Including Vapor Intrusion in Your Remediation Program

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Once upon a time not so long ago…..

- 1996 – Soil screening guidance provided quantitative methods to derive soil screening levels

  Established concentrations for the following residential exposure pathways:

  - Direct ingestion of soil
  - Inhalation of volatiles outdoors
  - Inhalation of dust outdoors
  - Ingestion of contaminated groundwater

Indoor air was assumed to be same as ambient air

Draft

Guidance Document for

Environmental Assessment of Soil Vapor

Intrusion into Buildings

Prepared for:

The Air Force Institute for Environmental, Safety, and

Occupational Health Risk Analysis (AFIERA)

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DISCLAIMER

This presentation includes technical and policy recommendations based on current understanding of the phenomenon of subsurface vapor intrusion. **This guidance does not impose any requirements or obligations on the U.S. Air Force. The sources of authority and requirements for addressing subsurface vapor intrusion are the applicable and relevant statutes and regulations.** Users of this guidance are reminded that the science and policies concerning vapor intrusion are complex and evolving. This guidance addresses the assumptions and limitations that need to be considered in the evaluation of the vapor intrusion pathway. This guidance also provides instructions for using first-tier screening level tools to identify sites needing further assessment. This presentation also provides instructions on the use of the most recent vapor transport model used to estimate the significance and impacts resulting from vapor intrusion.

- The Air Force need:
  - PRP at dozens of Superfund sites
  - 100's of contaminated sites on active facilities
  - ±80 installations subject to RCRA corrective action requirements
  - ±32 bases are being converted from military to civilian uses

Vapor Intrusion – Background & Theory

- The Air Force need:
- Dozens of contaminants but the big players include:
  - Trichloroethylene (degreasing solvent)
  - Tetrachloroethylene (dry cleaning solvent)
  - Gasoline (BTEX)
  - Diesel Fuel
  - Lubricating Oils
  - Dichloroethylene
  - Vinyl chloride
  - Benzene (solvent)

degradation fractions (Vinyl chloride, Benzene)

Goals

- Provide technical training on the

  “State of the Science”

- Provide tools for assessing the significance of vapor intrusion into building

History Lesson

- Almost 200 years have elapsed since the “notion” was born.
- It is just now becoming a mainstream consideration in remedial practices.
- Appendix A includes a Bibliography and Reference list of more than 200 publications.

Vapor Intrusion – Background & Theory

1803 William Henry found that the mass of a gas dissolved in a liquid is directly proportional to the gas pressure and that in a mixture of gases each gas behaves as if it were alone.

1974 William Farmer et al. published an article describing "A Model for Predicting Volatilization of Soil Incorporated Pesticides."

1983/84 Farmer and Jury published a series of articles describing the "Behavior Assessment Model for the Trace Organics in Soil."

Vapor Intrusion – Background & Theory

1988	Spencer and Jury published an article on volatilization of organic chemicals from soil as related to their Henry's Law Constant.
1989	Fitzgerald of MADEP uses an OVA inside a building, discovers concentrations higher than ambient outside air.
1990	Jury publishes article describing the need to evaluate the volatilization of organic chemicals residing below the soil surface.

Vapor Intrusion – Background & Theory

1991	Johnson and Ettinger publish "Heuristic Model for Predicting the Intrusion Rate of Contaminant Vapors into Buildings."
1992	EPA publishes guidance for assessing potential indoor impacts for Superfund sites.
1993	EPA publishes Exposure Model for Soil Organic Fate and Transport (EMSOFT) Model (derived from work by Jury).
1994	EQ publishes report comparing soil volatilization models in support of Superfund soil screening level development effort.

Vapor Intrusion – Background & Theory

1995	Shan publishes article describing numerical solution for vertical transport of volatile chemicals in the Vadose Zone.
1996	CtDep adopts numerical standards.
1996	EPA publishes soil screening level guidance.
1997	EPA publishes User's guide and model for evaluating vapor intrusion into buildings.

Vapor Intrusion – Background & Theory

1998	API publishes guidance for "Assessing the Significance of Subsurface Contaminant Vapor Migration to Enclosed Spaces, Site Specific Alternatives to Generic Estimates."
1999	EPA issues RCRA Environmental Indicator (EI) Guidance with footnote on vapor intrusion pathway.
1999	Several states begin developing regulations via the rule making process.
2000	USAF "requires" some sites to assess vapor intrusion pathway.

Vapor Intrusion – Background & Theory

2000 EPA conducts training on RCRA EI guidance at 10 workshops across the country.

2000 EPA publishes Supplemental Guidance for Developing Soil Screening Levels for Superfund sites.

2000 EPA publishes revised User's Guide for the Johnson & Ettinger model for subsurface vapor intrusion into buildings.

2001 EPA publishes revised guidance and supplement for the RCRA EI guidance.

Vapor Intrusion – Background & Theory

2001 Denver Post articles and interviews raise the level of consciousness.

2002 National meeting and seminar on vapor issues.

2002 EPA publishes revised guidance for evaluating the vapor intrusion to indoor air pathway from groundwater and soils (integrates RCRA/Superfund).

2003 Version 3 of the vapor intrusion model to be published by EPA any day now.

What is Vapor Intrusion?

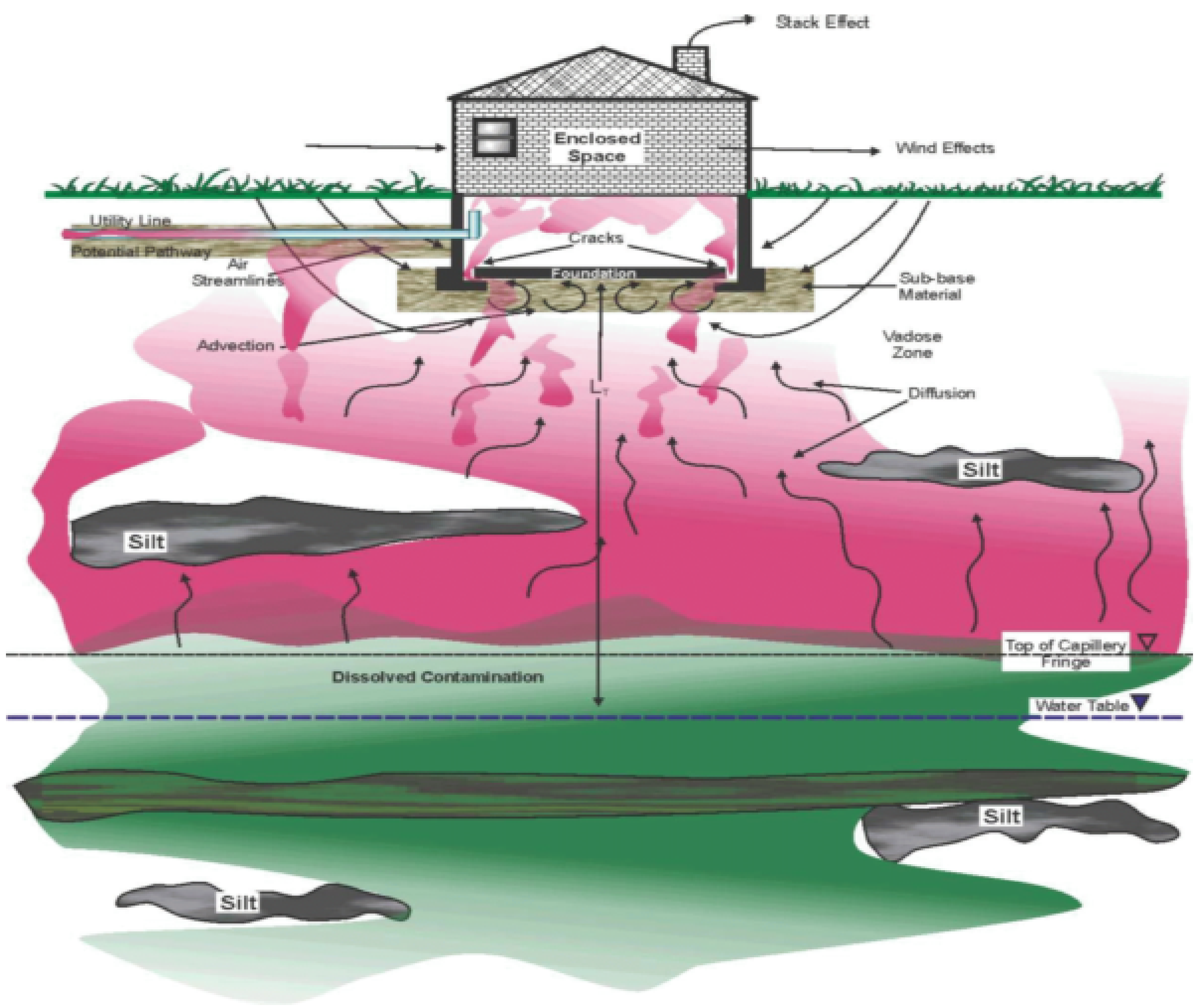
- Migration of toxic volatile chemicals from the subsurface into buildings.
- A chemical is considered to be volatile if its Henry's Law Constant is 1 x 10^{-5} atm-m^3/mol or greater.

What is Vapor Intrusion?

- A chemical is considered to be sufficiently toxic if the vapor of the pure chemical poses an incremental life time cancer risk greater than 10^{-6} for residential exposure scenario.

- A chemical is considered to be sufficiently toxic if the vapor of the pure compound creates a hazard index greater than 1.

Vapor Intrusion – Background & Theory



Henry's Law

- For dilute solutions of non-reactive gas dissolved in a liquid: $P_{gas} = H_k * C_{gas}$

  - P_{gas} = Pressure of the gas above the solution
  - C_{gas} = Mole fraction of the dissolved gas
  - H_k = Henry's constant for the defined temperature

Henry's Law – *An Interpretation*

Equilibrium between the gas above a liquid and the dissolved gas within the liquid is reached when the rates of evaporation and condensation of gas molecules become equal.

Why 1 x 10^{-5} atm-m^3/mol?

- An opinion that took into account:
  - Analytical methods differentiate between volatile and semi-volatile organic compounds by boiling points and molecular weights
  - This cut point is designed to exclude long chain heavy molecular weight compounds and still include the compounds that are on the cusp of being a volatile or a semi-volatile as defined by the analytical methods

Sufficiently Toxic?

- Worst case or best case?
  - Inhalation of saturated vapor does not cause an unacceptable level of risk or hazard using the “typical” adult residential exposure factors.

The List

160	Identified chemicals of potential concern at superfund and RCRA corrective action sites
-10	Chemicals where hazard index is less than 1 or the lifetime incremental cancer risk is less than 10^{-6}
-36	Chemicals that are not volatile using Henry's Law threshold of 10^{-5} atm-m^3/mol

114 players

Example of Table 1: Question 1 Summary Sheet

CAS No.	Chemical	(1) Is chemical sufficiently toxic?	Is Henry's Law Constant greater than $1x10^{-5}$ atm-m^3/mol?	(2) Is chemical sufficiently volatile?	Check here if known or reasonably suspected to be present (3)
83329	Acenaphthene	YES	YES	YES	
75070	Acetaldehyde	YES	YES	YES	
67641	Acetone	YES	YES	YES	
75058	Acetonitrile	YES	YES	YES	
98862	Acetophenone	YES	YES	YES	
107028	Acrolein	YES	YES	YES	
107131	Acrylonitrile	YES	YES	YES	
309002	Aldrin	YES	YES	YES	
319846	alpha-HCH (alpha-BHC)	YES	YES	YES	
62533	Aniline	YES	NO	NO	NA
120127	Anthracene	NO	YES	YES	NA

Vapor Intrusion – Background & Theory

Vapor concentration at the source of contamination – soil

$$C_{source\ soil} = C_{source} = \frac{H'_{TS}\, C_R\, r_b}{q_w + K_d\, r_b + H'_{TS}\, q_a}$$

- C_{source} = Vapor concentration at the source of contamination, g/cm^3-v
- H'_{TS} = Henry's law constant at the system (soil) temperature, dimensionless
- C_R = Initial soil concentration, g/g
- r_b = Soil dry bulk density, g/cm^3

- θ_w = Soil water-filled porosity, cm^3/cm^3
- K_d = Soil-water partition coefficient, cm^3/g (= K_{oc} x f_{oc})
- θ_a = Soil air-filled porosity, cm^3/cm^3
- K_{oc} = Soil organic carbon partition coefficient, cm^3/g
- f_{oc} = Soil organic carbon weight fraction

Vapor concentration at the source of contamination – groundwater

$$C_{source\ gw} = C_{source} = H'_{TS} C_w$$

- C_{source} = Vapor concentration at the source of contamination, g/cm^3-v
- H'_{TS} = Henry's law constant at the system (groundwater) temperature, dimensionless
- C_w = Groundwater concentration, g/cm^3-w

Henry's Law (Again)

$$H'_{TS} = \frac{\exp\left[-\frac{\Delta H_{v,TS}}{R_c}\left(\frac{1}{T_S} - \frac{1}{T_R}\right)\right] H_R}{RT_S}$$

- H'_{TS} = Henry's law constant at the system temperature, dimensionless
- $DH_{v,T}$ = Enthalpy of vaporization at the system temperature, cal/mol
- T_S = System temperature, ^oK
- T_R = Henry's law constant reference temperature, ^oK
- H_R = Henry's law constant at the reference temperature, atm-m^3/mol
- R_C = Gas constant (= 1.9872 cal/mol - ^oK)
- R = Gas constant (= 8.205 E-05 atm-m^3/mol-^oK)

Henry's Law (cont.)

$$\Delta H_{v,TS} = \Delta H_{v,b} \left[\frac{(1 - T_S / T_C)}{(1 - T_B / T_C)} \right]^n$$

- $\Delta H_{v,TS}$ = Enthalpy of vaporization at the system temperature, cal/mol
- $\Delta H_{v,b}$ = Enthalpy of vaporization at the normal boiling point, cal/mol
- T_S = System temperature, ^oK
- T_C = Critical temperature, ^oK
- T_B = Normal boiling point, ^oK
- n = Constant, unitless

Note: *As the critical temperature approaches the normal boiling point, the Henry's Law Constant can change radically when compared to standard conditions.*

Diffusion through the capillary zone

- Key assumption

$$q_{w,cz} = q_r + \frac{q_s - q_r}{\left[1 + (ah)^N\right]^M}$$

- No smear and no residual product in the soil void spaces
- no pumping caused by rising or falling water table heights

- $\theta_{w,cz}$ = Water-filled porosity in the capillary zone, cm^3/cm^3
- θ_r = Residual soil water content, cm^3/cm^3
- θ_s = Saturated soil water content, cm^3/cm^3
- a = Point of inflection in the water retention curve where $d\theta_w/dh$ is maximal, cm^{-1}
- h = Air-entry pressure head, cm (= 1/a and assumed to be positive)
- N = van Genuchten curve shape parameter, dimensionless
- M = 1 - (1/N)

Effective diffusion coefficient across the capillary zone

$$D_{cz}^{eff} = D_a \left(q_{a,cz}^{3.33} / n_{cz}^2 \right) + \left(D_w / H'_{TS} \right) \left(q_{w,cz}^{3.33} / n_{cz}^2 \right)$$

- D_{cz}^{eff} = Effective diffusion coefficient across the capillary zone, cm^2/s
- D_a = Diffusivity in air, cm^2/s
- $\theta_{a,cz}$ = Soil air-filled porosity in the capillary zone, cm^3/cm^3
- n_{cz} = Soil total porosity in the capillary zone, cm^3/cm^3
- D_w = Diffusivity in water, cm^2/s
- H'_{TS} = Henry's law constant at the system temperature, dimensionless
- $q_{w,cz}$ = Soil water-filled porosity in the capillary zone, cm^3/cm^3

Rate of mass transfer (flux) across the capillary zone

$$E = A\left(C_{source} - C_{g0}\right)D_{cz}^{eff} / L_{cz}$$

- E = Rate of mass transfer, g/s
- A = Cross-sectional area through which vapors pass, cm^2
- C_{source} = Vapor concentration within the capillary zone, g/cm^3-v
- C_{g0} = A known vapor concentration at the top of the capillary zone, g/cm^3-v (C_{g0} is assumed to be zero as diffusion proceeds upward)
- D_{cz}^{eff} = Effective diffusion coefficient across the capillary zone, cm^2/s
- L_{cz} = Thickness of capillary zone, cm

Diffusion through the capillary zone

Point of Interest

The range of published values for total porosity, residual water content, and water filled porosity leads one to believe that field measurement may be required if the model values are problematic.

Attenuation Coefficient

Simply stated:

$$a = \frac{Concentration\ in\ Building\ (C_{Bldg})}{Concentration\ Source\ (C_{Source})}$$

The Math

$$a = \frac{\left(\dfrac{D_T^{eff}\ A_B}{Q_{building}\ L_T}\right) x \exp\left(\dfrac{Q_{soil}\ L_{crack}}{D^{crack}\ A_{crack}}\right)}{\exp\left(\dfrac{Q_{soil}\ L_{crack}}{D_{crack}\ A_{crack}}\right) + \left(\dfrac{D_T^{eff}\ A_B}{Q_{building}\ L_T}\right) + \left(\dfrac{D_T^{eff}\ A_B}{Q_{soil}\ L_T}\right)\left[\exp\left(\dfrac{Q_{soil}\ L_{crack}}{D^{crack}\ A_{crack}}\right) - 1\right]}$$

- D_{eff} = Effective diffusion coefficient
- L_T = Depth to source
- A_B = Building area to contact with soil
- Q_B = Building ventilation rate
- Q_{soil} = Soil gas convection rate
- D_{crack} = Eff. Diff. Coeff. through cracks
- L_{crack} = Crack thickness
- η = Building crack factor
- D_{eff} = fn (H, D_{water}, D_{air}, O_T, O_W for each layer
- LT = Σ (L_i)
- Q_{soi}l = fn (k, DP, rcrack, zcrack, xcrack)

Vapor Intrusion – Background & Theory

Primary Parameters

- D_{eff} = Effective diffusion coefficient
- L_T = Depth to source
- A_B = Building area to contact with soil
- Q_B = Building ventilation rate
- Q_{soil} = Soil gas convection rate
- D_{crack} = Eff. Diff. Coeff. through cracks
- L_{crack} = Crack thickness
- η = Building crack factor

Secondary Parameters

- D_{eff} = fn (H, D_{water}, D_{air}, θ_T, θ_W) for each layer
- LT = Σ (L_i)
- Q_{soi}l = fn (k, ΔP, r_{crack}, z_{crack}, x_{crack})

- Model considers vapor concentration and vapor flux
  - Flux is mass transport rate per unit area (e.g., $mg/cm^2/sec$)
  - Conservation of mass require flux to be constant

Building flux = $C_{Bldg} * Q_{Bldg}$

Conservative flux = $C_{soil} * Q_{soil}$ (immediately below structure)

Diffusive flux = $D_{eff} * \frac{C_1 - C_2}{2}$ (C_1 = concentration top of capillary fringe)
(C_2 = concentration below enclosed space)
(2 = thickness of soil)

Building Ventilation

- Assumptions
  - Well mixed building
  - No background sources of chemical

$$Flux = Q_{Bldg} * C_{Bldg} = ER * A_{Bldg} * H_{Bldg} * C_{Bldg}$$

- ER = Air Exchange Rate
- A_{Bldg} = Building Foot Print Area
- H_{Bldg} = Building Height

- ER varies from 0.2/hour to over 1.0/hr
- Attenuation factor decreases or ER increases
- Potential impact on attenuation 1 to 5x

Soil Gas Convection Rate

- Soil gas convection into buildings depends on:
  - Pressure differential
  - Sub slab soil permeability
  - Number and size of cracks (assumed to be 1MM wide along perimeter and same thickness as slab)
  - Weather effects

Soil Gas Convection Rate (cont.)

- Typical range 1 - 10 L/min
- Attenuation factor decreases as Q_{soil} increases
- Potential impact on attenuation factor 1 to 5x

Q_{soil} - volumetric convective flow into building

Dependent on

- k_v, soil permeability
- ΔP, pressure differential between soil surface and enclosed space
- X_{crack}, floor wall seam perimeter length
- Z_{crack}, crack depth below grade
- R_{crack}, equivalent crack radius
- μ, viscosity of air

$$Qsoil = \frac{2 * \Pi * \Delta P * K_u * X_{crack}}{m * \ln(2 * Z_{crack} / r_{crack})}$$

Risk Based Soil or Ground water Concentration

Calculation of a risk-based media concentration for a carcinogenic contaminant takes the form:

$$C_C = \frac{TR \ x \ AT_C \ x \ 365 \ \ days \ / \ yr}{URF \ \ x \ EF \ \ x \ ED \ \ x \ C_{building}}$$

where C_C = Risk-based media concentration for carcinogens, µg/kg-soil, or µg/L-water

- TR = Target risk level, unitless
- AT_C = Averaging time for carcinogens, yr
- URF = Unit risk factor, $(\mu g/m^3)^{-1}$
- EF = Exposure frequency, days/yr
- ED = Exposure duration, yr
- $C_{building}$ = Vapor concentration in the building, $\mu g/m^3$ per µg/kg-soil, or $\mu g/m^3$ per µg/L-water

In the case of a non-carcinogenic contaminant, the risk-based media concentration is calculated by:

$$C_{NC} = \frac{THQ \ x \ AT_{NC} \ x \ 365 \ days / yr}{EF \ x \ ED \ x \ \frac{1}{RfC} \ x \ C_{building}}$$

- C_{NC} = Risk-based media concentration for non-carcinogens, µg/kg-soil, or µg/L-water
- THQ = Target hazard quotient, unitless
- AT_{NC} = Averaging time for non-carcinogens, yr
- EF = Exposure frequency, days/yr
- ED = Exposure duration, yr
- RfC = Reference concentration, mg/m^3
- $C_{building}$ = Vapor concentration in the building, mg/m^3 per µg/kg-soil, or mg/m^3 per µg/L-water

Calculation of Incremental Risks

Forward-calculation of incremental risks begins with an actual initial media concentration (i.e., ☞g/kg-soil or ☞g/L-water).

Carcinogenic contaminants:

$$Risk = \frac{URF \ x \ EF \ x \ ED \ x \ c_{building}}{AT_c \ 365 \, days/yr}$$

Non-carcinogenic contaminants:

$$HQ = \frac{EF \ x \ ED \ x \frac{1}{RfC} \ x \ C_{building}}{AT_{NC} \ x \ 365 \ days/yr} \quad .$$

Risk Assessment Math

2 + 2 = 4 ± order of magnitude implies:

0.4, 1, 4, 16, 40 are acceptable

30 + 50 = 80 ± order of magnitude implies:

8, 24, 80, 264, 800 are acceptable

Is there a correct number? ***Probably not***

Is there an acceptable range? ***Probably***

Cause and Effect of changes on selected parameters

Input parameter	Change in parameter value	Effect on building concentration
Soil water-filled porosity (Θ_W)	Increase	Decrease
Soil vapor permeability (K_v)	Increase	Increase
Soil-building pressure differential (ΔP)	Increase	Increase
Media initial concentration (C_R, C_W)	Increase	Increase
Depth to bottom of soil contamination (L_b)	Increase	Increase
Depth to top of concentration (L_T)	Increase	Decrease
Floor-wall seam gap (w)	Increase	Increase
Soil organic carbon fraction (f_{oc})	Increase	Decrease
Building air exchange rate (ER)	Increase	Decrease
Building volume	Increase	Decrease
Soil total porosity (n)	Increase	Increase
Soil dry bulk density (ρ_b)	Increase	Decrease

Uncertainty and Sensitivity

Input Parameter	Parameter Uncertainty Or Variablity	Parameter Sensitivity			
		Shallower Contamination Building Underpressurized	Deeper Contamination Building Underpressurized	Shallower Contamination Building Not Underpressurized	Deeper Contamination Building Not Underpressurized
Total Porosity	Low	Low	Low	Low	Low
Unsaturated Zone Water-filled Porosity	Moderate to High	Low to Moderate	Moderate to High	Moderate to High	Moderate to High
Capillary Transition Zone Water-filled Porosity	Moderate to High	Moderate to High	Moderate to High	Moderate to High	Moderate to High
Capillary Transition Zone Height	Moderate to High	Moderate to High	Moderate to High	Moderate to High	Moderate to High
Soft Bulk Density	Low	Low	Low	Low	Low
Qsoil	High	Moderate to High	Low to Moderate	N/A	N/A
Soil air permeability	High	Moderate to High	Low to Moderate	N/A	N/A
Building Depressurization	Moderate	Moderate	Low to Moderate	N/A	N/A
Henry's Law Constant (for single chemical)	Low to Moderate	Low to Moderate	Low to Moderate	Low to Moderate	Low to Moderate
Free-Air Diffusion Coefficient (single chemical)	Low	Low	Low	Low	Low
Building Air Exhange Rate	Moderate	Moderate	Moderate	Moderate	Moderate
Building Mixing Height	Moderate	Moderate	Moderate	Moderate	Moderate
Subsurface Foundation Area	Low to Moderate	Low to Moderate	Low to Moderate	Low to Moderate	Low to Moderate
Depth to base of Foundation	Low	Low	Low	Low	Low
Building Crack Ratio	High	Low	Low	Moderate to High	Low to Moderate
Crack Moisture Content	High	Low	Low	Moderate to High	Low to Moderate
Building Foundation Slab Thickness	Low	Low	Low	Low	Low

Summary of Vapor Intrusion Model

- Key Factors
  - Chemical Properties
  - Toxicity
  - Volatility
- Building Properties
  - Ventilation rate
  - Dept to Contamination
  - Dimensions

Summary of Vapor Intrusion Model

- Soil Properties
  - Thickness of each strata
  - Permeability
  - Porosity
  - Hydraulic conductivity
  - Diffusivity
- Risk Factors
  - Exposure scenario
  - Target/Acceptable risk level
  - Target/Acceptable hazard level

Vapor Intrusion – Regulatory Drivers

All Federal and State regulatory agencies possess a mechanism to determine action levels and cleanup standards that would directly or indirectly influence the impacts of vapor intrusion at hazardous waste sites and Superfund sites.

CERCLA – *Provides the authority to respond to actual or threatened releases of hazardous substances, pollutants, or contaminants.*

CERLA – *Does not specify cleanup standards; directs the agency to select cost-effective remedies that protect human health, welfare, and the environment.*

Applicable or Relevant and Appropriate Requirements (ARARs)

Two sets of requirements that must be achieved if Federal Superfund monies are involved

- Applicable
- Relevant and Appropriate

ARAR's

- Chemical-Specific Requirements
  - Health Risk numerical standards limiting concentration of a substance (e.g., maximum contaminant levels under the Safe Drinking Water Act)
  - **Location-specific requirements** – i.e., restrictions related to flood plain, historic sites, wetlands
  - **Action-specific requirements** – i.e., technology- or activity-based limitations

Indoor Air Quality

- Only a few states have established numerical standards for indoor air quality
  - Massachusetts
  - Connecticut
  - Colorado
  - Michigan
  - New Hampshire
  - Oregon
  - Others?

Ambient Air vs. Indoor Air

- Several states have developed ambient air toxic standards that may be considered as an ARAR.
  - Virginia
  - North Carolina
  - South Carolina
  - Massachusetts
  - Connecticut
  - Michigan
  - Oregon
  - Others?

If no ARAR's, then what?

- **Risk Assessment** - *a method(s) used to determine whether the contamination levels threaten human health or the environment*

Risk Assessment – Via vapor intrusion guidance

Route-specific Approach – considers the risks and hazards posed by each route of exposure in isolation. Assumes that hazards and risks from exposure to a chemical by multiple routes are unrelated.

1) This procedure will tend to underestimate exposure, risks, and hazards. The maximum under-estimation as result of using route specific approach is a factor of
2) Maximum under-estimation would occur when other pathway risks for a chemical are equal to the inhalation pathway risks.
3) If the risks are dominated by a non-inhalation route, the error introduced by the route-specific approach is minimal.

Acceptable Risk Levels?

A negotiated media-specific target concentration:

Cancer causing chemicals

1×10^{-4} to 1×10^{-6} incremental increase in lifetime cancer risks (EPA recommends 1×10^{-5} as reasonable) Several states use 1×10^{-6} as reasonable.

Injury/Hazard causing chemicals

Hazard quotient for non-cancer risks should be less than 1.

Some states are more stringent by assuming there are hazards from other sources.

Exposure Parameters

- Residential
- Adult
- Averaging time for carcinogens – 70 yrs
- Averaging time for non-carcinogens - 30 yrs
  - Exposure duration – 30 years
  - Exposure frequency – 350 days/year
- Chronic reference concentration (Rfc) for non-carcinogens
- Unit risk factors for carcinogens

Toxicology

- The vapor intrusion model includes toxicological data derived from:
  - Integrated Risk Information System (IRIS) – IRIS is the official repository of EPA-wide consensus of human health risk information
  - ***Note:*** Cancer slope factors (CSF's) are not available in IRIS. CSF's were calculated assuming an adult inhalation rate of 20 m^3/day and a body weight of 70 kg.

Toxicology (cont.)

- National Center for Environmental Assessment – published provisional chronic RfC’s and CSF’s that are still undergoing peer review.
- Health Effects Assessment Summary Tables (HEAST).
- Route-to-route extrapolated toxicity values were derived from oral reference doses.

Toxicology (cont.)

The numbers:

83	RfC's from IRIS
18	RfC's from NCEA
21	RfC's from HEAST
2	RfC's from other databases
46	URF's from IRIS
12	URF's from NCEA
7	URF's from HEAST
32	target indoor air concentrations were derived from route-to-route extrapolated data
1	chemical on the list with no toxic factors (Dimethylphthalate)

Screening Level Vapor Derived Groundwater Concentrations (Mg/l)

	Benzene	TCE	1,1-DCA
Mi	5,600	15,000	1,000,000
Or	180	NA	NA
VA	12	35	2,260
Ct	215	219	34,600
MA	2,000	300	9,000
NH	2,000	300	9,000
EPA R-4	140	5.3	2,300
EPA R-5	140	5.0*	2,300
EPA R-6	5.0*	5.0*	2,300
*Calculated value would be below the MCL.			

Why State to State Variations?

- Differing Hazard & Risk Levels (10^{-6} vs 10^{-5} vs 10^{-4} vs HI = 1 vs HI = 0.25)
- Differing Toxicology (extrapolate – some yes, - some no)
- Differing Soil Building Parameters (Basement vs. Slab on Grade)

Why State to State Variations? (cont.)

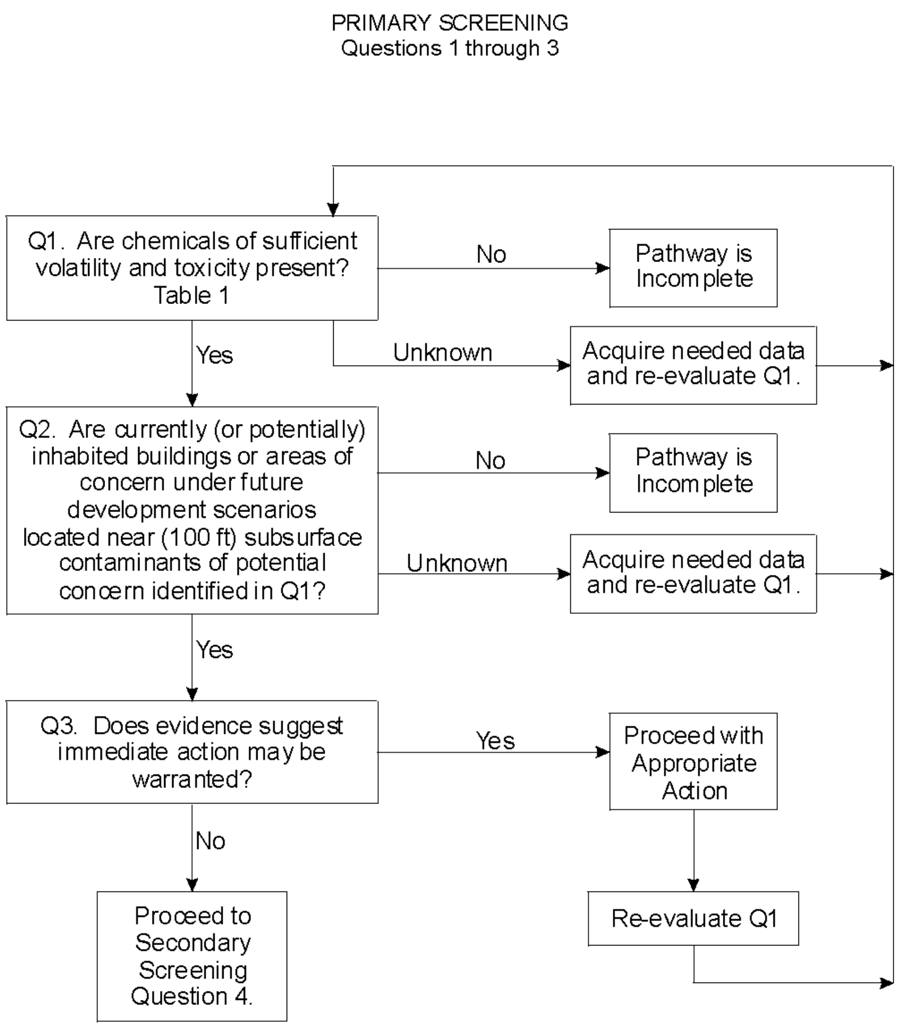
- Differences in several "Low Sensitivity" inputs can add up to large differences in screening values

- Recommend that all inputs be evaluated for reasonableness and conformance with site conditions

State Guidance

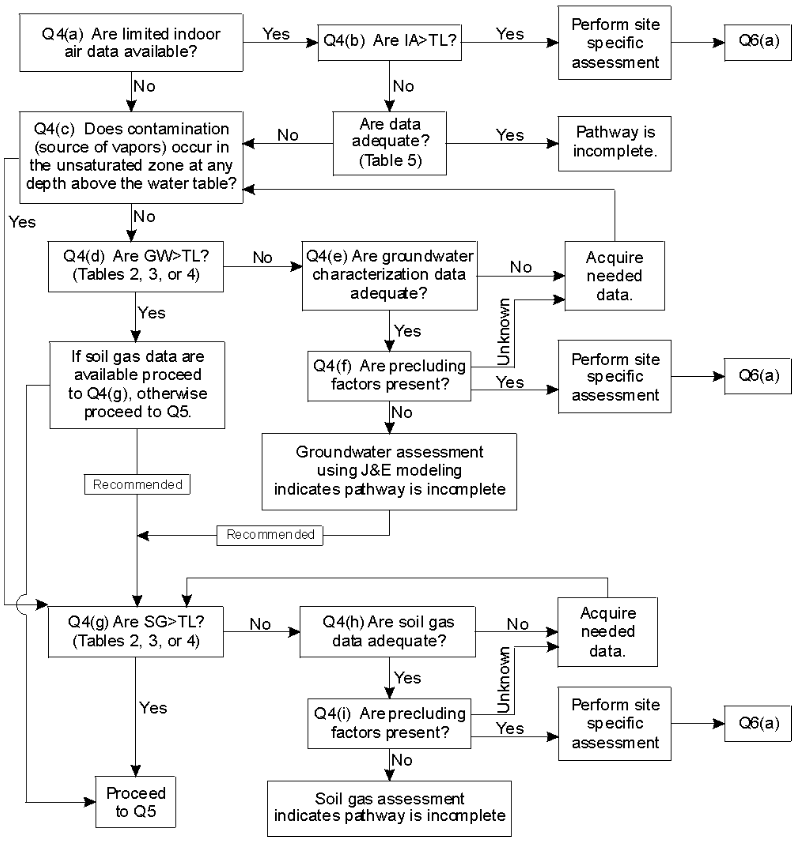
- Many states have published guidance and policy directives that are modified versions of EPA guidance
- Some are more stringent
- Some require indoor sampling if there is groundwater contamination
- The Devil is in the details

Vapor Intrusion – Data Needs & Input Parameters



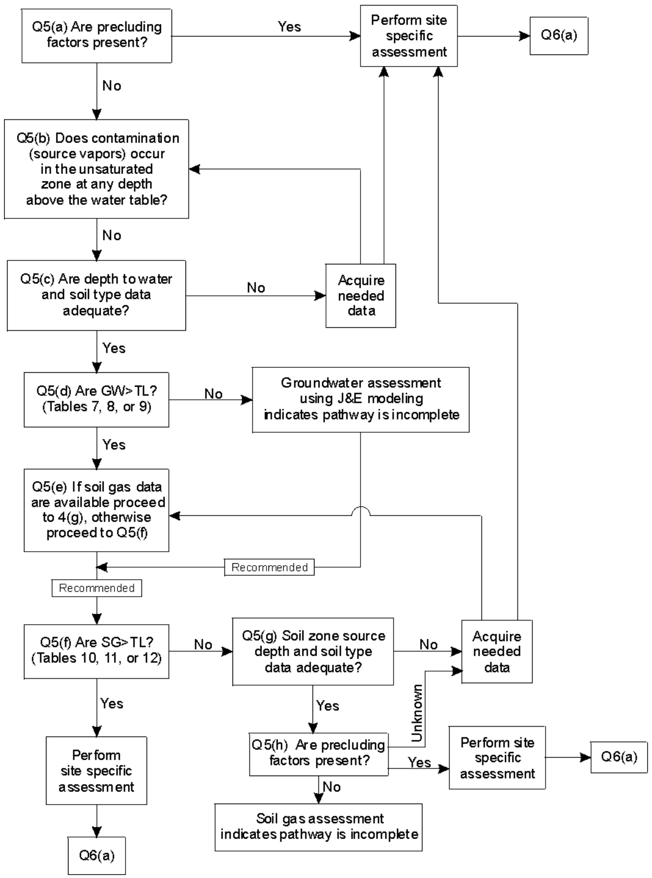
Vapor Intrusion – Data Needs & Input Parameters

SECONDARY SCREENING
Question 4
(TL = appropriate media specific target level)
(SG = soil gas concentration of each COPC)
(IA = indoor air concentration of each COPC)
(GW = groundwater concentration of each COPC)



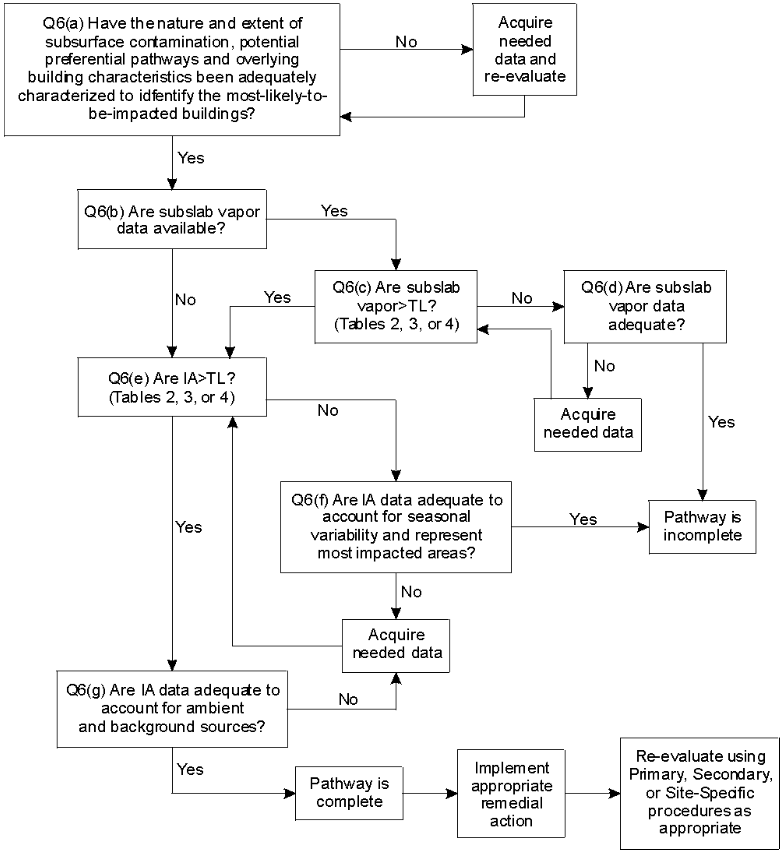
Vapor Intrusion – Data Needs & Input Parameters

SECONDARY SCREENING
Question 5 - Semi-Site Specific Screening
(TL = appropriate media specific target level)
(SG = soil gas concentration of each COPC)
(IA = indoor air concentration of each COPC)
(GW = groundwater concentration of each COPC)

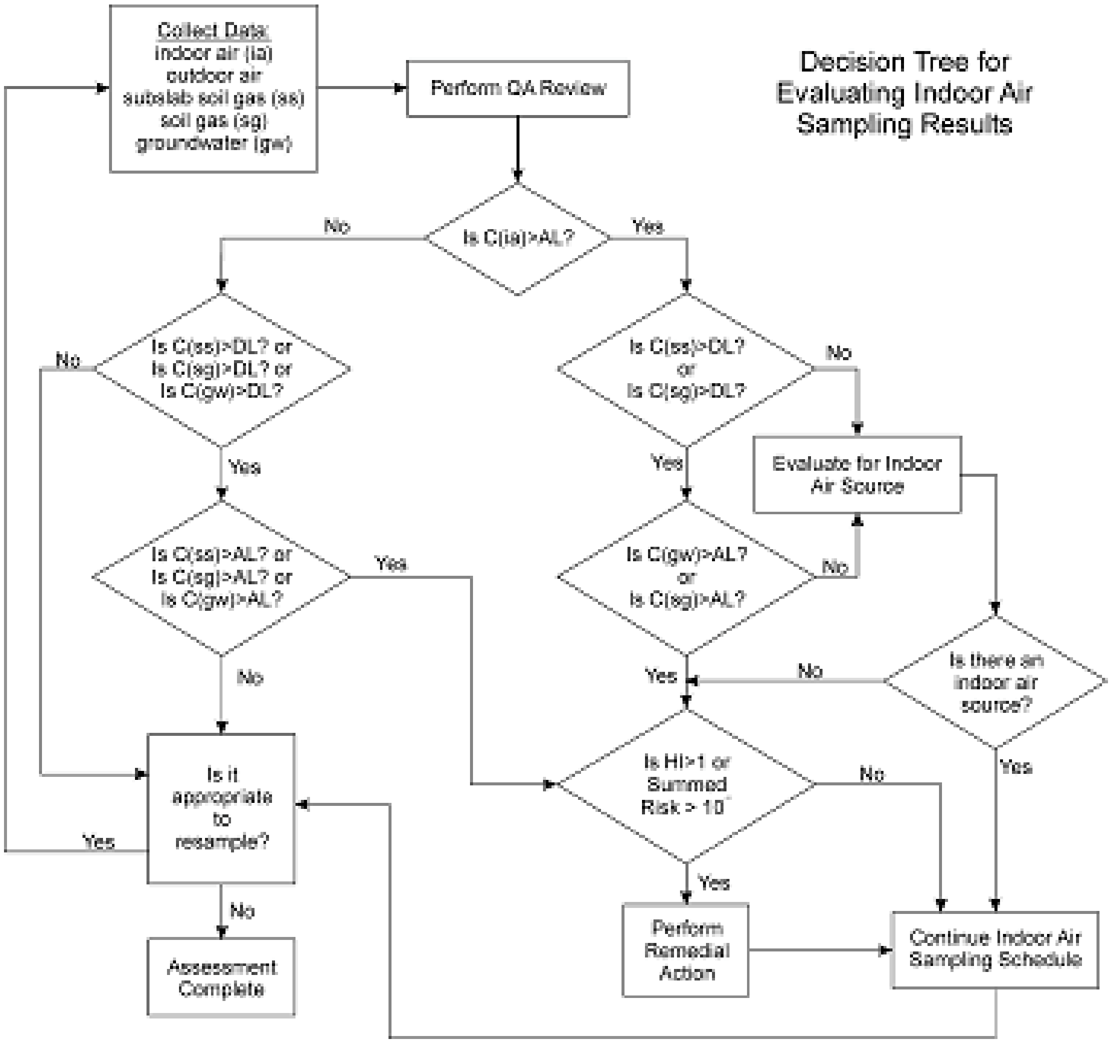


Vapor Intrusion – Data Needs & Input Parameters

SECONDARY SCREENING
Question 6
(TL = appropriate media specific target level)
(SG = soil gas concentration of each COPC)
(IA = indoor air concentration of each COPC)
(GW = groundwater concentration of each COPC)



Vapor Intrusion – Data Needs & Input Parameters



Johnson and Ettinger Model Inputs (Johnson, 2002)

Primary Inputs		Secondary Inputs	
Q_B (m^3/day)	volumetric fresh air flow rate into enclosed space	V_b (m^3)	enclosed space volume
		ER (1/hr)	indoor air exchange rate with outdoor air
Q_{soil} (m^3/day)	pressure-driven soil gas flowrate from the subsurface into the enclosed space	k (m^2)	soil permeability
		ΔP (g/m-s^2)	indoor/outdoor pressure difference
		X_{crack} (m)	total length of cracks with vapor flow
		Z_{crack} (m)	depth of crack opening below grade
		R_{crack} (m)	Effective crack width (=$\eta * A_b / X_{crack}$)

Johnson and Ettinger Model Inputs (Johnson, 2002) (cont.)

Primary Inputs		Secondary Inputs	
D^{eff}_{crack} (m^2/day)	vapor phase diffusion coefficient through foundation cracks	T_m (volume fraction)	soil moisture content
D^{eff}_{T} (m^2/day)	vapor phase diffusion coefficient in soil between the foundation and vapor source	T_T (volume fraction)	soil total porosity
		T_V (volume fraction)	soil vapor content
		H´	dimensionless Henry's law constant
		D_{air}	air diffusion coefficient
		D_{H2O}	water diffusion coefficient

Johnson and Ettinger Model Inputs (Johnson, 2002) (cont.)

Primary inputs without secondary inputs	
L_T (m)	soil depth to vapor source
A_B (m^2)	area of the building in contact with soil (building footprint)
L_{crack} (m)	foundation slab thickness
η	fraction of foundation floor area open for vapor intrusion
C_{src} (groundwater, mg/L; soil, mg/kg)	concentration of contaminant within source

Johnson and Ettinger Model Inputs in EPA's Spreadsheet (EQM, 2003)

Spreadsheet Inputs	Data Source
All Models	
Averaging time for carcinogens (years)	Average lifetime; default is 70 years
Averaging time for noncarcinogens (years)	Set equal to time in residence; default is 30 years (U.S. EPA, 1996a,b)
Exposure duration (years)	Time in residence; default is 30 years (U.S. EPA, 1996a,b)
Exposure frequency (days)	Number of days in house per year; default is 350 (U.S. EPA, 1996a,b)
Target risk for carcinogens	User-defined for risk-based soil or groundwater concentration; default is 10^{-6}
Target hazard quotient for noncarcinogens	User-defined for risk-based soil or groundwater concentration; default is 1
Initial soil or groundwater concentration (☞g/kg or ☞g/L)	Site-specific measurements or estimates beneath building
Average soil or groundwater temperature (☞F)	Geographical typical 10☜C (U.S. EPA, 1995)

Johnson and Ettinger Model Inputs in EPA's Spreadsheet (EQM, 2003) (cont.)

Spreadsheet Inputs	Data Source
Depth below grade to bottom of enclosed space (cm)	Depth from ground surface to bottom of house in contact with soil
Depth below grade to top of contamination (cm)	Site-specific measurements or estimates beneath building; enter depth to groundwater for groundwater contamination
Soil vapor permeability (cm^2)	Optional site-specific input; enter value for stratum A in advanced model)
SCS soil texture	One of 12 USDA soil textures (site-specific) or sand (S, as conservative default); enter value for stratum A in advanced model
Soil dry bulk density (g/cm^3)	Site-specific depth-averaged value; universal default is 1.5 g/cm^3 (U.S. EPA, 1996a,b); enter value or identify soil type for stratum "X" in advanced model
Soil total porosity (volume fraction)	Site-specific depth-averaged value (U.S. EPA, 1996a,b); enter value for stratum "X" in advanced model or identify soil type for default value
Soil water-filled porosity (volume fraction)	Site-specific depth-averaged annual average value; enter value for stratum "X" in advanced model, estimating site-specific value using HYDRUS (Vogel et al., 1998) or similar model. Identify soil type and accept default values)

Vapor Intrusion – Data Needs & Input Parameters

Spreadsheet Inputs	Data Source
Advanced Models Only	
Depth below grade to bottom of contamination (cm)	Used to calculate thickness of contamination for finitie source model; zero or values less than the top of contamination invoke finite source model
Thickness of soil stratum "X" (cm)	User can define up to three soil strata (X = A, B, C); stratum A extends downward from the soil surface and must be at least as thick as the depth below grade to the bottom of the building floor; the combined thickness of all strata should equal the depth
Fraction organic carbon (stratum "X," weight fraction)	Depth-averaged soil organic fraction; site-specific measurements (U.S. EPA, 1996a)
Enclosed space floor thickness (cm)	Model assumes impermeable concrete floor in contact with underlying soil; default is 10 cm (Johnson and Ettinger, 1991)

Vapor Intrusion – Data Needs & Input Parameters

Spreadsheet Inputs	Data Source
Soil-building pressure differential (Pascals)	Driving force for soil-gas entering building; range is 0-20 Pascals; default is 4 Pascals (EQM, 2000)
Enclosed space floor length and width (cm)	Site-specific value based on building footprint; default is 1000 cm x 1000 cm (10,000 square feet) (U.S. DOE, 1995)
Enclosed space height (m)	Total height of enclosed space (all floors and basement); default is 2.44 for house on slab and 3.66 m for house with basement (U.S. DOE, 1995)
Floor-wall seam crack width (cm)	Gap between floor perimeter and foundation, assumed to be only opening to soil; default is 0.1 cm (EQM, 2000)
Indoor air exchange rate (1/h)	Exchange rate outdoor air with indoor air; default is 0.25 (EQM, 2000)

Recommendations for Reasonable JEM Primary Input Values (Johnson, 2002)

Parameters reasonably estimated from available site assessment data				
L_T	Depth from foundation to the vapor source (m)	0.01 - 50 m	To be determined from site assessment data, sampling depths, or defined scenario	Experience
Parameters reasonably estimated from experience and intuition				
(V_B/A_B)	Ratio of enclosed-space volume to exposed surface area [m]	2-3 m	Approximately equal to the height of the enclosed space (e.g., basement height or height of first-floor room for slab-on-grade construction)	Experience
L_{crack}	Foundation thickness [m]	0.15 - 0.5 m	Based on typical construction practices	Experience
η	Fraction of surface area with permeable cracks	0.0005 - 0.005	η = 0.01 (worst-case) corresponds to a finger-width crack spaced 1-m apart and running across the floor; η = 0.0003 corresponds roughly to a 0.1 cm floor-wall seam perimeter crack around a 225 m^2 area	Intuition and (a)
ER	Indoor air exchange rate (1/d)	4.8 - 24	Based on building ventilation/energy efficiency studies	(b), (c)

Recommendations for Reasonable JEM Primary Input Values (Johnson, 2002) (cont.)

Primary Input	Definition	Reasonable Range	Comment	Reference
Parameters reasonably estimated indirectly from literature data				
Q_{soil}/Q_B	Ratio of the soil gas intrusion rate to the building ventilation rate	0.05 - 0.0001	Based on vapor attenuation coefficients reported for radon studies and contaminant vapor intrusion case studies	(d) - (h)
Parameters reasonably estimated from correlations and secondary inputs				
D^{eff} T	Effective overall vapor-phase diffusion coefficient between source and foundation	chemical-specific	Empirical correlations and secondary inputs	(i) -(l)
D^{eff} Crack	Effective overall vapor-phase diffusion coefficient through foundation cracks	chemical-specific	Empirical correlations and secondary inputs	(i) -(l)
Refences: (a) Eaton and Scott (1984); (b) ASHRAE (1985); (c) Kootz and Rector (1995); (d) Mose and Mushrush (1999); (e) Fisher et al. (1996); (f) Little et. al. (1992); (g) Olson and Corsi (2001); (h) Fitzpatrick and Fitzgerald (1996); (i) Brooks and Corey (1966); (j) Carsel and Parrish (1998); (k) Johsnon & Ettinger (1997); (l) EQM (2000)				

Cause and effect of changes on selected parameters

Input parameter	Change in parameter value	Effect on building concentration
Soil water-filled porosity (Θ_w)	Increase	Decrease
Soil vapor permeability (k_v)	Increase	Increase
Soil-building pressure differential (ΔP)	Increase	Increase
Media initial concentration (C_R, C_W)	Increase	Increase
Depth to bottom of soil contamination (L_b)	Increase	Increase
Depth to top of concentration (L_T)	Increase	Decrease
Floor-wall seam gap (w)	Increase	Increase
Soil organic carbon fraction (f_{oc})	Increase	Decrease
Building air exchange rate (ER)	Increase	Decrease
Building volume	Increase	Decrease
Soil total porosity (n)	Increase	Increase
Soil dry bulk density (ρ_b)	Increase	Decrease

Uncertainty and Sensitivity

Input Parameter	Parameter Uncertainty Or Variablity	Parameter Sensitivity			
		Shallower Contamination Building Underpressurized	Deeper Contamination Building Underpressurized	Shallower Contamination Building Not Underpressurized	Deeper Contamination Building Not Underpressurized
Total Porosity	Low	Low	Low	Low	Low
Unsaturated Zone Water-filled Porosity	Moderate to High	Low to Moderate	Moderate to High	Moderate to High	Moderate to High
Capillary Transition Zone Water-filled Porosity	Moderate to High	Moderate to High	Moderate to High	Moderate to High	Moderate to High
Capillary Transition Zone Height	Moderate to High	Moderate to High	Moderate to High	Moderate to High	Moderate to High
Soft Bulk Density	Low	Low	Low	Low	Low
Qsoil	High	Moderate to High	Low to Moderate	N/A	N/A
Soil air permeability	High	Moderate to High	Low to Moderate	N/A	N/A
Building Depressurization	Moderate	Moderate	Low to Moderate	N/A	N/A
Henry's Law Constant (for single chemical)	Low to Moderate	Low to Moderate	Low to Moderate	Low to Moderate	Low to Moderate
Free-Air Diffusion Coefficient (single chemical)	Low	Low	Low	Low	Low
Building Air Exhange Rate	Moderate	Moderate	Moderate	Moderate	Moderate
Building Mixing Height	Moderate	Moderate	Moderate	Moderate	Moderate
Subsurface Foundation Area	Low to Moderate	Low to Moderate	Low to Moderate	Low to Moderate	Low to Moderate
Depth to base of Foundation	Low	Low	Low	Low	Low
Building Crack Ratio	High	Low	Low	Moderate to High	Low to Moderate
Crack Moisture Content	High	Low	Low	Moderate to High	Low to Moderate
Building Foundation Slab Thickness	Low	Low	Low	Low	Low

Model Sensitivity

- Use Ratios to help avoid setting inconsistent parameter values:

$Q_{soil}/Q_{building}$ – Reasonable range 0.0001 to 0.05

V_B/A_B – Reasonable range for single family residence 2 to 4 meters

Dimensionless Parameters

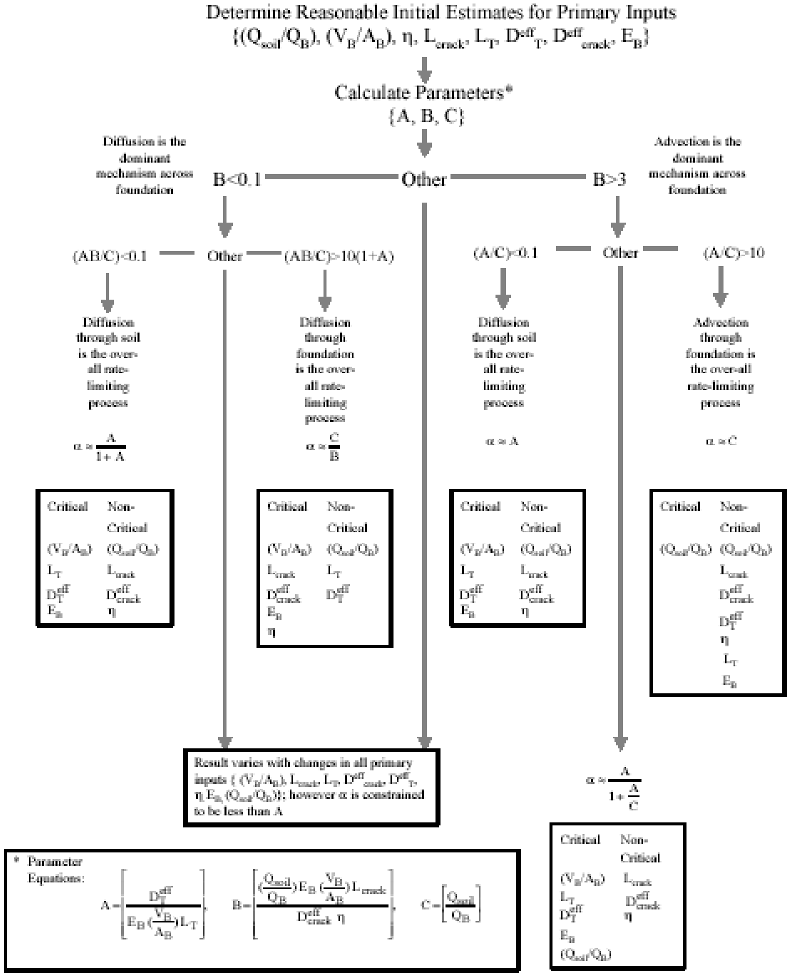
$$A = \left[\frac{D_T^{eff}}{E_B \left(\frac{V_B}{A_B} \right) L_T} \right]$$

$$B = \left[\frac{\left(\frac{Q_{soil}}{Q_B} \right) E_B \left(\frac{V_B}{A_B} \right) L_{crack}}{D_{cracl}^{eff} h} \right]$$

$$C = \left[\frac{Q_{soil}}{Q_B} \right]$$

- D_T^{eff} = effective overall vapor-phase diffusion coefficient in soil between the foundation and a depth L_T
- E_B = enclosed space air exchange rate
- VB = enclosed space volume
- AB = surface area of the enclosed space in contact with the soil
- LT = depth to the vapor source, measured from the foundation
- Qsoil = pressure-driven soil gas flow rate from the subsurface into the enclosed space
- Lcrack = enclosed space foundation thickness
- Dcrack eff = effective overall vapor-phase diffusion coefficient through wall and foundation cracks
- η = crack factor – the fraction of enclosed space surface area open for vapor intrusion

Flowchart for Identifying Critical JEM Parameters (Johnson, 2002)



Conceptual Site Model

- Dissolved phase VOC plume migrating under 200 homes
- Groundwater data (uppermost aquifer) ☞g/l

CAS No		MW-4	MW-3	MW-2	MW-1
75343	1,1-DCA	10 U	48	750	1000
75354	1,1-DCE	10 U	32 J	420	500
79016	TCE	5 J	120	5350	7000
75014	Vinyl Chloride	2 U	10 U	500 U	500 U

MW-2 Adjacent to single-family residence (SFR_1) (slab on grade)

MW-3 105 feet hydraulically downgradient of MW-2 & within 50 feet of SFR_2 with basement

MW-1 Epicenter of release (manufacturing facility), 5 acres, no other known sources

MW-4 200 feet hydraulically downgradient of MW3

Conceptual Site Model

- Depth to uppermost aquifer 400 cm below ground surface
- Soil types:

  MW-3 - Strata A – 383 cm – sandy clay
  Strata B – 17 cm – loamy sand
  Strata C – 0 cm

  MW-2 - Strata A – 200 cm – sandy clay
  Strata B – 17 cm – loam sand
  Strata C – 183 cm - sand
- SFR_1 = 1200 cm x 1200 cm x 244 cm complains about vapors
- SFR_2 = 800 cm x 800 cm x 366 cm

Volatile & Toxic?

- Consult Table 1 – Yes for 1,1-DCA, 1,1-DCE & TCE
  - We don't know about?
    - Vinyl chloride – Is it present?
    - Note elevated detection limit.
- Data Management & Quality Control is very important

- Are Building(s) Present?

  Yes

- Is there evidence of imminent hazard or Risk?

  Maybe/Yes

- Investigate odor complaint?

  When? ***How long?***

  How often? ***How strong?***

  Under what conditions? ***Physiological symptoms?***

  Conduct indoor air sampling?

Vapor Intrusion – Demonstration

- Is indoor air quality data available?

  No

- Is the potential source well known and characterized?

  Maybe do we need more data?

  Housing density and distance between MW-3 and MW-4 implies there may be other potentially affected homes above the plume

- Is SFR, closest to MW-1 the most affected building?

  Maybe, differing soil structure and groundwater concentrations probably should assess both scenarios.

Do groundwater concentrations exceed generic screening levels?

Risk Level	1,1-DCA		1,1-DCE		TCE		Vinyl chloride	
10^{-4}	2.2 E3	No	1.9 E2	Yes	5.3	Yes	2.5	Yes
10^{-5}	2.2 E3	No	1.9 E2	Yes	5*	Yes	2.5	Yes
10^{-6}	2.2 E^3	No	1.9 E2	Yes	5*	Yes	2.0*	Yes

*Defaults to MCL. Is MCL protective for this pathway?

Note vinyl chloride was not detected in any sample.

Note that TCE concentration is more than 50 times the screening levels.

Go directly to site-specific assessment for TCE.

- Any disqualifying conditions?

  None described

  - *But note soil horizons are not heterogeneously distributed across the entire study area*

- Can we identify most likely to be impacted building?

  No

  - *Differential soil types, COPC concentrations, building characteristics require each set of conditions to be evaluated separately*

Run the Model

	Risk Incremental	Hazard Index
SFR_1	?	?
SFR_2	?	?

Target groundwater concentration (μg/l) at 10^{-5} risk & HI = 1

	Area 1($SFR_{1)}$	Area 2 ($SFR_{2)}$
1,1 DCA	?	?
1,1 DCE	?	?
TCE	?	?
Vinyl chloride	?	?

Do model results predict unacceptable level of risks & hazards?

If yes – do sub-slab sampling (seasonality)

If no – pathway is incomplete, analysis is complete, and hazards and risks are acceptable for the time being.

If no – should confirmation sub-slab sampling be completed?

– depends on uncertainty analysis

- Do sub-slab sampling results exceed generic shallow soil gas concentrations for the defined levels of risk and hazards?

- If yes - collect indoor air samples?
  - seasonality
  - don't forget to characterize indoor background sources
- If no - pathway is incomplete, analysis is complete, and risk and hazards are acceptable for the time being.

Lockformer

- 1970 to present (release dates unknown)
- Manufactures and fabricates metal parts
- Hot TCE vapor degreaser (open top and closed system)
- OSHA Standards are complied with on-site soil concentrations – 680 ☞g/ml of soil

Lockformer

- 160 contaminated residential wells
- 16 wells above MCL (highest concentration was 20 ppb)
- Plume is ¼ mile wide x 2 miles long

Lockformer

- Depth to groundwater 1525 cm
- Interceptor sewer trench is preferential pathway for NAPL
- Vapor modeling demonstrated acceptable risks at 1×10^{-6} levels

Lockformer

- Remediation of soil and groundwater are required to meet the Illinois soil and groundwater protection standards

- Ambient, flux chamber, and indoor air monitoring are being done until remediation is complete

Kelly Air Force Base

- Groundwater-based vapor modeling
- Soil-vapor-based modeling 95% MCl used for concentration in modeling analysis
- question where temporal variations adequately addressed when collecting soil vapor samples

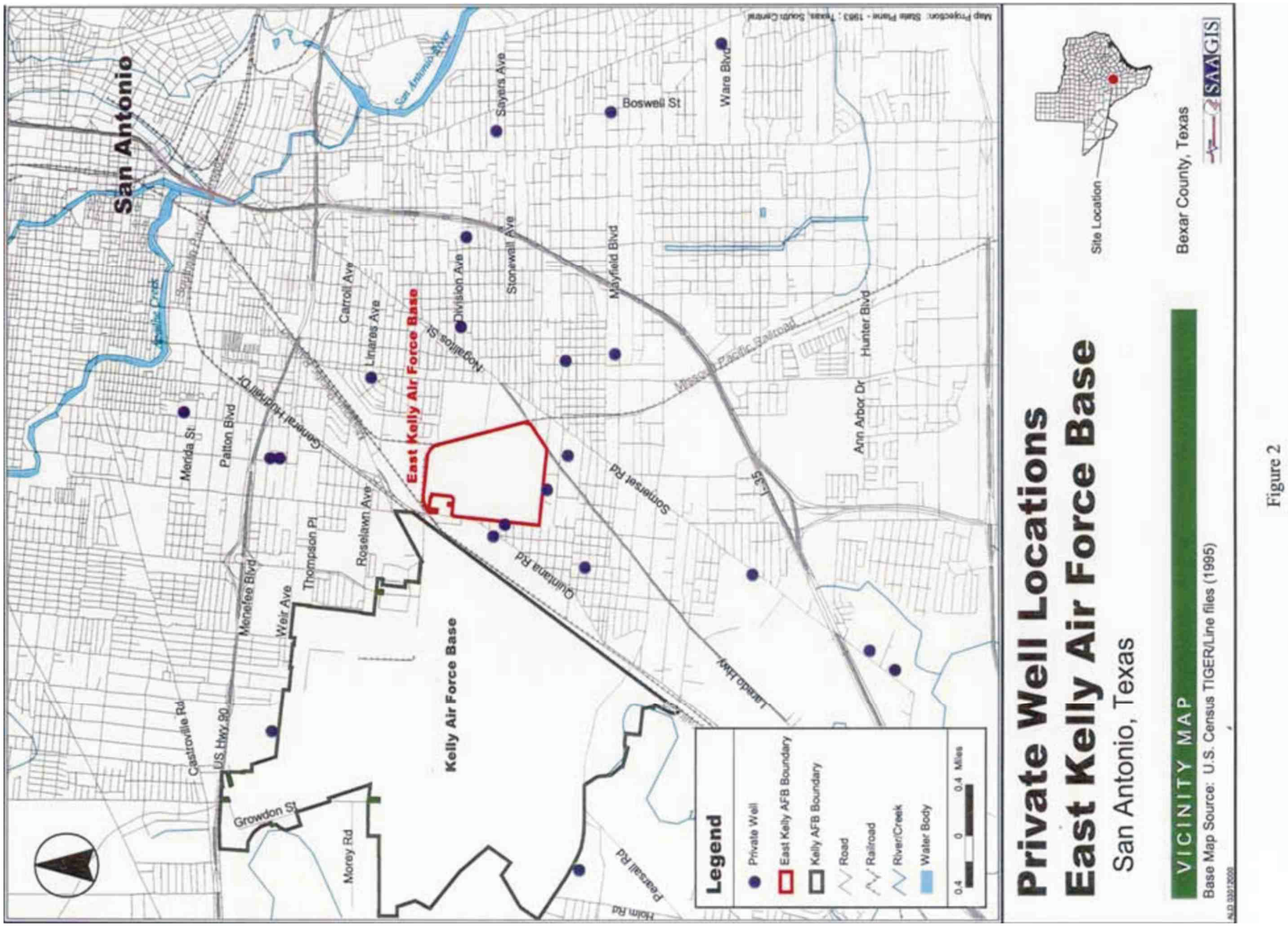
Kelly Air Force Base (cont.)

- Site-specific parameters for
  - home characteristics (size)
  - soil temperatures
  - vadose zone depth
  - soil characteristics

Kelly Air Force Base (cont.)

- Old J&E models – maximum risk 1.34 E-6 for Tetrachloroethylene
- New models - ?
  - Remediation decisions are being driven by groundwater MCL for TCE and PCE

Vapor Intrusion – Case Studies



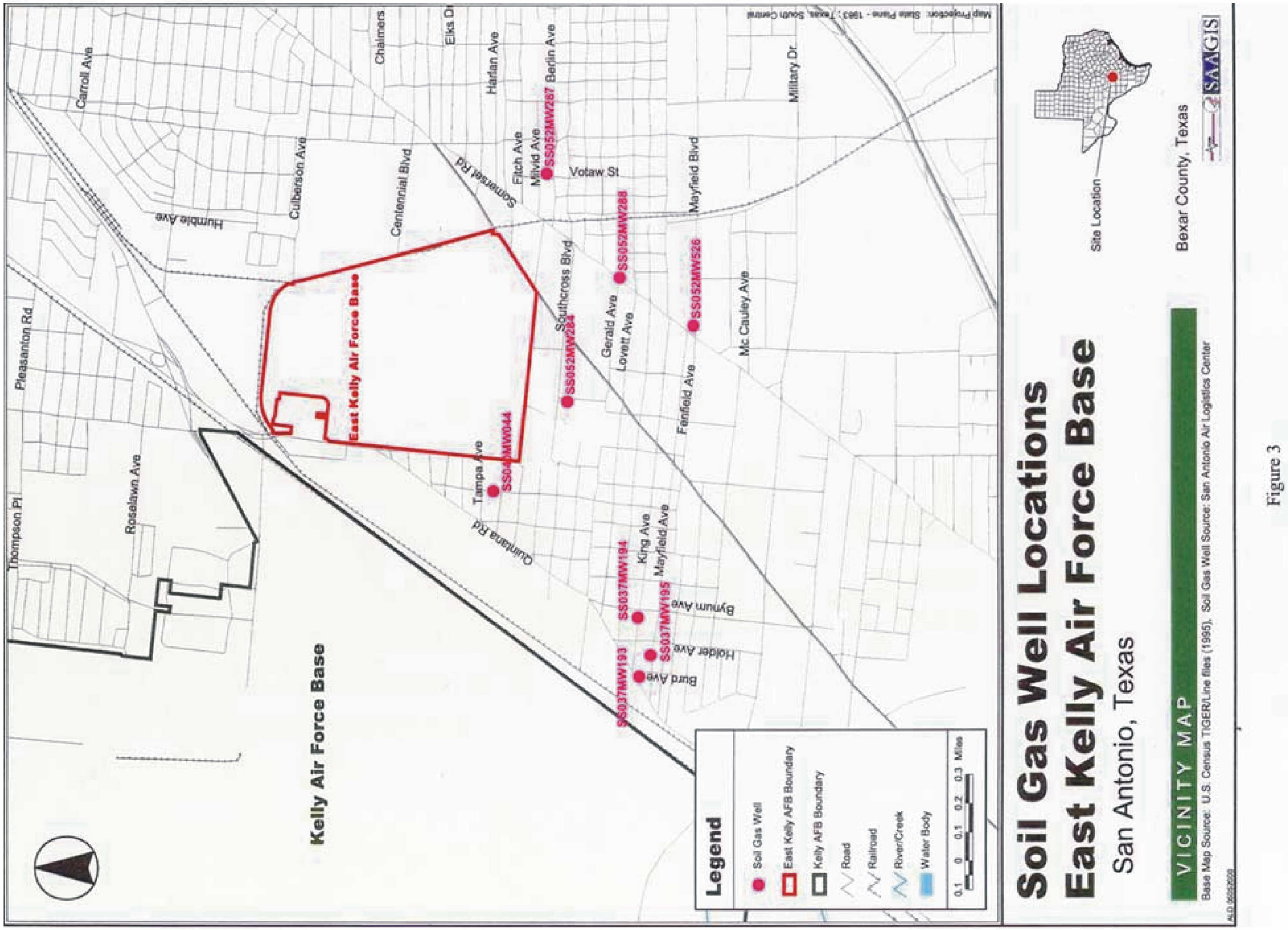
Kelly Air Force Base (cont.)

- Base commissioned in 1916 - today it is part of BRAC Program
- Leaky underground chemical waste collection pipes were major source of contamination
- Oils, solvents, paint products used in aircraft maintenance activities
- Shallow aquifer – 15 to 30 feet BGS

Kelly Air Force Base (cont.)

- 18 groundwater wells – 15 volatile COPC's
- 6-mile-long plume
- ASTDR conducted public health assessment that included vapor considerations

Vapor Intrusion – Demonstration



Atlas Tack Facility

- 1901 to 1985
- 40 chemicals of concern
  - Toluene (226,000 μg/l)
  - Benzene (250 μg/l)
  - PCBs (<50 μg/l)
  - PAHs (5 μg/l)

Atlas Tack Facility

- 7200 affected people
- Depth to groundwater 5 - 7 feet
- Groundwater tidal fluctuations
- Indoor air exchange rate 0.8/hr (ocean breeze)
  - HI = 1 Target groundwater concentration for toluene 146,000 μg/l
  - $13.1 million for remediation (includes vapor extraction, pump & treat)

Ray Mark

- 1919 to 1989 – automotive parts manufacturing
- Groundwater & soil contaminated with organic and inorganic compounds
- Groundwater 3-25 feet below ground surface (15 ft average)
- 225 affected homes
- 50 affected commercial businesses
- 5 volatile organic halides

Ray Mark

- 130 soil gas samples were collected during frozen ground conditions. All within 20 feet of occupied structure
- 8 indoor air samples were concurrently collected from occupied buildings.
- 4 buildings had indoor concentrations that exceed 1 x 10^{-6} risk level.
- 4 indoor mitigation systems were installed as an emergency action

Ray Mark

- J&E predicted attenuation factor that was 100 times higher than value calculated using maximum groundwater concentrations
- T&E predicted attenuation factor that was 7 times lower than value calculated using average groundwater concentrations
- Reported analytical detection limits exceeded the 1 x 10^{-6} risk level for some chemicals

Ray Mark

- Subsequent field studies
  - 60 additional vapor wells installed and monitored quarterly
  - 15 indoor air samples were collected during winter conditions
  - 3 additional homes exhibited unacceptable inhalation risks
  - 4 additional migration systems installed under emergency provisions. (1 quid pro quo)

Conclusions

- High groundwater concentration does not always result in high indoor air concentrations
- High vapor gas concentration does not always result in high indoor air concentrations

Ray Mark

- Remedial actions
- Capped facility and installed vapor extraction system
- 13 individual building mitigation systems were installed (owner maintained)

Ray Mark

- Semi-annual collection of soil gas from 80 vapor monitoring wells
- Remedial Design and feasibility study for groundwater contamination is being conducted


QUESTIONS?

THANKS!