candlestick Flare Station

If the flare is an enclosed flare, it is commonly operated at a predetermined temperature using a process controller (temperature controller) or programmable logic controller (PLC). Because flare temperature is a primary process control variable, the flare is said to be on temperature control.

An understanding of the blower-flare facility process at each site is essential for proper, safe and effective operation of the gas control system. It is helpful to study the equipment and refer to the mechanical piping plan, instrumentation and control drawings, piping and instrumentation diagram (P&ID), and electrical ladder-logic control diagrams in order to learn and understand the process operation of the facility. Operating staff should thoroughly read and study the manufacturers' literature and be familiar with each subsystem component. Although the operation of each facility is relatively simple and automatic, a thorough understanding of all features and functions is also necessary for both safe operation and the ability to perform process trouble-shooting, should equipment malfunction.

10.2.1. Blower-Flare Process Description

The LFG is transported in the field through the collection piping to the flare facility. Gas condensate, which collects at a low points in the collection piping is drained into traps, sumps or back into the landfill itself.

The gas continues through an inlet block valve into an inlet separator vessel or liquid knockout. Block and bypass valves may be available at some facilities to route gas around the inlet separator. To protect equipment and instrumentation however, it is not advisable to bypass the inlet separator. Normally, for inspection and maintenance of the inlet separator, the flare facility is shut down.

Collected LFG is then transported through piping to the blowers. The blowers compress the LFG providing typically 10 to 100 inches w.c. of total head or pressure. Suction vacuum is typically in the range of 15 to 85 inches w.c. of vacuum depending on the number of wells. 5-15 inches w.c. discharge pressure is typical, depending on the flare burner design and operating flow. The LFG is often routed through some form of flow metering to allow measurement and in many cases recording of the flow rate.

The LFG is then routed to an automatic block valve. These valves are commonly butterfly valves fitted with either a pneumatic, electric, or electro-hydraulic actuator. The valve will often be fitted with a valve position indicator.

The LFG then travels to a flame arrester located immediately upstream of the flare. Test ports are sometimes installed to monitor differential pressure across the flame arrester to check for plugging of the flame arrester element. Many flame arresters have locations for test ports. These must usually be drilled and tapped by the operator. If not already installed, it is a good idea to install a differential gage across these arrester ports. A high temperature sensor or fusible safety shutoff device is sometimes installed downstream of the flame arrester (i.e., before the flare) to act as a shutdown safety switch in the event of a flash back of the flare flame in the pipe.

The LFG then arrives at the flare where it is burned. For enclosed ground flares, the temperature of the combusted LFG is measured in the flare and the temperature is controlled by controlling air flow to the flare. A minimum temperature is maintained and it is recorded.

The LFG flare is typically equipped with a propane or natural gas pilot ignition system and a flame safeguard system. Solar powered igniters are sometimes also used. The flame safeguard system is usually of the ultra-violet or thermocouple type design. The flame safeguard controller insures that pilot and main flame have ignited and that the main flame is maintained. It shuts the flare unit down in the event of a flame failure. Refer to the particular manufacturers literature for complete instructions.

10.2.2. Typical Blower-Flare Start-Up Sequence

Most systems operate with one or two button or switch operation to start the flare ignition sequence. Upon initiating start-up, the pilot solenoid valve opens allowing the pilot fuel (usually propane) to flow. A spark ignitor ignites the pilot. The presence of a pilot flame is verified by the flame safeguard system, the automatic block valve begins to open and the blower starts. The main LFG flame will then ignite. Once ignition occurs and is proven by the flame safeguard controller, (within a specified time-out period), the pilot turns off, control requirements are satisfied and the flare is allowed to run. A common minimum permitted temperature for enclosed ground flares is 760°C. (1400°F). If the flare fails to come up to temperature within the time-out period or fails to "prove" the flame while operating, the flare is shutdown.

10.2.3. Temperature Controls

For enclosed ground flares, the flare operating temperature is the key process control variable to adequately destroy methane and VOCs in the LFG. Flare stack temperature is sensed using a thermocouple which is connected to a temperature controller or PLC. The output from the controller opens and closes air dampers to control the combustion temperature.

The flare dampers are continually adjusted (modulated) based upon the flare temperature sensed by the thermocouple. The flare temperature is controlled by regulating the cooling air which passes through the dampers. This control, in some cases, is handled by PLC. The thermocouple or temperature transmitter signal is fed to the controller which sends an output signal to the combustion air damper motor.

The Conventions For Color Coding Wiring of Thermocouples is Unique

For type "K" thermocouples, the most commonly used type on LFG flares, the yellow wire is positive and the red wire is negative. Thermocouple wiring convention varies by type and country standard.

For the enclosed ground flare, the temperature controller maintains flare temperature as measured at the flare thermocouple at the set point, typically 788 to 843°C (1450 to 1,550°F.). Low temperature shutdown is typically set at 760°C. (1,400°F.). The flare minimum operating temperature may be a condition of the facility operating permit. A typical high temperature shutdown may be set at 927 to 982°C. (1700 to 1800°F.) to protect the flare and thermocouple from excessive thermal stress. The enclosed type flare is equipped with visual sight ports for observation of the pilot and main flame.

Testing access ports are usually provided for flare performance "source" testing. Testing ports are typically located one-half a stack diameter down from the top of the flare and equally spaced at four quadrants. Because of the high temperature service, the ports should be lubricated with a nickel anti-seize compound and insulated from the heat. Some flares incorporate scaffolding or platforms for testing access.

10.2.4. Blower-Flare Facility Gages

Gages are located throughout the blower-flare facility to visually monitor key process parameters. Common pressure, differential pressure and temperature gages and their locations in the blower-flare facility are as follows:

- Inlet vacuum
- Inlet temperature
- Ambient temperature (shaded from direct sunlight)
- Inlet separator differential pressure
- Blower suction pressure
- Blower discharge pressure
- Blower discharge temperature
- Flame arrester differential pressure
- Flare inlet pressure
- Air receiver (instrument) air pressure.

Some pressure gages are subject to severe pressure pulsations that may destroy the gage in short order. In such service, gages should be fitted with pulsation dampers, snubbers, or filled with glycerin.

A direct readout of flare stack temperature is usually provided on the temperature controller or on a separate display. Many chart recorders also have digital displays.

10.2.5. Pilot Gas System

The flare is fitted with a pilot system to provide pilot fuel to the flare for ignition of the main burner. The system will normally use propane (LPG) or natural gas for the pilot fuel. A LFG pilot is not recommended and may not prove reliable. A typical pilot fuel system consists of:

- A fuel source (LPG or natural gas)
- Pressure regulator
- Steel piping to flare
- Solenoid valves
- Air fuel mixer and pilot burner (located inside the flare)
- Spark igniter system.

Pilot fuel pressure to the flare is controlled using a pressure regulator usually at or near the fuel source. Additional regulators may be incorporated in the pilot fuel train. Ignition of pilot fuel gas is achieved using a spark igniter and a high-voltage transformer. The ignition sequence typically lasts about 10 to 20 seconds. The spark igniter or ground rod is connected to the secondary side of a high voltage transformer.

If LPG tanks are used, they should be isolated from any potential sources of ignition. LPG tanks are equipped with pressure relief vents for safety and the location around the relief vent is a classified area (Class 1 Div. 1, Group D, propane) in accordance with NEC 500 as a point source of potential release of propane. As a result, propane tanks should not be stored in control rooms.

10.2.6. Purge Cycle

Enclosed ground flares can accumulate unburned LFG within them if the valves are left open. As a result, prior to ignition, all enclosed flares should undergo a purge cycle. Purging can occur for a period of time (typically 3 to 5 minutes) with the dampers fully open, which allows air to enter the flare and dilute any explosive gases present. A forced draft blower may also be used to force air into the flare.

10.2.7. Pilot system operation

When the pilot is initiated by starting the system, the pilot solenoid valve is opened, and high voltage is sent from the igniter transformer to the spark igniter, creating the pilot ignition spark. The igniter will usually spark for a set period of time such as 10 to 20 seconds before timing out. Some candlestick flares are fitted with an intermittent, recurring igniter. The pilot should stay lit for a minimum time sufficient to initiate and prove the main LFG combustion at the flare. Typically, about 1 minute should be a sufficient time for pilot operation.

10.2.8. Flame Safeguard System

Main flare ignition is verified by a flame safeguard sensor. The sensor is typically either a UV-scanner or a thermocouple. If flame is not detected by the flame safeguard sensor within a specified period of time (usually within one minute of pilot initiation), the flame safe guard unit will indicate a flame failure. Some systems attempt one automatic re-light after re-purging for safety. If the main combustion flame fails to "prove", the flare system shuts down, annunciates and locks out.

10.2.9. Flow Metering

A flow sensing element is best installed after the blowers because there is usually a straight section of pipe between the blower and the flare that can be used for the flow element. They may also be installed before the blowers and after the inlet separator. It is best to meter the LFG after the blower because the gas is drier and under slight pressure rather than vacuum. The most commonly used flow measuring devices are known as differential pressure devices. Examples are the orifice plate, pitot tube, venturi tube, etc. Some of these are known as primary devices because the flow can be measured using a standard mathematical formula without any need to modify the result based on performance testing, curve fitting or other proprietary device specific information. Other devices such as the Annubar™ rely on proprietary information supplied by the manufacturer such as a correction coefficient, chart or flow computer in order to determine the flow. The flow element (if a differential pressure device or primary device), may be read directly using a pressure gage or may be fitted with a differential pressure transmitter which provides a signal for a flow computer or flow readout device. Instantaneous flow is commonly recorded on a continuous recording chart recorder. In the case of primary devices flow can be determined or checked using information and factors taken from engineering handbooks. When using orifice plates it is helpful where possible to use standard incremental bore sizes in 0.125 inch increments rather than custom bores to facilitate quick manual calculation of the flow.

Some other flow measuring devices such as hot wire anemometers generate an electronic signal based on the cooling effect on the filament by the gas flow. These devices are sensitive to both the gas flow rate and gas composition. Devices that rely on the heat capacity of the gas mixture to measure flow can have their calibration and accuracy affected if the gas composition changes, as is often the case with LFG.

10.2.10. *Miscellaneous Control Functions*

The control panel should have several status lights and fault or failure lights that indicate problem conditions and reasons for shutdown. Some facilities will be fitted with an annunciator panel. Some annunciator panels have a first out feature which indicates which fault (of those present on the panel) was the very first to occur. This feature is very helpful when troubleshooting equipment problems and shutdowns.

The main control panel may also contain an ammeter for monitoring blower motor current draw. Some ammeters can also be set to provide low flow (i.e., low amperage) surge protection for centrifugal blowers. When flow is below the minimum the centrifugal blower was designed for, internal "slippage" of the gas results in increased heating in the equipment and can cause damage. This condition is known as "surge" and is actually a condition of intermittent flow reversal (Appendix A.13 covers this in greater detail). A blower should not be operated below its "surge point". Each blower should be fitted with hour meters to monitor total hours of service and allow balancing of time of operation where multiple blowers are installed in a facility.

For facilities equipped with flow metering, some combination of a flow computer, instantaneous and totalized flow digital readout, and a strip chart recorder may be installed in the control panel.

Many facilities have an automatic telephone dialer. Automatic telephone dialers are commonly used to notify operating personnel of facility equipment faults or shutdowns that occur during periods of unattended operation. It is necessary to have a bypass or override of the dialer channel inputs that indicate shutdowns or faults so that the dialer will not dial out when certain equipment is normally down or during testing at the facility. This is usually accomplished by means of a bypass switch. Sometimes timers are used so that the override is temporary in case it is forgotten.

Electrical power for operation of the blower-flare facility is most typically a 3 phase, 480 VAC, service. At some sites 3 phase, 240 VAC service or single phase service is used. Phase converters are sometimes used to convert single phase service to accommodate three phase equipment by artificially creating three phase power. The main electrical service will have a main breaker or a fused disconnect or both and will feed individual circuits for the blowers, utility air compressor, condensate pumps, lighting and other equipment. In larger installations, these may be located in a single motor control center (MCC). In addition, 120 VAC power is supplied by a transformer for the electrical control and instrumentation, and phone auto-dialer system.

Sometimes 120 VAC electrical outlets are mounted outdoors in weatherproof outdoor fixtures. In other cases they are mounted inside control cabinets. 120 volt power receptacles, whether inside the control cabinet or outside, should be fitted with a ground fault current interrupter (GFCI) for safety. In some locations this is a code requirement. In other instances, there may still be a requirement for using a GFCI with portable electrical equipment. Hence, a GFCI will still likely be required in any event. It is best if it is a permanent part of the facility and if not, a retrofit is recommended. A GFCI will detect a current fault to ground and cause almost immediate shut-off of that electrical circuit. This can provide life saving assistance in the case of an individual who is electrocuted from, for example, a faulty hand tool.

10.2.11. Electrical Controls

10.2.11.1. Electrical Controls - General

Most of the information necessary to understand and operate electrical controls for the blower-flare facility are located on the following three electrical control drawings:

1) Electrical (relay ladder) logic diagram

2) Electrical control wiring diagram

3) Electrical service ("one-line") drawing

Additionally, the PLC software program instructions (where used) and the P&ID for the facility are useful to understand the operation. Operating staff should be able to read these drawings. The electrical logic diagram or PLC software program instructions in particular are key to understanding the sequence of operation, control interaction, and the understanding necessary to troubleshoot system faults.

10.2.11.2. Electrical Control Logic

The following is an abbreviated explanation of the conventions of electrical control drawings. If operating staff are unfamiliar with electrical controls, they should seek professional training and assistance in learning, understanding and interpreting electrical controls.

Electrical control ladder drawings, or electrical elementary drawings are drawn in an "H" or "ladder rung" pattern by convention, and are read from the upper left hand corner across, then down. By convention, control power flows from left to right and from top to bottom, or from the control power source ("hot side") to a powered device such as an electric motor then to neutral on the right side. The left hand side of each ladder is the power or "hot" 120 volt side.

Wiring Convention

Conventions have been used for the color of wires to represent different functions, however, not everyone follows the conventions. Hence whenever working with electrical power, use extreme caution.

Power wiring (in the panel) is typically red in color by convention. The right hand side is the common or neutral side. Neutral or "return" wiring is white in color by convention. Ground wiring is green. Low voltage wiring is usually blue or orange. Additional wiring for multi-wire circuits or special purposes may be other colors. 120 volt power is usually used for control power for reasons of safety.

Also by convention, switches, latches, relay contacts, etc., are located on the left hand side of powered devices such as lights, relay coils, and motors, etc., and are ungrounded. If there is a short to ground in this part of the circuitry, the control transformer breaker will trip. If there is a short in the powered device, there will not be any device such as a switch between the powered device and the common bus. This is to keep persons out of the fault path for reasons of safety. For this reason also, fuses are always placed on the left or "hot" side.

To read the drawing, the operator must carefully trace out and follow each ladder line noting each device, and its condition, i.e., whether it is powered or not, its logic state, i.e., on or off, normally open or normally closed, etc. and note any changes in state caused by actuation by other devices such as switches or relays due to logic. To do this takes some time and patience. To facilitate this, each rung is numbered sequentially. (This has nothing to do with wire numbering inside the panel.) Additionally, inside the panel and on the drawing, wires and electrical devices are numbered. Related line numbers and names of control relays or devices are usually shown in the right margins of the ladder.

Electrical relays have two parts. The first part are sets of contacts. The second part is the coil wires that drives the relay. Relays have contacts that are normally open (N.O.) and normally closed (N.C.). This notation refers to the state of the contact in the relay's de-energized state. This means that the drawing is drawn as if the control power is turned off. The state of the contacts reverses upon being energized. To interpret the drawing, the reader needs to imagine the relays in the operating state as he/she steps through the drawing to "see what happens" under various logic conditions. When the coil is powered or "energized," the N.O. contact will close and the N.C. contact will open. A timer integral to a relay may control the length of time the relay coil is energized or de-energized prior to switching.

11. LFG SYSTEM OPERATION

11.1 LFG SYSTEM OPERATION

11.1.1 Operation - General

Proper operation of the LFG collection and control facility is essential to minimize environmental impact, control costs, maintain equipment and the landfill in proper condition, comply with regulatory requirements and reduce liability. The following serves as a guide for operation of the LFG control system. Some of the discussion is specific to blower-flare facility operation, however it also generally applies to most other types of facilities as well. Names of controls, push buttons and switch settings may vary with each facility, but the functions are pretty generic.

Some facilities require optimization of LFG conditions while others only require that minimum control objectives be met. Some objectives may be conflicting and compromise may be required. For some objectives compromise may not be tolerable.

11.1.2 Operational Criteria

The LFG Control System will usually be operated continuously. In some special cases, a facility will be operated intermittently by means of a timer. This most often occurs when the landfill is old or the facility is oversized.

In many areas permits may require regulatory notification if the facility becomes inoperative. If the facility will be down for an extended period, a variance may be required. Continuous flow and temperature recording using a strip chart recorder is sometimes a requirement of an operating permit. The flow and temperature strip charts are an important record and should be labeled, dated and saved. Whenever the system is shut down or tested appropriate notations made on the strip chart recorder will provide a convenient record of the outage. Such notations may also be required for regulatory documentation.

A minimum concentration of methane is desirable to maintain good combustion at the flare and for successful operation of energy recovery equipment. A practical minimum is about 25 percent methane for flares and boilers. Engines usually require 40 percent and greater. For most landfill gas control systems (LFGCS), maintaining methane at 40 percent or greater will provide for more stable and reliable system operation.

TABLE 11.1 - Example System Methane Operating Ranges

Operating Condition (In order of degree of extraction effort or aggressiveness)	Percent Methane	Percent Oxygen
High BTU Recovery	≥ 55 %	0 (N_2 less than 2%)
Relaxed migration or emission control	50 to 55 %	up to 1 %
Moderate migration or emission control	45 to 50 %	0.5 % and less
Aggressive migration or emission control	35 to 45 %	up to 1 %
Very aggressive migration or emission control	20 to 35 %	2 to 3 %
Very poor methane conditions (Consider placing LFGCS on timer for intermittent operation)	<35 %	No greater than 3.5 % oxygen shutdown alarm level recommended for safety
Practical minimum methane for combustion	25 %	

Note: Ranges shown are representative examples. Actual conditions, and actions to be taken will depend on site specific conditions.

In the "composite" LFG, as measured at the blower-flare facility, an absolute maximum limit for oxygen is 7.0%. A 3.5% maximum controller setpoint for oxygen is recommended for safety.

Achieving the desired objectives is best done by monitoring for methane in the perimeter probes. The landfill surface may also be monitored for surface emission hot spots to judge efficiency of recovery. Following an assessment of the data, the gas quality and flow at the LFG recovery wells is recorded and adjustments made. The composite LFG at the blower-flare facility is then checked to verify that it is within the acceptable operating range. Ideally, LFG parameters for many control situations will be maintained within the following ranges:

1) CH_4: 46 to 55 percent
2) O_2: 0 to 0.5 percent
3) N_2: 2 to 14 percent
4) Carbon Monoxide: Not Greater than 25 ppm
5) Gas Temperature at the Wellhead: Not More than 52 to 60°C. (125 to 140°F.)

For those landfills that do not or cannot fit within these parameters, the parameters may be adjusted to what can reasonably and prudently be achieved and based on a demonstrated history of successes at the site.

If maintenance of LFG parameters within these ranges is not possible due to declining methane (CH_4) production or regulatory emission control requirements, then methane gas quality should be maintained as close to the specified ranges as possible. Overly aggressive or inattentive operation of the wellfield may result in subsurface fires at some landfills.

11.1.3 Routine Facility Start-up

The following is a narrative description of a generic blower-flare facility start-up procedure. The actual procedure will vary with the design of any particular facility. It may also be helpful to refer to a "Short Form Start-up Checklist" for flare facility start-up located in Appendix C.7. A short form start-up procedure, as well as a routine and emergency shutdown procedure, tailored to your specific facility, should be prepared and kept readily available for operating staff.

An example routine procedure to start the blower-flare facility is as follows:

1) Ensure that flow control valves of selected gas wells in the LFG wellfield are appropriately set. There are several techniques to determine the appropriate setting for the valve. Set each wells flow rate immediately after starting up the blower for the first time.

2) Open the main block valve at the inlet of the blower-flare facility. (It should normally be throttled to about a 10 to 25% open position (range of travel) depending upon flow setting needed.)

3) Open the inlet and outlet valves to the inlet separator. Close the bypass valve if present.

4) Open the inlet and discharge block valves for each blower to be operated and close the block valves for non-operating blowers.

5) Verify the propane or natural gas system is ready to start.

6) Walk through the flare station to verify that there are no gas leaks or unusual odors.

7) Turn the power switch to the "On" position.

8) Set any "Hand-Off-Auto" switch for each blower to be run in an "Auto" position. Leave each blower which is not to be run in the "Off" or "Stand-by" position.

9) Verify that all alarms have been reset by pressing the main control panel "Alarm Reset" button.

10) Turn the automatic block valve switch to "Auto" position.

11) Press or turn the "Start" button to initiate the automatic start-up sequence.

Avoid Burns During Flare Ignition

Some flares have been known to start with a "poof". When this occurs, flames have shot through the flare dampers a substantial distance. Stay away from any openings on the flare during ignition.

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12) The blower should come on, the automatic block valve should open, and the flare should light. Watch for the flow meter indicator or strip chart (if present) to indicate flow and then verify that the flare main burner is lit. If flame fails to prove on an automatic system, the flare should time out and lock out. Some systems may attempt an automatic re-light. With a manual system, if the flare fails to light, shut the system down and allow sufficient time for a convection purge, before attempting a re-light.

13) Once the flare is lit and proven, check to be sure that combustion is satisfactory and that main fuel pressure (burner back pressure) and LFG flow to the flare is satisfactory. (Usually a minimum of 4 in w.c.; check the manufacturer's requirement.)

Note that for some facilities, some steps may be different or may not apply. If gas ignition problems persist, recheck gas quality, verify that fuel is supplied to the flare, check for pilot ignition, and if necessary, troubleshoot the pilot train and ignition system.

Once the system comes on-line verify the following:

1) Automatic block valve is fully opened

2) LFG Flow is adequate to satisfy minimum flow requirements of blower and flare

3) Listen for abnormal blower and motor sound

4) Check for unusual odors that could indicate a gas leak

5) Once the flare operation has stabilized, verify performance, temperature, and flow

6) Visually observe combustion inside the flare by looking through the view ports

7) Verify air damper operation.

If significant abnormalities exist, then equipment should be shutdown and checked out, (see Maintenance and Troubleshooting, Chapter 13).

11.1.4 Routine System Operation

The following is a typical routine for operation of the LFG collection and control facility and wellfield monitoring. This routine should be assisted by a detailed checklist in the form of what is known as a "reading sheet." The reading sheet is a form which identifies key data that is monitored and collected at the blower-flare facility. Examples of this data includes:

- flare temperature
- LFG flow
- units of LFG sold or kilowatts produced
- blower discharge temperature
- blower motor amps
- flame arrester differential pressure
- valve positions
- weather conditions, etc.
- comments and problems encountered or repairs made

The experienced technician will use instinct in addition to the reading sheet checklist for routine inspection. An example reading sheet is in Appendices C.1.

The reading sheet should always be accurate and never be guessed, assumed or falsified. In some cases the basis of commercial energy sale are based on the recorded data. In other cases, important environmental and regulatory decisions affecting the public are made. False recording of data is a serious offense and may be illegal in some jurisdictions.

An example of a typical daily operating routine is as follows:

- Make appropriate entries in facility log book and on flare strip chart recorder.
- Based on scheduled items and results of "quick check" decide on course of action for day/shift.
- Conduct field instrument maintenance activities. Record calibration results.

- Perform blower-flare facility readings. Record on daily blower-flare facility reading sheet.
- Conduct a walking inspection of the field. Use the field and collection system checklist. Log observations. Sometimes, at large sites a driving inspection is more practical on a frequent basis, however, a driving inspection should not be wholly substituted for regular performance of a detailed walking inspection of the system.
- Conduct facility and wellfield routine or scheduled maintenance activities. Log maintenance activities. Non-routine maintenance are scheduled as required consistent with other priorities.
- Perform and record any final field instrument calibration. Record results.
- At end of day or shift make final checks and record logbook entries. Check auto-dialer.
- A weekly/monthly maintenance reading sheet or maintenance record cards are used to monitor and log routine maintenance checks and service.
- Perform any scheduled maintenance. In situations where significant maintenance is to be performed, such maintenance is usually scheduled at the beginning of the day and may preempt other activities.

If problems or a shutdown are observed:

- As part of trouble-shooting, make "quick check" and evaluate all conditions, settings, etc.
- Note and record annunciator status (prior to resetting). Note any "first-out" annunciation.
- Make notes in logbook.
- Make appropriate notations on recorder strip charts.
- Take corrective actions.

11.1.5 Unattended Operation

Whenever leaving the facility for unattended operation, make appropriate checks and adjustments to the facility to prepare it for unattended operation. Verify that the automatic dialer is turned on, programmed, and that any bypass switches are correctly set. Check to see that the air compressor is operating properly and has the appropriate pressure for operation of instrument air (70 to 100 psig), and that there is an adequate amount of propane for the pilot fuel system. Verify that all lubrication levels are adequate.

11.1.6 Routine System Shutdown

To shut off the blower-flare combination, hit the "Stop" button or turn the "Start" switch to "Off" on the control panel. If necessary, bypass the automatic dialer signal so that a false nuisance alarm is not created by the auto-dialer. Turning off all control panel power as a practice should be avoided.

11.1.7 Unscheduled Shutdowns

Periodically, unscheduled shutdowns of equipment will occur. This will require that operating personnel respond to the facility to restore equipment to operation at the earliest possible opportunity.

The cause of the shutdown should be investigated and documented. It is useful to maintain a log of shutdowns including date, time, annunciation, identified cause, and whether it was a real or false indication. This is useful in trouble-shooting and identifying problem trends, causes of shutdowns, and equipment maintenance needs. See Chapter 13, Troubleshooting.

11.1.8 Notification System

Notification of facility shutdown is typically provided by either an auto-dialer, a PLC programmed function, or by periodically checking on the facility. The auto-dialer is a programmable automatic dialer that will, when properly programmed and set, dial out a preprogrammed list of phone numbers if a fault occurs. A "call out" list of personnel and their phone numbers is programmed into the auto-dialer for this purpose. The dialer may also be accessed remotely by phone to verify the status of the facility. To program and access the auto dialer follow the manufacturers instructions. Keep a list for phone numbers and duty schedule for primary and back-up responders handy and posted in an appropriate place.

Some facilities will include a visible alarm such as a flashing light beacon that can be seen from a distance. In some energy recovery facilities an annunciator horn is used for audible alarm.

Some systems with PLCs may be equipped for remote access by computer modem. This allows operating staff to remotely monitor the facility on a periodic basis and during shutdowns.

11.1.9 Emergency Shutdown

Emergency shutdown of the flare facility is accomplished by turning the "Start" switch to "Stop" or "Off", or by pushing a "Stop" or "Emergency Stop" button. Turning the main "Power On/Off" switch to "off" at the main control panel may sometimes be used depending on control logic, but it is not normally a good idea to kill all control power. Use an "Off" or "Stop" function if available. Ensure that the source of gas from the wellfield is blocked, outside the facility plot or otherwise stopped. Verify that the automatic block valve closes, but do not solely rely on it. There should be another (manual) block valve located at the facility plot limit or outside the facility. In the case of a fire, it is crucial to quickly isolate the facility from the source of combustible gas. Protect personnel first, including yourself, and if in doubt leave the facility immediately. If deemed safely possible, shut off the source of the gas from the field then turn the facility power off as described above. A gas fire cannot be put out with water. The gas source must be eliminated.

In an extreme emergency, main power may be cut off at the electrical service cabinet that contains the main and major equipment circuit breakers. It is important to note, for safety's sake, that large breakers should not be manually tripped under load except in cases of extreme emergencies. To do so will shorten the life of the breaker and may also result in sudden, catastrophic failure. The energy available in an electrical arc can be tremendous; (the heat generated may be many times hotter than the surface of the sun). This would be a safety hazard to personnel and could result in potential injury or death.

11.1.9.1 Manufacturers' Literature and Facility O&M Manual

A site specific O&M manual complete with all manufacturers' literature should be available to operating staff. Operating staff must read and become familiar with all the O&M manual material including manufacturers' literature. This is necessary to understand the proper operation, maintenance and troubleshooting for each component piece of equipment in the facility.

11.2 ENERGY RECOVERY/DISPOSAL FACILITIES

The EPA has developed a detailed handbook discussing development of LFG to energy facilities titled, "Turning Liability into an Asset: A Landfill Gas to Energy Handbook for Landfill Owners and Operators", (Draft, December 1994). The handbook is available from the USEPA Methane Outreach program.

12. THE LFG CONDENSATE HANDLING SYSTEM

12.1. LFG CONDENSATE

LFG condensate develops as a result of cooling in the LFG collection system. This is mostly water and sometimes is referred to as LFG "condensate water." For this reason, condensate is also loosely referred to as water (for example, the term "water trap" is understood to mean condensate trap).

LFG condensate must be removed from the collection piping system, and properly disposed of. The condensate liquid interferes with the steady flow and collection of LFG wasting energy and in some instances may cause a complete flow blockage.

From a regulatory standpoint, when condensate moves from one landfill unit to another or off the landfill, its regulatory status may change. Return of condensate to the landfill or its treatment or disposal may be closely regulated. A condensate spill on native soil may be considered by regulatory authorities as a serious hazardous or controlled waste violation issue.

Condensate is highly odorous. Condensate also usually contains a high concentration of iron which causes the condensate to stain concrete orange. Careful control of condensate handling, treatment and disposal is necessary to limit release of odors. Condensate stains may affect the facility's appearance.

Condensate Safety

Avoid condensate water skin contact. Use appropriate personnel splash protection when handling condensate. Always wash skin areas which have contacted condensate prior to any mouth or eye contact (eating, smoking, etc.).

12.2. GAS CONDENSATE HANDLING SYSTEM DESCRIPTION

To collect and remove LFG condensate, devices known as condensate traps, sumps, and knockouts are employed. Traps or sumps may be located in both the LFG collection system and in the blower-flare facility.

A gas condensate collection and handling system is usually located near, or associated with, the blower-flare facility. Where and how the condensate is drained and collected from each facility varies with the facility design. The condensate handling system may consist of:

- Drains and drain lines
- Traps
- Sumps
- Pumps
- Oil and water separator
- Clarifier or other treatment equipment
- Storage tank
- Utility air compressor (for pneumatically pumped systems)

Condensate is commonly collected from a number of drain points in the blower-flare facility. These points may include:

- Main gas collection header
- Inlet gas scrubber vessel
- Blower(s)
- Flare flame arrester
- Other low points in the flare facility piping.

12.3. LFG Condensate System Components

12.3.1. LFG Condensate Traps

LFG condensate traps collect and drain condensate from the collection system. Condensate collected in traps may be drained back to the landfill (where allowed) or to a collection sump or container.

Condensate traps come in many configurations. All employ a basic principle known in the refinery/chemical process and wastewater treatment industries as the "liquid" or "loop seal." A loop seal relies on liquid head pressure to overcome any countervailing force and maintain a seal.

A common trap known in the industry is the "J" or "P" style condensate trap. These are often fitted with a sealing check valve to seal the system and maintain vacuum in case the liquid seal is lost. Another is known as a "bucket" trap. These basically overflow into a sump or container or through a gravel pack and back into the landfill.

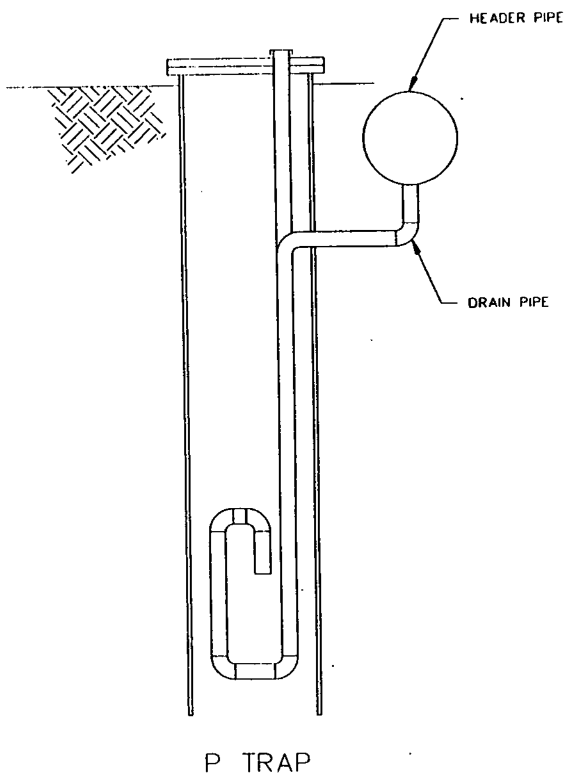


Figure 12.1

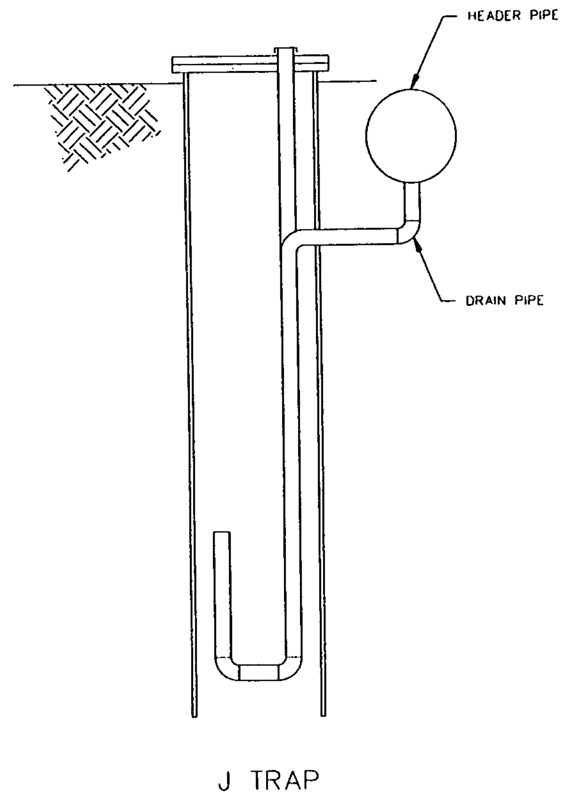


Figure 12.2

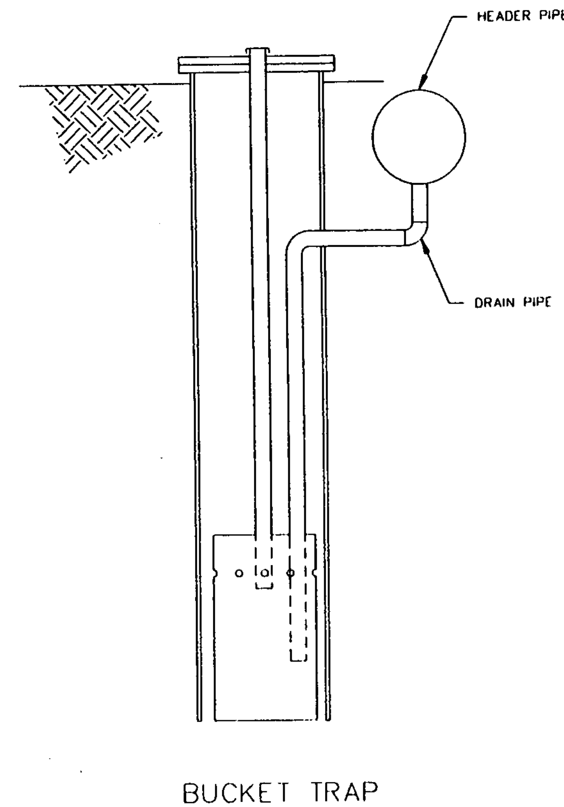


Figure 12.3

12.3.2. LFG Condensate Sumps

LFG condensate is often collected in sumps or containers. These may be manually or automatically drained or pumped.

Manual sumps must be monitored to identify when pumping is necessary or pumped on a regular basis. Manual sumps must have an adequate capacity to allow a reasonable frequency between pumpings. There should be sufficient reserve capacity in case a pumping cycle is missed.

Automatic sumps are fitted with a pump to deliver the condensate to a collection point such as a manhole, sump, tank sewer, leachate line, or another sump.

12.3.3. In-line Knockouts

The inline knockout is a relatively large liquid separator vessel that is, as the name implies, installed inline in a segment of piping and entrained liquid. The inline knockout employs the principles of a separator vessel or demister to remove the entrained liquids. The liquid may be drained back into the landfill, collected in sumps or pumped. An advantage of the in-line knockout is that it can be used in situations where there is little or no slope in the LFG piping.

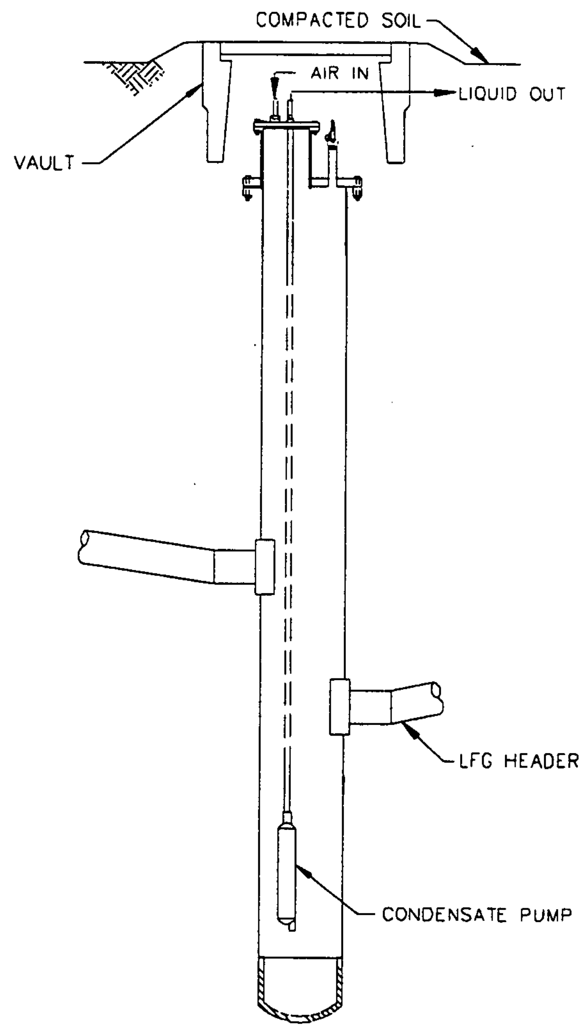


Figure 12.4
Typical LFG Condensate Sump

12.4. CONDENSATE COLLECTION AND STORAGE

It is a common practice to collect and store condensate in one or several storage tanks for later treatment and disposal. These tanks may be manually or automatically pumped. A single condensate tank in a suitable and accessible location is one of the most common configurations. The LFG technician must regularly check storage tank levels.

The condensate tank may be fitted with a level gage, flame arrester vent, vapor scrubbing or emission control system such as granular activated carbon, a secondary containment retention basin, anchoring tie-downs, drain valve and liquid transfer connection fittings.

12.5. CONDENSATE TREATMENT AND DISPOSAL

Depending upon condensate contaminants, treatment may be simple (pH adjustment or oil water separation) or complex. LFG condensate may consist of two phases, an aqueous (water based) and a hydrocarbon (organic solvent and oil based) phase. There are a number of options for treatment and disposal of LFG condensate. These include:

- Return to the landfill unit
- Physical and chemical treatment
- Biological treatment
- Discharge to water reclamation (for irrigation)
- Discharge into the leachate collection and disposal system
- Recycling (the hydrocarbon phase as waste hydrocarbon or oil)
- Disposal to sanitary sewer
- Disposal to a Publicly Owned Treatment Works (POTW)
- Disposal to a Class 1 (hazardous) treatment, storage and disposal (TSD)facility
- Treatment by advanced oxidation potential (AOP) also known as ultra-violet (UV) and ozone treatment
- Destruction by combustion in a LFG flare or incinerator.

12.6. HANDLING LFG CONDENSATE

LFG condensate may contain many trace chemicals and be highly biologically active. Appropriate protective gloves and splash protection equipment should always be employed when working with LFG condensate. Operating personnel should always avoid direct skin contact.

LFG condensate may release VOCs. The vapors emanating from condensate tankage may be flammable. These vapors may need to be controlled, scrubbed, or vented through a flame arrester. See the LFG Safety Chapter.

13. MAINTENANCE AND TROUBLESHOOTING

13.1 MAINTENANCE - GENERAL

There are two methods of performing equipment maintenance. The most common and preferred method is to be proactive with maintenance. In this case, equipment is repaired based on service life and outward signs. The other method is to be reactive. In this case, equipment is run until it fails and then repairs are performed. Reactive maintenance is typically only suitable for systems where operation is not critical. One disadvantage of reactive maintenance is that repairs may be needed during inopportune times. A second disadvantage is the potential for catastrophic equipment damage in some cases. As a result, it is strongly recommended that all maintenance be performed on a proactive basis.

Maintenance is broken down into four related categories:

1) Predictive and Preventive
2) Routine
3) Scheduled
4) Unscheduled

These categories are as follows:

1) **Predictive and preventive maintenance** — Predictive and preventive maintenance consists of those activities that identify potential problems and take necessary measures to reduce and eliminate equipment maintenance problems and failures. Predictive maintenance consists of routine observation and special diagnostic procedures such as ultrasonic testing or vibration and oil analysis. Preventive maintenance consists of those routine measures taken to maintain the equipment as recommended by the manufacturer other than major maintenance, repair or emergency maintenance.

2) **Routine maintenance** — Routine maintenance is that maintenance performed in the normal course of monitoring equipment and is conducted according to a stipulated frequency, usually daily or weekly. This is usually incorporated into the daily reading sheet.

3) **Scheduled maintenance** — Scheduled maintenance, in addition to routine maintenance, is done on a periodic basis according to a schedule. That frequency may be weekly, monthly, bi-monthly, quarterly, semi-annually, or annually, etc. Records of periodic scheduled maintenance are maintained to track and document the condition and history of the operating equipment. It is useful to review the maintenance histories of equipment when scheduling additional service work,

troubleshooting the equipment, or evaluating replacement equipment or component parts.

4) **Unscheduled maintenance and repair** — Unscheduled maintenance is done to bring the equipment back to proper operating condition when the need is identified or when a breakdown or mishap has occurred that reduces the equipment's operating effectiveness or stops the equipment from operating. Maintenance should be performed by persons qualified and familiar with the types of equipment to be maintained.

13.2 MAINTENANCE RECORD KEEPING

In industries that are heavily dependent on equipment maintenance, standardized practices have been developed for equipment maintenance management. These include scheduling techniques, records keeping and management, lubrication service and testing, non-destructive, preventive, and diagnostic testing, etc. The degree to which one adopts and follows these practices will depend upon, and should be adjusted to, the size and significance of the facility and its equipment and how critical their performance is to the facilities control or recovery objectives.

One practice is to schedule and document equipment maintenance on a file card that contains a calendar. This is one of the most accepted and conventional practices. For small amounts of equipment, the manual method of keeping maintenance records on cards is preferred. Maintenance records may also be maintained by computer program and wall calendar. For greater amounts of equipment, computerized records may be desirable. Use the manufacturer's maintenance frequency recommendations as a starting point and guide. Maintenance frequencies can and should be adjusted based upon actual equipment operating and maintenance experience. Example maintenance scheduling and record cards that can be printed on to card stock or computerized are in Appendices C.4 and C.5, Example Maintenance Scheduling and Record Cards.

Other practices are to keep an inventory of all spare parts on hand along with a list of items currently on valid requisition for follow up with vendors. It is also a good idea to keep a consolidated master vendor list with phone numbers handy. Compare the list of necessary spare parts periodically with the inventory of parts on hand. Keep a separate inventory of common consumable items such as lubricants, glycol, water or other treatment chemicals, etc. if used along with the schedule for deliveries or reordering.

A key to success, is routinely checking the schedule daily, and performing maintenance on time according to the schedule. There is normally an allowable tolerance or "float" period associated with each type of maintenance activity. Operating personnel should strive to stay within the float.

Performing Equipment Maintenance

Neglect in performing equipment maintenance is one of the most common causes of failure of LFG equipment. A proactive approach to performing equipment maintenance will prevent future system failures.

Another key is understanding what the proper maintenance is and performing it right. This is particularly important for lubrication issues, care of bearings, and care and overhaul of major equipment such as gas compressors and engine-generators and turbines.

Maintenance, plant management, and mechanic's and millwright's handbooks will provide the technician or maintenance manager with much information on general practices beyond the scope of this manual. Manufacturers' literature and more specific technical texts will provide information for maintenance requirements for specific equipment and component types.

Example check sheets for routine and periodic scheduled maintenance, spare parts list, and consumable supplies list are in Appendix C.

13.3 Diagnostic and Predictive Maintenance

The operating staff should avail themselves of the various diagnostic maintenance technologies available. Some of these include:

Ultrasonic thickness testing — to test for piping and vessel wall thickness in order to assess corrosion

Corrosion coupons — to measure the rate of corrosion of a specific material

Vibration analysis — to assess rotating equipment, bearings, etc., predicting bearing or equipment failure

Magna-flux or dye penetration testing — to analyze cracking and welds

Source testing of combustion equipment — to identify and correct emissions problems

Oil analysis — to assess oil condition and wear on metals, predicting bearing or equipment failure

Residue analysis — to assess impact or formation of chemical compounds for diagnostic purposes such as residues formed on piping, spark plugs, compressor valves, impellers, cylinders and pistons, etc.

Electrical diagnostic testing — to assess breaker and other protective device settings, internal integrity of motor windings, resistance to ground (megger check), etc.

Operating staff may also rely on maintenance contractors who employ millwrights, machinists, pipe fitters, and welders, etc. Maintenance managers should be skilled and experienced in dealing with such matters and select a reputable mechanical maintenance firm. There are many potential pitfalls in maintenance and repair of rotating equipment. One reason for this is the potential technical depth of the issues. Another reason, is that there is always a cheaper (and often inappropriate) way of attempting to accomplish the same thing.

13.4 WELLFIELD & COLLECTION SYSTEM MAINTENANCE

Wellfield maintenance involves the following:

- Repairs to the collection piping system due to damage caused by accident, settlement, environmental factors and aging
- Repair or replacement of system components (e.g., wellheads, access ports, flex hoses, valves, road crossings, condensate traps, sumps, etc.)
- Excavation for repair of damaged piping and components
- Re-installing lost, damaged or ineffective probes and wells
- Repairing and re-adjusting piping supports and anchors
- Re-sloping or re-leveling piping support earth berms and the landfill surface.

Types of problems that may develop with buried horizontal extraction wells include damage or separation due to landfill differential settlement, leachate or condensate blockage, or air leakage, particularly at buried tie-ins and horizontal to vertical transitions. Since horizontal collector wells may be buried deeply, those portions may be inaccessible. Therefore, when the well fails to perform, remedial options will typically consist of reducing well flow, tying-in the opposite end of the collector, pumping the well or vertical riser, or abandonment of the well in place. In shallow regions of the landfill it may be possible to excavate the piping for repair.

In many instances, repairing the collection system may require shutting down the blower-flare facility, which may require notification of regulatory agencies. The time duration of the shutdown should be kept to a minimum; the work should be scheduled to coincide with blower/compressor and flare shutdowns when possible.

Details on the specific procedures for repair of thermoplastic piping materials are available from piping manufacturers.

Refer to the health and safety Chapter of this MOP and the Health and Safety Section of the SWANA "LFG Field and Laboratory Practices and Procedures" manual for information on excavation and drilling safety procedures to be taken when performing collection system repair. See Chapter 19, Safety and References.

13.4.1 Landfill Surface

Good landfill cover and cap maintenance practices are important for effective operation and performance of the LFG collection and control system. The cover and cap should be considered an integral part of the system. The LFG collection and control system operator can assist the landfill operator in maintaining good landfill cover by identifying problem conditions and areas. A thorough visual inspection combined with surface emissions assessment monitoring using an organic vapor analyzer/flame ionization detector (OVA/FID) is helpful in identifying cracks, fissures, or bare spots in cover at uncapped sites. Experience has shown that in most cases, good cover maintenance will solve most landfill odor problems at uncapped sites. With membrane capped sites, the cap may not be keyed and sealed or welded to the landfill liner sidewall, the areas around the edges of the membrane cap should be checked for leakage in a similar manner.

13.4.2 Main Collection Header Line

Over time, the collection piping may develop air leaks. Air leakage should be kept as low as possible and it is recommended that oxygen in LFG not exceed 3½ percent by volume in the collection piping.

As an operating philosophy, if the LFG collection piping is kept free of air leakage, then it becomes easier to identify air leakage problems when they occur. LFG collection systems have been operated consistently with oxygen levels from trace oxygen to no more than several tenths of one percent. Normal operation should be no more than one percent oxygen in most cases, however older sites, and some migration control and side slope emission control systems may run higher than this out of necessity. The header should be kept tight so that it does not contribute air and oxygen to the LFG.

Leaks can occur in above grade PVC piping systems due to piping separations caused by thermal contraction resulting from cooling at night and during a system shutdown. A remedy for this is to install expansion joints and to properly anchor the piping at key locations. Anchor points are usually adjacent to wells, at junctions, and at fixtures such as condensate sumps, and at turns or elbows. Anchors are placed so that one end of the pipe segment is fixed and the other end is free to move due to expansion and contraction.

On below grade piping systems separations can occur due to differential settlement. Buried pipe is still subject to expansion and contraction, but to a lesser degree because of a more uniform temperature and the anchoring effect of the soil support within the trench.

Some systems have used gasketed pipe, which can be particularly problematic. Gasketed pipe joints may loosen and leak air into the gas collection piping, or if the system is shut down, may leak LFG into the atmosphere.

Condensate blockages in main and lateral headers can be evaluated by installing access ports for monitoring pressure/vacuum and gas composition in the header. Bracket (i.e., monitoring upstream and downstream of) the suspected problem area until the problem area is isolated.

With buried systems, it may be necessary to "pot hole" (i.e., perform exploratory excavation) with a backhoe to install access ports and conduct the monitoring. If the main header becomes blocked or restricted with condensate, it should be corrected by re-leveling the line, or installing an additional drain trap or sump.

The process of isolating problems can be enhanced by "bracketing" the problem area. The technique of "bracketing" involves identifying the boundaries or limits of the potential problem area, then "pot-holing" half way between the these two points. If there are no clues as to the likely location of the problem, this is the most efficient approach to locating it. Using the information (pressure/vacuum, gas composition) obtained from monitoring at this point the bracketed problem area (distance) is again split in half and the process repeated until the problem is found. This process can be very time consuming and expensive. This underscores the desirability of having a sufficient number of access ports installed at the time of construction.

13.5 Blower-Flare Facility Maintenance

13.5.1 Specific Equipment and Component Maintenance

A brief discussion of significant maintenance issues for specific equipment follows. For more detailed information refer to the appropriate manufacturer's information and commonly available maintenance management texts.

13.5.1.1 Process Plant Pipe and Fittings

Process plant pipe and fittings commonly consist of both steel and thermoplastic. Both types of piping should be visually inspected from time-to-time throughout the facility. Both are durable long-lived materials, however, thermoplastic piping can be subject to damage from shock, strain, or heat. Thermoplastic piping should not be used near sources of extreme heat such as the flare. Carbon steel piping can erode and corrode. Stainless steel, cast iron and aluminum piping have all been used successfully.

LFG and condensate exhibit corrosive properties. The presence of oxygen, carbon dioxide, and organic acids common to LFG together dissolved into LFG condensate provides for substantial synergy in promoting corrosion. Steel piping may be corroded when exposed to the above mixture. The most common point of wear due to erosion or corrosion in steel piping at a LFG collection and control facility is typically pipe elbows and other fittings that are subject to erosion and where liquid condensate accumulates. Periodically, on an annual, bi-annual, or other frequency basis, steel piping may be inspected using visual (through observation ports) or ultrasonic thickness (UT) testing techniques for corrosion wear. To be useful, UT testing requires skill in interpretation. Testing results may be compared with baseline information or standard piping wall thickness tables available in a piping handbook. This type of testing is not necessary for thermoplastic piping. If needed, a program of periodic and preventive replacement may be instituted.

13.5.1.2 Valves

Valve seats and stem seals may wear and eventually require replacement. Butterfly valves filled with elastomer seals, such as buna-N or EPDM, may be adversely affected by LFG. In such cases, it may be necessary to try other elastomer types to find a material more suitable to the service. Viton or filled Teflon™ valve seats in butterfly and ball valves respectively have had reasonably good wear performance.

13.5.1.3 Inlet Scrubber Vessel Maintenance

Over a period of time, the liquid knockout or inlet scrubber vessel, which acts as a filter, may develop a deposit of sludge or particulate. This deposit may need to be cleaned out of the vessel periodically. Material collected from the inlet separator vessel should be evaluated to determine the proper disposal method prior to disposal. An inlet scrubber vessel may typically have a filter or wire demister pad that will remove particles down to a certain minimum size. Demisters usually remove liquid droplets that are nominally 10 microns and larger. If the pad becomes clogged, coated, or biologically fouled, it will become necessary to open the vessel and clean the pad. The pad should be inspected annually for damage. Typically, inspection and maintenance of the demister pad is indicated when the differential pressure across the inlet separator is greater than one inch w.c. Ideally, differential pressure across the inlet separator should be maintained at less than 0.5 inches w.c. It is not advisable to run the blower-flare facility while bypassing the inlet separator vessel. The inlet separator vessel provides vital protection to prevent damage to the blowers that may occur from excessive exposure to particulates or liquids.

The liquid knockout or scrubber vessel should be visually inspected annually. If the vessel has an ASME code stamp, this is a requirement to maintain the validity of the stamp and rating. The vessel may be checked with an ultrasonic thickness tester.

Particular focus should be placed on checking for corrosion at piping elbows or below the liquid level line in the vessel. Usually LFG condensate will be acidic (low pH around 4 to 5.5). Very acidic LFG condensate may also indicate a subsurface fire is present in the landfill.

13.5.1.4 Blower Maintenance

Blowers are typically single or multi-stage centrifugal gas compressors that are either directly driven, or belt driven, by an electric motor. Consult the specific manufacturer's literature for detailed information on the maintenance of your blower(s).

Routine maintenance for blowers and motors consists of listening for signs of abnormal operating conditions, monitoring for excessive vibration or temperature, draining condensate from the blower housing periodically and before startup (if not automatically drained), and "running" (momentarily turning over) standby blowers (which are not currently being operated) weekly. The blower drive belt tension and wear should be checked on a monthly basis. If belts are glazed or cracked they should be replaced. At least one spare set of matched belts should always be on hand. On direct drive machines, flexible coupling alignment should be checked on initial setup and periodically as recommended by the manufacturer (typically quarterly to annually). Bearings should be greased or repacked according to the manufacturers' recommendations, typically quarterly to annually. The electric drive motor, if not equipped with sealed bearings, should also be greased. Blower seals and packing should be checked periodically for leakage. If blower seals continually leak or will not last, consult the manufacturer or try another type of seal or seal material.

Re-packing bearings should only be performed in a clean environment so that the potential for contamination entering the lubricated housing is minimized. Some prefer to only perform such invasive maintenance services in a controlled shop environment rather than in the field. If dust or other contaminants are allowed to enter the bearing compartment, more harm than good could be done to the equipment as a result of the service.

13.5.1.5 Discharge Check Valve

A check valve may be located downstream of the discharge of the blower. In the case of a multiple blower installation, the check valve prevents recirculation of gas through blowers that are not operating. Check valves are also used to limit a flashback in the pipe. If it is determined that the check valve has malfunctioned or is leaking, it should be removed, inspected, and serviced or replaced immediately. Reduced discharge pressure, increased inlet or discharge temperature and sometimes an audible noise are possible indications of a leaking check valve.

13.5.1.6 Gas Inlet Automatic Block Valve

Typically an automatic block valve shuts off the flow of LFG to the flare when the flare is not operating or when a fault or shutdown is initiated. This is usually a butterfly type valve. The valve is usually inspected and serviced only when a need is indicated. These valves are usually either pneumatically or electro-hydraulically operated. For pneumatic actuators to function properly, the supplied instrument air must be clean, dry, and at the specified pressure. Equipment manufacturers will specify how dry the air must be for the equipment to operate properly. The pneumatic actuator should open and close the valve fully without sticking. The air piping to the air motor and solenoid valves should not leak. Electro-hydraulically operated valves may experience problems below their minimum specified operating temperature. Hydraulic fluid levels should be maintained. The automatic block valve seat should maintain a gas tight seal whenever the valve is in the closed position. This is important to prevent release of LFG to the atmosphere through the flare possibly creating a safety hazard. Refer to the manufacturer's literature for information on service. Some automatic block valves are fitted with position or proximity switches that provide a signal indicating valve position to the electrical controls.

13.5.1.7 Flame Arrester

A flame arrester is designed to prevent the migration of burning LFG from the flare backwards into the process piping and the flare facility. This condition can cause what is known as "detonation" (an explosion) or "flashback" within the piping. This is a very dangerous condition, particularly in the case of high oxygen content. As an extra safety precaution, a high temp shutdown or fusible plug type device may also be used (e.g., in the instrument air line). This will usually be located between the flame arrester and the flare. Proper reassembly according to the manufacturer's instructions must be stressed. A flame arrester will only work properly if the velocity and pressure of the "flashback" in the pipe is within the allowable range and the flame arrester is properly assembled.

The differential pressure across the flame arrester should be checked during each monitoring period. The normal differential pressure is typically less than 0.5 inch w.c. The differential pressure across the flame arrester should not exceed 1.0 inch w.c. If excessive differential pressure is observed, the flame arrester should be serviced. A spare flame arrester element and gasket set should be kept on-hand. Refer to the manufacturer's instructions for servicing the flame arrester. To service the flame arrester, shut down the facility and block in the flame arrester upstream using the manual and automatic block valve and verify the valves do not leak. Closely follow the directions in the manufacturer's literature for maintenance and re-assembly of the flame arrester element. It is important to note that a flame arrester's effectiveness is based upon a design spacing or gap in the flame arrester element. During maintenance and re-assembly, this spacing or gap must be maintained according to the manufacturer's original specifications and requirements if the flame arrester is to provide the safety and protection that it was designed to provide. Ensure that all parts are returned and in the proper orientation when re-assembling the flame arrester. For plate type flame arresters never leave any plates out.

If the system is fitted with a high temperature shutdown/switch, it should be checked annually. This should be done by qualified electronics or instrumentation personnel. This would normally be done when instrumentation testing and calibration is scheduled and performed.

13.5.1.8 Flare

There are two general types of flares: candlestick and enclosed ground flares. An example of each type is pictured in Figures 13.1 and 13.2. The candlestick is a much simpler device than an enclosed ground flare and most of the maintenance practices that apply to the candlestick flare are included in the enclosed ground flare maintenance practices.

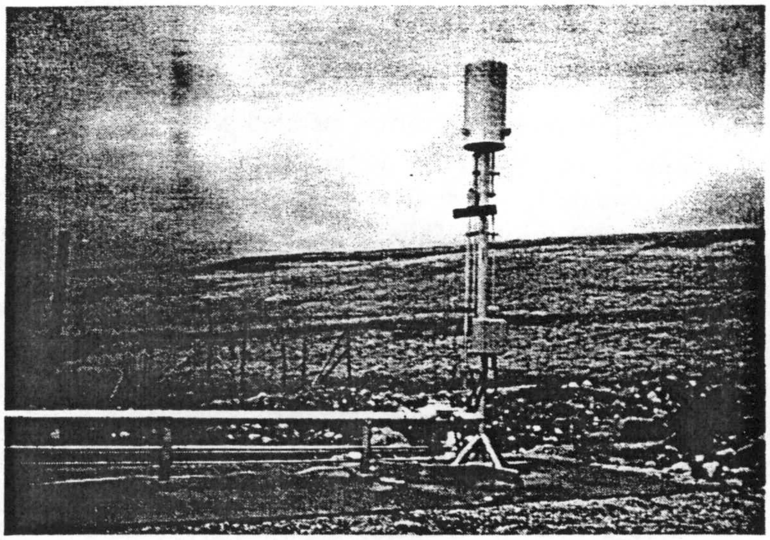


Figure 13.1
Typical Candlestick Flare
Source: Wisconsin Department of Natural Resources and GCE

Operation and maintenance of the candlestick flare is simple and consists of maintaining proper fuel pressure, keeping the burner and manual air dampers (when so equipped) properly adjusted, maintaining the pilot fuel and igniter systems, and keeping the flare drained of any condensate build-up. Proper fuel velocity, quality, mixing and flame condition is key to candlestick performance. Also, to operate consistently, the flare "tip" (i.e., burner assembly) must be adequately shielded from excessive wind. Refer to the following discussion for information on maintaining individual flare components for both types of flares. Problems with flame stability in a candlestick flare are usually caused by poor LFG methane quality.

The primary wear on flares is due to thermal stress. If the flare is operated in an imbalanced condition or at excessively high temperature, it will exhibit signs of accelerated thermal stress and possible insulation failure. This may be evidenced by localized discoloration of the exterior painted surfaces, or wear and deformation of the burners. Proper operation of the flare at minimum recommended temperatures acceptable for effective emission control will help extend the life of the equipment. Enclosed ground flares are internally inspected for refractory damage due to heat and other environmental factors. Sometimes damage can be externally identified visually. Refractory damage and the effects of excess heat stress can also be checked by thermal imaging.

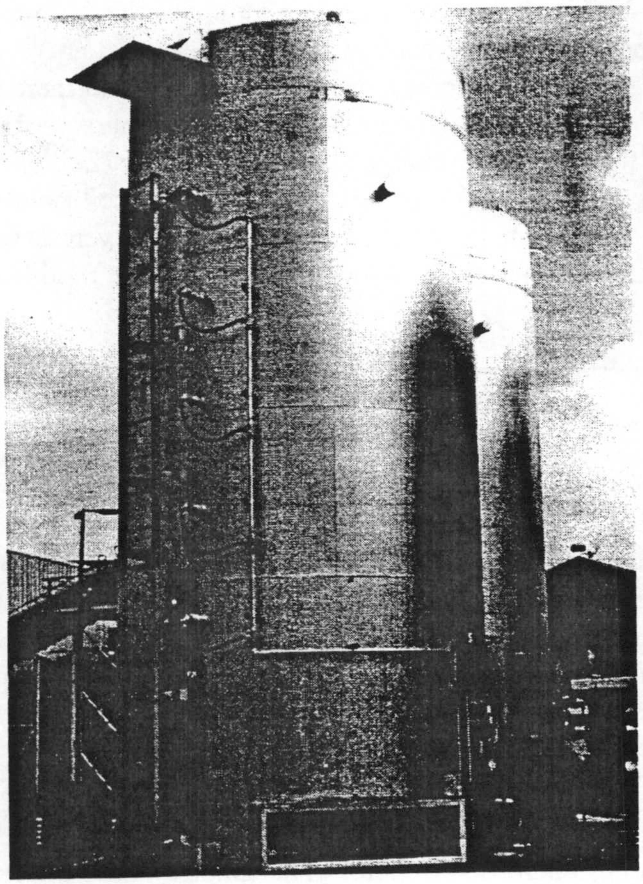


Figure 13.2
Typical Enclosed Ground Flare
Source: Perennial Energy™

The combustion temperature of a candlestick flare is a function of its design and the LFG flow rate. No separate combustion controls are usually included on candlestick flares. Enclosed ground flares, on the other hand, often times use temperature controlled air dampers to control the combustion temperature. Dampers can also be manual requiring the operator to "manually" adjust the combustion temperature. Still other flares are a combination of automatic and manual. One damper may be motor operated and another manual. In this case, it is common to hand set the manual damper to a position that allows the maximum range of the automatic damper.

On an annual or biannual basis, the flare, burners and refractory or insulation should be inspected. This is accomplished by opening the flare access man-ways, and entering the flare for inspection. Entry of the flare should be treated as a confined space entry, (i.e., difficult access and egress with a potentially harmful atmosphere). Appropriate testing for oxygen deficiency and explosive environment, safety precautions and confined space entry procedures should be performed prior to entry. State and Federal law delineates specific legal requirements for identifying and working in confined spaces.

Both enclosed ground and candlestick flares can require burner adjustment or modification to achieve and maintain proper combustion performance. Adjustment on a candlestick flare usually involves changing an orifice or burner ring, or moving or changing a plate. Consult the manufacturer or seek qualified assistance.

Depending on facility design, gas velocity to the flare is adjusted at the flare fuel manifold or valving, at the blower suction and discharge block valves and at the blower-flare facility inlet. This is accomplished by balancing the distribution of the blower's total pressure. Pressure distribution between blower suction (the wellfield vacuum) and the blower discharge pressure (fuel pressure to the flare) must be balanced so that there is sufficient fuel pressure at the flare. If pressure to the flare must be raised to increase fuel velocity, remove any impediments to flow on the discharge side of the blower (i.e., open up the blower discharge and flare fuel valving fully) then throttle at the flare facility inlet or blower suction. (Warning: Never, remove or gut the flame arrester.) In severe cases where adjustment will not work, the flare burner or the blower may need to be modified or replaced.

Flare Design Objective

The objective of the flare design is to burn all of the LFG gathered by the collection system. If the flare is flow limited, it will be necessary to either increase the flare capacity or to compromise the collection system operation to reduce flow. If , on the other hand, the LFG flow is insufficient, it will be necessary to increase flow by installing more wells, increasing the flow from existing wells, repair the system by eliminating flow restrictions or go to part-time flare operation.

On enclosed ground flares, the air dampers and linkage should be adjusted for proper operation throughout the entire operating range of the flare. The linkage and dampers should be inspected quarterly. Ensure the linkage is lubricated. For flares with automatic dampers, checking the stability of the combustion temperature can be a good indicator of the linkage adjustment and condition.

Sight glasses are provided on the body of the flare to allow visual inspection of the flare flame for good combustion characteristics. Over time, sight glasses tend to become opaque. Sight glasses which do not allow clear sight should be promptly cleaned or changed.

The secondary air damper pillow-block bearings which are part of the damper linkage should be greased monthly. The use of a high-temperature grease is usually recommended. The operation of the damper drive motors should be checked quarterly by stoking the damper from fully open to fully closed.

The flame safeguard sensor system typically consists of an electronic controller (usually mounted in the control panel) and a field sensor mounted in, or in the proximity of, the flame being monitored. Most systems employ a thermocouple, UV sensor or a flame rod as a sensing device to continuously monitor the flame. The most common flame sensors are UV scanners and thermocouples. It is a good idea to maintain several spare thermocouples or UV scanner parts on hand.

When removed, the electron UV sensing tube should never be exposed to sunlight. It is recommended that electron UV sensing tubes be replaced annually. Mounting can be direction or attitude sensitive (i.e., don't install upside-down) due to the presence of a shutter on some models. Orientation should be verified when mounting or replacing a position sensitive UV scanner. Performance of some common flame safeguard systems can be tested and verified using a micro-ammeter or volt meter. The micro-ammeter is connected to the control amplifier module which monitors the flame sensor signal output. Sometimes self-checking diagnostics are employed to provide a "working" indication of the continuous performance of the sensor and system to indicate positively that the system is "seeing" the flame. The UV scanner sensing tube coil, shutter, and control module should be checked out semi-annually.

A thermocouple can be checked independently with a volt meter and thermocouple tables (See Appendix D.2, Thermocouple Tables) or with a digital thermocouple test meter or digital thermometer. Proper polarity must be observed when installing and monitoring a thermocouple. Type "K" thermocouples are probably the most commonly used for these applications. If the thermocouple is subjected to flame impingement, its life may be considerably shortened. Thermocouples can be mounted in protective sheathing, however, this will cause some delay in response to temperature changes.

See your flare manufacturer's literature for specific component operation, maintenance, and troubleshooting information.

13.5.1.9 Flare Pilot Fuel Train

The propane or natural gas pilot spark ignition system is an important system to focus preventive maintenance upon to improve reliability of the overall flare system. The pilot piping train and components should be maintained free of leaks to avoid a serious safety hazard as well as wasting pilot fuel. If it is determined that the fuel pressure regulator leaks, the regulator should be promptly rebuilt or replaced.

The spark igniter is similar in appearance and function to an automotive spark plug. Quarterly, or when the igniter exhibits excessive wear, the spark igniter should be inspected for cracking of the ceramic insulator, wear of the igniter ground rod, short circuiting in the high voltage lead wire, and accumulation of moisture that may short out the igniter causing it to fail to perform. It is important that a proper gap be maintained for a good spark between the spark igniter ground rod and the pilot burner head. As the spark igniter is used the gap will increase and eventually may result in failure to spark. From time to time the gap may need to be adjusted. An ample supply (at least three is recommended per flare) of spare spark igniters should be maintained because they are a frequent wear item. Spark ignition wire will also wear due to heat stress and UV exposure. If this wire shows cracks, deterioration or signs of excessive wear due to thermal stress, it should be replaced. Ensure all components and connectors are corrosion free. Spark igniter wire may also be damaged from heat if not properly cooled or insulated when routed in conduit mounted on the flare body if not properly cooled or insulated. Another common problem with spark igniters is moisture, which will cause short circuiting to ground and malfunctioning of the ignition system. If moisture is detected, check the ignition components and clean and dry all connections. Ensure through visual inspection that the igniter ceramic insulation is not cracked.

13.5.1.10 Enclosed Flare Source Testing

On enclosed ground flares, usually located along the top portion of the flare are typically four inch diameter capped pipe nipples that are welded to the flare. These are test ports that are used for annual or periodic source performance testing of the flare as required by regulatory agency rules or operating permit. The threads on the pipe nipples should be lubricated with a high temperature (e.g. nickel) anti-seize compound to insure that they are easily accessible when needed. Candlestick flares do not require source testing nor can they be practically tested.

13.5.1.11 Air Compressor

Depending on the type of air compressor utilized, lubrication type oil, change out frequency, and even the compressor duty cycle can vary widely. Consult the air compressor manufacturer's literature for the specific maintenance requirements for your air compressor. Schedules included herein are generic and may not be suitable for your machine. Routine maintenance on the air compressor typically consists of checking of the air pressure, draining the air receiver of accumulated moisture daily or weekly if it is not fitted with an automatic drain, replacing filters and adding or replacing oil. If the air compressor is fitted with an automatic drain, it should be routinely checked to verify proper operation. The air compressor should be listened to for proper operation. Periodically, or at least annually, a leak down test should be performed. This is done by pressurizing the system and monitoring for loss of pressure by monitoring the change in pressure and temperature over time. Suspected leaks may be checked by "soap bubble" testing using a commercial product.

A simple test to check the compression components and air filter is to record the time it takes the compressor to build up pressure of a fixed volume (typically the air receiver). Be sure that valves and piston rings are working properly. The air compressor oil level should be checked weekly. The air line lubricator should be checked and filled as needed on a weekly basis. The air compressor air inlet filter should be cleaned monthly, along with the in-line compressed air line filter. The inlet air filter should be replaced or cleaned when dirty. If cooling is a problem, the inter-stage cooler (on multiple stage compressors) should be cleaned. Also, the air compressor drive belt tension and wear should be checked monthly. Keep at least two spare, matched sets of belts on-hand. Check that drive belts are properly tightened and not cracked, glazed, or slipping. Recheck belts for stretch shortly after initial replacement. The air compressor should be checked and serviced annually by checking the tightness of the air compressor fly wheel and motor pulley, servicing the air compressor valves and unloaders as needed, and checking the air system for leakage. The air compressor oil should also be changed using an appropriate grade of oil, as recommended by the manufacturer.

Maintenance should not be attempted until the compressor is removed from service. The air compressor receiver is isolated, the receiver is drained, the electrical disconnect is locked out and tagged, and all air pressure is relieved and verified. See Electrical and Mechanical Lockout Procedures in the Chapter 19 , Safety.

13.5.1.12 Electrical Equipment Controls and Instrumentation

Electrical service and control cabinets should be cleaned and vacuumed on an annual basis. Wire connections should be checked and tightened throughout the cabinets annually. Calibration and verification of instrumentation gages and thermocouples should be performed annually. Shutdown alarms and devices should be tested and the results recorded in a log. Thermocouples for sensing flare stack temperature should be maintained, and replaced when they no longer perform properly. This is normally evident by failure of the temperature controller to properly read or control the flare stack temperature (usually due to an open junction) or by loose or corroded connection terminals at the temperature transmitter, connector block, or temperature controller recorder. Most controllers are set to read open which results in a high temperature shutdown when the thermocouple fails.

All electrical equipment should be checked and cleaned at least annually. Equipment cabinets should be vacuumed and all connections tightened. Corrosion on contacts and connections should be cleaned or removed, space heaters checked and corrosion inhibitors replaced. Dust will accumulate in cabinets absorbing moisture from the air. Over sufficient time a conductive path can be created that can cause a catastrophic failure. Connections will also become loose over time due to thermal expansion and contraction. Check all terminal strips and wire connections. Test and recalibrate instruments, fault protection and shutdown devices. Large breakers or fused disconnects should be disconnected under load. Ensure high voltage breakers or disconnects are "racked out" or physically opened and isolated before working on equipment associated with them. Fuses should be physically pulled to isolate equipment. When the facility will be down for major maintenance or stand down, large breakers should be "racked out" (i.e., physically separated and disconnected) and the fuses should be pulled.

13.5.1.13 General Facility Maintenance

During each daily monitoring event at the blower-flare facility, all chart recorders should be checked for adequate chart paper remaining in the chart recorders. Completed charts should be collected and maintained as part of the operating record of the facility.

Equipment performance should be observed during each facility visit. These observations will normally be recorded on a daily reading sheet and in the operating log book. Monthly, the facility may be sprayed for weeds and insects, if needed. Outdoor lighting should be checked regularly for proper operation. The condensate drain system should be checked to make sure that it is functioning. Condensate sumps and pumps should be serviced. Bolts, nuts and fasteners should be checked and tightened periodically throughout the year.

13.5.1.14 Lubrication - General

Follow the manufacturer's recommendations for specific types and brands of lubricants. It is important to use the recommended type of grease and to not mix types or brands of grease. Do not over lubricate. More bearing damage is caused by over-lubrication than by under-lubrication. Personnel who perform lubrication services should be knowledgeable in lubrication practices and should follow the manufacturer's instructions for lubrication requirements. Usually a measured amount of lubricant is to be applied.

Determine in advance, how much lubricant per stroke your "grease gun" dispenses. In the case of grease, which is usually dispensed using a grease gun, the amount of grease dispensed by each stroke of a particular gun can be determined by constructing a measured paper cube (1 square centimeter or inch) and performing a test to determine the number of pump strokes required to fill a cube of known volume.

Establish an initial lubrication frequency based upon the equipment manufacturer's recommendation. It may be necessary to adjust the lubrication frequency interval based upon experience with the equipment.

Example lubrication schedules are included in the Maintenance Checklists in Appendix C.6. These may be modified to your specific equipment requirements.

13.5.1.15 Other equipment maintenance and operating tips

The equipment operator should be proactive, remain alert and develop a habit of observing equipment with the senses: sight, feel or touch, smell and hearing. Fingernails are the most sensitive part of the body for routine checking for equipment vibration. The ability to check for excessive vibration by hand is a skill developed with practice. Vibration monitoring equipment can be used for larger equipment but this requires technical training and understanding and a consistent program of monitoring to be meaningful. The operator should develop a sense of feel for what is excessive temperature. Special magnetic temperature indicators or color indicating crayons are also available.

Equipment noises (such as bearings) may be monitored by using an equipment stethoscope or using a wrench or similar tool by placing it on the equipment and placing the opposite end of the tool against the bone in front of the ear to listen. It is important to develop a sense of what baseline conditions are for comparison. The smell of leaking LFG or burned lubricant can indicate a seal, component or lubricant failure.

When checking motors or other electrical devices for temperature by feel, the back of the hand should be used. Approach the equipment slowly and feel for radiant heat which would indicate a very high temperature. If the equipment is too hot to maintain hand contact, it is at or above a threshold of about 60 to 63°C (140 to 145°F.) and may be considered excessive in many cases depending upon the equipment and service. The reason for using the back of the hand is that it is more heat sensitive and in the case of electrical fault to the casing, the natural reaction will be for the muscles of the arm to contract away from the device. This can prevent electrocution.

Personnel Clothing

Wearing synthetic clothing such as polyester can be fatal in a methane gas flash fire. Synthetic clothing is extremely flammable.

Operating personnel should wear all cotton clothing which provides some degree of protection in gas flash fires. Some synthetics such as polyester blends will readily melt. This can be fatal. Ties of loose items (e.g., identification badges hanging form or worn around the neck, etc.) should never be worn around rotating or belt-driven equipment. Remove all watches, rings, identification bracelets, etc., when performing electrical testing or troubleshooting.

It is important that maintenance supplies, lubricants, and spare parts be inventoried on a frequent basis to ensure that adequate stocks are maintained for when they will be needed. Supplies should be reordered and restocked as used.

13.5.1.16 Condensate Handling Systems

A blower-flare or energy recovery facility is usually fitted with various traps, drains, sumps, pumps and sometimes treatment or disposal equipment for handling condensate equipment. Mechanical traps, pumps and treatment equipment can be high maintenance equipment.

Condensate systems may contain filters that must be checked and cleaned periodically. The frequency of filter maintenance must be determined on a site-specific basis. Some condensate can be corrosive and the equipment will need to be checked carefully and frequently for the effects of corrosion. Seals, o-rings, slide valves and check valves are usually high maintenance items. Refer to the manufacturer's information for maintenance of individual equipment or components.

13.5.1.17 Energy Recovery and Other Process Equipment

It is beyond the scope of this manual to go into great detail on energy recovery equipment. To do so would require another manual in itself. A brief discussion is included on several major types of equipment commonly found in LFG energy recovery and some of the more common operation or maintenance issues associated with them.

Heat exchangers -- Types of heat exchanges that may be associated with LFG energy recovery include:

> **Gas/chilled water** - Commonly used to cool LFG and condense out much of the water to meet gas dew point specifications. The gas is sometimes reheated, usually with a gas/gas heat exchanger.
>
> **Gas/gas** - Commonly used to reheat the gas back to its original process or ambient temperature after chilling. This "super heats" the gas above its dew point.
>
> **Air exchangers or "fin-fan" coolers** - This type of exchanger is usually constructed of parallel rows of finned tubes over which a fan draws or pushes air. The most common use is to cool gas or water from compressors or processes. 304 or 316 stainless steel has been used with good success for heat exchanger tubes in LFG service.
>
> **Engine, compressor or turbine jacket water radiators** - This type of exchanger may be integral to the equipment it is related to or may be supplied separately. Its purpose is to maintain cooling jacket water or oil within the desired temperature range.
>
> **Cooling tower** - A cooling tower relies on evaporative cooling, usually down flowing water over baffles or shelves in the tower while air is drawn through the tower. Cooling towers are used to cool engine and compressor jacket water, in intermediate cooling loops, and in steam re-condensing and recovery systems. Cooling towers require close monitoring, often requiring chemical treatment for corrosion control and a biocide to control biological fouling. The total dissolved solids (TDS) content and conductivity of the water quality are often monitored. The tower may have a controlled continuous or intermittent "blowdown" to control water quality. The term "blowdown" used in reference to boilers and

cooling towers refers to control of water quality by controlling make-up water and water quality parameters such as conductivity and TDS. The degree of monitoring and control will depend upon specific process requirements. Sometimes chemicals are injected using metering pumps. These pumps are often high maintenance items.

Process chillers -- Process chillers are most often used in association with gas to chilled water/glycol mixture heat exchangers. They are used to suppress the dew point of the LFG so that the LFG product meets specification for use and will not condense out liquids which could interfere with that use. Depending on the design and type, process chillers can be very maintenance intensive or virtually maintenance free. Hermetically sealed chillers tend to require maintenance. Their operation and maintenance must be well understood if the operator is to successfully operate the facility. Refer to the manufacturer's literature and textbooks on refrigeration equipment operation and maintenance.

The operator must observe operating temperatures and pressures to monitor chiller performance. Poor or off specification performance may indicate any of the following:

- Improper adjustment of heat exchanger flows
- Refrigerant leaks in the chiller or low refrigerant level
- Refrigerant control problems or malfunction
- Chiller refrigerant compressor poor performance or failure
- Improper refrigerant
- Improper mixture of glycol (anti-freeze and water)
- Process chiller is overloaded or improper control setting.
- Heat exchanger fouling or freezing
- Process chiller condenser fouled or dirty.

Engines – Engines are commonly used as prime movers for compressors and generators in medium BTU LFG service. Engines typically require a reasonably high quality gas to function reliably. A minimum gas quality of 50% is not unusual. Engines may be naturally aspirated or pressure (turbo) aspirated. Pressure aspirated engines allow a greater range of fuel quality but generally exhibit a higher rate of wear for the same level of performance. One of the most common LFG related problems is formation of acids in the engine crankcase which can cause cylinder scoring and excessive wear. This can be reduced by maintaining the oil temperature well above the water dew point. Oil temperatures of 190° F are not uncommon. Additionally, jacket water temperatures of 200-250° F are also not uncommon. Another common problem with naturally aspirated LFG engine applications is inadequate surge volume capacity in the fuel gas train. Most engine starting problems are due to electrical ignition, carburetion or fuel injection type problems. Refer to manufacturers literature and troubleshooting charts supplied by the manufacturer and others.

Gas compressors – Gas compressors are used to pressurize LFG for supply to engines, turbines, boilers, and gas pipelines. Common types are the reciprocating and rotary-vane types. Bearing, seal and rod maintenance is a key to performance and longevity. Also key are (plate or poppet) valve or (rotary) blade maintenance. It may be necessary to periodically internally inspect the compressor for wear.

Gas turbines - Gas turbines are commonly used to drive generators to produce electricity. Gas quality and corrosion control can be a key factor in gas turbine performance.

Electrical generators – Generators are attached to a LFG driven prime mover such as an engine or gas turbine. Generators when properly operated and cared for do not require a great deal of maintenance. Generator windings must be properly heated or temperature controlled when not in service to keep the windings and insulation dry. The generator and excitor windings and insulation should be checked or "meggered" annually or as recommended by the manufacturer. To do this, a special resistance or "ohm" meter also called a "megger meter" is used to check insulation resistance. The generator openings should be protected from small animals such as rodents.

Boilers - Boilers are commonly used to heat water and generate steam. Boilers may be either high or low pressure rated. The key to boiler operation is fuel gas quality and corrosion control. Moisture in the fuel may enhance corrosion in the fuel train. It has been shown that boiler feedwater which contains both oxygen and carbon dioxide has up to ten times the corrosion potential as boiler feedwater containing either oxygen or carbon dioxide, but not both.

Properly regulated fuel delivery pressure and constant methane quality is key to good combustion and proper operation. Also important to combustion is draft control. Because of the potential for swings in methane and oxygen concentration in LFG as a boiler fuel, boiler operation and control may need to be more relaxed than natural gas (i.e., have more excess air so that if the methane quality increases, the flame will not make soot). A boiler operating on LFG may not be as closely controlled (for excess O_2) and hence economized as well as one operating on natural gas.

13.6 TROUBLESHOOTING

13.6.1 Troubleshooting - General

Sometimes due to wear, breakage, changed conditions, or other reasons, equipment, processes or systems fail to perform as designed. When this occurs, a process of deductive reasoning known as troubleshooting is used. Troubleshooting typically involves a systematic process of elimination of possible causes to establish a cause of a physical problem. To say that the troubleshooting process is systematic means that the troubleshooting procedure is applied in a logical, step-by-step procedure using available guidance (such as trouble shooting charts) along with experience to determine the cause of a problem or failure.

Troubleshooting may involve a very quick and simple assessment, or may require days and be very complex. Troubleshooting may simply require the application of basic common sense, or may require considerable technical skill.

Troubleshooting charts and tables are helpful and should be checked first, to help assess the problem. Charts are often provided by equipment manufacturers. By making use of troubleshooting charts first, considerable time can sometimes be saved. They will also facilitate mapping out a systematic approach that saves time, prevents overlooking the obvious and the obscure, and serves as a checklist.

Troubleshooting Tip

If charts or tables are not available or are incomplete, make a list of all possible causes for the equipment or process fault or failure including the most obvious or simple. Then go down the list eliminating appropriate items until the list is narrowed to one or just a few possibilities. If you are stumped, recheck your basic assumptions, try to think of what may have been left off the list or may be inappropriately assumed. Try not to take anything for granted.

It is important to start without bias as to what may be causing the problem. Playing an experienced hunch at first may be "OK." However, getting hung up on one possibility to the exclusion of all other possibilities is unproductive.

14. SPECIAL OPERATIONAL CONSIDERATIONS

14.1. COLD WEATHER OPERATION

For effective operation in cold weather LFG condensate must be kept from freezing. There is normally sufficient heat in the gas to prevent freezing as long as the system is operating and gas is flowing. However freezing of condensate can occur during shutdowns in cold weather.

Cold weather systems are normally insulated by burying in the landfill. Piping and equipment in the blower-flare facility may be insulated or heat tracing may be applied.

During extreme cold weather, ice-blocking may be a problem even with a buried and insulated system, the best procedure may be to shut down or reduce flow until the blockage thaws and clears. If the system freezes, there is no easy fix. The most sure fix is to excavate and replace or thaw the pipe. If the pipe is buried in the landfill, placing insulating material over the top will help by allowing the landfill heat to thaw the pipe. Hay bales, cover soil or insulation can all be used for this purpose. If the problem is localized, the situation may be correctable by increasing insulation, correcting piping slope or drainage, or installing a larger section of pipe. A temporary repair may be necessary until a permanent solution can be implemented. This again underscores the need to have and maintain the system in a free draining condition and to keep gas flowing through the pipe.

Light snow covering of the landfill often provides a better opportunity to observe gas venting, leakage, cracks or cover imperfections or areas of low extraction influence at the surface of the landfill. Areas of snow melting due to warm LFG escaping from the landfill may often be readily identified. Early morning at sunrise can be an excellent time to locate leaks as the LFG vapor appears as whitish vapor trails rising from the landfill where leaks occur.

14.2. WET WEATHER OPERATION

Heavy and prolonged precipitation will tend to seal the landfill surface. In unsealed landfills, liquid infiltration may increase moisture within the waste mass and can raise operating vacuum levels. In extreme cases this may cause severe operating difficulties by flooding wells. The increased moisture of precipitation or infiltration may tend to temporarily increase the LFG gas generation rate, and hence, the LFG methane quality and flow rate. There is also a tendency to improve methane capture and reduce air infiltration. This also can increase field vacuum. The combination of increased gas generation and a better sealed landfill surface may also lead to increased subsurface lateral movement of LFG.

Cold and wet weather can make a significant impact on both the design, and operation and maintenance of a LFG control system. Cold and wet weather also may reduce accessibility to the landfill for monitoring and maintenance. Planning can be critical. Systems with centralized well monitoring and control stations make operation more convenient at sites prone to cold and wet weather. Special planning or other considerations may be required to address access to sumps and tanks that may require pumping during extended inclement weather conditions.

Operating staff should ensure that mechanical equipment, storage areas and electrical controls are protected from the effects of moisture intrusion due to precipitation and freezing. After a heavy rain storm, lubricant levels and conditions should be checked for signs of water intrusion, emulsification or other damage. The ignition system on the flare may also be affected by moisture and should be frequently checked.

14.3. DRY WEATHER OPERATION

Sustained dry weather may result in a period of reduced LFG generation and increased air intrusion will reduce the methane quality and volume. Steps to be taken during extended dry weather periods may include:

- Reducing the overall extraction flow rate
- Reducing individual well flow rates
- Inspect and repair cracks and breaks in the landfill surface

In very arid climates there is little to no leachate generated in the landfill. LFG migration will still occur and in such cases may be a significant contributing factor in ground water contamination. One characteristic of wells in dry landfills is that they typically have a much greater radius of influence than wells in wet landfills. This can be significant for dry landfills that have exposed outside slopes. Wells within several hundred feet of the slope may be able to pull in sufficient air to increase the potential of fires.

The accumulation of dust and its effect on equipment, especially electrical equipment, must be closely monitored. Electrical cabinets should be checked and cleaned at least annually, but may require more frequent attention under very dusty conditions. Accumulation of dust has been known to be responsible for catastrophic electrical equipment failure.

14.4. HOT WEATHER OPERATION

Hot weather has a number of effects that may impact the LFGCS. These potential impacts include:

- Potential drying and cracking of the landfill surface possibly increasing danger of subsurface fires
- Undesirable effects on electrical and process equipment
- Increased thermal expansion and contraction of piping (where temperature differential is increased).

Hot weather may have effects on process equipment operating temperatures and limits. The operator should be alert for the effects of solar radiation (increased UV damage) and heat absorption on equipment particularly on electrical control and motor control cabinets and their contents (i.e., thermal overload switches on motor contact or components). Excessive heat will affect the rating and performance of electrical devices, and may damage electronic instrumentation and displays. It is not uncommon for motor overloads to trip during hot weather. If this occurs, it may be necessary to increase the size of the overloads as allowed by the National Electrical Code. Be aware of the operating ranges of each piece of equipment.

Steps that can be taken to limit the effects of hot weather include:

- Paint exposed PVC pipe for UV protection.
- Prepare and be alert for fire potential.
- Cut and control weeds and vegetative cover.
- Provide shade for heat sensitive equipment
- Provide adequate ventilation for equipment that requires cooling (e.g., engines).

Do not leave monitoring instruments or any device with liquid crystal displays (LCDs), either covered or uncovered, in direct sunlight as they may be damaged.

14.5. LIQUID SATURATED LANDFILL CONDITIONS

Liquid saturated conditions in, or circulation of liquids within a landfill may substantially accelerate MSW decomposition and increase LFG generation in that area of the landfill. Liquid may also cover well perforations inhibiting LFG recovery from the well and raising operating vacuum required. Increased operating vacuum may also increase surface air intrusion (with or without a sealed landfill) and must be considered in well adjustment. In severe cases, the well may need to be periodically pumped.

The liquid level should be monitored and evaluated with response to the LFG well locations. This information can be helpful in assessing well performance

Many saturated landfills have LFG wells fitted with leachate pumping systems to pump down the leachate head to improve gas recovery and control. Such systems are typically more maintenance intensive than a "LFG only" system and considered a severe service for the pumping equipment.

14.6. LANDFILL FIRES

14.6.1. Landfill Fires - Causes and Avoidance

If very large quantities of air are introduced into the landfill in a localized area, either through natural occurrence or overly aggressive operation of the LFG system, a poorly supported subsurface combustion of the buried MSW may occur and carbon monoxide may be readily detected. Subsurface fires will produce temperatures of several hundred degrees Fahrenheit within the landfill. This typically results from short circuiting air intrusion into:

- The landfill/cover soil interface
- Cracks, breaks or imperfections in the cover/cap
- Breaks in buried collection piping and extraction wells
- Backfill surrounding collection system components (e.g., from the filter or gravel pack of an extraction well or the gravel backfill around a sump)

Subsurface fires are difficult to control or extinguish once initiated, can present health and safety hazards, and can be quite costly. Therefore, prevention by good operation of the collection system and maintenance of the landfill cover, is the best course of action.

14.6.2. Testing for Landfill Fires

A landfill may be tested for the possible presence of a landfill fire by monitoring carbon monoxide. Carbon monoxide is a byproduct of incomplete combustion and hence an indicator of a possible subsurface landfill fire. It is not normally found in appreciable quantities of LFG. Carbon monoxide may be evaluated using diffusion tubes such as those made by Draeger and others, by carbon monoxide gas analyzers, and by gas chromatography. Aerial thermal imaging can sometimes be useful in assessing the areas affected by a large or shallow subsurface fire.

By continuing to monitor the landfill for carbon monoxide and elevated temperatures the location and condition of a subsurface landfill fire can be ascertained. Every effort should be made to operate the LFG collection system so as not to exacerbate the subsurface fire condition. Temperatures within the landfill should be stabilized at or below 140 degrees and maintained as low as possible for as long as possible.

14.6.3. Treating and Extinguishing Landfill Fires

The best way to treat a LFG fire is to starve the fire of oxygen. To accomplish this, all sources of air intrusion must be sealed as much as is practical. It will probably be necessary to reduce the rate of extraction of LFG and in some cases shut down the LFG control system in and adjacent to the affected mass. In areas where a subsurface fire breaks out to the surface, the area should be smothered and sealed with additional cover soil. Wherever there has been a subsurface landfill fire there exists a potential for sudden, rapid subsidence (cave-in) of the landfill surface. Care should be exercised by personnel when using heavy equipment in areas affected by subsurface fires to avoid a very dangerous hazard that may result from sudden, rapid subsidence. If the mass affected is small enough, it may be excavated and removed or treated using heavy equipment.

In extreme cases, carbon dioxide may be useful. Carbon dioxide has been used to successfully treat subsurface fires. Carbon dioxide is used to reduce temperatures in the area of the fire by cooling and thus arresting the chemical pyrolysis that sustains the fire. An effort is then made to try to keep the internal landfill temperatures at reduced levels for as long as possible while monitoring temperatures and carbon monoxide. Since the landfill is a good insulator, the colder temperatures may usually be maintained in the subsurface environment for some time once they are achieved. Nevertheless, this approach is not for all situations. In the case of a large fire this would be impractical and such an effect is short lived. It requires special preparation and considerable amounts of carbon dioxide.

Some have attempted to treat subsurface landfill fires with water. This is not normally recommended. Water may saturate MSW but is generally ineffective against methane gas fires. Introducing large volumes of water into the landfill is often unacceptable to regulatory agencies. It is also difficult to control where the water travels within the waste mass, as it tends to channel. If water is deemed appropriate in a particular situation, consideration should be given to use of a surfactant or what is known in the fire fighting trade as "wet water." Note: Never attempt to fight an above ground methane fire with water.

If large enough or in a sensitive location, a subsurface landfill fire is a special emergency situation that may require uncommon action to successfully treat it. It should be viewed cooperatively as a special situation worthy of exceptional and specialized treatment by regulatory agencies for the benefit of the public.

15. DATA MANAGEMENT & EVALUATION

15.1. THE DATA - COLLECTION, ASSESSMENT AND MANAGEMENT

Much of the work of collecting and controlling LFG involves the collection, evaluation and management of LFG data.

This process of collecting, evaluating and managing data may be relatively simple or very complex. The level of complexity depends on the problems that a site presents, the evaluation or control objectives, resources available and budget constraints. The process may be as simple as measuring and recording several key parameters on a reading sheet and making immediate on the spot adjustments in the field or as detailed as performing systematic analysis using sophisticated software employing graphing or plotting data in multiple dimensions.

Graphing LFG data trends can be particularly useful. To evaluate trends graphically, it is ideal to represent various LFG parameters (e.g., methane, oxygen, flow etc.) on the "y" axis (dependent variable) versus a key determining parameter (such as flow) on the "x" axis (independent variable) over time (a third variable) represented by the "z" axis. Specialized computer software more powerful than the typical commercial business software is necessary to do this, however. New developments and tools are continually being applied to LFG data management.

15.2. DATA COLLECTION

Data is collected routinely using reading sheets from the blower-flare facility, the wellfield, migration monitoring probes, structures, etc. These "readings" become a part of the facility operating record. There may be a local regulatory requirement for the length of time the records must be retained. In the absence of other guidance, a retention period of at least two years is recommended.

Data may also be collected for flare temperature and facility LFG flow using a strip chart recorder. The strip chart also becomes part of the operating record and should be retained. With the advent of computerized control, key facility parameters can be transmitted to a remote site, and trend summaries, graphs, and management exception reports (flagging of data outside of specified acceptable ranges) can be generated.

15.3. DATA ASSESSMENT

Data assessment is a process of evaluating wellfield and process equipment monitoring data by applying analytical and mathematical techniques, inductive and deductive logic, and subjective judgment. It has already been pointed out that there are a great number of factors that impact well performance and adjustment. Even though there are many techniques that may be applied, there is no substitute for subjective judgment in assessing LFG control system data. Whatever assessment technique or system that is tried, there are always exceptions that require human recognition and intervention. Development of these skills requires experience and practice. A skill the technician should strive to obtain is the ability to look at a set of data and identify errors or inaccuracies.

During the initial start-up and operation of a LFG system, baseline data should be acquired. The data should be representative of normal (not unusual, imbalanced, or irregular) conditions. These baseline data may be used in the future for comparison with current data. This is an important task, since new equipment operating parameters can never be obtained again. Typical parameters include pressure, differential pressure, temperature, and flow. (See Table 15.1 - Example Baseline Parameters.)

TABLE 15.1 - Example Baseline Parameters

ITEM	PARAMETER	POSSIBLE SIGNIFICANCE
Collection Header	Vacuum/pressure drop	Excessive pressure drop or vacuum loss indicates breakage, leakage, or liquid surging or blockage
Inlet Separator	Differential pressure (ΔP)	Excessive ΔP indicates accumulation or partial blockage
Blower	Differential (total) pressure ΔP)	Decrease in ΔP indicates decreased performance or efficiency
Blower	Discharge temperature and differential temperature (ΔT)	For same flow (work) may indicate developing mechanical problems
Flame Arrester	Differential pressure (ΔP)	Excessive ΔP indicates accumulation or partial blockage
Flare Burner	(Back) Pressure	Excessive pressure may indicate blockage in burner orifices or other changed operating conditions

Pressure is frequently mentioned above because it is an easily measured parameter. Pressure changes with changes in the gas flow, hence a range of conditions should be recorded. Similarly, the temperature rise across a blower will change based on the flow through it.

With the above caveat in mind, equipment performance may be compared with past or baseline performance under similar operating conditions. Persons assessing the data should be aware of the normal operating range for each parameter and note any changes and the reasons for that change. Equipment deterioration that can be either sudden or very gradual may be indicated by an abnormal parameter. Any such indications should be promptly investigated or reported. Flare facility data should fall within established parameters for normal operating ranges for that equipment based upon service conditions. Manufacturers' information and equipment operating experience along with judgment are required to assess facility data and determine these ranges.

Sometimes these "expected" or "acceptable" ranges are placed on the reading sheet as a guide for reference. However, whenever readings are taken, the operator should be thinking about, observing and understanding what is occurring throughout the entire "process" and not rely solely and mechanistically on fixed target ranges. The readings should simply serve as "guideposts" to assist the operator in holistically evaluating the complete process and identifying any abnormal or incorrect condition regardless of whether or not it is listed on the reading sheet.

Over the years a number of data assessment techniques for LFG well fields have been developed including:

1) Compare current performance data with baseline data.

2) Compare data with tables of acceptable ranges and conditions cross-referenced with recommended adjustments

3) Directly compare monitoring data with target criteria (e.g., methane, oxygen, nitrogen residual, wellhead vacuum, flow, etc.)

4) Assess individual well data parameters with subjective judgment (No specific analytical or mathematical method used)

5) Determine desired target well flow by a compensation factor (either fixed or determined by any one of a number of bases) applied to measured well flow.

6) Apply a weighted mathematical algorithm or formula to determine a new target flow rate, or methane or oxygen level, or other bases of well adjustment.

7) Perform a summation of total wellfield flow and comparing with predicted or prior demonstrated acceptable wellfield flow. This may be used to develop a compensation factor to calculate individual well flow targets and readjust the wells

8) Differentiate between air intrusion through landfill cover and waste mass, and collection piping leakage, and compensating accordingly (See 9. below.)

9) Evaluate of nitrogen residual by measuring nitrogen with a gas chromatograph or calculating nitrogen as a balance gas.

10) Compare a summation of individual well data with total composite wellfield flow, while accounting for piping leakage and flow measurement error.

11) Determine carbon dioxide to methane ratios (This method is simply an indirect method of reflecting nitrogen residual and the more direct method of observing nitrogen residual is recommended instead.)

12) Compare with a determined performance standard determined from field testing procedures (static, dynamic pump down, or probe influence testing)

13) Perform a special analysis of the extraction well, monitoring probe and waste mass boundary

14) Analyze surrounding lithology, geology, hydrogeology, natural and man-made pathways.

15) Present data trends in graphical and tabular formats.

These techniques should be used in conjunction with target criteria and established acceptable performance ranges for each extraction well. Refer to the guidance provided for wellfield adjustment and target criteria ranges in Chapter 9 - Monitoring and Adjusting the LFG Collection Wellfield and Collection System.

In addition, data may be assessed and related to other significant data such as perimeter migration probe monitoring, surface emissions monitoring, atmospheric, and shallow landfill surface or other influence probe data.

15.3.1. Facility Daily Log Book

Whenever the facility is visited for any reason, visiting staff should make appropriate entries in the Daily Log Book that is usually stored in an agreed upon location. As a minimum, log entries should include:

- Name of person making the entry
- Date and time

- Reason for the visit (e.g., routine, shutdown, specific monitoring or maintenance activity, etc.)
- Reason for any shutdown
- Actions taken or adjustments made
- Equipment status upon leaving
- Unusual observations made.

The daily log is used as a record of events regarding the facility and to communicate between operating personnel. The log entry also becomes part of the daily facility readings. Log entries may be color coded to indicate key activities such as routine scheduled maintenance, unscheduled shutdowns, "call-outs" (i.e., response to the facility during off-hours for a shutdown or other problem), etc. This can be helpful in quickly identifying a specific type of activity or occurrence such as equipment shutdowns, regulatory issues, or maintenance performed.

15.3.2. The Data Collection Routine

Data is usually collected manually in the field at the individual data points, i.e., at wells on the landfill, at migration monitoring probes surrounding the landfill, etc. Data may be recorded on paper reading sheets carried on a clipboard or entered into a data logger. Automated data collection using data loggers is becoming a more significant practice. These allow direct downloading of the data from the monitoring instrument to a computer. There is much interest in automated data collection and control. This works well for flare stations or recovery facilities where the system is controlled by a PLC or computer. For well fields, however, this is not been implemented to any significance as yet.

The typical data collection routine involves walking or driving around the landfill from point to point. Walking may be less practical on larger sites, however walking is better to visually inspect the entire LFG control system on a regular basis. It is often desirable to have monitoring locations clustered together. Monitoring access ports and wellheads are some times located at the collection header rather than on the well casing. This provides for convenience and ease of access during inclement weather. This can also avoid the difficulties associated with accessing vaults located throughout the wellfield.

Data points (wellheads, probes, header access ports, etc.) are numbered using some logical numbering scheme. It is important to maintain records of changes if at some time the system is modified or renumbered. It may be necessary to reference back to data collected under the old numbering scheme or original boring logs in assessing data and trends.

Equipment typically used for data collection includes:

- Monitoring instruments

- Monitoring vacuum pump
- Data reading sheets or data logger
- Clipboard and writing implement
- Pocket calculator
- Site map of the data points
- Carrying tray, tool box or backpack, etc.
- Calibration gases
- Tools needed to access the wellhead vault
- Spare parts for maintenance such as access ports, plugs, etc.

15.4. MANAGEMENT AND REPORTING OF DATA

15.4.1. Computer Data Entry

Often times collected data is transferred into a computer program. Data entry may be accomplished in one of several ways:

- Entry on data manually into a computer.
- Transfer of data using a data logger
- Transfer of data using a dedicated, integrated LFG monitoring instrument.

The ability to evaluate data changes over time is a powerful tool.the operator can use. This task is simplified by using a database versus doing it manually.

A computer database may either be developed using available commercial database software which has been programmed by the user or others or a proprietary program designed for environmental data management.

15.4.2. Reporting Data

Frequently reports are prepared for internal documentation, landfill management, and regulatory agencies. Data may be reported in several ways. Activities and significant events occurring during the reporting period should be summarized. Data may be presented as collected in the form of "raw" reading sheets, however some prefer to enter the data in the spreadsheet or database and present the data in tabulated form. It is usually best to also present the data in graphic form whenever practicable.

By far a most common practice which can also help in analyzing the data, is to enter the data into spreadsheet software. If a database or spreadsheet is used, the data can also be printed out in tabular form or in the form of graphs. Tabular and graphic data may be attached to reports. In reporting data, the data should be summarized.

16. INSTRUMENTATION

16.1. INSTRUMENTATION PRINCIPLES

16.1.1. Understanding Instrument Theory and Construction

There are many types of instruments used in LFG monitoring. A general understanding of basic instrument theory is important. Learning how to use, calibrate and maintain portable field instrumentation is especially important when working with explosive gases and in situations where oxygen deficiency may occur.

Most basic portable instruments are a combination of a detector or sensor element, an electronic circuit that responds to the detector or sensor and a user interface such as an analog current meter or digital meter. The electronic circuit amplifies the signal and, in some cases, may condition or modify the signal as well. In order to allow measurement of the phenomena of interest, the instrument must be calibrated.

Sometimes the term indicator is used rather than analyzer to indicate the inherent lack of precision of the instrument. In other words, the instrument may be relied upon to indicate the presence of a combustible gas but may not measure it accurately. An example is a simple combustible gas indicator or analyzer (CGI or CGA). The accuracy of any given instrumentation depends critically upon its accurate calibration. These instruments can read the presence of most combustible gases, hence, if it is calibrated for methane, other gases that are present may cause some amount of error in the reading.

The typical CGI uses a thermal conductivity sensor to detect methane. The thermal conductivity sensor which is simply an open air resistor is made a part of an electronic circuit known as a Wheatstone bridge (see Figure 16.1). The circuit typically includes three additional resistors one of which is variable. This resistor is used to vary the output of the circuit. In this way the circuit can be balanced or calibrated.

As the sample gas passes through a sample chamber in the instrument which contains the sensor, the gas cools the sensor element (resistor) changing its resistance. This change is seen as a meter needle movement (deflection) on a current measuring meter connected to the electronic circuit. The meter can be scaled and calibrated so that the amount of meter needle movement corresponds to the amount or concentration of methane or other hydrocarbons present in the gas.

CGIs and CGAs are for measurement of explosive levels of combustible hydrocarbon gases in the percent range. The instrument is meant for measurement of combustible gas in air. LFG however is primarily a mixture of methane and carbon dioxide. As a result, if oxygen is not present, some CGIs will not read accurately, or at all, on the low range (0-5% methane). On the high range (0-100% methane) when these instruments are carefully calibrated using a gas mixture similar to the LFG being measured, a CGI or CGA can usually be made to perform reasonably well.

An oxygen indicator works similarly in that an oxygen cell can be connected to a Wheatstone bridge. With the oxygen cell, oxygen diffuses through a membrane and results in an electro-chemical reaction generating electrical current flow. This causes meter movement in relation to the amount of oxygen present.

16.1.2. Instrument Characteristics

In understanding the operation of instrumentation and in evaluating performance or selection of instrumentation, an understanding of the characteristics of the various types of instrumentation is desirable. These characteristics are listed for consideration as follows:

- Operating principle and sensor type
- Detection range
- Accuracy
- Resolution
- Response time
- Acceptable operating ranges and conditions (e.g., temperature)
- Incompatibilities, interference, cross sensitivities, and sensor poisons
- Portability, ergonomics, and ease of operation
- Data logging and transfer capability and features and computer interface (method, type)
- Technology
- Reliability
- Durability
- Economy
- Selectivity (ability to distinguish between gases)
- Battery life, battery drain characteristics
- Power supply
- Ease and frequency of calibration
- Warranty
- Approvals, codes and standards (e.g., Factory Mutual, UL, CSA, etc.).

TABLE 16.1 - Sensor/Detector Types

Type	Common LFG Application
Thermal conductivity detector (TCD)	Methane 0-100% range
Catalytic combustion sensor (CCS)	Methane 0-5% range
Flame ionization detector (FID)	Methane ppm range
Infrared Bench Detector	Methane 0-100%, CO_2 0-100%
Chemical Reaction	Oxygen, H_2S, CO

16.1.3. Instrument Response

The response of any instrument will be specific to that instrument design, the detector(s) employed and the principal by which they operate, and the nature of the monitored sample. Since the constituents found in LFG will vary from site to site and over time, this will also affect instrument response. Examples are given in the discussion on some of the specific types of instruments. Response may vary with the type of hydrocarbon, pressure, humidity, altitude (atmospheric pressure), a compounds photo-ionization potential, etc.

Instrument Error

The most common cause of error in monitoring readings is a leak in the sample train. Leak checking should be done frequently, often before each reading.

16.1.4. Instrument Use

Before using the instrument, read the manufacturer's instructions and principle of operation. Each time before using an instrument, make sure it is properly calibrated and fully charged. Record the calibration information in a calibration log identifying the instrument serial number. For extended monitoring periods, take along spare batteries and calibration gas for verification of calibration.

During use, be alert to the potential for loosened connections of sample hoses, etc., that may cause sample leakage. Monitor battery charge level periodically. Recheck calibration when necessary. Avoid getting liquid into instruments when monitoring. Check the instrument filters periodically. Do not expose the meter to anything that will poison or damage the detector, or otherwise cause the instrument to malfunction. An example is silicone sealant vapors that will damage the catalyst in the catalytic combustion sensor (CCS) of some CGAs. Make sure sufficient oxygen is present when required by the instrument detector to operate. If oxygen is not present at the concentration level present for proper instrument function, note the fact in the reading sheet

When finished with the instrument, recheck and record calibration, clean the instrument and prepare it for its next use.

16.1.5. Special Considerations

Some of the issues that may require special consideration in planning and conducting various monitoring and sampling activities are as follows:

- Calibration
- Altitude
- Humidity
- Liquids or liquid accumulation in the sample stream
- Operating temperature range
- Oxygen cell inhibition limits (for CO_2)
- Calibration gas availability, logistical requirements (e.g., shipping restraints on compressed and flammable gases)
- Interferants and cross-sensitivities
- Catalyst and filament poisons

16.1.6. Instrument Calibration

Calibration requirements will vary with each type of instrument. Follow the manufacturer's directions. Record and maintain the calibration information in a log.

Use the correct calibration gas mixtures. Check that the calibration gas pressure, flow and temperature are correct. It is best to meter calibration gas using a pressure regulator, needle flow control valve, and a rotameter flow gage. Excess pressure can be relieved using a tee configuration of tubing and a needle valve. Another option is to fill a Tedlar™ bag with calibration gas from which the instrument draws its sample.

High Pressure Gas Bottles

Ensure high pressure compressed gas cylinders (CGCs) are properly, permanently, and individually fastened to a secure structure in the upright vertical position. Some compressed gas suppliers sell regulators for gas metering and brackets for securing CGCs.

16.2. PORTABLE FIELD INSTRUMENTATION

16.2.1. Combustible Gas (Methane) Analyzers (CGAs)

The three most common measurement scales found in combustible gas indicators are:

- 0 to 100 percent volume (% vol.)
- 0 to 100 percent lower explosive limit (% LEL) (equivalent to 0 to 5 percent volume)
- Parts per million (ppm).

CGAs may feature at least two scales; a percent volume scale and a percent LEL scale. As previously mentioned, the percent volume scale employs a thermal conductivity detector (TCD) sensor. The LEL scale function employs a catalytic combustion sensor (CCS). When present, the parts-per-million scale function also uses a CCS.

An important aspect of understanding the use of CGA is the performance characteristic of the CCS sensor. On an analog meter, if the CCS becomes overloaded (above the LEL level) the indicating needle on the meter will "peg" on the scale, in other words go to the maximum end or past 100 percent LEL (usually to the extreme right), then quickly drop back down to zero or below. If the instrument operator is not careful to observe this potential response, he or she may conclude that no methane exists, when in fact the level is beyond the ability of that scale to measure. Whenever in doubt, always check the response on the 0-100% methane scale first.

For the above reason, and because certain CGA instrument designs swap the function of the reference chamber and the active sampling sensor chamber when scales are changed the instrument must be cleared with uncontaminated ambient air between readings and when changing scales if required by the manufacturer.

Some detectors require a minimum level of oxygen in order to function. This depends on the detector employed. Where combustion (catalytic or open flame in a secure chamber) is involved in the detection principal varying levels of oxygen are required. This limitation must be kept in mind when using the instrument in order to obtain expected results and avoid erroneous data, such as a false negative response. This is true of the CCS and FID detectors in most CGAs and in the OVA/FID. Consult the instrument manufacturer's instructions and recommendations.

Keep the Gas Sample Dry

It is important to provide a liquid trap and filtration to prevent liquids and particulates from entering instruments. LFG as it leaves the wellhead is typically warm. Condensate water can condense inside the sample tube. Because of this, locate the liquid trap as close to the instrument as possible.

16.2.2. Oxygen Analyzers

The operation of an oxygen analyzer is similar to the operation of a methane analyzer. Analyzers may employ a hand or automatic pump. The analyzers commonly in use typically have a 0 to 25 percent oxygen scale. Some also have a 0 to 5 percent scale which is most useful where it is commonly necessary to measure and control oxygen between 0 and 1 percent (vol.). In analog meters, this scale provides better resolution over the range of interest (0 to 1 percent vol.). Some analyzers incorporate both the methane and oxygen analyzer functions in a common instrument.

In the typical oxygen meter, the sample stream is passed in contact with the oxygen cell. Most oxygen meters use what is known as a wet chemical cell or fuel cell to measure oxygen in the sample. As oxygen permeates a thin membrane, the cell generates an electrical current due to an electro-chemical reaction within the cell. Some oxygen cells are subject to poisoning, including poisoning by carbon dioxide. As carbon dioxide is a major constituent in LFG, instruments in this service may require a carbon dioxide inhibited cell to provide adequate cell life. Check with the instrument manufacturer.

Most cells can be calibrated to the oxygen in air (20.8 percent oxygen) and many cells' performance is relatively linear so that accuracy should extend to zero percent oxygen. This provides convenience in calibration but it is still a good idea to confirm performance with a zero gas or a low level span gas of interest, for example ½ or 1 percent oxygen (volume). Sometimes this percentage of oxygen is specified in a calibration gas mixture when a four component mixture is used (CH_4, CO_2, O_2, N_2). For this purpose 1 percent is commonly used.

When measuring oxygen in LFG, it is important to keep the sample pressure within the range recommended by the instrument manufacturer. Sample pressure can affect the accuracy of the reading because the oxygen cell is affected by pressure.

It is important when calibrating the oxygen meter to calibrate the meter at the same altitude and locale as where it will be used. This is because the meter measures the partial pressure of the oxygen in the gas and is affected by changes in atmospheric or sample pressure. For more information refer to the section on instrument calibration.

If sufficient oxygen is present in the gas to form an explosive mixture then a safety hazard exists. It is important to keep the oxygen level in the gas below any level that may approach a hazardous condition. See the discussion in the Health and Safety Section.

As with CGAs, it is important to provide for filtration to prevent liquids from entering the instrument.

16.2.3. Carbon Dioxide Analyzers

Carbon dioxide may be measured in the field using one of the following instruments:

- An Orsat type device such as a Bacharach Fyrite™
- An infrared type instrument
- A portable gas chromatograph.

The Fyrite™ analyzer or Orsat type device is a simple and easy to use instrument. It employs the principal of volume reduction of the vapor phase in the instrument by the selective absorption of carbon dioxide into a chemical fluid. The corresponding fluid expansion is read out on a scale. Orsat type devices are typically used to measure carbon dioxide and oxygen in the exhaust of fired combustion equipment such as boilers and furnaces. The gas sample is pumped into the sample chamber then the analyzer unit is inverted numerous times until absorption of the carbon dioxide fraction is complete. The reduction in vapor volume is then measured by a rise in the liquid level caused by the vacuum above it (from the reduced vapor volume) indicating the percent of carbon dioxide by volume in the gas. Accuracy of plus/minus 1 percent can be achieved with fresh fluid. Performance can be verified with calibration gas.

16.2.4. Dedicated LFG and Hybrid Analyzers

A new family of hybrid gas analyzers has been recently made available to the LFG operator. They are now becoming widely accepted as standard instruments for LFG wellfield monitoring. These units incorporate many instrument functions into one, however, they are more expensive than traditional CGA's, but are considerably more convenient and practical. The combination of several instruments into an integrated package provides greater portability and considerable savings in instrument weight. A key time saving feature of this instrument is logging and uploading data to a computer. This saves the technician time and allows him or her to get more done in the same amount of time.

Figure 16.3
Landfill Gas Monitor
Source: LANDTEC®

The use of an infrared analyzer on some instruments provides a different approach than that of the CGA. An advantage is a different detection principle which detects carbon dioxide as well as methane. In combination with an oxygen detection cell, three of the four major components of LFG can be detected, as previously mentioned. Nitrogen cannot generally be detected with direct reading field portable instruments. However, the instrument uses an algorithm to sum the other three major components in LFG, then subtracts that total percentage from 100 and reports the "balance gas."

As with CGAs and oxygen analyzers, it is important to provide for filtration to prevent liquids from entering the instrument.

16.2.5. Portable Gas Chromatograph

Portable gas chromatographs are now available that are practical, stable in their performance and relatively fast in producing analysis results. They are however relatively expensive when compared to direct reading portable field instruments and tend to be most appropriate in energy recovery applications, particularly high BTU recovery.

An example of a modern portable gas chromatograph uses the micro capillary tube. This instrument can sample and analyze four gases in about 1 minute. A laptop computer is required to integrate the results of the analysis and report the gas concentrations.

16.2.6. Pressure Reading Instruments

Portable pressure instrumentation is used to monitor pressure at monitoring probes, extraction wells, along collection header piping and in the blower-flare facility or other treatment or recovery equipment. Pressure instruments are also used to measure differential pressure access flow elements and process equipment such as scrubbers, blowers, and flame arresters.

In most LFG wellfields pressure and vacuum is read in units of inches of water column (w.c.). Typical vacuum readings in probes can be measured in units as low as tenths and hundredths of an inch of w. c. In the gas collection system, vacuum is usually measured in the range of 0 to 100 inches of w.c. In the blower flare facility pressure and vacuum are measured in inches of water column and pounds per square inch (psi) gage.

A very common instrument in wide use in the LFG industry is the Dwyer Magnehelic™ gauge for low pressure and vacuum readings. Magnehelic™ gages are available in a number of ranges from as low as 0 to 0.25 inches w.c. to as high as 0 to 150 inches w.c. Low range gauges provide the needed resolution for monitoring subtle pressures in soil, the landfill waste mass and in perimeter and well influence probes.

A simple device for low pressure measurement is the slack tube manometer. The slack tube manometer is a piece of clear plastic tubing filled with colored water with a scale delineated in inches. The slack tube manometer may be purchased or fabricated. They can be quite cumbersome to use and handle in the higher pressure ranges because of the tube length required.

Digital electronic manometers are also available. They are more convenient than carrying a range of gages but may not be as accurate, particularly in the lower pressure ranges. They usually have several scale ranges and are very convenient to use. One caution is that the accuracy is usually stated as a percent of full scale of the highest range. This means that accuracy will be poor in the lower ranges. Because of the digital readout the apparent precision and resolution of these instrument is much greater than the actual. In some digital manometers, the gas media is in contact with the electronics. Because of the corrosive nature of LFG, these instruments may be subject to early failure.

Span calibration of low pressure reading instruments can be verified by using a column of water or slack tube manometer to verify pressure applied to the instrument in question.

16.2.7. Portable Flow Measuring Instruments

Portable flow measuring instruments are used to measure flow at wellheads and at pipe ports. There are several types of portable flow measuring instruments available. One type in common use is the "hot wire" anemometer. These instruments are fairly repeatable but accuracy is affected by changes in gas composition, and gas content. Two of the manufacturers of anemometers that are frequently used on LFG are TSI and Kurz.

A standard pitot tube can be used, however due to the small ports in the instrument it is subject to liquid plugging. Standard pitot tubes require adequate room below the monitoring port so that they can be inserted. Pitot tubes are readily available through Dwyer.

Another type of instrument is a Velometer a type of averaging pitot tube. These instruments work reasonably well and are repeatable. An example is the Alnor™ velometer. Of the various types of portable flow measuring instruments, it is one the best choices. This device works strictly by differential pressure, hence it has no electronics and does not require batteries.

16.2.8. Temperature Reading Instruments

Temperature instruments range from a basic mercury thermometer (which is not very practical) to gages to digital thermometers and thermocouples. One-inch bimetalic thermometers are sometimes used on LFG wellheads. There are many different types and brands available.

Calibration of temperature instruments can be verified by immersion in ice water (32 deg. F.) and boiling water temperature based on barometric pressure.

16.2.9. Barographs & Barometric Pressure Instrumentation

A barograph is an instrument that measures and records atmospheric pressure. For the reasons mentioned in the discussion on atmospheric pressure effects on LFG, a barograph, can be very desirable and in some cases absolutely necessary to effectively assess the LFG migration. Important features of the barograph are the power source, the resolution, the chart length or time period, and chart speed.

The range and resolution of the barograph should be appropriate to the context of LFG and probe pressures. Normally resolution is in tenths of an inch of mercury. Resolution of as low as one hundredth of an inch of water column would be desirable, but is not commonly available. Any barograph will at least indicate the trend of rising and falling atmospheric pressure which is very useful and relevant information.

Consideration should be given to the power requirements and servicing period required by the barograph. The barograph may be powered by either a key-wind mechanism, battery, or AC power.

In considering placement of a barograph, locating it close to the landfill is desirable. It is also important to avoid placement in an environmentally sealed or "tight" building as this will cause inaccurate or erroneous atmospheric pressure readings. In these circumstances, air conditioning turning on and off can cause the barograph needle to change. The user should be able to generally see a clear correlation between atmospheric pressure effects and monitoring probe data.

16.2.10. Vacuum Pumps

A portable vacuum pump is often necessary to supplement internal pumps in portable instruments. A portable sample pump is desirable to purge deep probes and to overcome relatively high system vacuum. Pumps may be battery operated, operated remotely from a vehicle, or manually operated. Squeeze bulbs are the most common type of pump. When using electrically operated pumps (battery or other) it is extremely important that the pump and switch not generate spark that could ignite the LFG mixture.

16.2.11. Colorimetric Indicating Tubes

Colorimetric indicating tubes are typically used for detecting broad classes of chemicals for initial characterization, particularly in hazardous materials work. There is a potential for misuse on landfills if attention is not paid to the potential for cross-sensitivity and canceling effects of the tubes. They cannot be expected to work in all situations. They have a wide tolerance of accuracy and are suitable for indication only. Carbon monoxide (CO) tubes and hydrogen sulfide (H_2S) tubes are used in LFG application

16.2.12. Organic Vapor Analyzer - Flame-Ionization Detectors (FID)

The OVA/FID is a key instrument for LFG emissions work. There are several brands and models available. The OVA/FID is used to measure a range of from 0 to 10,000 ppm hydrocarbon as units of some hydrocarbon to which the instrument is calibrated. In the case of LFG work, the appropriate calibration and unit of measure is methane. Methane is then relied upon as a "surrogate" for total hydrocarbons. The OVA/FID may be used for a number of LFG applications:

1) The OVA/FID is commonly used to measure surface emissions.

2) The OVA/FID can also be used to monitor LFG probes at ppm levels (when necessary) when sufficient oxygen is present in the probe. This will not always be the case even when only low ppm levels of methane are present because aerobic bacteria may consume the oxygen in the soil.

3) The OVA/FID can also be used in the blower-flare, treatment or energy recovery facility to monitor for fugitive emissions.

4) The OVA/FID may also be used in special investigation activities such as monitoring structures off site, monitoring bar punch holes and driven probes and other special investigative techniques.

16.2.13. Organic Vapor Analyzer - Photo-Ionization Detectors (PID)

The photo-ionization detector based OVA is inappropriate for use on landfills and is not recommended for use on them. Because of the principle of operation, the OVA/PID cannot be relied to provide an appropriate or meaningful response on landfills due to the considerable number of constituents simultaneously found in LFG and the varied combined response by ionization-potential to any number of unknown trace constituents in LFG. Some instruments also exhibit a canceling effect (negative response) due to the predominant presence of carbon dioxide and methane in LFG.

16.2.14. Battery Supplies and Options

Extra and external battery supplies are often available from the instrument manufacturer or may be fabricated. It is recommended that extra batteries be readily available when performing monitoring. Some instruments may be operated from a vehicular power source (12 VDC). Note that external connection of a battery supply or other power source may invalidate the classification or rating of the instrument for working in classified or hazardous locations such as an environment where methane is present.

16.2.15. Data Loggers

Data loggers are available as separate stand alone devices and may also be built into portable instrumentation. The benefit of using a data logger is the ability to upload data into a computer for data analysis and reporting and unattended data logging in some applications

16.2.16. Calibration

The need for calibration cannot be over emphasized. Monitoring performed with instruments that are inaccurate could lead to problems if decisions are made based on the readings.

A typical calibration procedure involves introduction of an appropriate calibration gas mixture (see below) at a pressure, temperature and flow within the limits specified by the instrument manufacturer and representative of field conditions. Typical conditions might be very close to ambient pressure and temperature and a flow rate of 0.1 to 0.2 liters per minute (lpm). It is important the calibration conditions approximate conditions under actual sampling . The procedure is usually specified by the instrument manufacturer. However, the procedures indicated by the instrument manufacturers often addresses instrument use for detection of explosive gas safety hazards not LFG applications. Adjustment of the instrument is typically instrument specific. Setting the calibration involves adjustment of the potentiometers (variable resistors) located on the instrument circuit boards according to the manufacturer's instructions. With conventional instruments, it may be necessary to adjust calibration span and zero potentiometers following manufacturer's directions several times. An iterative process of zeroing and spanning the instrument is performed until calibration can be repeated and verified without further adjustment being necessary.

In the case of the dedicated, integrated LFG analyzer, calibration may be menu driven. When calibrating these types of instruments follow the manufacturer's direction and specific recommendation for calibration gas mixtures. Using a four component calibration gas mixture commonly used with TCD based instruments may lead to inaccurate or incorrect calibration results with dedicated LFG analyzers that employ infrared sensors.

As a standard practice a log or record of the calibration is normally kept indicating the serial number date and calibrated response. Calibration logs are maintained and are backup documentation that may be required when monitoring information is reported.

With certain types of explosibility monitoring, calibration and maintenance of a calibration log may be a legal requirement. Examples are when checking confined spaces and performing "hot work" or welding. There may be a mandatory retention period for such logs. The operator should review and be sure of the legal requirements in such cases.

16.2.17. Calibration Gases

For simple CGAs and oxygen indicators a four component mixture representative of the LFG to be measured should be used. The rational for selection of the span gas calibration gas mixture concentration levels is as follows:

Methane—A concentration should be selected that approximates the most typical or most important concentration level anticipated. For example, for monitoring interior extraction wells the target level for methane, e.g., 47 percent, may be appropriate. For monitoring of a perimeter migration control wells, where the landfill is old, methane quality is low or has declined, a concentration level of 39 percent may be more appropriate. For monitoring migration probes; 1% may be appropriate. Calibrate every range on the instrument.

Oxygen – The concentration of oxygen is selected based upon the low level concentration range of interest. The upper range is usually calibrated using air. Oxygen levels in LFG may range from zero to several percent or more. As a result nominally 1-2% O_2 in LFG is commonly used. It is certainly desirable to keep oxygen levels below ½ percent in extraction wells and 1 percent in control wells.

Nitrogen – The concentration level of nitrogen is selected based on the level of nitrogen that is most typically seen in the LFG being monitored. A range for nitrogen LFG in an active extraction system is about 4 to 18 percent. Refer to the discussion on nitrogen levels and extraction well overpull elsewhere in this manual. The level of nitrogen and carbon dioxide may be adjusted to accommodate the desired span concentration levels of methane and oxygen.

Carbon dioxide – The balance of the gas may consist of carbon dioxide to make up 100 percent of the mixture. The gas blender will make one gas as the "balance gas" to "take up the slack" of deviation or allowable error of blending. For the best results, carbon dioxide should be specified as the balance gas for mixture blending purposes. The normal range for carbon dioxide in LFG is approximately 32 to 44 percent.

CGA Calibration Gas

For conventional CGAs well monitoring applications an example recommended mixture is as follows:

Methane:	47 %
Oxygen:	1 %
Nitrogen:	12 %
Carbon dioxide:	40 %

(Total 100 percent)

For the CGA, the more representative the span concentration level the more accurate the field readings are likely to be.

The calibration gas mixture containing carbon dioxide may also be used to check calibration of the Orsat type carbon dioxide detector.

In situations where a gas chromatograph is used, hydrogen or carbon monoxide may be added to the calibration gas mixture for special purposes. Carbon monoxide may be present in the case of a landfill fire and can be detected by GC-FID.

Hydrogen is sometimes present in LFG and can affect the response of CGAs. If a calibration gas mixture containing hydrogen is used with some CGA instruments it will significantly affect instrument response. The typical CGA-TCD response to hydrogen is 5 times greater than that to methane. Thus, 2 percent hydrogen may equal a response of 10 percentage points of methane. This can contribute to instances where from 65 to greater than 100 percent have been recorded. This response will usually be discounted as it is usually due to hydrogen present in the LFG, or in some cases other trace hydrocarbons, to which the meter detector is very responsive. If unusually high readings are recorded, it may be desirable to collect a gas sample for laboratory analysis to find out what is happening.

In the case of instruments employing an infrared detector such as LANDTEC's GEM-500™, follow the exact calibration gas recommendations of the instrument manufacturer. The conventional four component gas mixture is inappropriate and may result in inaccurate performance with infrared bench based instruments. The infrared bench can also be affected by other hydrocarbons because the basis of response is entirely different from that of a CGA.

It is a common and desirable practice to calibrate the monitoring instrument immediately before and after monitoring has been performed. In instances when instrument supply voltage may drift due to battery drain, or in the case of a long monitoring day, it may be desirable to check (not recalibrate) calibration and record the results. In this way the operator or data interpreter may verify stability of calibration and may relate instrument calibration drift to the monitoring data. In cases where drift is severe, at least some interpolation may help to better interpret or "save" the data.

Calibration gas may be carried in the field in small DOT 39 series disposable containers, Tedlar™ bags, or small standard gas cylinders. When transported, gas cylinders should be properly secured, stored and mounted. In some instances, vehicle placarding may be required.

17. LFG LABORATORY ANALYSIS

Laboratory analysis is sometimes performed to determine the trace composition of LFG and to more precisely verify the major or "fixed" components, i.e., methane, carbon dioxide, nitrogen and oxygen. A variety of types of laboratory analysis can be performed. One common analysis is for major constituents of LFG which include methane, carbon dioxide, nitrogen and oxygen. Such analysis may also include hydrogen or carbon monoxide if the appropriate laboratory equipment is used. Other analysis may be performed for identification and quantification of trace gases.

A standard laboratory technique for characterization of a gas mixture is known as gas chromatography. The gas chromatograph uses a device commonly known as a "column" through which the gas is passed. The column is used to separate the gas stream into individual gases as a function of heat and time. The process involves selective molecular separation by absorption or adhesion and desorption of each of the constituents. There are two main classes of columns, capillary and packed columns. Additionally there are hybrids of these two classes.

Compounds are identified by the time it takes them to elute (become released) from the column. When more than one compound elutes at the same or close to the same time they are said to co-elute. In such a case, additional or a different analysis is required to distinguish the compounds. Gases leaving a column pass through a detector where the total amount of each constituent is measured. A detector is a device that employs a specific physical principle to detect and measure specific compounds or classes of compounds.

Numerous detectors are available for different purposes. Detectors are named by the physical principle by which they work. Available detectors and their common abbreviations and function are described in Table 17.1 as follows:

TABLE 17.1 - Table of Detectors used for Laboratory Analysis

Detector Type	Typically Used For
Mass-spectrometer (MS)	Identification and semi-quantitation of constituents
Thermal conductivity (TCD)	Quantification of fixed gases
Flame-ionization (FID)	Quantification of hydrocarbon gases or combustible gases (e.g., carbon monoxide)
Photo-ionization (PID)	Quantification of constituents capable of photo-ionization

Detector Type	Typically Used For
Electron Capture (ECD)	Quantification of compounds containing halogens (e.g., chlorinated hydrocarbons)
Flame-photometric (FPD)	Quantification of sulfur compounds when used in the sulfur mode (e.g., hydrogen sulfide)

By coupling one or more detectors to a gas chromatograph the laboratory technician can use various techniques to separate and measure the constituents in LFG.

The mass-spectrometer (MS) is a very powerful detector for identifying chemicals or compounds. This is because the mass-spectra pattern is unique for each chemical compound. A common practice is to run a check against a library of more likely or commonly expected chemicals. However, the GC-MS is frequently treated as if it can simultaneously identify all possible compounds that may be present in a sample. The GC separates components prior to measurement by the MS. A list of "tentatively identified" compounds is usually developed that may be confirmed through additional analysis. It is not very practical to attempt to identify all the constituents in a particular sample of LFG because there are so many. Therefore, analysis tends to focus on specific classes of pollutants that are of concern for regulatory or health and safety reasons.

Limits of detection may be higher than desired if the sample is composed of numerous compounds. This high saturation of compounds may, in some cases, mask lower concentration levels of other compounds. The limits of detection will be in part determined by the matrix and nature of the sample. In order to reliably match expectations of results the equipment and methods must be carefully matched to the classes of compounds that are of interest.

The thermal conductivity detector (TCD) is commonly used to measure the major (sometimes called fixed, permanent or elemental) gases found in LFG. This is one of the most common detectors used for LFG analysis. It is frequently necessary or desirable to measure the percent volume concentration of the principal major constituents in LFG. It is usually a good idea to periodically confirm results obtained using field instrumentation prior to laboratory analysis.

The flame-ionization detector (FID) is another commonly used detector that is used in various forms in both laboratory and field instrumentation. The FID is used to measure hydrocarbons in LFG and air. Hydrocarbons are separated and identified through chromatography. The hydrocarbons are then quantified by flame-ionization, that is by burning (ionizing) the sample constituent in a hydrogen flame.

There are other detectors which are not discussed here that are not generally applicable to LFG analysis.

There are also other specialized methods designed to accomplish a specific analytical task. A common method used for LFG is EPA Method 25. The procedure separates methane, non-methane hydrocarbons, carbon dioxide and carbon monoxide and quantitates each category by counting carbon molecules using flame-ionization detector. The non-methane hydrocarbon fraction may then be commonly reported as methane (C1) or hexane (C6). This method is useful to measure the concentration of trace hydrocarbons in LFG. Note that there are several variations of Method 25.

The use of analytical laboratory instrumentation such as a gas chromatograph is a valuable supplementary tool to verify gas composition. This normally requires collection of samples at the wellhead and analysis at some fixed location where the equipment is located. The drawbacks of relying on this method as a primary means for well field adjustment are time expended, cost, and probably most important, responsiveness to the needs of the wellfield for timely adjustment. Samples are typically collected in Tedlar™ bags, Summa™ canisters, or stainless steel canisters.

18. FACILITY MANAGEMENT AND OPERATION DOCUMENTATION

18.1. FACILITY MANAGEMENT PRINCIPLES

18.1.1. Facility Management Requirements

The level of effort for facility management will vary considerably depending upon the size of the LFG control or recovery system, operational objectives, equipment complexity and logistics, extent of facility problems (such as LFG migration, groundwater impact, etc.) and energy recovery efforts.

Generally it is desirable to provide for periodic oversight and review of important functional activities. These include:

- Migration monitoring and assessment
- Wellfield monitoring and data review
- Facility maintenance management
- Facility permits and regulatory compliance
- Operations management and energy recovery process optimization/economization
- Control and reduction of environmental impacts (e.g., groundwater or surface emissions)
- Safety.

Oversight and review may be provided by a second level of management, by external second party review or some other arrangement. Such a review can be valuable in providing a different view of the facility, a check on important activities, correction of oversights, and may be used to spur operating staff to achieve higher standards for regulatory control requirements or energy recovery process (revenue) optimization.

It is helpful to perform at least an annual review of the following items at a facility:

- Operating practices
- Process and equipment condition
- Performance (e.g., on-line time, energy production)
- Maintenance history
- Permits (e.g., facility, pressure vessel, etc.)
- Safety
- Administrative practices and documentation.

18.1.2. *Operation and Maintenance Management Documentation, Logs and Records*

Essential Operation and Maintenance (O&M) documentation may include:

- Facility daily log book
- Daily reading sheet records
- Facility records from chart recordings
- Facility shutdown log records
- Facility shutdown test log records
- Individual extraction well historical logs and graphs
- Individual monitoring probe historical logs and graphs
- Maintenance schedules
- Record of maintenance performed
- Calibration records
- Regulatory monitoring
- Records of gas or electricity sold
- Spare parts inventory
- Consumables, lubricant and other tankage inventory (e.g., water treatment chemicals, etc.)
- Vendor listings
- Purchase orders and order tracking records
- Facility management summary reports (usually monthly)

The specific records needed by each facility will vary. Sufficient manpower or time should be allocated to allow for upkeep of records. Management should review records periodically to verify that they are complete, accurate, and maintained.

18.1.3. *Unattended Operation*

Some facilities, either because of regulatory or permit requirements, sensitivity to migration potential, or energy production requirements must maintain a very high operational availability.

To address facility shutdowns during unattended operation facilities are often equipped with programmable telephone "auto-dialers" that dial out to a programmed list of contacts. The unit will typically have several channels. The channels typically monitor a pair of contacts (typically a relay) that monitors equipment and status of facility operation and faults. When a fault occurs, the dialer will dial-out rotating through several phone numbers until response is indicated. Some auto-dialers can receive calls to verify operational status.

It is desirable to have several individuals trained and available to respond to facility shutdowns. It may be necessary to provide for rotation and relief of these personnel from "on-call" status periodically. To do this, it is helpful to pool operation of several facilities together.

19. SAFETY

19.1. LANDFILL AND LFG HAZARDS

19.1.1. Safety for LFG

There are many important details that should be understood when working with LFG. This chapter provides just a brief overview and highlights key LFG health and safety topics. The SWANA Health and Safety Section of the LFG Field and Laboratory Practices and Procedures Manual is a guidance document containing more specific and detailed information about health and safety issues.. The reader should become familiar with this document.

19.1.2. Standard General Safety Procedures

Refer to Chapter 2, LFG Fundamentals for background information about landfill generated methane. Working with LFG requires awareness, alertness, knowledge of basic safety requirements and common sense. Basic safety rules for working on landfills are:

1) No smoking or other sources of ignition shall be allowed within 25 feet of any source or potential source of methane including structures, vaults, manholes, or the blower-flare facility.

2) Verify that all pressure is relieved before opening any pressurized device or vessel.

3) Always strictly comply with electrical lock-out procedures when performing inspection, maintenance or repairs on electrically operated equipment.

4) Persons entering confined spaces shall use confined space entry procedures and comply with all state and Federal requirements.

5) Before performing any welding or other "hot work," all sources of ignition shall be removed, sealed, or eliminated.
    - The work and surrounding area shall be regularly monitored before and during work for explosive concentrations of vapor using a calibrated combustible gas analyzer.
    - A designated fire watch shall be posted and fire extinguishers of adequate size (e.g., 80A:40BC) shall be present.
    - Drains shall be sandbagged and vents shall be sealed.
    - A written permit shall be issued by the person in charge of supervising the work and its safety.
    - Records of daily calibration of CGAs shall be maintained.

6) Persons working with excavations or trenches shall comply with all appropriate OSHA requirements for trenching and excavating.

7) Do not leave open excavations or drill borings unmarked and unsecured, or unattended. There should never be any exceptions to this rule.

19.1.3. Safety on the Landfill

Heavy equipment may move quickly on the active landfill. Always give heavy equipment the right of way. If working on the landfill while heavy equipment is operating, coordinate with equipment operators and be sure your work areas are well marked. Wear a visible florescent orange safety vest.

Do not eat, drink or smoke on the landfill. Observe good hygiene practices. Take care of any cuts or abrasions promptly and use antiseptic.

No Smoking

Smoking when working on the LFG wellfield should be prohibited. Avoid any possible source of ignition when working on the wellfield. Eating or smoking on the landfill should be avoided to reduce bacterial exposure..

19.1.4. Electrical Safety

The following rules must be adhered to:

1) Always de-energize electrical equipment before working on it.
2) Remove all watches and rings etc. when working on electrical controls and equipment.
3) Use properly grounded portable tools.
4) Where available use a portable ground fault current interrupter (GFCI) device during use of portable electrical tools and outdoor construction activities.
5) Always follow electrical lockout/block-out procedures below.

19.1.5. Lock-out/Block-out Requirements

The law requires a procedure be employed to protect personnel from death or injury when performing mechanical and electrical maintenance. This procedure is known as electrical and mechanical lockout and blockout. This procedure consists of a number of basic and common sense steps. The procedure prevents equipment from being energized, operated, or closed when someone is working on it.

The procedure is as follows:

1) The operator responsible locks out and tags the equipment.

2) The operator responsible identifies the equipment to be serviced and the lockout point (circuit breaker, mechanical barring device, manway, etc.) to each maintenance person or tradesman.

3) Each maintenance person applies his lock and tag with (or on top of) the previous tag(s). If a scissors type master locking device is not used, each tag is placed successively on top of the previous tag. Tags are removed only and strictly in the reverse order.

Important Rule: No one is ever allowed or authorized to remove the tag of another. Each maintenance person removes their own tag upon completion of their work. When all maintenance is completed the last maintenance person notifies the operator.

The operator responsible then checks the equipment, removes his tag (last), and restores the equipment to service.

Equipment needed:

- Permanent marking pen
- Operating and maintenance notice and warning tags
- Lockout devices (A scissors like device that will accept multiple locks and act as a master locking device.)
- Locks (Several locks with different keys are desirable).

APPENDIX A

APPENDIX A.1

CONVERTING ACFM TO SCFM

Flow of LFG is often measured with field instruments or inline equipment that is not capable of converting to standard cubic feet per minute (SCFM). The following method can be used to convert measured flow (ACFM) into SCFM. This method is valid assuming LFG acts as an ideal gas.

Use the following equation to convert to SCFM:
(Assumes standard conditions of 14.7 PSIA and 520°R

$$SCFM = \frac{P}{14.7} \times \frac{520}{(T + 460)} \times ACFM$$

where,

P = gas pressure, psi (gauge pressure + atmospheric pressure)
T = temperature of gas, °F

EXAMPLE:

Measured Flow = 80 ACFM
Gas Temperature = 110 °F
Gas Pressure = 4" w.c. gauge pressure

1. Convert gauge pressure from gauge, in. w.c. to absolute pressure, psi.

$$P_{ABS} = 14.7\text{psi} + \frac{4 \text{ in. w. c.}}{27.7 \text{ in. w. c./psi}}$$

$$= 14.84$$

2. Convert flow from ACFM to SCFM

$$\text{Flow} = \frac{14.84}{14.7} \times \frac{520}{(110 + 460)} \times 80 \text{ ACFM}$$

Note: 14.7 psi is assumed as the atmospheric pressure; actual atmospheric pressure depends on the site location.

APPENDIX A.2

MASS BALANCE METHOD FOR DETECTION OF OXYGEN

If a leak is suspected to exist somewhere in the landfill piping, a mass balance for oxygen can be performed at different points on the landfill to locate the source of the leak. The following equation is used to compute the mass balance.

$$\text{Total } O_2\% = \frac{O_2\%_1 \times \text{Flow}_1 + O_2\%_2 \times \text{Flow}_2 + \cdots + O_2\%_N \times \text{Flow}_N}{\text{Flow}_1 + \text{Flow}_2 + \cdots + \text{Flow}_N}$$

where: 1, 2, ··· N = Incremental components of flow

In order to utilize this equation, the operator must pick a header monitoring port and find all of the sources of gas to that point.

Example:

At the LFG collection system for the Sanitary Landfill (Figure A.2.1), a leak is suspected. Oxygen readings are taken at the header monitoring ports (HMP), and oxygen and flow rates are taken at all the extraction wells (EW). The results are as follows:

Well Item	$O_2\%$	CFM	HMP	$O_2\%$
EW-1	1%	12	1	1.9%
EW-2	3%	10	2	4%
EW-3	0%	13	3	2%
EW-4	2%	12		
EW-5	3%	9		

At HMP-3, three wells contribute to the flow at that monitoring port, wells EW-3, EW-4 and EW-5.

$$O_2\%_{HMP-3} = \frac{O_2\%_{EW-3} \times Flowrate_{EW-3} + O_2\%_{EW-4} \times Flowrate_{EW-4} + O_2\%_{EW-5} \times Flowrate_{EW-5}}{Flowrate_{EW-3} \times Flowrate_{EW-4} \times Flowrate_{EW-5}}$$

$$O_2\%_{HMP-3} = \frac{(1\%)(12CFM) + (3\%)(10CFM) + (0\%)(13CFM)}{12CFM + 10CFM + 13CFM} = 1.2\%$$

This oxygen level of 1.2% is the same as the reading taken in the field for HMP-3. It can thus be concluded that there is probably not a leak upstream of HMP-3. The oxygen reading taken out in the field for HMP-2 is 4%. HMP-2 also has only three wells contributing to the flow rate at that monitoring port, the same three wells that contribute to HMP-3. Therefore, the theoretical oxygen level at that point should also be 1.2%. Because the field reading is 4% at that point, there is most likely a leak in the header somewhere between HMP-3 and HMP-2.

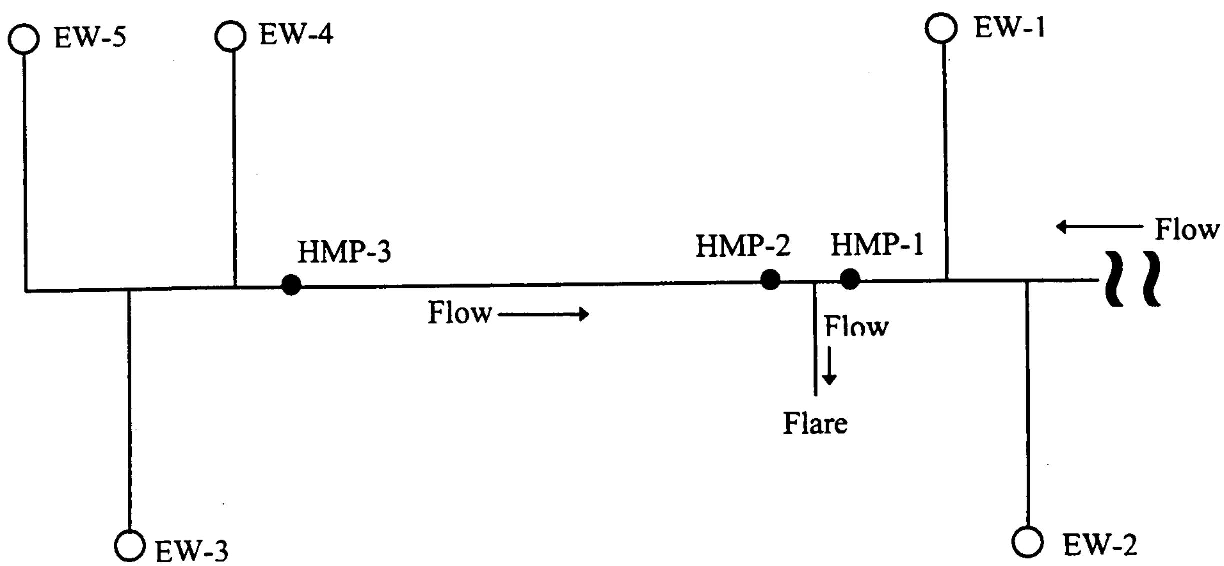


Figure A.2.1

APPENDIX A.3

PIPE WALL THICKNESS CALCULATION

For HDPE, find the pipe thickness and corresponding inside diameter for an 8" line, SDR17.

$$SDR = \frac{OD}{t} \rightarrow t = \frac{OD}{SDR}$$

$$ID = OD - 2t \rightarrow ID = OD\left(1 - \frac{2}{SDR}\right)$$

SDR = Standard diameter ratio
OD = Pipe outside diameter
t = Pipe wall thickness
ID = Inside diameter

given: 8" line, OD = 8.625", SDR = 17

$$t = \frac{OD}{SDR} = \frac{8.625}{17} = 0.507''$$

$$ID = 8.675\left(1 - \frac{2}{17}\right) = 7.610''$$

APPENDIX A.4

ORIFICE PLATE SAMPLE CALCULATION

Purpose: To demonstrate the relationship between pressure differential across an orifice plate and the corresponding flow

Assumption: Landfill gas acts as an incompressible fluid (valid for V>5.6 ft/min, ie, Q>0.1 ACFM for 2" line, or Q>4.4 ACFM for 12" line)

Equation:

$$Q = 31.5\, C\, d^2 \sqrt{\frac{\Delta P}{\rho}} \text{ ACFM}$$

P = gas pressure, lbf/in^2

ρ = gas density for ACTUAL conditons, lbm/ft^3

C = discharge coefficient, corrected for forward velocity, based on Beta ratio, β, (See attached table)

d = orifice plate bore inside diameter, in

D = line inside diameter in.

β = ratio of orifice to line diameters, d/D, in/in

Q = gas flow, ACFM

Given:

ΔP = 1" w.c. vacuum = 0.037 psi

d = 0.625 in

D = 1.939 in

ρ = 0.0695 lbm/ft^3, @ 100°F, 13.7 psi, SG = 0.8

Solution:

$$\beta = \frac{d}{D} = 0.322$$

C = 0.60 (see chart below)

$$Q = 31.5\,C\,d^2 \times \sqrt{\frac{0.037 \text{ psi}}{0.0695 \text{ lbm/ft}^3}}$$

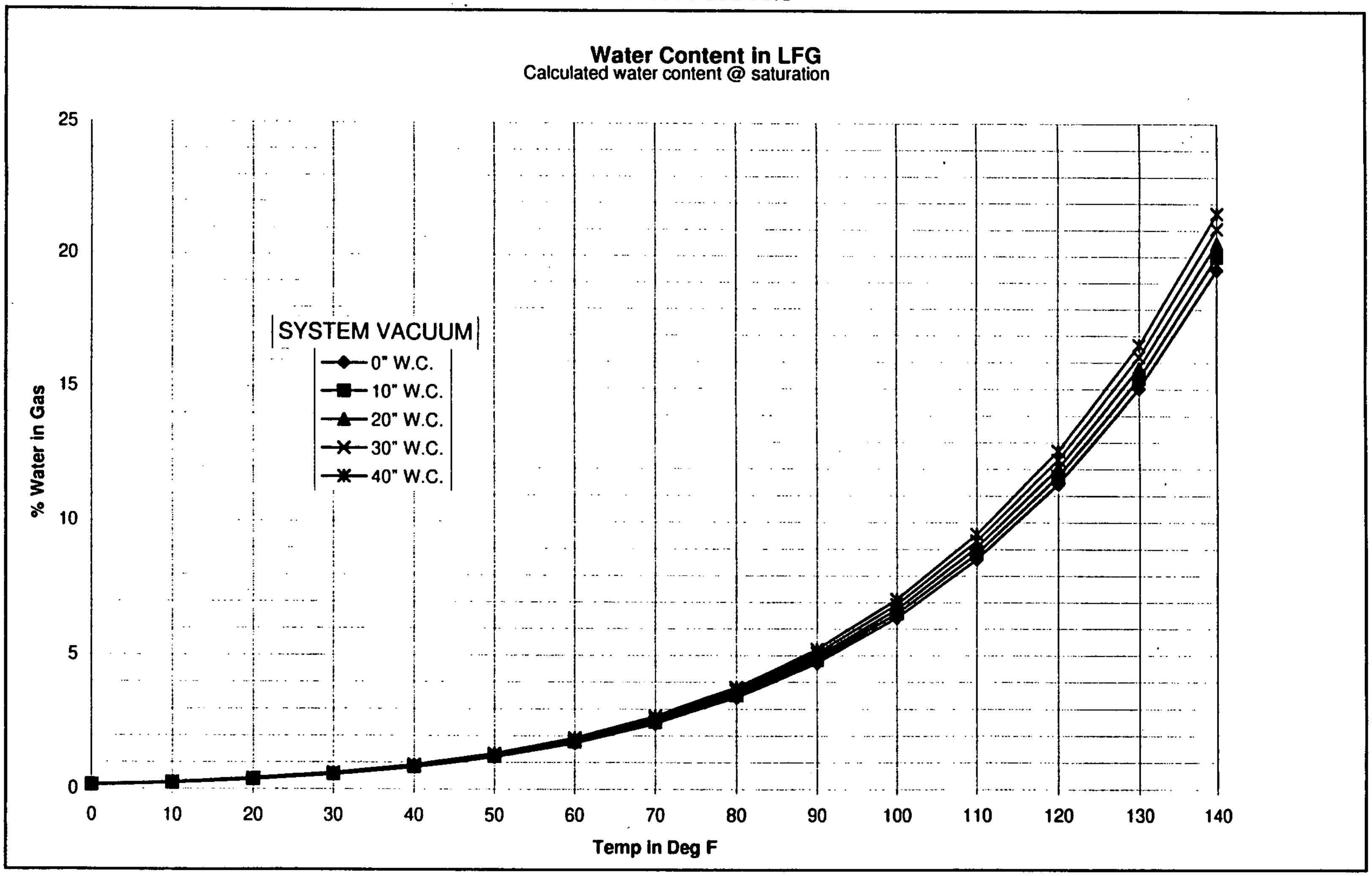
$$= 5.4 \text{ ACFM}$$

C = Corrected discharge coefficient for turbulent flow

β	C Re = 2 x 10^6 - 2 x 10^4
0.75	0.74 - 0.76
0.70	0.70 - 0.72
0.65	0.67 - 0.69
0.60	0.65 - 0.66
0.55	0.63 - 0.64
0.50	0.62 - 0.63
0.45	0.61 - 0.62
0.40	0.607 - 0.61
0.30	0.60
0.20	0.595

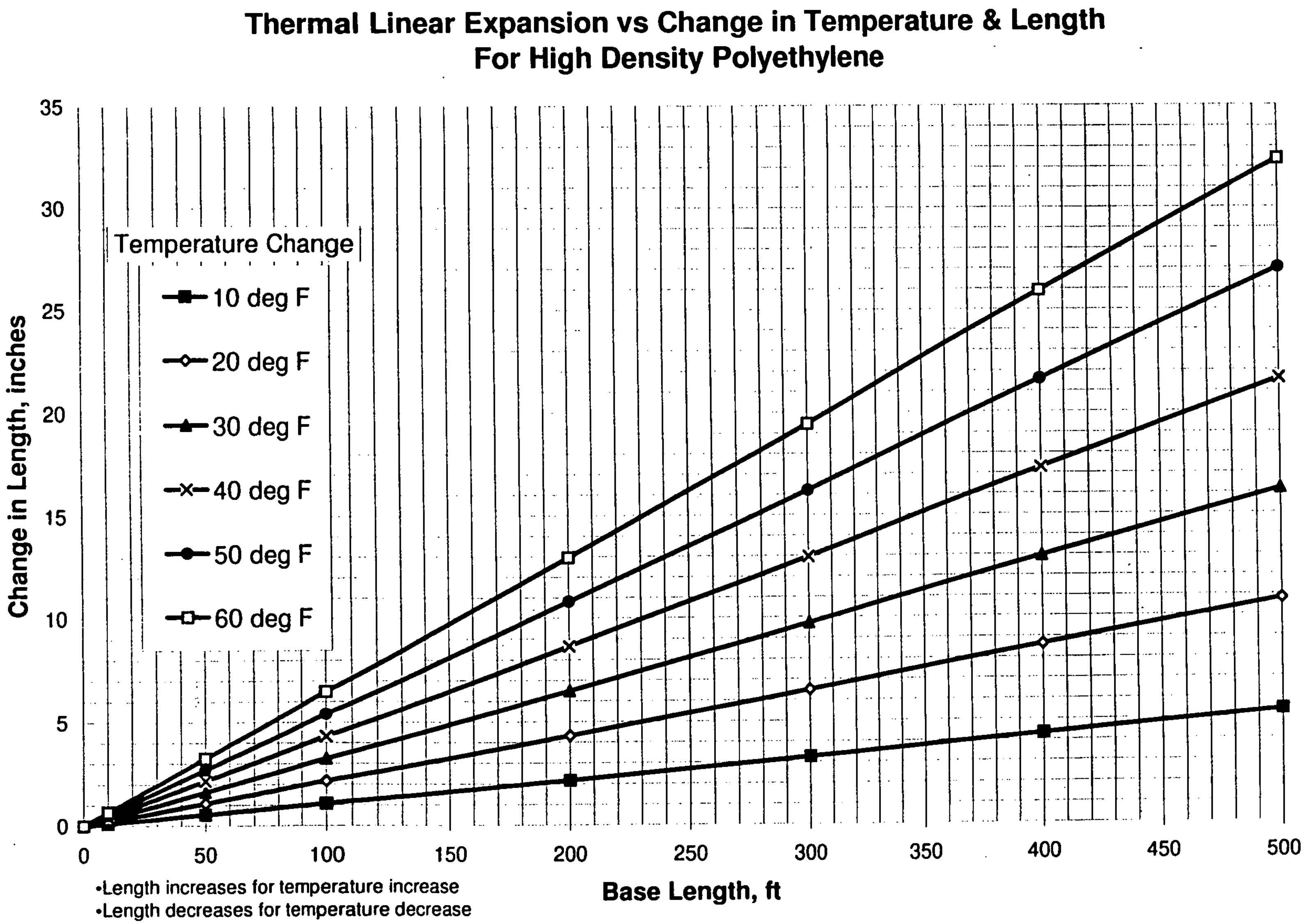
Ref: "Flow of Fluids through Valves, Fittings, and Pipe". Technical Paper No. 410, Crane Co., Engineering Division, 1978

APPENDIX A.5



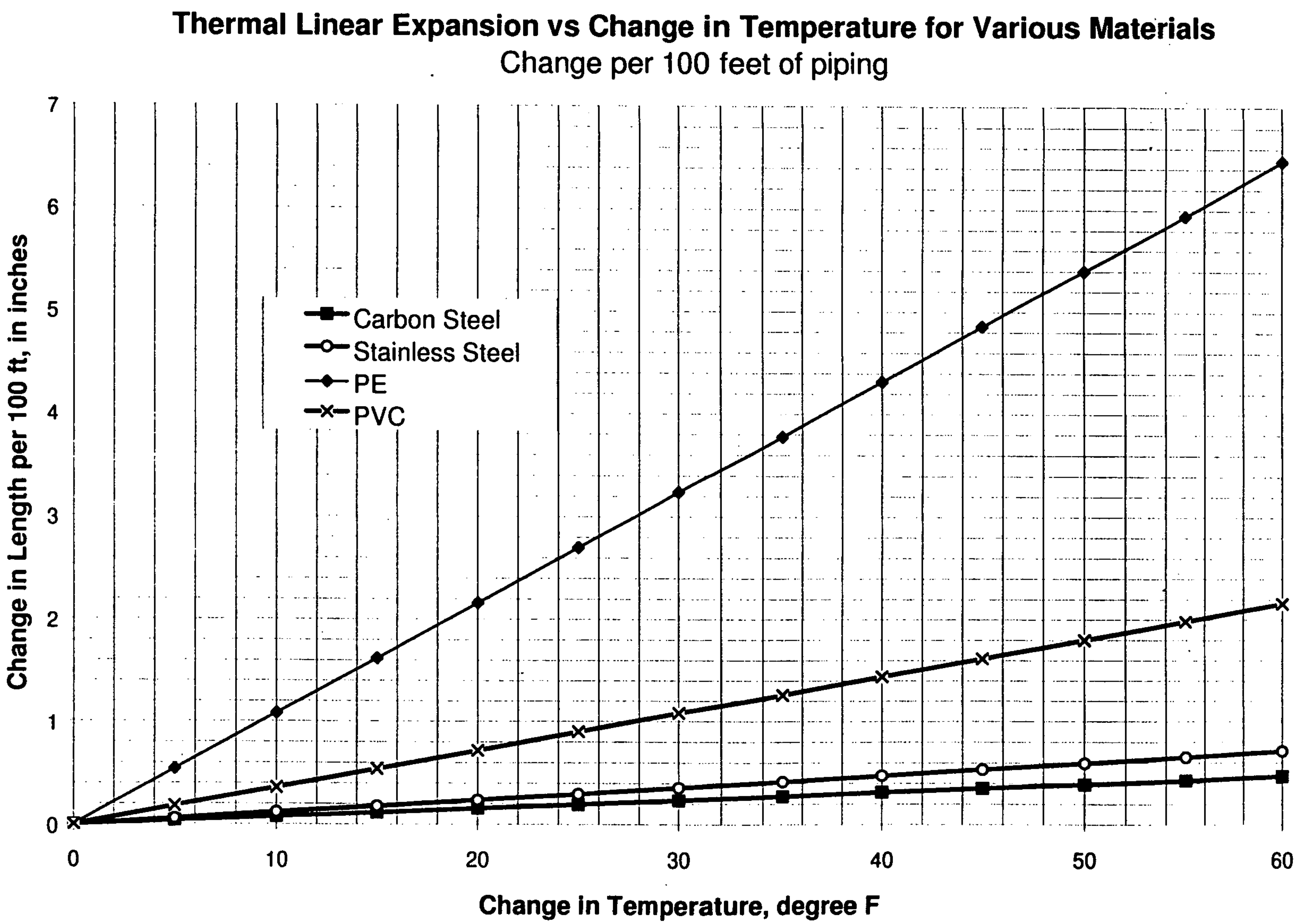
Water Content in LFG
Calculated water content @ saturation
% Water in Gas
0
5
10
15
20
25
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
Temp in Deg F
SYSTEM VACUUM
0" W.C.
10" W.C.
20" W.C.
30" W.C.
40" W.C.

APPENDIX A.6

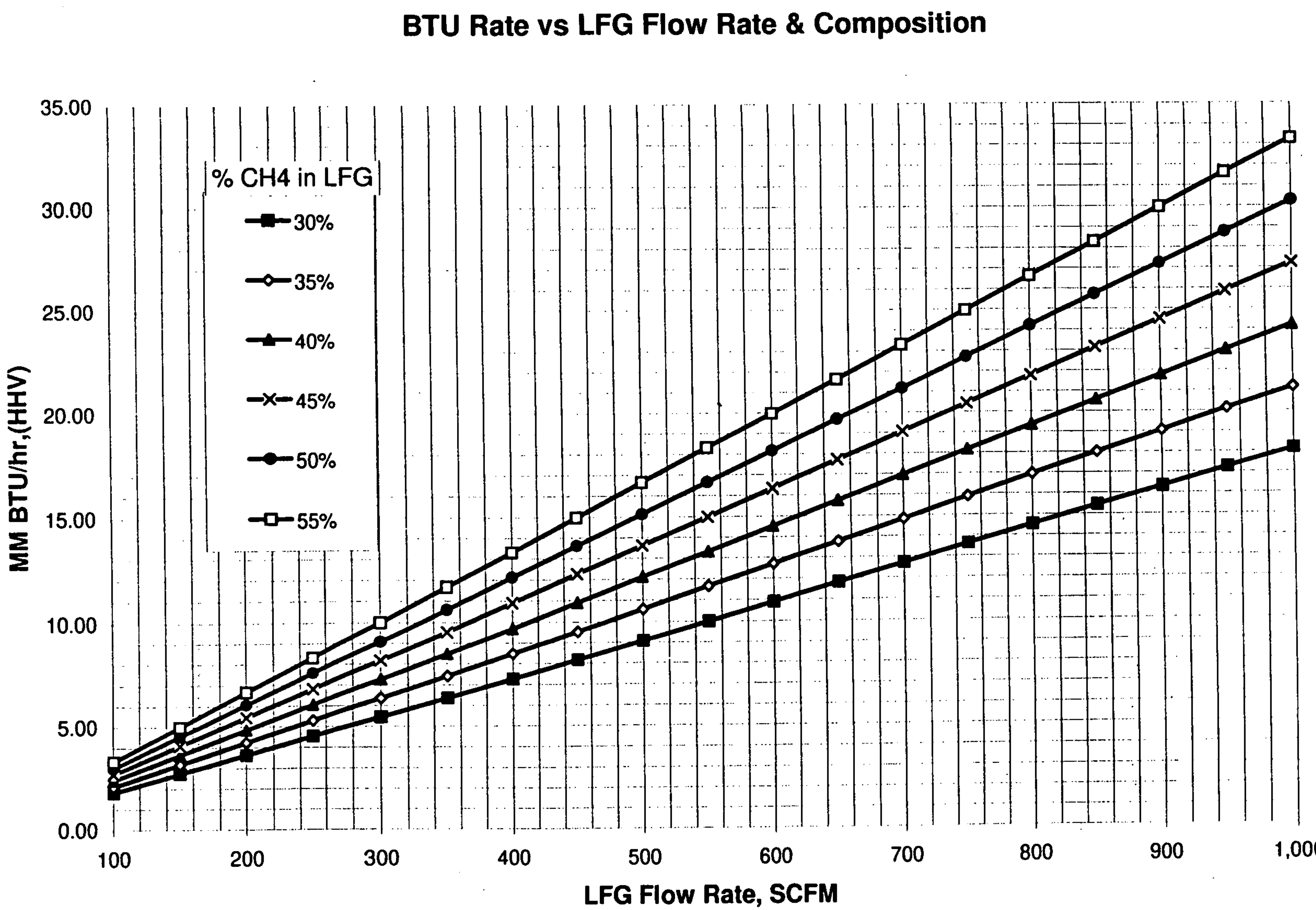


Thermal Linear Expansion vs Change in Temperature & Length
For High Density Polyethylene
Temperature Change
10 deg F
20 deg F
30 deg F
40 deg F
50 deg F
60 deg F
Change in Length, inches
0
5
10
15
20
25
30
35
0
50
100
150
200
250
300
350
400
450
500
Base Length, ft
•Length increases for temperature increase
•Length decreases for temperature decrease

APPENDIX A.7

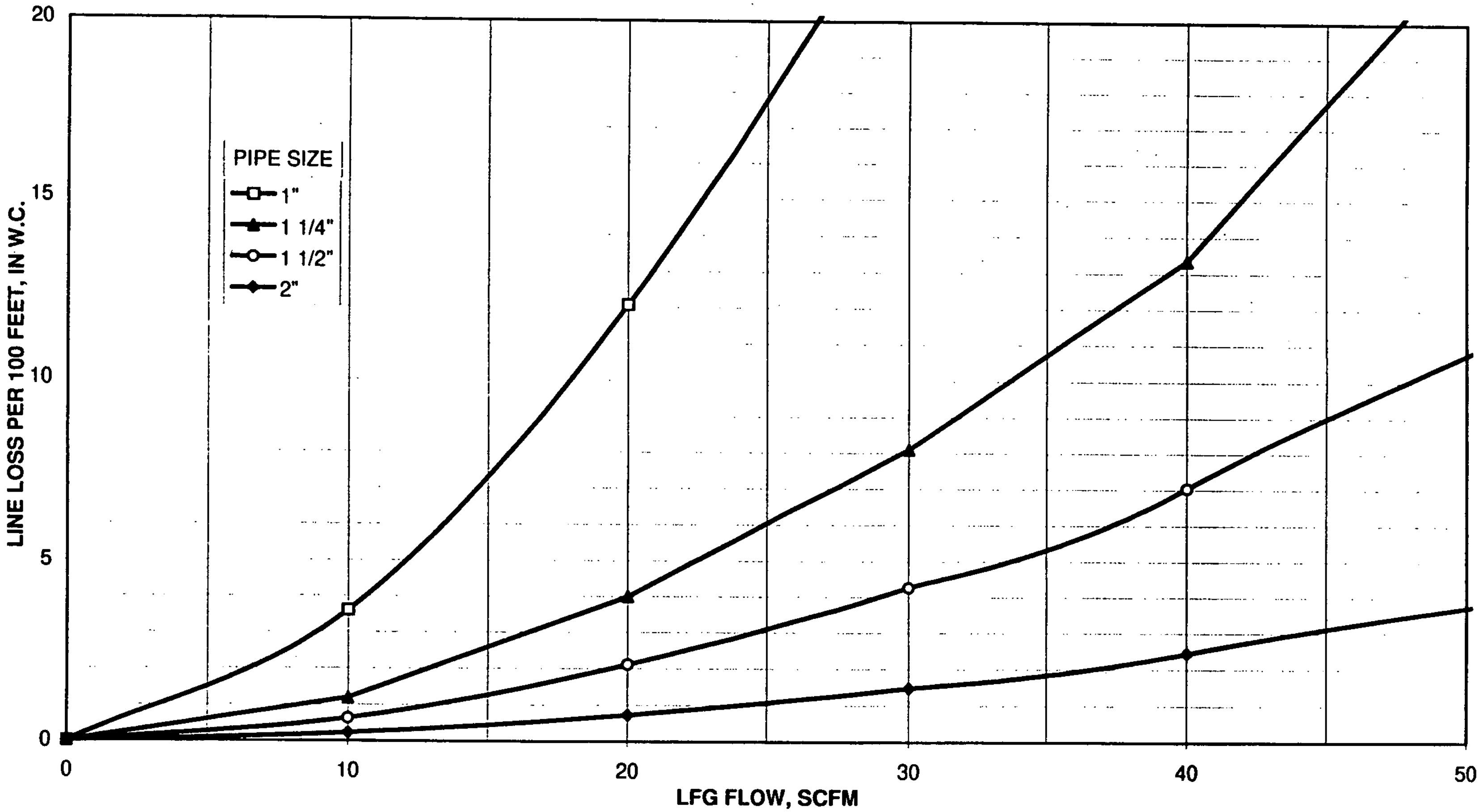

Thermal Linear Expansion vs Change in Temperature for Various Materials
Change per 100 feet of piping
Change in Length per 100 ft, in inches
Change in Temperature, degree F
Carbon Steel
Stainless Steel
PE
PVC
0
1
2
3
4
5
6
7
0
10
20
30
40
50
60

APPENDIX A.8

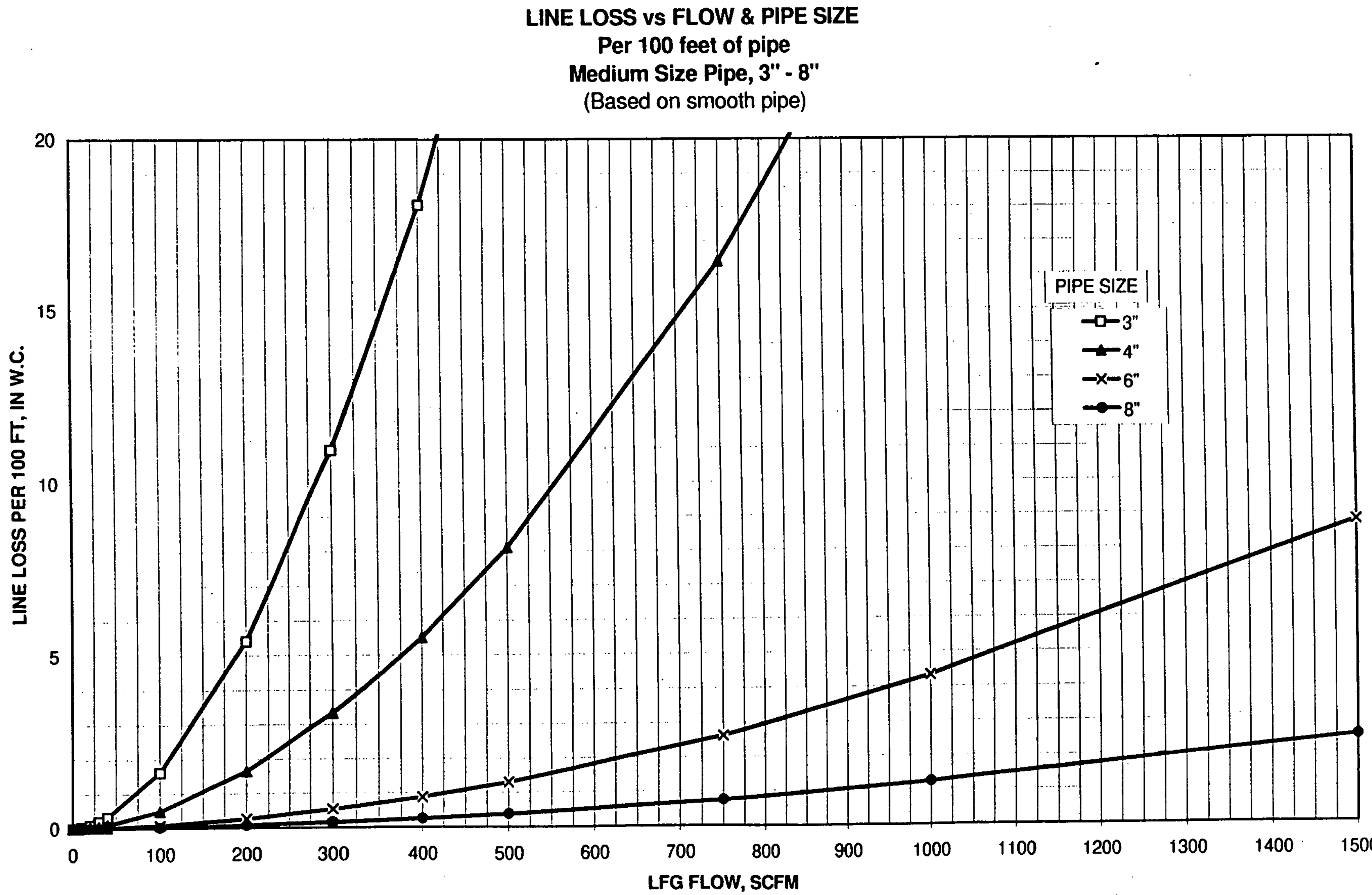

BTU Rate vs LFG Flow Rate & Composition
% CH4 in LFG
30%
35%
40%
45%
50%
55%
MM BTU/hr,(HHV)
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
100
200
300
400
500
600
700
800
900
1,000
LFG Flow Rate, SCFM

APPENDIX A.9

LINE LOSS vs FLOW & PIPE SIZE
Per 100 feet of pipe
Small Pipes, 1" - 2"
(Based on smooth pipe)

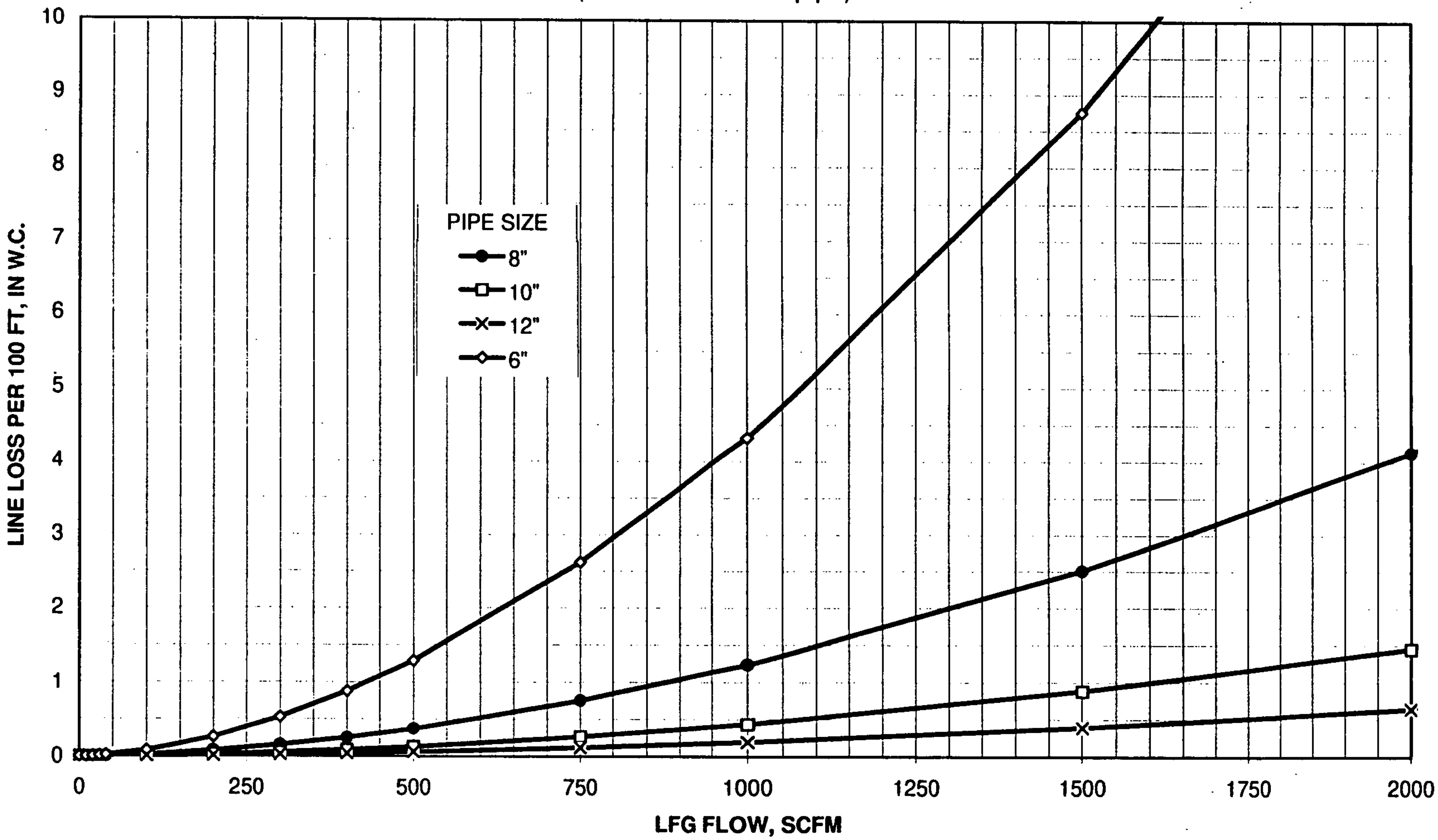


APPENDIX A.10



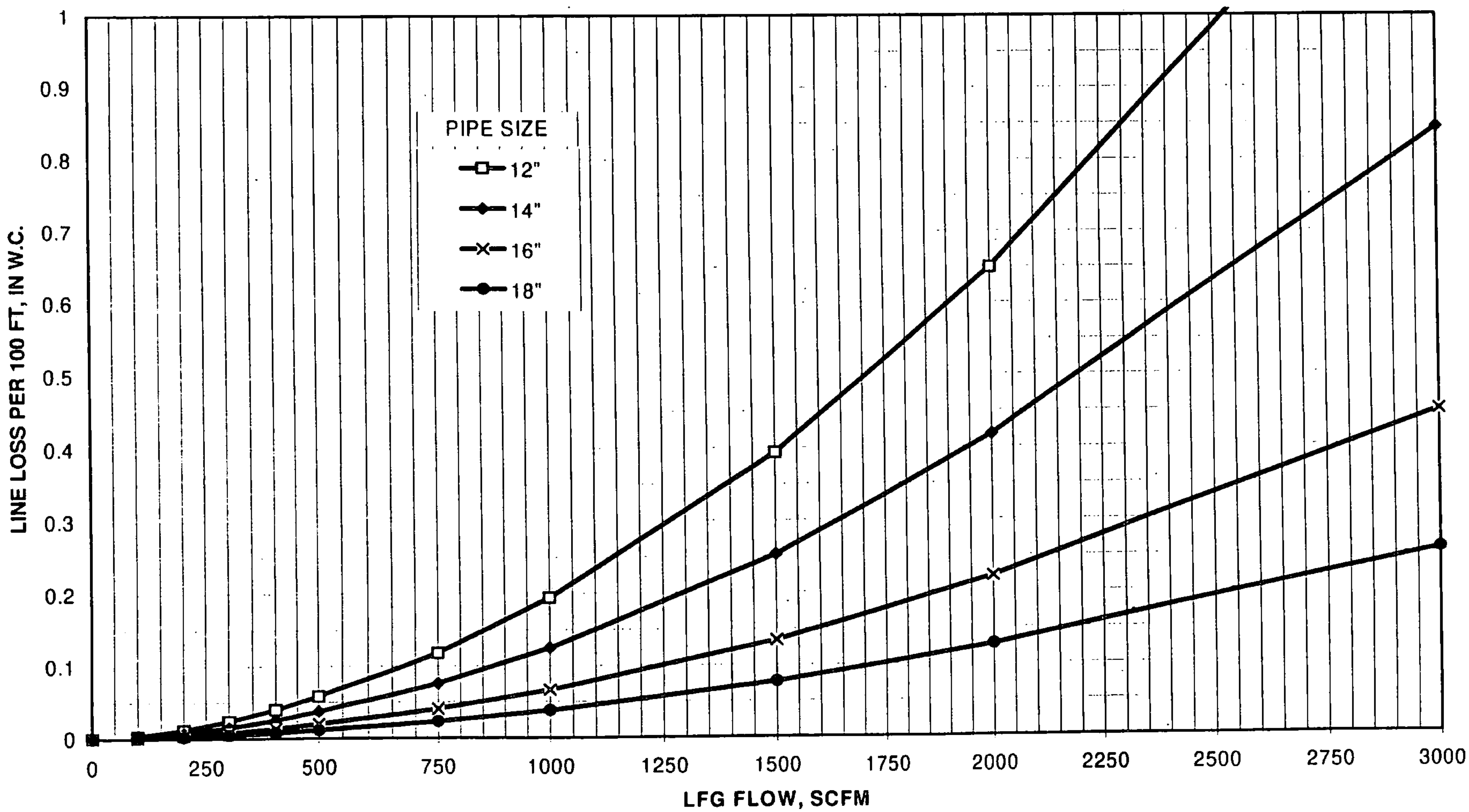
APPENDIX A.11

LINE LOSS vs FLOW & PIPE SIZE
Per 100 feet of pipe
Typical Header Line Sizes, 6" - 12"
(Based on smooth pipe)



APPENDIX A.12

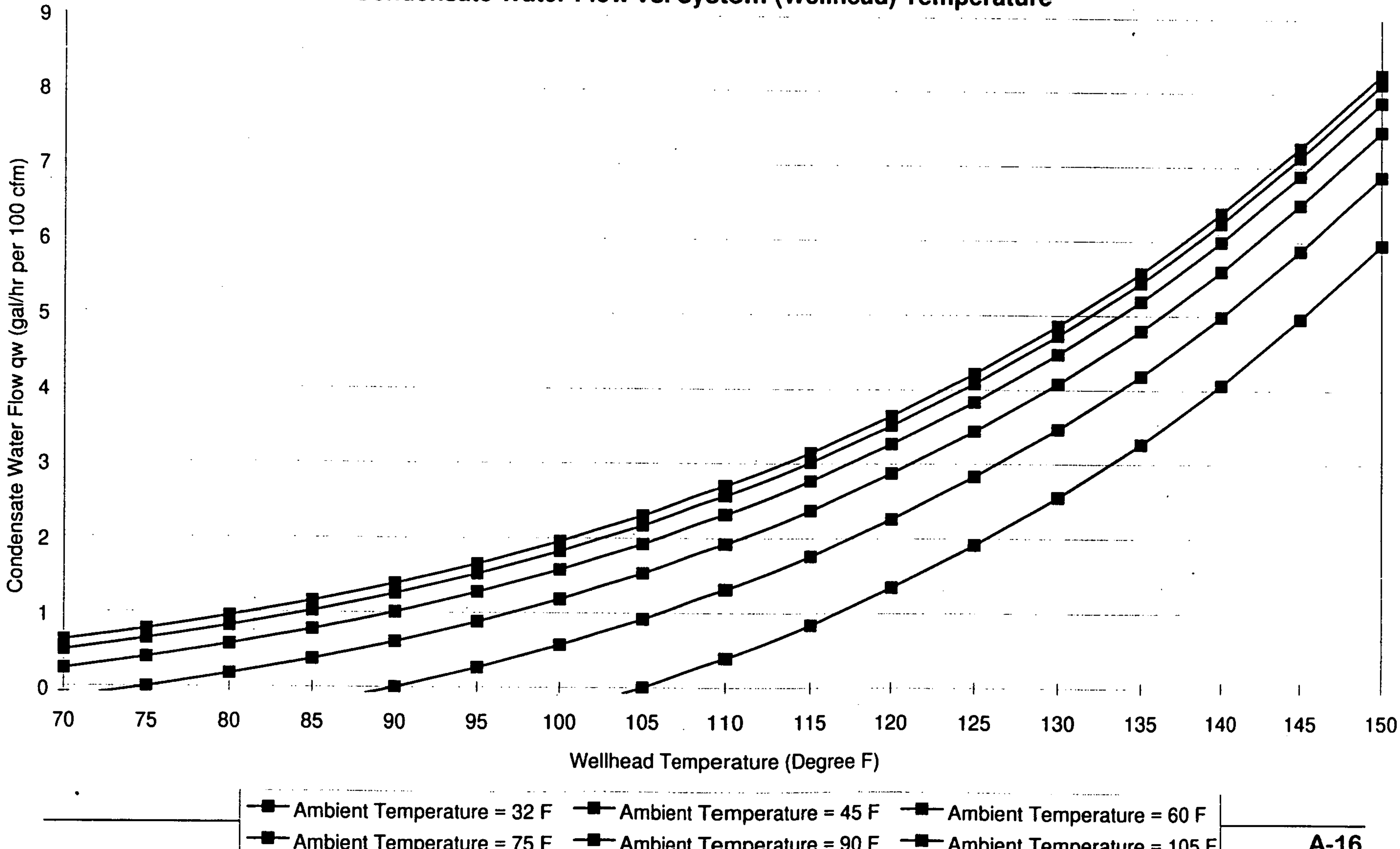
LINE LOSS vs FLOW & PIPE SIZE
Per 100 feet of pipe
Large Pipe, 12" - 18"
(Based on smooth pipe)



APPENDIX A.13

Determining Condensate Generation

Condensate Water Flow vs. System (Wellhead) Temperature



APPENDIX B

B.1 Pipe Data

B.2 Flange Dimensional Data (PVC)

B.3 Pipe and Tube End Size Chart (U.S.A.)

B.4 Thread and Tube End Size Chart (U.S.A.)

B.5 Probe Volumes in Liters

B.6 Decimal Equivalents

B.7 Drill Sizes for Pipe Taps - American Standard National Pipe Thread

B.8 Pipe Dimensions and Cross Sectional Areas (for flow calculations)

APPENDIX B.1

PIPE DATA

(Pipe weights are calculated in accordance with PPI TR-7)
Average inside diameter calculated on minimum wall plus 6%.

Pressure Ratings are for water at 73°F. For other fluids and service temperatures ratings may differ, refer to Application Note No. 6 Chemical and Environmental Considerations.

Pressure Rating		255 psi DR 7.3			200 psi DR 9.0			160 psi DR 11.0			130 psi DR 13.5			110 psi DR 15.5			
IPS* Pipe Size	Nominal OD (in.)	Minimum Wall (in.)	Average ID (in.)	Weight LB/FT	Minimum Wall (in.)	Average ID (in.)	Weight LB/FT	Minimum Wall (in.)	Average ID (in.)	Weight LB/FT	Minimum Wall (in.)	Average ID (in.)	Weight LB/FT	Minimum Wall (in.)	Average ID (in.)	Weight LB/FT	IPS* Pipe Size
1¼"	1 660	0.227	1.179	0 44	0.164	1.270	0.37	0.151	1.340	0.31	0.123	1.399	0.26	0.107	1.433	0.23	1¼"
1½"	1 900	0.260	1.349	0.58	0.211	1.453	0.49	0.173	1.533	0 41	0.141	1.601	0.34	0.123	1.639	0.30	1½"
2"	2 375	0.325	1.686	0 91	0.264	1.815	0.76	0.216	1.917	0.64	0.176	2.002	0.53	0.153	2.051	0.47	2"
3"	3 500	0.479	2.485	1.98	0.389	2.675	1.65	0.318	2.826	1.39	0.259	2.951	1 15	0.226	3.021	1.02	3"
4"	4 500	0.616	3.194	3.27	0.500	3.440	2.74	0.409	3.633	2.30	0.333	3.794	1.90	0.290	3.885	1.67	4"
5⅜"	5 375	0.736	3.815	4.66	0.597	4.109	3.90	0.489	4.338	3 27	0.398	4.531	2.72	0.347	4.639	2 40	5⅜"
5"	5 563	0.762	3.948	5.00	0.618	4.253	4 18	0.506	4.490	3 50	0.412	4.690	2.91	0.359	4.802	2.57	5"
6"	6 625	0.908	4.700	7 09	0.736	5.065	5.93	0.602	5.349	4.97	0.491	5.584	4 13	0.427	5.720	3 64	6"
7⅛"	7.125	0.976	5.056	8.20	0.792	5.446	6.87	0.648	5.751	5.75	0.528	6.006	4.78	0.460	6.150	4 21	7⅛"
8"	8 625	1.182	6.119	12.01	0.958	6.594	10.05	0.784	6.963	8.42	0.639	7.270	7.00	0.556	7 446	6 16	8"
10"	10 750	1.473	7.627	18.66	1.194	8.219	15.62	0.977	8.679	13.09	0.796	9.062	10.87	0.694	9.279	9 59	10"
12"	12 750	1.747	9.046	26.25	1.417	9.746	21.97	1.159	10.293	18.42	0.944	10.749	15.30	0.823	11.005	13 47	12"
13⅜"	13 375	1.832	9.491	28.88	1.486	10.225	24.17	1.216	10.797	20.26	0.991	11.274	16.83	0.863	11.545	14 83	13⅜"
14"	14 000	1.918	9.934	31.64	1.556	10.701	26.49	1.273	11.301	22.20	1.037	11.802	18 44	0.903	12.086	16 24	14"
16"	16 000	2.192	11.353	41.34	1.778	12.231	34 61	1.455	12.915	29.00	1.185	13.488	24 09	1.032	13.812	21.21	16"
18"	18 000	2.466	12.772	52.31	2.000	13.760	43.79	1.636	14.532	36.69	1.333	15.174	30.48	1.161	15.539	26 85	18"
20"	20 000	2.740	14.191	64.57	2.222	15.289	54 05	1.818	16.146	45.30	1.481	16.860	37 64	1.290	17.265	33 13	20"
22"	22 000	3.014	15.610	78.15	2.444	16.819	65 41	2.000	17.760	54.82	1.630	18.544	45.56	1.419	18.992	40.09	22"
24"	24 000	3.288	17.029	92.99	2.667	18.346	77 85	2.182	19.374	65.24	1.778	20.231	54.22	1.548	20.718	47 72	24"
†26"	26 000	3.562	18.449	109.15	2.889	19.875	91.35	2.364	20.988	76 58	1.926	21.917	63.63	1.677	22.445	56.02	†26"
†28"	28 000				3.111	21.405	105.96	2.545	22.605	88 79	2.074	23.603	73.76	1.806	24.171	64.94	†28"
†30"	30.000				3.333	22.934	121.62	2.727	24.219	101.94	2.222	25.289	84.68	1.935	25.898	74.56	†30"
†32"	32.000							2.909	25.633	115.99	2.370	26.976	96.35	2.065	27.622	84.88	†32"
†34"	34.000							3.091	27.447	130.92	2.519	28.660	108.80	2.194	29.349	95.83	†34"
†36"	36.000													2.323	31.075	107.40	†36"
†42"	42.000																†42"
†48"	48.000																†48"
†54"	54 000																†54"

Pressure Rating		100 psi DR 17.0			80 psi DR 21.0			65 psi DR 26.0			50 psi DR 32.5			40 psi DR 41.0			
IPS* Pipe Size	Nominal OD (in.)	Minimum Wall (in.)	Average ID (in.)	Weight LB/FT	Minimum Wall (in.)	Average ID (in.)	Weight LB/FT	Minimum Wall (in.)	Average ID (in.)	Weight LB/FT	Minimum Wall (in.)	Average ID (in.)	Weight LB/FT	Minimum Wall (in.)	Average ID (in.)	Weight LB/FT	IPS* Pipe Size
1¼"																	1¼"
1½"																	1½"
2"	2 375	0.140	2.078	0 43													2"
3"	3.500	0.206	3.063	0.93													3"
4"	4.500	0.265	3.938	1 54	0.214	4.046	1 26										4"
5⅜"	5 375	0.316	4.705	2.20	0.256	4.832	1 80	0.207	4.936	1.47							5⅜"
5"	5 563	0.327	4 870	2.35	0.265	5.001	1 93	0.214	5.109	1.58							5"
6"	6 625	0.390	5.798	3.34	0.315	5 957	2 73	0.255	6.084	2.23	0.204	6.193	1.80				6"
7⅛"	7 125	0.419	6.237	3.86	0.339	6.406	3 16	0.274	6.544	2.58	0.219	6.661	2.08				7⅛"
8"	8 625	0.507	7.550	5.65	0.411	7.754	4.64	0.332	7.921	3.79	0.265	8.063	3.05				8"
10"	10 750	0.632	9 410	8.78	0.512	9.665	7 21	0.413	9.874	5.87	0.331	10.048	4.75				10"
12"	12.750	0.750	11.160	12.36	0.607	11.463	10 13	0.490	11.711	8.26	0.392	11.919	6 67				12"
13⅜"	13 375	0.787	11.707	13 60	0.637	12.025	11.15	0.514	12.285	9.09	0.412	12.502	7.35				13⅜"
14"	14 000	0.824	12.253	14.91	0.667	12.586	12.22	0.538	12 859	9.96	0.431	13.086	8.05				14"
16"	16 000	0.941	14.005	19 46	0.762	14.385	15 97	0.615	14.696	13.02	0.492	14.957	10.51				16"
18"	18 000	1.059	15.755	24 65	0.857	16.183	20.19	0.692	16.533	16 48	0.554	16.826	13.29				18"
20"	20 000	1.176	17.507	30 42	0.952	17.982	24.92	0.769	18.370	20.34	0.615	18.696	16 41				20"
22"	22 000	1.294	19.257	36 81	1.048	19.778	30 19	0.846	20.206	24.62	0.677	20.565	19.87				22"
24"	24.000	1.412	21.007	43 82	1.143	21.577	35 92	0.923	22.043	29.29	0.738	22.435	23.62				24"
†26"	26 000	1.529	22 759	51 40	1.238	23.375	42 13	1.000	23.880	34.39	0.800	24.304	27 74				†26"
†28"	28 000	1.647	24.508	59 62	1.333	25.174	48 86	1.077	25.717	39 89	0.862	26.173	32 20				†28"
†30"	30 000	1.765	26 258	68 45	1.429	26 971	56 13	1.154	27.554	45.78	0.923	28.043	36.92	0.732	28.448	29.50	†30"
†32"	32 000	1.882	28.010	77 86	1.524	28 769	63.83	1.231	29.390	52.10	0.985	29.912	42.04	0.780	30.346	33 53	†32"
†34"	34 000	2.000	29.760	87 91	1.619	30.568	72.06	1.308	31.227	58 79	1.046	31.782	47 44	0.829	32.243	37.87	†34"
†36"	36 000	2.118	31.510	98 56	1 714	32.366	80 79	1.385	33.064	65.93	1.108	33.651	53 18	0.878	34 139	42 47	†36"
†42"	42 000				2.000	37.760	109 97	1.615	38.576	89 71	1.292	39.261	72 40	1.024	39.829	57.74	†42"
†48"	48 000				2.286	43.154	143 64	1.846	44.086	117.20	1.477	44.869	94.58	1.171	45.517	75.48	†48"
†54"	54 000				2.571	48.549	181 74	2.077	49.597	148.35	1.662	50 477	119 72	1.317	51.208	95 52	†54"

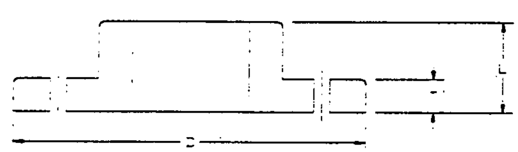
Bulletin No. 301 - PE 3408 Industrial Piping System Pipe Data and Pressure Ratings. Chevron Chemical Company. 1988 Rev 3/93.

APPENDIX B.2

FLANGE DIMENSIONAL DATA

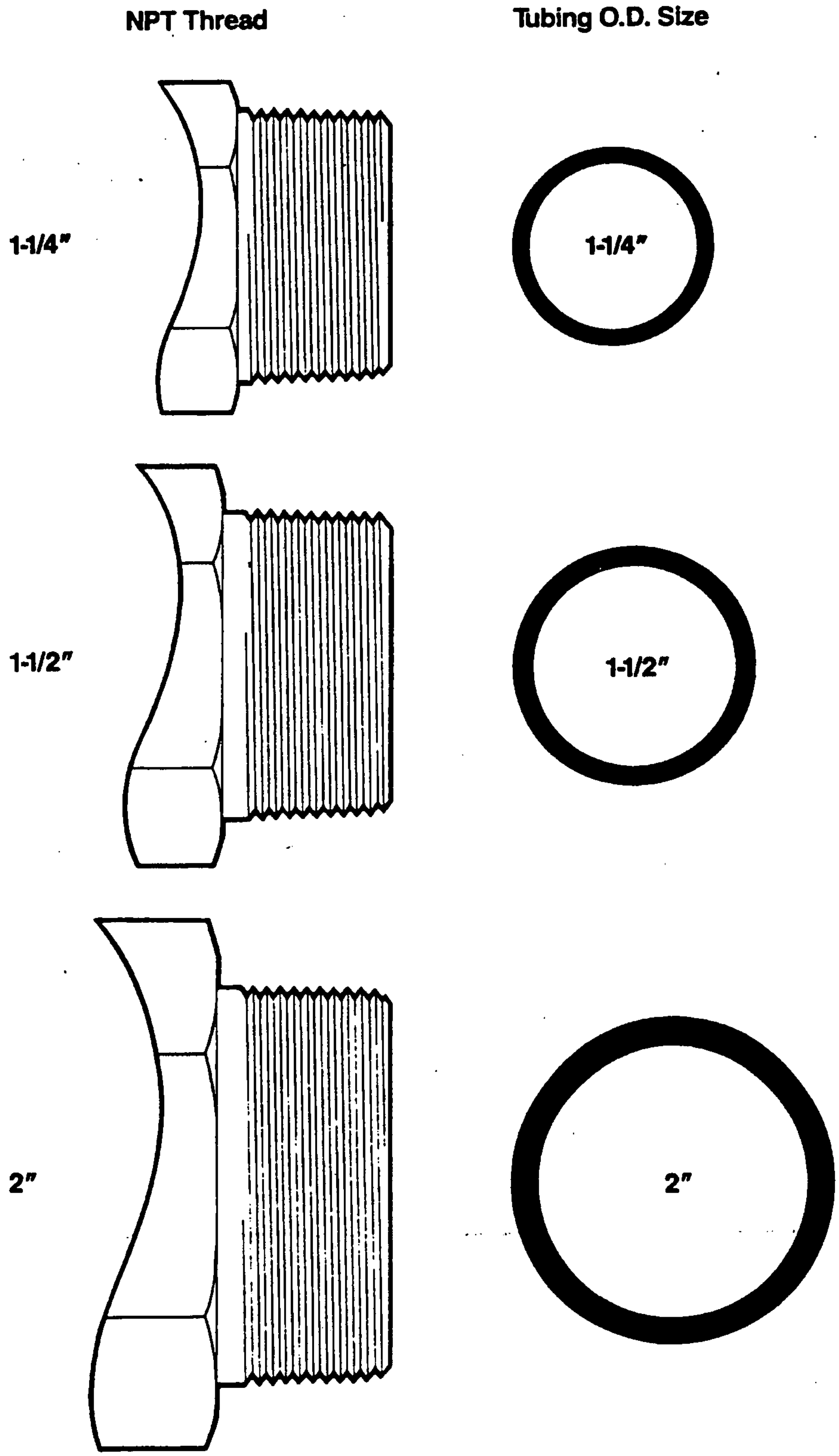
Typical Commercial Cast-Iron Companion Flanges
Class 125

Size	No. of Holes	Diameter of Bolts	Diameter of Bolt Circle	Diameter of Flange	Thickness of Flange	Thickness of Flange through hub
				D	T	L
		in.	in.	in.	in.	in.
½*	4	1/2	2-3/8	3.5	-	
¾*	4	1/2	2-3/4	3-7/8	-	
1	4	1/2	3-1/8	4.25	7/16	11/16
1-1/4	4	1/2	3-1/2	4-5/8	1/2	13/16
1-1/2	4	1/2	3-7/8	5	9/16	7/8
2	4	5/8	4-3/4	6	5/8	1
2-1/2	4	5/8	5-1/2	7	11/16	1-1/8
3	4	5/8	6	7-1/2	3/4	1-3/16
4	8	5/8	7-1/2	9	15/16	1-15/16
6	8	3/4	9-1/2	11	1	1-9/16
8	8	3/4	11-3/4	13-1/2	1/1/8	1-3/4
10	12	7/8	14-1/4	16	1/3/16	1-15/16
12	12	7/8	17	19	1-1/4	2-3/16

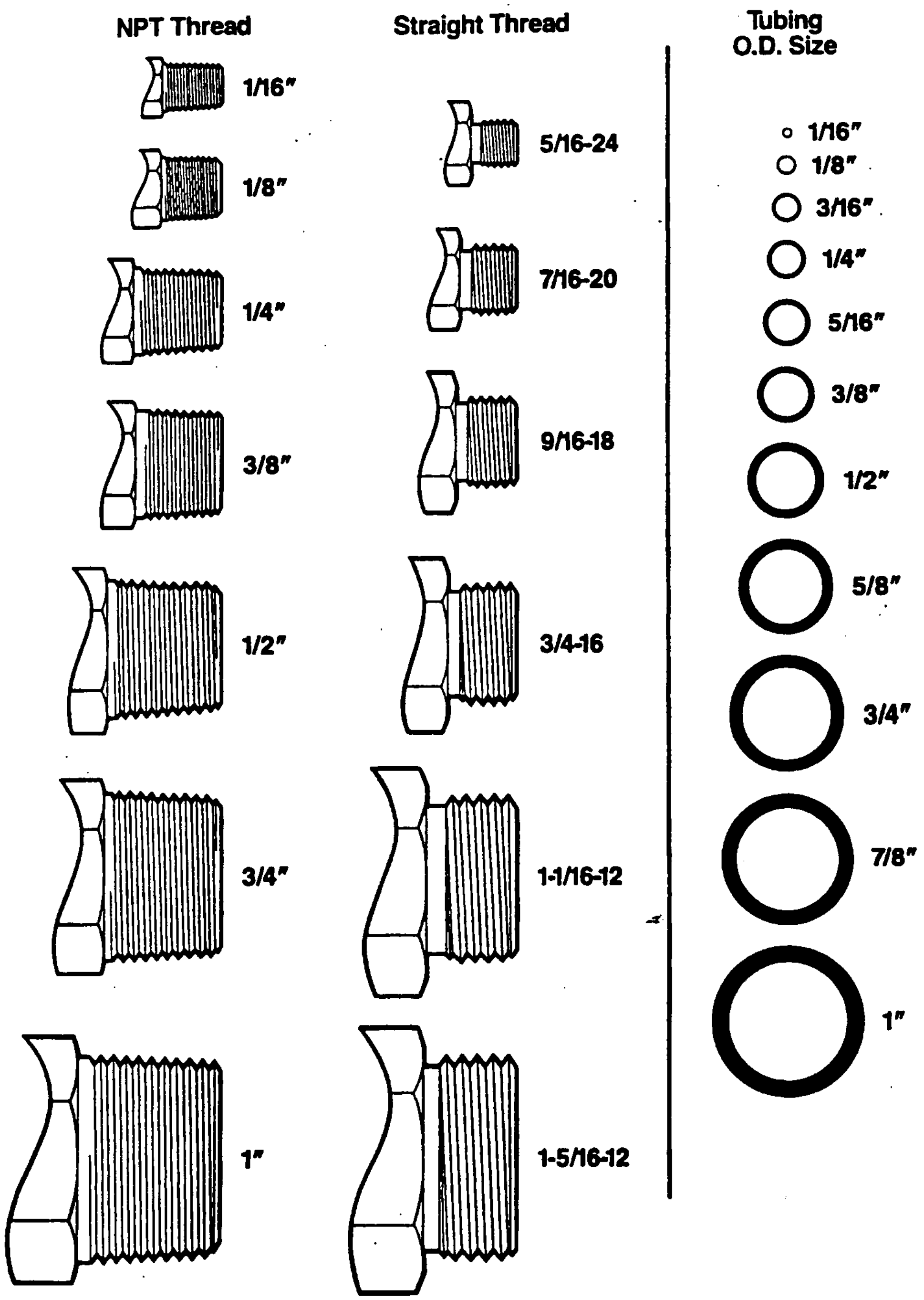


Nayyar, Mohinder L. *Piping Handbook*, Sixth Edition. McGraw-Hill Inc., New York, New York. 1992, p. A114-A116.

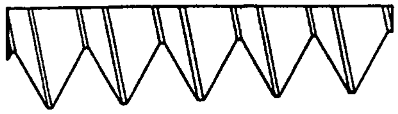
Pipe and Tube End Size Chart (U.S.A.)



Thread and Tube End Size Chart (U.S.A.)

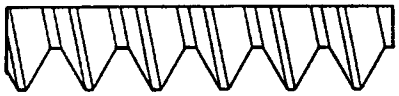


American Standard Pipe Thread (NPT)



60° thread angle • Pitch measured in inches
• Truncation of root and crest are flat
• Taper angle 1°47′

American Standard Unified Thread (Straight)



60° thread angle • Pitch measured in inches
• Truncation of root and crest are flat
• Diameter measured in inches

PROBE VOLUMES IN LITERS

SCHEDULE 40 PVC PIPE

Probe Depth (FT)	Nominal Pipe Diameter 1/2"	3/4"	1"	1-1/2"	2"	2-1/2"	3"	4"
pipe I.D. (in)	0.662	0.824	1.049	1.61	2.067	2.469	3.068	4.026
5	0.3	0.5	0.8	2.0	3.3	4.7	7.3	12.5
10	0.7	1.0	1.7	4.0	6.6	9.4	14.5	25.0
15	1.0	1.6	2.5	6.0	9.9	14.1	21.8	37.5
20	1.4	2.1	3.4	8.0	13.2	18.8	29.0	50.0
25	1.7	2.6	4.2	10.0	16.5	23.5	36.3	62.5
30	2.0	3.1	5.1	12.0	19.8	28.2	43.6	75.0
35	2.4	3.7	5.9	14.0	23.1	32.9	50.8	87.5
40	2.7	4.2	6.8	16.0	26.4	37.6	58.1	100.0
45	3.0	4.7	7.6	18.0	29.7	42.3	65.3	112.5
50	3.4	5.2	8.5	20.0	33.0	47.0	72.6	125.0
55	3.7	5.8	9.3	22.0	36.3	51.7	79.9	137.5
60	4.1	6.3	10.2	24.0	39.5	56.4	87.1	150.0
65	4.4	6.8	11.0	26.0	42.8	61.1	94.4	162.5
70	4.7	7.3	11.9	28.0	46.1	65.8	101.6	175.0
75	5.1	7.9	12.7	30.0	49.4	70.5	108.9	187.5
80	5.4	8.4	13.6	32.0	52.7	75.2	116.2	200.0
85	5.7	8.9	14.4	34.0	56.0	79.9	123.4	212.5
90	6.1	9.4	15.3	36.0	59.3	84.6	130.7	225.1

SCHEDULE 80 PVC PIPE

Probe Depth (FT)	Nominal Pipe Diameter 1/2"	3/4"	1"	1-1/2"	2"	2-1/2"	3"	4"
pipe I.D. (in)	0.546	0.742	0.957	1.278	1.939	2.323	2.9	3.826
5	0.2	0.4	0.7	1.3	2.9	4.2	6.5	11.3
10	0.5	0.8	1.4	2.5	5.8	8.3	13.0	22.6
15	0.7	1.3	2.1	3.8	8.7	12.5	19.5	33.9
20	0.9	1.7	2.8	5.0	11.6	16.7	26.0	45.2
25	1.2	2.1	3.5	6.3	14.5	20.8	32.5	56.5
30	1.4	2.5	4.2	7.6	17.4	25.0	38.9	67.8
35	1.6	3.0	4.9	8.8	20.3	29.2	45.4	79.1
40	1.8	3.4	5.7	10.1	23.2	33.3	51.9	90.4
45	2.1	3.8	6.4	11.3	26.1	37.5	58.4	101.7
50	2.3	4.2	7.1	12.6	29.0	41.6	64.9	113.0
55	2.5	4.7	7.8	13.9	31.9	45.8	71.4	124.3
60	2.8	5.1	8.5	15.1	34.8	50.0	77.9	135.6
65	3.0	5.5	9.2	16.4	37.7	54.1	84.4	146.9
70	3.2	5.9	9.9	17.6	40.6	58.3	90.9	158.2
75	3.5	6.4	10.6	18.9	43.5	62.5	97.4	169.5
80	3.7	6.8	11.3	20.2	46.4	66.6	103.8	180.8
85	3.9	7.2	12.0	21.4	49.3	70.8	110.3	192.1
90	4.1	7.6	12.7	22.7	52.2	75.0	116.8	203.4

APPENDIX B.6

Decimal Equivalents

fraction	decimal	fraction	decimal	fraction	decimal	fraction	decimal
1/64	0.01563	17/64	0.26563	33/64	0.51563	49/64	0.76563
1/32	0.03125	4/15	0.266	17/32	0.53125	7/9	0.777
3/64	0.04688	9/32	0.28125	8/15	0.5333	25/32	0.78125
1/16	0.0625	2/7	0.2875	35/64	0.54688	51/64	0.79688
1/15	0.0666	19/64	0.29688	5/9	0.5555	4/5	0.80
5/64	0.07813	5/16	0.3125	9/16	0.5625	13/16	0.8125
1/12	0.08333	21/64	0.32813	4/7	0.5714	53/64	0.82813
3/32	0.09375	1/3	0.3333	37/64	0.57813	5/6	0.8333
7/64	0.10938	11/32	0.34375	7/12	0.5833	27/32	0.84375
1/9	0.111	23/64	0.35938	19/32	0.59375	6/7	0.8571
1/8	0.125	3/8	0.375	3/5	0.60	55/64	0.8594
2/15	0.1333	25/64	0.39063	39/64	0.60938	13/15	0.8666
9/64	0.14063	2/5	0.40	5/8	0.625	7/8	0.875
1/7	0.14285	13/32	0.40625	41/64	0.64063	8/9	0.8888
5/32	0.15625	5/12	0.4166	21/32	0.65625	57/64	0.89063
1/6	0.1666	27/64	0.42188	2/3	0.6666	29/32	0.90625
11/64	0.17188	3/7	0.4285	43/64	0.67188	11/12	0.9166
3/16	0.1875	7/16	0.4375	11/16	0.6875	59/64	0.92188
1/5	0.20	4/9	0.4444	45/64	0.70313	14/15	0.9333
13/64	0.20313	29/64	0.45313	5/7	0.7142	15/16	0.9375
7/32	0.21875	7/15	0.46666	23/32	0.71875	61/64	0.95313
2/9	0.2222	15/32	0.46875	11/15	0.7333	31/32	0.96875
15/64	0.23438	31/64	0.48438	47/64	0.73438	63/64	0.98438
1/4	0.25	1/2	0.50	3/4	0.75000	1	1.00000

APPENDIX B.7

DRILL SIZES FOR PIPE TAPS - AMERICAN STANDARD NATIONAL PIPE THREAD

Size of Tap in Inches	Number of Threads per Inch	Diameter of Drill	Size of Tap in Inches	Number of Threads per Inch	Diameter of Drill (Inches)
1/8	27	11/32	2	11-1/2	2-3/16
1/4	18	7/16	2-1/2	8	2-9/16
3/8	18	37/64	3	8	3-3/16
1/2	14	23/32	3-1/2	8	3-11/16
3/4	14	59/64	4	8	4-3/16
1	11-1/2	1-5/32	4-1/2	8	4-3/4
1-1/4	11-1/2	1-1/2	5	8	5-5/16
1-1/2	11-1/2	1-49/64	6	8	6-5/16

Source: "The Pipe Fitters and Pipe Welder's Handbook", by Thomas W. Frankland, The Bruce Publishing Co., Milwaukee, WI.

APPENDIX B.8

TABLE OF PIPE DIAMETERS

PVC	PIPE OD	Wall Thick	PIPE ID	Cross Sect. Area In sq In	Cross Sect. Area In sq ft
Sch. 40					
2"	2.375	0.154	2.067	3.3556	0.0233
3"	3.500	0.216	3.068	7.3927	0.0513
4"	4.500	0.237	4.026	12.7303	0.0884
6"	6.625	0.280	6.065	28.8903	0.2006
8"	8.625	0.322	7.981	50.0270	0.3474
10"	10.750	0.365	10.020	78.8543	0.5476
12"	12.750	0.406	11.938	111.9317	0.7773
14"	14.000	0.437	13.126	135.3177	0.9397
16"	16.000	0.500	15.000	176.7146	1.2272
Sch. 80					
2"	2.375	0.218	1.939	2.9529	0.0205
3"	3.500	0.300	2.900	6.6052	0.0459
4"	4.500	0.337	3.826	11.4969	0.0798
6"	6.625	0.432	5.761	26.0667	0.1810
8"	8.625	0.500	7.625	45.6635	0.3171
10"	10.750	0.593	9.564	71.8404	0.4989
12"	12.750	0.687	11.376	101.6410	0.7058
14"	14.000	0.750	12.500	122.7185	0.8522
16"	16.000	0.843	14.314	160.9207	1.1175
CLS 125					
2"	2.375	0.073	2.229	3.9022	0.0271
3"	3.500	0.108	3.284	8.4702	0.0588
4"	4.500	0.138	4.224	14.0132	0.0973
6"	6.625	0.204	6.217	30.3565	0.2108
8"	8.625	0.265	8.095	51.4664	0.3574
10"	10.750	0.331	10.088	79.9282	0.5551
12"	12.750	0.392	11.966	112.4574	0.7810
14"	n/a				
16"	n/a				
CLS 160					
2"	2.375	0.091	2.193	3.7772	0.0262
3"	3.500	0.135	3.230	8.1940	0.0569
4"	4.500	0.173	4.154	13.5526	0.0941
6"	6.625	0.255	6.115	29.3686	0.2039
8"	8.625	0.332	7.961	49.7766	0.3457
10"	10.750	0.413	9.924	77.3505	0.5372
12"	12.750	0.490	11.770	108.8035	0.7556
14"	14.000	0.538	12.924	131.1849	0.9110
16"	16.000	0.615	14.770	171.3369	1.1898

TABLE OF PIPE DIAMETERS Cont' PAGE 2

CLS 200

2"		2.375	0.140	2.095	3.4471	0.0239
3"		3.500	0.206	3.088	7.4894	0.0520
4"		4.500	0.265	3.970	12.3786	0.0860
6"		6.625	0.390	5.845	26.8324	0.1863
8"		8.625	0.508	7.609	45.4721	0.3158
10"		10.750	0.632	9.486	70.6734	0.4908
12"		12.750	0.750	11.250	99.4020	0.6903
14"	n/a					
16"	n/a					

CLS 315

2"		2.375	0.176	2.023	3.2143	0.0223
3"		3.500	0.259	2.982	6.9840	0.0485
4"		4.500	0.333	3.834	11.5450	0.0802
6"		6.625	0.491	5.643	25.0098	0.1737
8"	n/a					
10"	n/a					
12"	n/a					
14"	n/a					
16"	n/a					

••

P E (Dimensions based upon minimum wall thickness; per ASTM D 3035, 1992

Sch. 40

2"		2.375	0.154	2.067	3.3556	0.0233
3"		3.500	0.216	3.068	7.3927	0.0513
4"		4.500	0.237	4.026	12.7303	0.0884
6"		6.625	0.280	6.065	28.8903	0.2006
8"		8.625	0.322	7.981	50.0270	0.3474
10"		10.750	0.365	10.020	78.8543	0.5476
12"		12.750	0.406	11.938	111.9317	0.7773
14"	n/a					
16"	n/a					

Sch. 80

2"		2.375	0.218	1.939	2.9529	0.0205
3"		3.500	0.300	2.900	6.6052	0.0459
4"		4.500	0.337	3.826	11.4969	0.0798
6"		6.625	0.432	5.761	26.0667	0.1810
8"	n/a					
10"	n/a					
12"	n/a					
14"	n/a					
16"	n/a					

TABLE OF PIPE DIAMETERS Cont'   PAGE 3

SDR 32.5					
2"	2.375	0.073	2.229	3.9022	0.0271
3"	3.500	0.108	3.284	8.4702	0.0588
4"	4.500	0.138	4.224	14.0132	0.0973
6"	6.625	0.204	6.217	30.3565	0.2108
8"	8.625	0.265	8.095	51.4664	0.3574
10"	10.750	0.331	10.088	79.9282	0.5551
12"	12.750	0.392	11.966	112.4574	0.7810
14"	14.000	0.431	13.138	135.5653	0.9414
16"	16.000	0.492	15.016	177.0918	1.2298
18"	18.000	0.554	16.892	224.1053	1.5563
20"	20.000	0.615	18.770	276.7059	1.9216
22"	22.000	0.677	20.646	334.7817	2.3249
24"	24.000	0.738	22.524	398.4565	2.7671
SDR 26					
2"	2.375	0.091	2.193	3.7772	0.0262
3"	3.500	0.135	3.230	8.1940	0.0569
4"	4.500	0.173	4.154	13.5526	0.0941
6"	6.625	0.255	6.115	29.3686	0.2039
8"	8.625	0.332	7.961	49.7766	0.3457
10"	10.750	0.413	9.924	77.3505	0.5372
12"	12.750	0.490	11.770	108.8035	0.7556
14"	14.000	0.538	12.924	131.1849	0.9110
16"	16.000	0.615	14.770	171.3369	1.1898
18"	18.000	0.692	16.616	216.8417	1.5058
20"	20.000	0.769	18.462	267.6994	1.8590
22"	22.000	0.846	20.308	323.9099	2.2494
24"	24.000	0.923	22.154	385.4732	2.6769
SDR 21					
2"	2.375	0.113	2.149	3.6271	0.0252
3"	3.500	0.167	3.166	7.8725	0.0547
4"	4.500	0.214	4.072	13.0228	0.0904
6"	6.625	0.315	5.995	28.2272	0.1960
8"	8.625	0.411	7.803	47.8204	0.3321
10"	10.750	0.512	9.726	74.2948	0.5159
12"	12.750	0.607	11.536	104.5202	0.7258
14"	14.000	0.667	12.666	125.9995	0.8750
16"	16.000	0.762	14.476	164.5838	1.1429
18"	18.000	0.857	16.286	208.3141	1.4466
20"	20.000	0.952	18.096	257.1906	1.7860
22"	22.000	1.048	19.904	311.1506	2.1608
24"	24.000	1.143	21.714	370.3135	2.5716

TABLE OF PIPE DIAMETERS Cont'

PAGE 4

SDR 17					
2"	2.375	0.140	2.095	3.4471	0.0239
3"	3.500	0.206	3.088	7.4894	0.0520
4"	4.500	0.265	3.970	12.3786	0.0860
6"	6.625	0.390	5.845	26.8324	0.1863
8"	8.625	0.507	7.611	45.4960	0.3159
10"	10.750	0.632	9.486	70.6734	0.4908
12"	12.750	0.750	11.250	99.4020	0.6903
14"	14.000	0.824	12.352	119.8297	0.8322
16"	16.000	0.941	14.118	156.5439	1.0871
18"	18.000	1.059	15.882	198.1072	1.3757
20"	20.000	1.176	17.648	244.6138	1.6987
22"	22.000	1.294	19.412	295.9583	2.0553
24"	24.000	1.412	21.176	352.1906	2.4458
SDR 15.5					
2"	2.375	0.153	2.069	3.3621	0.0233
3"	3.500	0.226	3.048	7.2966	0.0507
4"	4.500	0.290	3.920	12.0687	0.0838
6"	6.625	0.427	5.771	26.1572	0.1816
8"	8.625	0.556	7.513	44.3319	0.3079
10"	10.750	0.694	9.362	68.8378	0.4780
12"	12.750	0.823	11.104	96.8387	0.6725
14"	14.000	0.903	11.936	111.8942	0.7770
16"	16.000	1.032	13.678	146.9383	1.0204
18"	18.000	1.161	15.420	186.7492	1.2969
20"	20.000	1.290	17.162	231.3267	1.6064
22"	22.000	1.419	18.904	280.6708	1.9491
24"	24.000	1.548	24.000	452.3893	3.1416
SDR 13.5					
2"	2.375	0.176	2.023	3.2143	0.0223
3"	3.500	0.259	2.982	6.9840	0.0485
4"	4.500	0.333	3.834	11.5450	0.0802
6"	6.625	0.491	5.643	25.0098	0.1737
8"	8.625	0.639	7.347	42.3945	0.2944
10"	10.750	0.796	9.158	65.8705	0.4574
12"	12.750	0.944	10.862	92.6637	0.6435
14"	14.000	1.037	11.926	111.7068	0.7757
16"	16.000	1.185	13.630	145.9088	1.0133
18"	18.000	1.333	15.334	184.6719	1.2824
20"	20.000	1.481	17.038	227.9959	1.5833
22"	22.000	1.630	18.740	275.8221	1.9154
24"	24.000	1.778	20.444	328.2628	2.2796

TABLE OF PIPE DIAMETERS Cont' PAGE 5

SDR 11					
2"	2.375	0.216	1.943	2.9651	0.0206
3"	3.500	0.318	2.864	6.4422	0.0447
4"	4.500	0.409	3.682	10.6477	0.0739
6"	6.625	0.602	5.421	23.0807	0.1603
8"	8.625	0.784	7.057	39.1138	0.2716
10"	10.750	0.977	8.796	60.7660	0.4220
12"	12.750	1.159	10.432	85.4722	0.5936
14"	14.000	1.273	11.454	103.0396	0.7156
16"	16.000	1.455	13.090	134.5765	0.9346
18"	18.000	1.636	14.728	170.3638	1.1831
20"	20.000	1.818	16.364	210.3143	1.4605
22"	22.000	2.000	18.000	254.4690	1.7671
24"	24.000	2.182	19.636	302.8279	2.1030
SDR 9.3					
2"	2.375	0.255	1.865	2.7318	0.0190
3"	3.500	0.376	2.748	5.9309	0.0412
4"	4.500	0.484	3.532	9.7979	0.0680
6"	6.625	0.712	5.201	21.2453	0.1475
8"	8.625	0.927	6.771	36.0077	0.2501
10"	10.750	1.156	8.438	55.9202	0.3883
12"	12.750	1.371	10.008	78.6655	0.5463
14"	14.000	1.505	10.990	94.8605	0.6588
16"	16.000	1.720	12.560	123.8994	0.8604
18"	18.000	1.935	14.130	156.8102	1.0890
20"	20.000	2.151	15.698	193.5435	1.3441
22"	22.000	2.366	17.268	234.1930	1.6263
24"	24.000	2.581	18.838	278.7144	1.9355
SDR 9					
2"	2.375	0.264	1.847	2.6793	0.0186
3"	3.500	0.389	2.722	5.8192	0.0404
4"	4.500	0.500	3.500	9.6211	0.0668
6"	6.625	0.736	5.153	20.8550	0.1448
8"	8.625	0.958	6.709	35.3513	0.2455
10"	10.750	1.194	8.362	54.9174	0.3814
12"	12.750	1.417	9.916	77.2259	0.5363
14"	14.000	1.556	10.888	93.1078	0.6466
16"	16.000	1.778	12.444	121.6214	0.8446
18"	18.000	2.000	14.000	153.9380	1.0690
20"	20.000	2.222	15.556	190.0578	1.3198
22"	22.000	2.444	17.112	229.9807	1.5971
24"	24.000	2.667	18.666	273.6481	1.9003

TABLE OF PIPE DIAMETERS Cont'   PAGE 6

SDR 7					
2"	2.375	0.339	1.697	2.2618	0.0157
3"	3.500	0.500	2.500	4.9087	0.0341
4"	4.500	0.643	3.214	8.1130	0.0563
6"	6.625	0.946	4.733	17.5939	0.1222
8"	8.625	1.232	6.161	29.8121	0.2070
10"	10.750	1.536	7.678	46.3005	0.3215
12"	12.750	1.821	9.108	65.1532	0.4525
14"	14.000	2.000	10.000	78.5398	0.5454
16"	16.000	2.286	11.428	102.5724	0.7123
18"	18.000	2.571	12.858	129.8484	0.9017
20"	20.000	2.857	14.286	160.2918	1.1131
22"	22.000	3.143	15.714	193.9382	1.3468
24"	24.000	3.429	17.142	230.7878	1.6027

APPENDIX C

C.1 Flare Station Reading Sheet

C.2 Probe Monitoring Reading Sheet

C.3 Well Monitoring Reading Sheet

C.4 Maintenance Record

C.5 Equipment Repair Record

C.6 Sample Maintenance Schedule

C.7 Flare Facility Short Form Startup Procedures

C.8 Troubleshooting Table

Flare Station Reading Sheet

Site: ____________________

Date: ____________________ Technician: ________________________________

Strip Chart Time	hh:mm	
Real Time	hh:mm	
Gas Flow	SCFM	
Flare Temp	Deg. F	
Alarms Indicated		
Flare Low Temp	YES NO	
Flame Alarm	YES NO	
High LEL Level	YES NO	
Sump High Level	YES NO	
Low Vacuum	YES NO	
LEL Detector Channel 1	% LEL	
Control Panel Lights All Operating	YES NO	
Propane Tank Pressure	psig	
Blower Inlet Vacuum	in. W.C.	
Blower Discharge Pressure	in. W.C.	
Blower Inlet Temp	Deg. F	
Blower Discharge Temp	Deg. F	
Blower Discharge Methane	%	
Blower Discharge Oxygen	%	
Condensate Tank Level	inches	
Flame Arrestor Differential Pressure	in. W.C.	
Flame Condition		
Damper Position - North	% open	
South	% open	
Air Compressor Pressure	psig	
Blow Down (air compressor)	YES NO	
Flare Skin Temp	Deg. F	

Comments/ Maintenace Performed ________________________________

Signed ____________________ Reviewed ____________________

Date ____________________

Probe Monitoring Reading Sheet

PROBE TESTING

DATE:____________________

INSTRUMENT USED:____________

SITE:____________________

TECHNICIAN:______________________________

WEATHER CONDITION:______________________

BAROMETRIC PRESSURE:____________________

Probe Location	Probe Pressure (in. water)	Constant 30 Second Field Reading			Probe CO_2 %	Probe Testing Time hh:mm	Probe Depth (feet)	Probe Evacuation Time (seconds)
		Vault CH_4 %	Probe CH_4 %	Probe O_2 %				

NM= Not Measured, ND= Not Detected, TR= Trace, OR= Over Instrument Range

Reviewed:____________________ Date:____________ Signed:____________________

APPENDIX C.3

WELL MONITORING READING SHEET

SITE: ______________________

DATE: ______________________

PERSONNEL: ______________________

____

WEATHER CONDITION: ______________________

BAROMETRIC PRESSURE: ______________________

Well Number	Well Head Pressure (in. water)	CONCENTRATION %					Temperature Deg. F	Initial Velocity FPM	** Initial Flowrate CFM	Adjusted Velocity FPM	Adjusted Flowrate CFM	* CO ppm
		CH4	CO2	O2		Balance						

IO= Insufficient Oxygen, NM= Not Measured, ND= Not Detected, TR= Trace, OR= Over Instrument Range

* CO is monitored if a landfill fire is suspected

** Flowrate = Velocity X 0.022 (2" Pipe)

MAINTENANCE RECORD CARD (Front & Back)

19___	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEP	OCT	NOV	DEC
1												
2												
3												
4												
5												

CODE:
W-weekly
M-monthly
Q-quarterly
S-semi-annually
A-annually

✓-routine
X-minor repair
For major repair list line# on equipment card file.

Record, date, initials, maintenance type; routine, minor or major.

Section ____ Item # ______ Required Maintenance

weekly	
monthly	
quarterly	
semi annually	
annually	

APPENDIX C.5

REPAIR RECORD CARD (Front & Back)

Mfg. Name ______________________ Vendor Name ______________________

Address ______________________ Address ______________________

City/State/Zip ______________________ City/State/Zip ______________________

Telephone ______________________ Telephone ______________________

Equipment Description & use ______________________

Vital Statistics

Model ______	HP ______	Volts ______
Serial ______	Phase ______	Amps ______
Fig or Cat# ______	Cycle/HZ ______	S.F. ______
Frame ______	RPM ______	Size ______

Section ______ Item # ______ Maint. Cycle ______ Due Date J/F/M/A/M/J/J/A/S/O/N/D 1/2/3/4/5

Date	P.O. or Inv.#	By	Repairs on Equipment
			1
			2
			3
			4
			5
			6
			7
			8
			9
			10
			11
			12
			13
			14
			15
			16
			17
			18
			19
			20
			21
			22
			23
			24
			25
			26

APPENDIX C.6

SAMPLE MAINTENANCE SCHEDULE

	Maintenance	Frequency	Estimated Time*	Spare Item
Butterfly Valves	Check for Open/Close	Quarterly	10 min.	
Actuators	Proper operation	Quarterly	30 min.	
Flame Arresters	Remove debris from element	Annually	1 hr.	Grid assembly Gasket Screw Lockwasher
UV Scanner	Clean lens & replace scanner tube	Annually	1 hr.	UV Sensing Tube Quartz Viewing Window Gasket
Strip Chart Recorder	Check paper & pen supply	Monthly	30 min.	Pens Paper
Condensate Knockout or Separator	Check level is within range, gauges are operational	Monthly	30 min.	Level Actuator Emersion Oil
Damper Actuator	Check seals and proper operation	Annually	30 min.	Oil
Spark Plug	Visual inspection	Annually	15 min.	Ignitor
Solenoid Valves	Check and test	Monthly	1 hr.	
Blower Motors	Inspect and grease	Annually	1 hr.	Grease
Blowers	Inspect and grease	Monthly	30 min..	Bearing, drive end Bearing, opposite end Bearing, locknut Bearing, lockwasher Grease Slinger Grease
Blower Belts and Sheaves	Inspect for wear, alignment & tension	Bi-Annually	2 hrs.	Belt
Alarms	Check all shutdown alarms for proper operation	Quarterly		
Liquid Filters	Replace filter cartridge	Monthly		Filter Cartridge
Air Filter/Regulators	Clean out bowl	6 Months	30 min.	
Spare Blower	Hand rotate or bump	Weekly		
Thermocouple	Check for heat damage	Annually		

Note: This is a sample maintenance schedule, actual maintenance requirements for each site will differ.
* Estimated time does not include time for repair

APPENDIX C.7

FLARE FACILITY SHORT FORM STARTUP PROCEDURES

The procedures given below can be used as a checklist for the flare system startup. This procedure is a sample only. A site specific startup procedure should be prepared.

Flare Station Checklist

1. Check for any gas leaks or gas odors.
2. Check the pilot system tank for fuel, and open the fuel isolation valve.
3. Open the flare station inlet valve

Control Panel Procedures

1. Energize the main circuit breaker feeding the flare station.
2. Reset any emergency stop buttons.
3. Verify that any liquid knockouts have drained.
4. Reset alarms.
5. Turn the main switch to AUTO.
6. Check all systems to make sure that they are ready for operation.
7. Press the start button. This initiates the startup sequence. Do not allow anyone to stand by the flare or the blowers while it is being ignited.

Once the flare is lit, check the following:

1. Gas leaks in the flare station.
2. The blower for unusual noise or vibration.
3. Flame condition.
4. The gas flow to the flare.
5. The flare combustion temperature.
6. Check blower amperage and verify that is between the acceptable range.

APPENDIX C.8

TROUBLESHOOTING TABLE

Alarm	Explanation	Possible Causes	Attempt to Restart?
Purge Failure	No purge air	• Purge blower or flow switch failure	No
Pilot Failure	Pilot temperature has not reached set point in time allowed	• No propane • Ignition failure in wire or sparkplug • Ignition failure in transformer • Clogged pilot orifice	No
Flame Failure	Flare not confirmed by ultraviolet scanner	• UV scanner failure • Lack of methane (poor quality LFG or low flow) • Ignition failure or no propane • Liquid blockage in header • Line separation	Yes
High Stack Temp Shutdown	Stack temperature above maximum setpoint	• Damper failure • Temperature Controller failure • Excess LFG flow	No
Low Stack Temp Shutdown	Stack temp fell below minimum setpoint	• Damper failure • Low gas quality • Low gas flow rate • Using wrong thermocouple	Yes
High Blower Discharge Temperature	The temperature in the LFG inlet piping to the flare is high and may cause the pipe to melt.	• High inlet temperature • Blower surge • Low flow • Rubbing	No
LFG Blower Failure	Current flow to the blower is (1) too high (overload) (2) too low (surge)	• Blower malfunction • Break in piping • Inlet valve open too much • False signal caused by sun shining on panel • High ambient temperature • Pipe blockage, failure, or field valves closed too much • Insufficient flow	No
Shutoff Valve Fail	Automatic shutoff valve did not close completely prior to ignition	• Automatic shutoff valve failure • Limit switch failure.	No

APPENDIX D

APPENDIX D.1
Electrical Enclosures for LFG Applications

The LFG system operator will encounter different types of electrical enclosures depending on the design of the system. The operator should be familiar with the intended purpose of the enclosure. In particular, explosion proof enclosures with numerous bolts should always be secured with all of the bolts in place.

There are three methods of protecting electrical enclosures. These are installing the enclosures outside a hazardous area, purging the enclosure, or installing the electrical equipment in an enclosure designed for the particular hazardous location.

Enclosures are grouped into various categories by the National Electrical Manufactures Association (NEMA). The more commonly used ones are as follows:

- Type 1 enclosures are intended for indoor use to provide a degree of protection against contact with the enclosed equipment.
- Type 3 enclosures are intended for outdoor use to provide a degree of protection against windblown dust, rain, sleet, and external ice formation.
- Type 3R enclosures are intended for outdoor use to provide a degree of protection against falling rain, sleet and external ice formation.
- Type 4 enclosures are intended for indoor or outdoor use to provide a degree of protection against windblown dust and rain, splashing water, and hose-directed water.
- Type 12 enclosures are intended for indoor use to provide a degree of protection against windblown dust and rain, splashing water, and hose-directed water.
- Type 7 enclosures are for indoor use in locations classified as Class I, Groups A, B, C, or D as defined in the National Electrical Code.
- Type 8 enclosures are for indoor or outdoor use in locations classified as Class I, Groups A, B, C, or D as defined in the National Electrical Code.

If the enclosure type is followed by a letter, the enclosure uses purging with clean air to reduce the hazard level. The following letter designations are used:

- Type X - Will reduce the enclosure from a Division 1 to non-hazardous.
- Type Y - Will reduce the enclosure from a Division 1 to Division 2.
- Type Z - Will reduce the enclosure from a Division 2 to non-hazardous.

APPENDIX D.1
NEC Class and Group Definitions

Class I - Locations are classified as Class I when flammable gases or vapors are or may be present in the air in quantities sufficient to produce explosive or ignitable mixtures. Section 500-3 of the NEC divides Class I locations into four groups, Groups A through D:

Group A - Atmospheres containing acetylene

Group B - Atmospheres containing hydrogen, fuel and combustible process gases containing more than 30% hydrogen by volume, or gases or vapors of equivalent hazard, such as butadiene, ethylene oxide, propylene, oxide, and acrolein.

Group C - Atmospheres such as ethyl ether, ethylene, or gases or vapors of equivalent hazard.

Group D - Atmospheres such as acetone, ammonia, benzene, butane, cyclopropane, ethanol, gasoline, hexane, methane, natural gas, naphtha, propane, or gases or vapors of equivalent hazard.

Class II - Locations are classified as Class II when combustible dust is present. Class II locations are divided into three groups, Group E, Group F, and Group G.

Group E - Atmospheres containing combustible metal dusts, including aluminum, magnesium, and their commercial alloys, or other combustible dusts whose particle size, abrasiveness, and conductivity present similar hazards in the use of electrical equipment.

Group F - Atmospheres containing combustible carbonaceous dust, including carbon black, charcoal, coal, or coke dust that have more than 8 percent total entrapped voltatiles, or dusts that have been sensitized by other materials so that they present an explosion hazard.

Group G - Atmospheres containing combustible dusts not including Group E or F, including flour, grain, wood, plastic and chemicals.

Class III - Locations are classified as Class III when the presence of ignitable fibers or flyings exists, however these fibers or flyings must also not be in suspension in the air in quantities sufficient to produce ignitable mixtures.

APPENDIX D.2

Type K Thermocouples

Thermoelectric voltage as a function temperature (°F), reference junctions at 32°F.

	Thermoelectric Voltage (mV)											
°F	0	1	2	3	4	5	6	7	8	9	10	°F
-450	-6.456	-6.456	-6.457	-6.457	-6.458							-450
-440	-6.447	-6.448	-6.449	-6.450	-6.451	-6.452	-6.453	-6.454	-6.454	-6.455	-6.456	-440
-430	-6.431	-6.433	-6.435	-6.436	-6.438	-6.440	-6.441	-6.443	-6.444	-6.450	-6.447	-430
-420	-6.409	-6.411	-6.414	-6.416	-6.419	-6.421	-6.423	-6.425	-6.427	-6.429	-6.431	-420
-410	-6.380	-6.383	-6.386	-6.389	-6.392	-6.395	-6.398	-6.401	-6.404	-6.406	-6 409	-410
-400	-6.344	-6.348	-6.352	-6.355	-6.359	-6.363	-6.366	-6.370	-6.373	-6.377	-6.380	-400
-390	-6.301	-6.306	-6.310	-6.315	-6.319	-6.323	-6.328	-6.332	-6.336	-6.340	-6.344	-390
-380	-6.251	-6.257	-6.262	-6.267	-6.272	-6.277	-6.282	-6.287	-6.292	-6.296	-6.301	-380
-370	-6.195	-6.201	-6.207	-6.213	-6.219	-6.224	-6.230	-6.235	-6.241	-6.246	-6.251	-370
-360	-6.133	-6.139	-6.146	-6.152	-6.158	-6.165	-6.171	-6.177	-6.183	-6.189	-6.195	-360
-350	-6.064	-6.071	-6.078	-6.085	-6.092	-6.099	-6.106	-6.113	-6.119	-6.126	-6.133	-350
-340	-5.989	-5.997	-6.004	-6.012	-6.020	-6.027	-6.035	-6.042	-6.049	-6.057	-6.064	-340
-330	-5.908	-5.917	-5.925	-5.933	-5.941	-5.949	-5.957	-5.965	-5.973	-5.981	-5.989	-330
-320	-5.822	-5.831	-5.839	-5.848	-5.857	-5.866	-5.874	-5.883	-5.891	-5.900	-5.908	-320
-310	-5.730	-5.739	-5.748	-5.758	-5.767	-5.776	-5.786	-5.795	-5.804	-5.813	-5.822	-310
-300	-5.632	-5.642	-5.652	-5.662	-5.672	-5.682	-5.691	-5.701	-5.711	-5.720	-5.730	-300
-290	-5.529	-5.540	-5.550	-5.561	-5.571	-5.810	-5.592	-5.602	-5.612	-5.692	-5.632	-290
-280	-5.421	-5.432	-5.443	-5.454	-5.465	-5.476	-5.487	-5.497	-5.508	-5.519	-5.529	-280
-270	-5.308	-5.319	-5.331	-5.342	-5.354	-5.365	-5.376	-5.388	-5.399	-5.410	-5.421	-270
-260	-5 190	-5.202	-5.214	-5.226	-5.238	-5.249	-5.261	-5.273	-5.285	-5.296	-5.308	-260
-250	-5.067	-5.079	-5.092	-5.104	-5.116	-5.129	-5.141	-5.153	-5.165	-5.178	-5.190	-250
-240	-4.939	-4.952	-4.965	-4.978	-4.990	-5.003	-5.016	-5.029	-5.041	-5.054	-5.067	-240
-230	-4 806	-4.819	-4.833	-4.846	-4 860	-4.873	-4.886	-4.899	-4.912	-4.926	-4.939	-230
-220	-4 6G9	-4.683	-4.697	-4.710	-4.724	-4.738	-4.752	-4.765	-4.779	-4.792	-4.806	-220
-210	-4.527	-4.541	-4.556	-4.570	-4.584	-4.598	-4.613	-4.627	-4.641	-4.605	-4.669	-210
-200	-4.381	-4.396	-4.410	-4.425	-4.440	-4.454	-4.469	-4.484	-4.498	-4.512	-4.527	-200
-190	-4.230	-4.245	-4.261	-4.276	-4.291	-4.306	-4.321	-4.336	-4.351	-4.366	-4.381	-190
-180	-4.075	-4.091	-4.107	-4.122	-4.138	-4.153	-4.169	-4.184	-4.200	-4.215	-4.230	-180
-170	-3.917	-3.933	-3.949	-3.965	-3 981	-3.997	-4.012	-4.028	-4.044	-4.060	-4.075	-170
-160	-3.754	-3.770	-3.787	-3.803	-3.819	-3.836	-3.852	-3.868	-3.884	-3.901	-3.917	-160
-150	-3.587	-3.604	-3.621	-3.637	-3.654	-3.671	-3.688	-3.704	-3.721	-3.737	-3.754	-150
-140	-3.417	-3.434	-3.451	-3.468	-3.485	-3.502	-3.519	-3.536	-3.553	-3.570	-3.587	-140
-130	-3.242	-3.260	-3.277	-3.295	-3.312	-3.330	-3.347	-3.365	-3.382	-3.399	-3.417	-130
-120	-3.065	-3.082	-3.100	-3.118	-3.136	-3.154	-3.172	-3.189	-3.207	-3.225	-3.242	-120
-110	-2 883	-2.902	-2.920	-2.938	-2.956	-2.974	-2.992	-3.010	-3.029	-3.047	-3.065	-110
-100	-2.699	-2.717	-2.736	-2.754	-2.773	-2.791	-2.810	-2.828	-2.847	-2.865	-2.883	-100
-90	-2.531	-2.530	-2.549	-2.567	-2.586	-2.605	-2.624	-2.643	-2.661	-2.680	-2.699	-90
-80	-2.320	-2.339	-2.358	-2.377	-2.397	-2.416	-2.435	-2.454	-2.473	-2.492	-2.511	-80
-70	-2.126	-2.145	-2.165	-2.184	-2.204	-2.223	-2.243	-2.262	-2.281	-2.300	-2.320	-70
-60	-1.929	-1.949	-1.968	-1.988	-2.008	-2.028	-2.047	-2.067	-2.087	-2.106	-2.126	-60
-50	-1.729	-1.749	-1.769	-1.789	-1.809	-1.829	-1.849	-1.869	-1.889	-1.909	-1.929	-50
-40	-1.527	-1.547	-1.567	-1.588	-1.608	-1.628	-1.648	-1.669	-1.689	-1.709	-1.729	-40
-30	-1.322	-1.342	-1.363	-1.383	-1.404	-1.424	-1.445	-1.465	-1.486	-1.506	-1.527	-30
-20	-1.114	-1.135	-1.156	-1.177	-1.197	-1.218	-1.239	-1.260	-1.280	-1.301	-1.322	-20
-10	-0.904	-0.925	-0.946	-0.968	-0.989	-1.010	-1.031	-1.051	-1.072	-1.093	-1.114	-10
0	-0.692	-0.714	-0.735	-0.756	-0.777	-0.799	-0.820	-0.841	-0.862	-0.883	-0.904	0
0	-0.692	-0.671	-0.650	-0.628	-0.607	-0.585	-0.564	-0.543	-0.521	-0.500	-0.478	0
10	-0.478	-0.457	-0.435	-0.413	-0.392	-0.370	-0.349	-0.327	-0.305	-0.284	-0.262	10
20	-0.262	-0.240	-0.218	-0.197	-0.175	-0.153	-0.131	-0.109	-0.088	-0.066	-0.044	20
30	-0.044	-0.022	0.000	0.022	0.044	0.066	0.088	0.110	0.132	0.154	0.176	30
40	0.176	0.198	0.220	0.242	0.264	0.286	0.308	0.331	0.353	0.375	0.397	40
50	0.397	0.419	0.441	0.464	0.486	0.508	0.530	0.553	0.575	0.597	0.619	50
60	0.619	0.642	0.664	0.686	0.709	0.731	0.753	0.776	0.798	0.821	0.843	60
70	0.843	0.860	0.888	0.910	0.933	0.955	0.978	1.000	1.023	1.045	1.068	70
80	1.068	1.090	1.113	1.135	1.158	1.181	1.203	1.226	1.248	1.271	1.294	80
90	1.294	1.316	1.339	1.362	1.384	1.407	1.430	1.452	1.475	1.498	1.520	90
100	1.520	1.543	1.566	1.589	1.611	1.634	1.657	1.680	1.703	1.725	1.748	100
110	1.748	1.771	1.794	1.817	1.839	1.862	1.882	1.908	1.931	1.954	1.977	110
120	1.977	2.000	2.022	2.045	2.068	2.091	2.114	2.137	2.160	2.183	2.206	120
130	2.206	2.229	2.252	2.275	2.298	2.321	2.344	2.367	2.390	2.413	2.436	130
140	2.436	2.459	2.482	2.505	2.528	2.551	2.574	2.597	2.620	2.643	2.666	140
150	2.666	2.689	2.712	2.735	2.758	2.781	2.804	2.827	2.850	2.873	2.896	150
160	2.896	2.290	2.943	2.966	2.989	3.012	3.035	3.058	3.081	3.104	3.127	160
170	3.127	3.150	3.173	3.196	3.220	3.243	3.266	3.289	3.312	3.335	3.358	170

Type K Thermocouples

Thermoelectric voltage as a function temperature (°F), reference junctions at 32°F.

	Thermoelectric Voltage (mV)											
°F	0	1	2	3	4	5	6	7	8	9	10	°F
1,500	33.913	33.936	33.959	33.981	34.004	34.027	34.049	34.072	34.095	34.117	34.140	1,500
1,510	34.140	34.163	34.185	34.208	34.231	34.253	34.276	34.299	34.321	34.344	34.366	1,510
1,520	34.366	34.389	34.412	34.434	34.457	34.480	34.502	34.525	34.547	34.570	34.593	1,520
1,530	34.593	34.615	34.638	34.660	34.683	34.705	34.728	34.751	34.773	34.796	34.818	1,530
1,540	34.818	34.841	34.863	34.886	34.909	34.931	34.954	34.976	34.999	35.021	35.044	1,540
1,550	35.044	35.066	35.089	35.111	35.134	35.156	35.179	35.201	35.224	35.246	35.269	1,550
1,560	35.269	35.291	35.314	35.336	35.359	35.381	35.404	35.426	35.449	35.471	35.494	1,560
1,570	35.494	35.516	35.539	35.561	35.583	35.606	35.628	35.651	35.673	35.696	35.718	1,570
1,580	35.718	35.741	35.763	35.785	35.808	35.830	35.853	35.875	35.897	35.920	35.942	1,580
1,590	35.942	35.965	35.987	36.009	36.032	36.054	36.077	36.099	36.121	36.144	36.166	1,590
1,600	36.166	36.188	36.211	36.233	36.256	36.278	36.300	36.323	36.345	36.367	36.390	1,600
1,610	36.390	36.412	36.434	36.457	36.479	36.501	36.524	36.546	36.568	36.590	36.613	1,610
1,620	36.613	36.635	36.657	36.680	36.702	36.724	36.746	36.769	36.791	36.813	36.836	1,620
1,630	36.836	36.858	36.880	36.902	36.925	36.947	36.969	36.991	37.014	37.036	37.058	1,630
1,640	37.058	37.080	37.103	37.125	37.147	37.169	37.191	37.214	37.236	37.258	37.280	1,640
1,650	37.280	37.303	37.325	37.347	37.369	37.391	37.413	37.436	37.458	37.480	37.502	1,650
1,660	37.502	37.524	37.547	37.569	37.591	37.613	37.635	37.657	37.679	37.702	37.724	1,660
1,670	37.724	37.746	37.768	37.790	37.812	37.834	37.857	37.879	37.901	37.923	37.945	1,670
1,680	37.945	37.967	37.989	38.011	38.033	38.055	38.078	38.100	38.122	38.144	38.166	1,680
1,690	38.166	38.188	38.210	38.232	38.254	38.276	38.298	38.320	38.342	38.364	38.387	1,690
1,700	38.387	38.409	38.431	38.453	38.475	38.497	38.519	38.541	38.563	38.585	38.607	1,700
1,710	38.607	38.629	38.651	38.673	38.695	38.717	38.739	38.761	38.783	38.805	38.827	1,710
1,720	38.827	38.849	38.871	38.893	38.915	38.937	38.959	38.981	39.003	39.024	39.046	1,720
1,730	39.046	39.068	39.090	39.112	39.134	39.156	39.178	39.200	39.222	39.244	39.266	1,730
1,740	39.266	39.288	39.310	39.331	39.353	39.375	39.397	39.419	39.441	39.463	39.485	1,740
1,750	39.485	39.507	39.529	39.550	39.572	39.594	39.616	39.638	39.660	39.682	39.703	1,750
1,760	39.703	39.725	39.747	39.769	39.791	39.813	39.835	39.856	39.878	39.900	39.922	1,760
1,770	39.922	39.944	39.965	39.987	40.009	40.031	40.053	40.075	40.096	40.118	40.140	1,770
1,780	40.140	40.162	40.183	40.205	40.227	40.249	40.271	40.292	40.314	40.336	40.358	1,780
1,790	40.358	40.379	40.401	40.423	40.445	40.466	40.488	40.510	40.532	40.553	40.575	1,790
1,800	40.575	40.597	40.619	40.640	40.662	40.684	40.705	40.727	40.749	40.770	40.792	1,800
1,810	40.792	40.814	40.836	40.857	40.879	40.901	40.922	40.944	40.966	40.987	41.009	1,810
1,820	41.009	41.031	41.052	41.074	41.096	41.117	41.139	41.161	41.182	41.204	41.225	1,820
1,830	41.225	41.247	41.269	41.290	41.312	41.334	41.355	41.377	41.398	41.420	41.442	1,830
1,840	41.442	41.463	41.485	41.506	41.528	41.550	41.571	41.593	41.614	41.636	41.657	1,840
1,850	41.657	41.679	41.701	41.722	41.744	41.765	41.787	41.808	41.830	41.851	41.873	1,850
1,860	41.873	41.895	41.916	41.938	41.959	41.985	42.002	42.024	42.045	42.067	42.088	1,860
1,870	42.088	42.110	42.131	42.153	42.174	42.196	42.217	42.239	42.260	42.282	42.303	1,870
1,880	42.303	42.325	42.346	42.367	42.389	42.410	42.432	42.453	42.475	42.496	42.518	1,880
1,890	42.518	42.539	42.560	42.582	42.603	42.625	42.646	42.668	42.689	42.710	42.732	1,890
1,900	42.732	42.753	42.775	42.796	42.817	42.839	42.860	42.882	42.903	42.924	42.946	1,900
1,910	42.946	42.967	42.989	43.010	43.031	43.053	43.074	43.095	43.117	43.138	43.159	1,910
1,920	43.159	43.181	43.202	43.223	43.245	43.266	43.287	43.309	43.330	43.351	43.373	1,920
1,930	43.373	43.394	43.415	43.436	43.458	43.479	43.500	43.522	43.543	43.564	43.585	1,930
1,940	43.585	43.607	43.628	43.649	43.671	43.692	43.713	43.734	43.756	43.777	43.798	1,940
1,950	43.798	43.819	43.841	43.862	43.883	43.904	43.925	43.947	43.968	43.989	44.010	1,950
1,960	44.010	44.031	44.053	44.074	44.095	44.116	44.137	44.159	44.180	44.201	44.222	1,960
1,970	44.222	44.243	44.265	44.286	44.307	44.328	44.349	44.370	44.391	44.413	44.434	1,970
1,980	44.434	44.455	44.476	44.497	44.518	44.539	44.560	44.582	44.603	44.624	44.645	1,980
1,990	44.645	44.666	44.687	44.708	44.729	44.750	44.771	44.793	44.814	44.835	44.856	1,990
2,000	44.856	44.877	44.898	44.919	44.940	44.961	44.982	45.003	45.024	45.045	45.066	2,000
2,010	45.066	45.087	45.108	45.129	45.150	45.171	45.192	45.213	45.234	45.255	45.276	2,010
2,020	45.276	45.297	45.318	45.339	45.360	45.381	45.402	45.423	45.444	45.465	45.486	2,020
2,030	45.486	45.507	45.528	45.549	45.570	45.591	45.612	45.633	45.654	45.675	45.695	2,030
2,040	45.695	45.716	45.737	45.758	45.779	45.800	45.821	45.842	45.863	45.884	45.904	2,040
2,050	45.904	45.925	45.946	45.967	45.988	46.009	46.030	46.051	46.071	46.092	46.113	2,050
2,060	46.113	46.134	46.155	46.176	46.196	46.217	46.238	46.259	46.280	46.300	46.321	2,060
2,070	46.321	46.342	46.363	46.384	46.404	46.425	46.446	46.467	46.488	46.508	46.529	2,070
2,080	46.529	46.550	46.571	46.591	46.612	46.633	46.654	46.674	46.695	46.716	46.737	2,080
2,090	46.737	46.757	46.778	46.799	46.819	46.840	46.861	46.881	46.902	46.923	46.944	2,090
°F	0	1	2	3	4	5	6	7	8	9	10	°F

APPENDIX D.3

CHEMICAL	Plastics														Elastomers									Metals									Non-metals		
	ABS plastic	Acetal (Delrin®)	CPVC	Epoxy	Hytrel®	LDPE	NORYL®	Nylon	Polycarbonate	Polypropylene	PPS (Ryton®)	PTFE (Teflon®)	PVC	PVDF (Kynar®)	Buna N (Nitrile)	EPDM	Hypalon®	Kel-F®	Natural rubber	Neoprene	Silicone	Tygon®	Viton®	304 stainless steel	316 stainless steel	Aluminum	Brass	Bronze	Cast iron	Copper	Hastelloy C®	Titanium	Carbon graphite	Ceramic Al_2O_3	Ceramic magnet
Acetaldehyde	D	A	D	A	-	C	-	A	C^1	A^1	A	A	D	D	D	A	C	A	C	C	A	D	D	A	A	B	A	A	C	-	A	A	A	-	-
Acetamide	-	A	-	A	-	A	-	A	D	A^1	A	A	D	C	A	A	B	A	D	B	B	D	B	B	A	A	-	D	D	-	-	-	A	-	-
Acetate Solvent	-	-	C	A	-	A	D	A	-	B^1	A	A	D	A	C	A	C	A^1	C	D	C	D	D	A	A	A	A	C	D	A	A	A	A	-	-
Acetic Acid	D	D	C	C	-	A^2	A	D	B^1	B	A	A	D	C	C	A	C	A	B	C	C	D	B	D	B	B	D	C	D	B	A	A	A	A	-
Acetic Acid 20%	C	C	A	A^1	-	A	A	D	A^1	A	A	A	D	A	B	A	A	A	B	A	B	D	B	B	A	B	D	C	D	B	A	A	A	A	A
Acetic Acid 80%	D	D	C	B^1	-	D	A	D	B^1	A	A	A	C	C	C	A	C	A	C	C	B	D	B	D	B	B	D	C	D	B	A	A	A	A	A
Acetic Acid, Glacial	D	D	B^1	B^1	A^1	D	A	B	B^1	A^1	A	A	D	A^1	C	B	C	A^2	C	D	B	D	D	C	A	B	-	C	D	B	A	A	A	A	A
Acetic Anhydride	C^1	D	D	C	C	D	D	A^1	D	B^1	A	A	D	B^1	D	B	A	A	C	A	C	D	D	B	A	A^1	D	C	D	B	A	A	A	A	-
Acetone	D	A	D	B^1	B	B^1	D	A	D	A	A	A	D	D	D	A	C	A	C	C	D	D	D	A	A	A	A	A	A	A	A	A	A	A	-
Acetyl Bromide	-	-	-	-	-	D	-	D	-	-	-	A	D	-	-	-	-	-	-	-	-	D	-	-	-	-	-	-	-	-	-	-	-	-	-
Acetyl Chloride (dry)	D	D	C	D	-	D	D	B	D	D	A	A	C	A^2	D	D	D	A	D	D	C	C	A	A	A	D	D	-	B	A	A	-	-	-	-
Acetylene	-	A	C	A	A	D	-	A	D	A^1	A	A	A^1	A	B	A	B	A	B	B	B	A^1	A	A	A	A	B	C	A	D	-	-	A	-	-
Acrylonitrile	D	-	A	A	-	A	-	A^1	D	A^1	-	A	B^1	A^1	D	D	C	-	B^1	C	D	-	D	A^1	A^1	B^1	A	-	A^1	A	B	-	B	-	-
Adipic Acid	-	-	A^2	A	-	A	-	-	-	B^2	-	A	A^2	A^2	C	A^2	-	-	A^1	C	-	A^2	A^2	A^1	A^2	A	-	-	A	D	-	-	A^2	-	-
Alcohols: Amyl	-	A	A^2	B	-	B^2	C	A^1	B^1	B^1	A	A	A^2	A	B	A	A	A	B	A	D	A^2	B	A	A	B	A	A	B	A	A	B	A	A	-
Benzyl	D	A	A	C	-	D	D	B^1	-	A	A	A	D	A	D	B	C	A	D	C	-	D	A	B	B	B	-	A	B	B	A	A	-	A	-
Butyl	A^1	A	A^2	A	-	A	A	D	A^2	A	A	A	A^2	A	C	B	A	-	A	C	B	A^2	A	A	A	B	A	A	B	A	A	A	A	A	-
Diacetone	-	A	-	A	-	B^1	A	A	-	B^2	-	A	B^1	A^1	D	A	D	B^1	D	D	D	B^1	D	A	A	A^1	A	A	A	-	A	A	A	-	-
Ethyl	B^1	A^1	B	A^2	-	B	A^1	A^1	B^2	A	-	A	C	-	C	A	A	A	A	A	B	C	A	A	A	B	A	A	B	A	A	A	A	A	-
Hexyl	-	A	-	A	-	A	A	A	-	-	-	A	A^2	-	A	C	B	-	A	A	B	A^2	C	A	A	A	-	A	A	-	A	A	-	-	-
Isobutyl	B	A	-	A	-	A^2	A	A^1	-	A^1	-	A^2	A^1	-	B	A	A	-	A	A	A	A^1	A	A	A	B	-	A	C	-	A	B	A	-	-
Isopropyl	-	A	C	A	-	A^2	A^1	D	A^2	A^2	-	A^2	A^1	-	B	A	A	-	A	B	A	A^1	A	B	B	B	-	A	A	B	A	B	A	A	A
Methyl	D	A	A	B^1	B	A^1	A	B^1	B^1	A^2	A	A	A^1	A	A	A	A	A^1	A	A	A	A^1	C	A	A	A^1	A	A	A	B^1	A	B	A	A	A
Octyl	A^1	A	B^1	A	-	A	A	A	-	-	-	-	-	-	B	A	B	-	B	B	B	-	B	A	A	A	-	A	A	A	C	A	-	-	-
Propyl	B^1	A	A^2	A	-	A^2	A^2	D	-	A	A	A	A^1	A^2	A	A	A	-	A	A	A	A^1	A	A	A	A	A	A	A	A	A	A	A	A	-
Aluminum Chloride	A	-	A	A^1	C	B^2	A	B^1	A^1	A	A	A	A^2	A	A	A	B	A	A	A	B	A^2	A	B	B	D	D	D	D	B	A	B	A	A	-
Aluminum Chloride 20%	-	C	A	A^1	-	B^2	A	D	A^1	A	A	A	A^1	A	A	A	B	A	A	A	B	A^1	A	D	C^1	D	D	D	D	-	A	B	A	A	B
Aluminum Fluoride	A	C	A	B^1	-	A^2	A^1	A^1	-	A	A	A	A^2	A	A	A	A	-	B	A	B	A^2	A	D	D	B^1	-	-	D	D	B	A	A	-	B
Aluminum Hydroxide	B	A	A	B^1	-	A^2	A	A^1	B^1	A	-	A	A^2	A	A	A	A^2	A^1	D	A	-	A^2	A	A^1	C^1	B^1	B	C	A	D	B	B^1	A	-	-
Aluminum Nitrate	-	B^1	A	A^2	-	A^2	-	A^1	A^1	A^2	-	A	B^2	A^2	A^2	A^2	A^2	A^1	A^1	A	B^1	B^2	A^2	A	A	D	-	-	-	-	-	A	A^2	-	-
Aluminum Potassium Sulfate 10%	-	C	B	A^1	-	A^2	A^2	D	A^1	A	-	A	A^2	B	A	A	A	A	A	A	A	A^2	A	A	A	C	A	-	D	A^2	C	A	A	-	-
Aluminum Potassium Sulfate 100%	-	C	B	A^1	-	A^2	A^2	D	A^2	A	-	A	A^2	-	A	A	A	A	A	A	A	A^2	A	D	B^2	C	-	-	D	B	C	A	A	-	-
Aluminum Sulfate	A^2	B^1	A^2	A^2	B^1	A^2	A	A^2	A	A	A	A	A^2	A	A	A	A	A	A	A	A	A^2	A	B	B^2	B^1	B^1	B	D	A^2	B	A	A	A	-
Alums	-	-	A	A	D	A	-	A	-	A	-	A	-	-	A	A^1	-	-	A	B	A^1	-	A	-	A	A	-	-	D	C	B	A	-	-	-
Amines	-	D	D	A^2	A^1	C^1	D	D	D	B^2	B	A^2	D	-	D	B	D	A	B	B	B	D	D	A	A	B	B^1	D	D	-	B	B	A	-	-
Ammonia 10%	-	D	A	A^2	-	C^1	A^1	A	D	A^2	A^1	A	B^1	A	A	A	D	A	D	A	-	B^1	D	A	A	A^2	-	D	A	-	A	C	A	A	-
Ammonia Nitrate	-	C	B	A	-	A	A^1	D	-	A	A	A	B	A	C	A	D	-	-	C	-	B	D	A	A	C	-	D	A	-	-	-	-	-	-
Ammonia, anhydrous	D	D	A^1	A	D	B^2	B^1	A^1	D	A	A^1	A	A^2	A	B	A	D	A	D	A	C	A^2	D	A	A^2	A^1	D	D	A	D	B	C	A	-	-
Ammonia, liquid	-	D	A	A^1	-	C^1	-	B^1	D	A^2	A^1	A	A^1	A	C	A	D	A	D	A	-	A^2	D	B^2	A^2	A	-	D	A	-	B	C	A	A	-
Ammonium Acetate	-	-	A	-	-	A	-	A	-	A	-	A	A	-	B	A	-	-	-	A	-	A	A	B	A	A	D	D	-	-	-	-	-	-	-
Ammonium Bifluoride	A^2	D	A	A^1	-	A^2	A	-	-	A	-	A	A^2	A	B	A^2	-	-	-	D	-	A^2	A	D	B^1	B	-	D	D	-	B	-	A	-	-
Ammonium Carbonate	A^2	D	A	A^2	-	B^2	A^2	A^1	-	A	A	A	A^2	A	B	A	-	-	A	A	C	A^2	A	B	B	B	D	D	B	D	B	A	A	A	A
Ammonium Caseinate	-	D	-	A	-	-	A	-	-	-	-	-	-	-	-	-	-	-	-	A	-	-	-	-	A	-	-	-	-	-	-	-	-	-	-
Ammonium Chloride	A^2	B	A^2	A^1	A^1	A^2	A	B	A^2	A	A	A	A^2	A	B	A	A	A	A	B	C	A^2	A	C	B^2	B^1	D	D	D	D	D	B	A	A	A
Ammonium Hydroxide	B	C	A	A^1	C	A^1	A	A	D	A	A	A	A	A	D	A	A	A	D	A	A	A	B	A^1	A^1	B^2	D	D	D	D	B	A	A	A	A
Ammonium Nitrate	-	A^2	A^2	A^2	B^1	A^1	A	A^1	-	A	A	A	A^2	A	A	A	A	A	C	B	C	A^2	A	A^1	A	B^1	D	D	B	D	B	A	A	A	-
Ammonium Oxalate	-	B	-	A	-	-	-	-	A^1	A	-	-	A	-	D	A	-	-	-	A	-	A	-	A	A	-	-	D	D	C	A	-	-	-	-
Ammonium Persulfate	A^2	D	A	A^1	-	A^2	A^1	D	-	A	-	A^1	A^2	A^1	A	B	A	A	A	A	D	A^2	A	A	B	D	D	D	D	D	B	A	A	A	A
Ammonium Phosphate, Dibasic	A^2	B^2	A	A^1	-	A^2	A	C^1	A^2	A	A	A^2	A^2	A	A	A	A	A	A	A	A	A^2	A	B	C	B^1	B^1	D	D	D	B	A	A	-	-
Ammonium Phosphate, Monobasic	-	B	A	A	B^1	A	A	B	-	A	-	A	A	-	A	A	A	-	A	A	A	A	A	B	C	B	-	D	D	D	B	A	-	-	-
Ammonium Phosphate, Tribasic	-	B	A	A	-	C	A	B	-	A	-	A	A	-	A	A	A	-	A	A	A	A	A	B	B	B	-	C	D	D	B	A	-	-	-
Ammonium Sulfate	A^2	B^1	A	A^2	B^1	A^1	A	A^1	A^2	A	A	A	A^2	A	A	A	A	A	A	A	A	A^2	A	B	B	A^1	D	D	D	D	B	A	A	A	A
Ammonium Sulfite	-	D	A	-	B^1	B^2	A^2	A^1	-	A^2	-	A^2	A^2	-	A^1	A^1	A^2	A^2	A^2	A^1	-	A^2	D	B	B	D	-	A	D	D	-	-	D	-	-
Ammonium Thiosulfate	-	B	-	A	-	A	-	-	-	-	-	-	-	-	A	A^1	-	-	-	A	-	-	-	-	A	-	D	D	D	D	-	A	-	-	-
Amyl Acetate	D	B^1	D	A^2	C^1	C^1	D	B^2	D	B^1	A	A	D	A^2	D	A	D	A^1	D	D	D	D	D	A^1	A	A	A	A	C	A	A	A	A	A	-
Amyl Alcohol	A^1	A	A^2	B^2	A^1	B^2	C	A^1	-	B^1	A	A	A^2	A	B	A	A	A	B	B	D	B	D	A	A	B	A^1	A	B	A	A	B	A	A	-
Amyl Chloride	D	A	C	A^1	-	D	D	C^1	-	D	-	A	D	A	D	D	D	A	D	D	D	C	B^1	A^2	A^2	A^1	-	A	A	A	A^1	C	A	A	-
Aniline	D	A^1	B^2	D	D	C	D	A^2	D	A^1	A	A	C^1	A^1	D	B	D	A^2	D	D	B	D	A	A	B	C	D	C	C	D	B	C	A	A	-
Aniline Hydrochloride	D	-	D	D	-	D	-	D	D	D	-	A	B^2	A^2	D	B	-	-	A	D	D	D	A	D	D	D	D	D	D	B	D	A	D	-	-
Antifreeze	B	D	A	A	-	-	A	D	-	D	-	-	A	-	A	A	-	-	A	C	C	B	A	-	A	A	-	A	A	-	-	-	-	-	-
Antimony Trichloride	A^2	-	A^2	D	-	B^2	A^2	D	A^2	A	-	A	A^2	A	B	B^1	-	A	-	-	-	-	A^2	D	D	D	D	A	-	-	-	B	-	B	-
Aqua Regia (80% HCl, 20% HNO_3)	D	D	C^1	D	-	B^1	D	D	D	B^1	D	A	C^1	A^2	D	C	C	A	D	D	D	D	B	D	D	D	D	D	D	D	C	A^1	D	-	C
Arochlor 1248	-	-	-	A^2	C^1	C^1	-	A^1	-	D	-	A	-	-	C^1	B	D	A^1	D	D	B	-	A	B	B	A	A^1	A	B	-	A	A^1	-	-	-
Aromatic Hydrocarbons	-	A	D	A	C^1	C	D	-	-	D	-	-	D	-	D	D	D	-	D	D	D	-	A	-	C	A	-	C	A	-	-	-	-	-	-
Arsenic Acid	A^2	D	A^1	A^2	-	B^2	A^1	C^1	A^1	A	A	A	A^1	A	A^2	A^2	A	-	B	A	A	B	A^2	A^2	A^2	D	D	B	D	A	B	B	A	-	-
Arsenic Salts	-	-	-	-	B^1	B	-	A	-	-	-	-	A	-	-	-	-	-	-	-	-	A	A	-	-	-	-	-	-	-	-	-	-	-	-
Asphalt	-	B^2	A^2	A	B^1	A^1	-	A	D	B^1	A	A^1	A^2	A	B	D	D	A	D	D	D	-	A	B	A	A	B^1	A^1	A	A	-	-	A	-	-

Delrin, Hypalon, Hytrel, Teflon, Viton—Reg TM E. I. du Pont de Nemours & Co.
Hastelloy C—Reg TM Cabot Corporation

Kel-F—Reg TM 3M Co.
Kynar—Reg TM Elf Atochem North America
NORYL—Reg TM General Electric Co.

Ryton—Reg TM Phillips Petroleum Co.
Tygon—Reg TM Norton Co.

APPENDIX D.3

CHEMICAL	Plastics														Elastomers									Metals									Non-metals		
	ABS plastic	Acetal (Delrin®)	CPVC	Epoxy	Hytrel®	LDPE	NORYL®	Nylon	Polycarbonate	Polypropylene	PPS (Ryton®)	PTFE (Teflon®)	PVC	PVDF (Kynar®)	Buna N (Nitrile)	EPDM	Hypalon®	Kel-F®	Natural rubber	Neoprene	Silicone	Tygon®	Viton®	304 stainless steel	316 stainless steel	Aluminum	Brass	Bronze	Cast iron	Copper	Hastelloy C®	Titanium	Carbon graphite	Ceramic Al_2O_3	Ceramic magnet
Barium Carbonate	A^2	A	A^2	A^2	-	B^2	A^2	A^1	A^2	A	A^2	A	A^2	A	A^2	A	-	A	-	-	-	-	A	B^1	B	D	B^1	B	A	A	B	A	A	A	A
Barium Chloride	A^2	A	A^1	A^2	B^1	A^1	A	A	A	A	A	A	A^1	A	A	A	A	A	A	A	A	B	A	A^1	A^1	D	B^1	B^1	C	B^1	B	A	A	A	A
Barium Cyanide	-	B	D	A	-	B	-	A^1	-	D	-	A^1	D	-	C	A	A	-	-	C	-	-	A	A^1	A^2	C^1	C^1	C	C^1	D	A	-	-	-	-
Barium Hydroxide	A^2	D	A^2	A^2	B^1	B^2	A^2	A^1	D	B	A	A	A^2	A	A	A	A	A	A	A	A	-	A	B^1	B	D	D	D	D	-	B	B	A	A	A
Barium Nitrate	-	B^2	A	A^1	-	B^2	A	A^1	D	A	-	A^1	A	-	A^2	A	-	A	-	A	B	-	A	B^1	B	B	D	D	A	B	-	A	A	-	-
Barium Sulfate	A^2	B^2	B^1	A^2	D	B^2	A^1	A^1	D	B^1	A	A	B^1	A	A	A	A	A	A	A	A	-	A	B^1	B^1	B	B	C	B	B	A	B	A	A	A
Barium Sulfide	A^2	A	A^2	B^2	-	B^2	A^2	A^1	-	B	-	A	A^2	A	A	A	A	-	A	A	A	-	A	B^1	B^2	D	D	D	D	D	-	A	A	A	A
Beer	A^2	A^1	A^2	A^2	A^1	A^2	A^1	A^1	A^2	A^1	A^2	A	A^2	A	A	A	A	A	A	A	A	C	A	A	A	A	B	A^1	D	B	A^1	B	A	-	A
Beet Sugar Liquids	B	B	A^2	A^1	-	A^1	A	A	-	A^1	-	A^1	A^2	A	A	A	A	A	A	A	A	-	A	A	A	A	-	C	A	A	-	A	A	-	-
Benzaldehyde	B	A	D	D	B	A^1	B	A^1	D	D	A	A^1	D	A^2	D	A	D	A	D	D	D	D	D	B	B	B	-	A	A	B	A	A	A	A	A
Benzene	D	A^1	D	C^1	C	C^1	D	A^1	D	D	A	A	C^1	A^2	D	D	D	B	D	D	D	C	A	B	B	B	-	A	A	B	B	A	A	A	A
Benzene Sulfonic Acid	-	-	D	B	B	A^1	A	D	D	D	A	A	A	-	D	D	-	-	A	A	D	B	A	B	B	D	-	-	-	-	B	B	A	A	-
Benzoic Acid	-	B	A^1	A^1	D	A^1	B	D	B^1	B^1	A^1	A^2	A	A	D	D	D	A	D	B	B	A	A	B	B	B	-	B	D	-	B^1	A	A	A	A
Benzol	D	A	-	A^1	C	C^1	B	D	D	B	A	A	-	A	D	D	D	A	D	D	D	C^1	A	A^1	A^1	B^1	-	A	A	B	B	A	A	A	A
Benzonitrile	-	-	-	-	-	-	-	-	A^1	-	-	A^2	-	-	-	-	-	A^2	-	-	A^1	-	-	D	D	-	-	-	-	-	C	-	A	-	-
Benzyl Chloride	D	A	-	-	-	-	D	A^2	-	C^1	-	-	-	-	D	D	D	-	D	D	D	-	A^2	C^1	B^1	D	-	D	-	D	C	-	A^1	-	-
Bleaching Liquors	-	-	-	D	-	A^1	-	C	-	A^1	-	A	A^1	-	D	A	A	-	D	D	B	B	A	-	-	-	-	-	-	-	-	A	-	-	-
Borax (Sodium Borate)	-	B	A	A^1	A^1	A^2	A^1	A	-	B	A	A	A^1	A	B	A	A	A	A	A	B	-	A	A	A	B^1	-	B	A	B	B	B	A	-	A
Boric Acid	-	A	A	A^1	A^1	A^2	A^1	B	-	A	A	A	A^2	A	A	A	A	A	A	D	A	A	A	B^2	A^1	D	-	B	D	B	A	A	A	A	A
Brewery Slop	-	B	-	A	-	-	-	-	-	-	-	-	-	-	A	-	-	-	-	A	-	-	A	-	A	-	-	A	A	-	-	-	-	-	-
Bromine	D	D	D	D	D	D	A^1	D	C^1	D	D	A	C^1	A	D	D	D	A	D	D	D	B	A	D	D	D	-	D	-	-	A	D	D	A	A
Butadiene	-	A	A^1	A^1	-	D	D	C^1	D	C	A^1	A^2	C^1	A	D	C	B	A	D	B	D	-	B	A	A^1	A	-	C	-	C	C	-	A	-	-
Butane	B	A	C^1	A^1	-	C^1	D	A^2	D	A^1	A	A	C^1	A	A	D	B	A	D	A	D	C	A	A^2	A^2	A	-	C	-	C	A	A	A	-	-
Butanol (Butyl Alcohol)	-	A	A	D	B^1	B^2	A	B^1	B^1	A^1	A	A^2	C^1	A	A	A	A	A^1	A	A	B	B	A	A	A^1	B	-	A	-	B	B	B	A	-	-
Butter	B	A	-	A	-	-	B	-	-	-	-	A	-	-	A	A	B	-	D	B	B	B	A	C	A	A	-	D	D	-	-	-	-	-	-
Buttermilk	B	A	A^1	A^1	-	A^1	A	B^1	A^1	A^1	-	A	A^1	-	A	A^1	-	A	D	D	A	B	A	A	A	A	-	D	D	-	A	-	A	-	-
Butyl Amine	-	C^1	-	B^2	-	C^1	D	A^2	D	B^1	D	A^2	D	A^1	-	-	-	D	D	D	B^1	D	D	-	A	A^2	-	B	-	-	B^2	B^2	A^2	-	-
Butyl Ether	-	D	D	A^1	-	-	D	A^2	-	D	A^2	A^1	A^2	A^1	B^2	D	-	A^1	D	D	D	A^2	D	-	A^1	A^1	-	-	-	-	-	-	A^1	-	-
Butyl Phthalate	-	-	D	B^2	-	C^1	A^2	A^2	D	B^2	A	A^2	-	B^1	D	B^2	D	A^1	D	D	A^1	-	C^1	B^1	B^2	B^2	-	-	-	-	B^2	B	A^2	-	-
Butylacetate	-	A	C^1	B^1	B	C^1	B	A	D	B^1	A	A	D	B^2	D	B	D	A^1	D	D	D	D	D	B	A	A	A	A	A	A	A	A	A	-	A
Butylene	-	A	A	A^1	-	B^1	-	B^1	D	-	A	A	A^1	A	A	D	D	B^1	D	D	D	-	A	A	A	A	-	D	-	D	-	-	A	-	-
Butyric Acid	D	A	D	A	B^1	D	D	C^1	D	B^1	A	A^2	B^1	A	D	B	D	A	D	D	D	D	B^1	B^2	B^2	B	-	D	D	C	A^1	A	A	-	A
Calcium Bisulfate	-	-	-	A	-	-	-	-	D	-	-	-	-	-	A	A	-	-	A	A	C	-	-	-	A	-	-	C	D	-	-	-	-	-	-
Calcium Bisulfide	-	D	A^1	A	B^1	B^1	A	A	-	A	-	A	A^2	A	A^1	C	-	A	D	A	C	-	A	B	B	C	-	C	-	-	A	A	-	-	A
Calcium Bisulfite	-	D	A^1	A^1	B	A^1	A^1	A^2	D	A	A	A	B	A	A	D	A	A	D	A	A	-	A	B	A	D	-	-	-	-	B	A	A	-	A
Calcium Carbonate	-	A	A	A^1	-	B^1	A^2	A	C^2	A	-	A	A^2	A	A	A	A	-	A	A	A	-	A	A^1	B	D	-	A	-	-	B	B	A	A	-
Calcium Chlorate	-	A	A^1	-	-	-	-	-	-	-	-	A	B^2	A	A	A	B	-	A	-	-	-	A	-	-	-	-	-	-	A	-	-	-	A	-
Calcium Chloride	B	D	A^2	A^1	A^1	B^2	A	A^1	-	A^2	A	A	C	A	A	A	A	A	A	A	A	-	A	C^2	B^2	D	-	A	C	B	A	A	A	A	A
Calcium Hydroxide	-	D	A^2	A^1	B^1	A^2	A^2	A^2	D	A^2	A	A	B	A^2	A	A	A	A	A	A	A	B^2	A	B^1	B	C^1	-	D	A	-	A	A	A	A	A
Calcium Hypochlorite	-	D	B^1	A^1	C^1	A^1	A	D	D	A^1	A	A	B^1	A	C^1	B^1	A	B^1	D	D	B	A	A	C^1	B^1	D	-	D	D	-	B	A^1	A	A	A
Calcium Nitrate	A	D	A^2	A^2	-	A^1	A^2	A^1	A^2	A^2	A	A^2	A^2	A^2	A^2	A^2	A^1	A^1	A^1	A^2	B^1	A^2	A^2	C^1	B^2	B^1	-	B^2	B	-	B^2	B^2	A^2	A	-
Calcium Oxide	D	A	A	A	A	B^1	A	B	-	A	A	A	B	A	A	A	A	-	B	A	A	C	B	A	A	C	-	D	-	-	A	A	-	-	-
Calcium Sulfate	C	D	A^2	A^2	-	B^1	A	D	A^2	A	A	A	B^2	A	A^2	A	A	A	B	B	-	-	A	B	B	C	-	A	A	-	B	A	A	A	A
Calgon	-	A	-	A	-	-	A	A	-	A	-	-	-	-	A	A	A	-	A	A	A	-	A	A	A	-	-	C	D	-	-	-	-	-	-
Cane Juice	-	A	A^2	A	-	-	-	A	-	C^1	-	A	A^1	A^1	A	A	A	-	A	A	A	A	A	A	A	B	-	A	A	-	-	-	-	-	-
Carbolic Acid (Phenol)	D	D	B^1	C	D	D	D	D	D	B	A	A	D	A^1	D	B	D	B	D	D	D	B	A	B	B	A	D	B	D	D	A	A	A	A	-
Carbon Bisulfide	-	A	D	A	C^1	-	-	A	-	D	-	-	D	-	C	D	D	-	D	D	-	D	A	A	B	B	-	B	-	-	-	-	-	-	-
Carbon Dioxide (dry)	B	A	A	A^1	A^1	A^1	A^1	A^1	-	A^2	A	A	A^2	A	A	B	B	A	B	B	B	-	B	A	A^1	B^1	B	A	D	-	A	A	A	-	-
Carbon Dioxide (wet)	B	A	A	A^1	-	A^1	A^1	A^1	-	A^2	A	A	A^1	A	A	B	B	A	B	B	B	-	B	A	A^1	A^1	-	A	D	-	A	A	A	A	-
Carbon Disulfide	-	A^1	D	C^1	-	C^1	D	B^1	D	D	A	A	D	B^2	D	D	D	A	D	D	-	-	A^1	A^1	B	A	-	D	A	-	B	B	A	-	-
Carbon Monoxide	-	A	A^2	A^1	A	A^2	A^2	A^1	-	A	-	A	A^2	B	A	A	C	A^1	D	B	A^2	-	A	A	A	A	-	A	A	A	B	-	A	-	-
Carbon Tetrachloride	D	B^1	D	A^1	D	D	D	D	D	D	A	A	D	A^2	D	D	D	A^1	D	D	D	B	A	B	B	D	-	A^2	D	A	A^1	A	A	A	A
Carbon Tetrachloride (dry)	D	-	-	-	D	D	D	-	-	D	A^2	A	-	A^2	C^1	B^1	D	D	D	D	D	-	A^2	B	B^2	D	A^1	B^2	-	-	B	A^2	A^2	A	A
Carbon Tetrachloride (wet)	D	A^1	D	-	-	-	D	-	-	D	A^2	A	-	A^2	D	D	D	A^1	D	D	D	-	-	A^2	A^2	D	B^1	A^2	C	-	B	A^2	A^2	A	-
Carbonated Water	-	A	A	A	-	A	A	A	-	B	-	-	A	-	A	-	-	-	-	A	-	-	A	A	A	A	D	A	D	B	-	-	-	-	-
Carbonic Acid	-	B^1	A	A^2	D	B^2	A^1	A^1	A^1	A	A	A	A^2	A	D	B	C	A	C	D	A	-	A	A^1	A	B^1	D	B	D	-	A^2	B^1	A	A	-
Catsup	B	B	A	A	-	-	A	A	-	A	-	-	A	-	A	A	-	-	-	A	-	-	A	A	A	D	-	A	D	D	-	-	-	-	-
Chloric Acid	-	D	A	-	-	-	D	D	-	-	-	A	A^2	-	-	-	-	A	-	-	-	-	-	D	C^1	D	D	D	D	D	A^2	-	D	-	-
Chlorinated Glue	-	D	-	A	-	-	-	-	-	-	-	-	-	-	B	B	-	-	-	D	-	-	A	-	A	-	-	A	D	-	-	-	-	-	-
Chlorine Water	-	D	A^2	A^1	-	B^1	C^1	C^1	-	D	D	A	A^2	B	D	C	C	A	C	D	D	-	A	C	C	D	D	B	-	D	A^2	A	A	A	A
Chlorine, Anhydrous Liquid	-	A^1	D	C^1	-	D	B^1	D	C	D	D	A	D	A^1	D	B	C	B^2	C	D	D	B	A	C^1	C	D	D	D	D	-	D	D	A	-	C
Chlorine (dry)	-	D	D	D	D	D	B^1	D	-	D	D	A	D	A	B	A	D	D	D	C	D	B	A	A^1	B	C^1	D	B	D	A	A^2	D	A	-	-
Chloroacetic Acid	-	D	D	C^1	D	D	-	D	D	C^1	A	A	B^1	A^1	D	B	-	A^2	D	D	D	A	D	B^1	A^1	D	D	C	D	D	A^1	A^1	A	-	-
Chlorobenzene (Mono)	D	D	D	C^1	D	C^1	D	D	D	C^1	A	B	D	A^1	D	D	D	A^1	D	D	D	A	A	A	B	A	B^1	C	B	B	A	B	A	A	A
Chlorobromomethane	-	-	-	-	-	A	-	C	-	A	-	A	D	-	D	B	D	-	D	D	D	-	A	-	-	-	-	-	B	B	-	-	-	A	-
Chloroform	D	A	D	C^1	D	C^1	D	A	D	C^1	A	A^1	D	A	D	D	D	B^1	D	D	D	B	A	A	A	B^1	B^1	B	B	A	A^1	A^2	A	A	A

Delrin, Hypalon, Hytrel, Teflon, Viton—Reg TM E. I. du Pont de Nemours & Co.
Hastelloy C—Reg TM Cabot Corporation

Kel-F—Reg TM 3M Co.
Kynar—Reg TM Elf Atochem North America
NORYL—Reg TM General Electric Co.

Ryton—Reg TM Phillips Petroleum Co.
Tygon—Reg TM Norton Co.

APPENDIX D.3

CHEMICAL	Plastics														Elastomers								
	ABS plastic	Acetal (Delrin®)	CPVC	Epoxy	Hytrel®	LDPE	NORYL®	Nylon	Polycarbonate	Polypropylene	PPS (Ryton®)	PTFE (Teflon®)	PVC	PVDF (Kynar®)	Buna N (Nitrile)	EPDM	Hypalon®	Kel-F®	Natural rubber	Neoprene	Silicone	Tygon®	Viton®
Chlorosulfonic Acid	–	D	D	C^1	D	D	D	D	C^1	D	D	A	D	D	D	D	D	A^2	D	D	D	C	D
Chocolate Syrup	–	A	–	A	–	–	A	A	A	A^2	–	A	–	–	A	A	–	–	D	A	–	–	A
Chromic Acid 5%	B	D	A	D	D	D	A^1	D	B	D	A	A	A^2	A	D	A	B	A	B	D	C	B	A
Chromic Acid 10%	B	D	A^2	D	D	D	A^1	D	B	D	A	A	A^2	A	D	C	C	A	D	D	C	C	B
Chromic Acid 30%	B	D	A^1	D	D	D	D	D	C	D	B	A	A^1	A^2	D	B	C	A	D	D	C	B	A
Chromic Acid 50%	D	D	D	D	D	D	D	D	D	D	A^1	A	D	A^2	D	B	C	A^2	D	D	C	B	A
Chromium Salts	–	–	–	–	B^1	B	–	B	–	–	–	–	A	–	–	–	–	–	–	–	–	A	–
Cider	–	A	–	A	B^1	B	A	A	A	A	–	–	A	–	A	A	–	–	–	A	B^1	–	A
Citric Acid	D	B^1	B^2	A^1	A^1	D	A^1	A^1	A^1	A	A	A	B^2	A	A	A	C	A^2	A	A	A	–	A
Citric Oils	–	B	–	A	–	–	A	–	–	A	–	–	–	–	A	B	–	–	–	D	–	–	A
Clorox® (Bleach)	B	D	A	D	–	–	A	A	–	D	D	A	A	A	D	B	B	D	D	B	–	B	A
Coffee	–	A	A	A	–	–	A	A	–	A	–	–	–	–	A	A	A	–	A	A	A	–	A
Copper Chloride	A	A	A	A	A^1	–	A	D	–	A	A	A	A^1	A	A	A	C	A	C	A	A^1	A	A
Copper Cyanide	–	A	A	B^1	–	B^2	A^1	D	D	A	A	A	A^2	A	A	A	C	–	A	A	A	–	A
Copper Fluoborate	–	B	A^1	A	–	–	–	–	–	–	–	–	A	–	B	–	–	–	–	A	–	A	A
Copper Nitrate	–	A	A	A^1	–	B^2	A^1	D	D	A	A	A	A^2	A	A	–	–	A	C	A	–	B	A
Copper Sulfate 5%	–	D	A	A	A^1	A^2	A^1	D	A^1	A	A	A	A^2	A	A	A	C	A	C	A	A	–	A
Copper Sulfate >5%	–	D	A	A	A^1	A^2	A^1	D	A^1	A	A	A	A^2	A	A	A	C	A	C	A	A	–	A
Cream	–	A	A	A	–	–	A	A	–	A	–	A	–	–	A	–	–	–	–	D	–	–	A
Cresols	D	D	D	A^1	D	C^1	D	D	D	D	A	–	D	A^2	D	D	D	A^1	D	D	D	D	A
Cresylic Acid	–	D	D	D	–	B^1	–	D	D	A^1	–	A	D	B^1	D	D	D	–	D	D	D	–	A
Cupric Acid	–	–	–	A^2	–	B^1	A^2	D	A^1	A^2	A	A	A^2	–	B^2	A^2	–	A^2	B^2	A^2	A^1	A^2	A^2
Cyanic Acid	–	D	–	A^1	–	–	–	–	–	–	–	A	–	–	C	–	–	–	–	C	A^1	–	A
Cyclohexane	–	A^1	D	A^2	A^1	B^1	D	A	B	D	A	A	D	A	B	D	D	A	D	D	D	D	A
Cyclohexanone	D	A	D	C	–	D	D	A	D	D	A	A	D	D	D	B	–	A^1	D	D	D	D	D
Detergents	B	A^1	A	A^1	–	D	A^1	A^1	A^1	A	A	A	A	A	A	A	B	A	B	B	A	A	A
Diacetone Alcohol	–	–	D	A	–	A	–	A^1	D	A^1	–	A	D	D	D	A	A	B^1	–	D	D	–	D
Dichlorobenzene	D	–	D	A	–	–	–	D	D	C^1	–	A	D	A	D	D	D	–	D	D	D	–	C
Dichloroethane	D	A^1	D	D	–	C^1	A^1	A^1	D	D	–	A^1	D	A	D	–	C	A^2	D	D	–	D	C
Diesel Fuel	–	A	A^1	A	–	C^1	A	A	A^2	A^1	A	A	A^1	A	A	D	B	A^1	D	B	D	–	A
Diethyl Ether	D	–	D	D	C	–	–	A^1	D	A^1	A	A	D	A^1	D	D	D	C	D	D	D	–	D
Diethylamine	D	B	D	A	–	D	–	A	D	A^1	–	D	D	D	C	B	C	A	A	A	B	C	A
Diethylene Glycol	B	A^1	A^1	C	–	B^2	A^1	A^1	B^1	A^2	–	A^2	C^1	A	A^2	A^2	C	–	A^1	A^2	B^1	C^1	A^2
Dimethyl Aniline	D	D	D	A^1	–	–	D	A	D	D	A	A	D	A^1	D	B^2	–	A^2	D	D	D	D	D
Dimethyl Formamide	D	D	D	D	–	A	D	A	D	A	A	D	D	D	D	B	D	A	C	D	C	D	C
Diphenyl	–	–	–	–	–	–	–	–	–	D	–	A	–	–	D	D	B	B	D	B	D	–	A^2
Diphenyl Oxide	–	D	–	A	–	–	–	–	–	D	A	A^1	D	B^2	A	D	D	–	D	D	C	D	A
Dyes	–	C	–	A	–	–	A	A	–	–	–	–	B	–	–	–	–	–	–	C	–	C	A
Epsom Salts (Magnesium Sulfate)	B^2	B	A^1	A	–	A^2	A^1	A^1	A^1	A	A	A	A^1	A	A	A	A	A	B	A	A	B	A
Ethane	–	A^1	A^1	A^1	–	–	–	D	–	D	–	A	A^1	A	A	D	B	–	D	B	D	A	A
Ethanol	B^1	A^1	B	A^2	–	B	A^1	A^1	B^2	A	–	A	C	–	C	A	A	A	A	A	B	C	A
Ethanolamine	–	D	–	A^1	–	–	A	A	–	D	A	A^1	D	C^1	B	B	C	D	B	B	B	–	D
Ether	D	A^1	D	A^1	–	D	D	A	–	D	A	A	D	B^1	D	C	D	B^1	D	D	D	C	C
Ethyl Acetate	D	A	D	A	B	D	A^1	A^2	D	A^1	A	A	D	D	D	B	D	A^1	C	D	B	D	D
Ethyl Benzoate	D	–	D	–	–	C^2	A^2	–	D	B^1	–	A	D	D	D	–	–	–	D	D	D	D	A^1
Ethyl Chloride	D	A^1	D	D	C	C^1	D	A^1	D	D	A	A	D	A	A	A	D	B	B	C	D	D	A
Ethyl Ether	D	A^1	D	A^2	–	D	D	A^1	–	D	A	A	D	A^2	D	D	D	A^1	D	D	D	–	D
Ethyl Sulfate	–	–	–	A^1	–	–	–	–	–	–	–	A	–	–	A	–	–	A	–	–	–	–	A
Ethylene Bromide	D	–	D	–	–	D	–	–	D	D	–	A	D	A	D	C	C	B	C	C	D	D	A
Ethylene Chloride	D	A^1	D	D	–	D	D	A	D	C^1	A	A	D	A	D	D	D	A^1	D	D	D	–	B
Ethylene Chlorohydrin	D	D	D	D	–	D	–	D	D	D	–	A	D	A	D	B	C	–	C	A	C	D	A
Ethylene Diamine	D	D	D	A^1	–	A	D	D	A^2	–	A	A	D	B	A	A	B	D	B	B	A	–	B
Ethylene Dichloride	D	B^1	D	D	C	D	D	A^1	D	D	A	A	D	A	D	C	D	A^1	D	D	D	D	A
Ethylene Glycol	A	B	A	A	A	A^2	A	A	B^1	A	A	A	A	A	A	A	A	A	A	A	A	B	A
Ethylene Oxide	D	D	C^1	D	A	A	A^1	A^1	C^1	D	D	A	D	A	D	C	D	A	D	D	D	–	D
Fatty Acids	A	A	A	A	–	D	A^1	A^1	B^1	A	–	A	A	A	B	D	B	A	C	C	C	B	A
Ferric Chloride	A	D	A	A	C	A^1	A^2	A	A^2	A	A	A	A	A	A	A	B	A^1	A	B	B	B	A
Ferric Nitrate	A^2	D	A	A	–	A^2	A^2	A^1	A^1	A	A	A	A	A	A	A	A	A	A	A	C	–	A
Ferric Sulfate	A^2	D	A	A	–	A^2	A^2	A^1	A^1	A	A	A	A	A	A	A	A	A	A	A	B	B	A
Ferrous Chloride	A^2	D	A	A	–	A^2	A^2	D	D	A	A	A	A	A	A	–	A	B^1	A	A	–	B	A
Ferrous Sulfate	A^1	D	A	A	–	A^2	A^2	D	A^1	A	A	A	A	A	A^2	A	B	A	B	–	–	B	B
Fluoboric Acid	A^2	A^1	A^2	D	–	A^2	A^1	D	–	A	A	A	A	A^1	A	A^2	A	B	A	A	–	B	B
Fluorine	A^1	D	D	A^1	–	D	–	D	C	D	D	D	D	A^1	D	A^1	–	A	C	–	D	–	C
Fluosilicic Acid	A^2	A^1	A	C	–	A^2	A^2	D	A^1	A	A	A	D	A^1	A	A^2	A	C	A	A	–	B	B^1
Formaldehyde 40%	A^2	A^2	A^2	A^2	B	D	A	A	A^1	A	A	A	A	A	B	A	B	A	B	B^1	–	–	A
Formaldehyde 100%	B	A	A	A	–	B	A	D	A^2	C	B	A	A	A	C	A	C	A	C	C	B	B	D
Formic Acid	D	A^2	A^2	C^1	B	D	A	D	A^1	A^1	A	A	A^1	A	C	A	A^1	A^1	C	A	B	B	C

CHEMICAL	Metals									Non-metals		
	304 stainless steel	316 stainless steel	Aluminum	Brass	Bronze	Cast iron	Copper	Hastelloy C®	Titanium	Carbon graphite	Ceramic Al_2O_3	Ceramic magnet
Chlorosulfonic Acid	D	B^2	C	B	D	D	D	A^1	A	A	A	–
Chocolate Syrup	A	A	A	–	–	D	–	–	–	–	–	–
Chromic Acid 5%	B	A	C	D	B^1	D	D	B	A	A	A	A
Chromic Acid 10%	B	B	D	D	D	D	D	A	B	A	A	–
Chromic Acid 30%	B^2	B^2	D	D	D	D	D	D	A	A	A	–
Chromic Acid 50%	C	B^2	D	D	D	D	D	B	A^2	A^1	A	A
Chromium Salts	–	–	–	–	–	–	–	–	–	–	–	–
Cider	A	A	B	–	A	D	–	–	–	–	A	A
Citric Acid	B^1	A^2	C	D	D	D	D	A	A^2	A	A	A
Citric Oils	A	A	C	–	A	D	–	–	–	–	–	–
Clorox® (Bleach)	A	A	A	–	–	D	–	A	–	–	–	–
Coffee	A	A	A	–	A	–	–	A	A	–	–	–
Copper Chloride	D	D	–	–	D	–	–	–	D	–	A	A
Copper Cyanide	B	B	D	D	D	A	–	A^1	B	A	A	A
Copper Fluoborate	D	D	–	–	–	D	–	B	–	–	–	–
Copper Nitrate	A	A^2	D	D	D	D	D	B^2	B	A	A	A
Copper Sulfate 5%	B	B	D	D	B	D	B	A	A	A	A	A
Copper Sulfate >5%	B	B	D	D	D	D	–	A	A	A	–	A
Cream	A	A	A	–	A	D	–	–	–	–	–	–
Cresols	A^2	A	A	–	A	C	A	B^2	B	A	–	–
Cresylic Acid	A^1	A	B^2	–	D	A	B	B^1	A^1	A	–	–
Cupric Acid	D	B^2	D	–	–	–	–	A^1	A^2	A^2	–	–
Cyanic Acid	A	A	–	–	–	D	–	–	–	A	–	–
Cyclohexane	A^1	A	A	A	B	B	B	B	A	A	–	A
Cyclohexanone	A^1	A^2	A	–	B	B	B	A^1	–	A	A	A
Detergents	A^1	A^1	B	–	B	–	–	B	A^2	A	A	A
Diacetone Alcohol	B^1	B	A^1	A^1	B	–	A	–	–	A	–	–
Dichlorobenzene	–	B^1	B^1	–	B^1	–	–	A^1	–	A^2	–	–
Dichloroethane	B	B	B^1	B	D	–	A	A	B^1	A	A	–
Diesel Fuel	A^1	A^1	A^1	A^1	A	A	A	B	B	A	–	–
Diethyl Ether	B^1	B^2	B	B^1	A^1	–	A	B^1	A^1	A^2	–	–
Diethylamine	A	A	B	A	A	B	A	A	A	A	–	–
Diethylene Glycol	A^1	A	B^1	–	–	A	–	B^1	A^1	A^2	–	–
Dimethyl Aniline	B^2	B^2	A^2	–	–	–	–	B^2	A^2	A^2	–	–
Dimethyl Formamide	A	B	A^1	–	–	–	A	–	–	–	–	–
Diphenyl	B	B	B^2	B	B	–	B	B	B	–	–	–
Diphenyl Oxide	B^1	A	B^1	–	–	A	A	B^1	A^1	–	–	–
Dyes	A	A	B	A	–	–	A	–	–	–	–	–
Epsom Salts (Magnesium Sulfate)	A	B	B^1	A	A	A	A	B	A^1	A	–	–
Ethane	A	A^1	–	–	–	–	A	–	–	A	–	–
Ethanol	A	A	B	A	A	B	A	A	A	A	A	–
Ethanolamine	A	A	B	–	A	–	D	B	B	A	A	–
Ether	A	A	B^1	B^1	A	C	A	B^1	A^1	A	–	–
Ethyl Acetate	B	B	A^2	B	A	A	A	A	A^1	A	A	–
Ethyl Benzoate	–	–	–	–	–	–	A	–	–	–	–	–
Ethyl Chloride	A	A	B	A	A	C	B	B^1	A	A	A	–
Ethyl Ether	B	B	B^1	B	A	C	A	B^1	A^1	A^2	–	–
Ethyl Sulfate	D	D	–	–	D	–	B	–	–	A	–	–
Ethylene Bromide	A	A	B	–	B	–	–	B	B	A	–	–
Ethylene Chloride	B	B	B	–	A	–	B	–	B^1	A	–	A
Ethylene Chlorohydrin	B	B	B	B	B	–	B	B	B	A	–	–
Ethylene Diamine	B^1	B	B^1	D	B	–	D	C	A	–	–	–
Ethylene Dichloride	B	B	A^1	B	C	A	–	B	B	A	A	–
Ethylene Glycol	B	B	A	B^1	A	A	A	B^1	A^1	A	A	A
Ethylene Oxide	B	B	D	D	C	D	D	A	–	A	–	–
Fatty Acids	B	A	A	C	A	C	D	A	B	A	A	–
Ferric Chloride	D	D	D	D	D	D	D	B^2	A	A	–	–
Ferric Nitrate	B	B	D	D	C	–	D	B^1	A	A	–	–
Ferric Sulfate	B^1	A	D	D	C	D	D	A^1	A^1	A	A	–
Ferrous Chloride	D	D	D	D	C^1	D	B	B^1	A	A	–	A
Ferrous Sulfate	B	B	B^1	B^1	B	D	B	B	A^1	A	A	A
Fluoboric Acid	B	B	D	–	B^1	D	–	A^1	D	A	C	A
Fluorine	C	A	A	A	C	D	C	B^1	D	C	–	A
Fluosilicic Acid	C	B	D	B^1	B^2	D	D	B	D	A	C	A
Formaldehyde 40%	A^1	A	B	A	A	B	B^2	B	B	A	–	A
Formaldehyde 100%	C	A	A	–	B	C	A^2	A	A	–	–	A
Formic Acid	B^1	A^1	A	D	C	D	C	A	C^1	A	–	A

Clorox—Reg TM Clorox Co.
Delrin, Hypalon, Hytrel, Teflon, Viton—
Reg TM E. I. du Pont de Nemours & Co.

Hastelloy C—Reg TM Cabot Corporation
Kel-F—Reg TM 3M Co.
Kynar—Reg TM Elf Atochem North America

NORYL—Reg TM General Electric Co.
Ryton—Reg TM Phillips Petroleum Co.
Tygon—Reg TM Norton Co.

APPENDIX D.3

CHEMICAL	Plastics														Elastomers									Metals									Non-metals		
	ABS plastic	Acetal (Delrin®)	CPVC	Epoxy	Hytrel®	LDPE	NORYL®	Nylon	Polycarbonate	Polypropylene	PPS (Ryton®)	PTFE (Teflon®)	PVC	PVDF (Kynar®)	Buna N (Nitrile)	EPDM	Hypalon®	Kel-F®	Natural rubber	Neoprene	Silicone	Tygon®	Viton®	304 stainless steel	316 stainless steel	Aluminum	Brass	Bronze	Cast iron	Copper	Hastelloy C®	Titanium	Carbon graphite	Ceramic Al_2O_3	Ceramic magnet
Freon® 11	D	D	A[2]	A	A	C	B	D	-	A	A	A	A[2]	A	B	D	B	A	D	D	D	B	B	A	A	D	-	-	A	A	A	B	-	A	A
Freon 12	A[1]	B	A[2]	A[2]	A	A[1]	D	A[1]	-	A[2]	A	A	A[2]	A	A	B	A	C	C	A	D	D	B	B[1]	B	B[1]	B[1]	B	A	A	A	B	-	-	-
Freon 22	-	A	B	A	-	-	B	B	-	B	A	A	A	A	D	A	B	A	D	A	D	D	D	A	A	D	A	-	D	B	A	B	-	-	-
Freon 113	-	A	B	A	A	-	D	-	B[1]	D	A	A	B	B	A	D	A	-	D	C	D	D	B	-	-	-	-	-	-	A	A	C	-	A	A
Freon TF	-	A	B	A	A	-	-	D	-	D	D	A	B	B	A	D	A	-	D	A	D	D	B	A	A	D	-	-	A	A	A	B	-	A	A
Fruit Juice	B	D	A	A	-	A	B	A	-	B	-	A	A	A	A	-	B	A	D	A	-	B	A	A	A	A	D	-	D	A	A	A	-	A	A
Fuel Oils	D	A	-	A[1]	-	B	B	A[1]	B[1]	A	A	B	A[2]	B	D	D	C	A	D	B	D	A	A	A	A	C[1]	B	A	A	A	A[1]	A	A	-	-
Furan Resin	-	D	-	A[1]	-	D	-	-	-	D	A	A	A	D	D	C	D	A[1]	D	D	D	A	D	A[1]	A	A	-	-	-	-	B	-	-	-	-
Furfural	D	A	D	A[1]	-	D	D	B	D	D	A	A	D	B[2]	D	D	B	D	D	D	D	D	D	A	B	A[1]	-	B	B	A	B	A	A	-	-
Gallic Acid	-	-	C	-	-	A	A	A	-	A	A	B	B	A[1]	B	B	D	A	A	B	D	A	A	A	B	D	-	B	D	D	B[1]	B	B	-	-
Gasoline (high-aromatic)	D	B	C[1]	A	A	A	B	A	A	A	A	B	A	A	A	D	B	A	D	A	D	A	A	A	A	D	-	A	A	-	A	B	A	A	A
Gasoline, leaded, ref.	D	A	-	A[2]	A	-	B	A[2]	A[2]	B	A	A	B	A	A[2]	D	B	A[2]	D	B	D	C	A[1]	A[1]	A[2]	A	-	A[2]	-	B	A	A	A[2]	A	A
Gasoline, unleaded	D	A	C	A[2]	-	-	D	A[2]	A[2]	C[1]	A	A	C[2]	A	A[1]	D	A	A[2]	D	B	D	C	A[1]	A[1]	A[2]	A[2]	-	A[2]	A	B	A	A	A[2]	-	-
Gelatin	-	B	A[2]	B	-	A[2]	A[2]	A[1]	-	A	-	A	B	A	A	A	B	-	A	A	A	B	A	A[2]	A[2]	A	D	A	A	A	A	A	A	-	A
Glucose	B	A	A[2]	B	-	A[2]	A[2]	A	A[1]	A	B	A	A[2]	A	A	A	B	-	A	A	A	A	A	A[1]	A	A	A	-	A	A	A	A	A	-	A
Glue, P.V.A.	-	A	A	A	A	A[1]	-	A[1]	-	-	-	A	C	-	A	A	A	-	A	A	A	C	B	A[1]	A[2]	A	-	A	A	B	A	A	A	-	A
Glycerin	C	A	A	A	A	A[1]	A	A[1]	A[2]	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A[2]	A	A	B	A	A	A	A	A	A	A	-
Glycolic Acid	B	A	A	A	-	A[2]	-	-	-	A	A	A	B	B	A	A	A	B	D	A	A	A	A	A	A	-	-	-	-	-	A	A	A	-	-
Gold Monocyanide	-	A	-	A	-	-	-	-	-	-	-	D	-	A	A	-	-	-	-	A	-	A	A	A	A	-	-	-	D	-	-	-	-	-	-
Grape Juice	B	A	A	A	-	B	-	A	-	-	-	A	A	A	A	A	-	-	D	D	A	B	A	A	A	-	-	A	D	-	-	A	-	-	-
Grease	-	D	-	A	-	-	-	-	-	-	-	A	A	A	A	D	-	-	D	D	D	A	A	-	A	-	A	A	A	A	A	-	-	-	-
Heptane	D	A	A	A	-	B[1]	B	A	B	C[2]	A	A	C[1]	A	A	D	B	A	D	B	D	B	A	A	A	A	A	A	A	A	A	A	A	-	-
Hexane	D	A	B[1]	A	A	D	B	B	D	B[1]	A	A	B[1]	A	A	D	B	A	D	B	D	D	A	A	A	A	A	A	A	A	A	A	A	-	A
Honey	-	A	-	A	-	B	-	A	A[1]	A	-	A	A	A	A	A	-	-	A	-	A	A	A	A	A	A	-	A	A	-	A	-	-	-	-
Hydraulic Oil (Petro)	-	B	-	A	-	C	-	A[1]	-	D	D	A	A	A	A	D	A	-	D	A	B	A	A	A	A	A	A	A	A	A	A	-	B	-	-
Hydraulic Oil (Synthetic)	-	-	-	A	-	A	-	A[1]	-	D	-	A	A	A	D	A	A	-	D	A	B	A	A	A	A	A	A	A	-	A	A	-	B	-	-
Hydrazine	-	B	D	A	C	-	-	-	D	C	-	C	-	A	B	A	B	-	C	B	B	-	A	A	A	-	-	-	D	A	-	-	-	-	-
Hydrobromic Acid 20%	-	C	A	B[1]	-	B[2]	B	D	-	A[2]	-	-	B[2]	A	D	A	A	A	A	D	D	B	A	D	D	D	D	-	D	D	A	A	A	-	A
Hydrobromic Acid 100%	B	D	A[2]	D	-	B[1]	B	D	-	C[1]	A[1]	A	A[1]	A	D	A	A	A	A	D	D	B	A	D	D	D	D	-	D	D	C	A	A	-	A
Hydrochloric Acid 20%	A	C	A[2]	A[1]	B	A[2]	A	D	B[1]	B[2]	A	A	A[2]	A	-	A	A	A	A	C	D	A[1]	A	D	D	D	-	D	D	D	A[1]	D	A	C	A
Hydrochloric Acid 37%	A	C	A[2]	A	C	B[2]	A	D	D	C	A	A	B	A	B	C	B	A	A	B	B	A[1]	A	D	D	D	-	D	D	D	B	D	A	C	A
Hydrochloric Acid 100%	A	C	A	-	-	-	A	D	D	B[1]	A[1]	A	D	A	D	D	D	A	D	D	D	A[1]	A	D	D	D	D	D	D	D	A	D	A	C	A
Hydrochloric Acid, Dry Gas	-	-	A	A	-	A[2]	A	A[1]	-	B	A	A	A[2]	A	-	-	-	A	-	-	-	-	-	D	D	D	D	A	-	D	A	C	A	-	A
Hydrocyanic Acid	B	B	A	A	C	A[2]	A[1]	B	-	A	B	A	B	A	B	B	A	-	B	B	C	B	A	B[1]	A	A	D	A	D	D	A	B	A	-	-
Hydrocyanic Acid (Gas 10%)	-	C	A	-	-	-	C	-	B[1]	A	-	A	A	-	B	A	-	-	B	A	D	-	A	-	-	-	-	-	-	-	-	A	-	-	-
Hydrofluoric Acid 20%	C	D	C[1]	A	-	A[2]	C[1]	C[1]	D	A[2]	A	A	B	A	D	D	B	B	B[1]	B	D	C	A	D	D	D	-	B[2]	D	B	B	D	A	-	B
Hydrofluoric Acid 50%	C	D	C[1]	C[2]	D	A[1]	D	D	D	A[2]	A	A	B[1]	A	D	D	B	B	B[1]	D	D	C	B	D	D	D	-	B[2]	D	B	B	D	A	-	B
Hydrofluoric Acid 75%	C	D	C[1]	B[1]	D	C[1]	D	D	D	C[1]	B	A	C	A	D	C	B	B	D	D	D	C	B	D	D	D	-	B[1]	D	B	B	D	A	C	B
Hydrofluoric Acid 100%	D	D	C[1]	-	D	-	D	D	D	C[1]	D	A	C	A	D	D	B	A	D	D	D	D	B	B[1]	B[1]	D	-	B[1]	D	B	B	D	-	-	B
Hydrofluosilicic Acid 20%	-	B	A	C[1]	-	B[2]	B[2]	D	-	A	A	A	A[2]	A	A	A	B	A	A	B	D	A	A	C[2]	B[1]	D	-	B[2]	B	B	B	D	A	-	-
Hydrofluosilicic Acid 100%	-	A	-	C[1]	-	B[1]	B[2]	D	-	A	A[1]	A	B[1]	A[1]	B	A	B	B	A	B	D	D	A	D	D	D	-	B[2]	D	-	B	D	A	-	-
Hydrogen Gas	-	-	A[2]	-	A	A[2]	A[1]	A[2]	A[2]	A	A	A	A[2]	A	A	A	A	B	B	A	C	A	A	A	A	A	-	A	-	A	A	A	A	-	-
Hydrogen Peroxide 10%	A	D	A	C[1]	-	A	A[2]	C[1]	A[2]	A	A	A	A[1]	A	D	A	D	A	B	D	A	B	A	B[2]	B	A	-	B[1]	C	D	A	A	C	-	A
Hydrogen Peroxide 30%	-	D	A	B	-	C[2]	A[2]	D	A[2]	B[1]	A[1]	A	A[1]	A	D	B	D	B	C	D	B	B	A	B[2]	B	A	-	B[1]	B	D	A	B[1]	C	-	A
Hydrogen Peroxide 50%	-	D	A	-	-	C[2]	-	D	A[2]	B[1]	-	A	A[1]	A[1]	D	B	D	A	C	D	B	B	A	B[2]	A[2]	A	-	B[1]	-	D	A	A	C	-	A
Hydrogen Peroxide 100%	A	D	A	A	-	C[2]	A	D	A	B[1]	C	A	A	A[1]	D	D	D	B	C	D	B	B	A	B[2]	A[2]	A	D	B[1]	B	D	A	B	C	A	A
Hydrogen Sulfide (aqua)	B	C	A	A	-	A	A[1]	C[1]	A	A[1]	A	A	B[1]	A	D	B	D	A[1]	C	A	C	A	D	C	A	B	-	A	D	-	A	B	A	A	A
Hydrogen Sulfide (dry)	-	-	A	A	A	A	-	C[1]	-	A[1]	A	A	A[2]	A	D	B	B	B	C	A	C	D	D	C[1]	A	B	D	B	D	D	A	A	A	-	-
Hydroquinone	D	A	A	-	-	A	-	D	-	A	-	A	B	-	D	D	D	-	A	A	-	-	B	B	B	B	-	-	-	B	B	B	A	-	A
Hydroxyacetic Acid 70%	-	A	A	A	-	A	-	-	-	-	-	A	D	A	A	A	-	-	-	A	-	-	A	-	-	-	-	-	B	-	-	A	-	-	-
Ink	A	B	-	A	-	-	-	C	-	-	-	A	C	A	A	-	-	-	D	A	-	C	A	C	C	-	-	-	D	A	-	-	-	A	A
Iodine	D	D	D	C	B	A[1]	C[1]	A	-	C	D	A	A	A[2]	B	B	D	A	D	D	-	A	A	D	D	A	-	A	D	D	A	A	D	-	-
Iodine (in alcohol)	-	D	-	-	-	B	-	C	-	-	-	-	A	A	-	A	-	-	-	-	-	-	-	-	-	B	-	B	-	-	B	B	-	-	-
Iodoform	-	-	-	-	-	-	-	-	-	-	-	C	A	C	D	A	-	-	B	A	-	C	-	A	A	-	-	-	-	B	D	B	-	-	-
Isooctane	-	-	-	A[2]	A	B	D	A[1]	B[1]	A[2]	A	A	A[1]	A[2]	A[2]	D	-	A[1]	A[1]	B[1]	D	A[1]	A[1]	A[1]	A[1]	A[1]	A	A[1]	-	-	-	-	A[2]	-	-
Isopropyl Acetate	-	D	-	A	C	B[1]	-	B[1]	D	B[1]	-	A	D	D	D	B	D	-	D	D	D	-	D	C	A	D	-	A[1]	-	-	B	-	A	-	-
Isopropyl Ether	-	D	-	D	-	B	-	A[1]	D	B	-	A[1]	B	D	B	D	C	A	A	D	D	A	D	A	A	A	A	A	-	B	A	-	A	-	-
Isotane	-	-	-	A	-	-	-	D	-	D	-	-	A	A	A	-	-	-	-	D	-	-	A	-	-	D	-	-	-	-	-	-	-	-	-
Jet Fuel (JP3, JP4, JP5)	-	A[1]	-	A	-	D	D	C	A[1]	A[1]	A	A	C	B	A	D	D	A	D	D	D	A	A	A	A	A	-	A	A	A	A	A	A	-	-
Kerosene	D	A[2]	-	A	C	C[1]	D	A	D	B	A	A	A[2]	A	A	D	D	A	D	A	D	D	A	A	A	A	A	A	A	B	B	A	A	A	B
Ketones	A	D	-	C	-	C[1]	D	A[2]	D	C	A	A	D	C[1]	D	A	-	B[1]	A	D	-	D	D	A	A	B	-	A	-	A	A	A	A	A	-
Lacquer Thinners	A	D	-	A	D	A	D	A[1]	B	D	-	A	D	-	D	D	D	-	D	D	D	D	D	A[1]	A	A	A	A	C	A	A	C	A	-	-
Lacquers	A	D	-	A	-	A	D	A[1]	D	D	-	A	D	D	D	D	D	-	D	D	D	A	D	A[1]	A	A	-	A	C	A	A	-	A	-	-
Lactic Acid	D	B	A[1]	B[1]	D	A[1]	A	B	B	B	A	A	B[1]	B[1]	A	A	A	A[1]	A	A	A	A	A	B[1]	B[1]	B	D	B[2]	D	B	B[1]	A	A	A	-
Lard	-	A	-	B	-	A	A	A[1]	A[1]	B[1]	-	A	A[1]	A	A	D	B	-	D[1]	D	B	A	A	A	A	A	-	A	A	-	A	A	A	-	-
Latex	B	B	-	A	-	-	-	A[1]	-	A[2]	-	A	-	A	A	A	-	-	-	-	A	A	A	A[2]	A[2]	A	-	-	-	-	A	-	-	-	-

Delrin, Freon, Hypalon, Hytrel, Teflon, Viton—
Reg TM E. I. du Pont de Nemours & Co.
Hastelloy C—Reg TM Cabot Corporation

Kel-F—Reg TM 3M Co.
Kynar—Reg TM Elf Atochem North America
NORYL—Reg TM General Electric Co.

Ryton—Reg TM Phillips Petroleum Co.
Tygon—Reg TM Norton Co.

APPENDIX D.3

CHEMICAL	Plastics														Elastomers									Metals									Non-metals		
	ABS plastic	Acetal (Delrin®)	CPVC	Epoxy	Hytrel®	LDPE	NORYL®	Nylon	Polycarbonate	Polypropylene	PPS (Ryton®)	PTFE (Teflon®)	PVC	PVDF (Kynar®)	Buna N (Nitrile)	EPDM	Hypalon®	Kel-F®	Natural rubber	Neoprene	Silicone	Tygon®	Viton®	304 stainless steel	316 stainless steel	Aluminum	Brass	Bronze	Cast iron	Copper	Hastelloy C®	Titanium	Carbon graphite	Ceramic Al_2O_3	Ceramic magnet
Lead Acetate	B	B	A^2	A	–	A^2	A^1	A	–	A^1	A	A	B	A	B	A	D	A	A	A	A	B	D	B	B^1	D	–	B^1	A	–	B^1	A^1	A	A	–
Lead Nitrate	B	–	A^2	–	–	A^2	A^1	–	–	A^2	A	A^1	A^2	A^2	A^2	A^2	–	–	A^1	A^1	B^1	A^2	A^2	B^1	B^1	D	–	B^2	–	–	B^2	–	A^1	–	–
Lead Sulfamate	–	A	–	A	–	A^1	–	B^1	A^1	A^2	–	B	B	A	B	A	A	–	B	A	B	–	A	C	C	C	–	–	–	–	–	–	–	–	–
Ligroin	–	B	–	A	–	A	–	D	–	A^2	–	A	–	A	A	D	C	–	D	B	D	A	A	–	A	D	–	–	–	–	–	–	–	–	–
Lime	–	B	–	A	–	A	–	A^1	–	–	–	A^1	B	A	A	D	–	–	–	A	–	A	A	A	A	A	–	–	A	–	–	A	A	–	–
Linoleic Acid	A	B	A^2	–	–	A	–	–	–	B^1	–	A	A^2	A^2	B^1	D	D	–	D	–	B^1	A^2	B^1	B	A	A^2	–	–	–	D	–	–	A^2	–	–
Lithium Chloride	–	A	A^2	–	–	A^2	–	–	B^1	A^2	–	A	D	A^2	A^2	A^1	–	–	B^1	A^1	A^1	A^2	A^1	A^1	A^2	D	–	A^2	A	–	–	–	A^2	–	–
Lithium Hydroxide	–	–	–	–	–	–	–	–	D	–	–	A	–	–	C	–	–	–	–	–	–	–	–	B	B	D	–	B	–	–	B	–	B	–	–
Lubricants	–	A	–	A	A	D	C^1	A^1	A^1	A^1	A	A	B^2	A	A	D	A	–	D	D	D	B	A	A^2	A^2	A^2	–	A^2	A	A	A	A	A	–	–
Lye: KOH Potassium Hydroxide	A	A	A	A	D	A	A^1	C	D	A	A	A	B	A	B^1	A^2	A	B	B	B	C	B	B	B	A^1	D	D	D	B^2	B	B^1	D	C	D	A
Lye: NaOH Sodium Hydroxide	C	C	A	A	C	D	A	A	D	A	A	A	A	D	A^1	B^1	A	B	A^1	B^2	A^1	B	B^1	B	B^1	D	D	D	D	B	C	B	–	A	–
Lye: $Ca(OH)_2$ Calcium Hydroxide	–	D	A^2	A^1	B^1	A^2	A^2	A^2	D	A^2	A	A	B^2	A^2	A	A	A	A^2	B^2	A	A	B^2	B^1	B^1	B	C^1	–	D	A	–	A^1	A	A	A	A
Magnesium Bisulfate	–	–	–	–	–	–	–	A^1	A^1	A^2	–	A	A^2	–	B	–	–	–	B^2	B	–	A^2	–	A^1	A^1	D	–	A^1	–	–	–	–	A^1	–	–
Magnesium Carbonate	B	A	A^2	A	–	B	A^2	–	A^1	A	–	A^1	B	A	A^2	A	A	–	–	A	–	–	A	B	B	A	–	A	–	A	B	A	–	A	A
Magnesium Chloride	B	B^1	A	A	C	A^1	A^1	A^1	A^2	A^2	A^1	A	B	A	A^2	A	A^2	A	A	A	A	A	A^2	D	D	D	D	B	D	A^2	A^2	A^2	A^2	A^2	A
Magnesium Hydroxide	B	A	A	A	C	A^2	A^2	B^1	A^1	A	A	A	A^2	A	A	A	A	A	A	A	A	C	A	B	A^1	C^1	D	B	A	B	A	A	A	A	–
Magnesium Nitrate	B	A	A	A	–	A^2	A^1	A^1	A^1	A	A	A	A^2	A	A	A	A	–	A	A	–	–	A	B	B	B	–	A	D	B	A	A	–	A	A
Magnesium Oxide	–	A	–	A	–	–	–	–	–	–	–	A	–	–	A	–	–	–	–	A	–	–	C	A	A	B	–	–	A	–	–	–	–	–	–
Magnesium Sulfate (Epsom Salts)	B^2	B	A^1	A	–	A^2	A^1	A^1	A^1	A	A	A	A^1	A	A	A	A	A	B	A	A	B	A	A	B	B^1	A	A	A	A	B	A^1	A	–	–
Maleic Acid	–	A	A	A	–	B^2	A^1	A	–	A	B	A	A^2	A	D	D	D	–	B	D	–	C	A	A	B	B^1	–	B	A	–	B	A	A	–	–
Maleic Anhydride	–	D	–	A	–	D	–	–	–	D	–	A	–	A	D	D	D	–	D	D	–	–	A	A	A	A	–	–	–	–	–	–	–	–	–
Malic Acid	–	A	–	–	–	B^2	–	A	–	A^1	–	A	A^2	A	A	D	D	–	B	D	B	A	A	A	A^2	B^1	B	B^2	–	D	B	A	B	–	–
Manganese Sulfate	B^2	A^1	A	–	–	A^1	A^2	A^2	A^1	–	A^2	A	C	A^2	A^2	A^2	–	A^1	A^2	A^2	A^1	A^1	A^2	B	B^2	B^1	D	A^2	A	B	A^2	A^2	A^2	A	–
Mash	–	A	–	A	–	A	–	A	–	–	–	–	–	–	A	A	–	–	–	A	–	A	A	A	A	A	–	–	–	–	–	–	–	–	–
Mayonnaise	–	A	–	A	–	D	–	A	–	–	–	A	D	A	C	–	–	–	D	A	–	D	A	C	A	A	–	–	D	B	A	–	–	–	–
Melamine	–	A	A^2	A	–	–	–	A	–	A	–	A	D	–	C	A	–	–	–	D	C	D	A	–	D	–	–	–	D	–	–	–	D	–	–
Mercuric Chloride (dilute)	B	B	A	A	B	A	A^2	D	A	B	A	A	A	A	A	A^1	A	A	A	A	–	D	A	D	D	D	D	D	D	D	C	A^1	C	A	–
Mercuric Cyanide	B	–	A	A	–	A	–	A^2	–	B	A	B	A	A	A	A^1	–	D	–	A	A	–	A^1	C	C	D	–	D	C	D	A	A	–	A	–
Mercurous Nitrate	C^2	–	A^2	–	–	A	A^2	–	A^2	A	–	A	A	A	B^1	A^1	–	–	B^1	B^1	–	A^2	A^1	A^1	A^1	D	–	–	–	–	A^1	A^1	C	A	A
Mercury	B	A	A	A	B	A	A^1	A	D	B	–	A	A	A	A	A	A	A	A	A	–	D	A	A	A	D	D	A	A	D	A^2	A	C	A	A
Methane	–	A	–	–	–	–	–	A	–	A	–	A	B	A	A	D	B	–	D	B	D	–	A	A	A	A	–	A	–	–	A	–	B	–	–
Methanol (Methyl Alcohol)	D	A	A	B^1	B	A^1	A	B^1	B^1	A^2	A	A	A^1	A	A	A	A	A^1	A	A	A	A^1	C	A	A	A^1	A	A	A	B^1	A	B	A	A	A
Methyl Acetate	D	B	–	D	–	B^1	–	A^2	D	D	–	A	D	B^1	D	B	D	A	D	B	D	A	D	A	B	A	–	A	A	B	A	–	A	–	–
Methyl Acetone	–	D	–	C	–	–	–	A	–	–	–	A	D	D	D	A^1	–	–	A	D	–	A	D	A	A	A	A	A	A	–	–	–	A	–	–
Methyl Acrylate	–	B	–	A	–	–	–	–	–	D	–	–	–	B^1	D	B	D	–	D	B	D	–	D	A	–	–	–	–	A	–	–	–	–	–	–
Methyl Alcohol 10%	D	A	A	B^1	B	A^1	A^2	B^1	B^1	A^2	A	A	A^1	A	A	A	A	A^2	A	A	A	A^1	C	A	A	A^1	A	A	A	A	A	B	A	A	A
Methyl Bromide	D	D	D	B	–	C^1	–	B^1	–	C	–	A	D	A	B^1	D	D	–	D	D	–	–	A	A	A	D	–	–	A	B	–	–	A	–	–
Methyl Butyl Ketone	–	D	–	C	–	–	–	D	D	D	–	–	A	D	D	A^1	D	–	D	D	D	–	D	A	A	–	–	–	–	–	–	–	–	–	–
Methyl Cellosolve	–	D	D	C	–	–	–	C	D	B	–	A	D	A	A^1	B^2	D	–	D	B	D	C	D	B	B	B	A	A	C	B	–	–	A	–	–
Methyl Chloride	D	B	D	A	–	C^1	D	B^1	D	D	B	A	D	A	D	D	D	A^1	D	D	D	D	A^1	A	A	D	A	B^2	D	–	B	A	A	–	–
Methyl Dichloride	–	D	–	A	–	–	–	C	–	D	–	–	A	D	D	D	–	–	–	–	–	–	A^1	–	–	–	–	–	–	–	–	–	–	–	–
Methyl Ethyl Ketone	D	C	D	C^1	B	B^2	D	A^1	D	B	A	A	D	D	D	A^2	D	A^1	D	D	D	D	D	A	A	B	A	A	A	A	A	A	A	A	A
Methyl Ethyl Ketone Peroxide	–	–	–	–	–	–	–	–	–	–	–	–	–	–	D	D	D	–	D	D	B	–	D	–	–	–	–	–	–	–	–	–	–	–	–
Methyl Isobutyl Ketone	D	–	D	C	B	C	D	B^2	D	A	A	A	D	D	D	B^1	D	A	D	D	D	–	D	B	B	B	–	A	C	B	A	A	A	–	–
Methyl Isopropyl Ketone	–	–	–	A	–	D	D	A	D	–	–	A	D	–	D	C^1	D	–	D	D	C	–	D	A	A	A	–	A	C	A	–	–	A	–	–
Methyl Methacrylate	–	D	–	A	–	–	–	–	–	D	–	–	A	B^1	D	D	D	–	D	D	C	–	D	B	B	–	–	–	C	–	–	–	–	–	–
Methylamine	D	D	–	A	–	A^1	–	–	–	A^2	–	A	D	C	B	A^1	–	A	B	–	–	D	D	A	A	A	D	A^2	A	–	–	–	A^2	–	–
Methylene Chloride	D	B	D	A	D	D	D	C^1	D	B^1	A	A	D	B^1	D	C^1	–	A	B	–	–	D	B	B	B	C	A	B	B	B	B	B	A	–	–
Milk	B	A	A	A	–	A	A^2	A	A	B	–	A	A^2	A^2	A^1	A	A	A	A	A	A	B	A	A	A	A	D	A	D	D	A	A	A	A	A
Mineral Spirits	D	A	A	A	–	B	A	A	C	B	A	A	A	–	A	D	C	A	D	C	D	B	A	A	A	A	–	A	B	–	B	B	A	–	–
Molasses	B	A	A	A	–	A	A^2	A^1	–	B	–	A	A	B^1	A	A^1	–	A	A	A	–	B	A	A	A	A	B	A	B	A	A	A	A	A	A
Monochloroacetic acid	–	D	–	–	D	–	–	D	D	–	–	A^2	–	B^1	D	C	A^2	B^2	–	A^1	–	–	C	A^1	A^1	D	B	B^1	D	D	A^2	A^2	B^2	–	–
Monoethanolamine	–	D	–	A	–	C	A	A	–	B	A	A	D	C	B^1	B	D	–	B	D	B	–	D	A	A	B	–	A	A	D	–	B	A	–	–
Morpholine	C	–	–	–	–	–	D	A^2	D	B^2	C	A^2	–	B^1	D	D	–	–	A^1	D	–	–	–	–	A^1	A^1	–	–	–	–	A^1	–	A^1	–	–
Motor oil	C	B	A	–	B	C^1	A	A^2	A	A^1	A	A	B	B	A	D	–	A^2	–	B^1	–	A^2	–	A^1	A^2	A^1	–	A^1	–	–	–	A^1	A^2	A	A
Mustard	B	C	A	A	–	A	A	A	A	A	–	A	B	A	B	A	–	–	B	A	–	B	D	A	A	B	–	A	D	–	A	A	A	–	–
Naphtha	D	D	A	A	B	A^1	D	A	B	B	A	B	A^1	A	A	D	D	A	D	D	D	C	A	A	A	A	A	A	B	A	B	B	A	–	–
Naphthalene	D	D	D	A	B	C	D	A^1	–	B	A	A	D	A^2	D	D	D	A	D	D	D	C	A	A	A	B^1	–	A	A	–	A	A	A	A	–
Natural Gas	B	B	–	–	–	A	–	–	–	A	–	A	A	–	A	D	–	–	–	A	A	A	A	A	A	A	–	A	A	–	–	–	–	–	–
Nickel Chloride	A	A	A	A	–	A	A^1	C^1	A^2	A	A	A	A	A	A^1	A^1	A	A	A	B	A	B	A	D	C	D	D	B^1	D	–	B	A	A	A	–
Nickel Nitrate	A	–	A^2	A^1	–	A	A^2	A^1	D	A^2	–	A^2	A	A^2	A^1	A^2	D	A^2	A^1	A^2	–	A^2	A^2	B	B^2	D	–	A^2	C	–	B^2	–	–	A	A
Nickel Sulfate	B	A	A	A	–	A	A^1	A^1	A	A	A	A	A	A	A^1	A^1	A	A	B	A	A	A	A	B	B^1	D	D	B	D	–	B	B	A	A	–
Nitrating Acid (≤1% Acid)	–	–	–	–	–	–	–	–	–	C	C	A	D	–	–	–	–	–	C	A	–	D	–	C	A	D	–	–	–	–	A	–	–	–	–
Nitrating Acid (≤15% H_2SO_4)	–	–	–	–	–	–	–	–	–	C	C	A	D	–	–	–	–	–	C	A	–	D	–	C	C	D	–	–	A	–	A	A	–	–	–
Nitrating Acid (>15% H_2SO_4)	–	D	–	D	–	–	–	–	–	C	D	A	D	–	D	A^1	–	–	C	A	–	D	–	C	C	D	–	–	C	–	A	C	–	–	–
Nitrating Acid (<15% HNO_3)	–	–	–	–	–	–	–	–	–	C	C	A	D	–	–	–	–	–	C	A	–	D	–	C	D	D	–	–	C	–	A	C	–	–	–
Nitric Acid (5-10%)	B	D	A	A^1	C	B	A	D	A	A	B^1	A	A^1	A^1	D	A^1	B	A^1	D	B	C	D	A	A	A	A	D	A^1	D	D	A^1	A^1	A	A	–

Delrin, Hypalon, Hytrel, Teflon, Viton—
Reg TM E. I. du Pont de Nemours & Co.
Hastelloy C—Reg TM Cabot Corporation

Kel-F—Reg TM 3M Co.
Kynar—Reg TM Elf Atochem North America
NORYL—Reg TM General Electric Co.

Ryton—Reg TM Phillips Petroleum Co.
Tygon—Reg TM Norton Co.

CHEMICAL	Plastics														Elastomers									Metals									Non-metals		
	ABS plastic	Acetal (Delrin®)	CPVC	Epoxy	Hytrel®	LDPE	NORYL®	Nylon	Polycarbonate	Polypropylene	PPS (Ryton®)	PTFE (Teflon®)	PVC	PVDF (Kynar®)	Buna N (Nitrile)	EPDM	Hypalon®	Kel-F®	Natural rubber	Neoprene	Silicone	Tygon®	Viton®	304 stainless steel	316 stainless steel	Aluminum	Brass	Bronze	Cast iron	Copper	Hastelloy C®	Titanium	Carbon graphite	Ceramic Al_2O_3	Ceramic magnet
Nitric Acid (20%)	B	D	A^2	B^1	D	C	B^2	D	B^1	A^2	C	A	A^1	A	D	A^1	D	A^1	D	D	D	D	A	A	A	D	D	A^1	D	D	A^1	A^1	A	A	-
Nitric Acid (50%)	C	D	B^1	D	D	B^1	B^2	D	B	B	C	A	B^1	A^1	D	D	D	A	D	D	D	D	A	A^2	A^1	D	D	A^1	D	D	A^1	A^1	D	A	C
Nitric Acid (Concentrated)	D	D	D	D	D	C^1	B^1	D	C^1	D	C	A	B^1	A^1	D	D	D	A^1	D	D	D	D	A	A^1	A^1	D	D	A^2	D	D	B^1	A^1	D	A	C
Nitrobenzene	D	C	D	C^1	D	C^1	D	B^1	D	B^1	A^2	A	D	A^1	D	B^1	D	A^1	D	D	D	D	B	B	B	B	-	A	C	B	D	A	B	-	-
Nitrogen Fertilizer	-	-	-	-	-	-	-	-	-	-	-	A	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Nitromethane	D	A	-	-	C	A	D	B^1	D	B^2	A^2	A	B^2	A^2	D	B^2	-	A	B^1	D	D	B^2	D	A	A^1	A	-	-	-	A	A	-	A^2	-	-
Nitrous Acid	D	-	A	D	-	-	-	-	-	A	-	A	A	B	-	A	-	B	C	D	-	A	B	B	B	D	D	B	-	C	D	-	-	-	-
Nitrous Oxide	-	-	-	-	-	C	-	C	-	D	-	A	A	D	-	A	-	-	A	A	-	A	B	B	B	B	B	D	-	B	B	-	C	-	-
Oils: Aniline	D	D	-	A	D	-	D	A	-	A	-	A	D	A	D	B	D	-	D	D	D	D	C	A	A	D	D	A	A	D	B	D	-	-	-
Anise	-	D	-	A	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	D	-	-	-	-	A	-	-	A	A	-	-	-	-	-	-
Bay	-	D	-	A	-	-	-	-	-	-	-	-	-	A	-	-	-	-	-	D	-	-	A	-	A	-	-	A	A	-	-	-	-	-	-
Bone	-	D	-	A	-	-	-	-	-	A	-	A	-	A	A	-	-	-	-	D	-	A	A	-	A	-	-	A	A	-	-	-	-	-	-
Castor	A	A	C	A	B^1	-	-	A	-	A	-	A	A	A	B	B	A	-	A	A	A	A	A	A	A	A	A	-	A	A	-	A	-	A	A
Cinnamon	-	D	-	A	-	D	-	-	D	D	-	A	D	-	-	-	-	-	-	C	-	-	A	A	A	-	-	-	-	-	-	-	-	-	-
Citric	D	A	-	A	-	A	A	A	A	A	-	A	B	A	D	B	-	-	-	D	-	D	A	A	A	A	B	-	D	-	A	-	-	-	-
Clove	-	-	-	A	-	-	-	-	-	-	-	A	-	-	A	-	-	-	-	C	-	-	A	A	A	B	-	-	-	-	A	-	-	-	-
Coconut	A	A	A^1	A	-	A	-	-	-	A^1	-	A	A^1	A	A	D	C	-	D	C	A	A	A	A	A	A	-	-	A	-	A	-	-	-	-
Cod Liver	A	B	A^1	A	-	-	-	-	-	A^1	-	A	A^1	A	A	A	B	-	D	B	B	-	A	A	A	A	-	-	-	-	A	-	-	-	-
Corn	B	A	-	A	A	A	A	A	-	A^2	-	A	B	A	D	C	B	-	D	A	A	B	B	A	A	A	-	-	A	B	A	-	-	-	-
Cottonseed	A	A	A	A^1	A^1	A	A	B	-	A	A	A	B^2	A	A	D	B	A^2	D	C	A	B	A	A	A	A	A	-	A	A	A	A	A	A	-
Creosote	-	D	-	A	D	C	D	D	-	C	-	A	C	-	D	D	D	A	D	C	D	-	A	B	B	B	-	A	-	-	B	A	A	-	-
Diesel Fuel (20, 30, 40, 50)	-	D	-	A^1	A^1	A	D	A	-	A^1	A	A	B	A	A	D	B	A^1	D	B	D	A	A	A	A	A	-	A	A	-	B	B	A	-	-
Fuel (1, 2, 3, 5A, 5B, 6)	D	D	-	A^1	A	B	A^1	A	B	B	A	A	A^2	B	B	D	D	A	D	D	C	A	B	A	A	C^1	B	A	A	A	A^1	B	A	-	-
Ginger	-	A	-	A	-	-	-	-	-	-	-	A	-	A	A	A	-	-	-	A	-	-	A	D	D	-	-	D	-	-	-	-	-	-	-
Hydraulic Oil (Petro)	-	B	-	A	-	C	-	A^1	-	D	D	A	A	A	A	D	A	-	D	A	B	A	A	A	A	A	A	A	A	A	A	-	B	-	-
Hydraulic Oil (Synthetic)	-	-	-	A	-	A	-	A^1	-	D	-	A	A	A	D	A	A	-	D	A	B	A	A	A	A	A	A	A	-	A	A	-	B	-	-
Lemon	C	D	-	A	-	-	-	-	-	-	-	A	-	A	-	D	-	-	-	D	-	-	A	A	A	A	-	A	-	-	-	-	-	-	-
Linseed	-	A	C	A	B^1	A	A^1	A^1	-	A	B	A	A^2	A	A	D	C	-	D	D	A	A	A	A	A	B	B	A	-	B	B	A	A	A	A
Mineral	A	A	A	A	A	B^1	A^1	A	B	A	A	A	B	A	A	D	B	A	D	B	C	B	A	A	A	A	A	A	-	B	A	A	A	A	A
Olive	A	A	C	A	-	A^1	A^2	A^1	A^2	A	-	A^1	C	-	D	D	B	-	D	B	D	B	A	A	A	A	-	A	-	-	A	A	A	A	-
Orange	-	D	-	A	-	C^1	-	-	C^1	A	-	-	C^1	A	A	-	-	-	-	C	D	-	A	A	A	A	-	A	-	-	A	A	-	-	-
Palm	A	A	A	A	-	A	-	-	-	-	-	A	A	A	A	A	-	-	-	D	-	-	A	A	A	-	-	A	A	A	-	A	-	-	-
Peanut	-	A	C	A	-	A	-	-	-	D	-	A	A^1	A	A	D	B	-	D	B	A	A	A	A	A	A	-	A	A	A	-	A	-	-	-
Peppermint	D	D	-	A	-	-	-	-	-	-	-	A	-	A	D	-	-	-	-	D	-	-	A	A	A	D	-	A	-	-	-	-	-	-	-
Pine	D	A	A	A	-	D	-	A	A	B	-	A	D	A	D	D	D	-	D	D	D	D	A	A	A	A	-	A	C	-	-	A	-	-	-
Rapeseed	-	A	A	A	-	D	-	-	-	D	-	A	-	A	D	A	D	-	D	B	D	-	A	A	A	-	-	A	A	-	-	A	-	-	-
Rosin	-	-	-	A	-	B^2	-	A^1	-	A^2	-	A	C^1	A	A	-	-	-	-	-	-	-	A	A^1	A^1	B^1	-	B^1	-	B	A	-	A	-	-
Sesame Seed	A	D	A	A	-	-	-	-	-	A	-	A	A	A	A	-	-	-	-	D	-	A	A	A	A	-	-	A	A	-	-	A	-	-	-
Silicone	A	A	A	A	A	A	A^1	A^1	-	A	A^1	A	A	A	A	A	A	-	D	D	C	A	A	A	A	A	-	A	A	A	A	-	A	-	A
Soybean	A	A	A^2	A	B	A^1	-	A	-	A^1	-	A	A^1	A	A	C	C	-	D	C	A	B	A	A	A	A	-	A	A	-	A	A	A	-	-
Sperm (whale)	A	D	A	A	-	-	-	-	-	-	-	A	-	A	A	-	-	-	-	D	-	A	A	A	A	-	-	A	A	-	-	A	-	-	-
Tanning	-	D	-	A	-	-	-	-	-	-	-	-	-	A	A	-	-	-	-	D	-	-	A	A	A	-	-	A	-	-	-	-	-	-	-
Transformer	-	A	A	B	-	C^1	-	A^1	-	B	-	A	B	A	A	D	-	-	D	B	B	-	A	A	A	A	-	-	-	A	-	-	A	-	-
Turbine	-	A	A	A	-	C	-	A	-	B^1	-	A	A^1	A	B	A	D	-	D	D	D	A	A	A	A	A	-	A	A	A	-	A	-	-	-
Oleic Acid	D	A	A	A	A	C^2	A^1	A	-	B^1	A	A	C^2	A	B	B	C	B	D	C	D	C	B	A	A	A	D	B^1	-	A	A^2	B	A	A	-
Oleum 25%	-	D	D	D	C	D	-	D	-	D	A^1	A	D	C^1	D	D	D	A	D	D	D	-	A	B^2	B	B	-	B	-	-	A	D	D	-	-
Oleum 100%	D	D	D	D	-	D	A^1	D	-	D	A^1	A	D	D	D	D	D	A	D	D	D	C	A	A	A	B	-	D	-	-	D	D	D	-	-
Oxalic Acid (cold)	A	B	A	A	D	A^2	A^1	B^2	-	A^2	A	A^1	B	B	D	A	B	D	B	D	B	B	A	B	A	A	D	B^2	C	B	B	A	A	A	-
Ozone	B	C	A	-	C	C^1	-	D	A^1	B	-	A	B	A	D	A	A	A	D	C	A	-	A	B	A	B	-	B	-	A	-	-	-	-	-
Palmitic Acid	A	A	A^1	A	A	-	-	A	-	B^1	-	A^2	B^1	A^2	A^2	B^1	D	-	B^1	D	D	B^1	A^1	B^1	A^1	B	D	A	-	B	B	-	A^2	-	-
Paraffin	A	A	A	A	-	B	A	A^1	A^1	A^1	-	A	B	A	B	D	-	-	B	B	-	B	B	A	A	A	A	A	-	B	B	A	A	A	-
Pentane	-	B	-	A	-	D	-	A^1	A	D	-	A	A	A	A	D	B	-	D	B	D	A	A	C	C	B	-	C	-	-	A	-	A	-	-
Perchloric Acid	-	C	A^1	-	-	B	-	D	-	C	-	A	C	A	D	B	-	B	-	A	D	D	A	C	C	D	-	B	-	D	B	D	A	-	-
Perchloroethylene	D	B	C^1	D	C	D	D	C^1	D	D	A	A	C^1	A	C	D	D	A	D	D	D	C	A	B	A^1	C	-	B	A	B	B	A	A	A	-
Petrolatum	-	B	-	A	-	B	-	D	-	D	-	C	B	A	A	A	-	-	C	A	D	B	A	A	A	-	-	A	-	-	A	-	A	-	-
Petroleum	B	B	A^2	A^2	B	C^1	D	A^1	-	B^1	-	A^2	-	A	A^2	D	D	-	D	B^1	D	-	A^2	A^1	A^1	D	-	A^1	-	B	-	A^1	A^2	-	-
Phenol (10%)	D	B	A^1	C	-	B	D	D	B^1	B^1	A	A	C^1	A	D	B	D	B	A	D	D	C	A	B	B	A	-	B	D	B	B	B	A	A	-
Phenol (Carbolic Acid)	D	D	B^1	C	D	D	D	D	D	B	A	A	D	A^1	D	B	D	B	D	D	D	B	A	B	B	A	D	B	D	D	A	A	A	A	-
Phosphoric Acid (≤40%)	B	D	A	A	-	A	A	B^1	A	A^2	A	A	B	B	D	B	B	A	B	B	C	D	A	D	C	C	D	B	D	D	A^2	C	A	A	-
Phosphoric Acid (>40%)	C	D	A	B	-	B^1	A	B^1	A	A^2	A	A	B	B	D	B	B	A	B	B	D	D	A	D	D	C	D	B	D	D	A^2	C	B	A	C
Phosphoric Acid (crude)	C	D	-	B	-	B^1	A	B^1	A	B^2	A	A	B^2	A	D	B	B	A	D	D	D	D	A	D	B	C	-	B	D	D	A^2	C	A	-	-
Phosphoric Acid (molten)	D	D	-	-	-	-	-	-	-	D	-	-	D	D	-	-	-	-	-	A	-	D	-	-	C	C	-	-	-	D	C	D	-	-	-
Phosphoric Acid Anhydride	-	D	-	-	-	-	-	-	D	A	D	-	-	D	D	-	-	-	-	A	-	-	-	-	-	C	-	-	-	-	-	D	-	-	-
Phosphorus	-	B	B^1	-	-	B	-	-	-	A	-	A^2	A^1	A^1	-	-	-	-	-	-	-	B^1	-	A^2	A^2	B	-	A^2	-	B	A^2	-	D	-	-
Phosphorus Trichloride	D	D	D	A^1	-	B	-	-	C	-	A	A^2	D	A^2	D	A^1	D	A^2	D	D	-	-	A^1	A^1	A^2	D	-	-	-	D	A^2	A	A	-	-
Photographic Developer	B	D	A	A	-	A	A	-	A^2	A	-	A	A	-	A	B	A	-	A	A	B	-	A	A	A	-	-	A	D	D	B	A	A	A	A

Delrin, Hypalon, Hytrel, Teflon, Viton—Reg TM E. I. du Pont de Nemours & Co.
Hastelloy C—Reg TM Cabot Corporation
Kel-F—Reg TM 3M Co.
Kynar—Reg TM Elf Atochem North America
NORYL—Reg TM General Electric Co.
Ryton—Reg TM Phillips Petroleum Co.
Tygon—Reg TM Norton Co.

APPENDIX D.3

CHEMICAL	Plastics														Elastomers									Metals									Non-metals		
	ABS plastic	Acetal (Delrin®)	CPVC	Epoxy	Hytrel®	LDPE	NORYL®	Nylon	Polycarbonate	Polypropylene	PPS (Ryton®)	PTFE (Teflon®)	PVC	PVDF (Kynar®)	Buna N (Nitrile)	EPDM	Hypalon®	Kel-F®	Natural rubber	Neoprene	Silicone	Tygon®	Viton®	304 stainless steel	316 stainless steel	Aluminum	Brass	Bronze	Cast iron	Copper	Hastelloy C®	Titanium	Carbon graphite	Ceramic Al_2O_3	Ceramic magnet
Photographic Solutions	–	D	A	B^2	B	A	A^1	A^1	A^1	A^2	A^2	A^2	A	B^2	B	A^1	A^1	A^2	B	B^1	A	A^2	B^1	D	–	–	–	A^2	–	D	B^2	A^1	A^2	–	–
Phthalic Acid	B	C	B	–	–	B^2	–	B^1	–	A	–	A^2	–	A^2	D	A^1	A^2	–	–	A	B^1	–	A^1	B^2	A	B^2	–	B^2	–	C	B^2	A	A^1	–	–
Phthalic Anhydride	B	C	D	–	–	–	–	–	A^1	D	–	A	D	A	D	A	–	–	A	A	–	B	A	A	A	A	–	A	–	C	A	–	A	–	–
Picric Acid	A	A	D	A	–	A	–	C^1	D	B^1	A	A	D	A^1	C	B	B	A	D	A	D	D	A	B	B	C	–	B	A	D	B	A	A	–	–
Plating Solutions																																			
Antimony Plating 130°F	–	A	A	B	–	–	A	D	–	A	–	A	A	A	A	–	–	–	–	A	–	–	A	A	A	A	–	A	A	–	A	A	–	–	–
Arsenic Plating 110°F	–	A	A	B	–	–	–	A	–	A	–	A	A	A	A	–	–	–	–	A	–	–	A	A	A	A	–	A	A	–	A	A	–	–	–
Brass Plating:																																			
Regular Brass Bath 100°F	–	A	A	B	–	B	A	A	–	A	–	A	A	B	A	–	–	–	–	A	–	–	A	A	A	A	–	A	A	–	A	A	A	–	–
High-Speed Brass Bath 110°F	–	A	A	B	–	B	A	A	–	A	–	A	A	B	A	–	–	–	–	A	–	–	A	–	A	A	–	–	A	–	A	A	A	–	–
Bronze Plating:																																			
Cu-Cd Bronze Bath R.T.	–	A	A	B	–	–	A	A	–	A	–	A	A	A	A	A	–	–	–	A	–	–	A	A	A	A	–	–	A	–	A	A	–	–	–
Cu-Sn Bronze Bath 160°F	–	B	D	C	–	–	A	A	–	A	–	A	D	A	A	A	–	–	–	A	–	–	A	A	A	A	–	–	A	–	A	D	–	–	–
Cu-Zn Bronze Bath 100°F	–	A	A	B	–	–	A	A	–	A	–	A	A	A	A	–	–	–	–	A	–	–	A	A	A	A	–	–	A	–	A	A	–	–	–
Cadmium Plating:																																			
Cyanide Bath 90°F	–	A	A	B	–	–	A	A	–	A	–	A	A	A	A	–	–	–	–	A	–	–	A	–	A	A	–	–	A	–	A	A	–	–	–
Fluoborate Bath 100°F	–	C	A	B	–	–	A	D	–	A	–	A	A	A	B	–	–	–	–	C	–	–	A	A	A	A	–	–	D	–	D	D	–	–	–
Chromium Plating:																																			
Barrel Chrome Bath 95°F	–	D	A	C	–	–	D	D	–	A	–	A	A	C	D	–	–	–	–	D	–	–	C	–	D	A	–	–	C	–	D	C	–	–	–
Black Chrome Bath 115°F	–	D	A	C	–	–	D	D	–	A	–	A	A	C	C	–	–	–	–	D	–	–	C	–	C	A	–	–	A	–	D	A	–	–	–
Chromic-Sulfuric Bath 130°F	–	D	A	C	–	–	D	D	–	A	–	A	A	C	D	–	–	–	–	D	–	–	C	–	C	A	–	–	A	–	D	A	–	–	–
Fluoride Bath 130°F	–	D	A	C	–	–	D	D	–	A	–	A	A	C	D	–	–	–	–	D	–	–	C	–	D	A	–	–	C	–	D	C	–	–	–
Fluosilicate Bath 95°F	–	D	A	C	–	–	D	D	–	D	–	A	A	C	D	–	–	–	–	D	–	–	C	–	C	A	–	–	C	–	D	C	–	–	–
Copper Plating (Cyanide):																																			
Copper Strike Bath 120°F	–	A	A	B	–	–	A	A	–	A	–	A	A	B	A	–	–	–	–	A	–	–	A	–	A	–	–	–	A	–	A	–	–	–	–
High-Speed Bath 180°F	–	B	D	C	–	–	A	A	–	A	–	A	D	A	A	–	–	–	–	B	–	–	A	–	A	A	–	–	A	–	A	D	–	–	–
Rochelle Salt Bath 150°F	–	B	D	C	–	–	A	A	–	A	–	A	D	A	A	–	–	–	–	B	–	–	A	–	A	A	–	–	A	–	A	D	–	–	–
Copper Plating (Acid):																																			
Copper Fluoborate Bath 120°F	–	C	A	D	–	–	A	D	–	A	–	A	A	A	B	–	–	–	–	C	–	–	A	A	D	A	–	–	D	–	D	D	–	–	–
Copper Sulfate Bath R.T.	–	A	A	D	–	–	A	D	–	A	–	A	A	A	A	–	–	–	–	A	–	–	A	–	D	A	–	–	A	–	D	A	–	–	–
Copper Plating (Misc):																																			
Copper Pyrophosphate	–	A	A	B	–	–	A	A	–	A	–	A	A	A	A	–	–	–	–	A	–	–	A	–	A	A	–	–	A	–	A	A	–	–	–
Copper (Electroless)	–	D	A	B	–	–	A	A	–	A	–	A	A	A	D	–	–	–	–	D	–	D	A	–	–	A	–	–	–	–	–	A	–	–	–
Gold Plating:																																			
Acid 75°F	–	–	A	A	–	–	A	A	–	A	–	A	A	–	A	–	–	–	–	A	–	–	A	–	C	–	–	–	–	–	A	A	–	–	–
Cyanide 150°F	–	–	D	D	–	–	A	A	–	A	–	A	D	–	A	–	–	–	–	A	–	–	A	–	A	–	–	–	–	–	A	A	–	–	–
Neutral 75°F	–	–	A	A	–	–	A	A	–	A	–	A	A	–	A	–	–	–	–	A	–	–	A	–	C	–	–	–	–	–	A	A	–	–	–
Indium Sulfamate Plating R.T.	–	–	A	A	–	–	A	D	–	A	–	A	A	–	A	–	–	–	–	A	–	–	A	–	C	–	–	–	–	–	A	A	–	A	–
Iron Plating:																																			
Ferrous Am Sulfate Bath 150°F	–	–	D	D	–	–	A	D	–	A	–	A	D	–	A	–	–	–	–	B	–	–	A	–	C	–	–	–	–	–	A	A	–	–	–
Ferrous Chloride Bath 190°F	–	–	D	D	–	–	A	D	–	C	–	A	D	–	B	–	–	–	–	D	–	–	A	–	D	–	–	–	–	–	D	A	–	–	–
Ferrous Sulfate Bath 150°F	–	–	D	D	–	–	A	D	–	A	–	A	D	–	A	–	–	–	–	B	–	–	A	–	C	–	–	–	–	–	A	A	–	–	–
Fluoborate Bath 145°F	–	–	D	D	–	–	A	D	–	A	–	A	D	–	B	–	–	–	–	C	–	–	A	–	D	–	–	–	–	–	B	D	–	–	–
Sulfamate 140°F	–	–	A	A	–	–	A	D	–	A	–	A	A	–	A	–	–	–	–	A	–	–	A	–	D	–	–	–	–	–	B	A	–	–	–
Sulfate-Chloride Bath 160°F	–	–	D	D	–	–	A	D	–	A	–	A	D	–	B	–	–	–	–	C	–	–	A	–	D	–	–	–	–	–	D	A	–	–	–
Lead Fluoborate Plating	–	–	A	A	–	–	A	D	–	A	–	A	A	–	B	–	–	–	–	A	–	–	A	–	C	–	–	–	–	–	A	D	–	A	–
Nickel Plating:																																			
Electroless 200°F	–	–	D	B	–	–	D	D	–	D	–	A	D	–	D	–	–	–	–	D	–	–	A	–	–	–	–	–	–	–	–	–	–	–	–
Fluoborate 100-170°F	–	–	A	A	–	–	A	D	–	A	–	A	A	–	B	–	–	–	–	A	–	–	A	–	C	–	–	–	–	–	A	D	–	–	–
High-Chloride 130-160°F	–	–	D	D	–	–	A	D	–	A	–	A	D	–	A	–	–	–	–	B	–	–	A	–	C	–	–	–	–	–	A	A	–	–	–
Sulfamate 100-140°F	–	–	A	A	–	–	A	A	–	A	–	A	A	–	A	–	–	–	–	A	–	–	A	–	C	–	–	–	–	–	A	A	–	–	–
Watts Type 115-160°F	–	–	D	D	–	–	A	A	–	A	–	A	D	–	A	–	–	–	–	A	–	–	A	–	C	–	–	–	–	–	A	A	–	–	–
Rhodium Plating 120°F	–	–	A	A	–	–	A	D	–	A	–	A	A	–	A	A	–	–	–	B	–	–	A	–	D	–	–	–	–	–	D	D	–	A	–
Silver Plating 80-120°F	–	–	A	A	–	–	A	A	–	A	–	A	A	–	A	A	–	–	–	A	–	–	A	–	A	–	–	–	–	–	A	A	–	–	–
Tin-Fluoborate Plating 100°F	–	–	A	A	–	–	A	D	–	A	–	A	A	–	B	–	–	–	–	C	–	–	A	–	C	–	–	–	–	–	A	D	–	–	–
Tin-Lead Plating 100°F	–	–	A	A	–	–	A	D	–	A	–	A	A	–	B	–	–	–	–	C	–	–	A	–	C	–	–	–	–	–	A	D	–	–	–
Zinc Plating:																																			
Acid Chloride 140°F	–	–	A	A	–	–	A	D	–	A	–	A	A	–	A	–	–	–	–	A	–	–	A	–	D	–	–	–	–	–	D	A	–	–	–
Acid Fluoborate Bath R.T.	–	–	A	A	–	–	A	D	–	A	–	A	A	–	B	–	–	–	–	C	–	–	A	–	C	–	–	–	–	–	A	D	–	–	–
Acid Sulfate Bath 150°F	–	–	D	D	–	–	A	D	–	A	–	A	D	–	A	–	–	–	–	B	–	–	A	–	C	–	–	–	–	–	A	A	–	–	–
Alkaline Cyanide Bath R.T.	–	–	A	A	–	–	A	A	–	A	–	A	A	–	A	–	–	–	–	A	–	–	A	–	A	–	–	–	–	–	A	A	–	–	–
Potash (Potassium Carbonate)	A	B	A	A	D	A^1	A	A	–	A	–	–	A	A	A	A^1	–	–	A	A	–	B	A	B	B	D	–	B	C	B	B	A	A	D	–
Potassium Bicarbonate	A	C	A	A	–	A	A^1	A^1	–	A	A	A	A	B	A	A	–	A	A	A	A^1	A	A	B	B	D	–	B	A	B	B	A	A	A	A
Potassium Bromide	A^1	A	A	A	–	A	A^1	A^1	A^1	A	A	A	A	A	A	A^1	–	A	A	A	A^1	B	A	B	B	C^1	–	B	D	B	B	A	A	C	A
Potassium Chlorate	A	B	A	A	–	A^1	A^1	C^1	A^1	A	A	A	A	A	A^1	A^1	–	A^2	–	A	B	B	A	B^1	B	B	–	B^1	C	B^1	B	A	A^2	B	–
Potassium Chloride	A	A	A	A	B	A^1	A^1	A^1	A	A	A	A	A	A	A^1	A^1	A	A	A	A	A	A	A	B^1	A^1	D	D	B	A	B	A	A	A	–	–

Delrin, Hypalon, Hytrel, Teflon, Viton—
Reg TM E. I. du Pont de Nemours & Co.
Hastelloy C—Reg TM Cabot Corporation

Kel-F—Reg TM 3M Co.
Kynar—Reg TM Elf Atochem North America
NORYL—Reg TM General Electric Co.

Ryton—Reg TM Phillips Petroleum Co.
Tygon—Reg TM Norton Co.

APPENDIX D.3

CHEMICAL	Plastics														Elastomers									Metals									Non-metals		
	ABS plastic	Acetal (Delrin®)	CPVC	Epoxy	Hytrel®	LDPE	NORYL®	Nylon	Polycarbonate	Polypropylene	PPS (Ryton®)	PTFE (Teflon®)	PVC	PVDF (Kynar®)	Buna N (Nitrile)	EPDM	Hypalon®	Kel-F®	Natural rubber	Neoprene	Silicone	Tygon®	Viton®	304 stainless steel	316 stainless steel	Aluminum	Brass	Bronze	Cast iron	Copper	Hastelloy C®	Titanium	Carbon graphite	Ceramic Al_2O_3	Ceramic magnet
Potassium Chromate	-	C	A	C	-	A	A[2]	B	-	A	-	A[1]	A	B	A[1]	A[2]	-	-	B	A	-	B	A	B[1]	B[1]	B[1]	-	B[1]	A	-	A	-	A	B	-
Potassium Cyanide Solutions	A	C	A	A	B	A	A[1]	A[1]	-	A	A	A	A	A	A[1]	A[1]	A	A	A	B	A	A	A	B[1]	B[1]	D	D	D	B	D	B	A	A	D	-
Potassium Dichromate	B[1]	A	A	C	C	A	A[1]	B[1]	A[1]	A	A	A	A	A	A[1]	A[1]	A	A	B	A	A	C	A	B	B[1]	B	-	B[1]	A	B	B	A	A	B	A
Potassium Ferricyanide	B	B[1]	A	A[1]	-	A[2]	A[2]	B[1]	-	A[2]	-	A[2]	A	A[2]	D	A	A[1]	A[1]	B	A[1]	-	B	A	B[1]	B[1]	B[2]	-	B[2]	C	B	B[2]	A[2]	A[2]	B	A
Potassium Ferrocyanide	-	-	B	A	-	A[1]	A	B[1]	-	A	-	A	A	A	D	A	-	A	A	A	-	B	A	B	B	B[1]	-	B[1]	C	B	B	A	A	B	A
Potassium Hydroxide (Caustic Potash)	A	A	A	A	D	A	A[1]	C[1]	D	A	A	A	A[1]	A	B[1]	A[2]	A	B	B	B	C	B	B	B	A[1]	D	D	D	B[2]	B	B[1]	D	C	D	A
Potassium Hypochlorite	-	-	-	-	-	C[1]	-	B[1]	-	-	A	A[2]	B[1]	A[1]	A[1]	A[1]	A[1]	-	C[1]	B[2]	-	B[1]	-	C[1]	B	D	-	D	A	D	B[2]	A[1]	-	D	-
Potassium Iodide	B	-	A	-	-	B[1]	-	A[1]	-	A[2]	A[2]	A[2]	A[2]	A[2]	A[1]	A	A[2]	-	B	A	-	B	A	A[1]	A[1]	B[1]	-	A[1]	A	A[1]	A[2]	A[1]	A[1]	B	-
Potassium Nitrate	B	A	A	A	B	A	A[1]	B[1]	A[1]	A	A	A	A	A	A[2]	A	A	-	A	A	A	A	A	B	B	B	B	B[1]	A	A	B[1]	A	A	B	-
Potassium Oxalate	-	-	-	-	-	-	-	-	-	-	-	A[2]	-	-	-	-	-	-	-	-	-	-	-	B	B[1]	B[1]	-	A[1]	A	B	A[1]	A[1]	A[1]	A	-
Potassium Permanganate	B[1]	A	A[1]	A	D	A	A	D	A[2]	A[1]	A	A	A[1]	A	C	A	-	-	A[1]	A	-	B	A	B[1]	B	B[1]	-	A[1]	A	A	A[1]	A	B[1]	A	-
Potassium Sulfate	B	B	A	A	B	A[2]	A	A[1]	A[1]	A	A	A	A[2]	A	A[2]	A[1]	A	A[1]	A	A	A	A	A[2]	B[1]	A	C	D	A[1]	A	B	B[1]	A	A	A	A
Potassium Sulfide	B	-	A[2]	-	-	A[2]	A	A	-	A	A	A	A[2]	A	A	A	B	A	B	A	A	-	A	B	B	D	-	D	B	D	-	A	A	A	-
Propane (liquefied)	-	A	A[1]	A	A	C[1]	A[1]	A[1]	C[1]	A	-	A	A[1]	A	A	D	-	A	D	C	D	-	A	A	A	A	A	A[2]	A	A	A	-	A	-	-
Propylene	B	-	-	-	-	-	-	-	-	-	-	A[2]	B[1]	-	D	D	D	-	D	D	D	B[1]	A[1]	B[1]	A[1]	A	-	-	A	A	-	-	A[2]	-	-
Propylene Glycol	B	B	C[1]	B	-	B[2]	-	A	B[1]	A[2]	-	A	C[1]	-	A	A	A	-	A	C	A	-	A	B	B	B	-	A	A	A	B	A	-	A	A
Pyridine	-	B	D	A	C	B[1]	B	C[1]	D	A[2]	A	A	D	D	D	B	D	A[1]	D	D	D	D	D	A	A	B	B	B	A	B	B	B	A	A	-
Pyrogallic Acid	-	D	A	A	-	-	-	-	-	A	-	A	A	A	-	B	-	A	-	A	-	-	A	B[2]	B	B	-	A	D	B	B	A	A	-	-
Resorcinal	A	-	-	-	D	B[2]	-	D	B[1]	A[2]	-	A[2]	C	-	-	B[1]	-	-	-	D	-	C	A[1]	-	-	-	-	-	-	-	-	-	A[2]	-	-
Rosins	-	B	C[1]	A	-	B[1]	-	A[1]	-	A[2]	-	A	C[1]	-	A[2]	-	B	A	-	A	A	-	A	A[1]	A[1]	B[1]	-	B	D	B	-	-	A	-	-
Rum	-	A	A	A	-	-	A	A	-	A	-	-	A	-	A	A	A	-	A	A	A	-	A	A	A	-	-	A	-	-	-	-	-	-	-
Rust Inhibitors	-	A	-	A	-	-	-	-	-	A	-	-	-	-	A	-	-	-	-	C	-	-	A	A	A	-	-	A	C	-	-	-	-	-	-
Salad Dressings	-	A	-	A	-	-	A	A	-	A	-	-	-	-	A	-	-	-	-	-	-	-	A	A	A	B	-	-	D	-	-	-	-	-	-
Salicylic Acid	A	D	-	-	-	B[2]	-	A[1]	A[1]	A[1]	-	A[2]	B[1]	A	B	A	A	A[1]	A	-	-	B[1]	A[1]	B[2]	B[2]	B[2]	-	A	A	A	A[2]	A[1]	A[2]	-	-
Salt Brine (NaCl saturated)	-	-	A[2]	A	A[1]	A	A	A	A	A	A	A[2]	A	A	A	A	A[2]	-	A	A[2]	A[1]	-	A[2]	B[1]	A[2]	B[1]	-	B[2]	D	B	A[2]	A[2]	A[2]	-	-
Sea Water	-	A	A	A	A	A[2]	A[1]	A[2]	A[2]	A	A	A	A[2]	A	A[2]	A[2]	A	A	A[1]	B[2]	A[1]	-	A	C	C	B	D	A	D	B	A	A	A	-	-
Shellac (Bleached)	-	A	-	A	-	A[1]	-	A[1]	-	A	-	A	-	-	A[2]	A[2]	A	-	A[1]	B[2]	-	-	A	A	A	A	B	A	A	A	-	-	A	-	-
Shellac (Orange)	-	A	-	A	-	A[1]	-	A[1]	-	A	-	A	-	-	A	A	-	-	D	D	-	-	A	A	A	A	B	A	A	A	-	-	A	-	-
Silicone	D	A	A	A	A	-	A[1]	A[1]	A[2]	A	A[1]	A	A	A	A	A	A	-	C	A	C	-	A	A	A	A	-	-	A	A	-	-	A	-	-
Silver Bromide	-	C	-	A	-	A	A	-	-	-	-	A	-	-	-	-	-	A	-	-	-	-	-	D	D	D	-	D	D	-	A	-	-	-	-
Silver Nitrate	B	A	A[1]	A	-	A	A	A[1]	A[2]	A[1]	A	A	A[1]	A	B	A	A	A	A	A	A	B	A	B	B	D	-	B	C	-	A	A	A	-	-
Soap Solutions	A	A	A	A	A	D	A[1]	A[1]	A[1]	A	A	A	A	A[1]	A	A	A	-	B	B	A	B	A	A	A[1]	C	B	B	A	A	A	A	A	A	A
Soda Ash (see Sodium Carbonate)	B	A	A	C	B	B	A	B	A	A	A	A	A	A	A[1]	A[2]	A	-	A	A[1]	A	-	A	A	A	D	-	B	B	-	-	-	-	-	-
Sodium Acetate	B	B	A	A	-	A	A[1]	B[1]	A[1]	A	A	A	B[1]	A	B	A	-	A	A	B	D	-	D	B	B[1]	B	B	B	B	A	A	A	A	A	-
Sodium Aluminate	-	B	-	A	-	-	A	A[1]	-	-	A	A	-	-	A	A	A	-	B	A	-	-	A	A	A	-	-	A	A	-	B	A	A	-	-
Sodium Benzoate	A	-	A[2]	A[2]	-	A[2]	-	B[1]	A[2]	A[2]	-	A[2]	B[1]	A[2]	B	A	B	-	A	A[1]	-	B[1]	A[1]	-	-	A[1]	-	A	-	-	A[1]	A[1]	A[2]	-	-
Sodium Bicarbonate	A	A	A[2]	A	-	A[2]	A	A	A[2]	A	A	A	A[2]	A	A[1]	A[2]	A	A	A	A	A	B	A	A	A[1]	D	D	A	C	B	B[1]	A[2]	A	A	A
Sodium Bisulfate	A	B	A[2]	A	C	A[2]	A[1]	A[1]	A[1]	A	A	A	A[2]	A	B[2]	A[2]	A	A[2]	A	A	A	B	A	D	C	D	D	A[2]	D	B	B[2]	A	A	A	-
Sodium Bisulfite	A	C	A[2]	A	B	A[2]	A[1]	C[1]	A[1]	A	A	A	A[2]	A	A[2]	A[2]	A	-	A	A	A	B	A	B[1]	B[1]	D	-	B[1]	D	B	B	A	A	A	-
Sodium Borate (Borax)	A	-	A[2]	A	B	A[2]	A[1]	A[1]	A[1]	A[2]	A	A	A[2]	A	A[1]	A	A	-	A	A	A	-	A	B[2]	B	C	-	A	-	B	A	B	A	A	A
Sodium Bromide	B	A	A[2]	A	-	A[2]	A[2]	B[1]	-	-	-	A[2]	B[2]	A[2]	-	A	B	A[1]	A[1]	A[1]	-	B[2]	A[1]	C	C	D	-	A	C	D	-	A[1]	A[2]	-	-
Sodium Carbonate	B	A[1]	A[2]	C[1]	-	B[2]	A	B[1]	A[2]	A	A	A	A[2]	A	A	A[2]	A	A	A	A	A	B	A	A	A	D	B	A[2]	B	A	A	A[1]	A	A	A
Sodium Chlorate	A	A	A[1]	A	-	B[2]	A[1]	D	A[1]	A	A	A	A[1]	A	B	A	A	-	A	A	C	B	A	A	B[1]	C[1]	-	B[1]	-	B	B[1]	A	C	A	-
Sodium Chloride	A	A[1]	A[2]	A	A	A[2]	A	A[1]	A[2]	A	A	A	A[2]	A	A	A	A	A	A	A	A	B	A	B	B	C	D	B	D	B	A	A	A	A	A
Sodium Chromate	-	D	-	C	-	-	A	C	A[2]	-	A	A	-	A	A	-	C	A	B	A	-	-	A	B[1]	B	B	-	B	A	B	A	-	A	-	-
Sodium Cyanide	A	A	A[2]	A	B	A[2]	A[1]	A[1]	-	A	A	A	A[2]	A	A	A[2]	A	A	A	A[1]	A	-	A[2]	A[1]	B[1]	D	D	D	A	D	A	A	A	A	A
Sodium Ferrocyanide	-	A	A	A	-	A	A	-	-	A	-	A	A	A	A	A	B	-	B	A	-	A	A	B	B	A	-	-	-	D	A	-	A	A	-
Sodium Fluoride	A	-	A[2]	A	-	A[2]	A[2]	B	-	A	-	A[1]	A[2]	A	A[1]	A	B	-	-	A	-	D	A	D	D	B	-	A	C	D	A	A	A	A	-
Sodium Hydrosulfite	-	-	C	-	-	-	-	A	-	-	-	A	C	-	C	B	B	-	C	B	C	A	A	-	-	A	-	-	-	-	A	-	-	-	-
Sodium Hydroxide (20%)	B	A	A	A[2]	B	D	A	A	A[2]	A	A	A	A	A	A	B	A	A	A[1]	B[2]	A[2]	A[1]	B[1]	B	B[2]	D	B	B	A[2]	A[2]	B	A[1]	A[2]	A	-
Sodium Hydroxide (50%)	A	A	A	A	C	D	A	A	D	A	A	A	A	D	A[1]	B[1]	A	B	A[1]	B[1]	A[1]	A[1]	B[1]	B	B[1]	D	D	C	D	B	C	B	-	A	-
Sodium Hydroxide (80%)	A	D	A	A[1]	-	D	A	C	D	A	A	A[1]	A	D	D	B[1]	A[2]	A	A[1]	B[1]	A[1]	A[1]	B[1]	C	B[1]	D	D	C	D	D	A[1]	D	A[2]	A	C
Sodium Hypochlorite (100%)	-	D	C[2]	D	D	B[2]	A	D	-	B	A	A	B	A	D	B[1]	B	A	C	C	B	-	A[1]	D	D	D	D	C	D	-	B	C	C	A	A
Sodium Hypochlorite (<20%)	B	D	A	C	A	A	A	D	C	A	A	A	A	A	B	B	A	A	C	C	B	C	A[1]	C	C	D	D	C	D	-	A	C	B	A	A
Sodium Hyposulfate	-	-	-	C	-	-	-	-	-	-	-	A	-	-	-	-	-	-	C	C	-	-	-	A	A	D	-	-	D	-	-	-	-	-	-
Sodium Metaphosphate	-	B	A[1]	A	-	A[1]	-	A[1]	-	A[1]	-	A	A	A	A	A	B	-	A	B	A	-	A	A	A	C	D	A	C	B	-	-	A	-	-
Sodium Metasilicate	-	D	A	A	-	-	-	-	-	A	-	A	A	-	A	A[1]	B	-	A	A	A	-	A	A	A	D	-	A	A[1]	B	A	-	-	-	-
Sodium Nitrate	-	A	A	A	-	A[2]	A[1]	A[1]	-	A	A	A	A[2]	A	A[1]	A	A	A	B	B	D	B	A	B[1]	B[1]	B	-	B	B	D	B	A	C	A	A
Sodium Perborate	-	B	A[1]	B	-	A[1]	A	B[1]	-	A	-	A	A[2]	-	B	A	B	A	B	B	B	-	A	B	B	C	D	B	C	B	B	-	C	-	-
Sodium Peroxide	-	D	A[2]	C	-	A	-	A[1]	A[2]	B	-	A	B[2]	A	B	A	B	A	B	B[1]	D	-	A	A	A	C	D	A	C	B	B	-	A	-	-
Sodium Polyphosphate	-	B	A[1]	A	-	A	A[1]	A[1]	-	A	-	A	A[1]	A	A	A	B	A	C	B	D	-	A	B	B	D	D	B	D	A	A	A	A	-	-
Sodium Silicate	-	C	A[2]	A	-	A[2]	A[1]	A[1]	-	A	A	A	A[2]	A	A	A	A	A	A	A	A	B	A	A	B	A	D	B	B	B	B	A	A	A	-
Sodium Sulfate	-	B	A[2]	A	-	A[2]	A	A	A[2]	A	A	A	A[2]	A	A	A	A	A	B	A	A	-	A	B	B[1]	A	B	B	B	B	B	A	A	A	-
Sodium Sulfide	-	B	A[2]	A	-	A[2]	A	A[1]	D	A	A	A	A[2]	A	A	A[2]	A	A[1]	B	A	A	B	A[2]	B	D	D	D	B[1]	C	D	B[1]	A	A	A	-
Sodium Sulfite	-	-	A[2]	A	-	B[1]	A	D	-	A[2]	-	A	A[2]	A	A	A	A	A	B	A	A	A	A[2]	B	A	C[1]	D	B	A[1]	D	B	A	A	-	-

Delrin, Hypalon, Hytrel, Teflon, Viton—Reg TM E. I. du Pont de Nemours & Co.
Hastelloy C—Reg TM Cabot Corporation

Kel-F—Reg TM 3M Co.
Kynar—Reg TM Elf Atochem North America
NORYL—Reg TM General Electric Co.

Ryton—Reg TM Phillips Petroleum Co.
Tygon—Reg TM Norton Co.

APPENDIX D.3

CHEMICAL	Plastics														Elastomers									Metals									Non-metals		
	ABS plastic	Acetal (Delrin®)	CPVC	Epoxy	Hytrel®	LDPE	NORYL®	Nylon	Polycarbonate	Polypropylene	PPS (Ryton®)	PTFE (Teflon®)	PVC	PVDF (Kynar®)	Buna N (Nitrile)	EPDM	Hypalon®	Kel-F®	Natural rubber	Neoprene	Silicone	Tygon®	Viton®	304 stainless steel	316 stainless steel	Aluminum	Brass	Bronze	Cast iron	Copper	Hastelloy C®	Titanium	Carbon graphite	Ceramic Al_2O_3	Ceramic magnet
Sodium Tetraborate	-	B	A	A	-	A[2]	A	A	-	-	-	A	A[2]	-	A	A	A	-	A	B	A	-	A	A[2]	A	C	-	A	-	B	-	-	A	-	-
Sodium Thiosulfate (hypo)	-	C[1]	A[2]	A	-	A[1]	A	B	D	A[2]	A	A	A[2]	A	B	A[2]	A	A	B	A[2]	A	-	A	A[2]	B	A	D	A[2]	C	D	A[2]	A	A	-	-
Sorghum	-	A	-	A	-	-	-	A	-	-	-	-	-	-	A	-	-	-	A	A	-	-	A	A	A	-	-	A	A	-	-	-	-	-	-
Soy Sauce	-	A	-	A	-	-	A	A	-	-	-	-	-	-	A	-	-	-	-	A	-	-	A	A	A	A	-	A	D	-	-	-	-	-	-
Stannic Chloride	-	C	A[2]	A	-	A[2]	A[1]	B[1]	A[1]	A	A	A	A[2]	A	A	A	C[1]	A	A	C[1]	B	-	A	D	D	D	-	A	D	-	B	A	A	A	-
Stannic Fluoborate	-	C	-	A	-	-	A	-	-	-	-	-	-	-	A	-	-	-	-	A	-	-	A	-	A	-	-	-	D	-	-	-	-	-	-
Stannous Chloride	-	-	A[2]	A	C	B[2]	A[2]	C[1]	-	A	A[1]	A	A[1]	A	A	C	A[1]	A	A	A[1]	B	A	A	C[2]	A[2]	D	-	A[1]	-	-	B	A	-	A	-
Starch	-	A	A	A	-	B	A[2]	A[1]	-	A[2]	-	A	A	-	A	A	A	A	A	A	-	-	A	A	A	A	-	-	C	-	-	-	A	A	A
Stearic Acid	-	A	B[2]	B	C	B[1]	A	A[2]	A[1]	A[2]	-	A	B[2]	A	B	B	C	-	-	B[1]	B	B	A[1]	B	A	B	D	B	C	D	B	A	A	-	-
Stoddard Solvent	B	A	C[1]	A	-	C[2]	D	A	A[2]	C	A	A	C[1]	A	A	D	-	A	D	C[1]	D	C	A	A	A	A	-	A	A	A	A	A	A	-	-
Styrene	-	A	D	A	D	-	A	A[1]	D	-	-	A	D	-	D	D	D	-	D	D	D	-	B	A	A	A	A	A	A	B	D	-	A	-	-
Sugar (Liquids)	B	A	-	A	-	-	A[2]	A[1]	-	A	-	A	-	-	A	A	A	-	A	A	A	B	A	A	A	A	-	A	-	A	A	-	A	-	-
Sulfate (Liquors)	-	D	B	A	-	A[2]	-	B[1]	-	A	-	A	B	A	A[2]	A	B	-	B	B	B	-	A[1]	B	B	D	-	B	C	D	B	-	A	-	-
Sulfur Chloride	-	D	C[1]	C	-	C[1]	A	A[1]	-	C[1]	-	A	C[1]	A[1]	D	D	-	A	D	D	C	C	A	D	D	D	D	B	D	B	A	D	D	-	-
Sulfur Dioxide	D	B	A[2]	A[1]	C	B[1]	A	C[1]	-	A[1]	A	A	A[1]	A	D	A[2]	C	A	-	B	B	C	A	D	A[1]	B	D	B	-	B	C	A	A	-	-
Sulfur Dioxide (dry)	-	B	A[2]	A[1]	C	A[1]	A	B[1]	A[1]	A[1]	A	A	A[2]	A	D	A[2]	-	A	C	D	B	C	A	D	A	B	D	B	A	A	B	A	A	-	-
Sulfur Hexafluoride	-	-	-	-	-	B	-	B	-	-	-	-	B	-	B	B	B	-	D	A	B	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Sulfur Trioxide	-	-	A	A	-	-	D	D	-	C	-	A	A	-	D	C[2]	D	-	C	D	B	A	A	A	C	A	D	C	B	-	-	-	B	-	-
Sulfur Trioxide (dry)	-	D	A	A	-	C[1]	D	A[1]	-	D	-	A	A[1]	C[1]	D	C[1]	-	-	-	D	B	B	A	D	A	A	A	B	A	B	B	D	D	-	-
Sulfuric Acid (<10%)	B	D	A	A[1]	A	A[1]	A	C[1]	A[1]	A[2]	A	A	A[1]	A	A[1]	A	A	A	A[1]	B[2]	C	B	A	D	B	D	-	B	C	-	B[1]	D	A[1]	A	-
Sulfuric Acid (10-75%)	B	D	A	A[1]	-	A[1]	A	D	B[1]	A[1]	A	A	A[1]	A	B[1]	B[2]	B	A	C	B[1]	D	-	A[2]	D	D	D	-	B	D	-	B[1]	D	A[1]	A	-
Sulfuric Acid (75-100%)	-	-	C	C[1]	C	B[1]	A	D	D	C[1]	A[1]	A	D	A	C	B[1]	C	A	D	D	D	D	A[1]	C	D	D	-	B	D	D	B[1]	D	C[1]	A	A
Sulfuric Acid (cold concentrated)	-	-	D	D	B	C	A	D	-	A[2]	A[1]	A	D	A	D	C	C	A	D	D	D	D	B	C	B	B	-	B	D	-	A[1]	D	D	-	-
Sulfuric Acid (hot concentrated)	-	-	D	D	-	D	D	D	D	D	D	A	D	C	D	D	D	A	D	D	D	D	A[2]	D	C	D	-	B	D	-	D	D	D	A	-
Sulfurous Acid	-	C	A[2]	A	-	B[2]	A	D	-	A	A	A	A[2]	A	B[1]	B	A	A	B	C	D	B	A	B[1]	B	B[1]	-	B	D	D	B	A	A	-	-
Sulfuryl Chloride	-	A	-	A	-	-	-	-	-	-	-	A	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Tallow	-	A	-	A	-	C	A	A[1]	-	A[2]	-	A	-	-	A	A	C	-	-	B	-	-	A	A	A	A	-	-	-	-	-	-	A	-	-
Tannic Acid	-	B	A[1]	A	A	B[2]	A[2]	C[1]	C	A	A	A	A[1]	B	A	A	A	A	A	A	B	B	A	B[1]	A	C	B	B	C	A	B[1]	A	A	A	A
Tanning Liquors	-	B	A[1]	A	-	A[1]	A[2]	A[1]	-	A[1]	-	A	A[1]	-	B[1]	B	B	-	C	A	B	B	A	A[2]	A[2]	A	-	A[2]	-	-	B	A	A	-	-
Tartaric Acid	-	B	A[1]	A	C	A[1]	A[1]	B[2]	-	A	A	A	A[1]	B	A	B	A	A[2]	A	A[2]	A	B	A	C[2]	C[2]	B[1]	D	B[1]	C	A	B	A[1]	A	A	A
Tetrachloroethane	-	A	C	A	-	-	D	C[1]	-	C	-	A	C	A	D	D	D	A	D	D	D	-	A	B	A	C	-	-	A	A	A	A	A	-	-
Tetrachloroethylene	-	A	D	-	-	B	D	A[1]	D	D	-	A	D	-	D	D	D	A	D	D	D	-	A	-	A	-	-	-	A	A	-	-	A	-	-
Tetrahydrofuran	-	A	D	A	B	C[1]	D	A	D	C[2]	A	A	D	B[1]	D	D	D	A[1]	D	D	D	-	D	A	A	-	-	A	-	-	A	B	A	A	-
Tin Salts	-	-	-	-	-	-	-	-	-	A	-	A	A	A	A	B	A	-	A	-	B	A	A	-	D	D	-	-	-	-	C	A	-	-	-
Toluene (Toluol)	D	C[1]	D	B[1]	B	C[1]	D	A[1]	D	C[1]	A	A	D	A[1]	D	D	D	B[2]	D	D	D	D	C	A	A	A	A	A	A	A	A	A	A	A	A
Tomato Juice	B	B	-	A	-	A[1]	A	A[1]	A[1]	A	A	A	A	A	A	A	-	A	-	A	-	-	A	A	A	A	-	A	-	-	-	-	A	-	-
Trichloroacetic Acid	-	-	-	D	-	A	-	C	D	A	A	A	B	B	-	B	-	A	C	D	D	C	C	D	C	D	-	-	D	D	B	D	A	A	-
Trichloroethane	-	A	-	A	-	-	D	C[1]	D	C	-	A	C	A	D	D	D	A	D	D	D	-	A	B	B	D	-	A	B	-	A	A	A	-	-
Trichloroethylene	D	D	D	C[1]	C	D	D	C[1]	-	C[1]	A[1]	A	D	B	D	D	D	A	D	D	D	-	A	B	B	D	-	B	C	A[1]	A	A	A	A	A
Trichloropropane	D	A	-	A	-	-	D	-	-	-	-	A[1]	-	-	D	-	-	A	D	A	-	D	A	A	A	D	-	A	A	A	A	-	-	-	-
Tricresylphosphate	B	C	D	A	-	B[1]	A	A[2]	-	A[1]	-	A	D	D	D	A	D	-	B	C	C	D	A[2]	B	B	D	-	A[2]	B	B	A	B	A	D	-
Triethylamine	-	D	A	A	-	-	B	A[1]	-	D	-	A	B	A[2]	C	A	-	A	B	A	-	A	D	A	A	-	-	-	A	A[1]	-	-	A	B	-
Trisodium Phosphate	B[1]	A	A	A	A	A	A	A	-	A	A	A	A	A	A	A	-	-	A	A	A	A	A	B	B	D	-	A	-	B[1]	A	-	A	-	-
Turpentine	D	A[2]	A	B	-	D	D	B	D	D	A	A	D	A	-	D	D	A	D	D	D	B	A	A	A	A	D	A	-	B	B	B	A	A	-
Urea	B	A	A	-	-	A	A	A	D	A	A	A	D	A	B	A	-	-	-	B	B	B	A	B	B	B	-	B	-	-	B	A	A	B	-
Uric Acid	-	-	-	-	-	B	-	A	-	-	-	A	A	-	-	-	-	-	-	A	-	A	-	B	B	D	-	B	D	A	B	A	A	D	-
Urine	-	A	A	A	-	A[2]	A[2]	B	-	A	-	A[1]	A	A	A[1]	A[1]	-	-	D	D	-	-	A[1]	A	A	B	-	A	A	-	-	-	A	-	-
Varnish	-	A	-	A	-	A	D	A	-	A	-	A	D	-	B	D	D	A	D	D	D	D	A	A	A	A	A	-	C	B	A	-	A	-	-
Vegetable Juice	B	A	-	A	-	-	A	A	-	-	-	A	-	-	A[2]	A	-	-	-	-	B	A	A	A	A	D	A	A	D	A	-	-	-	A	-
Vinegar	A	B	A	A	-	A	A[1]	A	A[2]	A	A	A	B	B	B	A	A	A	B	B	A	A[1]	A	A	A	D	D	A	D	B	A	A	A	A	A
Vinyl Acetate	-	-	D	A[1]	-	A	-	-	-	B[1]	-	A[2]	D	A[2]	D	B[2]	A[2]	-	D	D	D	D	A[1]	B	B	A[1]	-	-	B	B	-	-	A[2]	B	-
Vinyl Chloride	D	-	D	-	-	-	-	A[1]	-	-	-	A[2]	D	B[1]	D	C	-	-	C	D	-	D	A[1]	B[2]	A[1]	B[1]	-	A[2]	B	B	A[2]	A	A[2]	A	-
Water, Deionized	-	-	A	A[2]	-	-	A[2]	A[1]	-	A[2]	A	A[2]	A[2]	A[2]	A[1]	A[1]	A[2]	A[1]	A	A	-	A[2]	A[1]	A[1]	A[2]	A[2]	A	-	D	B	A[2]	A[2]	A[2]	B	-
Water, Acid, Mine	B	A[1]	A	A	-	A[2]	-	A	B[2]	A	A	A	B	A	A	A	-	A	B	C	B	-	A	B	B	D	D	A	D	D	A	A	A	A	-
Water, Distilled	B	B	A	A	-	A[2]	A	A[1]	A[2]	A	A	A	A[2]	A	A	A	-	A	A	A	C	B	A	A	A	A	A	A	D	B	A	A	A	-	-
Water, Fresh	A	A[2]	A	A	A	A[2]	A	A[1]	A[2]	A	A	A	B	A	A	A	-	A	A	A	B	B	A	A	A	B	D	A[1]	D	B	A	A	A	A	-
Water, Salt	-	A	A	A	A	A[2]	A	A[2]	A[2]	A	A	A	B	A	A	A	-	A	A	A	B	B	A	B	B	B	D	A	D	B	A	A	A	B	-
Weed Killers	-	A	-	A	-	-	-	A	-	-	-	-	-	-	A	-	-	-	-	C	A	-	A	A	A	D	-	-	-	-	-	-	-	B	-
Whey	-	A	-	A	-	-	-	-	-	-	-	A	-	-	A	-	-	-	-	-	-	-	A	A	A	B	-	-	-	-	-	-	-	-	-
Whiskey & Wines	C	A	A[2]	B	-	C	A[2]	A[1]	A[1]	A	-	A	A[2]	A	A	A	A	A	A	C	A	C	A	A	A	C[1]	B	A	D	B	-	A	A	A	A
White Liquor (Pulp Mill)	-	D	A	A	-	A[2]	A[1]	A[1]	-	A[1]	-	A	A[2]	A[1]	A	-	-	-	-	A	A	-	A	A	A	B	B	A	C	-	A	-	A	-	-
White Water (Paper Mill)	-	B	-	A	-	-	D	A	-	A	-	-	A	-	-	-	-	-	-	A	-	-	A	A	A	-	-	-	A	-	-	-	-	-	-
Xylene	D	A	D	A	B	B	B	A[2]	D	B	A	A	D	A	D	D	D	A	D	D	D	D	D	B	B	A[1]	A	A	B	A	A	A	A	A	-
Zinc Chloride	A	C	A	A	A	A[1]	A[1]	A	A[2]	A	A	A	B	A	A	A	A	A	A	A	B	A	A	B	B	D	D	B[1]	D	C	B	A[1]	A	D	-
Zinc Hydrosulfite	A	C	-	A	-	-	A	A	-	-	A	A	-	-	A	A	-	-	-	A	-	-	-	A	A	D	-	-	D	B	-	-	-	-	-
Zinc Sulfate	A	C	A	A	-	A[2]	A[1]	A	A[2]	A	A	A	A[2]	A	A	A	A	A	B	A	A	A	A	B[1]	A	D	B[2]	B	D	B[1]	A[2]	A[2]	A	D	A

Delrin, Hypalon, Hytrel, Teflon, Viton—
Reg TM E. I. du Pont de Nemours & Co.
Hastelloy C—Reg TM Cabot Corporation

Kel-F—Reg TM 3M Co.
Kynar—Reg TM Elf Atochem North America
NORYL—Reg TM General Electric Co.

Ryton—Reg TM Phillips Petroleum Co.
Tygon—Reg TM Norton Co.

APPENDIX D.4

Regulations Pertaining to LFG Control from the RCRA Standard - Subtitle D

§ 257.3-8 Safety.

(a) *Explosive gases.* The concentration of explosive gases generated by the facility or practice shall not exceed:

(1) Twenty-five percent (25%) of the lower explosive limit for the gases in facility structures (excluding gas control and recovery system components); and

(2) The lower explosive limit for the gases at the property boundary.

(b) Fires. A facility or practice shall not pose a hazard to the safety of personnel or property from fires. This may be accomplished through compliance with § 257.3-7 and through periodic application of cover material or other techniques as appropriate. . . .

(e) As used in this section: . . .

(3) *Explosive gas* means methane (CH_4).

(4) Facility structures means any buildings or sheds or facility or drainage lines on the facility.

(5) *Lower explosive limit* means the lowest percent by volume of a mixture of explosive gases which will propagate a flame in air at 25 deg. C and atmospheric pressure. . . .

[Note the following applies to all MSWLF units that receive waste on or after October 9, 1993.]

§ 258.23 Explosive gases control.

(a) Owners and operators of all MSWLF units must ensure that:

(1) The concentration of methane gas generated by the facility does not exceed 25 percent of the lower explosive limit for methane in facility structures (excluding gas control or recovery system components); and

(2) The concentration of methane gas does not exceed the lower explosive limit for methane at the facility property boundary.

(b) Owners and operators of all MSWLF units must implement a routine methane monitoring program to ensure that the standards of paragraph (a) of this section are met.

(1) The type and frequency of monitoring must be determined based on the following factors:

(i) Soil conditions;
(ii) The hydrogeologic conditions surrounding the facility;
(iii) The hydraulic conditions surrounding the facility; and
(iv) The location of facility structures and property boundaries.

(2) The minimum frequency of monitoring shall be quarterly.

(c) If methane gas levels exceeding the limits specified in paragraph (a) of this section are detected, the owner or operator must:

(1) Immediately take all necessary steps to ensure protection of human health and notify the State Director;

(2) Within seven days of detection, place in the operating record the methane gas levels detected and description of steps taken to protect human health; and

(3) Within 60 days of detection, implement a remediation plan for the methane gas releases, place a copy of the plan in the operating record, and notify the State Director that the plan has been implemented. The plan shall describe the nature and extent of the problem and the proposed remedy.

(4) The Director of an approved State may establish alternative schedules for demonstrating compliance with paragraphs (c) (2) and (3) of this section.
[Part 258.28 Explosive gases control. continued]

(d) For purposes of this section, *lower explosive limit* means the lowest percent by volume of a mixture of explosive gases in air that will propagate a flame at 25 deg. C and atmospheric pressure.

§ 258.24 Air criteria.

(a) Owners and operators of all MSWLFs must ensure that the units not violate any applicable requirements developed under a State Implementation Plan (SIP) approved or promulgated by the Administrator pursuant to section 110 of the Clean Air Act, as amended.

(b) Open burning of solid waste except the infrequent burning agricultural wastes, silvicultural wastes, landclearing debris diseased trees, or debris from emergency cleanup operations, is prohibited at all MSWLF units.

258.28 Liquids restrictions.

(a) Bulk or noncontainerized liquid waste may not be placed in MSWLF units unless:

(1) the waste is household waste other than septic waste; or

(2) The waste is leachate or gas condensate derived from the MSWLF unit and the MSWLF unit, whether it is a new or existing MSWLF, or lateral expansion, is designed with a composite liner and leachate collection system as described in § 258.40(a)(2) of this part. The owner or operator must place the demonstration in the operating record and notify the State Director that it has been placed in the operating record.

(b) Containers holding liquid waste may not be placed in a MSWLF unit unless:

(1) The container is a small container similar in size to that is normally found in household waste;

(2) The container is designed to hold liquids for use other than storage; or

(3) The waste is household waste.
[Part 258.28 Liquids restrictions. continued]

(c) For purposes of this section:

(1) *Liquid waste* means any waste material that is determined to contain "free liquids" as defined by Method 9095 (Paint Filter Liquids Test), as described in "Test Methods for Evaluating Solid Wastes, Physical/Chemical Methods" (EPA Pub. No. SW-846).

(2) *Gas condensate* means the liquid generated as a result of gas recovery process(es) at the MSWLF unit.

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Source: 40 CFR Parts 257 and 258.

GLOSSARY

Absorption - *Chem./Mech. Process* The uptake and retention of a substance into a solid or liquid.

Active landfill - *Solid Waste* A landfill which is still receiving waste or one that has not completed closure.

Adsorption - *Chem./Mech. Process* The uptake and retention of a substance upon a surface.

Active collection system - *LFG.* A LFG extraction and collection piping system which is placed under active vacuum extraction.

Aerobe - *Biology.* Bacteriological organism that can live and grow only in the presence of free oxygen (as distinguished from molecular oxygen). An organism which requires free oxygen.

Aerobic - *Biol.* Characterized by the presence of free oxygen. Refers to a condition in which the aerobic class of bacteria are active.

Alkanes - *Chem.* A group of straight chain, saturated hydrocarbons containing no double or triple bonds; includes methane.

Anaerobe - *Biol.* An organism that can grow in the absence or near absence of oxygen. There are two general types: facultative anaerobes can utilize free oxygen; obligate anaerobes are poisoned by it.

Anaerobic - *Biol.* Generally (loosely) considered bacteria living in a condition in which oxygen is absent. Anaerobic bacteria (anaerobes) do not require the respiration of oxygen to liberate energy. Refers to a condition in which the anaerobic class of bacteria are active.

Anoxic - *Biol.* Lacking oxygen.

Aquifer - *Civil Eng./Hydrology* Water bearing strata of soil or bedrock.

Asphyxiation - *Safety/Industrial Hygiene.* Akin to suffocation. A physical or medical human condition caused by insufficient oxygen for breathing. May lead to permanent physical damage or death.

Biogenic - *Biol.* Derived from action of bacteria on organic matter.

CAA - *Regulatory.* Clean Air Act.

Calibrate - *Electronics/Analytical Instrumentation.* To adjust precisely based on reference standards.

Carbon - *Chemistry.* Carbon is a basic element and building block of all hydrocarbons. Carbon along with hydrogen are also the basic elements that make up methane. Carbon is the sixth element of the Periodic Table of chemical elements. Atomic No. is 6; Atomic Weight is 12.

Carbon dioxide - *Chemistry.* A gas made up of two atoms of oxygen and one of carbon. Atomic weight is 44. Carbon dioxide is produced through both aerobic and anaerobic decomposition processes. Chemical notation: CO_2.

Carbon monoxide - *Chemistry.* A gas made up of one atoms of oxygen and one of carbon. Atomic weight is 28. Chemical notation: CO.

Catalyst - *Chem.* A substance which speeds up a chemical reaction (such as oxidation) without itself undergoing any permanent change.

Cell - *Solid Waste* A compartment of waste in the landfill enclosed by intermediate cover.

CERCLA - *Regulatory.* See Comprehensive Environmental Response, Compensation and Liability Act.

CH_4 - *Chemistry.* Chemical notation for methane.

Chromatograph - *Chemistry/Analytical Instrumentation.* A device used to separate chemical mixtures. Usually applying a principle of adsorption or partitioning to separate compounds so that they may be measured using a detector.

Closure Plan - *Solid Waste* A plan which specifies how a landfill will be closed specifying what measures are to be taken to secure the site and protect the environment from impacts by the waste.

CO_2 - *Chemistry.* Chemical notation for carbon dioxide.

Combustible - *Chemistry/Physics/Fire Science.* Common meaning: A material that will burn

Compaction - *Solid Waste* Refers to the process of compressing or increasing the density of landfilled waste to conserve landfill capacity.

Composting - *Civil Engineering.* A process of decomposing MSW aerobically my maintaining aerobic conditions. The body of knowledge developed in the study of composting is helpful in understanding the process decomposition under aerobic conditions. By overpulling a LFG extraction well the volume of waste around the well is inadvertently "composted" sometimes with destructive results.

Compound (Chemical) - *Chemistry.* In chemistry refers to a formulation of more than one or several chemicals or elements of definite proportions independent of how the compound is formed or produced. In popular usage, synonymous with chemical.

Comprehensive Environmental Response, Compensation and Liability Act - *Regulatory.* An Act passed by congress in 1980 to address the control and cleanup of hazardous waste sites. Sometimes referred to commonly as Superfund.

Condensate - *LFG/Mechanical Process Engineering.* A liquid formed by the cooling of a gas as certain portions transition from a gaseous state to a liquid as a result of a reduction of the gas temperature. In the case of LFG, LFG condensate collected in the LFG collection system is mostly water with some trace hydrocarbons present.

Control - *LFG* The extraction, processing and disposal or destruction of LFG to reduce and mitigate the environmental impacts of LFG migration and emission.

Controlled Tip - *Civil Eng.* A British Commonwealth term for sanitary landfill.

Cover - *Solid Waste* Material, usually soil, used to cover waste daily during the landfilling process.

Decomposition - *Biol.* Bacteriological decay. The (bio-chemical) breakdown of MSW in to simpler chemical structures aided by naturally occurring bacteria. Decomposition may occur by either aerobic or anaerobic bacteriological action. Chemical reactions also play and important role in this process.

Density - *Physics* Bulk density. The mass per unit volume. In a landfill context the ratio of the combined mass of fill and cover material to unit volume.

Detector - *Electronics/Analytical Instrumentation.* An instrument used to detect and measured chemical compounds by application of a specific scientific principal.

Differential - *Mathematics/Physics.* A term from the calculus referring to an incremental change in an independent variable x, where y, a dependent variable is a function of x.

As in: y = function of (x)

A change in variable x may produce a corresponding change in variable y.

Differential Pressure - *Physics/Mech. Process Eng.* A difference in pressure between two points. Indicative of pressure drop across a section of piping, orifice, vessel, etc. Differential pressure is commonly measured in inches of water column and pounds per square inch (psi).

Differential Settlement - *Civil Eng.* Changes or differences in original surface or elevations due to settlement.

Differential Temperature - *Mech. Process Eng.* Difference in temperature between two points.

Discharge - *Environ. Eng.* The release of waste to the environment (i.e., the air, water or soil).

Effluent - *Civil/Mech. Process Eng.* The medium discharged from a process. Examples might be LFG vented from carbon canisters or liquid released from a wastewater treatment system.

Electrolyte - *Chem.* A substance which undergoes a partial or complete dissociation into ions in solution, and acts as a conductor of electricity. Commonly employed in batteries and fuel cells such as an oxygen sensor.

Emission - *Environ. Eng.* Release or discharge to the environment. Usually in reference to a gas or odor released into the air.

Evapotranspiration - *Civil Eng.* The total water transferred to the atmosphere by evaporation from the soil surface and transpiration by plants. Evapotranspiration can play an important role in water balance at landfills that do not have geo-synthetic membrane caps.

"Existing" landfill - *Regulatory* From the NSPS/EG. An "existing" landfill is defined as an MSW landfills that satisfy both of the following conditions: 1) The construction, modification, or reconstruction of the landfill began before May 30, 1991; and 2) The landfill received waste on or after November 8, 1987 or has additional capacity which may be filled in the future.

Extraction - *LFG.* The collection of LFG under vacuum.

Facultative - *Biol.* Able but not obliged to function in the way specified: a facultative anaerobe can grow in (and perhaps use) free oxygen, but also survives and grows in its absence.

Fill - *Solid Waste/Civil Eng./Geotechnical* Refers to waste material placed in a landfill. In a general civil engineering context, may also refer to engineered and compacted soil fill in general civil construction.

Final Cover - *Solid Waste* Refers to cover material incorporated into the final closure cap.

Flow - *Physics/Mechanical Process Eng.* The movement of material. Generally in this MOP refers to volumetric flow of LFG.

Flux - *Chemistry/Physics.* Transfer of material (e.g., LFG) or condition (temperature) across a boundary. An example might be movement of LFG from the waste mass through the surface soil cover and into the atmosphere. Sometimes analogous to flow (gas emissions, heat, etc.)

Gage pressure (psig) - *Physics/Mech. Process Eng.* A pressure reading measured from a pressure gage. Refers to a pressure referenced to atmospheric (barometric) pressure above atmospheric is a positive value and pressure below atmospheric is a negative value.

Ground water - *Civil Eng./Hydrology* Water present in soil and bedrock.

Ground water monitoring - *Environ./Civil Eng.* The monitoring of basic indicator parameters (e.g., pH, TDS, etc.) and for priority pollutants and other substances.

Ground water monitoring wells - *Environ./Civil Eng.* Wells used to monitor ground water.

Head - *Civil/Mech. Eng.* Pressure often used in the context of pressure exerted by a standing fluid.

Heterogeneous - *Chemistry/Physics.* A characteristic describing by dissimilar or diverse ingredients or constituents. A common, virtually universal characteristic of MSW landfills. Opposite of homogeneous.

Homogeneous - *Chemistry/Physics.* A characteristic describing uniform make up or composition. Opposite of heterogeneous.

Hot spots - *LFG.* Refers to areas of detected methane or hydrocarbon emissions at the surface of a landfill. Also may refer to areas of subsurface combustion or unusually active methane generation.

Hydrogen - *Chemistry.* Hydrogen is frequently found in LFG at low levels, less than one percent to several percent. All hydrocarbons contain hydrogen as well as carbon. Hydrogen is highly flammable. The explosive range is 4 to 74 percent in air. Hydrogen can generate sufficient static electricity to cause its own auto ignition.

Hydrogen sulfide - *Chemistry* A gas made up of two atoms of hydrogen and one of sulfur (H_2S). A dangerous toxic gas that can be fatal at relatively low levels. Calcium sulfate (gypsum) , a common component in construction debris such as drywall material, may readily react in an acidic environment common to MSW landfills to produce hydrogen sulfide. Hydrogen sulfide reacts with iron to cause iron sulfide.

Hydrogeology - *Hydrogeology* The study of water in rock and soil.

Hysteresis - *Mech. Eng.* Failure to return to original condition after adjustment.

Infiltration - *Civil Eng.* Pass, penetrate or permeate. The entry of water into soil or landfill usually as rain or melting snow. Usually in reference to air or liquid *infiltration.*

Landfill - *Civil Eng.* A land based depository of waste, or debris. For the purposes of this MOP unless explicitly stated otherwise refers to a MSW landfill (as opposed to a hazardous waste landfill). A landfill may be uncontrolled or poorly controlled , often referred to as a "dump" site, or a modern engineered sanitary landfill operated in accordance with modern conventions, standards, and regulations.

Leachate - *Solid Waste* As water infiltrates and moves through the waste mass it extracts or "leaches" trace materials and contaminants from the waste. The resultant liquid is known as leachate.

LFG - *LFG.* Landfill gas. LFG consists principally of methane, carbon dioxide, oxygen and nitrogen with some trace gases.

Loop Seal - *Mech. Process Eng.* Typically a U-shaped liquid trap often used in refinery, chemical process and waste water treatment industries to seal low pressure within a container or to isolate instrumentation. In LFG often used in gas condensate traps sometimes known as "J", "P" or bucket traps. Also known as a liquid seal.

Methane - *Chemistry.* Methane is the principal component of concern in LFG. Methane consists of one carbon atom and four hydrogen atoms. Explosive limits of methane if 5-15% in air.

Migration - *LFG.* The movement of LFG from the landfill to the surrounding soils

Municipal solid waste (MSW) - *Civil Eng.* Solid waste derived from residential household and commercial sources. Solid waste consists of in a large part of wood and paper products with garbage (food and vegetable matter), construction , inerts (glass, metal, plastics, ash, etc.) May also include construction and demolition debris which may also be considered a separate category of waste for characterization purposes.

Native soil - *Civil Eng.* refers to natural or undisturbed soil (not containing waste) usually surrounding the landfill.

"New" landfill - *Regulatory* From the NSPS/EG. A "new" landfill is defined as each MSW landfill that started construction (including reconstruction) or modification, or began initial waste acceptance on or began initial waste acceptance on or after May 30, 1991.

Nitrogen - *Chemistry.* Nitrogen is typically introduced into LFG by pulling air into the landfill. While oxygen may be converted a nitrogen residual typically remains as an indicator of the extent of extraction well overpull or stress. It is thus one of the key parameters along with methane that indicate the state of anaerobic productivity of the waste mass. Air contains 79.1 percent nitrogen. Nitrogen is the seventh element of the Periodic Table of chemical elements. Atomic No. is 7; Atomic Weight is 14.

NMOC - *Regulatory.* Non-methane organic compound. All organic compounds other than methane found in landfills or LFG. Usually a reference to the volatile fraction.

NSPS - *Regulatory.* New Source Performance Standard. In the solid waste context, refers to an air pollution control regulation promulgated under the authority of the Clean Air Act which regulates emissions to the atmosphere (i.e., LFG and its methane and NMOC constituents).

Obligate - *Biol.* (Re: bacteria) Obliged to function in the way specified: an obligate anaerobe cannot grow (and may not survive) in the presence of free oxygen.

O_2 - *Chemistry.* Chemical notation for oxygen gas.

Oxygen - *Chemistry.* Oxygen is typically introduced into LFG by pulling air into the landfill. Oxygen is required to support most carbon based life. Oxygen may be utilized as free oxygen or as molecular oxygen. Oxygen poisons (i.e., kills) certain anaerobic bacteria that produce methane and transforms the environment to an aerobic one. Air contains 20.8 percent oxygen. Oxygen is the eighth element of the Periodic Table of chemical elements. Atomic No. is 8; Atomic Weight is 16. All hydrocarbons contain hydrogen as well as carbon.

Oxygen deficiency - *Safety/Ind. Hygiene.* A lack of sufficient oxygen to support life. A concentration of oxygen below 19.5 percent is considered legally deficient and hazardous.

Overpull - *LFG.* A term that refers to the act or condition of extracting too much LFG from an extraction well or wellfield and upsetting the balance or damaging the normal anaerobic state of the landfill.

Passive control - *LFG* Control of LFG by non-active (or mechanical) means

Partial Pressure - *Physics.* Refers to the pressure of an individual gas constituent as part of a mixture.

Parts-per-million - *Chemistry/Physics.* Volume relationships of two components are sometimes stated in parts per million (ppm). Mathematically one part per million (1 ppm) is 0.000001.

Pitot Tube - *Aero. and Mech. Eng.* Also known as pitot-static tube. A metal tube which is used to measure flow. It is configured with two orifices. One port is oriented into the flow stream and measures the sum of the velocity head and static head, or "total" pressure in the flow stream. The other port is oriented perpendicular or sometimes pointing away from the direction of flow and measures only the static component. By taking a differential pressure reading, the static component is subtracted out, leaving only the velocity head component of the total pressure. This datum can be used in flow measurement calculations to determine the volumetric or mass flow of a fluid in motion in piping or duct.

Pressure - *Physics.* Pressure is a measure of force per square unit of surface area. Pressure is referred to in terms of absolute pressure or gage pressure. In the Process Industries pressure is usually measured in units of pounds per square inch. In the Metric System pressure is measured in units of Newtons per square meter, millimeters of water and millimeters of mercury (torr). Standard atmospheric pressure is given as 14.7 psia at sea level at ___ deg. C.

Pressure Drop - *Mech. Process Eng.* A drop or reduction in pressure due to friction loss in a piping or process system between two points in the system, e.g., across a section of piping, orifice, vessel, filter, flame arrester, etc.

Resistor - *Electronics.* A common component found electrical circuits which presents a resistance or impediment to the flow of electrical current and thus acts as a load performing work by converts current to waste heat. A common material used for resistors is the graphite form of carbon. More complex kinds of resistors such as perform useful work such as a light bulb which gives off light.

ROG - *Regulatory.* Reactive organic gases. Refers to that fraction of VOCs that are chemically or photo-reactive and contribute to photo-chemical smog and other forms of air pollution. Generally a subset of VOCs. Many ROGs are used as industrial solvents. ROGs are found in trace quantities in LFG.

Structure - *Regulatory.* A construction such as building, vault, manhole, culvert pipe, storage shed, etc. in which LFG may accumulate. A structure may be occupied or unoccupied. Originally defined in an early preamble to the RCRA Act with respect to LFG and safety.

Subtitle C - *Regulatory.* Federal Regulations (40 CFR Parts ____) pertaining to hazardous and industrial waste and materials. See **Solid Waste.**

Subtitle D - *Regulatory.* Federal Regulations (40 CFR Parts ____ and specifically Parts 257 and 258) pertaining to municipal solid waste. See **Solid Waste.**

Superfund - *Regulatory.* A fund established by Congress through the CERCLA act for the clean up of hazardous waste sites. As slang, refers to sites (as Superfund sites) that undergo regulatory action and cleanup pursuant to CERCLA.

Temperature - *Physics.* A measurement of heat.

Vacuum - *Physics.* Pressure less than ambient atmospheric pressure. Negative gage pressure.

VOC - *Regulatory.* Volatile organic compound. Organic compounds that are volatile or in a gaseous state at ambient temperature (typically given for this purpose as 80 degrees). Many VOCs are found in LFG in trace quantities. Many are used industrially as solvents. Some are considered as priority pollutants and are of concern as air and ground water pollutants.

Waste mass - *Civil Eng.* referring generally to the main body of waste placed in the municipal solid waste (MSW) landfill.

Wheatstone Bridge - *Electronics* A special type of basic electric circuit used in instrumentation, commonly with a meter movement, which uses two pairs of balanced resistors. The resistors may include sensors and a variable resistor to adjust or calibrate the circuit.

Principal references where used for the definitions are as follows:

Walker, Prof. Peter M. B. Chambers Science and Technology Dictionary. W & R Chambers Ltd. and Chambers University Press, Cambridge, England. 1988.

ACRONYMS

ABS - acrylonitrile butadiene-styrene

acfm - actual cubic feet per minute

ACGIH - American Conference of Governmental Industrial Hygienists

ANSI - American National Standards Institute

ASTM - American Society of Testing and Materials

ASME - American Society of Mechanical Engineers

BACT - Best Available Control Technology

BDT - Best Demonstrated Technology

BTU - British thermal unit

CAA - Clean Air Act

CAAA - Clean Air Act Amendments

CCS - catalytic combustion sensors

CERCLA - Comprehensive Environmental Response, Compensation, and Liability Act

cfm - cubic feet per minute

CFR - Code of Federal Regulations

CGA - combustible gas analyzer

CGA - Canadian Gas Association

CSA - Canadian Standards Association

DOT - Department of Transportation

ECD - electron-capture detector

EG - Emission Guidelines

FID - flame ionization detector

FPD -flame-photometric detector

FM - Factory Mutual

FRP - fiberglass reinforced piping

GAC - granulated activated charcoal

GC - gas chromatograph

GEP - good engineering practice

GFCI - ground fault current interrupter

HDPE - high density polyethylene

LCD - liquid crystal display

LCS - leachate collection system

LED - light emitting diode

LEL - lower explosive limit

LFG - landfill gas

LFGCS - landfill gas control system

LPG - liquefied petroleum gas

MCC - motor control center

MS - mass spectrometer

MSW - municipal solid waste

MSWLF - municipal solid waste landfill

N.D. - non detect or none detected

NEC - National Electrical Code

NFPA - National Fire Protection Association

NIOSH - National Institute of Occupational Safety and Health

NMOC - non-methane organic compounds

NREL - National Renewable Energy Lab

NSC - National Standards of Canada

NSPS - New Source Performance Standard

NTIS - National Technical Information Service

O&M - operation and maintenance

OS&Y - operating stem and yoke

OSHA - Occupational Safety and Health Administration

OVA - organic vapor analyzer

P&ID - piping and instrumentation diagram

PID - photo-ionization detector

PLC - programmable logic controller

psia - pounds per square inch absolute

psig - pounds per square inch gage

PVC - polyvinyl chloride

RCRA - Resource Conservation and Recovery Act

R&O - rust and oxidation

ROG - reactive organic gases

SCBA - self-contained breathing apparatus

scfm - standard cubic feet per minute

SWANA - Solid Waste Association of North America

TCD - thermal conductivity detector

TNMHC - total non-methane hydrocarbons

TOC - total organic carbon

UEL - Upper explosive limit

USDOE - United States Department of Energy

USEPA - United States Environmental Protection Agency

UL - Underwriters Laboratories

UT -ultrasonic thickness

UV - ultraviolet light

VAC - volts alternating current

VDC - volts direct current

VOC - volatile organic compound

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BIBLIOGRAPHY

Bear, Jacob. *Dynamics of Fluids in Porous Media*. Dover Publications, Inc. New York, NY. 1972.

Chambers Biology Dictionary. Chambers Cambridge. 1989.

Chambers Science and Technology Dictionary. Chambers Cambridge. 1988.

Crowhurst, D. and Manchester, S.J., "The measurement of methane and other gases from the ground" - CIRA Report No. 131 Building Research Establishment, Garston, Watford, England. 1993.

EMCON Associates. *Methane Generation and Recovery from Landfills*. Ann Arbor Science. Ann Arbor, MI. 1980.

EMCON Associates. "State of the Art of Methane Gas Enhancement in Landfills (ANL/CN-SV-23)." Argonne National Laboratory. National Technical Information Service. Springfield, VA. June 1981.

"Landfill Gas Characterization". California Integrated Waste Management Board. Sacramento, CA. 1988.

Levett, Paul N., Anaerobic Bacteria, A Functional Biology, Open University Press, Philadelphia, PA. 1990.

Metcalf & Eddy. *Wastewater Engineering, Treatment, Disposal, Reuse*. 3rd Ed. McGraw-Hill, Inc. New York, NY. 1991.

North American Combustion Handbook, Third Edition, Vol. 1. 1986.

Operator's Handbook, Gulf Publishing Company, Houston, TX. 1961.

O'Leary, Philip R., Walsh, Patrick W., Ham, Robert K. "Managing Solid Waste". Scientific American. Volume 259, Number 6, Pages 36 - 42. 1988.

Rice, Frederick C., et al, "SWANA Landfill Gas Course," Solid Waste Association of North America, Silver Springs, MD 1993.

Solid Waste Association of North America. "Press Release: USEPA Signs off On NSPS for Landfill Gas Emissions," Solid Waste Association of North America, Silver Spring, Maryland. March 1, 1996.

Tchobanoglous, G.; Theisen, Hillary; Vigil, Samuel A. *Integrated Solid Waste Management - Engineering Principles and Management Issues.* McGraw-Hill, Inc. New Yori, NY. 1993.

Tchobanoglous, George and Burton, Frank L. Metcalf and Eddy - Wastewater Engineering - Treatment, Disposal, Reuse, 3rd Ed., McGraw-Hill, New York, NY. 1991.

Walker, Prof. Peter M. B. Chambers Science and Technology Dictionary, W & R Chambers Ltd. and Chambers University Press, Cambridge, England. 1988.

Wheeler, James H. "Impact of the USEPA MSW NSPS on Landfill Gas Collection and Control System Design and Operation," Unpublished paper. 1992 and 1995.

Wheeler, James H. Landfill Gas Engineering Design Guide, Unpublished book. October 1993.

Wheeler, James H. Landfill Gas Engineering Design Manual, Unpublished book. November 1993.

REFERENCES AND RECOMMENDED PUBLICATONS

Addison-Wesley Publishing Company. *Introduction to Fluid Mechanics*. 1966.

American Gas Association. *A.G.A. Plastic Pipe Manual For Gas Service*. Arlington, VA. 1989.

American Petroleum Institute. *American Petroleum Institute Recommended Practice 500 CRP 500. Recommended Practice for Classification of Locations for Electrical Installations at Petroleum Facilities."* American Petroleum Institute. Washington, DC. June 1991.

American Society for Testing and Materials. *1992 Annual Book of ASTM Standards, Section 4, Construction.* American Society for Testing and Materials. Philadelphia, PA. 1992.

American Society for Testing and Materials. *1992 Annual Book of ASTM Standards, Section 8, Plastics.* American Society for Testing and Materials. Philadelphia, PA. 1992.

ASHRAE Handbook 1985 Fundamentals. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, GA. 1985.

Asimov, Isaac. The World of Carbon. Collier Macmillan Publishers. London. 1979.

Avallone, Eugene A., Baumeister III, Theodore. *Marks' Standard Handbook for Mechanical Engineers*. 9th Ed. McGraw-Hill Book Company. New York, NY. 1986.

Bagchi, Amalendu. *Design, Construction & Monitoring of Sanitary Landfill.* John Wiley and Sons. New York, NY. 1990.

Bloch, Heinz P. *Practical Machinery - Management for Process Plants. Volume 1 Improving Machinery Reliability*, Gulf Publishing Company, Houston, TX. 1982.

Brater, Ernest F.; King, Horace W. *Handbook of Hydraulics.* 6th Ed. McGraw-Hill Book Co. New York, NY. 1976.

Benedict, Robert P. *Fundamentals of Pipe Flow.* John Wiley & Sons. New York, NY. 1980.

Benedict, Robert P. *Fundamentals of Temperature, Prressure, and Flow Measurements.* 2nd. Ed. John Wiley & Sons. New York, NY. 1977.

California Integrated Waste Management Board. "Procedural Guidance Manual for Sanitary Landfills, Volume I, Landfill Leachate Monitoring and Control Systems." Sacramento, CA. 1989.

REFERENCES AND RECOMMENDED PUBLICATONS

California Integrated Waste Management Board. "Procedural Guidance Manual for Sanitary Landfills, Volume II, Landfill Gas Monitoring and Control Systems." Sacramento, CA. 1989.

Cameron Hydraulic Data. Ingersoll-Rand. Woodcliff Lake, NJ. 1988.

Chemtrol. "Thermoplastic Piping Technical Manual." Nibco, Inc. Indianapolis, IN. 1991.

Cheremisinoff, Nicholas P.; Cheremisinoff, Paul N. *Compressors and Fans.* Prentice Hall. Englewood Cliffs, NJ. 1992.

Crane Co. *Flow of Fluids Through Valves, Fittings, and Pipe (Technical Paper No. 410).* Crane Co. Joliet, IL. 1988.

Crocker, Sabin; King, Reno C. *Piping Handbook.* 5th Ed. McGraw-Hill. New York, NY. 1967.

Datta-Barua, Ph.D., Lohit. *Natural Gas Measurement & Control.* McGraw-Hill, Inc. New York, NY. 1992.

Daugherty, Robert L.; Franzini, Joseph B. *Fluid Mechanics With Engineering Applications.* 7th Ed. McGraw-Hill Book Company. New York, NY. 1977.

Detector Tube Handbook, Air Investigations and technical gas analysis with Dräger Tubes. Lübeck. 1989.

Fan Engineering, *An Engineer's Handbook* on Fans and Their Applications. Eighth Edition. Buffalo Forge Company. Buffalo, NY. 1983.

Ham, Robert K. "Predicting Gas Generation From Landfills." Waste Age. Washington, DC. Nov. 1979.

Harrington Industrial Plastics, Inc. *Harrington's Engineering Handbook.* Chino, CA. 1990.

Ingersoll-Rand. *Gas Properties and Compressor Data.* Ingersoll-Rand. Washington, DC. 1981.

Kirk, Franklyn W., Rimboi, Nicholas R. *Instrumentation.* 3rd. Ed. American Technical Publishers, Inc. Alsip, IL. 1962. (paperback).

Lang, Robert, Herrera, Teresa, Chang, Daniel P.Y., Tchobanoglos, George. "Trace Organic Constituents in Landfill Gas". Department of Civil Engineering, UC Davis, CA. 1987.

REFERENCES AND RECOMMENDED PUBLICATONS

Loomis, A. W. *Compressed Air and Gas Data.* 3rd Ed. Ingersoll-Rand. Washington, DC. 1980.

Maslansky, Carol J., Maslansky, Steven P. *Air Monitoring Instrumentation.* Van Nostrand Reinhold. New York, NY. 1993. (paperback).

Miller, Richard W. *Flow Measurement Engineering Handbook.* 2nd. Ed. McGraw-Hill Publishing Company. New York, NY. 1977.

Nelson, Carl A., Millwrights and Mechanics Guide. Audel & Co. Indianapolis, NY. 1983.

Oberg, Erik; Jones, Franklin D.; Horton, Holbrook L.; Ryffel, Henry H, Ed. *Machinery's Handbook.* 23rd Ed. Industrial Press Inc. New York, NY. 1989.

Perry, Robert H.; Green, Don. *Perry's Chemical Engineers' Handbook.* 6th Ed. McGraw-Hill Book Company. New York, NY. 1984.

Phillips Driscopipe, Inc. "Systems Design." Phillips Driscopipe, Inc. Richardson, TX. 1991.

Reed, Richard J. *North American Combustion Handbook.* 3rd Edition. North American Mfg. Co. Cleveland, OH. 1988.

Reid, Robert C.; Prausnitz, John M.; Poling, Bruce E. *The Properties of Gases & Liquids.* 4th Ed. McGraw-Hill Book Company. New York, NY. 1987.

Sherwood, Daniel R., Whistance, Dennis J. *The "Piping Guide".* Syrntek Books Company, Inc. San Francisco, CA 9revised). 1980.

University of Wisconsin at Madison. "Courseware - Sanitary Landfill Design." University of Wisconsin. Madison, WI. 1992.

Urquhart, Leonard C., C.E., (Ed). *Civil Engineering Handbook.* 4th Ed. McGraw-Hill. New York, NY. 1959.

Vennard & Street Elementary Fluid Mechanics, Sixth Edition. John Wiley & Sons. 1982.

Wilkey, M.L.; Zimmerman, R.E.; Isaacson, H.R. "Methane From Landfills: Preliminary Assessment Workbook (ANL/CNSV-31)." Argonne National Laboratory. National Technical Information Service. Springfield, VA. June 1982.

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