Environmental Issues in Underground Coal Gasification

(with Hoe Creek example)

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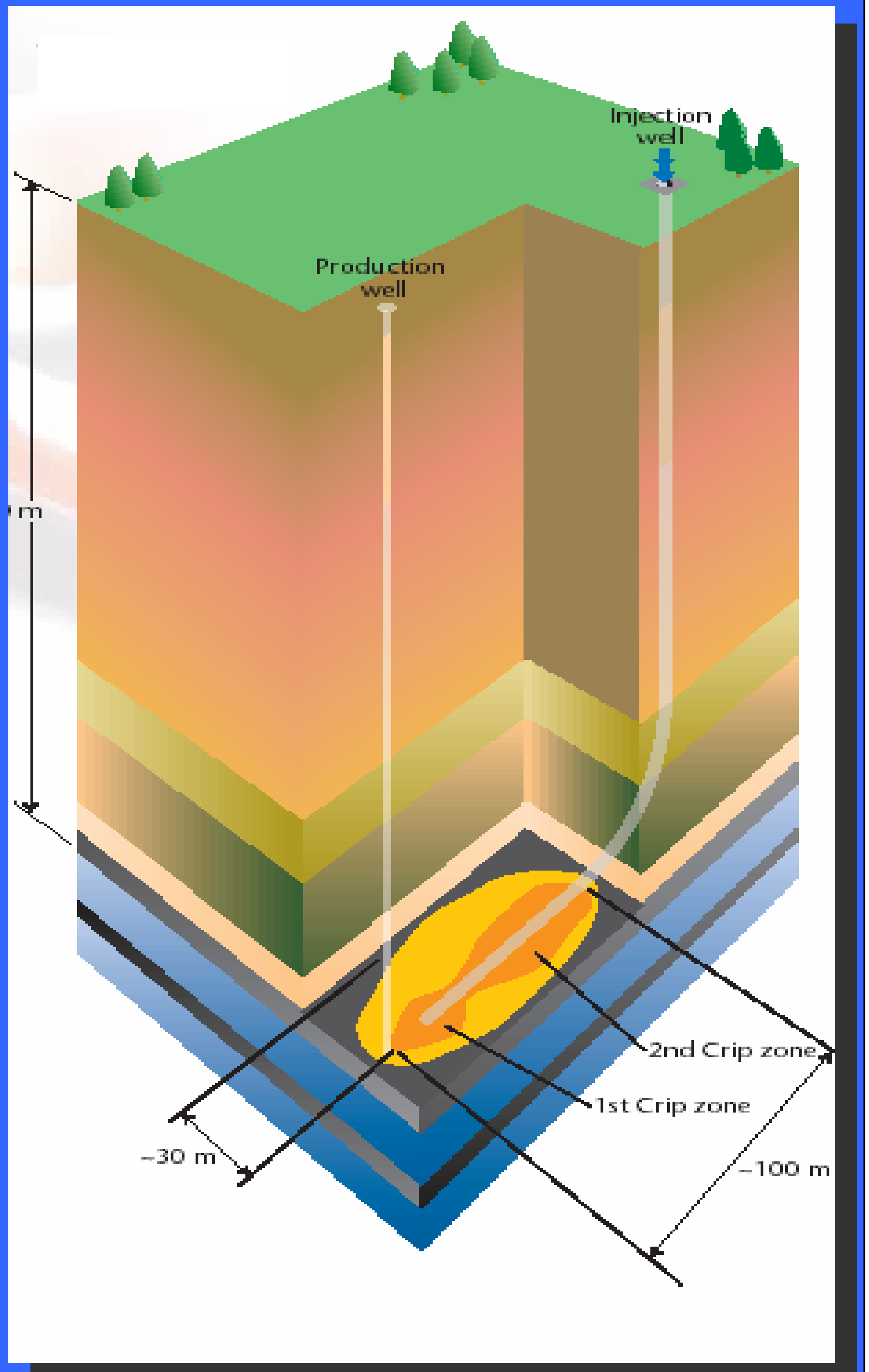
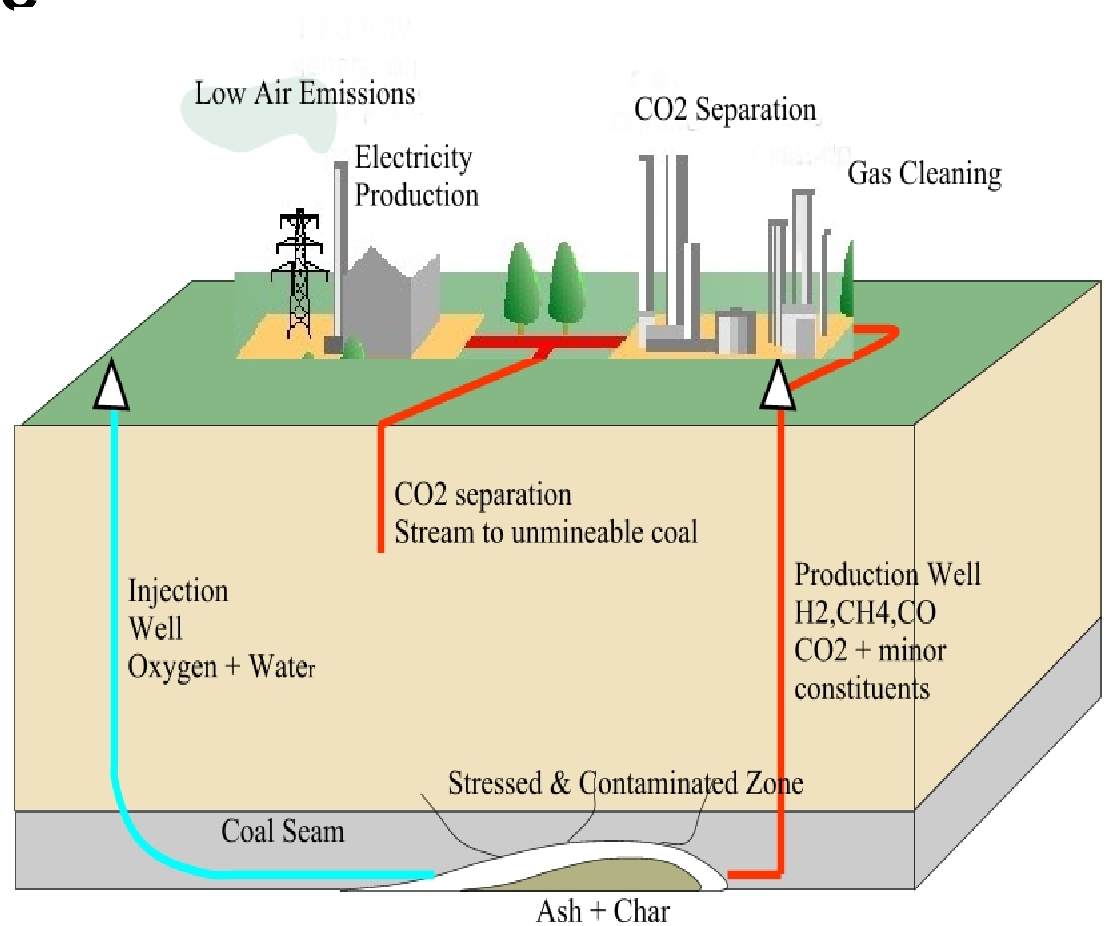


Environmental Advantages of UCG

- No mining; no surface ash management
- Smaller footprint for surface facilities
- Fewer particulates, NOx, SOx
- Good coincidence between sites for carbon storage and UCG



Environmental Issues In UCG

- **Migration of VOCs in vapor phase into potable groundwater**
- **Organic compounds derived from coal and solubilized metals from minerals contaminating coal seam groundwater**
- **Upward migration of contaminated groundwater to potable aquifers due to:**
  - Thermally-driven flow away from burn chamber
  - Buoyancy effects from fluid density gradients resulting from changes in dissolved solids and temperature
  - Changes in permeability of reservoir rock due to UCG.

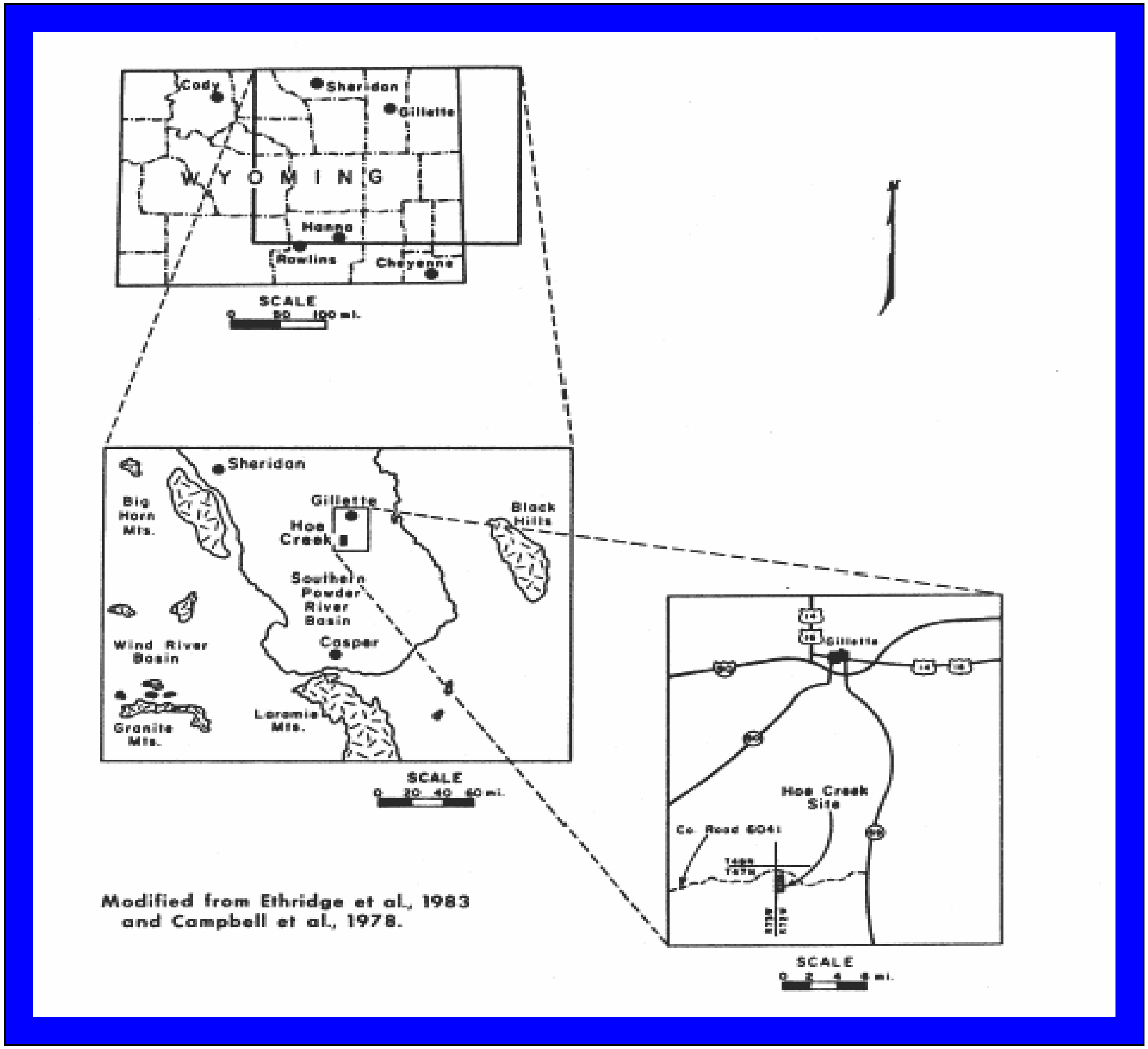
Groundwater Chemistry Before and After Pilot UCG Burn

Chemical constituent	Before burn (mg/l)	After burn (mg/l)
Ca	20	200
Mg	5	15
Na	100	300
HCO_3^-	300	500
SO_4^{2-}	4	1150
H_2S	0.02	0.4
Cl^-	30	40
NH_3	1	100
TDS	350	2300
Phenols	0.1	20
TOC	20	200
CH_4	0.42	0.16

(From Humenick and Mattox, 1978)

Hoe Creek

- **Hoe Creek site: 80 acres (32 hectares)**
- **Powder River Basin, Wyoming, USA**
- **Area also now has active CBM extraction**



Modified from Ethridge et al., 1983 and Campbell et al., 1978.

Case Study: Environmental Consequences of UCG, Hoe Creek

Trials from 1976-1979

- Hoe Creek I: 11 days, 10 m well separation, 123 tons gasified, 207 kPa, air feed gas

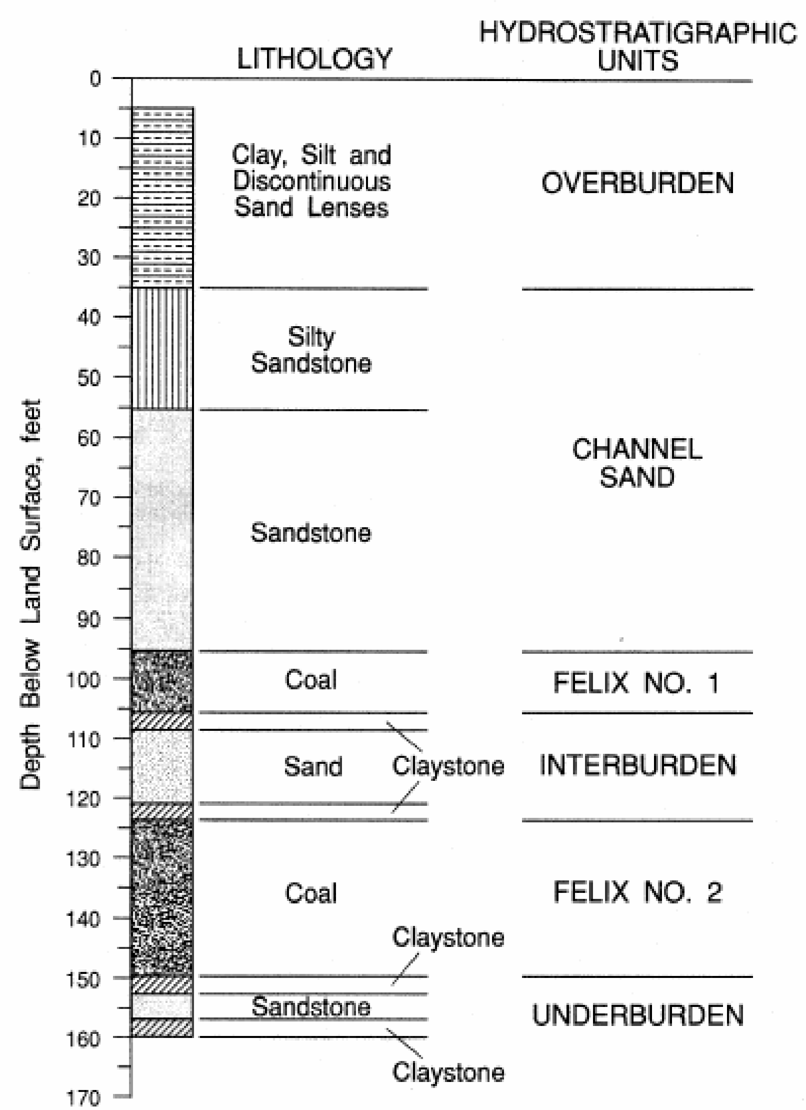
- Hoe Creek II-air: 13 days, 18 m well separation, 286 tons gasified, 324 kPa, air feed gas
- Hoe Creek II-O2: 2 days, 18 m well separation, 47 tons gasified, 324 kPa, oxygen feed gas
- Hoe Creek II-air-2: 43 days, 18 m well separation, 1155 tons gasified, 324 kPa, air feed gas

- Hoe Creek III-air: 7 days, 40 m well separation, 256 tons gasified, 297 kPa, air feed gas
- Hoe Creek III-O2: 47 days, 40 m well separation, 3251 tons gasified, 297 kPa, oxygen, steam

Case Study: Environmental Consequences of UCG, Hoe Creek

- **Fluvial depositional sequence of fine and coarse sands**
- **Coals interbedded with sandstones**
- **Coals are sub-bituminous**
- **Rapid changes in thickness of overlying units— no continuous confining unit above coal seam**
- **Coal seams and channel sand are aquifers**

Tests in Felix No. 2 coal



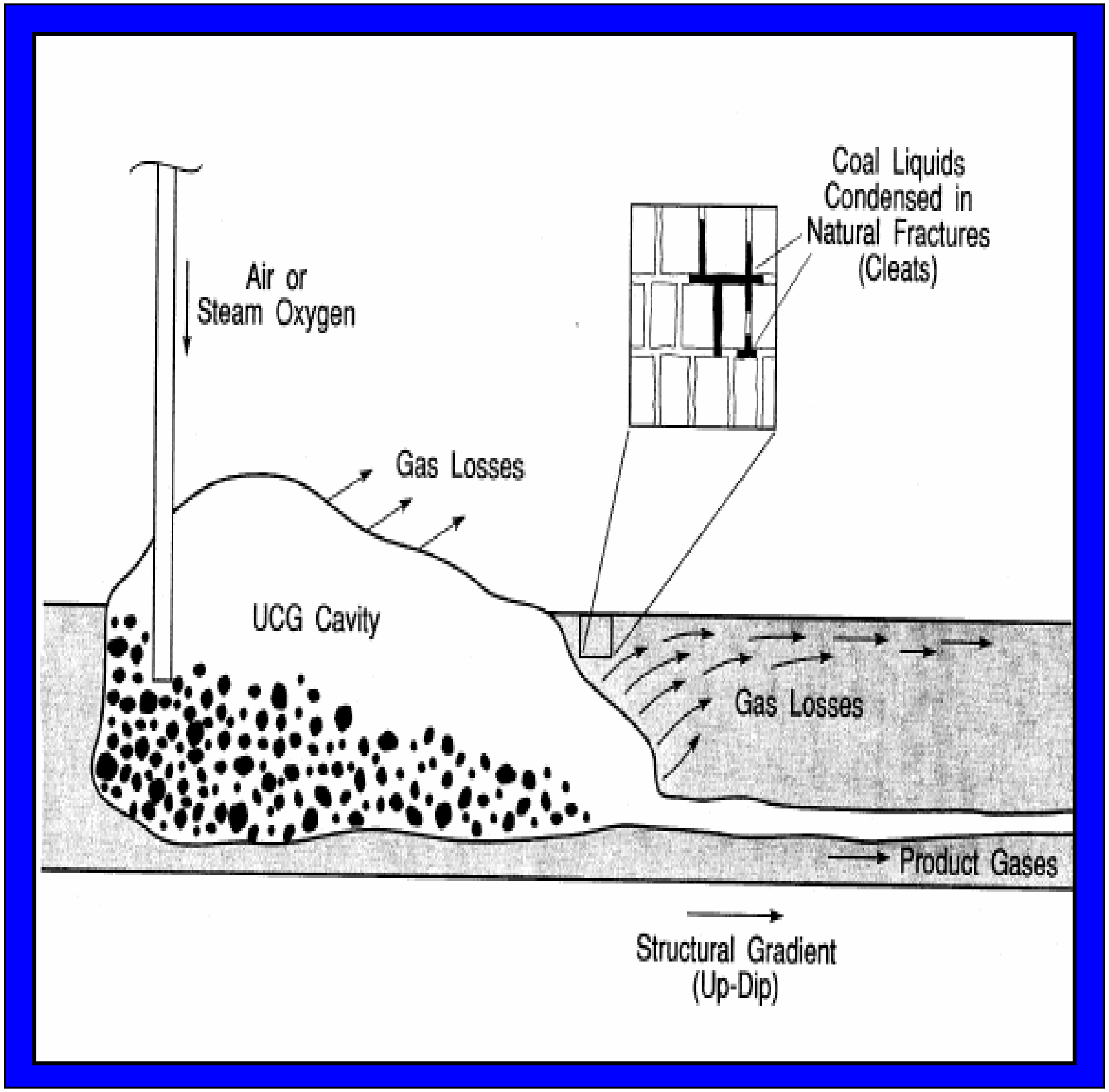
Case Study: Environmental Consequences of UCG, Hoe Creek

Test name	Permeability enhancement technique	Result
Hoe Creek I	Explosive fracturing	7% gas loss
Hoe Creek II	Reverse combustion	To combat water influx that lowered gas quality, increased operating pressure: 20% gas loss burn zone collapse exposes upper coal seam which is at lower hydrostatic pressure subsidence eventually propagated to surface; groundwater contamination
Hoe Creek III	Horizontally drilled linkage with reverse combustion	Burn zone moved into upper coal seam, 17% gas loss subsidence eventually propagated to surface; groundwater contamination

Case Study: Environmental Consequences of UCG, Hoe Creek

Possible mechanisms for aquifer contamination:

- Hot product gases escape during the burn into surrounding strata
- Post-burn, gasification cavity fills with water, leaching out contaminants
- Gasification cavity collapse connects coal to previously unconnected aquifer



Remediation History and Approach: Hoe Creek

- **Contaminant source is coal pyrolysate accumulations condensed out during operations that continue leaching into the groundwater**
  - Elevated levels of coal tars, residual organic carbon, BTEX (benzene, toluene, ethyl benzene, xylene) found in coal seam and overlying aquifers
- **Low-molecular weight compounds with high aqueous solubilities, low sorptive properties are most problematic**
  - Phenols
  - Benzene— carcinogen
- **Benzene migration caused by normal groundwater flow**
  - Benzene contamination confined to areas within 300ft of burn zone
  - Benzene is persistent, concentrations up to 3000 μg/l in Felix I

Remediation History and Approach: Hoe Creek

- 1993 assessment for U.S. DOE concluded that groundwater contamination posed a significant potential risk to humans and livestock that obtained drinking water from nearby wells
- Contaminated groundwater had migrated to private property adjacent to original test sites

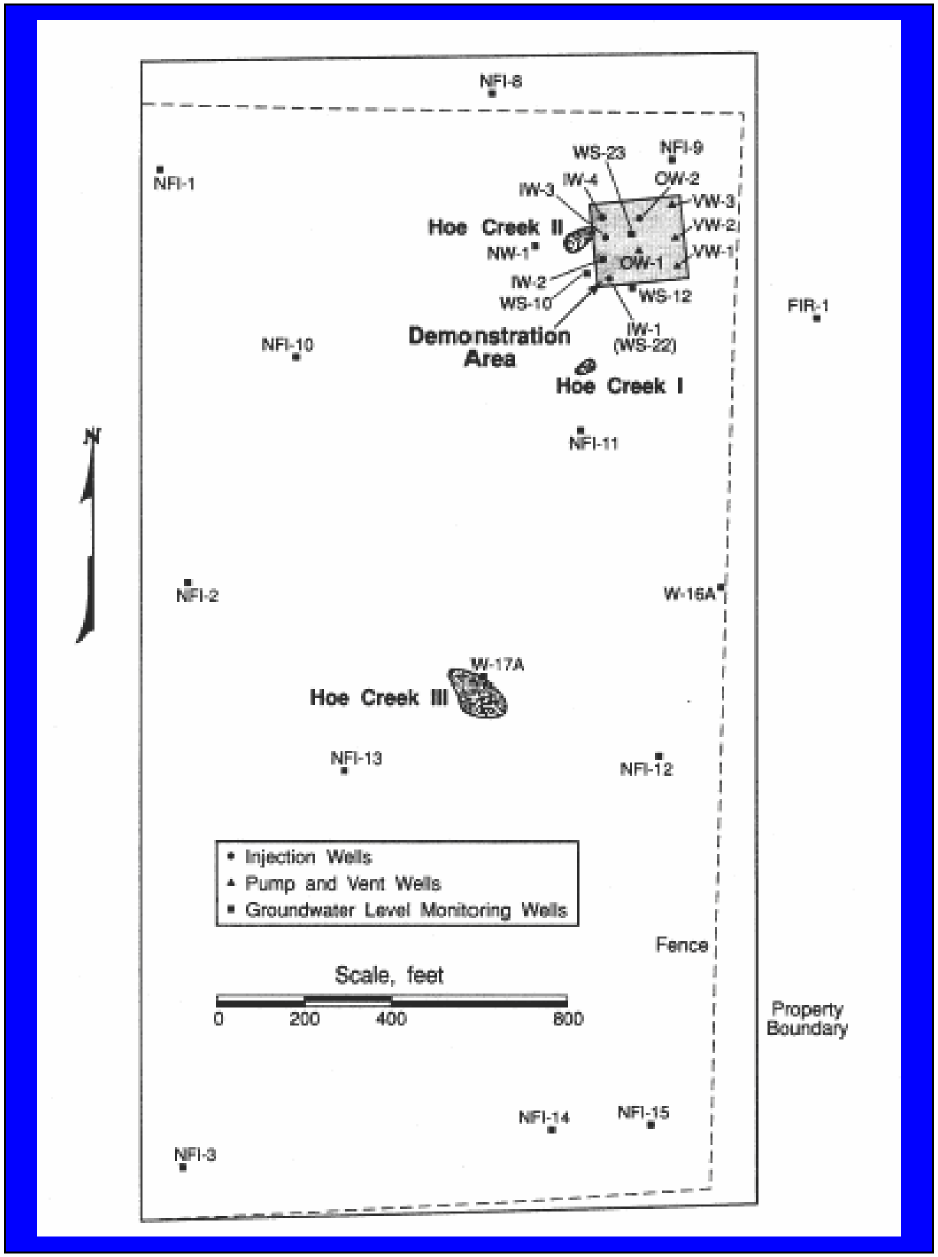
Remediation History and Approach: Hoe Creek

Pump-and-treat initiated 1986

- 20 million gallons groundwater treated with GAC
- Benzene concentrations unaffected by treatment

Air-sparge remediation initiated

- 64 air sparge wells at Hoe Creek II site in 1998
  - 45 in Felix No. 1
  - 19 in Felix No. 2
- 50 air sparge wells at Hoe Creek III site in 1999
  - 42 in Felix No. 1
  - 8 in Felix No. 2



Lessons Learned: Hoe Creek

Factors leading to aquifer contamination:

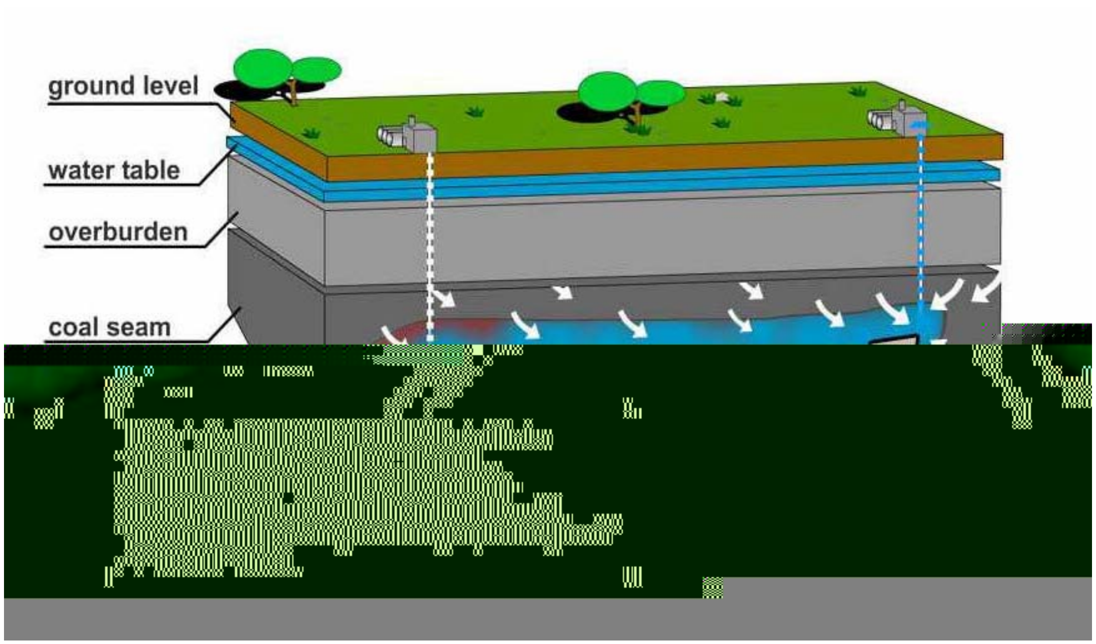
- **Shallow coal strata close to potable aquifers selected for pilot**
- **Burn cavity over-pressured during operation**
- **Organic compounds volatilized and migrated out of the cavity, then condensed as liquid phases outside the burn cavity, providing a persistent source for contamination**
- **Potential environmental consequences/contaminant migration potential poorly understood at the time of the tests.**

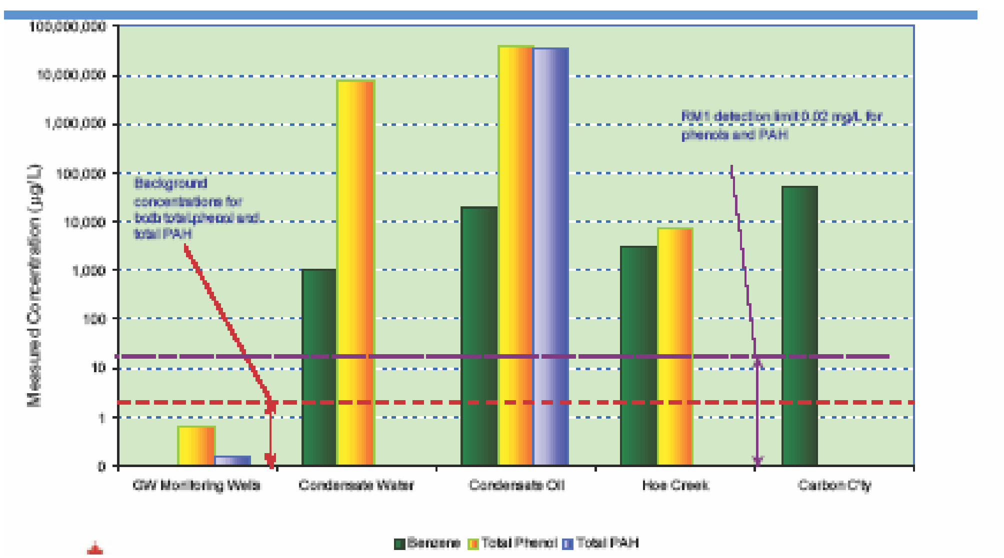
Can Risk to Groundwater Aquifers be Managed?

- **Environmental risk must be factored into operations:**
  - gasifier pressure less than hydrostatic pressure = no flow into surrounding strata
- **Proper geologic and hydrologic characterization must be part of site selection**
- **Integrated simulations are needed for environmental assessment**
- **Careful environmental and operations monitoring must be done during and after gasification**

Only 2 of over 30 UCG U.S. trials resulted in environmental contamination

Case Study: Environmental Consequences of UCG, Chinchilla, Australia





- Operating conditions kept pressure in the gasifier lower than pressure in the coal seam and in the surrounding strata.
- As a result, there is no drive for groundwater flow from the gasifier chamber or loss of product or contaminants into the surroundings
- Site is subject to annual audit, and has been in full compliance with the environmental management plan and applicable environmental agency regulations
- Continuous groundwater monitoring (by 19 monitoring wells) in the vicinity of the project.

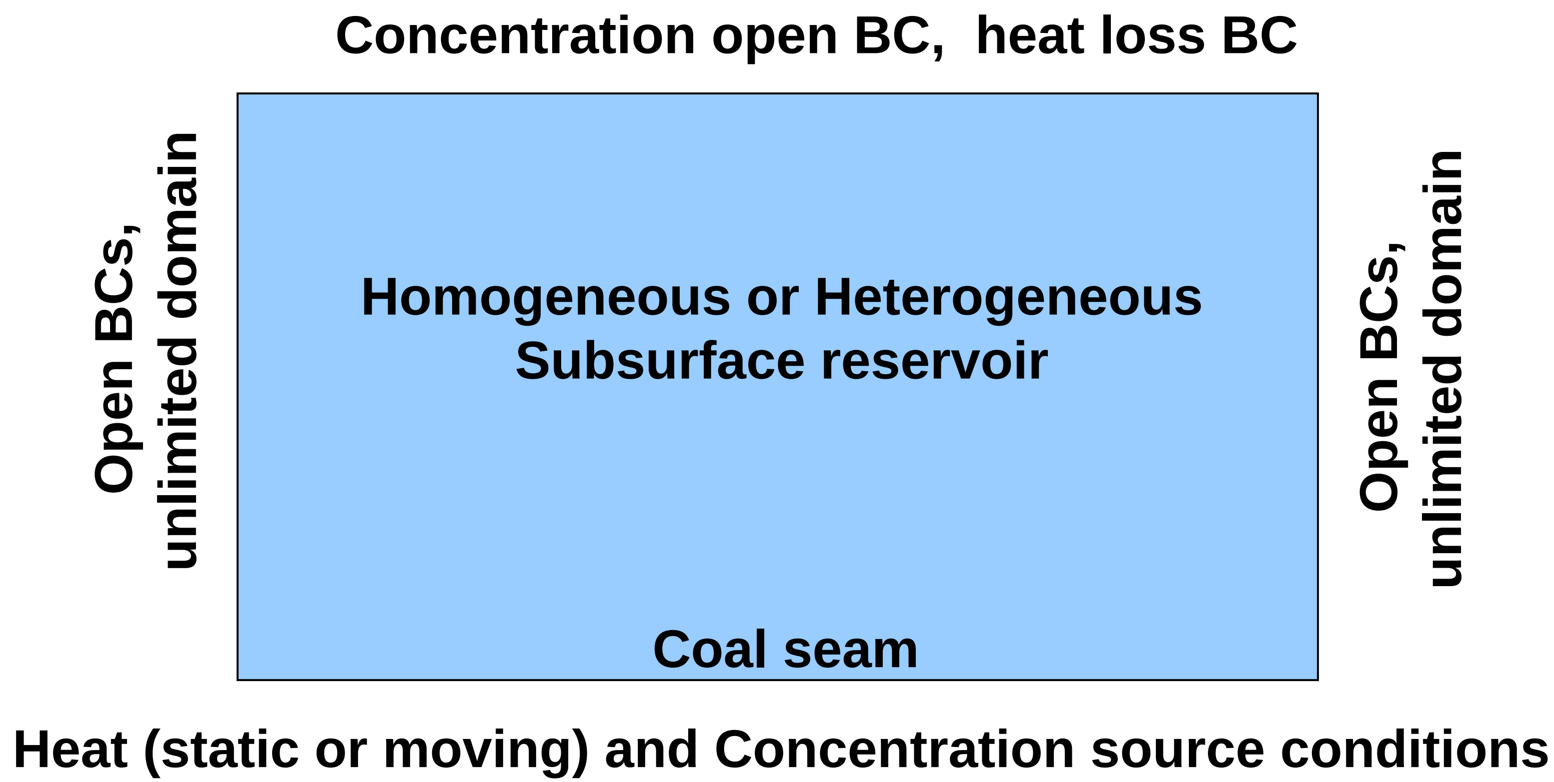
Coupled Modeling of UCG Effects on Contaminant Transport

(courtesy of Walt McNab and Souheil Ezzedine)

- **Coupling (modifed version of Flex)**
  - Flow equation (reformulated into streamlines)
  - Mass transport equation (single, could be multi components)
  - Heat transfer equation
  - EOS: density function of temperature and dissolved concentrations
- **Numerics**
  - Finite Elements Method formulation
  - Adaptive Mesh Refinement to resolve details and fronts
  - Streamlines formulation to highlight circulation cells
  - Recycling boundary conditions (coupling terms, penalty terms)
  - Parallel code (single & multi-threads)
  - Newton scheme, Conjugate Gradient solvers
- **Hardware**
  - Runs conducted on a Linux box w/ 2 threads
  - CPU 3GH, MEM 4 GB
  - Visualization VTK Plateforms (VisIt)

Boundary and Initial Conditions for UCG Contaminant Plume Model

Boundary conditions



Initial conditions

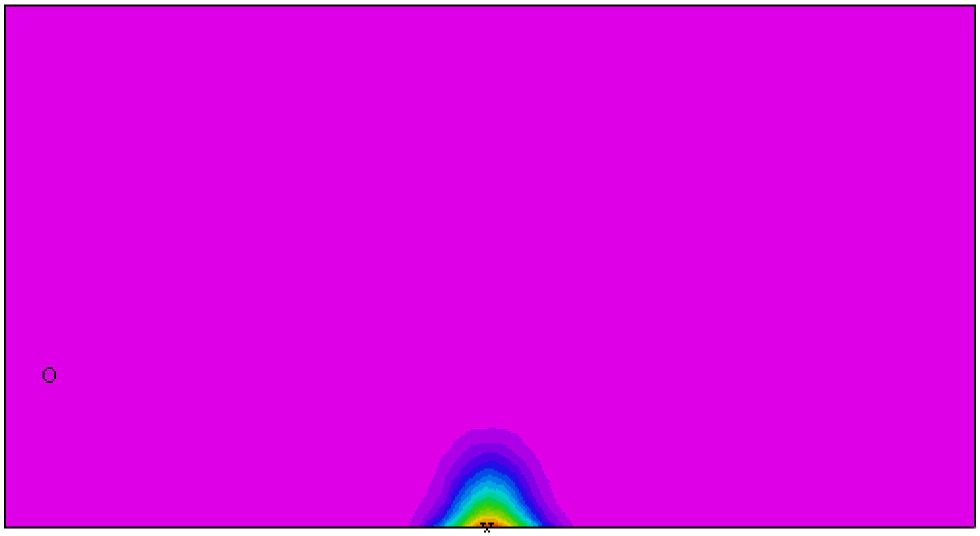
Constant ambient heat distribution, clean subsurface reservoir

Four Cases Modeled to Study Thermal Effects

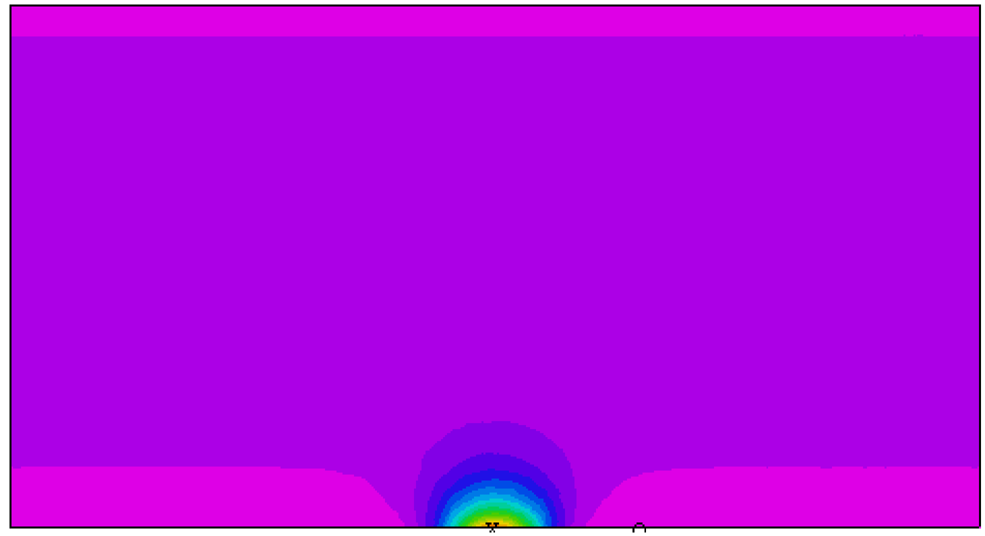
- **Case 1**
  - Continuous heat and contaminant sources
  - Homogeneous reservoir
- **Case 2**
  - Non continuous heat and contaminant sources
  - Heat source life is shorter than contaminant life source
  - Homogeneous reservoir
- **Case 3**
  - Continuous moving heat source (moving burning chamber)
  - Continuous contaminant source
  - Homogeneous reservoir
- **Case 4**
  - Same as Case 2
  - Permeability contrasts added to homogeneous reservoir

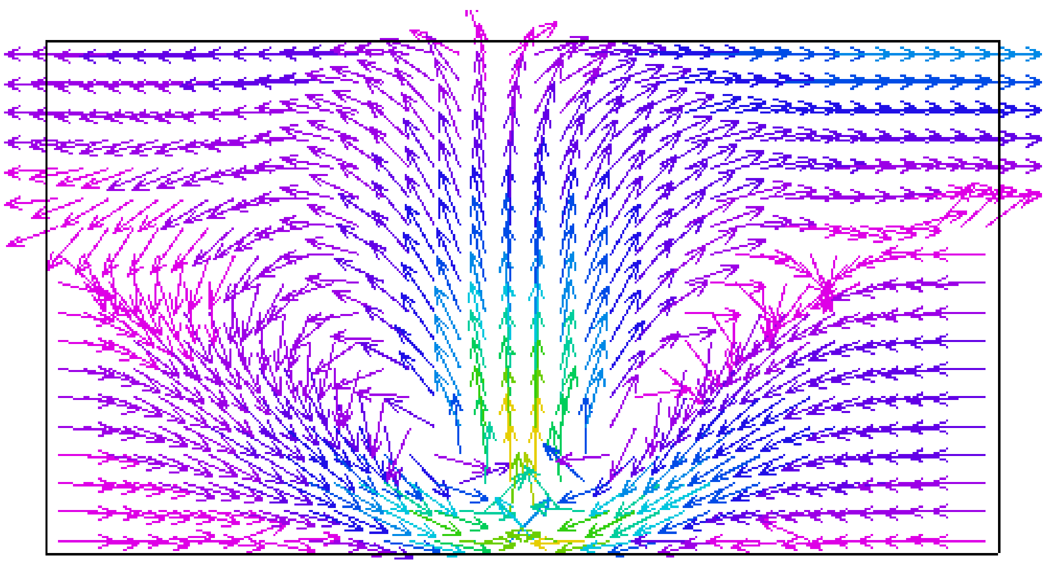
Case 1: Continuous sources for heat and contaminant, homogeneous reservoir

Contaminant

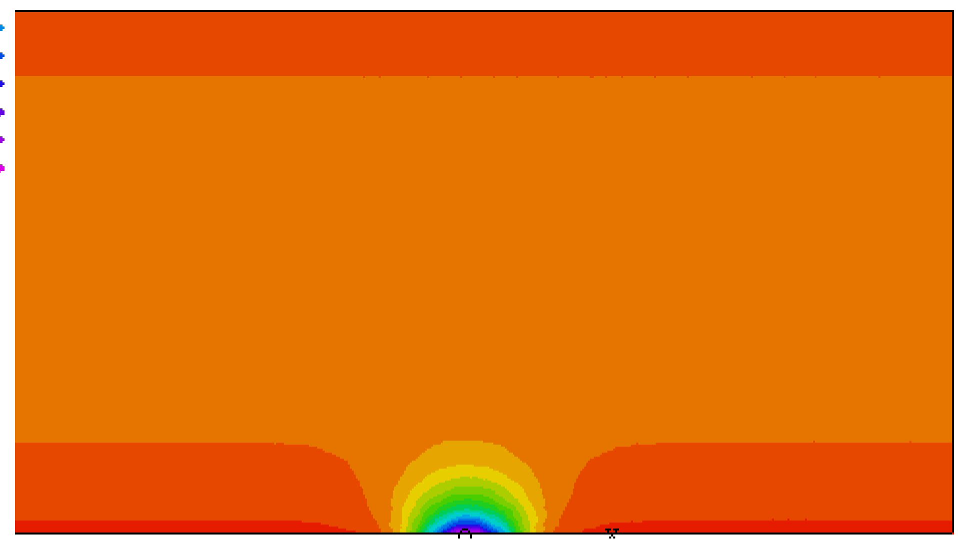


Heat





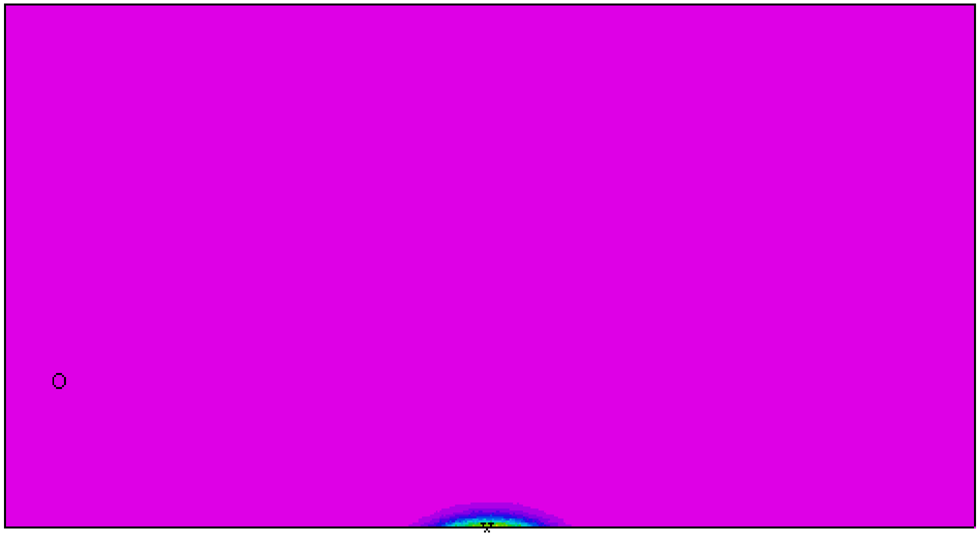
Velocity field



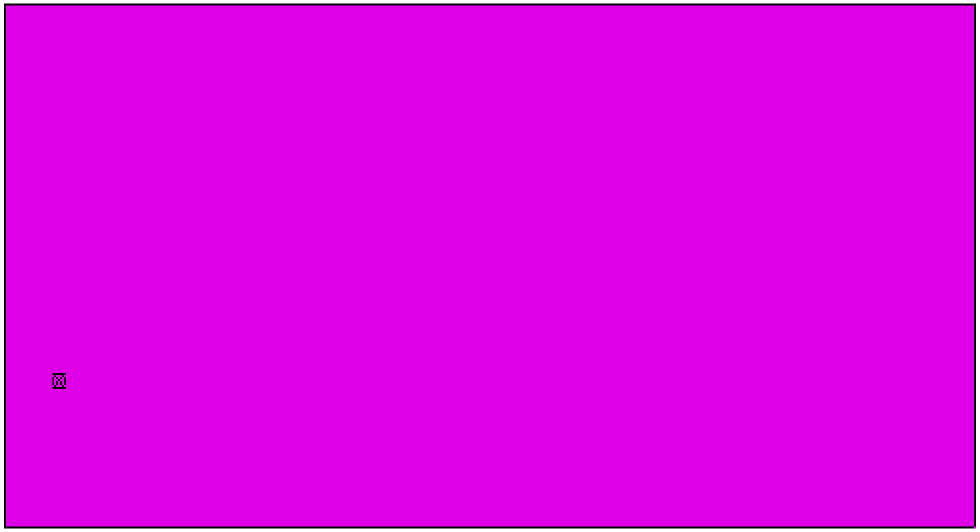
Density

Case 2: Noncontinuous sources, heat stops first, homogeneous reservoir

Contaminant



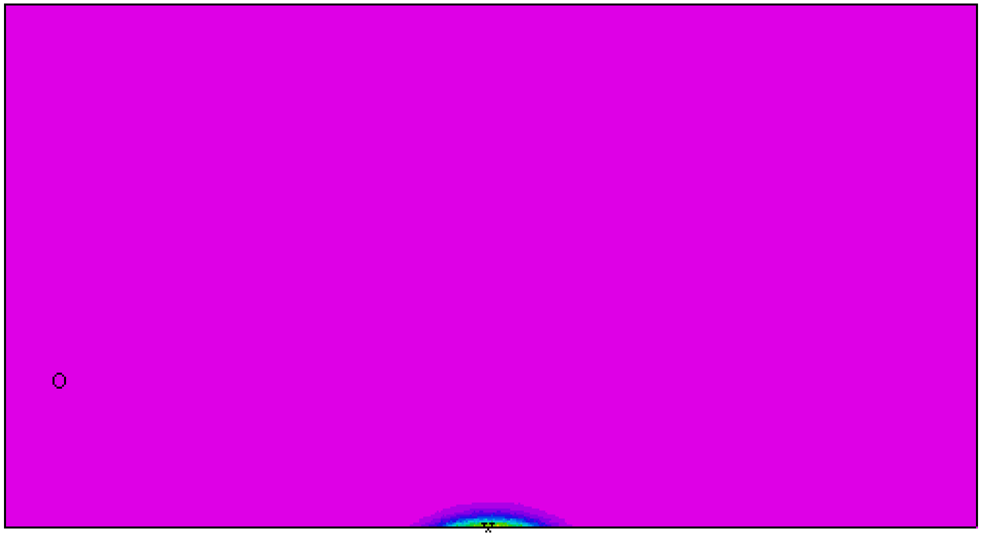
Heat



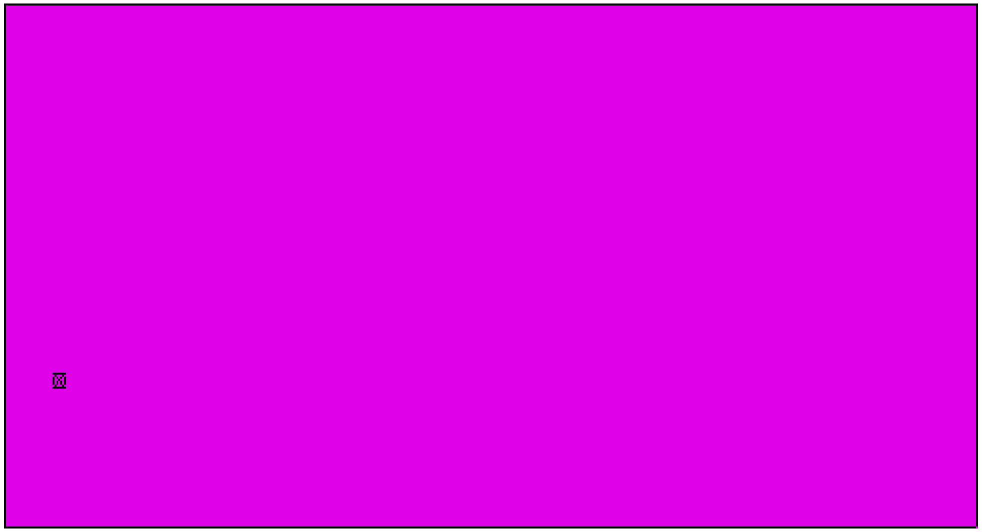
Velocity field

Case 3: Continuous moving heat source, continuous contaminant, homogenous reservoir

Contaminant



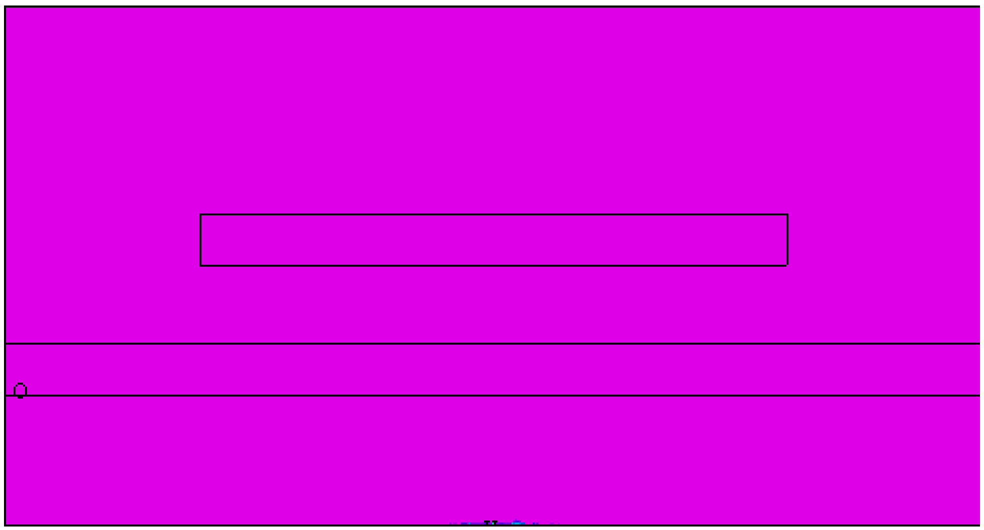
Heat

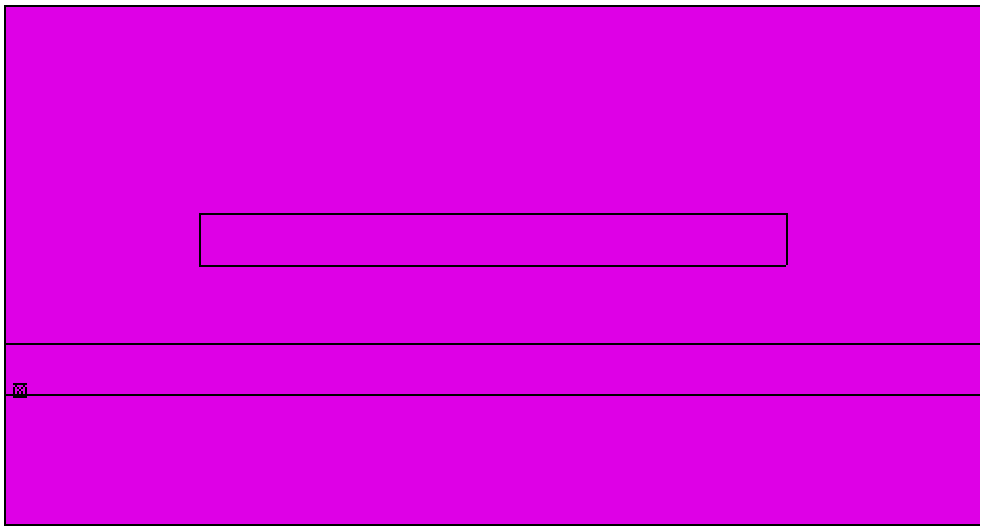


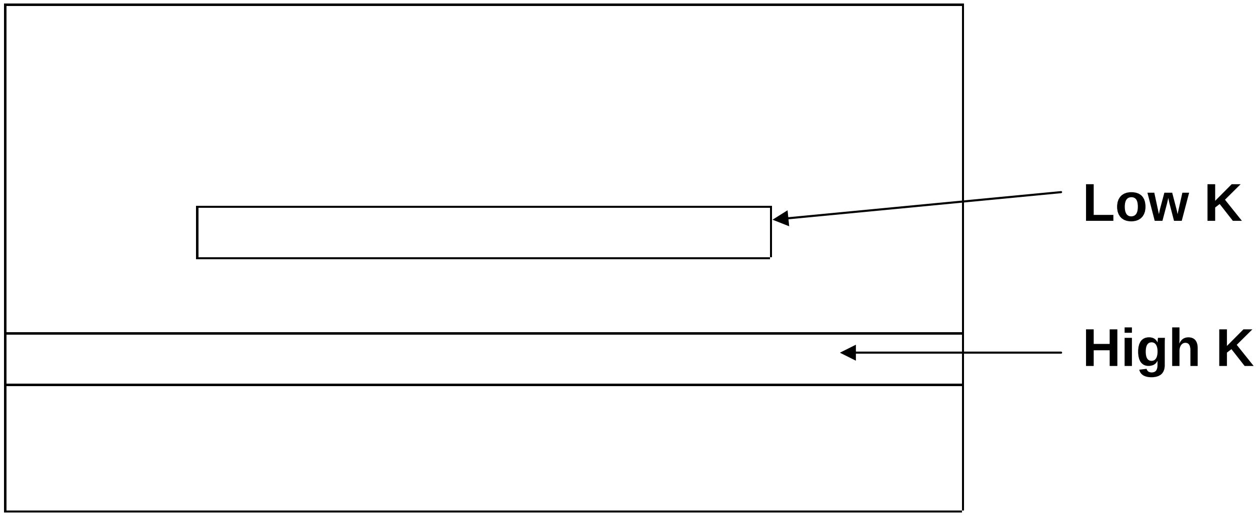
Velocity field

Density

Case 4: Case 2 with Permeability Contrasts







Velocity field

Disclaimer and Auspices Statements

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