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MEMORANDUM

To:	Bob Wyatt, NW Natural	**Date:**	March 18, 2009
From:	David Keith, Mike Riley, and John Edwards, Anchor QEA	**Project:**	000029-02
Cc:			
Re:	Evaluation of Potential DNAPL Mobilization in Former Effluent Pond Area by Shoreline Source Control Extraction Wells, Gasco Site, Portland, Oregon		

INTRODUCTION

This memorandum provides an evaluation of the potential for the mobilization of dense non-aqueous phase liquids (DNAPL) in the former effluent pond area as a result of groundwater pumping at the Gasco Site in Portland, Oregon. The evaluation is in response to an Oregon Department of Environmental Quality (DEQ) request that NW Natural assess the potential migration of DNAPL in the former effluent pond area under the pumping influence of shoreline source control wells.

The sources and distribution of DNAPL at the site are described in detail in the Remedial Investigation Report (RI) (HAI 2007). The RI Report describes root macropores in the former effluent pond area that provide a very limited method for migration of DNAPL through the silt in this area. The RI report also concludes that mobile DNAPL is now largely absent in the fill in the former effluent pond area. DNAPL recovery efforts conducted to date at Gasco and the findings from manufactured gas plant (MGP) sites around the United States have shown that mobile DNAPL oil migrates very slowly (Gerhard 2007), while the solid tar does not migrate at all. The results from TarGost borings completed in 2008 showed that the RI did a good job of defining the extent of DNAPL in the former effluent pond area.

Although DEQ has stated in recent documents that they believe DNAPL is currently migrating in lenses toward the shoreline, evidence of current movement has not been found. The extensive offshore investigations completed in 2007 (Anchor 2007) indicated that the only DNAPL present in shoreline sediments is very shallow and is the result of historic direct

discharge of effluent into the river, not the result of subsurface migration of DNAPL from the former effluent pond area into river sediments. This was conclusively demonstrated in near shoreline borings GS-01 through GS-12, where DNAPL was absent in deep sediments, thereby showing that DNAPL detected in upland nearshore alluvium has not migrated into nearshore sediments. Therefore, subsurface DNAPL has not migrated from upland site areas into river sediment after nearly 100 years since the former effluent ponds began operation.

In summary, these extensive investigations have shown that any migration of DNAPL that may exist occurs so slowly as to be insignificant. However, at DEQ's request we have prepared this technical memorandum to further evaluate the potential for DNAPL migration to be influenced during proposed source control activities.

The next section provides a conceptual model for DNAPL flow in the subsurface based on literature descriptions. The subsequent sections focus on development and interpretation of various analytical solutions specific to mobilization of subsurface DNAPL occurrences in saturated porous groundwater systems.

DNAPL CONCEPTUAL SITE MODEL

Subsurface DNAPL is acted upon by three distinct forces in a groundwater environment (Yan et al. 1994) including:

1. Gravity
2. Capillary pressure
3. Hydrodynamic force

After release, DNAPLs will generally migrate vertically downward because they are denser than groundwater and gravitational forces are dominant compared to hydraulic forces in most groundwater systems. The rate of flow of a DNAPL through a geologic medium depends on: 1) the density and viscosity of the DNAPL; 2) the pressure driving the DNAPL migration; 3) the intrinsic permeability of the geologic medium; and 4) the degree of DNAPL saturation of the pore space in the medium. More permeable media and higher DNAPL saturations will permit higher rates of DNAPL flow. Higher-density and lower-viscosity fluids, such as chlorinated solvents, are subject to higher flow rates than lower-density and higher-viscosity fluids such as MGP wastes like those at Gasco (Pankow and Cherry 1996).

Nearly all movement of subsurface DNAPL occurs within zones of continuous (i.e., connected) DNAPL. In such zones, the DNAPL in different pore openings forms an immiscible-phase continuum through the intervening pore throats. Once the release of DNAPL into the subsurface ceases, the forces driving DNAPL movement eventually dissipate and the DNAPL in the pore openings become disconnected to form zones of residual DNAPL. DNAPLs distribute themselves in the subsurface in the form of disconnected blobs and ganglia of organic liquid referred to as residual occurrences, and in higher saturation configurations along bedding discontinuities referred to as pools (Gerhard et al. 2007). Very high hydraulic gradients are required in groundwater to induce movement of residual DNAPL occurrences (Pankow and Cherry 1996), which is one of the reasons remediation/recovery of DNAPL is so difficult. Wilson and Conrad estimated that a gradient of 0.1 foot/foot is necessary to start some blobs or ganglia of DNAPL moving in a fine gravel (approximately 10 cm/sec permeability). This is a steep, but not unreasonable, gradient. However, typical hydraulic gradients at Gasco are two orders of magnitude lower than 0.1 foot/foot, and there are no gravel zones associated with DNAPL at the Site. In a medium sand (approximately 10^{-3} cm/sec permeability), the gradient necessary for residual DNAPL movement is on the order of 10 feet/foot.

For most DNAPLs, which are non-wetting on the mineral grains of an aquifer with respect to water, water will coat the soil grains and occupy the smaller pores and pore throats; therefore, the DNAPL is restricted to the larger pore openings. When the DNAPL is non-wetting, like the DNAPL at Gasco, capillary forces oppose the entry of the DNAPL into wet geologic media. The forces driving subsurface DNAPL movement are a function of the DNAPL density and the pressures resulting from its release into the subsurface. For DNAPL movement to occur in wet media, these driving forces must overcome the capillary resistance. The DNAPL in the larger pore openings must deform to pass through smaller pore throats to reach other pore openings. The pressure required for this deformational movement is the entry pressure. The value of the entry pressure is proportional to the interfacial tension between the DNAPL and the water, and inversely proportional to the size of the pore throats. Therefore, the entry of a DNAPL into a fine-grained porous medium or into a fractured medium having small apertures requires high driving forces to overcome high entry pressures.

Consequently, low permeability strata (permeabilities of 10^{-5} cm/sec or less) can be barriers to DNAPL migration (Pankow and Cherry 1996). Vertical permeability tests were run on six

shelby tube samples obtained during geotechnical soil borings completed along the proposed vertical barrier alignment in 2007. This work was done at the request of DEQ. The samples were obtained at depths ranging from 61 to 96 feet below top of the shoreline bank. Following are the measured vertical permeabilities in cm/sec:

Silt	4.42E-07
Clayey silt	9.60E-08
Clayey silt	1.67E-07
Clayey silt w/fine sand	3.19E-07
Clayey silt w/fine sand	2.68E-07
Fine sand	6.14E-05

Subsurface investigations have shown that the upper alluvium contains a higher percentage of fine-grained layers than the lower alluvium. This explains why DNAPL is not found below the upper alluvium in most of the former effluent pond area.

The Gasco Site is underlain by a heterogeneous granular aquifer. In these environments, small horizontal zones of residual or free-phase DNAPL are not solely caused by particularly low permeability zones such as silt or clay. A minor contrast in grain size distribution and permeability, as from a coarse sand layer to a finer sand, causes variation in DNAPL entry pressure. A DNAPL moving downwards through a coarse-grained material will encounter a higher entry pressure when a finer-grained layer is contacted. This will cause lateral spreading of the DNAPL. The DNAPL will accumulate on the finer-grained layer while spreading laterally until it reaches the edge of the layer, or until the height of free product accumulation on the layer exceeds the entry pressure for the layer. In the latter case, the DNAPL will pass through the layer and continue its downward movement towards the bottom of the aquifer (Pankow and Cherry 1996). Pools of DNAPL generally form at stratigraphic discontinuities, where finer-grained and lower permeability materials prevent vertical DNAPL migration because intergranular surface tension and capillary forces prevent further penetration. It should be noted that DNAPL pools that form on stratigraphic discontinuities will generally flow in the direction of stratigraphic dip because of gravitational forces, and this direction may be different than the dominant direction of groundwater flow defined by the hydraulic gradient.

DNAPL MOBILIZATION AT GASCO

Based on the conceptual models for the distribution of DNAPL in groundwater environments described above, and site observations of the occurrence of DNAPL at Gasco, there are two cases for potential mobilization of DNAPL as a result of pumping, including:

- Mobilization of a DNAPL pool
- Mobilization of residual ganglia or blobs of DNAPL

Case 1. Mobilization of a DNAPL Pool

McWhorter (1992) provided an equation that describes the movement of a DNAPL pool along a stratigraphic discontinuity at a slope (a) to horizontal as follows:

$$q_{nwi} = \frac{-kk_{rnw}}{\mu_{nw}} p_w g \frac{d}{dx_i}\left[h + \frac{Pc}{p_w g} + \frac{\Delta p}{p_w} z\right] \tag{1}$$

Where:

q_{nwi}	=	DNAPL mass flux
k	=	the intrinsic permeability
k_{rnw}	=	the relative permeability to DNAPL
μ_{nw}	=	the viscosity of the DNAPL
p_w	=	the water density
g	=	the gravitational acceleration
h	=	the hydraulic head in the aqueous phase
Pc	=	the capillary pressure
Δp	=	the density difference between the DNAPL and water
z	=	the vertical coordinate
x_i	=	the coordinate direction (defined as the direction of slope)

At equilibrium, the flux of DNAPL is 0 and Equation 1 becomes:

$$\frac{d}{dx_i}\left[h + \frac{Pc}{p_w g} + \frac{\Delta p}{p_w} z\right] = 0 \tag{2}$$

Integrating Equation 2 from 0 to L (the length of a DNAPL pool) yields the following equation:

$$p_w \frac{dh}{dx_i} L\cos\alpha + \frac{Pc}{g} + \Delta p L \sin\alpha = 0 \qquad (3)$$

Where

α = the slope angle as defined in Figure 1

Physically, the first term in Equation 3 represents the hydraulic force acting on a unit area of DNAPL, the sign of which can be positive or negative, depending on whether water flow is upslope or downslope compared to the dip of the host stratigraphy. The second term represents the capillary force that is resisting the flow of DNAPL. This force is always opposite to that of the resultant of the hydraulic flow and gravity forces. The third term is the gravity or buoyancy force of DNAPL at equilibrium in the direction of the stratigraphic dip (Yan et al. 1994).

Geologic three point problems were solved on the top of two continuous apparent bedding layers from cross sections at Gasco to determine the slope of bedding at the Site. Figure 2 is a map showing the locations of the TarGost borings used to assess the slope of bedding at the Site. The base of fill/top of silt and the top of the lower sand layer were used for the calculations. The calculated angles for those bedding layers were less than 0.5 degrees and indicate that the bedding that DNAPL would tend to pool on at Gasco is essentially horizontal. Table 1 shows the slope of the bedding layers. This information was developed from the TarGost borings provided on the left side of the table.

Table 1
Summary of Bedding Strike and Dip Calculations for the Base of Fill/Silt and Top of Medium Sand Contacts

Borings			Base of Fill/ Silt contact			Top of Medium Grained Sand		
			Gradient (ft/ft)	Direction (degrees)	ATAN of Gradient (Alpha - degrees)	Gradient (ft/ft)	Direction (degrees)	ATAN of Gradient (Alpha - degrees)
TG-3	TG-5	TG-11	0.037	21	0.037	0.10	39	0.10
TG-3	TG-5	TG-8	0.065	26	0.065	0.11	39	0.11
TG-1	TG-7	TG-3	0.019	335	0.019	0.15	229	0.15
TG-1	TG-1S	TG-13	0.033	28	0.033	0.32	48	0.31

Because Sinα ≈ 0 and Cos α ≈ 1 under these conditions, Equation 3 reduces to:

$$pw\frac{dh}{dx_i}L + \frac{Pc}{g} = 0 \qquad (4)$$

Groundwater model output for the Site previously presented to the Oregon DEQ (Anchor and SSPA 2008) included predicted groundwater gradients under ambient and pumping conditions, and these results were used to evaluate potential DNAPL movement due to hydraulic stress (Anchor and SSPA 2008). These results were combined to look at the change in groundwater gradient between ambient and pumping conditions. A review of the model output shows the shallow well configuration imposes the largest increase in groundwater gradients and the intermediate well configuration has the least effect. The subsurface profiles on Figures 3a, 3b, and 3c show the predicted gradients using shallow, intermediate depth, and paired extraction wells. Figure 3d shows the map location of the subsurface profiles. Groundwater gradients in the former effluent pond area under the shallow extraction well configuration increase by 0.01 to 0.02 while groundwater gradients increased by only 0.001 to 0.002 with intermediate depth extraction wells.

The maximum effect of these changes in gradient can be computed from Equation 1 by making the following assumptions:

- Capillary forces = 0
- Stratigraphic slope (α) = 0, which has been shown to be negligible at the Site
- Relative permeability = 1, which is the maximum value
- Intrinsic permeability computed for the Site = 6e-8 cm2
- Porosity = 0.3

These assumptions provide the maximum DNAPL velocity that can be expected due to pumping, and travel distance derived for different time periods can be computed. The results are shown in the Table 2 for changes in gradient in the former effluent pond area due to shallow and intermediate depth extraction wells.

Table 2
Predicted Horizontal DNAPL Travel Distance due to Increased Gradient from Nearshore Groundwater Pumping

Extraction Well Configuration	Groundwater Gradient Increase in Former Effluent Pond Area	Velocity (ft/day)	Distance traveled (ft) over the following time periods			
			0.5 years	1 year	2 years	3 years
Shallow Depth Extraction Wells	0.01	0.0047	0.9	1.7	3.5	5.2
	0.02	0.0095	1.7	3.5	6.9	10.4
Intermediate Depth Extraction Wells	0.001	0.00047	0.1	0.2	0.3	0.5
	0.002	0.00095	0.2	0.3	0.7	1.0

From this analysis, enhanced groundwater movement in the former effluent pond area due to shoreline extraction wells is minimal and would not substantially change DNAPL distribution over time, especially if the capillary term were factored into the calculation. The analysis also shows that pumping from the intermediate wells produces significantly smaller potential distances of travel. Therefore, it is unlikely that that shallow extraction wells will be selected for design of the shoreline extraction system.

Case 2. Mobilization of Residual Ganglia or Blobs of DNAPL

Residual DNAPL in the form of ganglia or blobs can also be mobilized by increasing hydraulic gradients, such as what may occur during pumping. In this case, the capillary number, (σ), the ratio of capillary to viscous forces, provides a measure of the propensity of DNAPL trapping and mobilization (Cohen and Mercer 1993). It is defined as:

$$Nc = \frac{kpwgJ}{\sigma} \tag{5}$$

Where:

σ = the interfacial tension between the DNAPL and water

J = the hydraulic gradient

Other terms are defined in Equation 1

The critical value (N_c) of the capillary number is defined as the value at which motion of some of the DNAPL blob is initiated. Based on experimental data, Wilson and Conrad (1984)

noted a strong correlation between displacement of residual DNAPL and the capillary number. Conrad and Wilson found that initial movement occurred when the gradient produced N_c values greater than 2e-5. The hydraulic gradient necessary to initiate ganglia mobilization for various permeabilities and interfacial tensions is shown in Figure 4.

Figure 4 shows that in very permeable media (e.g., gravel and coarse sand) it is theoretically possible to obtain sufficient hydraulic gradients to mobilize DNAPL blobs. In soils with medium permeability (e.g., fine to medium sands), some of the residual DNAPL can be hydraulically mobilized. In less permeable materials, mobilization is not possible unless surfactants are used to drastically reduce interfacial tensions (Cohen and Mercer 1993). This is another example of why DNAPLs are difficult to recover from groundwater environments.

At Gasco, measured interfacial tensions between DNAPL and water were 14.2 and 15.8 dynes/cm and most of the soil where DNAPL occurs would be classified as silty sands or finer (HAI 2007). The intrinsic permeability was calculated from the hydraulic conductivity of the shallow alluvium used in the Site MODFLOW model of 15 feet/day, which gives an intrinsic permeability of 6e-8 cm^2. Based on Figure 4, the hydraulic gradient that would be required to mobilize residual DNAPL under these conditions would be near 1 foot/foot or greater, which is much higher than any gradient that could be induced in the former effluent pond area under non-pumping or pumping conditions at the Site.

SUMMARY DISCUSSION AND CONCLUSIONS

The lack of stratigraphic gradient and the presence of silt interbeds in the upper alluvium at the Gasco Site indicates that the most likely mechanism for potential lateral DNAPL movement is by pooling on silt lenses and flowing along stratigraphic interfaces to the edge of the silt lens. Upon reaching coarser and more permeable media at the edges of silt lenses, DNAPL would tend to flow downward under the influence of gravity until reaching another lower permeability stratigraphic discontinuity.

The maximum effect of changes in hydraulic gradient was computed from Equation 1 by making the following assumptions:

- Capillary forces = 0
- Stratigraphic slope (α) = 0, which has been shown to be negligible at the Site
- Relative permeability = 1, which is the maximum value

- Intrinsic permeability computed for the Site = 6e-8 cm^2
- Porosity = 0.3

These assumptions, which neglect the capillary forces that would resist DNAPL flow, provide the maximum DNAPL velocity that can be expected due to pumping, and travel distance derived for different time periods can be computed. The results, summarized in Table 2 above, show that changes in gradient in the former effluent pond area due to shallow and intermediate depth extraction well pumping would cause maximum distances traveled over a 3 year period to range between approximately 5.2 to 10.4 feet using shallow extraction wells, and 0.5 to 1.0 feet for intermediate depth extraction wells.

From this analysis, enhanced groundwater movement in the former effluent pond area due to shoreline extraction wells is minimal and would not substantially change DNAPL distribution over time. These calculations are conservative approximations of the potential distances that DNAPL could travel and the true estimate would be less if the capillary term were factored into the calculation. The analysis also shows that pumping from the intermediate wells produces significantly smaller potential distances of travel. Therefore it is unlikely that that shallow extraction wells will be selected for design of the shoreline extraction system.

Finally, as shown in Case 2, mobilization of residual DNAPL (as opposed to pools) is not expected to occur at Gasco in the former effluent pond area because groundwater gradients that result from pumping, and the material properties of the aquifer matrix and of the DNAPL produce a capillary number that is well below the critical value (Figure 4).

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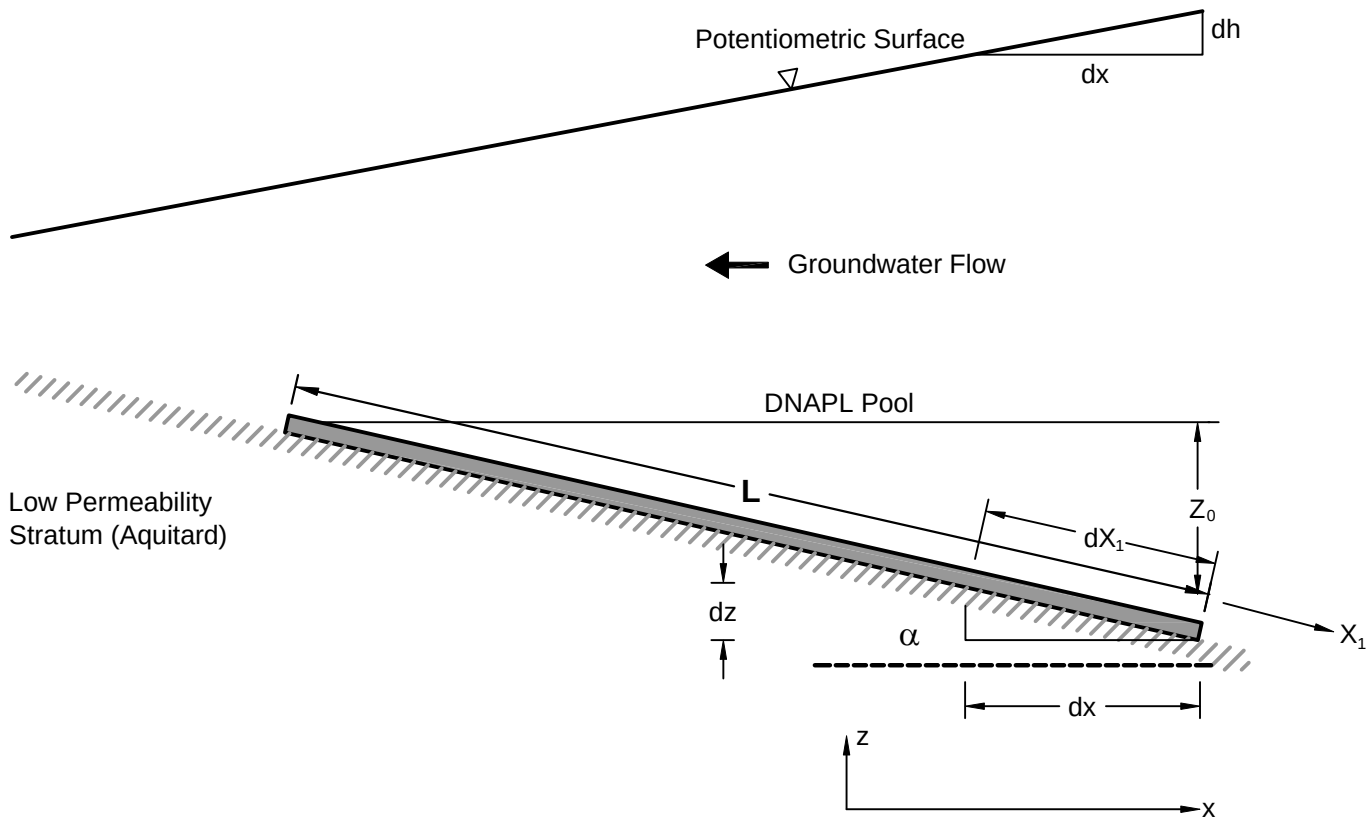

Source: Yan, S., G.R. Landry and T. Tate, 1994.

Feb 03, 2009 10:59am cdavidson K:\Jobs\000029-GASCO\00002902\00002902-RP-018.dwg FIG 1

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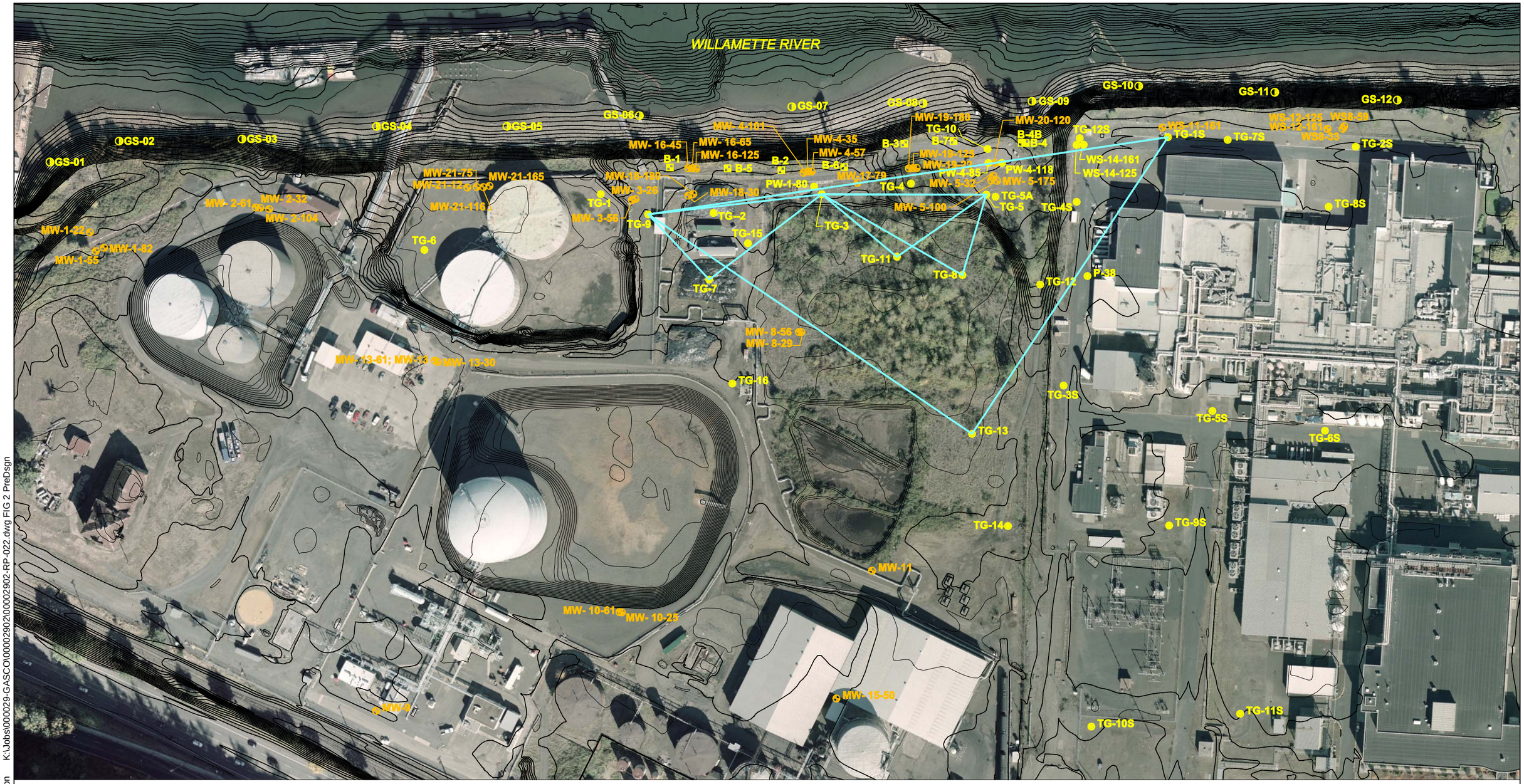
Figure 1

Diagram of DNAPL Pool held in Aquifer on a Low Permeability Sloping Bed

Gasco/Siltronic

Portland, Oregon



Legend

TG-9	Boring Location and Number
MW-2-12	Existing Monitoring Well Location and Number
GS-01	Gasco Phase 1 Offshore Boring Location and Number
B-1	Geotechnical Boring Location and Number

Area used to Calculate Bedding Slope

0 150
Scale in Feet

K:\Jobs\000029-GASCO\00002902\00002902-RP-022.dwg FIG 2 PreDsgn
Feb 17, 2009 2:22pm cdavidson

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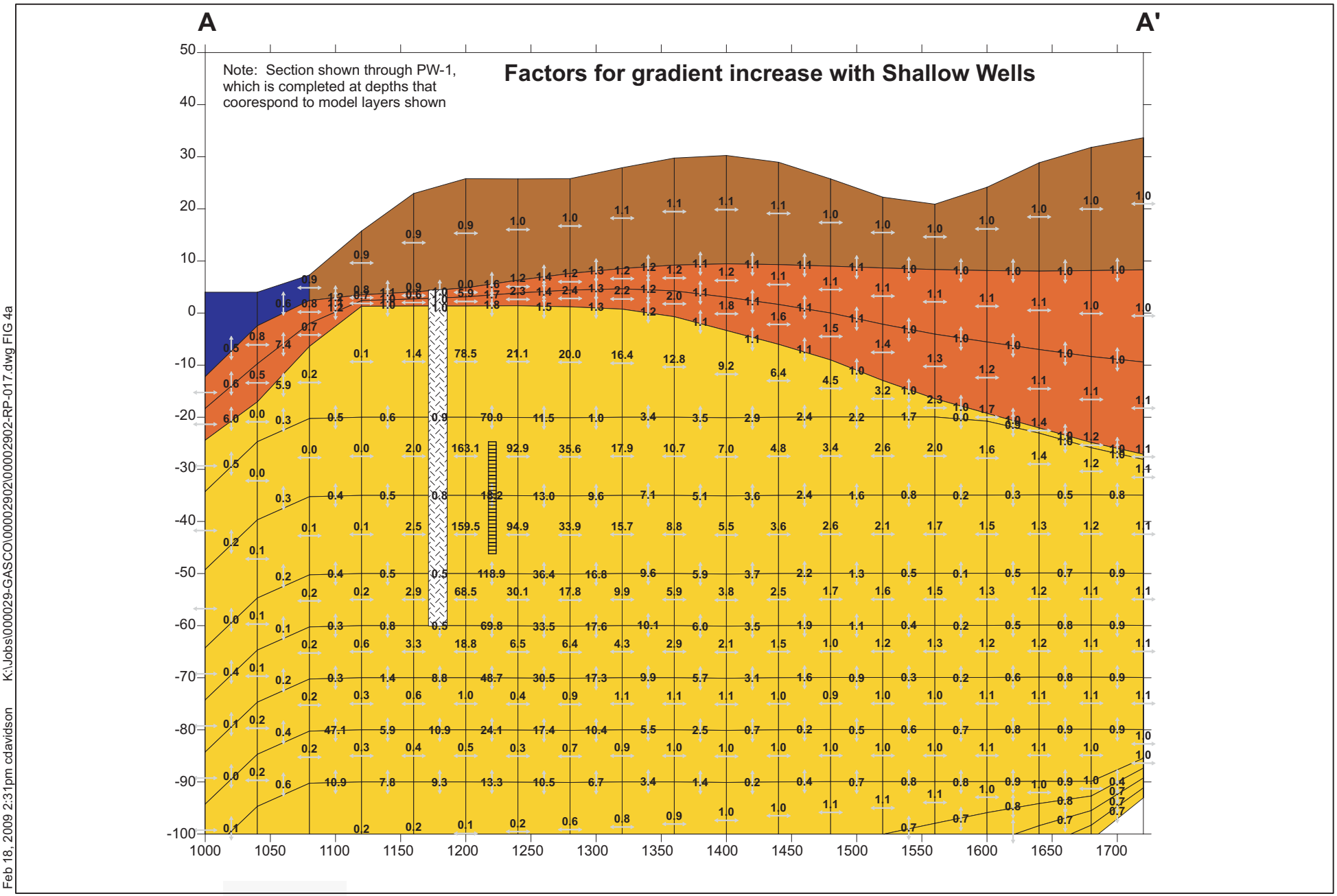
Figure 2
Location of Bedding Slope Calculations
Gasco, Portland, Oregon



Feb 18, 2009 2:31pm cdavidson K:\Jobs\000029-GASCO\00002902\00002902-RP-017.dwg FIG 4a

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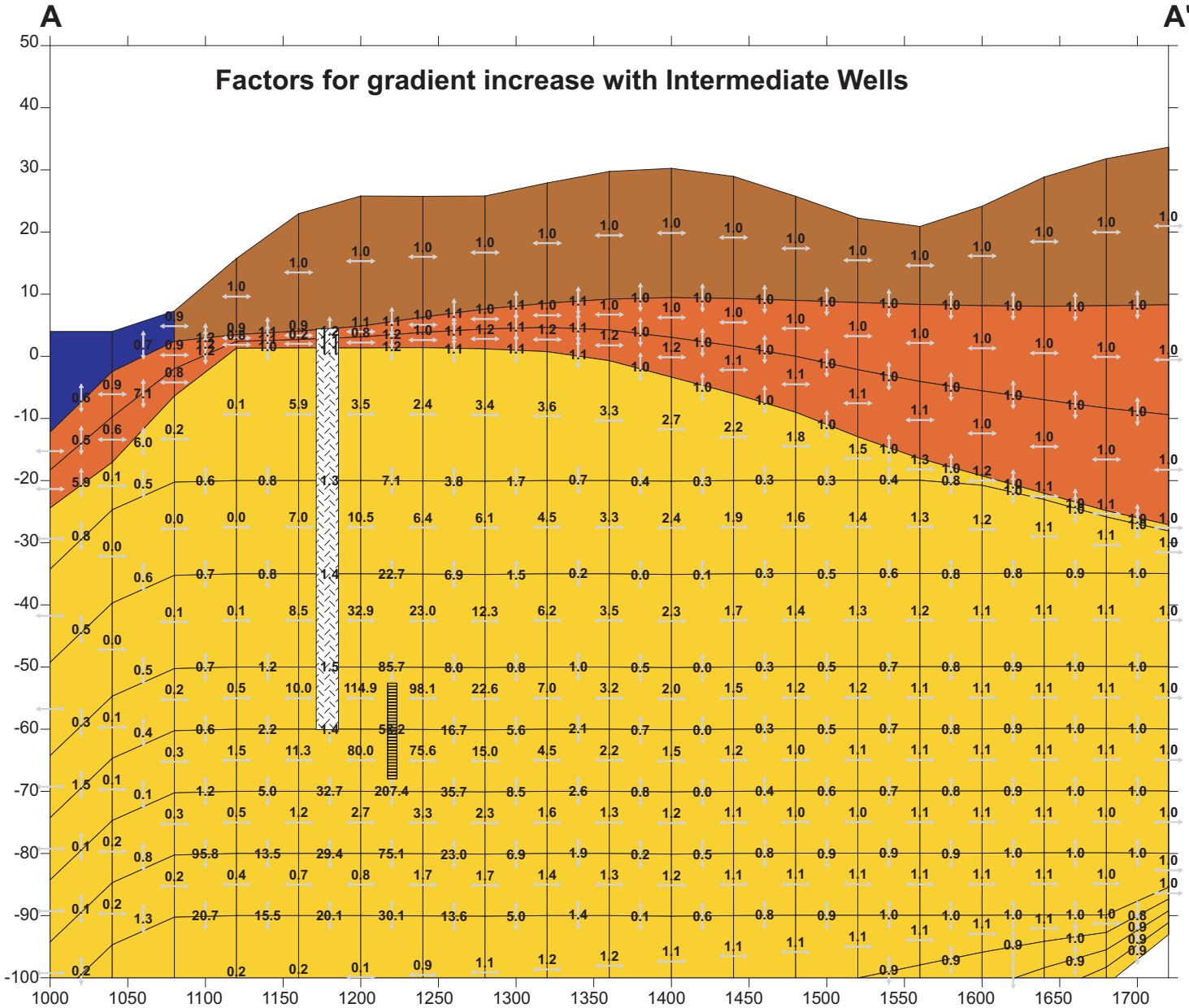
$\Sigma^2\Pi$

Figure 3a

Predicted Factors for Hydraulic Gradient Increases Under Pumping Conditions for Shallow Wells
Gasco/Siltronic
Portland, Oregon



Feb 18, 2009 2:32pm cdavidson K:\Jobs\000029-GASCO\00002902\00002902-RP-017.dwg FIG 4b

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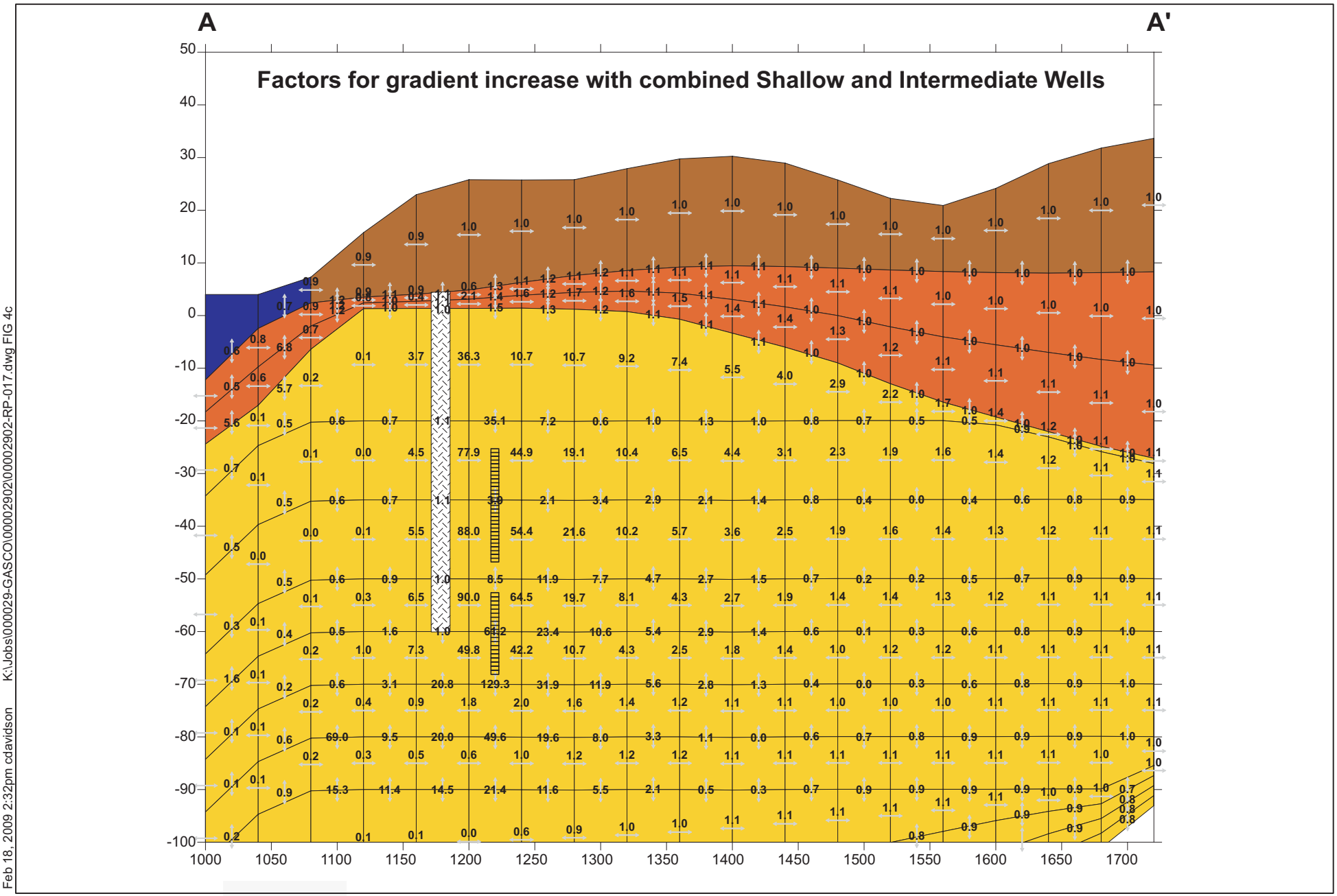
$\Sigma^2\Pi$

Figure 3b

Predicted Factors for Hydraulic Gradient Increases Under Pumping Conditions for Intermediate Wells
Gasco/Siltronic
Portland, Oregon



Feb 18, 2009 2:32pm cdavidson K:\Jobs\000029-GASCO\00002902\00002902-RP-017.dwg FIG 4c

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$\Sigma^2\Pi$

Figure 3c

Predicted Factors for Hydraulic Gradient Increases
Under Pumping Conditions for combined Shallow and Intermediate Wells
Gasco/Siltronic
Portland, Oregon

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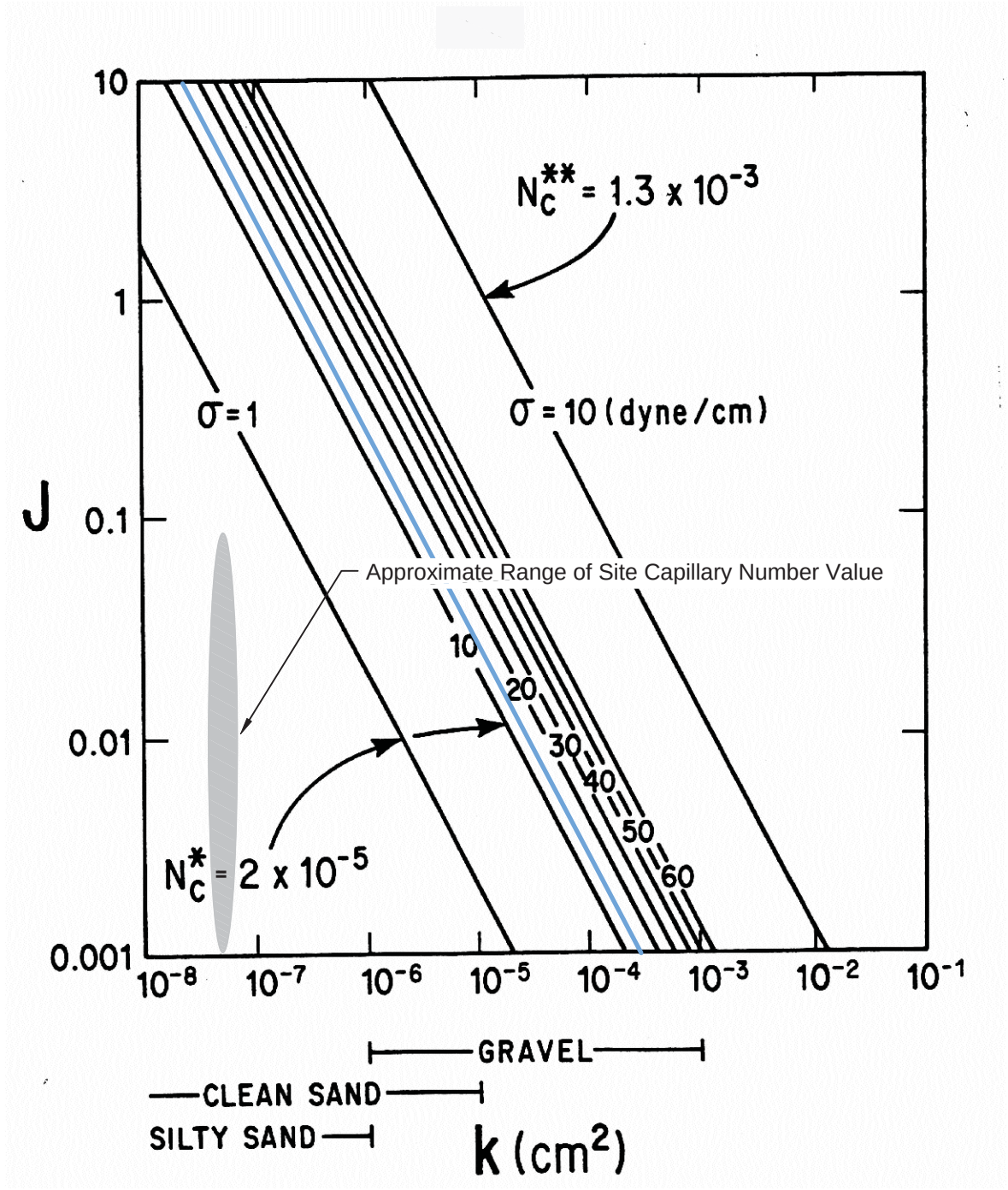
0 150
Scale in Feet
1 inch = 150 feet

Figure 3d
Approximate Location of Cross Sections Showing Predicted Changes in Hydraulic Gradients Under Pumping Conditions at the Gasco Site
Gasco/Siltronic
Portland, Oregon



Line of Critical Capillary Values for σ of 15 dynes/cm

Source: Mercer and Cohen, 1993.

Feb 19, 2009 10:28am cdavidson K:\Jobs\000029-GASCO\00002902\00002902-RP-017.dwg FIG 5

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Figure 4
Hydraulic Gradient Necessary to Initiate DNAPL Blob Mobilization in Soils of Various Permeabilities
Gasco/Siltronic
Portland, Oregon