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Effectiveness of Subsurface Treatment Technology at Alberta Sour Gas Plants

Phase I:

Assessment of Subsurface Contamination and Remediation at Alberta Sour Gas Plants

July, 1990

CANADIAN PETROLEUM ASSOCIATION

Report to
Canadian Petroleum Association
and
Environment Canada

Effectiveness of Subsurface Treatment Technology at Alberta Sour Gas Plants

Phase I:

Assessment of Subsurface Contamination and Remediation at Alberta Sour Gas Plants

By
PITEAU ENGINEERING LTD.
and
INTEGRATED ENVIRONMENTS LTD.

July, 1990

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EXECUTIVE SUMMARY

A study of subsurface contamination and remediation at Alberta sour gas plants was conducted. The study was based on groundwater monitoring reports from 54 sour gas plants submitted to Alberta Environment pursuant to the Clean Water Act, and soil sampling data from seven facilities, collected directly from plant operators.

For the purposes of this study, contamination was defined as "any chemical substance whose concentration exceeds background or which is not naturally occurring in the environment" (Environment Canada, 1984). A detailed set of procedural and numerical criteria for establishing the presence of contaminants in groundwater and soil are provided in the body of the report. The numerical criteria were especially designed for the study set, and were based on a systematic evaluation of available data. The scope of the report did not include the establishment of recommended clean-up criteria, and contamination does not imply the need for clean-up.

Data available in monitoring reports provided by Alberta Environment were insufficient for determination of the seriousness (need for clean-up) of the contamination situations identified. The degree of concern attached to a particular situation, and thus the perceived need for remedial action, is a function of several factors, including plant location, contaminant types, concentrations and transport rates, the projected fate of contaminants, and regulatory considerations. Much of this key information was not available in the reports on which this study was based.

The monitoring data provided by Alberta Environment were thoroughly reviewed, and contamination situations at each gas plant were identified and classified. The contamination situation classification (CSC) system developed for this study was based on three elements: source of contamination,, contaminant types, and hydrogeological zone of contamination. Determinations of source, type and zone were made only for those gas plants where sufficient data were available.

The quality and completeness of data provided in the monitoring reports from the different plants was extremely variable, reflecting in part the lack of standardization and guidelines for groundwater monitoring in Alberta. Of 54 plants, 32 had sufficient data for a rigorous assessment of subsurface conditions. Full contamination situation classifications (CSC) were developed for these 32 plants.

Of the plants reviewed where sufficient data were available to make the determinations, only one did not exhibit some form of impact on groundwater quality, however in most cases contamination was restricted to the plant site. The most common sources of contamination were process water ponds, process area, landfills and sulphur block areas. The most common types of deleterious substances detected in groundwater were dissolved organics and dissolved inorganics (main ions). Free phase condensate contamination of groundwater was identified at five gas plants, and hydrocarbon contaminated soils were found at 6 of the 7 plants with soil data. The most common zone of groundwater contamination was one of moderate hydraulic conductivity, typical of inter-till sand and silt layers, or fractured bedrock common to Alberta. Most plants were situated in areas where low and moderate hydraulic conductivity geologic materials predominate near the surface. The most common contamination situation

involved dissolved organics and main ions in a moderately conductive aquifer, originating from process water ponds.

Based on the data provided and the CSC's generated, seven candidate sites for possible future subsurface contamination remediation demonstration projects were recommended. All seven sites are equally capable of fulfilling the requirements of the demonstration projects, and each must be individually assessed by the selection committee based on such factors as cooperation of the operators, logistical considerations, and suitability of the precise goals of the project.

Information on five remediation schemes at Alberta sour gas plants was obtained directly from operators. Detailed case histories are present for four of these facilities, including assessment of the applicability and effectiveness of the technology used, and discussion of possible future courses of action.

A review of subsurface monitoring and remediation guidelines, regulations, and legislation from Alberta, Canadian federal, and other provincial jurisdictions was conducted. Applicable guidelines published by the US Environmental Protection Agency were also reviewed and discussed.

A brief review of available subsurface remediation technology was completed, including groundwater recovery, treatment, containment and in-situ bioremediation methods, and soil remediation techniques.

A computer database system designed for IBM and compatible PC's was developed to store the acquired data. The database has sections for plant information, monitoring system details, monitoring data (sequential data is accommodated, referenced by date), and remediation system details and performance data. Each section provides room for comments, and a special appended memo feature allows complete text reports to be included in each gas plant field. Reports can be generated easily from the database with full flexibility, and new data can be entered as they become available to keep the database current. The primary users of the database will likely be Alberta Environment personnel engaged in regulating gas plant monitoring and remediation. The database system (excluding data from other operator's plants) will be made available to CPA member companies.

Key recommendations of the report include the need for standardization of monitoring requirements at Alberta sour gas plants. The need for remediation should be assessed on a case-by-case basis, based on the data provided by complete monitoring reports and an appropriate level of risk assessment. Risk analysis would essentially provide an indication of the expected migration and impacts of groundwater contamination on nearby users and the environment.

The concept of initiating one or more subsurface remediation demonstration projects is endorsed. By demonstrating not only appropriate new technology and techniques, but also approach and methodology, such a program and its resulting documentation could assist industry in selecting the most appropriate remediation technologies. The anticipated benefit of the proposed projects to operators and the environment is considerable.

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1. INTRODUCTION

1.1 BACKGROUND

The province of Alberta is fortunate to have an abundance of natural gas, much of which is associated with varying concentrations of hydrogen sulphide gas (H_2S). Sour gas plants remove hydrogen sulphide from the natural gas stream through a variety of processes, producing elemental sulphur and sales gas.

There are presently more than one hundred and fifty sour gas plants and six sulphur forming/handling facilities operating in Alberta. Plants range in capacity from as little as 11,000 m^3/day to more than 17,000,000 m^3/day of raw gas (Oilweek, 1987). The oldest facilities have been in operation since the early 1950's, and several new complexes are now in the design stage. This fact is reflected in the wide range of process types and plant designs present in Alberta.

Due to the nature of the processes involved in sour gas processing and the wastes and by-products produced, sour gas plants may affect local groundwater quality. Soil horizons and the unsaturated zone may also be affected. Possible sources of contamination at plant sites include free phase and dissolved hydrocarbon products (such as condensate), process water and chemicals (such as amines, glycols, and degradation products), produced waters (brines, saline and brackish water), solid wastes and sludges, seepage waters, surface runoff (from sulphur blocks, process and loading areas), and active or abandoned landfills on site. Contaminants entering the subsurface from one or more of these sources may impact on the natural environment through discharge to nearby lakes, rivers, streams and marshes, or on nearby groundwater users.

2. DATABASE DEVELOPMENT

The development of a database system to accommodate sour gas plant contaminant monitoring and remediation data provided to Alberta Environment by plant operators pursuant to the Clean Water Act was one of the stated objectives of this project (tasks 4 and 5). The database could be used by Alberta Environment, the CPA, and its member companies to record and assess groundwater and subsurface monitoring and remediation efforts at sour gas plants.

The database, designed for use on IBM and compatible personal computers, allows contaminant monitoring and remediation data to be quickly stored, retrieved and manipulated, allowing users rapid access to information hitherto found in series of cumbersome reports. Introduction of such a system could represent a significant advancement in the way monitoring data can be used by environmental personnel. For instance, the database allows users to search on common parameters among different facilities, by date, or by owner/operator, and then generate customized reports summarizing the data. The database can also be used for such things as keeping track of required monitoring schedules, assessing compliance, determining the nature of contaminant situations at a given facility, and recording remediation milestones.

All data entered into the database has been thoroughly reviewed, screened, and rated for quality using a three-tiered data quality index. Figures 1 through 4 show the information which can be stored in the database, and Figure 5 shows a schematic diagram of database design. Figure 6 represents an example of the type of report which can be easily generated with the database.

Appendix I of this report describes the development of the database from inception through to data entry, including preliminary research and user consultation, database design, data screening and quality control, software and hardware choices, and report generation. Example data input forms are also included.

FIGURE 1

CPA
ALBERTA SOUR GAS PLANT
SUBSURFACE CONTAMINATION DATABASE
DATA FORM

GENERAL INFORMATION

Plant Name____________________C20 Plant Identifier____________
Operator____C25

Plant Location:
Lsd______AN3 Sec._____N5 Tp.________N3 Rg.________N3 Mer_______AN4
Nearest Town______________________________C15

Contacts:
Plantsite; Name________________________C15
Title________________________C15
Telephone_____-___________N7

Office; Name________________________C15
Title________________________C15
Telephone_____-___________N7

Plant Information:
Process Type(s)____/_____/______/_____N12 (See Index List)
Plant Startup Date____________D8
Comments____C50

Data Available: Hydrogeological/Monitoring System ___L1
Subsurface Monitoring ___L1
Remediation Data___L1
Subsurface Remediation___L1

Groundwater Monitoring System in Place?______L1 Date Installed________________D8
Contamination Remediation System in place?_____L1 Date Installed_____________D8

Contaminant Situations Present:

Situation 1: Source:___N3 Type:______N4 Contaminated Zone____N3
Comment 1____C50
Situation 2: Source:___N3 Type:______N4 Contaminated Zone____N3
Comment 2____C50
Situation 3: Source:___N3 Type:______N4 Contaminated Zone____N3
Comment 3____C50
Situation 4: Source:___N3 Type:______N3 Contaminated Zone____N3
Comment 4____C50
Comment:____
____C125

Data Reference____
____
____C200

FIGURE 2

CPA
ALBERTA SOUR GAS PLANT
SUBSURFACE CONTAMINATION DATABASE

DATA FORM

HYDROGEOLOGICAL/MONITORING SYSTEM

Plant Name________________________C15 Plant Identifier____________

General Plant Site Geology:
Surficial Deposit Type________________C15 Thickness____ - _____m N8
Surficial Deposit Type________________C15 Thickness____ - _____m N8
Bedrock Type__________________C15 Formation_____________C15

General Plant Site Hydrogeology:
Aquifer 1 Type________________C15 Depth to Top________m N8 Thickness_______m5
Hydraulic Conductivity_________________m/s N8 Lithology_____________C10
Pump Test (y/n)_____L1 Flow Direction____________C8
Aquifer 2 Type________________C15 Depth to Top________m N8 Thickness_______m5
Hydraulic Conductivity_________________m/s N8 Lithology__________C10
Pump Test (y/n)_____L1 Flow Direction_____________C8
Aquifer 3 Type________________C15 Depth to Top________m N8 Thickness_______m5
Hydraulic Conductivity_________________m/s N8 Lithology___________C10
Pump Test (y/n)_____L1 Flow Direction_____________C8

Monitoring System Data:

Piezometer Number	Installation Date (yr.m.d)	Top of Screen (depth in m) (below GL)	Screen Length (m)	Lithology of Completed Zone	Status

FIGURE 3

CPA
ALBERTA SOUR GAS PLANT
SUBSURFACE CONTAMINATION DATABASE

DATA FORM

SUBSURFACE MONITORING

Plant Name________________________C15   Plant Identifier_______________

SEQUENTIAL MONITORING DATA REFERENCED BY DATE

Sampling Date____________D8
Data Quality____N2

Piezometer Number	SWL (mBGL)	Selected Water Quality Parameters/Contaminants/Indicators Type1/conc	Type2/conc	Type3/conc	Type4/conc	Type5/conc

Comment1____C125

Comment2____C125

Comment3____C125

FIGURE 4

CPA
ALBERTA SOUR GAS PLANT
SUBSURFACE CONTAMINATION DATABASE

DATA FORM

SUBSURFACE REMEDIATION

Plant Name ______________________ C15   Plant Identifier ______________

Remediation System 1:
Remediation Target:

____

____ C125

Contaminant Situation Classifications Present   __________ AN8
__________ AN8
__________ AN8

Specific Contaminants Present   Contaminant1 ______________ C10
Contaminant2 ______________ C10
Contaminant3 ______________ C10

Remediation Start Date ______________ D8
Piezometer Number Indicative of Contamination ______________________________ C25

Remediation methods: _____ N3 _____ N3 _______ N3   (see index lists)
treatment/disposal methods: _____ N3 ______ N3 _____ N3   (see index lists)

Comment ____ C50

Remediation History:

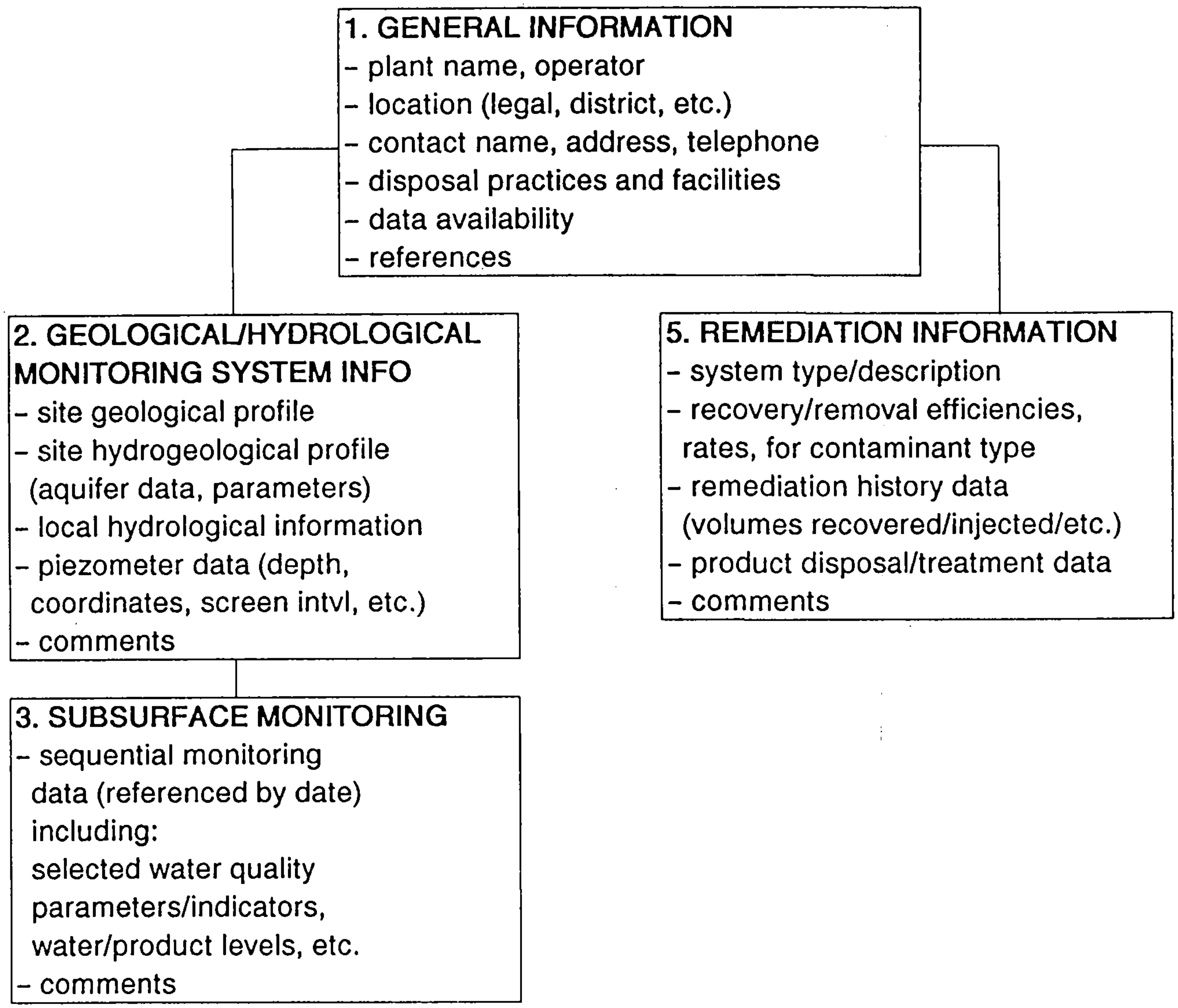
Estimated Initial Mass of Contaminant ______________ AN8

Date	Action	Est. cumm. mass contaminant removed	recovery efficiency	comment

Comments ____

____ C125

DATABASE DESIGN SCHEMATIC



NB: Only general categories of data are listed

FIGURE 5

FIGURE 6
EXAMPLE RELATIONAL REPORT WRITER REPORT

SEARCH CRITERIA: Select all plants which have at least one CSC involving free phase hydrocarbon (A or T), and list CSC's involved, if remediation systems are in place and what data are available in the data file.

Plant ID: P-33

sources:	7 ,	1 ,	6 ,	4	Monitor sytem data?:	T
types:	T	M	M	M	Monitoring Data?:	T
zones:	II	II	II	II	Remediation Data?:	F

Remediation System in Place? T

Plant ID: P-37

sources:	9 ,	4 ,	2 ,	0	Monitor sytem data?:	T
types:	A	M	D		Monitoring Data?:	T
zones:	III	III	II		Remediation Data?:	F

Remediation System in Place? F

Plant ID: P-42

sources:	6 ,	1 ,	1 ,	5	Monitor sytem data?:	T
types:	P	M	D	A	Monitoring Data?:	T
zones:	III	III	III	III	Remediation Data?:	F

Remediation System in Place? F

Plant ID: P-48

sources:	1 ,	4 ,	9 ,	0	Monitor sytem data?:	T
types:	M	B	A		Monitoring Data?:	T
zones:	III	III	III		Remediation Data?:	T

Remediation System in Place? T

Plant ID: P-54

sources:	1 ,	2 ,	4 ,	0	Monitor sytem data?:	T
types:	T	D	N		Monitoring Data?:	T
zones:	III	III	III		Remediation Data?:	T

Remediation System in Place? T

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3. SUBSURFACE CONTAMINATION AND REMEDIATION AT ALBERTA SOUR GAS PLANTS

This part of the report describes the evaluation of monitoring and remediation data from sour gas plants, including assessment of groundwater and unsaturated zone contaminant situations, identification of the most common sources, types, and locations of subsurface contamination, review and assessment of remediation projects currently underway, and identification of candidate sites for possible future remediation demonstration projects.

For the purposes of this study, subsurface contamination was defined as the presence of "any chemical substance whose concentration exceeds background concentrations or which is not naturally occurring in the environment." (Environment Canada, 1984).

3.1 ASSESSMENT OF GROUNDWATER CONTAMINATION

3.1.1 Available Information

Data for this study was provided by Alberta Environment, and consisted of documents submitted to the Standards and Approvals Division by plant operators pursuant to the Clean Water Act. Groundwater monitoring reports to be included in the study were selected by Alberta Environment personnel, sent for photocopying and delivered to the consultant. To reduce photocopying, it was agreed that Piteau Engineering would use its own records on groundwater monitoring systems for 21 sour gas plants.

A package received from Alberta Environment included data on 33 sour gas plants, bringing to 54 the number of plants to be considered in the study. Table 1 (found in Appendix II) provides a master list of gas plants and the type of information that was available for review and assessment. Considering the confidential nature of the data contained in the reports, plant and operator names have been withheld. Instead each plant involved in the study has been assigned a unique code number, corresponding to the computer database file ID number. Alberta Environment, the keepers of the database, have sole access to the code key.

The terms, conditions and requirements attached to the licence provided to plant operators by Alberta Environment usually specify that the operator should establish patterns of groundwater movement and establish groundwater quality in the vicinity of industrial landfills, surface water runoff and process water retention ponds, and near other potential sources of contamination.

Information on groundwater movement patterns were available for 32 gas plants. Groundwater flow velocities were calculated for different geological units at 26 gas plants. More information is available on groundwater quality, including the following:

- main ion analyses (complete or indicators only) are available for 43 gas plants;

- organic indicator analyses (DOC, TOC, etc.) are available for 44 gas plants;

- metal analyses are available for 35 gas plants.

The above summary shows the significant differences in approach among plant operators with respect to existing groundwater monitoring requirements. Some operators submitted complete reports summarizing all work conducted, including: borehole logs; instrument construction, development, testing and sampling; chemical analysis results and evaluation of both groundwater quality and circulation conditions. Others elected to submit groundwater quality information without providing details on piezometer depth, completion zone, test and sampling procedures. As a result, the technical level of reports is highly variable, despite the fact that all had been accepted by Alberta

Environment, and complied with the terms and conditions of the existing guidelines.

Examination of Table 1 (found in Appendix II) shows that for many plants, the data available in monitoring reports were insufficient for determination of the presence of subsurface contamination. In some cases even basic hydrogeological information such as groundwater flow directions, geological logs and piezometer locations, was not available. In general, the level of reporting on Alberta sour gas plant subsurface monitoring and remediation has lacked the consistency and uniformity made possible by the presence of a firm set of guidelines or minimum monitoring and reporting requirements.

3.1.2 Methodology

Information on plant operator, location, start-up date and process type was obtained from published materials. All reports, proposals and correspondence received from Alberta Environment were carefully reviewed, screened and entered into the data forms. To assure that uniform approach and criteria were applied during data review, all of the data assessment work was performed by a qualified hydrogeologist with many years of experience, much of it associated with the Alberta petroleum industry. Selection of such an approach was elected when a wide variability in technical approaches and reporting formats for different sour gas plant was recognized.

Completion of Data Forms

Geological and hydrogeological information was extracted from reports, generalized and entered into the data form. All piezometer/observation well construction details were entered into the data form if their number did not exceed 12, although the database can be modified to provide space for additional data. For plants where more than twelve piezometers were installed, selection had to be made of which piezometers should be entered into the database. Criteria for piezometer selection were:

- longest, continuous (seasonal) monitoring records;
- complete geological and testing records;
- highest levels of groundwater contamination observed in relation to other monitoring points with provision for background data; and,
- operational status during last sampling program.

Hydrochemical monitoring data from at least two sampling periods were entered into the database. Due to space limitations, data for a maximum of 12 piezometers could be entered on each form. The database, however, can be expanded easily to accommodate a greater number of piezometers. Thus, preliminary screening of data had to be made. It followed the same criteria as that applied to piezometer completion records with one addition. Data were introduced representing all groundwater chemical types and data representing all specific/typical contaminant groups characteristic for a particular sour gas plant.

3.1.3 General Assessment Procedure

One of the main objectives of this study was the compilation of data on subsurface contamination situations and remediation systems at sour gas plants in Alberta. Since no previous studies on this topic were available in the literature, the authors of this study had to develop a set of assessment criteria for different contaminant scenarios.

Development of the assessment criteria was complicated by the following factors:

- variable hydrogeological conditions within Alberta,
- natural gas processed in different plants originates from various geological units, and thus is of varying chemical character,

- the quality of formation waters associated with produced gas may vary greatly, ranging from nearly fresh water to highly mineralized brine,

- different processes are used in gas sweetening, potentially contributing a wide range of chemical compounds to plant effluents.

A methodology and set of assessment criteria for evaluation of groundwater contamination at sour gas plants were developed especially for this project.

The following groups of criteria were used in review of the information submitted by sour gas plant operators to Alberta Environment. It should be stressed that in determining Contamination Situation Classifications, all available data were considered using all the applicable methodologies described herein. Initial indications of contamination were confirmed by alternate parameters and criteria wherever possible. If some doubt existed about the presence of contamination, no CSC was assigned. The groups of criteria applied for assessment of monitoring data were:

Comparison to Background

Standard hydrogeological practice dictates that when attempting to detect and describe an occurrence of groundwater contamination, background groundwater quality should be established. Water quality downgradient of the supposed source of contamination can then be compared to the quality of water unaffected by the source. Significant differences between upgradient and downgradient groundwater quality serve as an indication of groundwater contamination.

The US Environmental Protection Agency (USEPA) recommends a rigorous application of this procedure for all monitoring and assessment of groundwater contamination. The RCRA Groundwater Monitoring Technical Enforcement Guidance Document (1986), published by the USEPA, specifies the methodology to be used in comparing background and downgradient groundwater quality. Background groundwater quality is to be determined through repeated periodic samplings (with several replicate samples to be collected at each sampling). Through use of student's t-test, downgradient water quality is compared to established background. The document states that

> "if the mean concentration of <u>any</u> IP (indicator parameter) in <u>any</u> downgradient well is larger by a statistically significant amount than the background concentration, then contamination may have occurred".

While the types and amounts of data available for this study did not allow the application of statistical methods, the general concept of using background as a reference when identifying contamination was applied whenever data allowed.

Direct Indicators of Groundwater Contamination

The presence of certain products which do not occur in nature, and are common sour gas plant products, by-products, or inputs, is a direct indication of groundwater contamination by plant activities (assuming the site was not occupied by some other industrial facility or landfill before plant construction). Examples of such indicators are:

- Presence of products, eg. gas condensate, sulphate (if origin confirmed by isotope analysis).

- Presence of chemicals used in gas sweetening processes or plant operation and maintenance, corrosion inhibitors, pesticides and soil sterilants (eg. amines, sulfolane, chromium, arsenic, mercury).

Indirect Indicators of Groundwater Contamination

A complete hydrogeologic assessment of a given site should include some consideration of local and regional hydrogeochemistry, and the behaviour of groundwater under natural conditions. Consideration should be given to:

- General knowledge of groundwater origin, occurrence, quality and circulation (seasonal changes in main ion concentrations and ionic ratios).

- Information on regional hydrochemical conditions (eg. natural groundwater quality in different stratigraphic/lithological units, and presence or absence of specific ions or general indicators of groundwater quality.

- Areal distribution of main ions within identified hydrogeological units, and variations in concentrations of main ions over time and with the seasons. Data collected in the plant vicinity that exhibit no obvious signs of groundwater contamination and may be considered as background.

For each sour gas plant reviewed, a combination of the methods described above was applied. As data availability allowed, all direct and indirect indicators of contamination were assessed, along with background and downgradient groundwater quality information. In this way, considering all available information for each facility, the presence, source and locations of contamination were identified (if possible), and the information classified accordingly. The following section describes the specific hydrochemical criteria used in the assessment review.

3.1.4 Hydrochemical Assessment Criteria

The following criteria were selected based on available hydrochemical data. It should be noted however, that the analytical schedule for different gas plants varied greatly, depending on the programs proposed by individual operators and subsequently approved by Alberta Environment. Thus, for some plants there are several sets of complete main ion, organic and nitrogenous indicators as well as trace metal analyses (eg. Plants P-20, P-35, P-37, P-54, P-51, P-42, P-49, and P-52). The other end of the spectrum is represented by companies which tested groundwater for four to eight parameter selected from the following: pH, electrical conductance, TOC, COD, TKN, TDS (or TFR), chloride, sulphate and sulphide (eg. P-26, P-25, P-15, P-21, and P-18).

Variation in the analytical schedule and possibly in the quality of analyses made selection of a few, very strict quality criteria, that could be applied to all the plants, impractical. Instead, a more general group of criteria was used to assess the groundwater contamination situations at each plant on an individual basis, making use of whatever data was available. These criteria were:

1. **Presence of direct indicators of groundwater contamination that can be associated with plant operation and/or maintenance.**

   Free Phase Hydrocarbon

   Free gas condensate was reported in the subsurface at five gas plants (P-54, P-37, P-48, P-42, P-18).

   Sulphate Ion

   Presence of sulphate concentrations elevated above background levels in the areas adjacent to the sulphur block and/or runoff control system was assumed as a direct indicator of groundwater contamination. Numerical criteria developed for this study were based on a survey of all available background water quality data at the 54 plants, and are explained in detail in the following pages. In some instances, sulphur isotope analyses were available to confirm origin of sulphate ion.

Chemicals used in gas sweetening process, plant operation and maintenance

Various fuels, oils and greases may be used during plant operation and maintenance. If leaks, spills, or improper disposal practices occurred, these substances may have contaminated groundwater. Process chemicals may include a wide range of organic or inorganic compounds (eg. glycol, amines, sulfolane, catalysts). Presence of compounds of this nature was determined at a few plants (P-53, P-20, P-35, P-37, P-54, P-51, P-42, P-49).

Various corrosion inhibitors were commonly used in the sour gas plants. Sludges may therefore contain elevated concentrations of various compounds or metals (eg. chromium). Presence of high chromium concentrations in either soil or groundwater may be interpreted as a direct indication of contamination originating from plant activities.

Soil sterilants and herbicides are commonly used within the plant site to prevent growth of vegetation that dry could create a fire hazard. Excessive use could introduce contaminants into both soil and groundwater systems. If identified, such compounds could be treated as indicators of groundwater contamination originating from the plant site.

2. Indirect Indicators of Groundwater Contamination

Unusual Changes in Groundwater Quality Over Time

Groundwater quality of a given aquifer under natural conditions is typically subject to small seasonal variations, reflecting the impacts of varying recharge rates and other mechanisms. However, high variation in main ion concentrations (eg. exceeding 25% within one year) may be an indication of:

- groundwater contamination,
- improper piezometer construction and/or development,
- improper sampling, and,
- analytical (laboratory) error.

Under these circumstances, such fluctuations cannot be taken as evidence of groundwater contamination, but may serve as a primary indication that a problem may exist. Before a contamination situation was identified, other indicators of groundwater contamination had to be present.

Areal Distribution of Main Ions (Hydrochemical Type)

Groundwater naturally occurring in a hydrogeologic unit is characterized by similar recharge and circulation regimes, thus chemical composition is expected to be similar. Substantial changes in ionic composition in the same aquifer or groundwater-bearing zone, encountered within a small area (eg. plant site), may be interpreted as a general indication of the impact of plant operations on groundwater quality.

Detailed hydrogeological studies may allow determination of the source of groundwater contamination (eg. process area, waste water pond(s), sulphur block) and the extent of the plume. Exploration results interpreted in relation to background and potential sources of contamination can be utilized for assessment of the nature and potential impacts of the contamination situation.

Regional Hydrochemistry and Indicators of Groundwater Quality

Most shallow aquifers in the Rocky Mountains, Foothills and Alberta Plains contain fresh or brackish groundwater of calcium-magnesium-bicarbonate, sodium-bicarbonate, calcium-magnesium-bicarbonate-sulphate, calcium-magnesium-sulphate-bicarbonate, and calcium-magnesium-sulphate chemical types. Table 2 presents a summary of groundwater quality indicators used in the contamination assessment process.

Chloride

Chloride concentrations in shallow near-surface groundwater in Alberta are typically below 10 mg/l (Ozoray and Barnes, 1977; Gabert, 1975; Piteau Engineering Ltd.; 1985, 1986, 1987, 1988, 1989, 1990). A review of background water quality at all plants in the study set for which data was available confirmed this fact. No background chloride concentrations higher than 5 mg/L were reported. Higher concentrations may originate from other sources (eg. formation water, septic system, salt application on the highways or salt blocks placed on range for cattle).

Concentrations between 10 mg/l and 250 mg/l (maximum acceptable for drinking water) were generally considered as elevated, while concentrations above 250 mg/l are considered high. For each plant where elevated or high chloride concentrations in groundwater were found, other indicators of contamination (such as spatial and temporal variability in concentrations, comparison to background, and the association of other contaminant species) were also used to confirm the impacts of plant operations. Then an attempt was made to define the

TABLE 2
GROUNDWATER CONTAMINATION INDICATORS
SPECIFIC IONS AND GENERAL INDICATORS

PARAMETER	CONCENTRATION (mg/l)		
	BACKGROUND (from study data)	ELEVATED	HIGH
CHLORIDE	<10	10 - 250	>250
SULPHATE	variable	variable - 500	>500
TFR/TDS	variable	variable - 1000	>1000
TKN	<1	1 - 5	>5
TOC/DOC	<10	10 - 50	>50
COD	variable	variable - 50	>50
O & G	<1	1 - 10	>10
ALUMINIUM	<1	>1	
ARSENIC	<0.05	>0.05	
CADMIUM	<0.005	>0.005	
BARIUM	<1	>1	
COPPER	<1	>1	
MERCURY	<0.001	>0.001	
SELENIUM	<0.01	>0.01	

sources of contamination. This required knowledge of groundwater flow directions (both areal and vertical) and circulation regime.

Sulphate

Sulphate concentrations in shallow groundwater, especially in southern Alberta, vary naturally within a wide range, from a few mg/l to several thousand mg/l. Therefore, caution is required using this ion as an indicator of groundwater contamination related to sour gas plant operation. Distribution of sulphate in relation to the sulphur block, sulphur block runoff pond and drainage network was considered for each plant, where sufficient information was available, prior to contaminant situation classification.

Background groundwater quality was reviewed at all plants in the study set for which data was available. Background sulphate concentrations ranged between about 50 mg/l and 100 mg/l, and did not exceed 200 mg/L. Based on these data, and a general knowledge of Alberta hydrogeochemistry, sulphate concentrations between background and 500 mg/l were considered as elevated, and concentrations above 500 mg/l were considered as high. If concentrations were in the "elevated" range, other confirmations of the presence of groundwater contamination were sought before categorization.

Total Dissolved Solids (TDS) or Total Filterable Residue (TFR)

Mineralization of groundwater may vary greatly in shallow aquifers in Alberta. Criteria similar to those for sulphate concentrations were applied for this indicator. Background values in the study set ranged from around 150 to 250 mg/L, and did not exceed 300 mg/L. Based on these data, TFR concentrations between background and 1000 mg/L were considered elevated, and those above 1000 mg/L were considered to be high.

Electric conductance (EC) also defines groundwater mineralization. However, due to the dependence of the parameter on temperature and conversion coefficients depending on dominant ion(s), this measurement is less accurate than laboratory determination of TDS or TFR. Therefore, EC measurements were not considered in this part of contamination situation assessment.

Nitrogenous Compounds

Amine degradation products may enter the groundwater system, contributing to increases of nitrogenous compound concentrations. Elevated TKN values may be used as an indicator of groundwater contamination. It should be noted however, that high ammonia nitrogen and nitrate concentrations may occur naturally in Alberta (Hendry, McCready and Gould, 1984). These two compounds could therefore not be considered as reliable indicators of groundwater contamination.

General Organic Indicators

COD, BOD, TOC and DOC may be considered as another group of indicators that could assist in assessment of the nature and source of groundwater contamination. Natural organic compounds, such as humic and fulvic acids, often occur in groundwater. Their presence may cause elevated values of each of these indicators. For this reason, other groups of indicators should be used to confirm contaminant situation assessment. The literature, however, does contain studies which show that total and dissolved organic carbon can be successfully used as indicators of organic groundwater contamination (Spruill, 1987). Significant differences in organic indicators from background may provide an initial indication of organic contamination, to be confirmed by other parameters.

Oil and Grease

Oil and Grease is a parameter commonly used to determine the presence of dissolved petroleum hydrocarbons. The technique involves measuring concentrations of hydrocarbons extracted from the sample by a solvent, commonly freon. Natural groundwaters do in general contain high levels of O&G, and it's presence in significant quantities when compared to background levels is a good indication that groundwater has been impacted by man-made substances.

Metals

Some metals, including iron and manganese, occur commonly in shallow groundwaters in Alberta. Both may often be present in concentrations exceeding Canadian Drinking Water Quality Standards. Use of these metals as indicators of contamination was therefore impractical. Many other metals, may have been introduced as the result of plant operations. Catalysts, corrosion inhibitors, and wood preservatives, are among the substances commonly associated with plant construction and operation which contain metals, including zinc, cadmium, vanadium, and lead. Presence of elevated levels of these and other metals not normally found in natural groundwaters may be considered as an indication of groundwater contamination. The technique of comparison to background quality was used when assessing contamination situations.

Table 3 summarizes the groundwater quality assessment criteria.

Three examples of the application of these criteria in assessing groundwater contamination are provided in Section 3.1.6. The examples are from plants included in this study, and provide a step by step consideration of the available data.

3.1.5 Generation of Contamination Situation Classifications

General Approach

One of the objectives of this study was the determination of the most common contamination situations found at Alberta sour gas plants, based on available data. To accomplish this, a system was developed for classifying and grouping similar occurrences. This system, called Contamination Situation Classification (CSC), was designed to provide meaningful groupings of like situations without sacrificing resolution.

It was found that attempting to provide too many groups made identification of meaningful trends quite difficult. For instance, if a classification scheme attempted to use each chemical contaminant type as a separate group, the result would be a large number of categories each with one or two examples.

Methodology

Using the criteria given in Sections 1.3 and 1.4, groundwater monitoring data from each plant were assessed, and the presence of groundwater contamination was determined. If sufficient data was available, the source, type and geologic host of contamination was determined for each contamination situation. From these three pieces of information (the source of contamination, the type of contaminants detected, and the hydrogeologic unit in which they are found) Contamination Situation Classifications, or CSC's were developed.

TABLE 3
GROUNDWATER QUALITY ASSESSMENT CRITERIA

DIRECT INDICATORS OF GROUNDWATER CONTAMINATION

- GAS CONDENSATE
- PROCESS CHEMICALS
- CORROSION INHIBITORS
- WOOD PRESERVATIVES
- SOIL STERILANTS
- FUEL (DIESEL, GAS), LUBRICATIONG OIL AND GREASES

INDIRECT INDICATORS

- TEMPORAL CHANGES IN GROUNDWATER IONIC COMPOSITION (EXCEEDING 25% BETWEEN DIFFERENT SAMPLING PROGRAMS CONDUCTED WITHIN ONE YEAR)
- RAPID CHANGES IN MAIN ION DISTRIBUTION WITHIN PLANT SITE
- REGIONAL HYDROCHEMISTRY
  - SPECIFIC IONS
  - GENERAL INDICATORS

For the purposes of this study, a Contamination Situation is defined as: "An occurrence of subsurface contamination at a given sour gas plant, distinct from other occurrences at the same plant in that it has a different source, or the contamination is found in a different hydrogeological unit (for the purposes of this definition, the unsaturated zone is defined as a distinct hydrogeological unit)". To each Contamination Situation, a classification is assigned (CSC), based on assessment of monitoring data. The CSC has three parts: source of contamination, the types of contaminants present, and the hydrogeological unit in which they are found. Figure 7 shows the breakdown of CSC categories.

Contaminant Source

Sources of contamination, once determined in the data review, are assigned one of 9 categories: process area, sulphur block and sulphur loading areas, surface runoff, process water ponds and burn pits, product loading area, on-site landfills, injection wells, and other. If the source was undetermined, no source indicator was provided.

Contaminant Type(s)

Once types of contaminants were established, one or more of 6 categories were assigned to the CSC. Categories consisted of: Free hydrocarbons, including condensate and gasoline; Dissolved organics, directly determined or detected by the use of general indicators such as TOC; main ions, notably chloride; contamination associated with sulphur block areas (sulphur products), such as sulphate ion (in groundwater) and free sulphur (in soils); metals such as chromium and arsenic; and others, such as TKN and other nitrogenous compounds.

Contaminated Zone:

Once the contaminated zone was determined, one of four categories was assigned, data permitting. Categories were: the unsaturated zone; highly hydraulically conductive units (K > 10E-5 m/s) such as glaciofluvial gravels; moderately hydraulically conductive units (10E-

FIGURE 7
CONTAMINANT SITUATION CLASSIFICATION SYSTEM

CONTAMINANT SOURCE	CONTAMINANT TYPE	CONTAMINATED ZONE
1. Process Area 2. Sulphur Block 3. Surface Runoff 4. Process/Produced Water Ponds 5. Product Loading Facility 6. Landfill 7. Injection well 8. Other 9. Unknown	A. Free Hydrocarbons B. Dissolved Organics C. Main Ions D. Sulphur Products E. Metals F. Other (e.g. TKN, priority pollu- tants, etc.)	I. Unsaturated Zone soils, surficial material, bedrock Saturated Zone II. High Hydr. Cond K > 10E-5 m/s III. Moderate K 10E-5 > K > 10E-8 m/s IV. Low K K < 10E-8 m/s

Such a system addresses where contaminants originate, what form they take, and where they are presently located.

The database has been designed so that site clasification can be done by the computer. Users can produce reports which use site classification as a search parameter.

Example: Classification 1A (II), would be hydrocarbon contamination in moderately conductive till/bedrock, originating from the process area.

A given site may have more than one classification type.

5 m/s > K > 10E-8 m/s) such as inter-till sand layers and sandstone or fractured bedrock; and low hydraulic conductivity units (K < 10E-8 m/s) such as till and siltstone/shale bedrock.

Source, type and location categories are combined to form a CSC, and it is possible for several CSC's to exist at a given plant. For example, a facility may have a small sulphate plume in the uppermost groundwater bearing zone (a sandy clay till layer of low hydraulic conductivity) extending from the sulphur block area, and a larger plume consisting of high concentrations of chlorides and dissolved organics (high TOC and sulfolane identified in trace organics scan) originating from the evaporation pond, in another part of the same uppermost aquifer, but also found in a deeper bedrock aquifer of moderate hydraulic conductivity.

Consulting Figure 7, three CSC's can be developed for this scenario:

2 D IV: sulphur products from sulphur block in low K zone;

4 BC IV: ions and dissolved organics from evaporation pond in a low K zone;

4 BC III: ions and dissolved organics from evaporation pond in a moderate K zone.

3.1.6 Examples of Site Assessment and Contamination Situation Classification

The following section provides three examples of the application of assessment criteria to monitoring data and the associated development of CSC's. The examples have been chosen to illustrate the variability in the amount and quality of available data. The first example is Plant P-53, for which a relatively complete set of data was available. The second example, Plant P-19, is typical of a number of plants for which insufficient data were available for a complete analysis of the source, type, and zone of contamination. The third, Plant P-21, had minimal data only.

Example 1: Plant P-53

A multiphase hydrogeological exploration and site characterization program was conducted between 1986 and 1990. Borehole logs, locations and construction details for all piezometers and recovery wells are available. Hydraulic conductivity data is provided for all completed zones, rates, patterns and directions of groundwater flow in the two uppermost aquifers have been defined. Hydrochemical data was available from successive seasonal groundwater sampling programs.

Background groundwater quality was satisfactorily established in Piezometer 86-1, upgradient of the plant site. Seasonal variations were found to be slight, based on four years of fall and spring sampling. Background values were determined to be:

chloride:	1.5 to 3.0 mg/L
sulphate:	280.0 to 352 mg/L
DOC:	2.2 to 4.0 mg/L

Review of available data indicated the presence of four sources of groundwater contamination. These were:

a) The process area

The following contaminants or hydrochemical indicators were detected in piezometers immediately downgradient of the process area:

Chloride: concentrations ranged:

Piezometer 86-4:	15.1 to 41.1 mg/L
Piezometer 86-11:	12.5 to 28.8 mg/L
Piezometer 87-17:	20.4 to 26.4 mg/L
Recovery Well 6:	20.3 to 32.1 mg/L

Sulphate: concentrations ranged:

Piezometer 86-4:	363 to 1030 mg/L
Piezometer 86-11:	1010 to 2000 mg/L
Piezometer 87-17:	1820 to 2020 mg/L
Recovery Well 6:	1460 to 1950 mg/L

Dissolved Organic Carbon (DOC): concentrations ranged:

Piezometer 86-4:	97 to 510 mg/L
Piezometer 86-11:	11 to 30.4 mg/L
Piezometer 87-17:	6.2 to 10.1 mg/L
recovery Well 6:	23 to 48.2 mg/L

Chemical analyses from the four downgradient monitoring points shown above show considerable temporal fluctuation in main ion and hydrochemical indicator concentrations at individual monitoring points. For example, in 86-4 chloride concentrations range from 41.1 mg/L in May 1987 to 17.2 mg/L in October 1987. Similarly, sulphate (1000 mg/L in Oct. 1987 to 363 mg/L in June 1988) and DOC (97.0 mg/L in June 1988 to 460 mg/L in Sept. 1989) exhibit relatively large fluctuations in concentration with time.

In addition to the unusual seasonal fluctuations, substantial changes in groundwater quality within relatively short distances (e.g. piezometers 86-4 and 86-12 situated approximately 120 m apart, and completed in the same uppermost groundwater bearing zone) were considered as being indicative of groundwater contamination. Table 4 shows variation in four chemical parameters among two nearby piezometers downgradient of the process area.

These fluctuations in concentration of parameters usually stable under natural conditions were considered as an indirect indication of groundwater contamination downgradient of the

TABLE 4
EXAMPLE 1: SELECTED HYDROCHEMICAL PARAMETERS

	PIEZOMETER No.	
	86–4	86–12
CHLORIDE, mg/l	15.1 – 41.1	3.3 – 23.6
SULPHATE, mg/l	363.0 – 1030.0	1300.0 – 1640.0
DOC, mg/l	97.0 – 510.0	28.3 – 82.0
TFR, mg/l	1450.0 – 2000.0	2458.0 – 2800.0

process area. Examination of background data confirms that seasonal ranges of these parameters are small.

Direct indication of groundwater contamination was provided by the comparison of downgradient and background water quality. As shown from the summary of data above, chloride concentrations downgradient of the process area ranged from four to over twenty times background, sulphates from approximately two to eight times background levels, and DOC from about three to over two hundred times background.

Review of drilling records, groundwater flow data and chemical analyses led to the conclusion that groundwater contamination originated from the process area. Types of contaminants distinguished were dissolved organic compounds and main ions (chlorides, sulphate, sodium). Contamination was found in an aquifer of moderate hydraulic conductivity, ranging from 10^{-5} to 10^{-8} m/s.

These results were provided with a CSC of:

Source: 1 (process area)
Type: B and C (dissolved organics and main ions)
Contaminated Zone: III (moderate K),
or, 1 BC III

b) Sulphur Block Area

Assessment of contamination downgradient of the sulphur block followed the procedures described above. Sulphate contamination was detected in piezometers immediately downgradient of the sulphur block, in the same uppermost groundwater bearing zone as the process area plume. Further downgradient, it appeared that the two plumes had merged. However, since data indicated that sulphate only was originating from the block, the following CSC was assigned:

Source: 2 (sulphur block)
Type: D (sulphur products)
Contaminated Zone: III (moderate K aquifer)

c) **Process Water Ponds**

Groundwater quality downgradient of the evaporation pond was assessed using the methodology described above and in Section 3.1.2. To determine the exact nature of organic compounds originally indicated by the presence of elevated DOC, extractable priority pollutant and purgeable/volatile organics broad spectrum scans were run. These scans proved the presence of sulfolane and 3 dimethylamino-3-isopropyl amino-2-propenal in both evaporation pond and downgradient monitoring points. This plume was also associated with elevated levels of chlorides.

Based on these data, the following CSC was assigned:

Source: 4 (evaporation pond)
Type: B,C,F (dissolved organics, main ions, and process chemicals)
Contaminated Zone: III

d) **Landfill**

Groundwater quality downgradient of the plant landfill was determined at two piezometers (86-2 and 86-3). Comparison to background and the general instability of groundwater chemistry over time and between piezometers indicated the presence of contamination similar to that found downgradient of the process area. CSC assigned:

Source: 6 (landfill)
Type: B and C (dissolved organics and main ions)
Contaminated Zone: III (moderate K aquifer)

In summary, four separate contamination situations were detected at this plant. Each was assigned its own CSC, based on the data available. CSC's were: 1 BC III, 2 D III, 4 BCF III, and 6 BC III.

The level of site characterization and monitoring at this plant is quite complete compared to the other facilities included in this report. Monitoring points were well distributed over the plant, and background groundwater quality was adequately determined for the two uppermost aquifers. All potential sources of contamination were investigated. Monitoring was conducted over several years at regular intervals, chemical analyses were complete and backed up by more sophisticated tests when warranted.

Example 2: Plant P-19

Assessment was based on data provided by Alberta Environment, and included:

- 1984 Annual Environment Report;
- Proposal regarding groundwater and biological monitoring, 1985;
- 1985 Annual Environmental Report;
- 1988 Annual Environmental Report;
- 1988 Annual Report Water Quality Data (1989.05.16).

None of these reports or proposals included borehole logs, piezometer construction details, or hydraulic conductivity and groundwater surface measurements. The 1984 Annual Report indicated that 21 piezometers and one well in the plant area were monitored on a weekly basis for pH and sulphate concentrations. Later, five additional piezometers were installed in the plant area, however, no information on these was available at the time this study was performed.

With the available information, two sources of groundwater contamination were identified:

a) Process Area

Chemical analyses of groundwater samples were available for each of four piezometers that contained water during july, August, September, and October 1984 sampling programs. Piezometer MP4 was dry throughout the sampling period, and piezometer MP4 was dry during September and October 1984. A summary of the available chemical analysis is provided in Table 5.

Piezometer MP1 was considered as a control piezometers by the authors of the 1984 report. From the available data it appears as if chloride and sulphate concentrations in MP1 are near or at background levels. However, organic compounds and selected metals are present in their highest concentrations at this location. Without data on piezometer construction details and groundwater flow directions, the validity of using MP1 as an indicator of background groundwater quality cannot be determined.

However, the chemical data presented in Table 5 does provide general indications of groundwater contamination. As with example 1 above, concentrations of certain parameters (main ions, TOC, arsenic, and iron) show large variations over time and across relatively small distances. The chemical makeup of groundwater in natural conditions is remarkably stable in a given aquifer, and is subject only to relatively small, regular seasonal fluctuations.

Table 5 shows that sulphate concentrations in piezometer MP3 are over 150 times those found in MP1, the supposed "control" piezometer. However, levels of TOC and DOC in MP1 are several times higher than the lowest levels found amongst the nearby piezometers. The iron concentrations measured in MP1 were about 150 times higher than those measured in MP5, and arsenic levels in MP1 were two or more orders of magnitude higher than in MP5.

TABLE 5
EXAMPLE 2: SUMMARY OF ANALYSES

	PIEZOMETERS			
	MP1 (mg/l)	MP2 (mg/l)	MP3 (mg/l)	MP5 (mg/l)
CHLORIDE	5.1 – 9.0	6.9 – 9.9	2.8 – 6.2	4.2 – 9.6
SULPHATE	<1.0 – 1.6	20.3 – 95.5	110.0 – 143.0	14.0 – 17.3
TOC	29.6 – 67.5	11.7 – 29.6	6.4 – 7.6	7.6
COD	11 – 260	27 – 40	12 – 31	19
PHENOLS	0.017 – 0.028	<0.002 – 0.008	0.002 – 0.004	0.005
ARSENIC	0.0280 – 0.0811	0.0004 – 0.0203	0.0004 – 0.0012	0.0006
IRON	77.7 – 104	0.219 – 0.857	0.046 – 6.35	0.583

Although the information available was incomplete, a partial CSC could be determined:

Source: 1 (process area)
Type: B,C,E (dissolved organics, main ions, metals)
Contaminated Zone: Unknown

b) **Sulphur Storage Area**

Table 6 provides a cross-section of pH values and sulphate concentrations measured in 1984 within an area of approximately 1200 m by 400 m. Changes in groundwater quality within very short distances (from MP2 to MP23 is approximately 400m), high variability in pH and sulphate concentrations within one season, and anomalous concentrations of these parameters when compared to MP2 (considered by the authors of the source report as a background well), are indicative of groundwater contamination.

The 1985 and 1988 Environmental Reports contain data similar to that described above. During these periods the scope of analysis was expanded to include 29 metals. As expected, concentrations of some metals were very high in the acidic conditions existing near the sulphur storage area. The following data from piezometer MP2, historically the location exhibiting the lowest pH, illustrate the presence of metals in groundwater:

Aluminum:	291 mg/L
Arsenic:	0.119 mg/L
Chromium:	0.371 mg/L
Cobalt:	0.159 mg/L
Iron:	741 mg/L
Lead:	0.096 mg/L
Manganese:	6.68 mg/L

TABLE 6
EXAMPLE 2: SELECTED PARAMETERS NEAR SULPHUR BLOCK

	pH	SULPHATE mg/l
PIEZOMETER 2	6.85 - 7.45	17.1 - 53.4
PIEZOMETER 7	2.57 - 3.49	4320 - 6810
PIEZOMETER 27	2.92 - 4.20	3500 - 13500
PIEZOMETER 32	0.96 - 1.84	4900 - 12300

These results were categorized in the database with the following CSC:

Source: 2 (sulphur block)

Type: C,E,F (sulphur products, metals, and other)

Contaminated Zone: unknown

In summary, two incomplete CSC's were developed for this facility. Both CSC's lacked data on the location of the contamination, as no information on piezometer construction or completion intervals was provided in the data.

Of the 54 plants considered in this study, 13 had insufficient data on record at Alberta Environment to generate complete CSC's. As with this example, information on piezometer construction and hydraulic conductivities of the groundwater bearing zones at the site was most often lacking. The data from this plant suffered also from inadequate definition of background groundwater quality (see Tables 5 and 6). Despite the lack of data, groundwater contamination, particularly in vicinity of the sulphur block, was evident.

Example 3: Plant P-21

Data provided for this plant consisted of a letter addressed to Alberta Environment, with attached groundwater monitoring data for December 2, 1986.

Water samples from three wells, nos. 1, 2, and 3, were tested for pH, sulphate, chloride, and TOC concentrations only. Based on the data quality rating system described in part II of this report, these data were assigned a data quality index of 3, as this type of analysis offers no opportunity for a check of analytical accuracy (ion balance). Depth to groundwater surface from the top of the standpipe was also provided (without height of standpipe stickup from ground level).

Groundwater quality results are summarized in Table 7. No other data were available. With such limited information, development of full CSC's was not possible. Based on the variability and absolute values of TOC in the available data, the possibility of groundwater contamination by dissolved organics was indicated, however the source and location of possible contamination were unknown. The following CSC was recorded in the database, backed up with all the available data:

Source: 9 (unknown)
Type: B (dissolved organics)
Contaminated Zone: unknown

This facility is another, albeit more extreme, example of plants for which very little data was available from Alberta Environment, and only partial CSC's could be developed. Clearly, submission of water quality data without any information on how and from where samples were taken, and considered without the frame of reference provided by data on the hydrogeological setting and flow regime at the site, is of little value (Barcelona et al, 1985).

TABLE 7
EXAMPLE 3: AVAILABLE HYDROCHEMICAL DATA

	WELL #1	WELL #2	WELL #3
pH	7.48	7.42	6.62
SULPHATE, mg/l	170	310	175
CHLORIDE, mg/l	4	4	5
TOC, mg/l	24	84	45

3.1.6 Discussion

As described in the previous sections, groundwater monitoring data provided for the study was reviewed and assessed using a set of criteria developed for this study, and where possible the presence, source, nature and location of contamination were determined. These three factors were combined to produce contamination situation classifications or CSC's for each occurrence of contamination at a given gas plant.

Clearly, one concern in the assessment process was the completeness of data provided for the study. Although Alberta Environment provided all data available to them, several reports included on their original list were missing, and could not be traced in time to be included in the study. In addition, there were no indications given as to the completeness of the records provided to Alberta Environment by plant operators. Although several facilities had very little or no data on file, it is possible that additional information has been gathered by plant operators and had not been requested by or offered to Alberta Environment.

Because of these circumstances, there exists in the data a slight correlation between the completeness of the monitoring data available for a given facility and the number of contamination situations identified there. Incomplete data led to incomplete CSC's. Small monitoring networks which did not cover all areas of possible contamination, or networks improperly installed (piezometers completed above the uppermost groundwater bearing zone and perennially dry, for example), consisting of only a few piezometers, may well have failed to detect all groundwater contamination present. In light of this, the data presented as a result of this review should not be taken solely as an indication of the relative care with which plants have controlled and disposed of plant wastes and by-products, but rather the relative degree to which they have attempted to assess the subsurface contamination present at their sites.

Two of the main objectives of this study were the determination of the most common contamination situations at Alberta sour gas plants, and the identification of candidate sites for possible subsurface remediation demonstration projects. Despite the variability in the data available for different plants, these goals were not jeapordized. Within the context of the study group of 54 sour gas plants (of which 32 had sufficient data for full CSC determination), the relative frequency of occurrence of various contamination sources, types and locations could be satisfactorily determined. These results are discussed fully in Section III.3 of this report. Possible candidate sites were compared only after data availability and completeness were addressed.

Seriousness

The seriousness of contamination situations identified at gas plants was not explicitly considered in this study, nor was it included as a parameter in the database. Determination of the "seriousness " of a given contamination problem is somewhat subjective, unless based on some firm guidelines, criteria, or action levels. Such guidelines are not presently available in Alberta, and development of criteria for assessing the seriousness or degree of concern to be attached to a given contamination situation is beyond the scope of this study.

Many factors should be considered when attempting to determine the "seriousness" of a subsurface contamination problem. These would include:

- the types, mass, concentrations, toxicity, and chemical behaviour of the contaminants.

- the nature of the geologic material in which they are contained.

- the proximity of other users of water and land, or areas/features of environmental significance.

- the hydrogeological regime of the area, including groundwater flow rates, patterns, and directions.

- the results of detailed risk analysis studies.

Information of this sort was limited in the data provided by Alberta Environment for this study. A few gas plants provided information on nearest users of groundwater, including distances to and locations of nearby wells, or proximity to nearby surface water bodies. Risk analyses were not conducted for each plant as part of this study, and in fact, much more data would have been required if such a task was to be satisfactorily accomplished.

Despite these facts, determination of risk and possible impacts associated with subsurface contamination are an important part of the overall assessment of a contaminant problem. Risk analysis is necessary to determine how , when and where subsurface contamination may impact others or the environment. Without this information, informed decisions on the need for remediation are difficult to make. Indeed, in some instances a contamination situation which may appear relatively serious at first examination, may prove to pose no threat to individuals or the environment, after detailed study. Such a conclusion could redirect remediation funds to other higher risk contamination problems requiring immediate attention.

Risk analysis studies (specifically the assessment of potential future migration patterns and rates of contaminant plumes, and determination of the types of substances involved and their expected concentrations under various scenarios) may be conducted at certain facilities where contamination situations of particular concern exist. Conditions requiring risk assessment could include presence of certain dangerous substances in the plume, proximity of groundwater users or major rivers, etc. In this way, the "seriousness" of contamination situations could be objectively evaluated for each facility on an individual basis. This would avoid the potentially dangerous use of strict blanket-type guidelines or criteria developed for the province as a whole, and promote case-by-case review of situations.

3.2 ASSESSMENT OF SOIL/ UNSATURATED ZONE CONTAMINATION

Contamination in and around sour gas plants in most cases begins by facility process materials, products and wastes being deposited on the ground surface by spillage, uncontained storage or storage in landfills. Uncontrolled and/or unremediated contamination of the unsaturated (soil) zone may eventually lead to contamination of shallow groundwater.

Unsaturated zone contamination will tend to act as a continuous source of groundwater contamination, as compounds are mobilized and flushed towards the groundwater surface by infiltrating precipitation.

3.2.1 Available Information

No data on soil sampling programs was contained in the documents provided by Alberta Environment for this study. However, considering the importance of this type of information in an overall assessment of monitoring and remediation effectiveness, a decision was made to collect information directly from plant operators. A form letter was sent out to seventeen representatives of firms involved in sour gas processing in Alberta, requesting available soil sampling data in and around sour gas plants. Assurances were given that the data would remain confidential. The letters were followed up with telephone calls. Inclusion of this additional task resulted in an extension of approximately two months to the project schedule.

The response to the data requests was not overwhelming, but sufficient data was collected for at least a preliminary view of the nature of unsaturated zone contamination at Alberta sour gas plants. In total, twelve reports from seven gas plants were collected. At the time of report preparation, promises of additional data were still outstanding. Many operators, on being contacted, explained that no such testing had been done.

All other information reviewed on soil quality in and around sour gas plants was derived from reports produced as part of soil sampling programs completed either as a partial requirement for the plant Clean Water License or as part of a facility remediation/decommissioning program.

Soil data as represented in the reports reviewed were from a variety of areas at the sour gas plants (many of which may have been disturbed during facility construction. These areas were:

- landfills including waste materials and soils mixed during placement and backfill;
- sulphur block pads;
- surface drainage ditches excavated into the final grade material or native soils depending on site preparation;
- process water ponds (sludges and underlying soils) excavated into native material;

- surface water runoff ponds (sediments and underlying soils) for process areas and sulphur block areas;
- waste pits (waste material and underlying soils) excavated into native material;
- scrapyards/boneyards
- main process areas
- rail loadout sites
- light hydrocarbon/condensate loadout areas

The common feature of all data reviewed is that they were representative of the unsaturated zone at the facility. For the purpose of this review the unsaturated zone was considered as that portion of the surficial material above the upper most saturated zone and included the A, B and C soil horizons. The words "soils" and "unsaturated material" are used interchangeably.

3.2.2 Methodology

Information from the collected reports was compiled and organized according to location within the gas plant.

Soils data was extracted from reports and compiled in a spreadsheet format, as shown in Figure 8. Data was then reviewed and contamination situations developed based on criteria discussed in the following section. A data quality rating was assigned to each sour gas plant data set. A value of 1, 2, or 3 was assigned; 1 if background data was available and a description of analytical methods were provided, 2 if background data but no analytical method information was provided, and 3 if neither were available.

No soils field was established in the groundwater monitoring database, as the information was not in the public domain, and was returned to the

FIGURE 8
EXAMPLE OF FORMAT USED FOR SUMMARIZING AND ASSESSING SOIL DATA

PLANT NAME	FACILITY LOCATION	SOIL PARAMETER	BACKGROUND RGE. 0-80cm	CONTAMINANT LEVEL	CRITERIA LEVEL FOR CLEANUP	DATA QUALITY	COMMENTS
P - 49	RUNOFF BASIN	pH	7.1-7.3	1.7-8.3	6.0-8.0	1	
		EC	0.6-1.2dS/m	2.2-27.4 dS/m	>4.0 dS/m		
		Na	0.2-0.5 mg/l				
		K	0.03-0.33 mg/l				
		Ca	5.5-10.0 mg/l				
		Mg	0.9-2.7 mg/l				
		SAR	0.1-0.2				
	EVAPOR. POND	EC					
		Hg		2.6 ug/g			
	LANDFILL	pH	7.1-7.3	4.2-7.9			
		EC	0.6-1.2dS/m	3.1-8.3 dS/m			
		HC		2.2-6.2 %	2% tot. HC		
		Cd		1.1-4.8 ug/g	4.0 ug/g		
		Cu		72-920 ug/g	250 ug/g		

companies at the end of the project.

3.2.3 Assessment Criteria

The criteria used to assess whether the unsaturated zone was contaminated were applied on a case by case basis, depending on the data available. Wherever possible the criteria used were based on background soil quality data. When background data was not available, site specific criteria adopted by the source report authors for the clean-up of contaminated soils were used. Both background and clean-up criteria levels were established where possible and entered onto the data sheets (see Figure 8).

The use of background soil data was the preferred method for two reasons:

1. When soils contamination is assessed for clean-up and only those sites where values exceed a set of criteria are provided many low level contamination problems could be overlooked. Although acceptable for remediation purposes, in no way do these types of data provide an indication of the extent of soil contamination. Therefore no accurate correlation between total soil contaminant loading and groundwater contamination could be determined for the facilities reviewed.

2. Depending on waste disposal and product storage practices, soil contamination at a sour gas plant operating over a period of 20 years could be extensive. Contaminants present in soil will tend to migrate downward over time, depending on the properties of soils, the annual moisture input, and the nature of compounds involved. Eventually, contaminants may be introduced into the saturated zone. Soil samples collected 20-30 years after contamination originally began, are therefore not representative of

natural soil properties. Background samples are necessary to determine the ability of contaminants to move through soils and the soils' contaminant absorbtion potentials.

3.2.4 Generation of Soils Contaminant Situation Classification

For each sour gas plant the sources and types of contamination were determined. From this information a number of contamination situation classifications were developed. Wherever soil parameters were elevated either above background values or above clean-up criteria a contaminant situation classification was assigned. CSC development follows the procedures outlined in Section 3.1.5, and summarized in Figure 7.

The only difference in the CSC system for soils is the addition of two contaminant type designations. Contaminant types used in the soil contamination situation classification system were:

A. Free Hydrocarbons
B. Dissolved Organics, other organics
C. Main ions
D. Sulphur
E. Metals
F. Other, including Herbicides/Sterilants
J. depressed or elevated pH
K. Elevated Sodium Absorption Ratio (SAR)

The contamination situation classifications developed through review of the soils reports provided are shown in Table 8.

3.2.5 Example

Figure 8 shows the data extracted from site decommissioning reports compiled for Plant P-49. Data was compiled from all available reports. Contaminant situation classifications were assigned to each area of the gas plant. For example, a number of contaminants could be present in different samples around the landfill sites. All the data for these

TABLE 8
SUMMARY OF SOIL CONTAMINATION SITUATION CLASSIFICATIONS
AT SELECTED SOUR GAS PLANTS IN ALBERTA

PLANT IDENTIFIER	CONTAMINANT CLASSIFICATION			DATA QUALITY
	SOURCE	TYPE	ZONE	
P - 49	3	J	I	1
	4	C,E,J	I	
	6	C,E,J	I	
	2	C,E,J	I	
	1	C,E,J	I	
	5	A,C,D,J	I	
	6	A,C,D,J	I	
	3	B (organics)	I	
P - 20	2	C,D,E	I	2
	5	C,J	I	
	6	A,C,J,K,E,C	I	
	3	A,C,D,J	I	
	4	A,C,J,E,C	I	
P -37	2	J	I	2
	3	J	I	
	4	J	I	
	1	B	I	
	6	A,C,J,K,E,C	I	
P -35	1	A,E	I	1
	2	A,C,D,J	I	
	6	A,C,J,K,E,C	I	
P - 51	6	A,C,J,K,E,C	I	1
P -43	2	D	I	3
P -42	6	A,C,J,K,E,C	I	2

samples were condensed into a single contaminant situation where applicable. The plant landfill area, therefore, was assigned a contaminant situation code of 5 A,C,E,J (I), indicating hydrocarbon, main ion, metal and pH contamination originating from the landfill. The contamination extended down from 30 cm below the ground surface.

There were insufficient data to develop any definitive conclusions regarding the precise nature of unsaturated zone contamination at the facility.

3.2.6 Discussion

Determination of soil contamination in and around a particular sour gas plant is a difficult task if no information on soil type and background quality is available. A review of sour gas plant soils data available through the AMD-81, AMD-86, AMD and other available soil reports would be necessary before a more detailed assessment of soil contamination at sour gas plants could be undertaken.

Many instances of groundwater contamination are a result of vertical movement of contaminants through the unsaturated soil column into the upper saturated zone. Accurate background soil data is necessary to provide an understanding of how contaminants will interact with and move through the soil column.

Although limited, the available information suggests that soils will often become contaminated as a result of sour gas plant operations. Without the occurrence of such contamination, little groundwater contamination would be evident.

Data indicates that all areas of operation may contribute to soil contamination. In many cases this is likely the result of leaking or unlined process water ponds, spillage at loading areas, and landfilling of solid and semi-solid waste streams. Some of these practices have either been discontinued or are being phased out.

As discussed previously, the number of data available on soil sampling at sour gas plants was limited. Several operators indicated that such information was scarce, and in some cases non-existent. It must therefore be concluded that systematic sampling of soils at and around sour gas plants in Alberta is not a common practice, and is not regularly done as part of overall monitoring efforts.

Many methods of dealing with contaminated soils are presently available. Removal of contaminated soil and diversion of the contamination source will prevent continued groundwater contamination. Advances in soil treatment technologies in the areas of fixation, bioremediation, and gasification have provided acceptable methods for dealing with contaminated soil, although costs can be high.

3.3 RESULTS OF CONTAMINATION ASSESSMENTS

Available information from each gas plant was reviewed, and contamination situations identified and categorized following the procedures described in the preceding sections. This part of the report summarizes the findings of the assessments, and will present a breakdown of the most common sources, types and locations of subsurface contamination at Alberta sour gas plants.

3.3.1 Reporting Methodology

As described in the previous sections, data available for the plants included in this study was quite variable. Some plants had full data with which to determine contamination situation classifications (CSC's); others had data from which only source and type could be determined; others had no relevant information. Results presented are based on plants for which appropriate data were available only.

It is possible for a single gas plant to have more than one CSC. For example, groundwater contamination of the upper moderately conductive groundwater bearing zone may originate from the landfill in one part of the site, and from the evaporation pond in another, creating two distinct plumes with different contaminants. These would be assigned separate CSC's. Because of this, there are two fundamental ways in which the CSC results can be viewed: by comparing results to the entire set of CSC's (113 full or partial CSC's were identified at 45 gas plants for which information was available), or by tallying the number of gas plants at which a given situation occurs at least once. Both methods are used to present results.

It should be noted, however, that the number of CSC's identified at a given site may also be a function of the level of effort devoted to site assessment, and how much of the collected data was passed on to Alberta Environment. For example, if the site assessment at a given plant did not include monitoring of groundwater downgradient of the sulphur block, no appropriate CSC could be developed. Therefore, the absence of a particular CSC does not necessarily mean that no such contamination is present. The advantage of this is that it provides the results with a measure of built in conservatism. Necessarily, the results represent only those contamination situations which have been detected - and thus reflect the best case at Alberta sour gas plants.

For all these reasons, a tabulation of the number of facilities at which at least one instance of a particular situation has been detected will provide more meaningful results. In this way the effects of varying levels of site assessment are reduced.

3.3.2 Data

Groundwater monitoring documents were provided for 54 Alberta sour gas plants. Of these, 32 contained sufficient data for determination of full CSC's, 13 had data for partial CSC determination only (one or two of the three elements of the CSC could not be determined due to lack of data), 5 had insufficient data for any CSC determination, and 4 had no monitoring systems yet installed (documents consisted of proposals only). This information is shown graphically in Figure 9. Table 9 (found in Appendix II) presents a list of all CSC's generated at each of the S4 plants, along with other relevant information.

Of the 45 plants for which information allowed assessment of the presence of groundwater contamination, only one showed no signs of impact of plant activities on groundwater quality. Figure 10 shows the number of plants at which one, two, three, and four CSC's were determined. Two or more contamination situations were identified at 36 of the 45 plants. From these 45 plants, 112 contamination situations were identified.

Data on soil contamination were collected for 7 sour gas plants. At least one contamination situation was found at each plant (see Table 8). There seemed to be a strong correlation between the amount of sampling done at a given plant and the number of contamination situations which were identified. This is not surprising considering that soil sampling programs are often initiated in response to particular problems which may be suspected at a facility. The plants with the most contamination situations (P-49 and P-20) were also those for which comprehensive sampling leading to plant decommissioning had been undertaken. As described in Section 3.3.2, data from the other five plants were produced as the result of specific and limited sampling programs, such as sampling of pit sludges, analysis of the top 30 cm of the soil horizon downwind of the sulphur block, or scattered sampling of soil near a landfill for the presence of metals.

3.3.3 Sources of Contamination

There was sufficient data available at 42 plants to determine the source of groundwater contamination. Figure 11 shows the number of plants with at least one contamination situation originating from each of the nine source categories (process area, sulphur block area, surface runoff,

DATA AVAILABILITY

from 54 Alberta sour gas plants

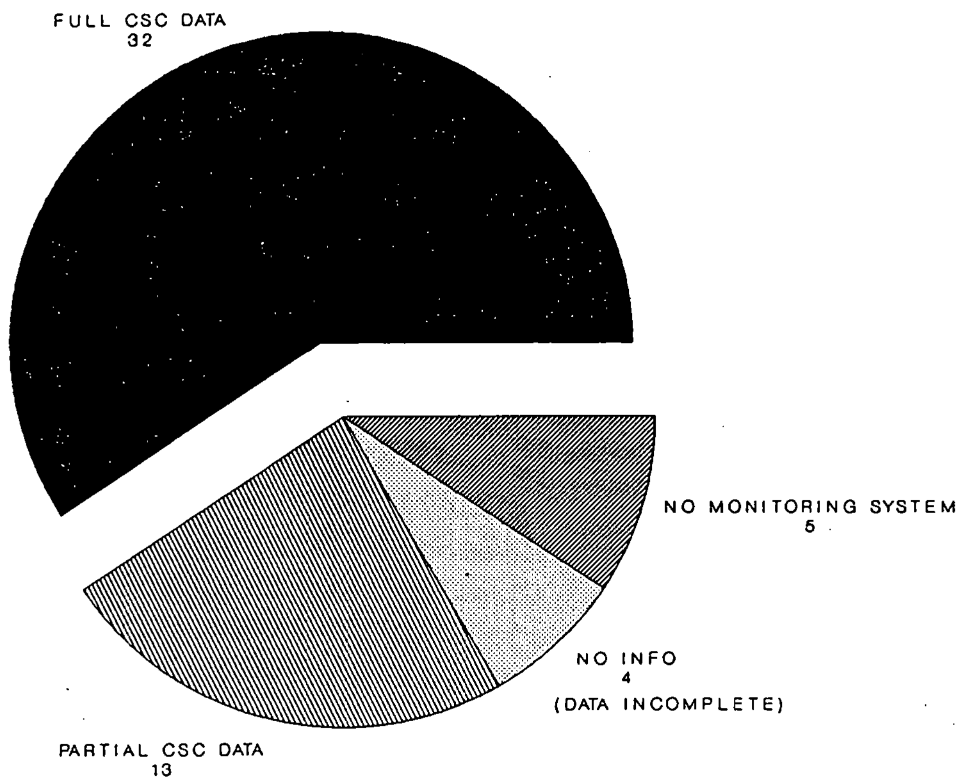
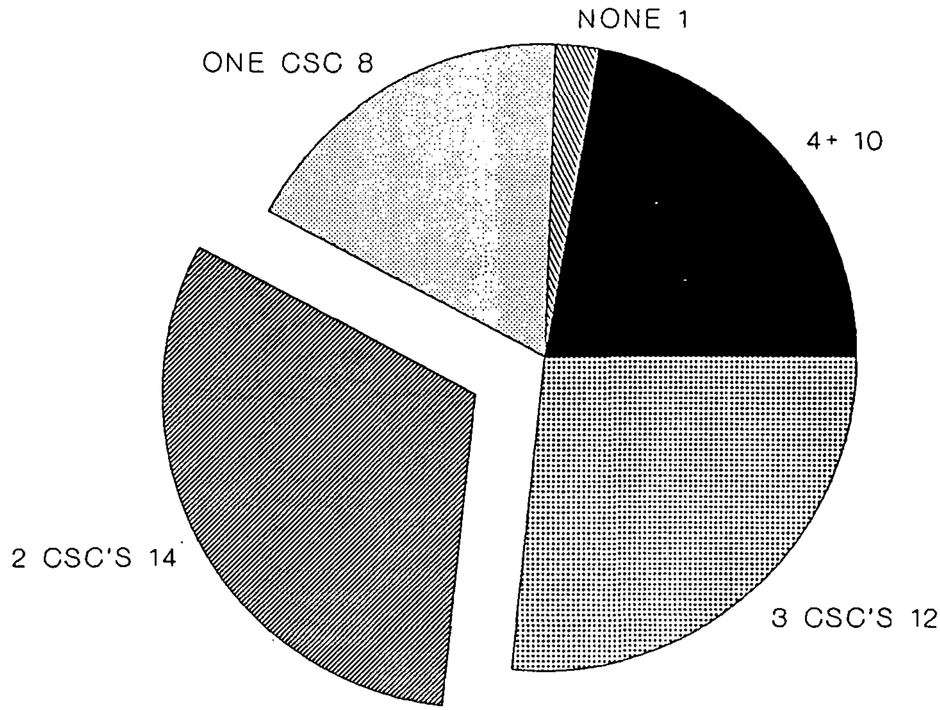


FIGURE 9

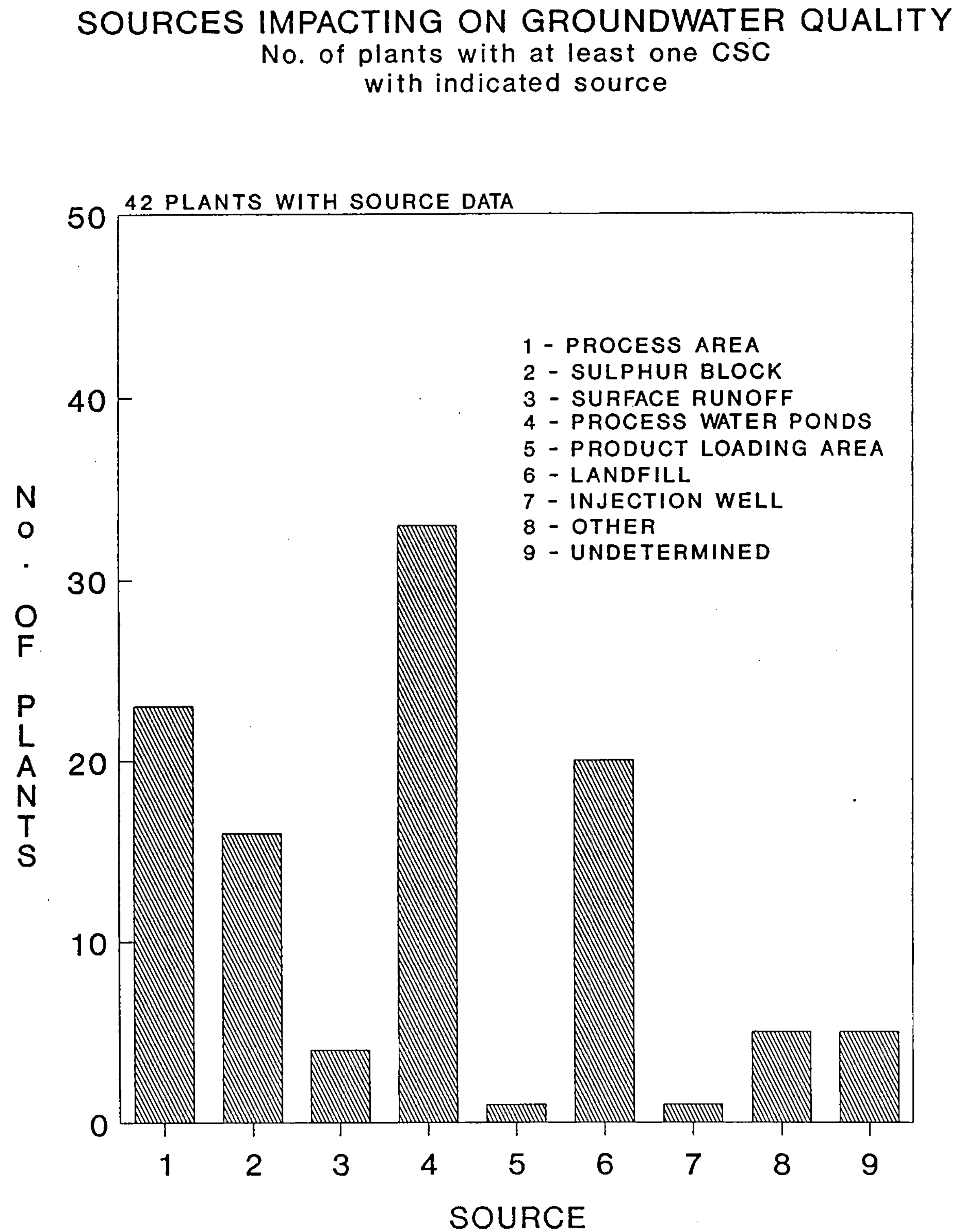
NUMBER OF CONTAMINATON SITUATIONS
determined at each plant



OF 45 GAS PLANTS WITH FULL OR PARTIAL CSC DATA

NOTE: Level of seriousness of impacts are not considered.

FIGURE 10



NOTE: Level of seriousness of impacts are not considered.

FIGURE 11

process water ponds, product loading area, landfill, injection well, other, undetermined).

Thirty-three of the 42 plants (78.5%) had at least one contamination situation originating from the process water/evaporation pond. Twenty three, or about 55% of the 42 plants, had at least one occurrence of groundwater contamination originating from the process area, and 20 had on-site landfills which were impacting groundwater. The sulphur block area was identified as a source at 16 plants, or slightly more than one third of the study set.

Of a total of 111 fully or partially classified contamination situations at these 42 plants, 35 involved process water/evaporation ponds, 24 the process area, and 20 landfills. This information is presented in Figure 12.

The most common source of soil contamination at the seven plants considered was the on-site landfill, identified in at least one contamination situation at six plants. At five of the plants, the sulphur block was the identified source of at least one CSC. Figure 13 shows the breakdown of the most common identified sources of soil contamination.

3.3.4 Types of Contamination

There was sufficient data available at 44 plants to determine the types of contaminants in groundwater. Figure 14 shows the number of plants with at least one contamination situation involving each of the six major contaminant groups (free phase hydrocarbon, dissolved organics, main ions, sulphur products, metals and other).

Main ions and dissolved organics were the most commonly identified groundwater contaminants, being present in at least one contamination situation at 42 and 41 gas plants respectively. Groundwater

SOURCES IMPACTING ON GROUNDWATER QUALITY

of 111 contamination situations at
42 plants with source data

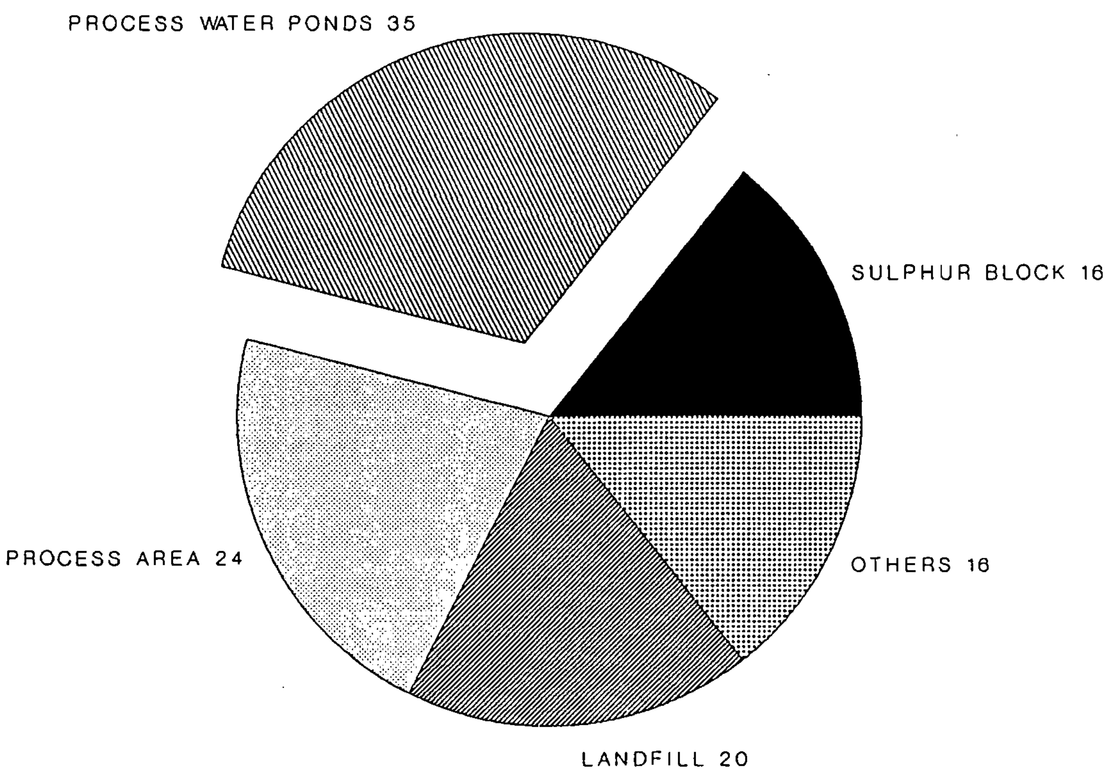


FIGURE 12

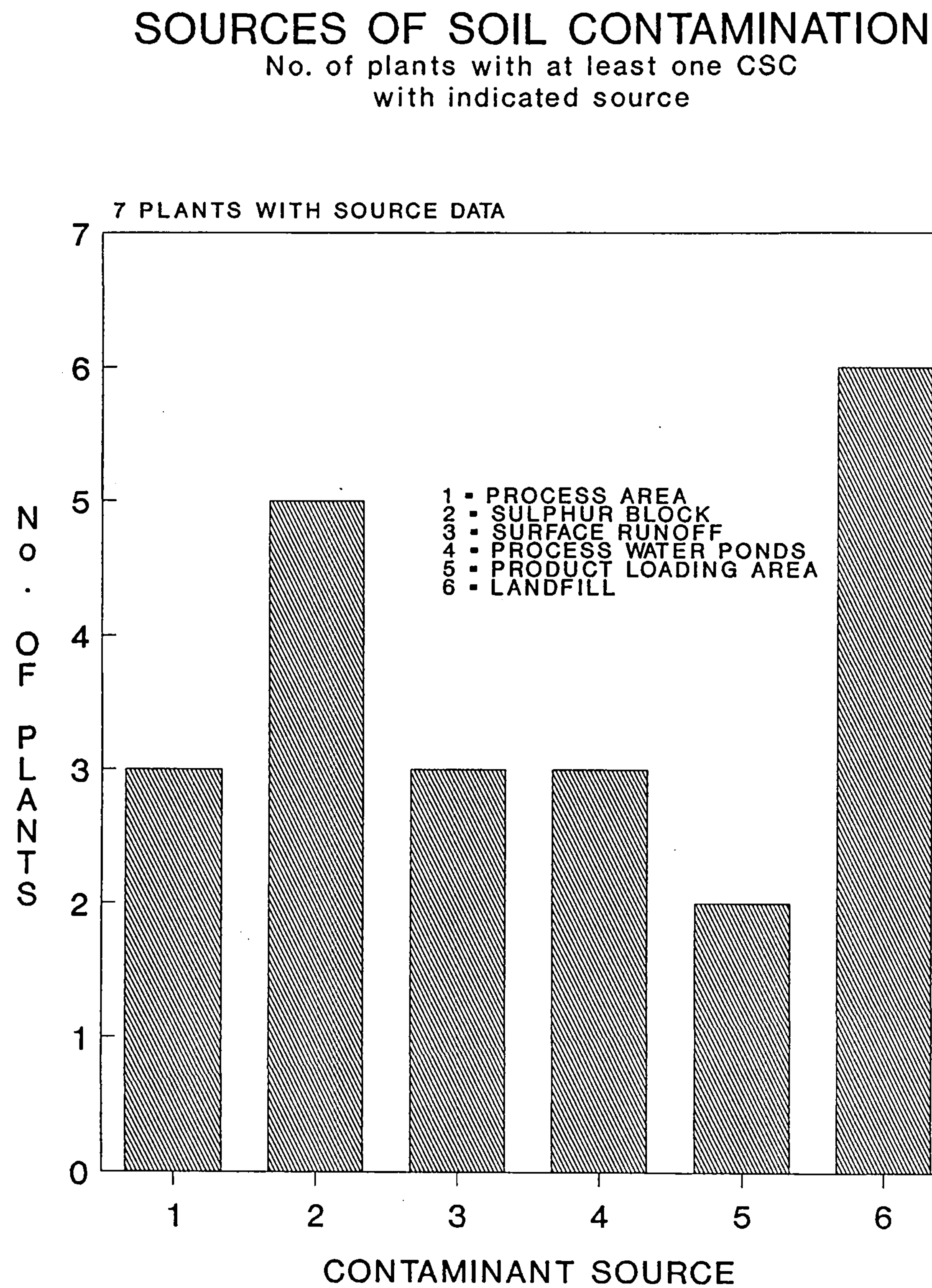
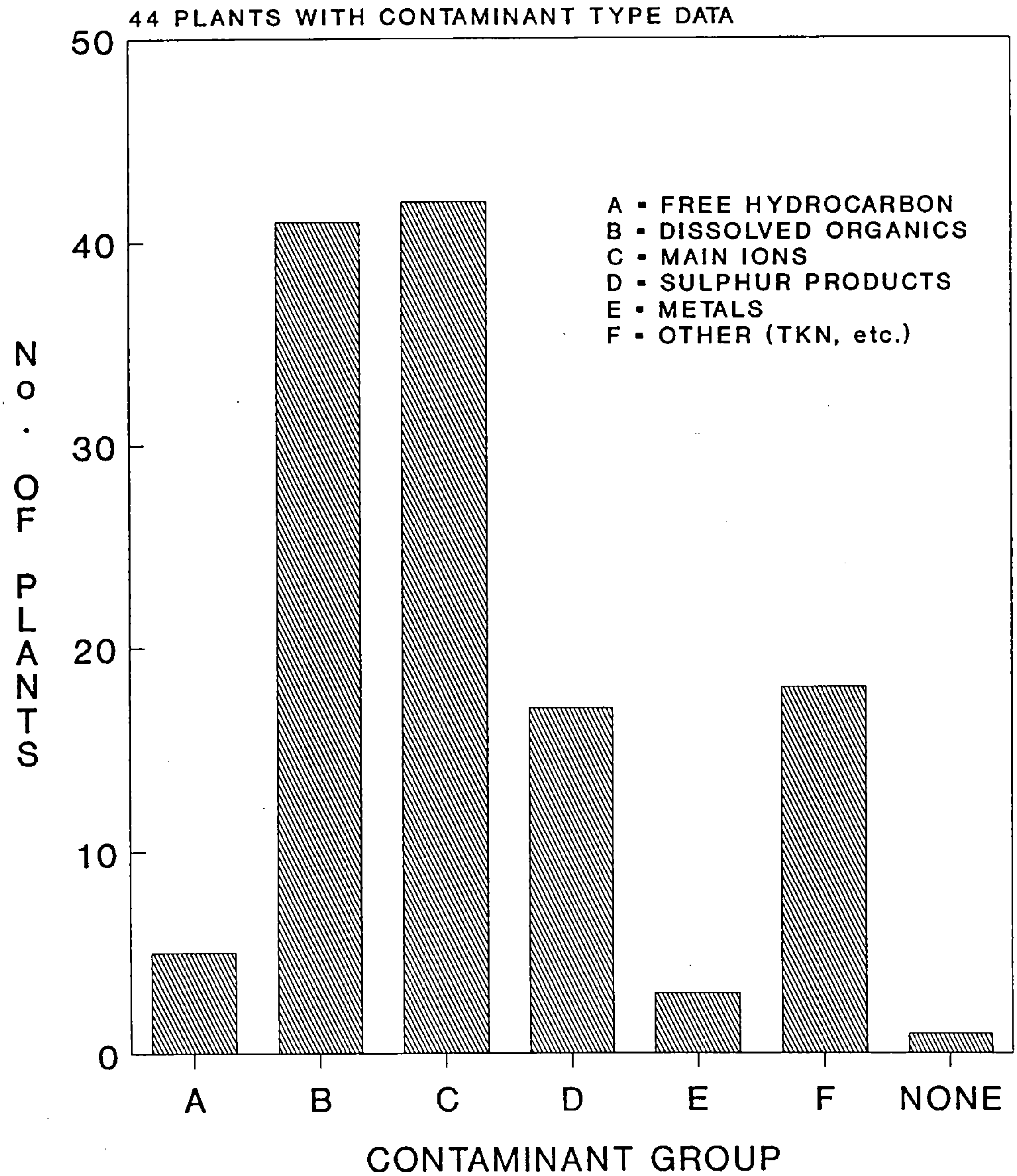

SOURCES OF SOIL CONTAMINATION
No. of plants with at least one CSC
with indicated source
7 PLANTS WITH SOURCE DATA
1 - PROCESS AREA
2 - SULPHUR BLOCK
3 - SURFACE RUNOFF
4 - PROCESS WATER PONDS
5 - PRODUCT LOADING AREA
6 - LANDFILL
No. OF PLANTS
CONTAMINANT SOURCE
0
1
2
3
4
5
6
7

FIGURE 13

TYPES OF GROUNDWATER CONTAMINATION

No. of plants with at least one CSC
with indicated contaminant group



NOTE: Level of seriousness of impacts are not considered.

FIGURE 14

contamination by sulphur products, notably sulphate and in some cases low pH, was identified at 17 of the 44 plants, or about 27%. Free phase condensate was identified at five plants.

Contaminants in groundwater often occurred in combinations. For instance a particular plume emanating from an evaporation pond may have contained main ions, dissolved organics, and metals. All such combinations were recorded during the data review phase. Figure 15 shows a breakdown of the occurrence of the various combinations. Among gas plants in the study set, half (22) had at least one situation where groundwater was contaminated by dissolved organics and main ions.

In total, 111 contamination situations were identified at 43 plants (one plant had no detected groundwater contamination). Figure 16 shows the breakdown of these situations among the most common contaminant type groupings. Again, it can be seen that dissolved organics combined with main ions was the most common contamination situation.

It must be noted that the results are partially affected by the analytical schedules which the various operators chose to run on their groundwater samples. If certain parameters were not analyzed for, they could not be detected, and would not appear in the CSC's. If more comprehensive analyses were to be done, additional contaminant types may have been identified.

Of the 7 plants for which soil sampling information was obtained, 6 exhibited contamination by hydrocarbons, main ions, and metals (landfill pollution). Contaminant type data for soils is summarized in Figure 17. The same caveat regarding the extent of the soil sampling program and the number of CSC's generated, mentioned in the previous section, applies to contaminant type data.

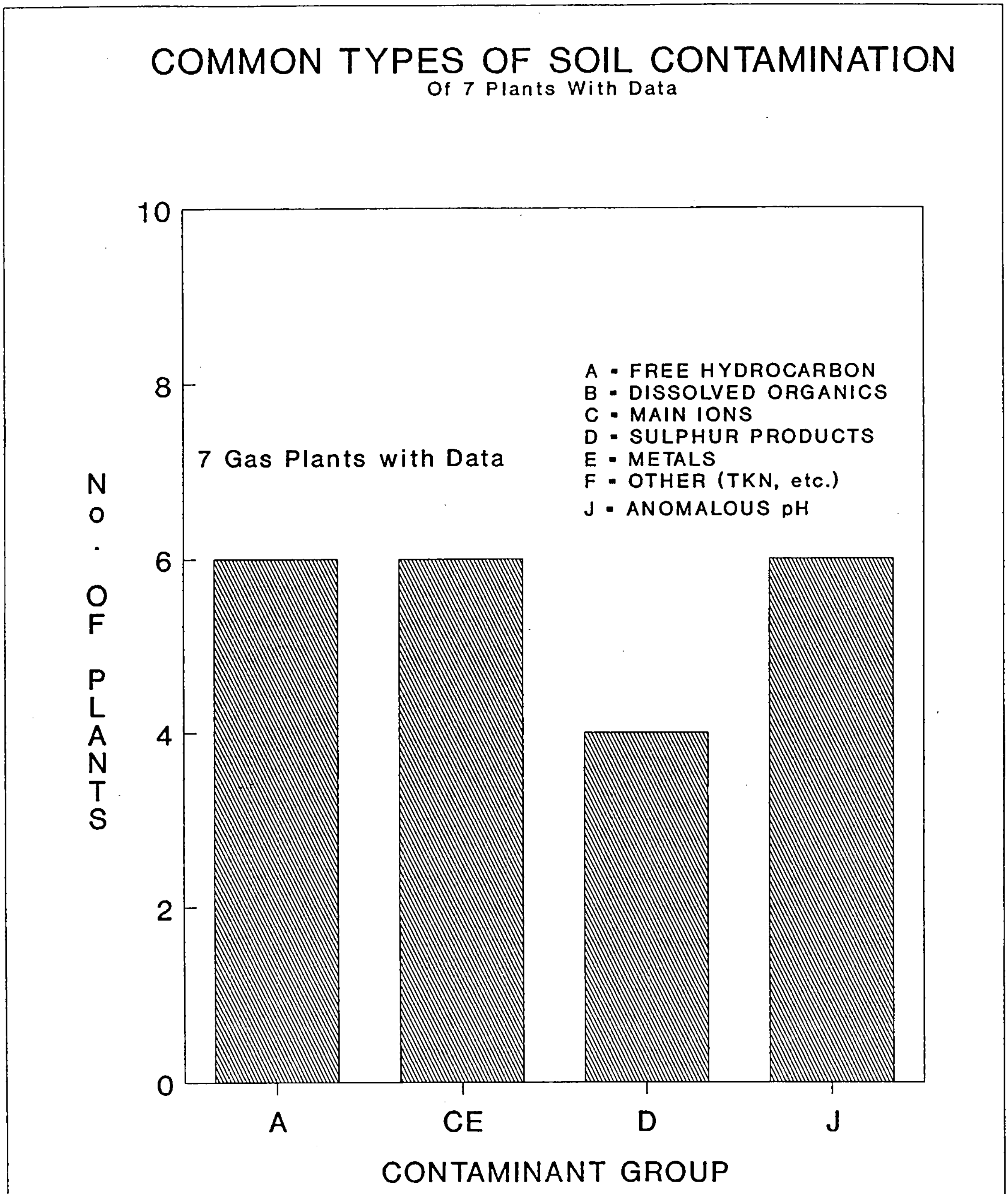

COMMON TYPES OF SOIL CONTAMINATION
Of 7 Plants With Data
7 Gas Plants with Data
A - FREE HYDROCARBON
B - DISSOLVED ORGANICS
C - MAIN IONS
D - SULPHUR PRODUCTS
E - METALS
F - OTHER (TKN, etc.)
J - ANOMALOUS pH
No. OF PLANTS
0
2
4
6
8
10
A
CE
D
J
CONTAMINANT GROUP

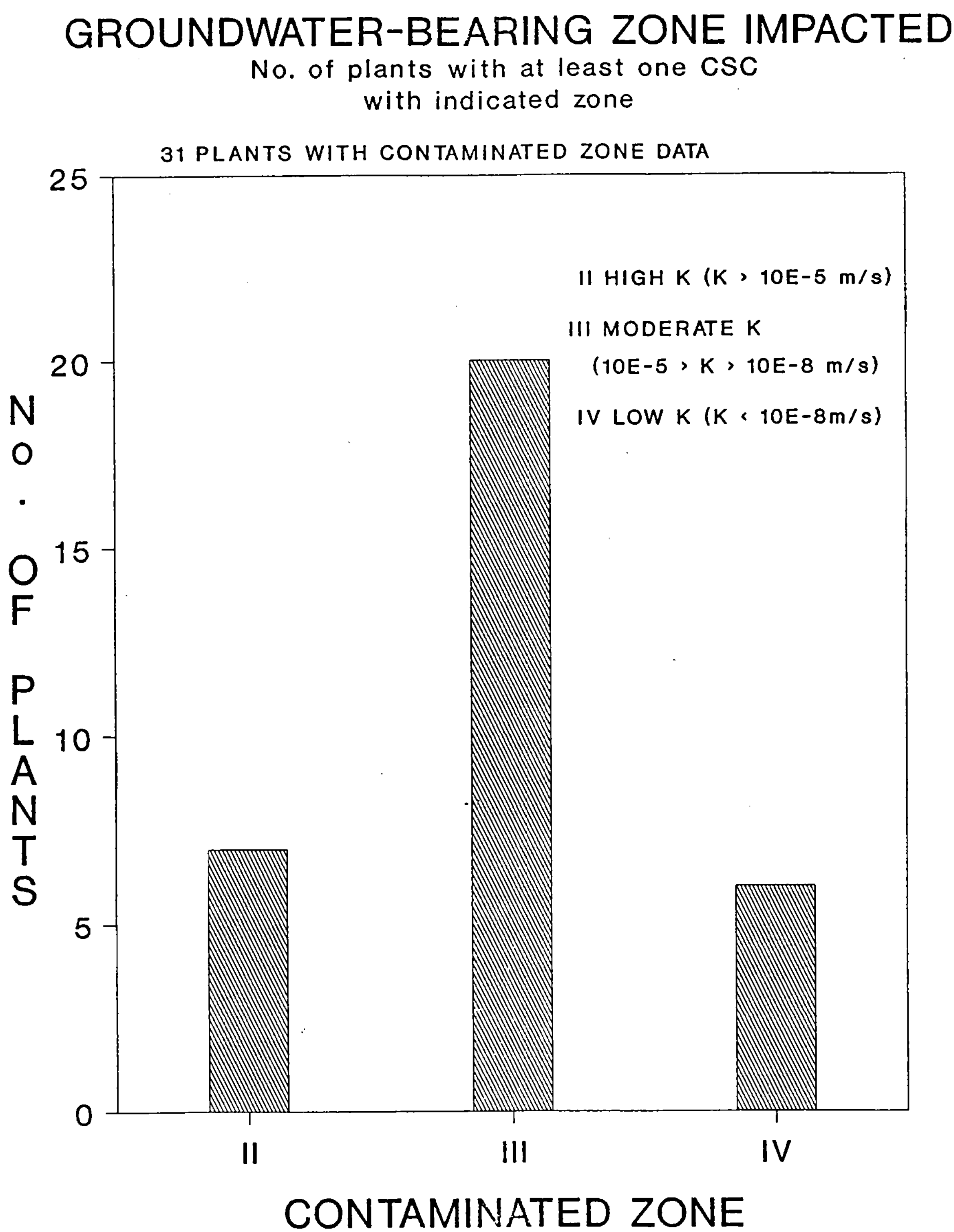
FIGURE 17

3.3.5 Groundwater-Bearing Zone Impacted

Data with which the location of groundwater contamination could be determined was scarcest in the reports provided by Alberta Environment for this study. All of the 13 plants for which only partial CSC's could be generated lacked sufficient data to classify the zone of contamination. In most instances, borehole logs or piezometer construction details were not supplied by operators, making it impossible to determine which groundwater-bearing zone was being sampled. As a result the location of groundwater contamination could be determined at only 32 of the 54 plants in the study group.

As described in Section 3.1.5, zones were classified according to their hydraulic conductivity, to provide some indication of the ability of contamination to migrate away from source. Unsaturated zone (soil) contamination was provided a separate classification (Type I). Figure 18 shows the number of plants at which contamination occurs in each of the three saturated zone classifications. The majority of groundwater contamination situations at Alberta sour gas plants seem to occur in zones of moderate hydraulic conductivity (10E-5 < K < 10E-8 m/s), represented by such materials as inter-till clayey sand and silt layers and fractured bedrock, common in Alberta. These types of surficial materials were also most common at the plants in the study group.

Although directly related to the surficial geology of Alberta, this breakdown does serve to confirm that most groundwater bearing zones which are impacted by sour gas plant operations are not extremely hydraulically conductive, as would be the case if a majority of plants were built on alluvial sand and gravel deposits, or unconfined sand aquifers. Twenty-six of 36 plants had contamination in groundwater bearing zones whose hydraulic conductivity was less than 10E-5 m/s. This helps to put the situation at Alberta sour gas plants into perspective. In the majority of cases, groundwater contamination is unlikely to be migrating at very



NOTE: Seriousness of impact on groundwater are not considered.

FIGURE 18

high rates, depending of course on the hydraulic gradients involved, the influence of fracture permeability, contaminant soil interactions and the accuracy of hydraulic conductivity data provided in reports. However, estimation of contaminant transport rates at the various gas plants was beyond the scope of this study, and should be determined as part of the risk analysis exercise recommended for each gas plant.

Figure 19 shows the total number of contamination situations involving each of the three zones. In total, 79 contamination situations were identified at 31 plants with data on contaminant locations.

3.3.6 Contamination Situations

Contamination Situation Classifications (CSC's) are made up of three elements: source, type, and location. Each of these elements has been discussed separately in the previous sections. The most common source of groundwater contamination at Alberta sour gas plants was the process water pond (4), the most common type of contamination dissolved organics and main ions (BC), the most common zone one of moderate hydraulic conductivity (III).

Despite the large number of possible combinations of CSC's, one would tend to expect that the most common CSC would involve the most frequently occurring categories of each of the three elements. Figure 20 shows that this is exactly the case. The most common CSC at Alberta sour gas plants was 4 BC III. The other most common 20 CSC's were 2 D III (sulphur products in moderate K zone originating from the sulphur block area), and 1 BC III (dissolved organics and main ions in moderate K zone originating from the process area).

Table 10 shows grouping of similar CSC's. Situations involving dissolved organics and main ions, alone or associated with other aqueous phase contaminants such as metals and nitrogenous compounds, originating from process water ponds and located in moderate K groundwater bearing zones

GROUNDWATER-BEARING ZONE IMPACTED

of 79 contaminant situations
at 31 plants with zone data

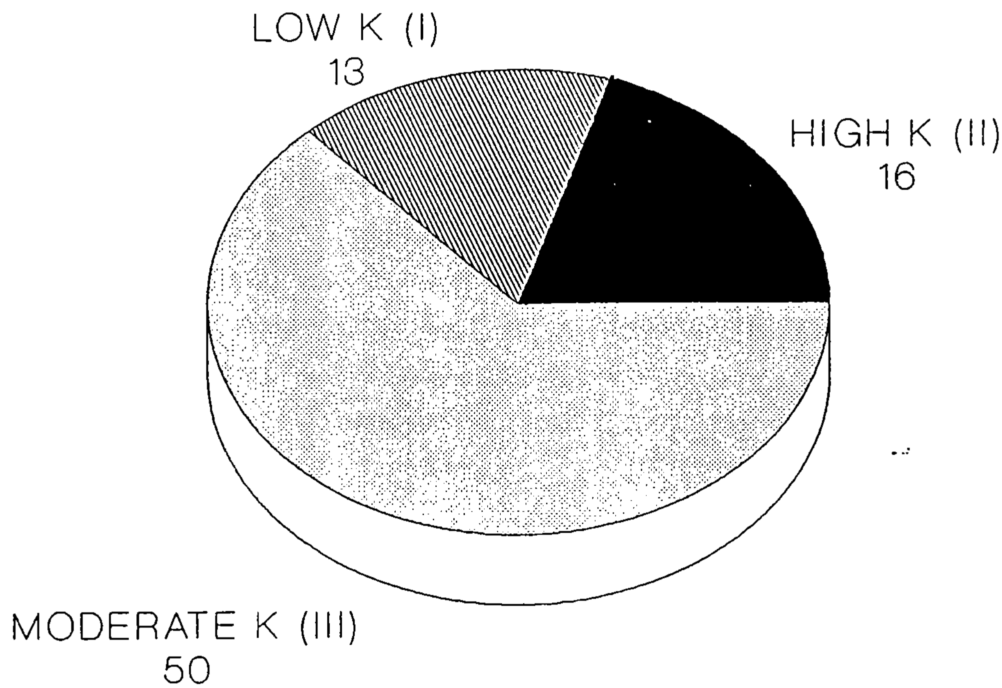
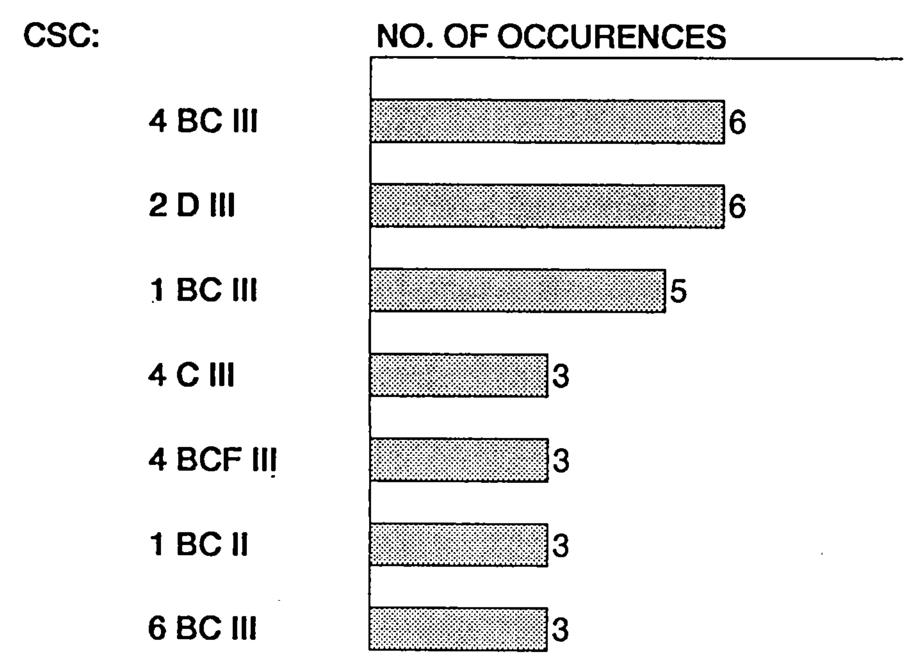


FIGURE 19

FIGURE 20
MOST COMMON CONTAMINATION SITUATIONS
AT ALBERTA SOUR GAS PLANTS
of 83 situations at 32 plants with full CSC data



4 BC III: SOURCE (4) = PROCESS WATER POND
TYPE (BC) = DISSOLVED ORGANICS + MAIN IONS
ZONE (III) = MODERATE K

occur at 15 of the 32 plants. this type of situation is clearly the most common at sour gas processing facilities in the province.

Table 10 also shows the group of CSC's which involve free phase hydrocarbon contamination in moderate or high hydraulically conductive aquifers, from a variety of sources. Although this group included only five of the 32 plants, the relative concern attached to this type of contamination makes it of particular interest to this study. Free phase hydrocarbon contamination is difficult and expensive to remediate, and very low levels of dissolved hydrocarbon render water unfit for human or animal consumption.

Review of soils data also indicates that contamination of the unsaturated zone by hydrocarbons may be a common situation. Six of seven plants reviewed had some form of soil hydrocarbon contamination.

3.3.7 Trends in Contamination Situations

Contamination situation results at sour gas plants were reviewed and compared to a number of different parameters in an attempt to discover any trends that may have existed in the data.

No meaningful correlations were found between the type or thickness of geologic materials composing the surficial materials and the incidence of groundwater contamination at plants of the study group. This is not surprising, as clay and silt till are the dominant surficial types, present at over half of plants for which information was available. This prevalence of a single surficial material type makes meaningful comparisons based on this parameter difficult.

Similarly, the greatest incidence of groundwater contamination was found at sour gas plants using refrigeration and diethanolamine processes, which were present at 39 and 18 of the 48 plants for which process type was determined, respectively. This result is likely due to

TABLE 10
CONTAMINANT SITUATION GROUPINGS
OF 83 SITUATIONS AT 32 PLANTS WITH FULL CSC DATA

GROUPING	EXPLANATION	No. OF SITUATIONS
1. 4 M III 4 N III 4 O III 4 P III 4 C III 4 B III	Situations with: Source = Proc. ponds Zone = mod K aquifers Types = dissolved organic and main ions, alone or with other dissolved contaminants	15
2. 2 D III 2 D II 2 D IV	Situations with: Source = Sulphur block Type = Sulphur products Zones = all groundwater bearing zones	9
3. 5 A III 9 A III 1 T III 7 T II	Situations with: Free phase hydrocarbon (+/– other contaminants) in moderate or high K groundwater zones	5

the prevalence of these particular processing methods in the Alberta sour gas industry, rather than any significant link between process type and subsurface contamination.

No trends in the areal distribution of sour gas plants and the types or numbers of contamination situations present at the plants were noticed. Intuitively, it should be expected that other factors such as the design of and maintenance of waste disposal facilities, the volumes and concentrations of wastes produced, and the waste and product handling practices in place at the site will have the greatest bearing on subsurface contamination at a given facility.

Figure 21 shows a plot of facility start date (corresponding to plant age) against the number of groundwater contamination situations identified at the facility. The single plant with no detected groundwater contamination was built in 1985. Eight of the nine plants with four or more contamination situations were built before 1964, and no plants built since 1971 had four CSC's present. The data exhibits a loose correlation: the older a plant, the more likely it is to be experiencing or to have several contamination situations.

3.4 SUBSURFACE REMEDIATION AT ALBERTA SOUR GAS PLANTS

3.4.1 Data Available

In total, information was obtained on subsurface remediation programmes at five sour gas plants in Alberta. Of these, two were primarily soil remediation operations (plant decommissionings), and three were groundwater remediation schemes currently installed at operating facilities.

Data obtained by Piteau Engineering contained only technical information, such as:

PLANT START-UP DATE
Vs.
OF CONTAMINATION SITUATIONS IDENTIFIED

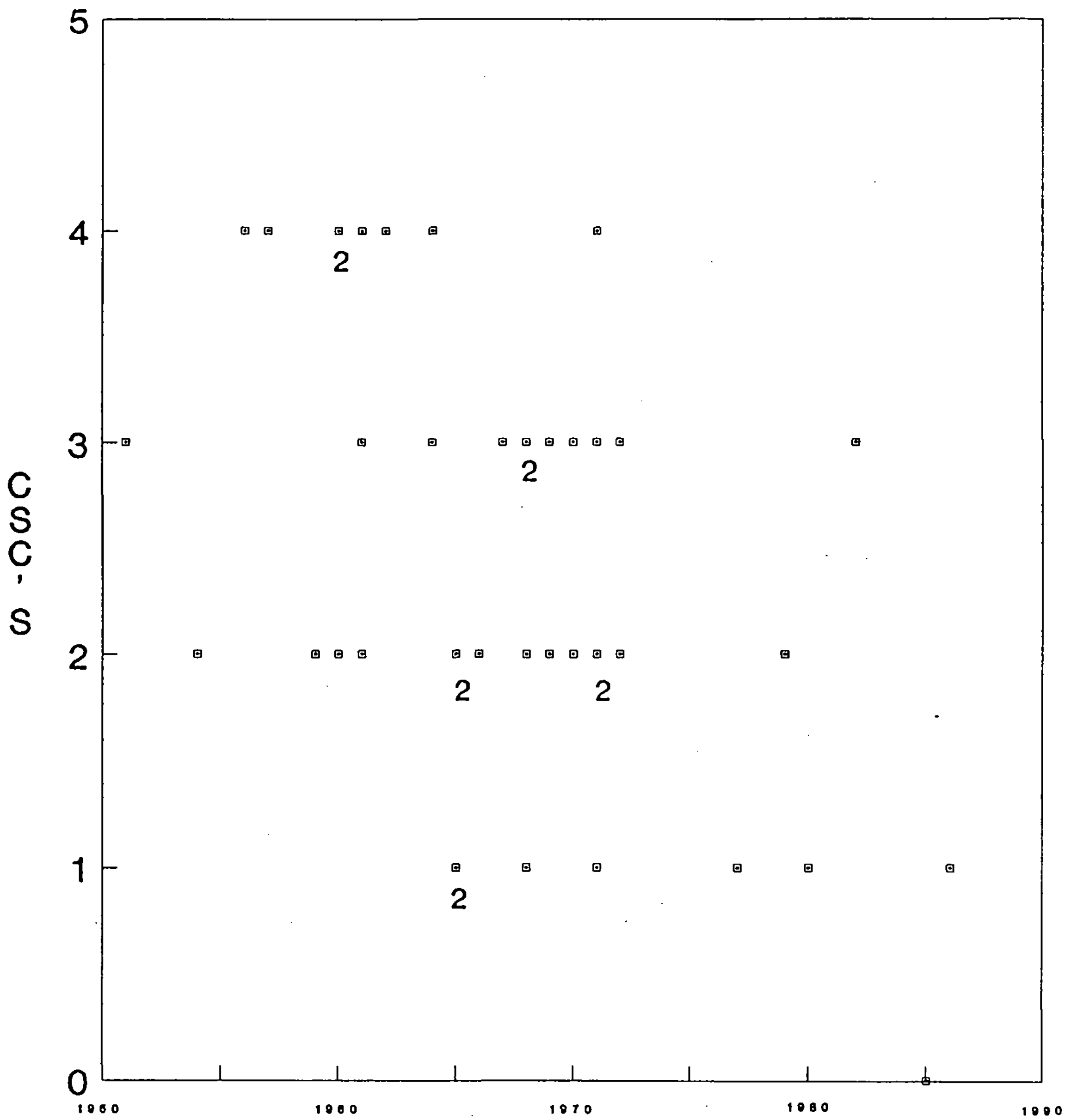


FIGURE 21

- types of contaminants present: immiscible, dissolved in groundwater, soil contaminants;

- remediation system design, construction and implementation details;

- third party costs related to system installation;

- some information on system rationale.

Information on recovery rates, system efficiencies, operational procedures and operating costs, could not be obtained.

3.4.2 Assessment of Available Data

Considering the data available, development of a rigid set of criteria for the assessment of the applicability, efficiency and effectiveness of remediation systems was not practical. Instead, for each plant an attempt was made to:

- determine the target of remediation - what contamination situation is being cleaned-up?

- identify the exact nature of contaminants involved - free phase hydrocarbons, toxic organics, main ions, etc.

- establish the physical properties of the contaminated zone, including geologic and hydrogeologic parameters,

- assess the contamination migration potential;

- evaluate the remediation techniques being used in relation to the target contamination situation;

- determine methods used for treatment and disposal of recovered material;

- assess the efficiency of the recovery/remediation system and the level of clean-up achieved;

3.4.3 Case Histories

Detailed assessments of the three groundwater remediation systems and one of the soil remediation operations for which data were available are presented. Of the plants involved, three (P-48, P-53, and P-54) are situated in the Rocky Mountains - Foothills physiographic region, and one (P-49) is found in the Alberta Plains physiographic regions. These regions are characterized by different topography, drainage, and geology, all of which can have an effect on the selection, design and operation of remediation systems. A summary of Subsurface remediation programs at Alberta sour gas plants is provided in Table 11.

Case History 1: Plant P-48

Background and Recovery System Design

A contaminant recovery system was installed in about 1972, and consisted of five large diameter wells designed to intercept gas condensate which had leaked from a broken pipeline. The recovery wells formed a passive system, as the low hydraulic conductivity material in which the condensate was found made continuous pumping impractical.

Systems of this type are useful when contaminants are found in groundwater-bearing low hydraulic conductivity tills and inter-till sand and silt lenses, a common situation in Alberta. Indeed, the results of this study indicate that over 75% of groundwater contamination at Alberta sour gas plants occurs in

TABLE 11
SUMMARY OF SUBSURFACE REMEDIATION ACTIVITIES

PLANT IDENTIFIER	REMEDIATION TARGET	TYPE OF CONTAMINANTS CSC	REMEDIATION SYSTEM				TREATMENT AND DISPOSAL METHOD	REMEDIATION EFFECTIVENESS	COST OF SYSTEM OPERATION
			DATE INIATED	REMEDIATION METHOD	OPERATION PERIOD	TYPE OF OPERATION			
P - 48	Immiscible fluids	Gas condensate	1972	Large diameter wells	1972–present	periodical	Recycle hydrocarbon contaminated water to waste water treatment facility	Condensate discharge into adjacent creek valley reduced to zero. Condensate inflow to wells reduced from significant volume to trace (odour)	No data available from Alberta Environment
P - 54	Immiscible fluids Contaminated groundwater	Gas condensate Dissolved organic compounds Dissolved inorganic compounds	1986	Small diameter wells	1986–present	Seasonal (summer)	Contaminated water to waste water treatment facility	Considerable volume of contaminated water removed from formation. Expansion of the remediation system required	No data available from Alberta Environment
P - 53	Contaminated groundwater	Dissolved organic compounds (process chemicals) Dissolved inorganic compounds	1986	Small diameter wells	1986–present	Continuous	Contaminated water stored in tank on site and trucked to injection well	Considerable volume of contaminated water removed from formation. Expansion of the remediation system required	No data available from Alberta Environment
P - 49	Contaminated soils assoc. with evap. ponds and pits	Free product, organics, main ions, sulphur	1988	Excavation	1988–present	Decommissioning	Removal of material to secure landfill	All identified contaminated soil removed from landfill and ponds Groundwater contamination not addressed	No data available
P -35	Contaminated soils and sludges. Sulphur contaminated soils, landfill	Sulphur products Hydrocarbon product, and process chemicals in soils metals in sludges	1983	Excavation Experimental bioremediation studies	1983–85	Decommissioning	Removal of material to secure landfill	All identified contaminated soils removed Low levels of groundwater contamination deemed non-toxic and relatively immobile remain	No data available

zones of low and moderate hydraulic conductivity (>10E-5 m/s). In these situations, conventional recovery wells may be pumped dry after only a few minutes. Large diameter wells, 0.9 metres or more in diameter, are periodically pumped dry, inducing flow of contaminated groundwater towards the well.

It is not known if any investigations of soil/unsaturated zone contamination were conducted. No information on any soil clean-up activities associated with this spill was available.

Treatment and Disposal of Produced Fluids

At Plant P-48 the recovered hydrocarbon liquids were recycled, and produced groundwater was disposed of into an appropriate waste treatment facility prior to discharge to surface drainage and an irrigation system.

Contaminant Recovery

Volumes of recovered condensate have decreased steadily with time since 1972, and in 1989 only condensate odour was present in the wells. Condensate seeps previously noticed in a nearby valley disappeared before 1985.

Assessment of Clean-up Level

There is no data with which to assess, in quantitative terms, the effectiveness of the remediation system. However, it is clear that condensate discharge to the valley and recovery wells was halted. From this standpoint, program objectives were achieved. No information was available on possible plans to monitor for and remediate residual contamination which may exist at the site.

Case History 2: Plant P-54

Background and Recovery System Design

The groundwater remediation program at Plant P-54 was initiated by plant personnel in 1986. During this year four 114 mm OD diameter wells were installed to recover condensate and contaminated groundwater originating from the process area and evaporation ponds. Subsequently, a more detailed hydrogeological study of the plant site and surroundings was completed. This study refined understanding of groundwater flow patterns at the site and the distribution and properties of the various hydrogeologic units at the site, and accurately delineated the extent of the plume. The new information indicated the need for an improved contaminant recovery system.

In 1989, five 130 mm test wells were placed downgradient of the plant, near the downgradient edge of the condensate plume. These wells were tested to provide information on the hydrogeologic properties of the contaminated aquifer, which consists of fractured bedrock. Based on these results, two larger diameter wells are scheduled for 1990. These wells will be fitted with a dual pump systems designed expressly for the recovery of light non-aqueous phase liquids (LNAPL) from the groundwater surface.

An area of muskeg approximately 500 m downgradient of the plant site was also found to have condensate contamination. An interception trench is planned for 1990/91 to contain the plume in this area.

Contaminant Recovery

Of the four original wells, Well #1 was the best producer. During a period of approximately 14 months between 1986 and 1988, it recovered over 12,000 m3 of contaminated groundwater. Wells #2 and #4 produced approximately 3000 m3 and 800 m3 respectively during the same period. Discharge lines were not winterized, and consequently the system operated only during the summer months. Despite recovering significant volumes of groundwater, little condensate was recovered.

No information on soil contamination was available, and no major soil remediation projects have been initiated at the site.

Recovered groundwater was pumped to the lined process water pond prior to deep well injection.

System Assessment

In terms of groundwater, the site characterization and remediation programs conducted at Plant P-54 were found to be one of the most thorough and advanced of all plants involved in the study (for which data allowed comparative assessment).

Before the most recent site characterization program was begun, a pumping well recovery system was installed. The system consisted of shallow wells of conventional design. As described above, the wells produced considerable groundwater but little condensate. It is now clear that the use of single well systems for recovery of free product at this site is inappropriate. The reasons for this are discussed below.

The level of site characterization at Plant P-54 is high: A detailed exploration program involving the installation of numerous piezometers and test wells was conducted; the contaminant plume has been accurately delineated, both areally and vertically; the geology and hydrogeologic properties of the strata involved are relatively well understood. The exact source of the condensate remains to be located, however.

Taking advantage of the knowledge provided by the site characterization, the plant is now initiating a free phase recovery scheme which will employ the latest dual pump technology. This system is specially designed for recovering free-product on the groundwater surface. A groundwater pump is installed below the groundwater-product interface. This pump depresses the groundwater table, inducing flow of hydrocarbons towards the well, but does not take in product. A second "skimmer" pump, specially designed to float on the hydrocarbon surface, skims free product and pumps it to the surface. The advantages of this system include: product and groundwater are recovered separately, eliminating the need for costly separation at surface; the system operates with lower drawdowns than a single pump arrangement, reducing flow velocities and turbulence which can increase mixing of product and water, and reducing the magnitude of fluctuations in the hydrocarbon surface which can cause "smearing " of the product across the formation. Due to capillary pressure effects and the natural wettability of near-surface aquifer materials, hydrocarbon can become entrapped in the unsaturated zone, where it is essentially immobile. Residual oil saturation in the unsaturated zone can be as high as 50%. Furthermore, with air as the third phase, hydrocarbons tend to become concentrated in low hydraulic conductivity layers. Reducing the magnitude of water/product level fluctuations will help to lower the amount of hydrocarbon trapped in the subsurface as residual saturation. For a more complete discussion of this subject, refer to Lenhard and Parker (1989).

Although initial costs for a dual scavenger pump system are higher (a dual scavenger type pump may sell for as much $30,000), the overall savings in terms of fluid treatment and disposal costs, contaminant recovery efficiency, and total clean-up time will be significant. The literature is replete with examples and case histories which support this (Yaniga, 1982; Blake and Lewis, 1983).

As far as the authors are aware, this represents the first use of such technology for groundwater remediation at Alberta sour gas plants. Although this type of technology has been widely applied in the USA and Canada for gasoline recovery, this is the only known example of its application among plants in the study group.

Assessment of Clean-up Level

No information was available with which to quantitatively assess the clean-up level achieved at the plant, or the costs involved in operations to date. The initial attempt at using single pumping wells to recover condensate was not successful, and a more suitable system is now being introduced.

Case History 3: Plant P-53

Background and Recovery System Design

A contaminant recovery system was installed at Plant P-53 between 1986 and 1987, consisting of four small diameter (141 mm ID) wells located to intercept contaminated groundwater originating from the evaporation pond, landfill and process areas, and prevent it from migrating further downgradient. Wells were designed to pump groundwater from a shallow fractured shale bedrock aquifer. Groundwater was contaminated with a variety of aqueous phase organic and inorganic contaminants (the contamination situations being targeted were 1 M III, 2 D III, 4 P III, and 6 M III).

Groundwater remediation operations were preceded by a relatively detailed hydrogeological exploration and site characterization program conducted over several years. The uppermost groundwater bearing zones were identified and their groundwater flow regimes and hydraulic properties determined, and the extent and nature of groundwater contamination was defined. These efforts were, however, confined to the plant site until 1989.

Contaminant Recovery

The average annual production of the recovery system over the 1987 to 1989 period was approximately 8000 m^3 of contaminated groundwater. Three of the wells are continuously in operation, with one being used as a standby. The average chloride concentration of water produced from Well #1, downgradient of the evaporation pond, is about 275 mg/L. This water also contained variable concentrations of dissolved organics, including process chemicals.

No estimates of the mass of contaminants present in groundwater, or the recovery efficiency of the pumping scheme could be developed with the available data.

Treatment and Disposal of Produced Fluids

Contaminated groundwater produced by the recovery wells was pumped to holding tanks and subsequently trucked to a deep injection well off-site for disposal. No on-site treatment was performed.

System Assessment

Installation of the recovery system at Plant P-53 was preceded by a complete site characterization. The information provided by such an assessment is vital to the proper selection and design of recovery/remediation systems.

The recovery wells presently operating at the site were designed to intercept contaminated groundwater, and slow further downgradient migration of the plumes. The design and construction of the wells are suitable for their intended purpose, the hydraulic characteristics of the aquifer and the type of contamination present. Small diameter wells completed with steel water well casing, slotted steel liners and fitted with a single pump, are appropriate for the recovery of groundwater contaminated with dissolved organic and inorganic compounds.

At present, a detailed hydrogeological exploration program is being conducted in areas downgradient of the plant site, to determine the possibility and extent of off-site migration of contaminants. This program is being supplemented by detailed hydrogeological modelling of the plant area to assess risk and aid in the design of future remediation systems.

Hydrogeologic contaminant transport models provide an excellent tool with which to optimize recovery system design in order to achieve maximum clean-up at lowest possible cost. Models of this type can be used to compare clean-up levels achieved using different well spacings, locations, and pumping rates, estimate clean-up times required for various well configurations, and predict the future progress of plume development under various conditions (e.g. source of contamination eliminated, source still active and four downgradient pumping wells installed, line drive system of pumping and injection/flushing wells installed, etc.). Models of this type require a significant amount of good quality field data for calibration.

No significant studies of soil contamination at the plant have been conducted, and no substantial soil remediation efforts have been documented.

No information on the capital or operating costs of the recovery system were available.

Case History 4: Plant P-49

Background

A sour gas facility where a significant quantity of recent soils data were collected is Plant P-49. The plant began operation in 1960 and has been operating in a much reduced capacity since 1988. In 1988, the plant was decommissioned with the exception of a portion of the process area.

At that time, a soil sampling program was initiated as part of the requirements for plant decommissioning, including assessment of waste materials for compliance under the Alberta Hazardous Waste Regulations and Waste Transportation Regulations . Some additional soils data had been collected for the landfill area, possibly as a result of Clean Water License requirements. No other data sources were provided on soil quality in and around the plant site.

Remediation Operations

Soil data indicated that contamination of the unsaturated surface materials had occurred and was concentrated in the runoff and process waste water ponds, the sulphur storage areas, and the landfill sites.

Background levels were established for the A, B, and C soil horizons. Criteria for soil clean-up were developed (Figure 8) and material was slated for removal if soil parameters exceeded these criteria. Soil contamination that exceeded one or more of the parameters specified in these criteria was found in the landfill areas, process area, sulphur storage area, surface runoff ponds, process water ponds, product loading areas, and scrap yards.

Material identified as exceeding the clean-up criteria was excavated and removed to secure landfill. The available information did not indicate that any on-site treatment of contaminated material was undertaken. No groundwater remediation was undertaken as part of the initial decommissioning process, however investigations into the need for groundwater remediation are presently underway. Work to date has included installation and sampling of monitoring wells, and preliminary contaminant transport modelling.

Assessment of Clean-up Level

The unsaturated zone at the plant site extended to a depth of approximately 7.5 metres and has a soil moisture content from 3-7.5 meters of 5.% (according to the report). The B and C horizons to a depth of 2-3 metres consist of brown inorganic clay of medium to low plasticity. Below 3 meters the material changed to a brown very hard, inorganic clay of low plasticity.

Over the 27 years of plant operation, contaminants introduced at surface migrated down through these clay layers towards the groundwater surface. The level of contamination in soil samples below 3 metres, although elevated above the specified criteria, was not extremely high.

Available data indicates that all soil and sludges exceeding clean-up criteria levels were excavated and removed, and the site backfilled with clean material. These actions successfully remediated soil contamination at the site to specified levels.

At the time of soil remediation, no parallel program was instituted for groundwater. Subsequently, groundwater contamination was discovered at the site, including dissolved organics and main ions such as chloride. Presently, a detailed hydrogeological evaluation of the plant area is underway to further define the extent of the plume and assess the need for remedial action. This program is to include groundwater solute transport modelling as an aid in risk evaluation and possible remediation system design.

In any remediation program, a priority must be the identification and elimination of the source of contamination. Once this has been done, and new contaminants are no longer entering the subsurface, subsurface remediation proper can begin. This first important step has been taken at Plant P-49, and residual contamination problems are now being addressed.

In addition to the case histories presented above, advanced exploratory work and site characterization to assess the need for remediation, or leading to the design of contaminant recovery programs are being conducted at four plants (P-33, P-37, P-51, and P-42).

3.4.4 Discussion

Data on remediation operations were obtained from five sour gas plants in Alberta. Of these, three had groundwater remediation systems in place, and two had completed soil remediation operations towards site decommissioning. In addition, Alberta Environment indicated that they were aware of other minor remediation test projects presently underway at other sour gas plants.

The four case histories presented provide an indication of the types of systems and the level of sophistication of remediation efforts which have been applied in the province. Where geologic conditions dictate, large diameter passive collection systems have been used to recover free-phase hydrocarbon. Attempts to recover free phase condensate in more hydraulically conductive aquifers using single well pumping schemes have, not unexpectedly, been relatively unsuccessful. Application a two-pump scavenger system to recover free phase condensate and groundwater separately is being considered at several facilities. This type of system is representative of the new generation of groundwater remediation technology, developed over the last ten years in response to mounting public concern over the environment, and the need for more effective and cost-efficient clean-up methods.

Traditional pumping well methods are being applied for the recovery of groundwater with dissolved contaminants, and the control of plume migration. Deep well injection is the favoured method for disposing of contaminated groundwater.

Two examples of soil remediation involved full or partial plant decommissionings. In both cases, clean-up criteria were developed expressly for the site, and material meeting the criteria was excavated and removed to secure landfill. In each instance however, concomitant groundwater remediation was determined to be unnecessary.

No information was available with which assessments of the cost effectiveness or efficiency of remediation programs could be evaluated. Financial information was not included in any of the documents. Little quantitative information with which remediation system performance could be assessed was available.

The number of plants at which remediation operations are known to be presently underway is relatively small, considering the number of operational plants in the province. In many cases, remedial action has been deemed unnecessary due to geologic conditions and relative isolation of plants, far from any nearby groundwater users, water courses or population centres. In some instances, remediation has been deemed impractical due to limitations of available technology. However, rapid advances in the understanding of processes governing contaminant migration in heterogeneous geologic media, and new developments in remedial technologies should improve our ability to remediate difficult sites. One consideration to date has undoubtedly been the relatively high cost of subsurface remediation (the cost of excavation and removal to landfill of contaminated soil from a relatively small gas plant could reach several millions of dollars, and a properly designed groundwater remediation system could cost as much as $500,000 over 10 years), and the fact that at present no regulations or guidelines are available for these operations.

At present, facility operators, in cooperation with Alberta Environment, are taking it upon themselves to clean-up subsurface contamination which they consider to be unacceptable. As could be expected, different operators view similar contamination situation with different levels of concern, and react accordingly.

The complex and variable hydrogeological conditions present in Alberta, combined with the wide range of potential contaminants associated with sour gas plant activities make design and operation of an effective remediation system a challenging task. Proper design, installation and operation of such systems requires an appropriate level of expertise and familiarity with the concepts of hydrogeology, soil science, and contaminant behaviour.

The available data seems to indicate that some groundwater remediation operations have proceeded on an ad-hoc basis, with insufficient preliminary site characterization and contaminant delineation resulting in a piecemeal approach to system design. In the authors' experience, this has largely been the result of the low funding levels previously available for these projects. It must be stressed that such a piecemeal, trial an error type of approach may lead to higher overall costs, lower ultimate clean-up levels, and longer clean-up times.

Ideally, a subsurface remediation program should not begin until several key steps have been taken. A complete hydrogeological investigation of the site and areas downgradient of identified contamination should be completed. This provides information on groundwater flow directions and velocities, the number, depths, continuity, and hydrogeological properties of groundwater bearing zones at the site, and the nature and extent of soil and groundwater contamination. Using this information, the need for remediation can be assessed through risk analysis. If the risks associated with not cleaning up the site are unacceptable, then remediation or abatement should proceed. Risk analysis may indicate that contaminants have little likelihood of impacting the public or the environment, and that the concentrations of the particular contaminants are not of concern. Results of the risk analysis can then be provided to regulators to ensure a case-by-case assessment of the need for remediation at sour gas plants.

Gas processing facilities in the province are found in such diverse locations, and represent such a wide range of hydrogeological and climatic conditions, that universal application of a single set of rigid criteria is not recommended. A case-by-case consideration of facilities would help to ensure the economical application of the limited resources available for site clean-up. Companies could then direct funds toward the most serious problems, rather than spreading available funds over a number of unequally needy sites.

Once a remediation program has been initiated, detailed records of system performance should be kept. For groundwater recovery systems, for example, data on volumes recovered, concentrations of key parameters in produced water and monitoring points, and piezometric heads should be kept. These data can be used to monitor the progress of remediation, and indicate the need for modifications or additions which may be required.

The design of any remediation scheme should take into consideration both soil and groundwater contamination. In addition to cleaning-up groundwater, sources of additional long-term groundwater contamination should be removed.

3.5 IDENTIFICATION OF CANDIDATE SITES FOR REMEDIATION DEMONSTRATION PROJECTS

One of the stated goals of the project was to select candidate sites for the possible implementation of one or more subsurface remediation demonstration projects. The purpose of these schemes could be to demonstrate remediation technologies applicable to the most common contamination situations present at Alberta sour gas plants. However, initiation of a demonstration recovery project involving less frequently occurring, but potentially more serious contamination situations (such as free phase condensate), should also be considered.

The most frequently occurring situations have been identified in Section 3.3, and the present level of subsurface remediation technology being applied at sour gas plants has been discussed in Section 3.4. This section will discuss the selection of candidate sites.

3.5.1 Selection Procedure

Based on the criteria put forth in the original request for proposal, the basic requirements for a candidate site are:

- That the site be representative of the most common contamination situations identified at Alberta sour gas plants, so that a demonstration project and the associated research will be of most benefit to the industry as whole.

- That the site have already available a detailed hydrogeological and if possible soil assessment, including a relatively complete monitoring network, and acceptable identification and delineation of contamination situations. This requirement will allow the demonstration project(s) to proceed with a minimum of additional site characterization.

The last criterion automatically eliminates from consideration any plants for which no or insufficient data were available. Also the plant at which no contamination was detected is eliminated, as are the decommissioned and partially decommissioned plant. The total number of plants to be considered is thus reduced by 25, from 54 to 29.

Of the 29 remaining plants, 19 have at least one occurrence of the most common contamination situation (dissolved organics and main ions (with or without other aqueous phase compounds) in type III (moderate K) or type II (high K aquifers) originating from one of the three most common sources (ponds, process area, landfill).

Plants with relatively detailed site characterization, and for which relatively extensive monitoring networks are already available are preferred. Consideration was given to the number of applicable CSC's, the relative extent of monitoring networks, if soil sampling data was available, and the general quality of data.

Of the remaining 19 plants, 7 are considered to have the necessary level of site characterization to allow implementation of a subsurface remediation demonstration project without substantial additional work. Table 12 provides pertinent information for each plant.

3.5.2 Discussion

Selection of a site for the remediation demonstration project could be made from among the seven candidate sites listed in Table 12. Each is capable of fulfilling the requirements of the proposed project, based on the available information. Final selection of a site would depend on several factors, including:

- The cooperation of the plant operator. This may be the most important factor in wether a plant will be selected for the project. The operating company must be willing

TABLE 12
FINAL CANDIDATE SITES
PERTINENT INFORMATION

PLANT IDENTIFIER	CSC'S PRESENT	No.OF PIEZOMETERS IN G/W MONITORING SYSTEM	FREE PHASE HYDROCARBON CONTAMINATION PRESENT	SOIL DATA AVAILABLE	CONTAMINATION DOCUMENTED OFF-SITE
P - 54	4 M III 9 M III 4 D III	21+	X		X
P - 20	6 P III 4 M III 2 W III 1 P III	15		X	X
P - 33	7 T II 1 M II 6 M II 4 M II	13	X		X
P - 37	9 A III 4 M III 2 D II	21+	X	X	X
P - 51	2 P III 6 P III	21+		X	X
P - 52	1 P II 2 D II 4 P II 6 P II	21+			X
P - 53	1 M III 2 D III 4 P III 6 M III	21+			X

NOTE: M = BC T = ABC
P = BCF W = BD

to allow a research oriented project of this nature at their plant, and willing to cooperate in the project as a whole, including provision of records, and eventual publication of the study results. Companies will have to be approached and briefed fully on the proposed conditions of the project, the responsibilities of the various groups involved, and the technical program to be followed. Piteau Engineering has approached representatives of each of the companies who operate the seven final candidate plants regarding their interest in such a program. All expressed interest in the proposed program, and requested additional information when it became available. Several indicated they would be willing to participate financially in the project if one of their plants was selected.

- The relative technical merits of each plant, and how they fit with the final form of the project. Each of the final seven plants has characteristics which may make it more attractive for certain types of projects. For instance, if program administrators wanted to address the problem of free phase hydrocarbon contamination as well as dissolved organics and ions, plants P-20, P-37, and P-51 would be ideal. If technology more suited to higher hydraulic conductivity zones were being considered, plant P-33 would be the best choice.

Once the final administrative details of the remediation project have been worked out and the technical approach defined, each of the seven plants should be reviewed in detail to determine which best fits the proposed project. The seven should be ranked in order of preference, and the operators approached.

Another alternative for implementing the proposed remediation demonstration projects could be to select a site where very little initial site characterization has been done, but where the presence of a contamination situation of interest has been tentatively identified or is strongly suspected. The demonstration project could then involve preliminary and detailed site characterization and contaminant delineation, risk assessment by modelling, and subsequent design, implementation and operation of a suitable recovery system. This approach has the elegance of a complete project, from start to finish, providing not only a model for remediation, but also for site investigation and characterization. Several factors should be considered however:

- Once a plant is selected and preliminary site investigations have begun, researchers may find that the site is unsuitable for the proposed project, either because of the types or lack of contamination situations discovered, or the nature of the geology at the site.

- Inclusion of preliminary investigation and detailed site characterization phases to the project may require additional time and funds.

- Selection of a plant for the project will be largely subjective, as very little or no data will be available with which to make the final decision.

Moreover, it should be stated that the opportunities for detailed investigation of site hydrogeology, geology, and contaminant behaviour are considerable at all of the plants considered for this study. Even at the seven candidate sites, where relatively extensive site characterizations have been undertaken, the possibilities for research remain great. Depending on the anticipated research content of the proposed project, much additional work could be done at each of these sites prior to selection and design of the remediation system. Site characterization research could include use of new monitoring technologies such as multi-port samplers, vapour surveys and geophysical techniques, detailed lithologic and structural characterization of host geologic materials, research into mechanical and chemical behaviour of contaminants of interest in the subsurface, and detailed modelling of contaminant transport.

4. LEGISLATION AND TECHNOLOGY REVIEW

4.1. SUBSURFACE REMEDIATION GUIDELINES AND LEGISLATION

This section of the report presents a brief review of guidelines, regulations and legislation which exist in various jurisdictions regarding the monitoring and remediation of subsurface contamination, as they apply to the sour gas processing industry. The review included Alberta, other Canadian provinces and federal regulations, and the United States.

Most jurisdictions have tended to produce regulations or legislation which cover the subject of groundwater protection and site remediation in general. Guidelines are used to supplement regulations, and focus on certain specific areas, such as the petroleum refining industry, or industrial site decommissioning. In Canadian law, regulations have force of law, whereas guidelines are codes of practice considered to be consistent with the "spirit of the law". Failure to comply with guidelines does not in itself constitute an offence, however it may mean that portions of the governing act are being transgressed (Environment Canada, 1987).

4.1.1 GROUNDWATER

Canada

In Canada, groundwater and its protection falls under provincial jurisdiction, except in Yukon and Northwest Territories, where groundwater is administrated by the Department of Indian and Northern Affairs, and the territorial governments. The federal government may, however become involved in provincial groundwater issues through the Fisheries Act, or the Canada Water Act. Under the Fisheries Act, the government of Canada has authority over water quality related to fish life. Under the Canada Water Act, the federal government also has indirect authority over groundwater where critical conditions require federal assistance, or where contamination produces a situation where public health may be impaired.

Most provinces have established their own regulations supplementing the federal legislation. Under the present environmental regulations, federal and provincial, groundwater contamination as a result of waste disposal and storage should no longer occur. The situation with respect to groundwater contamination in Canada is summed up by Vonhof (1985) in his inquiry on federal water policy paper:

> "Under present environmental regulations and policies enacted by both levels of government, waste disposal to the terrestrial environment should no longer cause groundwater contamination. However, regulations are no good unless they are properly enforced. Unlike American environmental legislation, which is relatively specific and detailed, Canadian environmental laws are more general and their enforcement depends in many instances on the discretion of government officials."

The federal government has also produced regulations and guidelines for specific industries. The Federal Petroleum Refinery Effluent Regulations and Guidelines, for instance, contain standards for effluent wastewaters from refineries, and include limits on water quality parameters such as oil and grease, phenols, TDS and pH. The intent of such regulations is to set baseline standards for the country as a whole.

Environment Canada in presently engaged in several studies concerned with groundwater contamination and remediation, and regularly produces environmental status reports on specific industries, such as Canadian petroleum refining.

Alberta

At present in Alberta, issues relating to groundwater contamination are dealt with under the Clean Water Act. This piece of provincial legislation deals with all aspect of water contamination and protection, and therefore includes groundwater. The legislation and regulations are supplemented with guidelines for specific industries. Guidelines have been published for Alberta brine storage reservoirs, waste water management standards for gas processing facilities, waste water effluent guidelines for Alberta petroleum refineries, industrial landfill guidelines, and other topics.

Under the present regulations, sour gas plants in Alberta require a licence to operate from Alberta Environment. Before licences are issued for "class B" sulphur-recovering sour gas plants, Alberta Environment requires that the operator install a groundwater monitoring system at all sources of potential contamination. The minimum requirements include one upgradient and two downgradient piezometers. The operator is required to submit a report providing details of the proposed monitoring system, which Alberta Environment can assess, and approve or modify.

In practice, this system suffers from several deficiencies. Operators are not provided with specific guidelines on how a monitoring system should be set up, what it should consist of, and how it should be operated. In some cases, operators have neglected to monitor for contamination from sulphur blocks and process areas. The results of this study show that the process area and sulphur block are two of the most common sources of groundwater contamination at sour gas plants. In addition, no specific reporting requirements on the groundwater monitoring system are specified. This has resulted in Alberta Environment receiving reports of widely varying quality and completeness. Many operators retain qualified hydrogeological consultants to install the monitoring system and provide a detailed report on the systems and the groundwater quality at the plant site, even though such thoroughness is not explicitly required under the terms of the licence. Others, however, choose to satisfy only the minimum requirements, and the tasks of monitoring system installation and reporting are sometimes not performed by qualified hydrogeologists. This fact was made evident during the data review conducted as part of this study.

Alberta Environment is now formulating a new set of groundwater monitoring guidelines for the province as a whole, to be applied to all industries and facilities which have the potential to contaminate groundwater. These guidelines are to include detailed information on groundwater assessment and monitoring requirements, including numbers and locations of piezometers, and recommended sampling schedules. In addition, the need for an explicit statistically-based definition of groundwater contamination, similar to the USEPA system of comparing upgradient and downgradient water quality with Student's t-test will be assessed. In addition, Alberta Environment will require submission of a detailed report, including full presentation and interpretation of results, with which the situation at a given gas plant can be evaluated, and the need for remedial action assessed.

At present, the need for groundwater remediation is assessed on the basis of monitoring reports submitted by operators. Information from each plant is reviewed by Alberta Environment, and if necessary, remedial measures are suggested to the operator. With this system, special conditions present at each plant can be taken into account when deciding on remediation approaches, rather than applying a rigid set of criteria to all plants, regardless of location, proximity to other users of groundwater, and the results of risk analysis . In practice, however, the success of this system is dependent on the quality of monitoring reports submitted by operators. Historically, there may have been a tendency for operators who installed proper monitoring networks and submitted complete reports to be penalized, while operators who fulfilled only the minimum requirements, and had perhaps not investigated all areas of potential contamination, may have appeared to have fewer cases of contamination. However, under the new guidelines, operators renewing licences will come under much more strict scrutiny.

The new guidelines, which may be available as early as mid 1990, should substantially improve the overall quality of groundwater monitoring at sour gas plants, and help to identify those facilities where remediation is required.

Ontario

Groundwater contamination in the province of Ontario is legislated under the Environmental Protection Act (EPA), the Environmental Assessment Act (EAA), and the Ontario Water Resources Act (OWRA). Of the Canadian provinces, Ontario and Quebec have developed the most comprehensive regulations dealing with site clean-up, including groundwater remediation.

Ontario regulations are quite advanced in terms of enforcement. The "Guidelines for Decommissioning and Clean-up of Sites in Ontario" (Environment Ontario, 1989) state that:

> "MOE (Ministry of Environment) staff may use Section 17 of the EPA to issue orders to enforce... the site clean-up process when proponents are unwilling to meet MOE ... site clean-up objectives or timeframes."

The guidelines also stipulate that "in principle, remediation will be required whenever contaminants are present in concentrations above ambient background levels". However, the operator or site owner may develop site specific clean-up criteria above background levels, as long as these criteria do not violate basic MOE standards of protection of public health, land use practice, and general groundwater protection guidelines.

Assessment of groundwater contamination in Ontario is governed by the "Reasonable Use Concept". According to the MOE (Vonhoff, 1985), the wide variation in the quality and quantity of groundwater makes a fixed standard approach impractical. Therefore, the MOE decides what constitutes the "reasonable use" potential of groundwater. In the case of land associated with sites which have the potential for contaminating groundwater, assessment is done on a site-by-site basis. "Reasonable Use" is based on the present use of the groundwater, its potential use, and the amount and quality of groundwater that is available.

According to Vonhof (1985), the "reasonable use" concept is flawed. Under this system, the standards for groundwater protection are discretionary. A determination of "potential use" must be made for each aquifer, a procedure which is bound to be subjective - for instance, the potential uses of a given aquifer may change over time as economic, land-use, and environmental conditions change.

Quebec

The province of Quebec has published a detailed set of guidelines pertaining to the remediation of contaminated sites (Quebec Mininstry of the Environment, 1988). As with the Ontario guidelines, a case-by-case evaluation is recommended. The guidelines also provide a comprehensive list of possible groundwater contaminants, and suggested action levels for each parameter. These are not intended as strict standards, but rather as indicators of what the Environment Ministry would find acceptable. The list includes metals, monocyclical aromatic hydrocarbons, and indicators such as oil and grease. Above the indicated levels, the guidelines suggest that "prompt remedial action may be necessary". A partial list of the Quebec clean-up guidelines criteria is presented in Table 13.

TABLE 13
SUMMARY OF QUEBEC CLEAN-UP GUIDELINES CRITERIA

COMPOUND	SOIL (ppm)			GROUNDWATER (ug/L)		
	A	B	C	A	B	C
OIL AND GREASE	100	1000	5000	100	1000	5000
PHENOLIC COMPOUNDS	0.1	1	10	1.0	2	5
ANTHRACENE	0.1	10	100	0.2	7	20
NAPTHALENE	0.1	5	50	0.2	10	30
CHRYSENE	0.1	1	10	0.1	1	5
PHENANTHRENE	0.1	5	50	0.1	1	5
PYRENE	0.1	10	100	0.2	7	30
PAH (SUMMATION)	1	20	200	0.2	10	50
BENZENE	0.1	0.5	5	0.5	1	5
ETHYLBENZENE	0.1	5	50	0.5	50	150
TOLUENE	0.1	3	30	0.5	50	100
XYLENE	0.1	5	50	0.5	20	60

United States

In the United States, the protection of groundwater from contamination and the clean-up of contaminated aquifers are the responsibility of the federal Environmental Protection Agency (USEPA). The USEPA has put into place a strict and comprehensive set of procedures controlling the monitoring, assessment and remediation of contaminated groundwater.

Under the Resource Conservation and Recovery Act (RCRA), the Ground Water Monitoring Technical Enforcement Guidance Document provides instructions to operators on how monitoring should proceed, and how it should be conducted. The first phase is detection monitoring. If groundwater contamination is detected, the operator must move to "assessment monitoring", which includes detailed site characterization, and enhanced monitoring frequency. The results of the assessment monitoring are then reviewed by USEPA personnel, and the need for remediation assessed. The USEPA has power of law in enforcing requirements for monitoring and remediation, and may bring legal action to bear against offenders to recover costs of remedial operations.

The guidelines include a comprehensive definition of groundwater contamination. If concentrations of any one regulated parameter are found to exceed established background levels by a statistically significant amount, based on the Student's t-test, in any one of the downgradient piezometers, groundwater contamination is said to exist.

Section 264.100 of the Code of Federal Regulations describes the implementation of corrective action programs. A corrective action program must be established within 180 days of determining that the groundwater protection standards are being exceeded. The operator does however have the opportunity of demonstrating that another source caused the contamination, or that the increase resulted from an error in sampling, analysis, or evaluation. The regulator will specify the groundwater protection standard for the site, including the compliance point and period, and concentration limits for each of the hazardous constituents specified in the guidelines (including metals such as lead, arsenic, and cadmium, and organics such as endrin and toxaphene).

In addition, the owner/operator must establish and implement a groundwater monitoring program to demonstrate the effectiveness of the corrective action program.

In recognition of the differences in hydrogeological conditions across the United Stated, the USEPA has encouraged states to draft their own groundwater protection legislation to supplement the federal regulations. Forty-eight states have or are developing comprehensive groundwater management plans, and 33 have or are developing groundwater quality standards or classification systems (Government Affairs Committee, 1988).

4.1.2 SOILS

Alberta

No legislated standards have been developed in Alberta for the clean-up of contaminated soils. Site contamination problems are dealt with on a case by case basis, often with reference to the Quebec guidelines discussed below. Clean-up criteria have been developed for two sour gas plant decommissionings; Plants P-35 and P-49. The criteria were:

Parameter	P-49 Criteria	P-35 Criteria
pH	6.5 units	6.0 units
EC	4.0 dS/m	4.0 dS/m
Elemental S	none	>2000 ug/g
tot. HC	2% by weight of free oil	>2% by weight exclusive
tot. Zn	1200 ppm	>1600 ug/g
tot. Cu	400 ppm	>250 ug/g
tot. Pb	1000 ppm	>1000ug/g
tot. Ni	300 ppm	>300 ug/g
tot. Cr	1000 ppm	>1000 ug/g
tot. Cd	4.0 ppm	>4.0 ug/g
tot. Hg	2.0 ppm	>2.0 ug/g
tot. Va	none	>1000 ug/g

Standards do exist for the handling and disposal of hazardous wastes. If any soil contaminant is sufficiently elevated to classify it as a hazardous waste disposal options become severely limited.

Quebec

The province of Quebec developed assessment criteria in 1988 for the characterization and remediation of contaminated sites. These criteria deal with both soils and groundwater. Pertinent excerpts from these guidelines are provided in Table 13. For each parameter a threshold value is assigned which determines the extent of intervention required for further assessment and/or remediation. These guidelines have been modified slightly and adopted for the clean-up of BC Place in Vancouver. B.C. The B.C. Ministry of Environment has indicated that these criteria may be adopted for the province.

Ontario

Environment Ontario published a set of guidelines in February 1989 entitled "Guidelines for the Decommissioning and Clean-up of Sites in Ontario". These guidelines provide for a phased approach to evaluation of a site and allow for the development of site specific remediation criteria based on future land-use and background levels. However no numerical criteria for clean-up are provided.

Federal

Environment Canada in conjunction with the US EPA and the provinces has been developing a model named AERIS. The project was started to develop and validate a method for establishing site-specific clean-up criteria. The Nanticoke Refinery is being used as a test site. The model may be available this year for use in studies of sour gas plant remediation projects.

4.2 SUBSURFACE REMEDIATION TECHNOLOGY REVIEW

This section of the report provides a brief overview of some of the technology available for remediation of contaminated soils and groundwater. Many of the technologies described are relatively new, and have yet to be tried at Alberta sour gas plants. The intention is not to describe each process in detail, but rather to present a list of possibilities, and provide an idea of the range and scope of available systems.

4.2.1 GROUNDWATER

Recovery Systems

In many cases, the most practical solution to a groundwater contamination problem is to remove the water from the aquifer, and then treat it or dispose of it at surface. Recovery methods must be designed to suit the hydrogeological properties of the aquifer in question, and the types of contaminants present. To date, recovery of groundwater for surface treatment or disposal has been the most commonly practised remediation method. Types of recovery systems for miscible contaminants include:

-pumping wells:

Wells designed to remove groundwater from the aquifer by pumping. Wells should be properly completed and developed to ensure optimum efficiency. Wells can be fitted with standard water well pumping systems, including submersible electric pumps. Effectiveness will also depend on the hydraulic properties of the aquifer, and well configuration. Small diameter well points can also be used.

-large diameter wells:

As described in one of the case histories in this report, large diameter wells can be effective in low hydraulic conductivity (K) materials such as are commonly found in Alberta. In such situations, conventional pumping wells may be pumped dry after only a few hours of operation. Large diameter wells are pumped down periodically, inducing flow of groundwater toward the well. These systems have proven useful in low hydraulic conductivity tills.

-interception trenches and galleries:

These types of recovery systems are especially useful fro intercepting plumes and preventing further downgradient migration in shallow groundwater bearing zones. Beyond depths of about 3 metres, excavation problem and safety concerns make trenches impractical. Good for low K materials, are relatively cheap and can take advantage of natural gradients or pumping. Trenches can be open, or backfilled with permeable material, and fitted with collection pipes or drains.

For immiscible contaminants, such as condensate and gasoline, occurring as a free phase layer on the groundwater surface, the above techniques can also be used, however different pumping methods are required. The most widely used and effective recovery methods involve installation of two pump systems. One pump lowers the water table, and pumps only groundwater, the other skims product from the surface. The advantages of this method over single pump systems suitable for miscible contaminants are many, including separate phase recovery, more efficient and higher ultimate recovery, reduced clean-up time, and lower entrapment of residual hydrocarbon. Most practitioners now recommend dual pump/ free phase skimming technology for product recovery. Single pump systems may be used in situations where oil/water recovery rates are relatively slow (<2000L/hr.), when it is expected that the recovery system will be in operation for a short period of time only, or when the use of more sophisticated methods are not justified by a cost-benefit analysis (Fussel et al, 1981). Trenches and large diameter systems can also be used effectively in certain situations.

Variations on the dual pump recovery system include two pumps fitted in-line in one well, two pumps in two nearby wells, double shaft wells, and combined well and collecting chambers. More complete discussions of recovery methods for free phase product are found in Fussell et al (1981), and Report 2/PN/1, Environmental Protection Service (1989).

Recovery may be assisted by in several ways. Produced water may be re-introduced to the aquifer to help flush out contaminants and drive them towards recovery points. Water may be injected into the aquifer through wells oriented in specific patterns (five-spot, line drive, etc.), or may be introduced through artificial recharge methods such as spray irrigation of infiltration ponds. Both methods are widely employed in the United States as a way of simultaneously coping with produced water and enhancing ultimate contaminant recovery levels. Studies done by the US Salinity Laboratory have shown that ultimate recovery of immiscible contaminants can be markedly improved by cyclic flushing with produced water (Fessler et al, 1984). Care must be taken in these instances to ensure re-introduced water has been properly treated. Success of such systems depends largely on proper design and operation. In addition, free phase recovery can be enhanced through the injection of polymers or surfactants which reduce interfacial tension and increase mobility of hydrocarbons in the aquifer. Carbon dioxide injection is an example.

Groundwater Treatment

Once contaminated groundwater has been recovered, contaminants must be removed before water can be discharged to the water shed or used for artificial recharge. Presently in Alberta, deep well injection of contaminated groundwater is common. Treatment methods for contaminated groundwater include:

-Carbon adsorption:

Commonly used, this method takes advantage of the properties of activated carbon to purify contaminated water. The method depends on the physical properties of the molecules being adsorbed, the types of carbon filter used, the pH and concentration of the solution, temperature and contact time. Clarification (filtration) of the water is often required first. Carbon adsorption can remove 95 to 100 % of contaminants associated with hydrocarbons (benzene, toluene, xylene).

-Air Stripping:

This technique uses air to strip dissolved volatile organic compounds (VOC's) from groundwater. The water is introduced into a column of packing material through which a current of air is blown. Removal of immiscible product must be achieved prior to air stripping (another argument for use of separate groundwater and free phase product recovery). Presently in ALberta, the off-gases produced during air stripping are not subject to regulation. In the USA, however, off-gases must also be treated to meet air quality standards. Removal efficiencies as high as 99 % for dissolved VOC's are common.

-Reverse Osmosis:

Osmosis involves movement of solute across a semi-permeable membrane as the result of a concentration gradient. Reverse osmosis uses pressure applied on the higher concentration side to drive water across the membrane, while solutes are rejected. Separation is determined by the chemical nature of the membrane. Environment Canada's Environmental Emergencies Technology Division tested such a system and achieved 97 % removal of benzene using a polyether-polysulphone membrane (EPS, 1989).

For contamination by dissolved metals, neutralization followed by precipitation can be used. Ion exchange methods, reverse osmosis and electrodialysis are also effective depending on types of metals and the nature of other contaminants in groundwater. Dissolved organics can be removed by aeration followed by catalyzed chemical oxidation and activated carbon filtering. High TOC groundwater can be treated by using bacterial methods, multi-media filters, and carbon filters. Phenol contaminated water can be treated using a two-stage biological system, composed of conventional actuated sludge and fixed film sludge.

In general, a wide variety of groundwater treatment techniques are available. Choosing the right system for a given problem depends on knowledge of the nature, concentrations and volumes of groundwater involved, compatabity with the proposed recovery system, the eventual outfall for treated water, and results of cost benefit analysis.

In-Situ Remediation

Over the past few years, the interest in and use of in-situ groundwater remediation techniques has grown considerably. The advantages of this type of remediation are numerous, including relatively low cost, and high levels of remediation under the proper circumstances. Of particular interest is bioremediation.

Often the natural bacteria present in the subsurface are capable of degrading hydrocarbons. The rate of degradation depends on such factors as temperature of the subsurface and the amount of oxygen available for aerobic degradation. Lee et al (1988) report that in-situ biodegradation was adversely affected by low hydraulic conductivity in a field demonstration. They also quote the optimal subsurface temperature for biodegradation as between 20 and 30 degrees celsius, although much work is done at temperatures of between 10 and 15 degrees celsius.

Methods include:

-enhanced biodegradation:

To increase rates of biological activity, and thus remediation rates, substances an be added to the groundwater to enhance the growth and activity of the natural biota. Oxygenation can be accomplished through injection of hydrogen peroxide, ozone, air (air sparging), or colloidal gas (microdispersion of air into a surfactant - the resulting foam is injected). Hydrogen peroxide gives concentrated oxygen delivery, but may be toxic to organisms at species-specific concentrations (Lee et al, 1988). Controlled addition of water to the system can be used to keep concentrations within required ranges.

Biological activity can also be enhanced by delivering nutrients such as nitrogen and phosphorous to the subsurface.

-Inoculation:

If natural biota in the subsurface are not suitable for biodegradation, appropriate species can be introduced into the aquifer. Combined with techniques of oxygenation and nutrient addition, the success of this technique has yet to be determined conclusively.

Containment and Hydrodynamic Control

Contaminated groundwater can be removed and treated, or treated in-situ, but in some cases simply preventing further migration of contaminants can be a desirable solution. Methods of containment include isolation of the plume using grout curtains or walls. Infiltration is prevented by installation of an impermeable cap over the contaminated zone.

Hydrodynamic control involves the use of wells, ditches and other methods to change the hydraulic regime and prevent further migration of contaminants. This objective is often combined with contaminant recovery.

In summary, there are numerous techniques available with which to remediate contaminated groundwater. These techniques represent a wide range of costs and sophistication. One common requirement of all remediation technologies is, however, the need for detailed study of local conditions to determine their suitability and design specifications for optimal recovery. Such determinations require thorough site characterization and detailed review and planning of the proposed scheme. For instance, remediation using dual pump systems to remove free condensate can be designed and planned with the help of computer simulation techniques. Once calibrated with field data, anticipated recovery levels for various well configurations and pumping rates can be modelled, and the optimum configuration chosen. Such techniques can be extremely cost-effective when compared to a trial-and-error approach.

Many remedial methods are tried and tested, their success documented in the literature, although to date few objective third party assessments have been made of the relative effectiveness of various methods available. Some methods are newer, and require further study. Often the most effective approach makes use of several remedial methods in combination. Suitability of various methods to Alberta sour gas plants must be studied in greater detail. The technology demonstration projects proposed as part of this study should provide an excellent opportunity for the detailed evaluation of one or more remediation technologies at Alberta sour gas plants.

4.2.2 SOILS

As determined by a review data from recent reports, contamination of soils in and around gas plants consists of five main components. These are:

- sulphur
- hydrocarbon(s)
- metals
- anions/cations
- sterilants

In most where contamination was present more than one contaminant was found in the unsaturated zone at a particular facility location.

Historical Perspective

Research and development of remediation methodologies for contaminated surficial materials was primarily directed towards sulphur block pads during recent high sulphur demand periods. More recently, experience involving partial or complete decommissioning of sour gas plant sites has generated increased interest in remediation methods for process water pond sludges, hydrocarbon contaminated soils, and metal contaminated soils. During the 1980's a number of remediation methodologies were developed and tested at sour gas facilities. In many cases on-site remediation was considered too expensive or the success of a methodology was uncertain. In most of these cases contaminated soils have been removed to an off-site disposal facility such as a regional landfill.

Current criteria established for soil clean-up around sour gas plants have allowed a certain level of organic and inorganic contamination to remain in the unsaturated soil zone. For example at Plant P-49 the lower limit for removal of contaminated soils was 2% total hydrocarbon by weight. This does not pose any significant problem in the upper 30 cm of the aerobic zone. If the contamination extends below this level biological activity is curtailed and the hydrocarbon continues to be a source of organic contamination to groundwater.

-Sulphur Pad Reclamation:

Sulphur block base pad clean-up has generally involved the removal of the highly contaminated soils for sulphur recapture and the subsequent treatment of the sulphur block pad area with lime and fertilizers to increase pH levels and promote vegetation regrowth. The success of this procedure and the length of time required for sulphur pad soil remediation depends on the remaining sulphur concentration and soil and climatic conditions.

-Solidification/Fixation:

Solidification/fixation has been utilized successfully to stabilize process sludges and underlying contaminated soils, oil and metal contaminated sludges, and landfill sludges and underlying contaminated soils. The fixation methods have depended on the site specific conditions and contaminated soil properties. The main constituent of solidification mediums is a cement. Various plastic polymer additives have also been used in the process.

Process pond sludges and oily sludges have been solidified in-situ with little or no disturbance of the materials surrounding the ponds. Specialty equipment is used to mix the contaminated materials and fixation additives within a confined pond. The ponds were then capped and the site revegetated. Other ponds have been excavated and the contaminated materials mixed with the solidifying agents in a special batch mixing unit. The contaminated soils underlying the pond sludges have then been ripped to the required depth and the soils mixed with the solidification agents. The excavated, batched material was then placed into the pond and the site capped and revegetated. One landfill (including the underlying contaminated soils) was excavated and batch mixed with a Portland cement. The cement was then used to construct non-structural items around the plant site such as concrete pads, sidewalks, and drainways. The cleaned landfill was allowed to remain open to allow natural flushing of the site.

Landtreatment:

The treatment of certain organic contaminated soils has been tested at sour gas plants. Oily sludges and amine/glycol contaminated sludges mixed with contaminated soils have been treated in this manner. Generally these have been one-time treatment applications completed under approval from the appropriate regulatory agency and where groundwater monitoring systems were established. No permanent landtreatment facilities have been established to deal with contaminated soils or organic wastes generated at sour gas facilities.

-Incineration:

Several tests have been completed on incineration of soils contaminated with organics, caustics and sulphur from gas plant activities. The tests have also been referred to as soils drying and gasification. Soils from a chemical waste pit dried at 650

°C were found to be non-toxic and to have no organic components remaining after treatment.

Potential Remediation Technologies

A number of technologies could be reviewed for use in the remediation of sour gas plant contaminated soil remediation.

These include:

- Bioremediation through bioinoculation and augmentation;
- In-situ vitrification;
- In-situ radio frequency soil decontamination;
- Thermal destruction and gasification of soil organics;
- Solidification/fixation;
- Vacuum extraction;
- Solvent extraction and critical fluid extraction; and
- Soil washing

-Bioremediation:

Bioremediation is well known through the development of landtreatment operations either on a one-time application or on an on-going basis. Several oil reclaimers and oil refineries have established landtreatment operations. Further effort is required to assess the effectiveness of bioinoculation and bioaugmentation on the breakdown of hydrocarbons. The use of specific microbial species at high concentrations could significantly reduce the time required for the maintenance and monitoring of a landtreatment area.

-In-situ Vitrification:

This process uses electrical current through the soils to produce a temperature of 1040 °C. Most organics are pyrolyzed and migrate to the surface for capture and treatment (flaring).

Inorganics are bound in the soil as a solidified glass. The leaching rate of the vitrified soil mass is reported to be lower than marble or bottle glass. The maximum depth of treatment varies inversely with the spacing of electrodes. Maximum spacing of electrodes is 6 meters.

The technology is past the development stage and a pilot plant has been developed and successfully tested by Battelle Pacific Northwest Laboratories.

-In-situ Radio Frequency Soil Decontamination:

The process uses electromagnetic energy to heat soil. Up to 5000 tonnes of soil can be treated at one time. The process removes volatile organic carbons from soil through vaporization. Originally developed for the recovery of hydrocarbons the process has been used to heat tar sands at depths of 300 meters. The process is not effective for removal of metals or other inorganics. The process is more effective if coupled with vacuum extraction through hollow electrodes.

-Thermal Destruction and Gasification:

Destruction and/or removal of organics from contaminated soils is well established in the United States and is considered one of the most cost effective methods of treating contaminated soils on-site. A variety of incinerators are commercially available using various heat ranges and gas recovery systems. The common types are:

- Rotary Kilns
- Fluidized Beds
- Infra-Red Furnaces
- Pyrolytic Gasifiers
- Low Temperature Direct and Indirect Fired Volatilizers

Each type has advantages and disadvantages depending on the soil/ contaminant matrix. The costs for operation range from $150 to $1500 per tonne of soil depending on the economies of scale.

-Solidification/Fixation:

The use of fixation agents to contain contaminants within a soil matrix has been extensively used in the United States, Europe and Japan. The process is effective for soils contaminated with a mixture of organics and inorganics. The leaching potential increases as the organic content of the treated soil material increases. A number of solidification projects have been completed at sour gas facilities in recent years. Solidification tends to be viewed with some distaste since the contaminated material remains on-site and may present a liability. The process could be effective for low level soil contamination that would be considered for on-site disposal if the leaching potential could be reduced to an acceptable level.

-Vacuum Extraction:

Vacuum extraction has been successfully employed for the removal of volatile organic carbons such as gasoline at gas stations and spill sites. There may be some opportunity to employ the technology where condensate spill have occurred. The use of this technology is limited to situations where contamination is in moderate to highly permeable soils.

-Solvent Extraction and Critical Fluid Extraction:

These processes have been successfully employed to remove hydrocarbon and chlorinated organic compounds. Although effective they operate most efficiently when a continuous flow system can be established. They do not remove inorganic components such as metals.

-Soil Washing:

Soil washing is effective for the removal of organics to <2% total hydrocarbon and is useful for the removal of inorganics such as salts. Soils contaminated with hydrocarbon and salts are often one of the major problems at sour gas facilities. This process could be used effectively in conjunction with landtreatment to reduce cation/anion content and allow microbial activity to proceed uninhibited on the remaining organics. There is presently a mobile pilot plant available for site testing from Alberta Solids Treatment Company Ltd. that has been successful in treating soils contaminated with heavy oils and salts. Metals can be addressed if the exact type and concentration is known prior to process setup.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

1. A computer database for subsurface monitoring and remediation data has been developed for Alberta sour gas plants. The system is designed to run on IBM compatible PC's. Data from 54 sour gas plants, obtained from Alberta Environment for this study, have been entered into the database. The database system could be used by Alberta Environment and CPA personnel to more effectively track the monitoring efforts of the various plants, assess the need for remedial action, and document compliance. The database system is also available to CPA member companies for in-house management of groundwater monitoring data.

2. For the purposes of this study, contamination is defined as the presence of "any chemical substance whose concentration exceeds background concentrations or which is not naturally occurring in the environment". (Environment Canada, 1984). The scope of this report does not include the establishment of recommended clean-up criteria, and contamination does not imply the need for clean-up. A detailed set of procedural and numerical criteria for establishing the presence of impacts on groundwater and soil were developed.

3. Industry subsurface monitoring data from 54 plants which had submitted reports to Alberta Environment pursuant to the Clean Water Act were reviewed. At each plant where sufficient data were available, the source, type, and location of contaminants were identified and recorded. Contamination situation classifications (CSC's) for each plant were generated with this information. Available data were insufficient for analysis of the potential risk posed by the contamination situations identified.

4. The standard of reporting found in the submissions to Alberta Environment was extremely variable, yet all reports had been accepted by Alberta Environment. Data ranged from complete and of excellent quality, to partially complete, and virtually nonexistent. This reflects in part the lack of detailed guidelines for subsurface monitoring at Alberta sour gas plants.

5. The most common sources of groundwater contamination among the plants where data allowed determination of source, were, in descending order of frequency: the process water ponds (78% of plants had at least one case of contamination from the process water pond), process area (55%), landfill (48%), and sulphur block areas (38%). It is likely that the number of identified cases of groundwater contamination originating from the sulphur block is low, as many plants did not monitor groundwater quality downgradient of the sulphur block.

6. The most common types of deleterious substances found in the groundwater at sour gas plants in the study set were, in descending order of frequency: main ions (95%), dissolved organics (93%), and sulphur products (39%). Free phase hydrocarbon (condensate) was identified at five (11%) of the 44 plants with sufficient data to determine contaminant type. The most common combination of contaminant types was dissolved organics and main ions, with or without other constituents such as process chemicals and nitrogenous compounds.

7. The most commonly impacted groundwater-bearing zones at sour gas plants in the study set were groundwater bearing zones of moderate hydraulic conductivity (10E-5<K<10E-8 m/s), such as near-surface inter-till sand and silt layers or fractured bedrock units common in Alberta. Most of the plants reviewed as part of this study were located in areas where near surface

geology was dominated by low and moderate hydraulic conductivity materials.

8. The most commonly occurring group of groundwater contamination situations among sour gas plants of the study set was a combination of dissolved organics and main ions (possibly including process chemicals and nitrogenous compounds), found in a near surface aquifer of moderate hydraulic conductivity, originating from the process water pond. At least one example of this situation was identified at 15 of 32 plants with sufficient data to determine full CSC's. The next most common situation group, sulphur products from the sulphur block, was identified at 9 of 32 plants.

9. An attempt was made to obtain soil sampling data directly from plant operators. Reports from 7 plants were collected. The dominant sources of soil contamination at these plants were on-site landfills and sulphur blocks. The most common types of soil contaminants were hydrocarbons (found at 6 of the 7 plants), main ions and metals. The small number of plants exhibited widely varying levels of sampling density, analysis and data completeness.

10. A loose correlation was determined between the number of contamination situations present at a given plant, and the plant's age. The older a plant, the more likely it may be to have several contamination situations. No other significant trends in the pattern of contamination situations at Alberta sour gas plants were noticed.

11. The number of Alberta sour gas plants at which remediation programmes are underway is relatively small, and the general level of technology being employed is low.

12. Seven plants that reflect the most commonly occurring contamination situations were selected as potential candidates for implementation of a subsurface remediation demonstration project. Relatively detailed site characterization has been completed at each of the seven plants.

5.2 RECOMMENDATIONS

1. If the database developed for this study is to be used by Alberta Environment, efforts should be made to keep it up to date by entering all new data on sour gas plant monitoring and remediation as they become available. CPA member companies should consider using the database as a tool for in-house management of groundwater monitoring data.

2. This study supports the need for the new set of proposed guidelines currently being formulated for subsurface monitoring at industrial facilities in Alberta. These guidelines should include minimum standards for the design, construction and location of monitoring instruments, provide an indication of expected sampling frequencies and analytical schedules to be used, and require a level of basic interpretation of results. Standardization of reporting will assist Alberta Environment personnel in assessing the need for clean-up. In addition, operators are encouraged to comply with the new guidelines, and engage in properly designed and conducted remediation programmes once the need for clean-up has been established.

3. Once a contamination situation has been identified, the application of risk analysis techniques such as contaminant transport modelling to determine the fate of contaminants should be considered. Such studies could provide important information with which the need for remediation can be assessed.

4. Gas processing plants in Alberta are found in such diverse locations and represent such a wide range of climatic and hydrogeological conditions, that application of a single set of rigid clean-up criteria is not recommended. Risk analysis studies could provide the information necessary for case-by-case assessment of contamination problems.

5. It is recommended that the industry consider developing a set of guidelines for the design and implementation of subsurface remediation programmes. These guidelines, like the Ontario site clean-up guidelines (Environment Ontario, 1989), would provide an indication of general procedures to be followed, rather than a set of detailed numerical criteria. The availability of such a document would be of assistance to operators in the planning, design, monitoring and verification of proper remediation programmes.

6. The initiation of one or more subsurface remediation demonstration projects, designed to address contamination situations present at Alberta sour gas plants, would be of benefit to all operators in the province. By demonstrating not only appropriate new technology, but also approach and methodology, such a program and its resulting documentation would likely set a standard for subsurface remediation for the industry as a whole. Lessons learned and technologies and procedures tested during the demonstration programme could be applied to similar situations at other gas plants in the province. Such a situation would represent a significant savings in effort and resources for the sour gas processing industry, when gauged against the alternative of several companies working independently on similar types of problems.

7. Final selection of one or two candidates from the plants described in this report should be based on the willingness and ability of the operator to cooperate in the venture (by providing support staff and services, access to site and records, financial participation, permission to fully publish study results, and freedom to conduct experimental activities as part of the overall programme), the location of the site, logistical considerations, the unique hydrogeological and geological conditions of the site, and the perceived applicability of the site to the goals and anticipated direction of the project.

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APPENDIX I

SOUR GAS PLANT DATABASE SYSTEM

AND EXAMPLES OF COMPLETED DATA FORMS

APPENDIX I
SOUR GAS PLANT DATABASE

1. DESIGN PHILOSOPHY

Initial database design took into consideration two main factors: the types of data to be accomodated, and the preferences and requirements, present and future, of intended users. This approach involved several steps. A thorough review of the data provided for the study was conducted to determine the types, quantity, quality, and ranges of data to be accomodated in the database. This review is described in greater detail in Section 2 of this appendix. Also, Alberta Environment personel intended as users of the system were consulted, and their software preferences, hardware constraints, and anticipated future requirements determined. The findings of these consultations are discussed in Section 4. Before final coding of the database was performed, a trial version was provided to Mr. Ceroci of Alberta Environment for review and comment.

Information gathered at this stage was used as a basis for design of the database, reflecting the philosophy that an information system should be designed to fit the data it is intended to house and the needs of intended users, rather than attempting to fit data into a pre-concieved database format.

2. DATA

Data for this study was provided by Alberta Environment, and consisted of subsurface monitoring reports and proposals submitted to the Standards and Approvals Division by plant operators in compliance with the Clean Water Act. This data was thoroughly reviewed to determine the form and types of data present, and their quantity, ranges, and general quality. Section 3 of this appendix discusses in detail the findings of this review, including problems in data assembly, completeness of information, data quality, and types of data available.

2.1 Data Input Forms

Based on the findings of the data review, Data Input Forms (DIF's) were developed. These forms list the parameters to be included in the database, and mimic the database input screens. Figures 1 through 4 in the main body of the report show the final version of the data forms, which include sections for general information, hydrogeological and monitoring system details, sequential subsurface monitoring data, and remediation system information and operating history.

As data were extracted from reports and other documents, they were screened, rated for quality and consistency, and recorded on the standard data form. Use of the forms greatly reduced the time required for data sorting, input and management, reduced the number of errors during computer data input, and also provided a convenient hardcopy library as backup to the database. Examples of completed forms for two gas plants are presented in this appendix.

2.2. Data Screening and Quality Control

The quality of the data contained in a database is as important as the quantity. If the quality of data is suspect, user confidence is affected, and the effectiveness of the database as a tool for technical evaluations and decision making suffers. Certain categories of data, in particular chemical analyses, are subject to variability in quality. For instance, if the ion balance for a potability analysis is poor, the validity of the data may be suspect. Ion balance can be affected by such things as low pH, high concentrations of organic compounds and analytical error. Sampling and field preservation techniques may also affect the quality of analytical data.

To help ensure quality control of information housed in the database, a data data quality index was developed for monitoring chemical analysis data. All data were rated on a three-tiered scale, consisting of categories 1 (good), 2 (fair), and 3 (incomplete or inferior). Each rating is assigned following specific guidelines based on such things as sources of data, sampling techniques used, ion balance and use of other laboratory checks, etc. Data quality ratings are assigned based on the following guidelines:

1. GOOD
   - complete potability analysis available
   - ion balance within 0.95 to 1.05 range
   - accepted sampling techniques used (if known)

2. FAIR
   - complete potability analysis available
   - no ion balance or other laboratory quality control checks reported in data
   - accepted sampling and preservation techniques used (in known)

3. INCOMPLETE
   - selected analytical parameters/ indicators only
   - no ion balance, or unacceptable ion balance
   - other quality control checks indicate problems with analysis
   - obvious errors or questionable sampling practices used

As the monitoring reports provided by Alberta Environment were reviewed and the data forms completed, data was sytematically screened and rated for quality. The data quality ratings appear in the database, and can be used as a search parameter by users. For example, a user may specify that only data of quality 1 and 2 be included in a printout, providing an added degree of confidence in the data provided by the database.

3. DESIGN

3.1 Database Software

The sour gas plant database system is based on the popular dBase IV software, the improved version of the well known dBase III and IIIPlus packages developed by Ashton Tate Corporation. DBase has been the industry standard for many years and is unquestionably the most widely used database management system (DBMS) for micro-computers. Many other DBMS's emulate dBase, and files can be used interchangeably if required.

The choice of software for the database was made based on the preferences expressed by Alberta Environment personel, the intended end users of the system. Users were familiar with dBase programming, and had built and used various dBase III databases in the past.

3.2 Hardware Requirements

The sour gas plant monitoring and remediation database is designed to run on IBM compatible AT (286) and 386 (or higher) machines. Minimum requirements include 640 K RAM (of which at least 590 K must be available - memory resident programs should be stripped before attempting to run the database), 2 Mb of hard disk space, and DOS 3.1 or newer. Speed of operation will vary depending on processor speed and power; for example a 386 25 MHz machine will sort and retrieve data more quickly than a basic 12 MHz AT/286. Colour or monochrome monitors are supported, however the full screen editors are designed for a 25 line screen. The config.db file must be altered if a 41 line screen is desired..

3.3 Design and Contents

The database is divided into four linked data fields, which together comprise a file. Each gas plant is assigned a file and a unique identification number. The four data fields are:

1. **General Information:** Includes data such as plant name and location, references, data available, and a summary of contamination situations identified at the plant.

2. **Hydrogeological/Monitoring System:** Provides information on general geology and hydrogeological conditions at the plant, including aquifer depths, types, hydraulic conductivities, and lithology; and lists monitoring system information such as piezometer installation depths, screen positioning, and lithology of the completed zone. The database can accommodate up to 12 piezometers per site.

3. **Subsurface Monitoring:** Provides sequential groundwater quality monitoring results, including static water level and a full range of water quality parameters with data quality rating, for the monitoring system described in data field 2 (Hydrogeological/Monitoring system). These types of data are stacked sequentially by date - the database can accomodate results from up to 999 successive samplings for the monitoring system. Water quality parameters are indexed to improve program efficiency, and include full potability parameters, metals, and organic indicators. Additional parameters can be easily added by users as required.

4. **Subsurface Remediation:** Accomodates information about remediation systems installed at gas plants. For each system, data on the specific targets of the remediation effort, start date, remediation and treatment/disposal methods used, and remediation history can be entered. The database accomodates data from multiple remediation systems.

Large comment fields are provided in each field for additional notes and information. A slot is provided for reference to source documents. In addition, the database includes a special file which appends to the subsurface monitoring field, in which the user can store entire text reports. This could be used for general notes, information on licencing compliance, etc.

Figure 5 in the main body of the report shows a schematic diagram of the database structure, illustrating the four information categories, and Figures 1 through 4 show the data form sheets, which mimic the database screens for each field.

4. MAINTENANCE AND OPERATION

The database has been designed for flexibility and user friendliness. The program is interactive, and features main and sub menus, command bar, and numerous help files. Data can be added, deleted, or edited within the database simply and quickly. Commands allow the user to move freely within a gas plant file (from one data field to the next), and among the various plant files. The user may search for, tally and list plants corresponding to given criteria, or filter data using any of the databse parameters.

The database and database files should be run from a hard drive, but all data (.dbf) files should be backed up on disc. It is recommended that the prime user or database custodian maintain control over data input, file creation and modification. Controlling data input prevents the duplication of files and data, and guards against the existence of equivalent but slightly different data sets within an organization (two users have been inputting data as it becomes available, one user's database contains 55 gas plants, another's has 73, and data from common plants is not identical). Such a situation rapidly leads to confusion, and often abandonment of the database by users.

A convenient solution to this problem is the Relational Report Writer software package, and its numerous commercial equivalents. This software is designed to access, manipulate and produce reports from Dbase IV data files. Data files created by the database custodian are provided to users without the surrounding database system. Using Relational Report Writer, these users can access all the data freely, but cannot edit, delete, or add data.

5. OUTPUT

Reports can be generated from the database in two different ways: by creating resident reports using dBase IV programming language inside the database, or by using Relational Report Writer add-on software independent of the database.

Resident Reports

Reports can be created within the dBase environment, and would be accessed through the main menu's report option. Such reports would likely consist of data frequently required by users.

Relational Report Writer Reports

As described above, this add-on software allows the user to access data files directly, independent of the dBase IV system. Reports can be quickly and easily generated with complete flexibility; any number of parameters can be used as search criteria and printed. For example, the user could ask for a printout of all gas plants built between 1975 and 1985, their operators, locations, all contaminant situations present, and if a remediation system is in place. Searching is done with and/or statements: for example one could list all plants within a certain township and range area having a contaminant situation involving free product and/or dissolved organics, and which have at least 6 monitoring instruments installed on site. Figure 6 in the main body of the text provides an example of a report generated with this software.

It is expected that the database will prove an excellent medium for enhanced record keeping, licencing, compliance assesssment and evaluation of subsurface monitoring and remediation systems at Alberta sour gas plants.

EXAMPLES OF COMPLETED DATA FORMS

CPA
ALBERTA SOUR GAS PLANT
SUBSURFACE CONTAMINATION DATABASE

DATA FORM

Facility: ______________________

Plant Identifier P-17

CPA
ALBERTA SOUR GAS PLANT
SUBSURFACE CONTAMINATION DATABASE
DATA FORM

GENERAL INFORMATION

Plant Name ________ C20 Plant Identifier P-17 C25
Operator ________

Plant Location:
Lsd ____ AN3 Sec. ____ N5 Tp. ____ N3 Rg. ____ N3 Mer ____ AN4
Nearest Town ________ C15

Contacts:
Plantsite; Name N/A C15
Title ________ C15
Telephone ____ - ________ N7

Office; Name N/A C15
Title ________ C15
Telephone ____ - ________ N7

Plant Information:
Process Type(s) 23 / 11 / 26 / 18 N12 (See Index List)
Plant Startup Date 1966 D8
Comments ________ C50

Data Available: Hydrogeological/Monitoring System Y L1
Subsurface Monitoring Y L1
Remediation Data N L1
Subsurface Remediation N L1

Groundwater Monitoring System in Place? Y L1 Date Installed 87.07.31 D8
Contamination Remediation System in place? N L1 Date Installed N/A D8

Contaminant Situations Present:

Situation 1: Source: 3 N3 Type: M N4 Contaminated Zone 111 N3
Comment 1 ________ C50
Situation 2: Source: 1 N3 Type: M N4 Contaminated Zone 111 N3
Comment 2 ________ C50
Situation 3: Source: ____ N3 Type: ____ N4 Contaminated Zone ____ N3
Comment 3 ________ C50
Situation 4: Source: ____ N3 Type: ____ N3 Contaminated Zone ____ N3
Comment 4 ________ C50
Comment: ________ C125

Data Reference ORIGINAL SOURCE REPORT
________ C200

CPA
ALBERTA SOUR GAS PLANT
SUBSURFACE CONTAMINATION DATABASE

DATA FORM

HYDROGEOLOGICAL/MONITORING SYSTEM

Plant Name ____________ C15 Plant Identifier P-17

General Plant Site Geology:
Surficial Deposit Type SILT/CLAY C15 Thickness ____ - 7.6 m N8
Surficial Deposit Type ____________ C15 Thickness ____ - ____ m N8
Bedrock Type SILTSTONE/SHALE C15 Formation ____________ C15

General Plant Site Hydrogeology:
Aquifer 1 Type CONFINED C15 Depth to Top >7 m N8 Thickness >5 m5
Hydraulic Conductivity <1x10⁻⁶ m/s N8 Lithology COAL/SH/SLTST. C10
Pump Test (y/n) N L1 Flow Direction SE C8
Aquifer 2 Type ____________ C15 Depth to Top ______ m N8 Thickness ______ m5
Hydraulic Conductivity ____________ m/s N8 Lithology ____________ C10
Pump Test (y/n) ____ L1 Flow Direction ____________ C8
Aquifer 3 Type ____________ C15 Depth to Top ______ m N8 Thickness ______ m5
Hydraulic Conductivity ____________ m/s N8 Lithology ____________ C10
Pump Test (y/n) ____ L1 Flow Direction ____________ C8

Monitoring System Data:

Piezometer Number	Installation Date (yr.m.d)	Top of Screen (depth in m) (below GL)	Screen Length (m)	Lithology of Completed Zone	Status
1A	87.09.05	5.5	3.0	CL/SH/C	CP
1B	87.09.05	9.5	1.5	SH	CP
2	87.08.04	10.7	1.5	SH	CP
3A	87.09.05	6.14	3.0	CL/SH	CP
3B	87.08.04	9.47	1.5	SILTST	CP
4A	87.08.04	6.1	3.0	CL/COAL	CP
4B	87.07.30	10.7	1.5	SH	CP
5A	87.08.05	5.5	3.0	CL/SH	CP
5B	87.08.04	10.9	1.5	SH	CP
6	87.07.30	7.84	1.5	SH	CP
7	87.07.30	10.7	1.5	SS	CP
8	87.07.30	11.01	1.5	SH	CP
9	87.09.05	10.95	1.5	SH	CP

CPA
ALBERTA SOUR GAS PLANT
SUBSURFACE CONTAMINATION DATABASE

DATA FORM

SUBSURFACE MONITORING

Plant Name ______________ C15   Plant Identifier P-17

SEQUENTIAL MONITORING DATA REFERENCED BY DATE

Sampling Date 87.09.09 D8
Data Quality 2 N2

Piezometer Number	SWL (mBGL)	Selected Water Quality Parameters/Contaminants/Indicators Type1/conc	Type2/conc	Type3/conc	Type4/conc	Type5/conc
1A	1.63	51/ 73.6	15/ 653	53/ 28	56/ 11	
3A	2.12	51/ 453.0	15/ 1130	53/ 56	56/ 14	
4A	3.55	51/ 46.6	15/ 521	53/ 12	56/ <1	
5A	4.74	51/ 57.0	15/ 678	53/ 37	56/ <1	
5B	5.58	51/ 21.8	15/ 504	53/ 18	56/ 6	
7	5.87	51/ 28.3	15/ 1050	53/ 45	56/ 1	
8	5.67	51/ 65.9	15/ 510	53/ 6	56/ 1.	
9	3.08	51/ 6.0	15/ 513	53/ 23	56/ <1	

Comment1 ______________ C125

Comment2 ______________ C125

Comment3 ______________ C125

CPA
ALBERTA SOUR GAS PLANT
SUBSURFACE CONTAMINATION DATABASE

DATA FORM

SUBSURFACE REMEDIATION

Plant Name________________________C15 Plant Identifier_______________

Remediation System 1:
Remediation Target:
NO SYSTEM HAS BEEN INSTALLED
____C125

Contaminant Situation Classifications Present ___________AN8
___________AN8
___________AN8

Specific Contaminants Present
Contaminant1_______________C10
Contaminant2_______________C10
Contaminant3_______________C10

Remediation Start Date______________D8
Piezometer Number Indicative of Contamination______________________________C25

Remediation methods:_____N3_____N3_______N3 (see index lists)
treatment/disposal methods:_____N3______N3______N3 (see index lists)

Comment NO SUBSURFACE REMEDIATION C50

Remediation History:

Estimated Initial Mass of Contaminant_______________AN8

Date	Action	Est. cumm. mass contaminant removed	recovery efficiency	comment

Comments____
____C125

CPA
ALBERTA SOUR GAS PLANT
SUBSURFACE CONTAMINATION DATABASE

DATA FORM

Facility: ______________________

Plant Identifier P-50

CPA
ALBERTA SOUR GAS PLANT
SUBSURFACE CONTAMINATION DATABASE
DATA FORM

GENERAL INFORMATION

Plant Name ________ C20 Plant Identifier P-50 C25
Operator ________

Plant Location:
Lsd ____ AN3 Sec. ____ N5 Tp. ____ N3 Rg. ____ N3 Mer ____ AN4
Nearest Town ________ C15

Contacts:
Plantsite; Name N/A C15
Title ________ C15
Telephone ____ - ________ N7

Office; Name ________ C15
Title ________ C15
Telephone ____ - ________ N7

Plant Information:
Process Type(s) 23 / 18 / 9 / ____ N12 (See Index List)
Plant Startup Date 1982 D8
Comments ________ C50

Data Available: Hydrogeological/Monitoring System Y L1
Subsurface Monitoring Y L1
Remediation Data N L1
Subsurface Remediation N L1

Groundwater Monitoring System in Place? ____ L1 Date Installed 1988.11.30 D8
Contamination Remediation System in place? ____ L1 Date Installed N/A D8

Contaminant Situations Present:

Situation 1: Source: 4 N3 Type: P N4 Contaminated Zone III N3
Comment 1 HYDROXIDE RICH FLUIDS C50
Situation 2: Source: 8 N3 Type: V N4 Contaminated Zone III N3
Comment 2 SEEPAGE FROM DOMESTIC SEWAGE C50
Situation 3: Source: 1 N3 Type: C N4 Contaminated Zone III N3
Comment 3 ________ C50
Situation 4: Source: ____ N3 Type: ____ N3 Contaminated Zone ____ N3
Comment 4 ________ C50
Comment: ________ C125

Data Reference ORIGINAL SOURCE REPORT C200

CPA
ALBERTA SOUR GAS PLANT
SUBSURFACE CONTAMINATION DATABASE

DATA FORM

HYDROGEOLOGICAL/MONITORING SYSTEM

Plant Name ____________ C15 Plant Identifier P-50

General Plant Site Geology:
Surficial Deposit Type SAND & GRAVEL C15 Thickness 0 - 6 m N8
Surficial Deposit Type ____________ C15 Thickness ____ - ____ m N8
Bedrock Type SHALE/SILTSTONE/SANDST C15 Formation PASKAPOO C15

General Plant Site Hydrogeology:
Aquifer 1 Type CONFINED C15 Depth to Top 17-31 m N8 Thickness >4 m5
Hydraulic Conductivity 1x10^{-6} to 3x10^{-7} m/s N8 Lithology SANDSTONE C10
Pump Test (y/n) N L1 Flow Direction N/A C8
Aquifer 2 Type ____________ C15 Depth to Top ______ m N8 Thickness ______ m5
Hydraulic Conductivity ____________ m/s N8 Lithology ____________ C10
Pump Test (y/n) _____ L1 Flow Direction ____________ C8
Aquifer 3 Type ____________ C15 Depth to Top ______ m N8 Thickness ______ m5
Hydraulic Conductivity ____________ m/s N8 Lithology ____________ C10
Pump Test (y/n) _____ L1 Flow Direction ____________ C8

Monitoring System Data:

Piezometer Number	Installation Date (yr.m.d)	Top of Screen (depth in m) (below GL)	Screen Length (m)	Lithology of Completed Zone	Status
BH-201	88.11.30	30.50	4.60	SS	CP
BH-202	88.11.30	6.10	3.00	SS/SH	CP
BH-203	88.11.30	16.50	5.00	SS	CP
BH-204	88.11.30	11.60	4.60	SS	CP
BH-205	88.11.30	20.40	4.60	COAL/SH	CP
BH-102A	85	N/A	N/A	N/A	N/A
BH-102B	85	N/A	N/A	N/A	N/A
BH-102C	85	N/A	N/A	N/A	N/A
BH-106	85	N/A	N/A	N/A	N/A

CPA
ALBERTA SOUR GAS PLANT
SUBSURFACE CONTAMINATION DATABASE

DATA FORM

SUBSURFACE MONITORING

Plant Name ______ C15   Plant Identifier P-50

SEQUENTIAL MONITORING DATA REFERENCED BY DATE

Sampling Date 89.01.06 D8
Data Quality N2

Piezometer Number	SWL (mBGL)	Type1/conc	Type2/conc	Type3/conc	Type4/conc	Type5/conc
BH-102A	36.62	6/ 32.7	5/ 18.8	9/ 8.3	52/ 44.2	105/<1
BH-106	15.02	6/ 9.9	5/ 3.1	9/ 7.8	52/ 15.2	105/ 3
BH-201	18.69	6/ 45.9	5/ 6930	9/ 7.5	52/ 72.2	105/ 4
BH-203	17.20	6/ 289.0	5/ 6.0	9/ 12.9	52/ 60.2	105/<1
BH-204	13.09	6/ 30.2	5/ 6.0	9/ 6.9	52/ 9.9	105/ 16
BH-205	0	6/ 18.5	5/ 13500	9/ 7.3	52/ 52.2	105/ 1
SPRING	N/A	6/ 6.9	5/ 55	9/ 8.1	52/ 7.7	105/ 1

Comment1 ______ C125

Comment2 ______ C125

Comment3 ______ C125

CPA
ALBERTA SOUR GAS PLANT
SUBSURFACE CONTAMINATION DATABASE

DATA FORM

SUBSURFACE REMEDIATION

Plant Name____________C15 Plant Identifier P-50

Remediation System 1:
Remediation Target:
NO SYSTEM HAS BEEN INSTALLED
____________C125

Contaminant Situation Classifications Present ______AN8
______AN8
______AN8

Specific Contaminants Present
Contaminant1______C10
Contaminant2______C10
Contaminant3______C10

Remediation Start Date______D8
Piezometer Number Indicative of Contamination______C25

Remediation methods:____N3____N3____N3 (see index lists)
treatment/disposal methods:____N3____N3____N3 (see index lists)

Comment____________C50

Remediation History: NO SUBSURFACE REMEDIATION

Estimated Initial Mass of Contaminant______AN8

Date	Action	Est. cumm. mass contaminant removed	recovery efficiency	comment

Comments____________
____________C125

APPENDIX II

DATA MASTER LIST (54 SOUR GAS PLANTS)

LIST OF ALL CONTAMINATION SITUATION CLASSIFICATIONS GENERATED

CPA
ALBERTA SOUR GAS PLANTS STUDY
DATA MASTER LIST

PLANT IDENTIFIER	SOIL	GROUNDWATER MONITORING SYSTEM					GROUNDWATER CIRCULATION			GROUNDWATER QUALITY DATA					SURFACE PONDS			CONTAMINATION PRESENT	
	DATA AVAIL	INST. DATE		GEOL LOGS	PIEZO CONST	K TEST	SURF ELEV	FLOW DIR	FLOW VEL	MAIN IONS	ORG IND	N CMPDS	METALS	GC/MS	MONITORING PERIOD	INST ALLED	ANAL YSIS	GDW	SOILS
P-1	N	85		Y	Y	N	Y	Y	N	Y	Y	Y	Y	N	85–87	Y	Y	Y	U
P-7	N	84		Y	Y	N	Y	Y	N	Y	Y	Y	Y	N	88	Y	N	Y	U
P-13	N	84		N	N	N	Y	N	N	Y	Y	Y	Y	N	85–88	Y	Y	Y	U
P-2	N	84		N	N	N	Y	Y	N	Y	Y	Y	Y	N	84–88	Y	N	Y	U
P-15	N	88		Y	Y	Y	Y	Y	N	Y	Y	Y	N	N	88	Y	Y	Y	U
P-16	N	87		Y	Y	N	Y	Y	N	Y	Y	Y	Y	N	87–88	Y	N	Y	U
P-17	N	87		Y	Y	Y	Y	Y	Y	Y	Y	Y	N	N	87	Y	Y	Y	U
P-18	N	81		N	N	N	N	N	N	Y	Y	N	N	N	82–88	Y	N	Y	U
P-33	N	85		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	85	Y	Y	Y	U
P-44	N	87		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	87	Y	Y	Y	U
P-34	N	86		Y	Y	Y	Y	Y	Y	Y	Y	N	N	N	86–89	Y	Y	Y	U
P-19	N	84?		N	N	N	N	N	N	Y	Y	Y	Y	N	84–88	Y	N	Y	U
P-5	N	?		N	N	N	N	N	N	N	N	N	N	N	–	Y	N	U	U
P-4	Y	86		N	N	N	N	N	N	Y	Y	Y	Y	N	86–87	Y	N	Y	Y
P-3	N	86		N	N	N	N	N	N	Y	Y	Y	Y	N	86–87	Y	N	Y	U
P-6	N	?		N	N	N	N	N	N	N	N	N	N	N	–	Y	N	U	U
P-8	N	?		N	N	N	N	N	N	Y	Y	Y	Y	N	88	Y	N	U	U
P-9	Y	?		N	N	N	N	N	N	N	N	N	N	N	–	Y	N	U	Y

CPA
ALBERTA SOUR GAS PLANTS STUDY
DATA MASTER LIST

PLANT	SOIL	GROUNDWATER MONITORING SYSTEM					GROUNDWATER CIRCULATION			GROUNDWATER QUALITY DATA					SURFACE PONDS			CONTAMINATION PRESENT	
	DATA AVAIL	INST. DATE		GEOL LOGS	PIEZO CONST	K TEST	SURF ELEV	FLOW DIR	FLOW VEL	MAIN IONS	ORG IND	N CMPDS	METALS	GC/MS	MONITORING PERIOD	INST ALLED	ANAL YSIS	GDW	SOILS
P - 10	N	83		N	N	N	Y	N	N	Y	Y	Y	Y	N	83–88	Y	N	Y	U
P - 11	N	86		N	N	N	Y	N	N	Y	Y	Y	Y	N	86–88	Y	N	Y	U
P - 12	N	84		Y	Y	N	N	N	N	Y	Y	Y	Y	N	84–87	Y	N	Y	U
P - 14	N	?		N	N	N	N	N	N	N	N	N	N	N	–	Y	N	U	U
P - 47	N	88		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	88–89	Y	Y	Y	U
P - 53	N	83		Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	86–89	Y	Y	Y	U
P - 20	Y	85		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	85–87	Y	N	Y	Y
P - 35	Y	82		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	82–89	Y	Y	Y	Y
P - 54	Y	84		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	84–89	Y	Y	Y	U
P - 37	Y	86		Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	86–89	Y	Y	Y	N
P - 50	N	88		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	89	Y	Y	Y	N
P - 21	N	?		N	N	N	N	N	N	Y	Y	N	N	N	86	U	N	Y	U
P - 22	N	85		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	85	Y	N	Y	U
P - 23	N	N		N	N	N	N	N	N	N	N	N	N	N	–	U	N	U	U
P - 24	N	N		N	N	N	N	N	N	N	N	N	N	N	–	U	N	U	U
P - 26	N	86		Y	Y	Y	Y	Y	N	N	Y	Y	N	N	86–87	Y	Y	Y	U
P - 25	N	86		Y	Y	Y	Y	Y	N	N	Y	Y	N	N	86–88	Y	Y	Y	U
P - 27	N	89		Y	Y	Y	Y	Y	Y	Y	Y	Y	N	N	89	Y	Y	Y	U
P - 51	Y	86		Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	86–88	Y	Y	Y	U

CPA
ALBERTA SOUR GAS PLANTS STUDY
DATA MASTER LIST

PLANT	SOIL	GROUNDWATER MONITORING SYSTEM					GROUNDWATER CIRCULATION			GROUNDWATER QUALITY DATA					SURFACE PONDS			CONTAM-INATION	
	DATA AVAIL	INST. DATE		GEOL LOGS	PIEZO CONST	K TEST	SURF ELEV	FLOW DIR	FLOW VEL	MAIN IONS	ORG IND	N CMPDS	METALS	GC/MS	MONITORING PERIOD	INST ALLED	ANAL YSIS	GDW CONTAM PRESENT	SOILS CONTAM PRESENT
P - 28	N	86		Y	Y	Y	Y	Y	Y	Y	Y	Y	N	N	86–88	Y	Y	Y	U
P - 43	N	85		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	85–88	Y	Y	Y	U
P - 40	N	87		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	87–89	Y	Y	N	U
P - 45	N	85		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	88–89	Y	Y	Y	U
P - 42	N	84		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	84–88	Y	Y	Y	U
P - 41	N	86		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	86–88	Y	Y	Y	U
P - 29	N	89		Y	Y	Y	N	N	N	N	N	N	N	N	–	Y	N	U	U
P - 30	N	N		N	N	N	N	N	N	N	N	N	N	N	–	Y	N	U	U
P - 36	N	85		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	85–89	Y	Y	Y	U
P - 38	N	85		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	85–88	Y	N	Y	U
P - 48	N	85		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	85–88	Y	N	Y	U
P - 39	N	85		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	85–89	Y	Y	Y	U
P - 52	N	83		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	83–89	Y	Y	Y	U
P - 46	N	85		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	85–88	Y	Y	Y	U
P - 49	Y	85		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	85–88	Y	Y	Y	Y
P - 31	N	N		N	N	N	N	N	N	N	N	N	N	N	–	Y	N	U	U
P - 32	N	84		Y	Y	Y	N	N	N	Y	N	N	Y	N	84–89	Y	Y	Y	U

NOTE:

Y – DENOTES INFORMATION AVAILABLE

U – DENOTES UNKNOWN

? – DENOTES STATUS UNKNOWN

N – DENOTES NO INFORMATION AVAILABLE

LIST OF ALL CSC'S GENERATED FOR THE STUDY

PLANT	CSC1	CSC2	CSC3	CSC4	Startup date	Process types			
P-1	1 Q III	4 O III	2 D III	6 N III	01/01/64	23	2	13	0
P-2	4 O III	0	0	0	01/01/68	23	25	0	0
P-3	2 D	4 Q	8 V	0	01/01/69	23	2	18	0
P-5	0	0	0	0	01/01/81	23	4	13	0
P-6	0	0	0	0	01/01/57	0	0	0	0
P-7	4 P	4 P	0	0	01/01/65	23	25	4	9
P-4	4 M	1 C	0	0	01/01/68	1	23	13	0
P-8	4 D	0	0	0	01/01/65	23	2	18	0
P-9	0	0	0	0	01/01/71	26	28	0	0
P-10	2 C	1 B	0	0	01/01/68	2	23	18	9
P-11	6 C	3 R	1 W	0	01/01/67	23	4	18	0
P-12	4 P	6 C	0	0	01/01/65	23	13	2	0
P-13	6 P	2 D	4 P	0		0	0	0	0

P-14 0 0 0 0
Startup date 01/01/76 Process types:23 11 18 0

P-15 1 M III 0 0 0
Startup date Process types:0 0 0 0

P-16 0 P 0 0 0
Startup date 01/01/86 Process types:23 3 25 0

P-17 3 M III 1 M III 0 0
Startup date 01/01/66 Process types:23 11 26 18

P-18 1 M 4 M 0 0
Startup date 01/01/72 Process types:23 18 9 3

P-19 1 M 2 R 4 0
Startup date 01/01/71 Process types:2 23 18 26

P-20 6 P III 4 M III 2 W III 1 P III
Startup date 01/01/56 Process types:2 23 13 9

P-21 9 B 0 0 0
Startup date 01/01/86 Process types:17 1 23 6

P-22 1 V III 2 D III 4 M III 6 C III
Startup date 01/01/60 Process types:18 23 2 4

P-23 0 0 0 0
Startup date 01/01/64 Process types:1 11 4 6

P-24 0 0 0 0
Startup date Process types:0 0 0 0

P-25 4 C IV 6 P IV 0 0
Startup date 01/01/69 Process types:23 4 11 0

P-26 4 M IV 0 0 0
Startup date 01/01/77 Process types:18 23 17 0

P-27 4 C III 1 B III 0 0
Startup date 01/01/71 Process types:23 18 0 0

P-28 1 P III 2 D III 4 P III 6 V III
Startup date 01/01/61 Process types:4 13 2 0

```
P-29       0             0              0             0
    Startup date   01/01/88  Process types:23 18   0   0
 ----------------------------------------------------------------- --

P-30       0             0              0             0
    Startup date   01/01/62  Process types:2  13   0   0
 ----------------------------------------------------------------- --

P-31       0             0              0             0
    Startup date   01/01/76  Process types:1  18   0   0
 ----------------------------------------------------------------- --

P-32       6 M II        1 M II         0             0
    Startup date   01/01/54  Process types:2  23  19   5
 ----------------------------------------------------------------- --

P-33       7 T II        1 M II         6 M  II       4 M  II
    Startup date             Process types:0   0   0   0
 ----------------------------------------------------------------- --

P-34       4 M IV       6 C IV          8 C  IV       0
    Startup date   01/01/68  Process types:23 13   0   0
 ----------------------------------------------------------------- --

P-35       4 P IV       2 D IV          6 P  IV       8 R  IV
    Startup date   01/01/57  Process types:0   0   0   0
 ----------------------------------------------------------------- --

P-36       1 M II       2 M II          0             0
    Startup date   01/01/70  Process types:1  25   0   0
 ----------------------------------------------------------------- --

P-37       9 A III      4 M III         2 D  II       0
    Startup date   01/01/61  Process types:2  23  13   0
 ----------------------------------------------------------------- --

P-38       6 P III      4 M III         0             0
    Startup date   01/01/79  Process types:25 23   0   0
 ----------------------------------------------------------------- --

P-39       3 C IV       6 M II          4 C  IV       0
    Startup date   01/01/69  Process types:2  23  25   0
 ----------------------------------------------------------------- --

P-40       0             0              0             0
    Startup date   01/01/85  Process types:18  7  23  27
 ----------------------------------------------------------------- --

P-41       4 C III       0              0             0
    Startup date   01/01/80  Process types:11  2   0   0
 ----------------------------------------------------------------- --

P-42       6 P III       1 M III        1 D  III      5 A  III
    Startup date   01/01/64  Process types:23 26  18   5
 ----------------------------------------------------------------- --

P-43       9 M II        6 C II         0             0
    Startup date   01/01/61  Process types:1  13   0   0
```

```
P-44        8 M          4 M           0             0
    Startup date   01/01/59  Process types:1   8   0   0
----------------------------------------------------------------- --

P-45        4 M III      9 M III       4 D  III      0
    Startup date   01/01/70  Process types:23 18   0   0
----------------------------------------------------------------- --

P-46        4 P IV       0             0             0
    Startup date   01/01/71  Process types:23 25   0   0
----------------------------------------------------------------- --

P-47        4 C III      2 D III       1 C  III      0
    Startup date   01/01/72  Process types:23 13   0   0
----------------------------------------------------------------- --

P-48        1 M III      4 B III       9 A  III      0
    Startup date   01/01/51  Process types:23  2  13  25
----------------------------------------------------------------- --

P-49        1 M III      3 D III       4 M  III      6 M  III
    Startup date   01/01/60  Process types:23 13   0   0
----------------------------------------------------------------- --

P-50        4 P III      8 V III       1 C  III      0
    Startup date   01/01/82  Process types:23 18   9   0
----------------------------------------------------------------- --

P-51        2 P III      6 P III       0             0
    Startup date   01/01/60  Process types:23 18  25   0
----------------------------------------------------------------- --

P-52        1 P II       2 D II        4 P  II       6 P  II
    Startup date   01/01/62  Process types:2  23  25  26
----------------------------------------------------------------- --

P-53        1 M III      2 D III       4 P  III      6 M  III
    Startup date   01/01/71  Process types:11 23   7   0
----------------------------------------------------------------- --

P-54        1 T III      2 D III       4 N  III      0
    Startup date   01/01/71  Process types:23 18   3   0
----------------------------------------------------------------- --
```