**PEGN 624A: Compositional Modeling – Application to Enhanced Oil Recovery**

**Instructor: Prof. Dr.** Hossein Kazemi

**Spring 2009**

**Course Outline**

1. Hydrocarbon reserves and energy issues
2. Poroselasticity & thermoelasticity and their effects on reservoir performance
3. Streamflooding and heat conduction as related to cracking of heavy molecules for in-situ upgrading of crude
4. CO2 WAG and modeling
5. Compositional modeling
6. Rich condensate reservoir enhanced oil recovery

**Reading Material**

* Applied Enhanced Oil Recovery by Aurel Carcoana, Prentice Hall, 1992
* Improved Oil Recovery by Interstate Oil Compact Commission (IOCC)
* Thermal Recovery by Michael Prats, SPE Monograph, Volume 7
* “Nuclear Heat Advances Oil Shale Refining in-situ” by Judy R. Clark, Oil&Gas Journal, Aug 11, 2008, Page 22-24.

**Session 2: Jan 15, 2009**

**Oil shale**

2,000 ft thick

2.5 x 106 STB/acre

30-35 gallon/ton of oil from oil shal

60 x 103 MW/d for 5 x 106 STB/d

**Unit conversion**

1 kW-hr = 3,414 BTU

1 MSCF of gas = 1,000,000 BTU

1 STB of oil = 6,000,000 BTU

1 Therm = 100,000 BTU

1 lbm of coal = 7,000-10,000 BTU

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**HW#1**

**Oil content of reservoir rock**

1. Calculate the potentially recoverable oil content of 1 acre-ft of high quality oil shale in Green River Basin
2. Calculate the oil in place for 1 acre-ft of a carbonate reservoir
3. Calculate the recoverable reserves for Part (b)
4. Calculate the BOE of coal per acre-ft

**Given Data:**

 Oil shale:

g/cc

Assay gallons/ton

Carbonate reservoir:

 



 RF=50%

Coal:

g/cc

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**HW#2**

How many tons of coal will be used to generate electricity to keep a 100-W light bulb for one year?

**Given Data:**

* 1 kW= 3,414 
* Coal provides energy of 7,000 
* Conversion efficiency of coal power plant to electricity to transmission, etc. = 35%

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**HW#3**

Calculate how many pounds of CO2 and other by-products are generated when one burns 1 lbm of

1. Coal (Carbon)
2. CH4
3. C6H14

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Note:

 - 1 lbm of coal at 30% power plant efficiency produces 10 lbm of CO2

- A mid-size 500 MW power plant produces 3.5 x 106 ton of CO2 per year

- A typical oil field steam generator is 15 MW of electricity or 50 x 106 BTU/hr

**Diffusion in 1-D (Cartesian)**



**Heat Conduction in 1-D (Cartesian)**



**Diffusion in 1-D (Radial)**

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Where:

 for 

**Heat Conduction in 1-D (Radial)**













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**Note:** Pressure solution in field unit

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Where:

, 

, , , , , , 

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**HW#4**

**Heat conduction in a reservoir rock**

Using the following data, calculate and make a log-log plot of the temperature and the radial distance from the wellbore (r: 0.5 ft to 100 ft) at 1, 10, 100 and 1,000 days.

**Given data:**











 ft

MegaBtu/hr

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**Session 3: Jan 22, 2009**

**Reading Material**

* Thermal Recovery by Chieh Chu

**Mohr’s circle**

Failure envelope







Where = Horizontal stress (psi)

 = Biot constant

  = Pressure (psi)

= Linear coefficient of thermal expansion (1/o F or 1/ o R)

= Bulk modulus (psi); 

= Temperature (o F or o R)

= Reservoir temperature (o F or o R)

 = Young’s modulus

 = Poisson’s ratio

 

 

 

**Example:**

**Given:**

= 10-5 (1/o F)

 = 100 o F

 

 

  psi



**Calculation**

 psi

  psi 🡪 Mohr’s circle shifts towards left 🡪 Rock breaks easier.

 

  psi

**Combined Flow and Earth Stress Equilibrium (Poroelasticity & Thermoelasticity)**

Single-phase Fluid and Heat Flow

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Where:

= Heat capacity (Btu/(lbm. o F))

 = Displacement vector; 

 = Depth from datum level

 = Shear modulus; 

= Enthalpy (Btu/lbm)

 = Thermal conductivity (Btu/(o F.day.ft))

 = Bulk modulus; 



  = Reference temperature (absolute), F

  = Velocity vector 



 = Thermal expansion coefficient of fluid

= gravity vector, only has a component,  in  and  direction.

 = Bulk strain

= Volumetric strain

 = Lame’s first parameter : 

Subscript

 = Fluid

 = Solid

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**HW#5**

a) Expand the following equations in three dimensions (x-, y- and z-directions)

** **

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b) Expand equations obtained from Part a) in z-direction only.

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**HW#6**

Please review the following articles on packing of uniform-sized spheres.

[Weisstein, Eric W.](http://mathworld.wolfram.com/about/author.html) "Sphere Packing." From [*MathWorld*](http://mathworld.wolfram.com/)--A Wolfram Web Resource. <http://mathworld.wolfram.com/SpherePacking.html>

[Weisstein, Eric W.](http://mathworld.wolfram.com/about/author.html) "Hexagonal Close Packing." From [*MathWorld*](http://mathworld.wolfram.com/)--A Wolfram Web Resource. <http://mathworld.wolfram.com/HexagonalClosePacking.html>

[Weisstein, Eric W.](http://mathworld.wolfram.com/about/author.html) "Cubic Close Packing." From [*MathWorld*](http://mathworld.wolfram.com/)--A Wolfram Web Resource. <http://mathworld.wolfram.com/CubicClosePacking.html>

Based on the equations presented in these articles, use the values provided in class as needed. Assume a sphere radius of 10 micrometers. In the following, include the changes to the porosity, the changes to the rock matrix, and the changes to the fluid.

1. Discuss the effects of increasing the pore pressure by 1,000 psi
2. Discuss the effects of decreasing the pore pressure by 1,000 psi
3. Discuss the effects of increasing the temperature of the whole system by 100 oF
4. Discuss the effects of decreasing the temperature of the whole system by 100 oF
5. Discuss the effects of increasing the pore pressure by 1,000 psi and increasing the temperature of the whole system by 100 oF
6. Discuss the effects of decreasing the pore pressure by 1,000 psi and decreasing the temperature of the whole system by 100 oF

---------------------------------------------------------------------------------------------------------------------------**Hook’s Law**

 

Note: 

 

 

 

 

 

 

 

 

 

 

 

  

**Compact Form**

 

 

**Session 4: Jan 29, 2009**

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**HW#7**

Derive the following effective horizontal stress equation

 

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**Tensile failure**

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x x

x x

**Shear failure**

**Brittle + Ductile**



Effective stress:

  ; used with Mohr’s circle to determine the type of failure

Real rock stress:



**Example:** Depleted reservoir

psi,  psi,🡪 psi

psi,  psi,🡪 psi

 Rock breaks easily for depleted reservoir (low pore pressure)

**Fault/Fracture System**











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**HW#8**

1. Calculate the SOR (Steam Oil Ratio) for the following given data set:

 ft  (dip angle) md 

  ft cp 

1. Change the height to ft
2. Change the height to ft

Please refer to Thermal Recovery by Chieh Chu page 46-15 posted on blackboard for the regression equations for estimating SOR (Steam Oil Ratio).

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**Steam Injection**

***Steam Oil Ratio***

 Steam Oil Ratio (SOR) is volume of steam in bbl used to produce 1 bbl of oil.

In California: SOR ~ 4.85-5 bbl. Thus, is the breaking point used to determine whether the steam injection method is economic (based on energy balance.)

  🡪 Economic

 🡪 Uneconomic

***Quality of Steam***

Typically, 80-85% quality steam (mixture of 80-85% steam and 15-20 %water) is used for injection.

***Steam Energy***

 of water = 350 

  of steam = 

Thus, 80% quality steam provides 

 of oil yields  (< due to solid and other impurities)

In general, the ratio of energy provided (per barrel) by oil and steam is about 10: 1.

***Energy Gain (Power Gain)***

References:

1. Roberto C. Callarotti (Venezuelan Institue of Scientific Research), “Electromagnetic Heating of Oil,”
2. Petroleum Engineering Handbook Vol.VI, SPE (2007), Sec. 12.3.8., p. VI-588.
3. SPE 115723 “Production Improvement of Heavy Oil Recovery by using Electromagnetic Heating,” M.A. Carrizales, Larry W. Lake, R. T. Johns.

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Where: = Incremental oil rate (bbl/d)

 = Energy used (kW)

 = Efficiency of power generation; 

Derivation of the constant of 68.4 in EG equation

 1 kW = 3.414 kBtu/hr = 81.9 kBtu/d

 1 bbl/d of oil (BO) = Btu

 

Derivation of EG equation

 

**Example:** Instantaneous heating

**Given:** = 46 bbl/d, = 60 kW, 

 🡪 Too optimistic

To be realistic, energy gain should be calculated from:

 

Where:  and 

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**HW#9**

Calculate the energy gain for producing oil at stabilized rate of 76 B/D (incremental bbl) for the following source of electric power, when the applied electrical power source is 150kw.

1. Thermal (Steam) Efficiency of power generation 
2. Hydroelectric Efficiency of power generation 
3. Microwave Efficiency of power generation 

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**Threee-Phase, Two components, Steam Flood Simulator – A Teaching Tool & Model**

Phase: water, oil and gas (water vapor or steam)

Component: water and oil (water = 1, oil =2)

***Component Mass Balance***

**Water:**



**Oil:**

***Energy Balance***

 ****



 

***Note:***

 ******

Where = internal energy and = specific volume

**Session 5: Feb 5, 2009**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  |  |  |  |  |
| W |  |  |  |  |
| O |  |  |  |  |
| E |  |  |  |  |
| G |  |  |  |  |

If then 

 

 

 

 

If 

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  |  |  |  |  |
| W |  |  |  |  |
| O |  |  |  |  |
| E |  |  |  |  |
| G |  |  |  |  |

 

 

 

 

**Algorithm**

**If , then  , then**

 *Water component:*

 

 *Oil component:*

 

 *Energy:*

 

 *Thermal constraints:*

 

 where,

  in °R

  in psi

**If , then , then**

 *Water component:*

 

 *Oil component:*

 

 *Energy:*

 

 *Thermal constraints:*

 , 

**Note:**

 

**Term project**

|  |  |  |
| --- | --- | --- |
|  |   |   |

Phase 1: 

Phase 2: 

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  |   |   |   |  |
|   |   |   |   |   |
|   |   |   |   |   |
|   |   |   |   |   |
|  |   |   |   |   |

Phase 3: 

**Component Mass Balance**

**Water:**





 

Transmissivity coefficient (mD.ft/cP)

 

Mobility ratio

 

Harmonic-averaged permeability

  ; for uniform grid

Upstream weighting

 



 

**HW#10**

**Session 6: Feb 12, 2009**

***Important issues:***

* Temperature of steam affects the stress field
* If only water vapor exists,
* If hydrocarbon gas also exists,

**Thermodynamics constraints:**

 ; for

 ; for

*Newton-Raphson technique:*

For this particular case,

**Enthalpy and Internal Energy**

, can be derived in the same way.

;

Where

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**HW#11**

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**HW#12**

Please answer all parts of question #1 and #2 from exam #1.

**#1:**

1. Define: *Primary production, typical IOR methods* and *typical EOR methods*.
2. Which publication is a good source of data for worldwide EOR?
3. What is the *current daily oil production* in the world?
4. What is the *current daily oil production* in the U.S.A.?
5. How much of the daily oil production in the U.S.A. is by *water flood*?
6. What is a good estimate of the *daily EOR oil production* in the U.S.A.? Please give a breakdown of how oil is produced from *each* *major EOR method.*
7. What is an estimate of the current *EOR oil production in the world*?
8. Based on the above information, will EOR oil production from the remaining oil make a major impact on our future energy needs?

**#2:**

1. What is a good estimate of the number of *producing oil wells* in the U.S.A.?
2. What is the *current daily oil consumption* in the U.S.A.?
3. What is the *current oil production recovery efficiency* in the U.S.A.? That is, what percentage of original oil in place is produced and how much is left behind?
4. What is the current *oil production recovery efficiency in the North Sea*? If different than in the U.S. and the rest of the world, what do you think is the reason?
5. What is a *stripper oil well* and what is an *stripper gas well* (based on daily production rate) in the U.S.?

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**Session 7: Feb 19, 2009**

**Water :**

***Where:***

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***Note: Fully implicit:***

= Harmonic-averaged permeability value to take into account the discontinuity in pressure derivative

, , = Single point upstream weighted values depending on the flow direction

LHSW:

RHSW:

* Diagonal-dominated pressure and temperature matrices

**Example:**

Energy used to create 100% quality steam = 250,000

Energy created from crude oil = 20,000

 (100% efficiency)

**Enthalpy**

Tc

T2

c

T1

P (psia)

Latent heat

 Hw (Btu/lbm)

Water:

 ;

 ;

Gas (Steam):

 ;

Oil:

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**HW#13:**

1. Left-hand-side expansion

a) Water equation

b) Oil equation

1. Energy equation expansion
2. Left-hand-side for
3. Left-hand-side for
4. Right-hand-side for
5. Right-hand-side for

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**HW#14:**

Please answer all parts of question #3, #4, and #5 from exam #1.

**#3:**

1. What is the *annual gas production (consumption) in the U.S.A*.; thus, what is the daily gas production?
2. Please convert the daily gas production (consumption) in the U.S.A. to BOE/D and compare it with the daily U.S. oil production rate.
3. What is the daily coal consumption (mostly for electricity generation) in the U.S. in BOE/D?
4. On the average, what is the daily level of gas consumption (on the BOE basis) as compared to oil consumption?

**#4**:

1. How much  is produced from one pound of oil, one pound of natural gas, and one pound of medium grade coal?
2. What is the current estimate of the cost of sequestering one ton of removed from the air? Of course, this cost is in addition to the capital cost for the infrastructure.
3. If the cost of sequestering  is too high (or impractical), what is next best thing we can do to reduce  emission?

**#5:** The known estimate of the *oil resource in the world* is 11.8 trillion barrels of oil (light, medium, and heavy).

1. In discussing the proven oil reserves, what do we mean by the *first trillion*, the *second trillion*, and the *third trillion barrels of oil*? What is the period of time associated with these numbers?
2. Based on the above information, what is the estimated conventional oil recovery fraction worldwide? What is the lesson here for the future of petroleum technology?

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**Session 8: Feb 26, 2009**

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**HW#15**

**Part (a):**

Calculate the atmospheric pressure at 6500 ft elevation.

Given:



**Note**: The temperature is in 



Use the following data:



Approximate temperature at 6500 ft elevation in the spring is 50

Reference depth and pressure should be based on mean sea level.

**Part (b):**

Calculate the saturation temperature (boiling temperature) of water at 6500 ft.

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**Reading Material:**

Crookston, R.B., Calhum, W. E. and Chen, W. H. *“Numerical Simulation Model for Thermal Recovery Processes”*, SPEJ (Feb, 1979) pp.37-58.

**Heat source term:**

*Approximated solution* – used for the following assignments

Where:

 ,

 , F

 , = (note

*Exact solution for multiple layer*

 ;

|  |  |  |
| --- | --- | --- |
| **LHS** |  | **RHS** |
| **Po** | **T** | **So** | **Ts** |  | **Po** | **T** | **So** | **Ts** |  | **Po** | **T** | **So** | **Ts** |  | **Po** | **T** | **So** | **Ts** |  | **Po** | **T** | **So** | **Ts** |  | **Po** | **T** | **So** | **Ts** |
| x | 0 | 0 | 0 |   | x | 0 | 0 | 0 |   |  |  |  |   |  | x | x | x | 0 |   |  |  |  |  |   |  |  |  |   |
| x | 0 | 0 | 0 |   | x | 0 | 0 | 0 |   |  |  |  |   |  | x | x | x | 0 |   |  |  |  |  |   |  |  |  |   |
| x | x\* | 0 | 0 |   | x | x | 0 | 0 |   |  |  |  |   |  | x | x | x | 0 |   |  |  |  |  |   |  |  |  |   |
| 0 | 0 | 0 | 0 |   | 0 | 0 | 0 | 0 |   |  |  |  |   |  | x | 0 | 0 | x |   |  |  |  |  |   |  |  |  |   |
|   |   |   |   |   |   |   |   |   |   |   |   |   |   |  |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| x | 0 | 0 | 0 |   | x | 0 | 0 | 0 |   | x | 0 | 0 | 0 |  |   |  |  |  |   | x | x | x | 0 |   |  |  |  |   |
| x | 0 | 0 | 0 |   | x | 0 | 0 | 0 |   | x | 0 | 0 | 0 |  |   |  |  |  |   | x | x | x | 0 |   |  |  |  |   |
| x | x | 0 | 0 |   | x | x\* | 0 | 0 |   | x | x | 0 | 0 |  |   |  |  |  |   | x | x | x | 0 |   |  |  |  |   |
| 0 | 0 | 0 | 0 |   | 0 | 0 | 0 | 0 |   | 0 | 0 | 0 | 0 |  |   |  |  |  |   | x | 0 | 0 | x |   |  |  |  |   |
|   |   |   |   |   |   |   |   |   |   |   |   |   |   |  |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
|   |  |  |  |   | x | 0 | 0 | 0 |   | x | 0 | 0 | 0 |  |   |  |  |  |   |  |  |  |  |   | x | x | x | 0 |
|   |  |  |  |   | x | 0 | 0 | 0 |   | x | 0 | 0 | 0 |  |   |  |  |  |   |  |  |  |  |   | x | x | x | 0 |
|   |  |  |  |   | x | x | 0 | 0 |   | x | x\* | 0 | 0 |  |   |  |  |  |   |  |  |  |  |   | x | x | x | 0 |
|   |   |   |   |   | 0 | 0 | 0 | 0 |   | 0 | 0 | 0 | 0 |  |   |   |   |   |   |   |   |   |   |   | x | 0 | 0 | x |
|   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| **LHS** |  | **RHS** |
| x | 0 | 0 | 0 |   | x | 0 | 0 | 0 |   |  |  |  |   |  | x | 0 | 0 | 0 |   |  |  |  |  |   |  |  |  |   |
| x | 0 | 0 | 0 |   | x | 0 | 0 | 0 |   |  |  |  |   |  | x | x | 0 | 0 |   |  |  |  |  |   |  |  |  |   |
| x | x\* | 0 | 0 |   | x | x | 0 | 0 |   |  |  |  |   |  | x | x | x | 0 |   |  |  |  |  |   |  |  |  |   |
| 0 | 0 | 0 | 0 |   | 0 | 0 | 0 | 0 |   |  |  |  |   |  | x | 0 | 0 | x |   |  |  |  |  |   |  |  |  |   |
|   |   |   |   |   |   |   |   |   |   |   |   |   |   |  |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| x | 0 | 0 | 0 |   | x | 0 | 0 | 0 |   | x | 0 | 0 | 0 |  |   |  |  |  |   | x | 0 | 0 | 0 |   |  |  |  |   |
| x | 0 | 0 | 0 |   | x | 0 | 0 | 0 |   | x | 0 | 0 | 0 |  |   |  |  |  |   | x | x | 0 | 0 |   |  |  |  |   |
| x | x | 0 | 0 |   | x | x\* | 0 | 0 |   | x | x | 0 | 0 |  |   |  |  |  |   | x | x | x | 0 |   |  |  |  |   |
| 0 | 0 | 0 | 0 |   | 0 | 0 | 0 | 0 |   | 0 | 0 | 0 | 0 |  |   |  |  |  |   | x | 0 | 0 | x |   |  |  |  |   |
|   |   |   |   |   |   |   |   |   |   |   |   |   |   |  |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
|   |  |  |  |   | x | 0 | 0 | 0 |   | x | 0 | 0 | 0 |  |   |  |  |  |   |  |  |  |  |   | x | 0 | 0 | 0 |
|   |  |  |  |   | x | 0 | 0 | 0 |   | x | 0 | 0 | 0 |  |   |  |  |  |   |  |  |  |  |   | x | x | 0 | 0 |
|   |  |  |  |   | x | x | 0 | 0 |   | x | x\* | 0 | 0 |  |   |  |  |  |   |  |  |  |  |   | x | x | x | 0 |
|   |   |   |   |   | 0 | 0 | 0 | 0 |   | 0 | 0 | 0 | 0 |  |   |   |   |   |   |   |   |   |   |   | x | 0 | 0 | x |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| LHS |  | RHS |  | LHS+RHS |
| **Po** | **T** | **Po** | **T** | **Po** | **T** |  | **Po** | **T** | **Po** | **T** | **Po** | **T** |  | **Po** | **T** | **Po** | **T** | **Po** | **T** |
| x | 0 | x | 0 |   |   |  | x | 0 |   |   |   |   |  | xx | 0 | x | 0 |   |   |
| x | 0 | x | 0 |   |   | + | x | x |   |   |   |   | = | xx | xo | x | 0 |   |   |
| x | 0 | x | 0 | x | 0 |  |   |   | x | 0 |   |   |  | x | 0 | xx | 0 | x | 0 |
| x | 0 | x | 0 | x | 0 |  |   |   | x | x |   |   |  | x | 0 | xx | x0 | x | 0 |
|   |  | x | 0 | x | 0 |  |   |  |   |   | x | 0 |  |   |  | x | 0 | xx | 0 |
|   |   | x | 0 | x | 0 |  |   |   |   |   | x | x |  |   |   | x | 0 | xx | x0 |

**Matrix solving methods:**

1. Standard Gauss 2. Banded Gauss

3. Bandsolve 4. Block tridiagonal

**Viscosity, cp**

Where

**Density, lbmole/ft3**

Where and in psia

**Heat capacity coefficient, Btu/(lbmole oR**

Where

**Given data:**

 psi

**Session 9: March 5, 2009**

**Steam-Assisted Gravity Drainage (SAGD)**

Injecting steam

Producing oil

Problems associated with SAGD

* Steam is condensed due to energy loss
* Steam doesn’t go very far as expected

Injecting other gases i.e. CO2, N2 or CH4 would increase the oil recovery factor from injecting steam alone. The incremental recovery factor for each gas is listed and shown below.

 Injected gas Incremental RF (%)

 Steam 8

 CO2 9

 N2 7

 CH4 7

Injecting

steam

Injecting

different

gases

CO2

N2 or CH4

Steam

RF

Time

*Note:*

 - CO2 is soluble in oil and has thermodynamic behavior advantages, so it has great effect on improving the RF. CO2 can be extracted from flue gas generated from steam generation.

- N2 and CH4 have similar thermodynamic behavior, so they gain about the same incremental RF.

**Thermodynamics constraints:**

Method 1:

Method 2: (Better for matrix solving than Method 1)

**Flow rate**

 ;

**Relative permeability**

 ; ;

 ; ;

 ; ; ;

k ro\*

k rw\*

Swr

Sorw

k rg\*

Slr

Sgc

kro, krg

 krw

 Sw Sl

Note:

For oil-water system:

For oil-gas system:

Typically since gas reduces

**Capillary pressure**

 ;

Pc = 5 psi @ Sw= 50%

Pc\*

 Pc

 Sw

**Molar flow rate**

**Heat**

 Heat = Btu

Phases Composition

 W Light oil C1

 O Distillate C2

 G Non-volatile C3

 Water C4

…

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**HW#16**

Please answer all parts of question #6 and #7 from exam #1.

**#6:**

1. Define energy (or power) gain ratio.
2. Define steam-oil-ratio (SOR) and explain the favorable range of SOR from an economic point of view.
3. Give the typical BTU value of crude oil and medium grade coal.
4. What is the basis for the definition of BOE?
5. In using lease crude for fuel, how much steam can be generated per bbl of lease crude?
6. What is the steam-generating capacity of a steam generator in the field?

**#7:**

1. Define *effective stress* to include both pore pressure and temperature.
2. Draw the *rock failure envelop,* and explain the *critical stress state criterion*.

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**HW#17**

For the term project, we have specified analytical forms of correlations. For temperature changes, use temperatures of 100ºF, 150ºF, 200ºF, 250ºF, 300ºF, 350ºF, and 400ºF. For pressures, use pressure of 100psia, 200psia, 300psia, 400psia, 500psia, and 600psia. For saturations, use values of 0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, and appropriate endpoints.

1. Viscosity as a function of temperature. Create a table of viscosity values using the list of temperatures above. Plot viscosity as a function of temperature.
	1. Oil viscosity 
	2. Water viscosity 
	3. Steam viscosity 
2. Molar density as a function of pressure and temperature. Create a table of molar densities as a function of temperature and pressure using the temperature and pressure values above. Plot molar density as a function of temperature for each pressure.
	1. Oil molar density 
	2. Water density 
	3. Steam density 
3. Heat capacity as a function of temperature. Create a table of heat capacities as a function of temperature for the list of temperatures above. Plot the heat capacity as a function of temperature.
	1. Heat capacity of oil 
	2. Heat capacity of water 
	3. Heat capacity of steam 
4. Relative permeability as a function of saturation. Create a table of values as a function of the list of saturations above. Plot relative permeability as a function of saturation.
	1. Relative permeability to water .
	2. Relative permeability to oil 
	3. Relative permeability to gas .
5. Capillary pressure as a function of saturation. Create a table of values as a function of the list of saturations above. Plot capillary pressure as a function of saturation.
	1. Gas-oil capillary pressure 
	2. Water-oil capillary pressure 

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**Session #10: March 19, 2009**

**Molar Density, lbmole/ft3**

**Steam injection with three phases and four components**

**Component Mass Balance**

C1:

C2:

C3:

C4:

Note: and

**Energy Balance**