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INNOVATIVE REMEDIATION TECHNIQUES IN COMPLEX LITHOLOGIES

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1.0 Introduction

This paper presents the implementation of an integrated and phased approach to the site investigation and remediation of a former gas plant facility using innovative and cost-effective technologies. The combined use of both ex situ and in situ remediation methods, as well as remediation enhancement techniques used during the site remediation work, are described.

2.0 Background

The former Corbett Creek Gas Plant is located approx. 140 km northwest of Edmonton, Alberta, Canada, near the town of Fort Assiniboine. It was commissioned in 1972 as a sweet gas plant. The site is approx. 0.9 hectares (ha.) in size. The facility was expanded in 1973 and 1974 and operated continuously until the fall of 1990. An investigation was carried out in 1991 as part of due diligence for a proposed property transaction. This led to the discovery of volatile hydrocarbon contamination near the former flare pit. Site investigation was hindered due to the proximity of the highway immediately west of the site.

3.0 Site Investigations

Further investigations were performed to gain a better understanding of the extent of the problem in 1992 and 1993. Ten test holes were drilled and groundwater monitoring wells installed in August of 1992 to establish the nature and extent of on-site subsurface contamination. A further six test holes were drilled in November, 1992 to delineate the extent of off-site contamination. In May, 1993 an additional eight test holes were drilled to further delineate the extent of off-site contamination.

Based on the occurrence of free-phase liquid hydrocarbons in some of the off-site monitoring wells, an expanded investigative borehole and surface geophysics program was initiated in July, 1993 to better characterize the subsurface lithology.

The geophysical program comprised an electromagnetic and electrical resistivity survey to measure electrical conductivity, natural gamma radiation, and resistivity of the subsurface soils. High electrical conductivities correspond to fine grained materials, and high resistivities correspond to coarser grained materials. A gamma log was used to indicate clay content; a relatively high gamma count corresponds to a high clay content, and a relatively low gamma count corresponds to a low clay content. The geophysical surveys were correlated with the investigative borehole findings to assist in the interpretation of the geology underlying the site.

A total of 31 test hole locations were drilled and monitoring wells were installed at 28 locations in the investigative phases of the site characterization *(Figure 1)*.

4.0 Results of Site Investigations

The results of the site investigations supported by laboratory analytical results from soil and groundwater sampling indicated contamination in the form of free-phase and dissolved-phase natural gas condensate present in subsurface soils. It is postulated that the condensate originated in a nearby flare pit into which it was discharged during occasional process upsets *(Figure 1)*. The base of the flare pit was connected to underlying sand layers which facilitated the off-site migration of the condensate towards the northwest.

The lithology observed during the borehole drilling program consisted of sandy silt to silty sand with varying amounts of clay, underlain by a stiff, highly plastic clay. Interbedded in the silt and clay were fine-grained sand lenses and laminae. The interpretation of the geophysical survey results indicated a series of west to east trending channel deposits of low conductivity materials (sands) which cut through higher conductivity background materials (clays). The elongation and continuity of the channel deposits across the site suggests a glacio-fluvial depositional environment.

The hydraulic conductivity values in subsurface sediments ranged from 10^{-9} m/sec (clays) to 10^{-6} m/sec (silts and silty sands) with a ground water velocity of approx. 15-30 m/year. A groundwater divide was inferred from groundwater surface elevation data collected across the site. The groundwater divide bisects the site near the location of the former flare stack. The groundwater flow south of the divide is towards the south while flow north of the divide is to the north. The average hydraulic gradient was 0.13 metres.

Free phase condensate measured in monitoring wells indicated condensate thicknesses of up to 4.2 meters. The liquid condensate was generally encountered at depths of between eight to twelve metres below the ground surface. The condensate consisted of light end (C_7 to C_{11}) hydrocarbons with xylene and octane prevalent. The distribution of free-phase liquid condensate present on the groundwater table in October, 1994, prior to the start of any remedial measures, if shown in *Figure 2*. The in situ volume of free-phase condensate was estimated to be approximately 500 m^3. The total maximum concentrations of benzene, toluene, ethylbenzene, and xylene (BTEX) compounds in the soil and groundwater was 36,000 ppm and 3,200 ppb, respectively. The estimated volume of impacted groundwater and contaminated subsurface soil was approximately 10,000 m^3 and 20,000 m^3, respectively.

5.0 Pilot Scale Remediation Program

A pilot scale remediation program was initiated as a necessary prerequisite for the subsequent design and implementation of a full-scale site remediation program. The overall objective of the pilot scale remediation program was to test the technical and economic feasibility of potential soil and groundwater remediation methods that could best mitigate the impacts of subsurface hydrocarbon contamination in a reasonable time frame (i.e. within 5 to 6 years).

The site-specific goals of the pilot scale remediation program were to :

- determine optimum placement of recovery systems;
- gain a better understanding of the contaminant transport mechanisms;
- prepare cost/benefit comparisons for various options; and,
- allow the subsequent design of components for a full scale treatment system.

Pilot scale testing conducted in 1994 determined the radius of influence for groundwater pumping to be only 1.5 m to 2.0 m, and for soil vapour extraction (SVE) to be between 5 m and 8 m. The corresponding hydraulic conductivity and air permeability values derived were small, ranging from 5×10^{-9} m/s to 3×10^{-8} m/s (hydraulic conductivity) and 10^{-12} cm^2 to 10^{-11} cm^2 (air permeability), respectively. The total liquid recovery rate measured from 7 recovery wells equipped with pneumatic pumps was 400 L/day of which condensate comprised 18% of the total flow, the remainder being water. Short term hydrocarbon mass removal rates using SVE were estimated to range between 1.7 kg/day and 8.2 kg/day. Incremental hydrocarbon degradation due to bio-venting was estimated to be in the range of 25-30% over vapour extraction.

6.0 Remediation Goals

The primary remediation goals for the Corbett Creek site, developed in consultation with Alberta Environmental Protection, were to:

- prevent further contaminant migration from occurring;
- remove the bulk of free-phase condensate within a 5 year period;
- mitigate the dissolved and residual subsurface contaminants;
- reduce the public health, ecological, and environmental risks to an acceptable level;
- obtain site closure.

Discussions were held with regulatory agencies to establish Alberta Tier 2 remediation objectives based on the site specific conditions. It was agreed that the dissolved-phase hydrocarbon plume did not present an unacceptable risk to humans, based on risk assessment modeling conducted. Land use restrictions were recommended to limit any future site usage to industrial or commercial purposes and allow no groundwater extraction. The risk assessment showed that the plume, if left unattended, could reach a nearby pipeline corridor in about 4 years, and a recreational lake in about 10 years.

Modeling indicated plume containment and capture would be achieved in 7 years without hydraulic soil fracturing. Since a minimum of fifty recovery wells would be required to capture the entire plume and take 21 years to recover the bulk of the free phase condensate, hydraulic fracturing was recommended as an enhancement technique.

7.0 Hydraulic Soil Fracturing and Performance Testing

Hydraulic soil fracturing is a relatively new technology in the environmental industry where it is used to increase the bulk permeability of fine grained soils and thereby enhance site remediation. The technology has been adapted and modified from the oil and gas industry where it has been used for over 50 years to enhance the recovery of oil and gas from petroleum reservoirs. Hydraulic soil fracturing creates a network of discrete sub horizontal to sub vertical fracture pathways in a contaminated soil mass. These induced fracture pathways are filled with permeable sand or “proppant” which keep the fractures propped open. The fracture pathways function as permeable conduits to facilitate and expedite the removal or in-place degradation of contaminants.

Due to the relatively low permeability of the sediments, conventional wells were not considered practical or cost effective for site remediation purposes. Bench scale testing conducted in early 1995 indicated that soil conditions were ideal for hydraulic soil fracturing and that full-scale implementation of this enhancement technology was feasible.

The main objective for the hydraulic soil fracturing program was to increase bulk soil permeability by 4-fold. A total of 14 fractured recovery wells (8 in 1995 and 6 in 1996) were installed using the FRAC RITE™ process. A fracture slurry (i.e. sand mixed with a viscous water-based guar and additives) was formulated. Fractures were induced at 0.5 m vertical intervals in the contaminated zone using pumping equipment supplied by Halliburton Energy Services. Six individual fractures were initiated in each fracture borehole at depths corresponding to the location of free-phase producing a total of 84 fractures. The average fracture radius was approximately 5 metres. Data collected from surface mounted tilt meter stations used for mapping subsurface fracture geometry indicated that the fractures ranged in thickness from 4-22 mm with a maximum thickness of 47mm, and trended NW- SE along the axis of the plume.

Subsequent performance testing was carried out on the fractured recovery wells in 1995 and 1996. This testing involved pump testing to evaluate liquid flow rates, radius of influence, condensate recovery, and hydraulic conductivity. Soil vapour extraction testing was also carried out on fracture recovery wells using regenerative and liquid ring vacuum equipment to evaluate air permeability, radius of influence, and vapour flow rates. These test data were then compared to the remedial performance of conventional recovery wells tested at the site. A short term pump test comparison made on conventional recovery well P11 and fractured recovery well GFW-2 is summarized below.

TABLE 1

Post Hydraulic Fracturing (72 hour test) GFW-2			Pre-Hydraulic Fracturing (66 hour test) P11		
K_{ave} (m/s)	**Radius of Influence (m)**	**Condensate Recovery (L/day)**	**K_{ave} (m/s)**	**Radius of Influence (m)**	**Condensate Recovery (L/day)**
4.0×10^{-6}	> 4.5	~ 360	3×10^{-7}	1 to 1.5	~ 48

Results from testing of the fractured recovery wells generally indicated that an increase in bulk permeability of up to 2 orders of magnitude was realized compared to conventional wells. This was accompanied by a 4-fold increase in liquid removal rates and a 5-fold increase in vapour removal rates. The percentage of condensate recovered in fractured recovery wells increased from 77% of total fluids recovered, compared to 18% condensate recovered in conventional recovery wells. Also, the fracturing resulted in a reduction in the number of recovery wells required to achieve capture of the plume from 50 wells to 17 wells (14 fractured recovery wells and three conventional recovery wells). The groundwater radius of influence increased to between 5 to 7 metres in fractured recovery wells compared to a radius of influence of 2 metres in conventional recovery wells. Similarly, the radius of influence for soil vapour extraction increased to between 15 to 35 metres in fractured wells compared to a radius of influence between 5 to 8 metres in conventional recovery wells

8.0 Full Scale Remediation

Full scale remediation efforts commenced with the ex situ treatment of contaminated soils from the former flare pit area. Soils in this area were excavated to a maximum depth of 6 meters and treated on-site in a lined cell in 1996. Treatment consisted of mixing the material with a straw bulking amendment, moisture and nutrient solution addition, a and a schedule of soil tilling and soil quality monitoring. The treatment cell was left in place and has subsequently been used for treating material from another site in the area.

The remediation system began full-scale operation on March 12, 1997 after a six week commissioning period. The remediation system is comprised of a pneumatic pumping system to remove free product from wells, a multi-phase extraction (MPE) system designed to removed both liquids and hydrocarbon vapours, and a groundwater treatment facility designed to separate water from condensate, then treat and reinject groundwater on site through an infiltration gallery. The configuration of the treatment components is shown in *Figure 1.*

8.1 Pneumatic Pumping System

A series of 8 fractured recovery wells, FW1 to FW8 located east of Highway #658 *(Figure 1)*, were drilled in a regular grid pattern near the center of the contaminant plume. These wells were subsequently equipped with a pneumatic pumping system. The pumps are located in the well at a level which allows for the recovery of the free product from above the water phase. The efficient operation of these pumps is dependant on the proper placement in the wells and are influenced by the seasonal fluctuation of the natural ground level. Pumping is optimized through the use of automated pump logic controllers.

8.2 Multi-phase Extraction System (MPE)

Mulit-phase extraction (MPE) or "bioslurping" is an innovative remediation technique that incorporates a high vacuum blower connected to a tube that is placed near the hydrocarbon interface to extract liquids (groundwater and free-phase hydrocarbons) and vapours in the same process stream from the subsurface. The MPE system was installed in early 1997 to capture the leading edge of the condensate plume. A series of nine wells located near the leading edge of the condensate plume on the west side of the highway *(Figure 1*) were tied in to the MPE system. The MPE unit supplies a vacuum to the wells through the manifold system and thereby removes product and water. The fluids are transferred to a 100 barrel capacity holding tank.

In 1998 the MPE system was extended to the facility side fracture wells to deal with free-phase "hot spots" during the summer months. The MPE system on-line time was initially 43% (1997) but improved to 82% in 1998 and 86% in 1999. On-line time was deemed to be a priority in order to achieve our remediation goals. A 6-fold improvement in liquid and vapour removal rate was achieved using the combination of fracturing and MPE.

8.3 Groundwater Treatment Components

An automated groundwater treatment system was designed and constructed for the contaminants identified at the Corbett Creek site; specifically the removal of BTEX from the groundwater once the condensate has been separated. Groundwater is pumped to an air stripping tower to remove dissolved BTEX. The treated groundwater is disposed by gravity feed into a well completed inside a constructed infiltration gallery. The treatment system is designed to reduce BTEX concentrations in the groundwater to below the site-specific remediation guidelines. Following treatment, groundwater is discharged to an infiltration gallery running parallel to the northwest side of the tank berm and up-gradient of the contaminant plume. Free condensate is collected in the 100 barrel tank and sent to an appropriate disposal facility.

9.0 Long Term Remedial System Performance

Based on hydrogeologic and systems operational data collected from 1994 to the 2000, it appears that the contaminant plume is being positively impacted by the remedial systems presently in operation. The reduction in the size of the dissolved and free-phase plume in 1994 (before the start of full-scale site remediation), 1997 (one year after full-scale remediation) and 2000 (four and a half years after full-scale remediation) is depicted in *Figures 2, 3, 4,* respectively. The volumes of hydrocarbons recovered as free-phase liquids or liquid equivalent as hydrocarbon vapours is summarized in Table 2.

TABLE 2

VOLUME OF HYDROCARBONS RECOVERED		
Year Ending	Yearly Volume (m^3)	Cumulative Volume (m^3)
1995	10	10
1996	7	17
1997	84	101
1998	177	278
1999	112	390

The estimated percentage breakdown of liquid and vapour phase hydrocarbons collected is 65% as vapour by MPE (multi-phase extraction); 25% as free-phase liquids by liquid pumping; and, 10% as vapour by SVE (soil vapour extraction).

10.0 Cost Analysis

Remediation options considered potentially feasible for the Corbett Creek site were put through a rigorous screening of their technical, logistical, and cost merits in a remediation assessment matrix. The three most feasible candidate remedial options were costed as shown in Table 3.

TABLE 3

COST COMPARISON OF CANDIDATE REMEDIAL OPTIONS (in 1995 Cdn $)		
Remedial Option	**Estimated Cost ($ Cdn)**	**Estimated Cost Including Site Characterization ($ Cdn)**
Excavation and Disposal	4.0 million	4.3 million
Conventional Recovery Wells	2.2 million	2.5 million
Fracture-Enhanced Rec.Wells	1.0 million*	1.3 million

*Cost of fracturing program comprised $150,000 of this total.

11.0 Summary

Approximately 500 m^3 of hydrocarbon condensate was delineated in subsurface soils underlying a former gas plant. Both dissolved and free-phase product were also present off-site. A remediation method(s) was required that could contain and recover the bulk of the free phase condensate and contaminated groundwater present cost-effectively and expeditiously within in a reasonable time frame (5 to 6 years) in a complex lithology of difficult, low permeability sediments, and meet applicable regulatory criteria.

A rigorous process of assessing feasible candidate remediation technologies and their associated costs, consideration of innovative alternative remedial technologies, intelligent use of pilot field trials, a phased and integrated approach to full-scale remediation, and a comprehensive monitoring/sampling/maintenance program, resulted in the selection and implementation of effective remediation technologies that met all of the criteria specific required for the Corbett Creek site.

FIGURE 1 - SITE PLAN

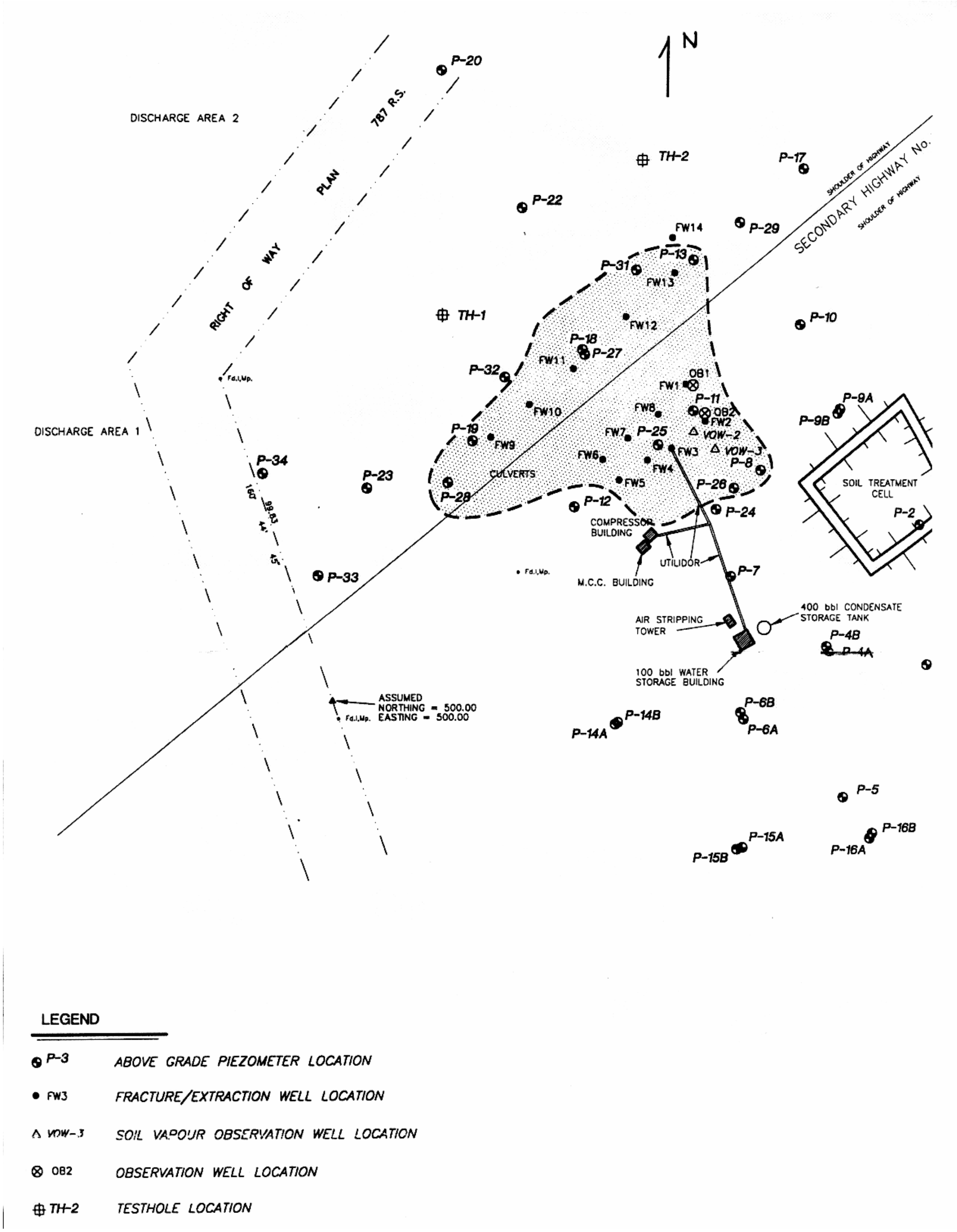

FIGURE 2 – EXTENT OF DISSOLVED AND FREE PHASE CONTAMINATION (1994)

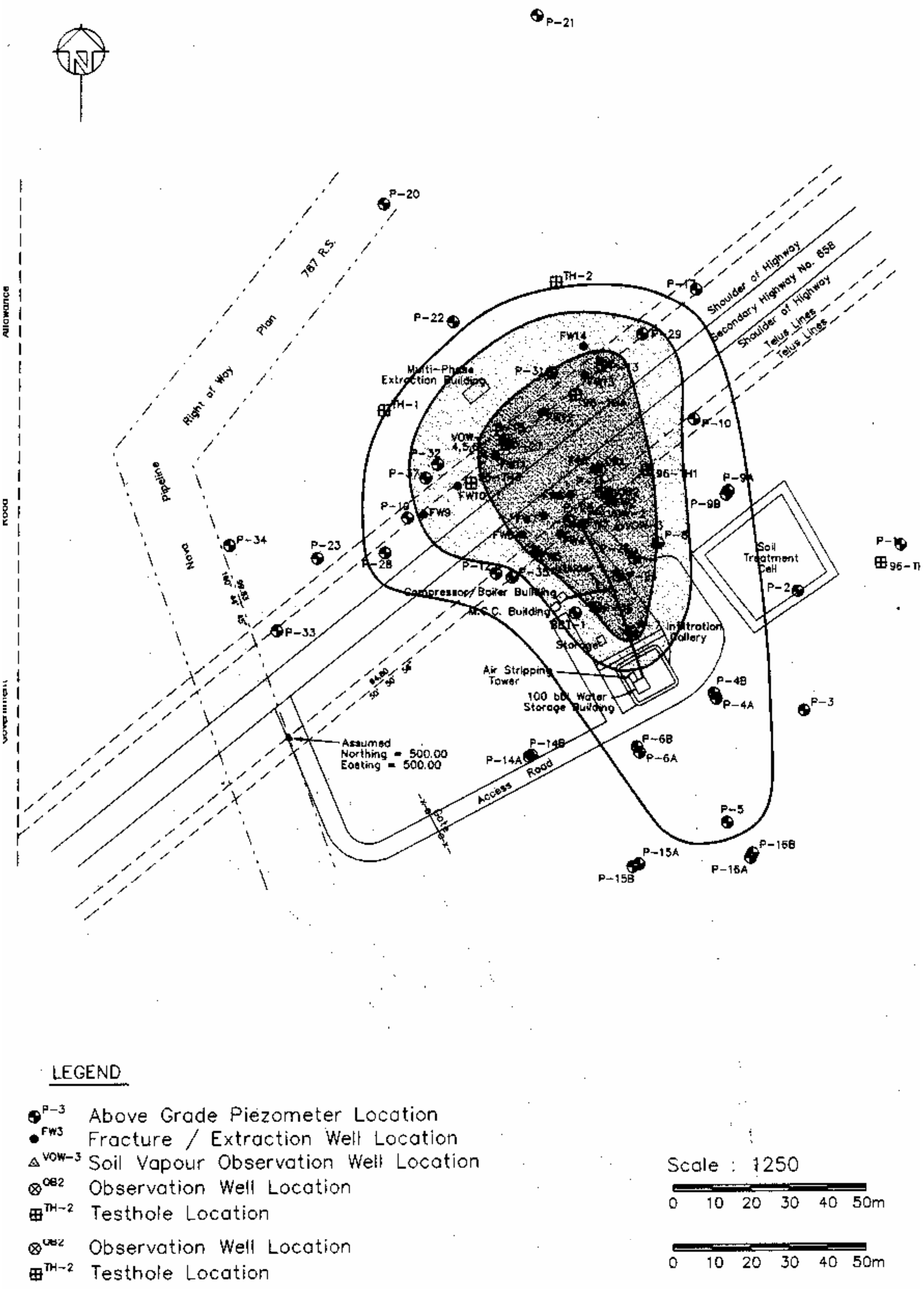

FIGURE 3 - EXTENT OF DISSOLVED AND FREE PHASE CONTAMINATION (1997)

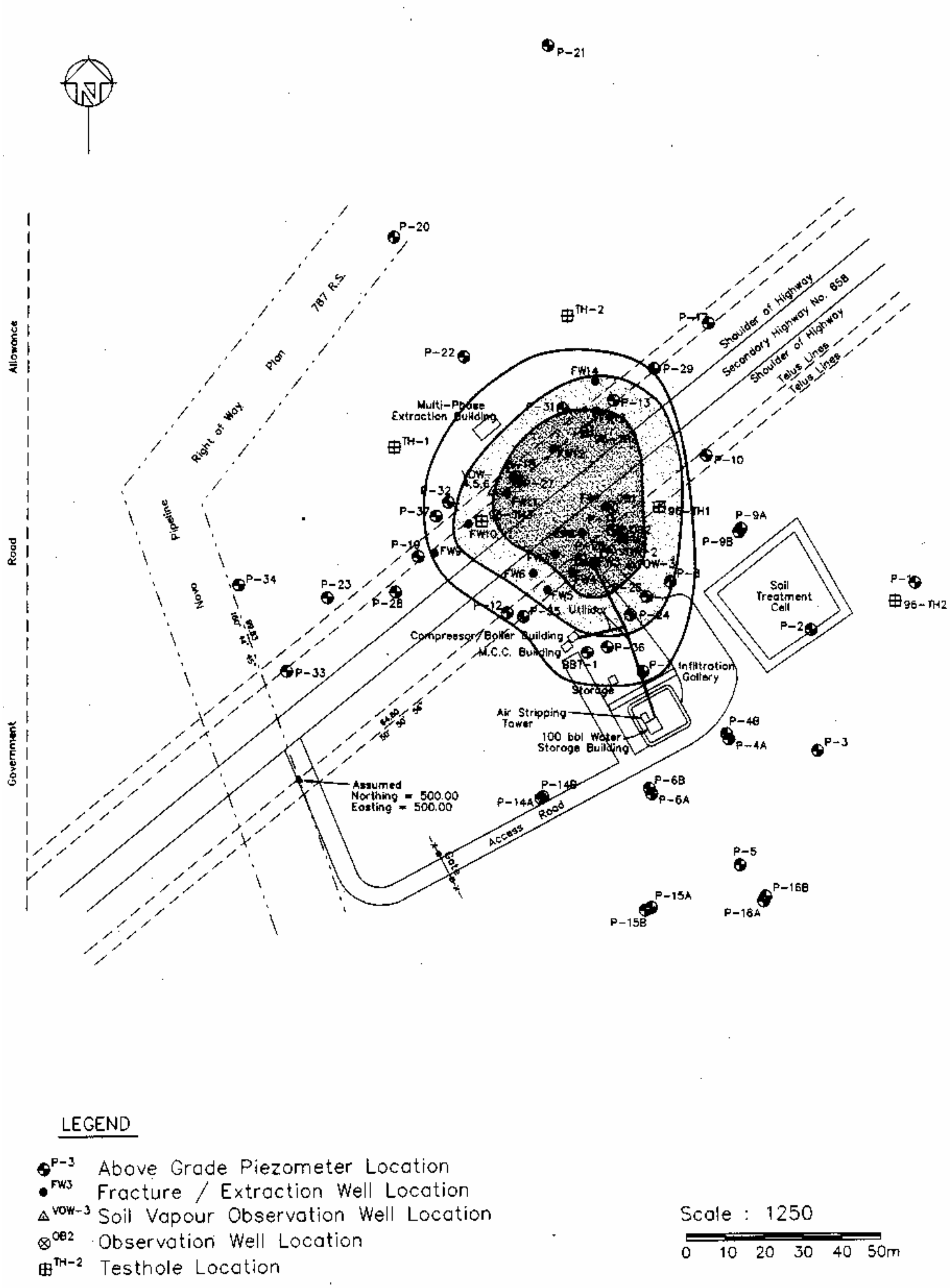

FIGURE 4 – EXTENT OF DISSOLVED AND FREE PHASE CONTAMINATION (2000)