SHALE OIL: Exploration and Development

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Senior Capstone Project

Spring 2006

Current Energy Crisis

- World's main source of energy: Petroleum
- Demand exceeding supply
  - April 17, 2006: Oil reaches $70/barrel
- Opportunity to develop alternate energy sources
  - Large economic incentive

Why Shale Oil?

- Currently, United Arab Emirates hold 50% of world's known oil reserves

How much does the US hold?

2%

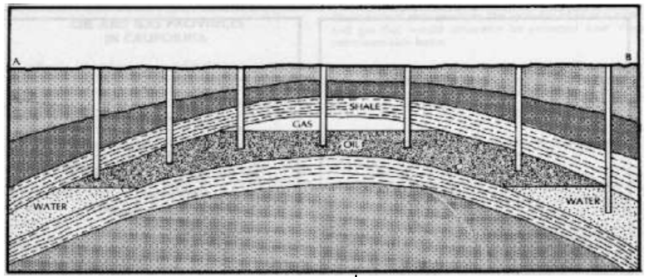
How many reserves would be added from developing oil shale?

2 TRILLION BARRELS

- ***Result:*** US takes over as leader in the world in oil reserves.

Outline

- Introduction to Shale Oil
- Project Statement
- Subsurface Operations
  - Reservoir Temperature Profiles
  - Heating
  - Freeze Walls
  - Reservoir Composition Analysis
- Surface Facilities
  - Oil/Gas Processing
  - Power Plant
- Pipelines to Market
- Production Schedule
- Economics and Risk



Shale Oil: Definition

- Sedimentary rock with a high organic content
  - Organic matter is known as kerogen
- Kerogen:
  - $MW_{avg.}$=3000
  - Approximate formula $C_{200}H_{300}SN_5O_{11}$[1]

1. Feng H.Y. Rates Of Pyrolysis Of Colorado shale oil. p. 732. *American Institute Of Chemical Engineers Journal* . Vol. 31 No. 5. 1985.

Shale Oil: History in the US

- Office of Naval Petroleum and Shale Oil Reserves formed in 1912
- First Demonstration mine opened outside of Rifle, Colorado just after World War II

Shale Oil: History in the US

- TOSCO opened an experimental mine and production plant near Parachute, Colorado in 1960’s

- Exxon opens Colony II project outside of Parachute, Colorado in 1980
  - Colony Project is closed in May of 1982
  - Nearly 2,200 people unemployed
  - Loss of more than $900 million.

Project Statement

- Determine which method of production of shale oil is the most feasible.

- Analyze production process to determine
  - Subsurface designs
  - Reservoir characteristics
  - Surface processing facilities
  - Scheduling of project
  - Pipelines

- Perform an economic analysis on project.

Shale Oil Production Methods

Above Ground Retorting

- Mining of ore
- Well known technology
- Large environmental impact
  - Popcorn effect
  - Large open mines
  - Emissions

In-Situ Conversion

- Underground conversion
- Research in progress
- Lower environmental impact
- Not commercially proven

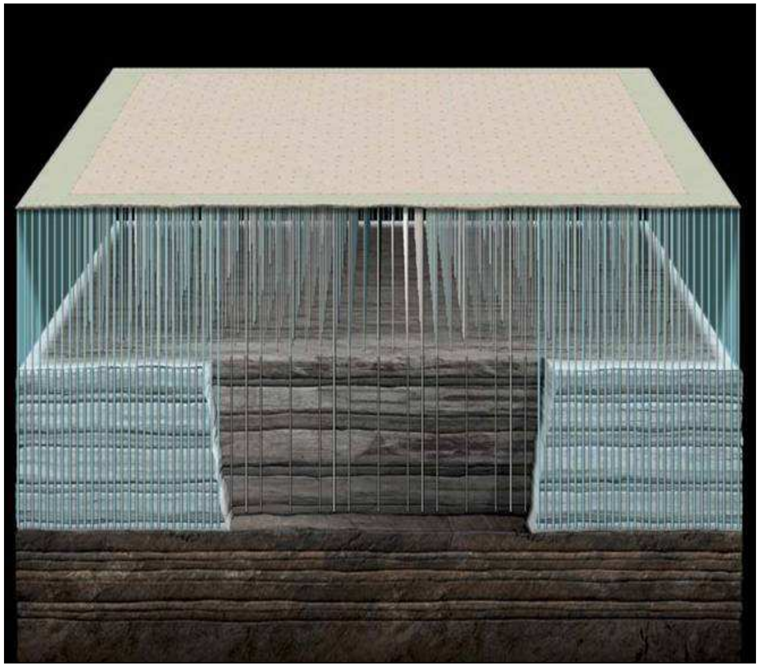
In-Situ Conversion

- Currently being explored by Shell Oil with the Mahogany Project.

- Entails the heating of kerogen in the ground and extracting the produced hydrocarbons for further processing.

In-Situ Process Overview

- Step 1: Heating
  - Conversion of kerogen to oil and gas
- Step 2: Freeze Wall Construction and Water Removal
  - Impermeable wall around production site
  - Prevents large environmental impact



1. Mut, Stephen. The Potential of Oil Shale. 8/20/05

In-Situ Process Overview

- Step 3: Production
  - Products from kerogen conversion
- Step 4: Processing and Transportation
  - Oil and gas separation
  - Pipelines to market

Schedule Table

site preparation: drilling wells, freeze wall formation, water removal

heating only

Production: refrigeration and heating continues

water injection

site reclamation

Reservoir Temperature Profile

- Unsteady state 1D temperature profile
- Profile created for
  - Heater to heater 60 feet apart (25 heaters/acre)[1]
  - Heat given off by reaction accounted for
  - Initial Reservoir temperature 150°F

1. Bartis et. al. *Oil Shale Development in the United States*. Rand Santa Monica, California: 2005 p. 50.

Reservoir Temperature Profile

- Heat balance on reservoir

$$\rho C_p \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial z^2} - q$$

Accumulation — Conduction — Generation

- Concentration due to cracking

$$\frac{dC_k}{dt} = -Ae^{\left(\frac{-E_a}{RT}\right)} C_k$$

1. Guerin, Gilles 2000. Acoustic and Thermal Characterization of Oil Migration, Gas Hydrates Formation and Silica Diagenesis, PhD. Thesis, Columbia University

Reservoir Temperature Profile

- Approximation Equation

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial z^2} - \frac{q}{\rho C_p}$$

$$T_i|_{t+\Delta t} - T_i|_t = \frac{\alpha \Delta t}{\Delta x^2}(T_{i+1}|_t + T_{i-1}|_t) - \frac{2\alpha \Delta t}{\Delta x^2} T_i|_t - \frac{Ate^{(\frac{-E_a}{RT})} C_k (-\Delta H_{rx})}{\rho C_p}$$

Temperature at certain time and distance between heaters

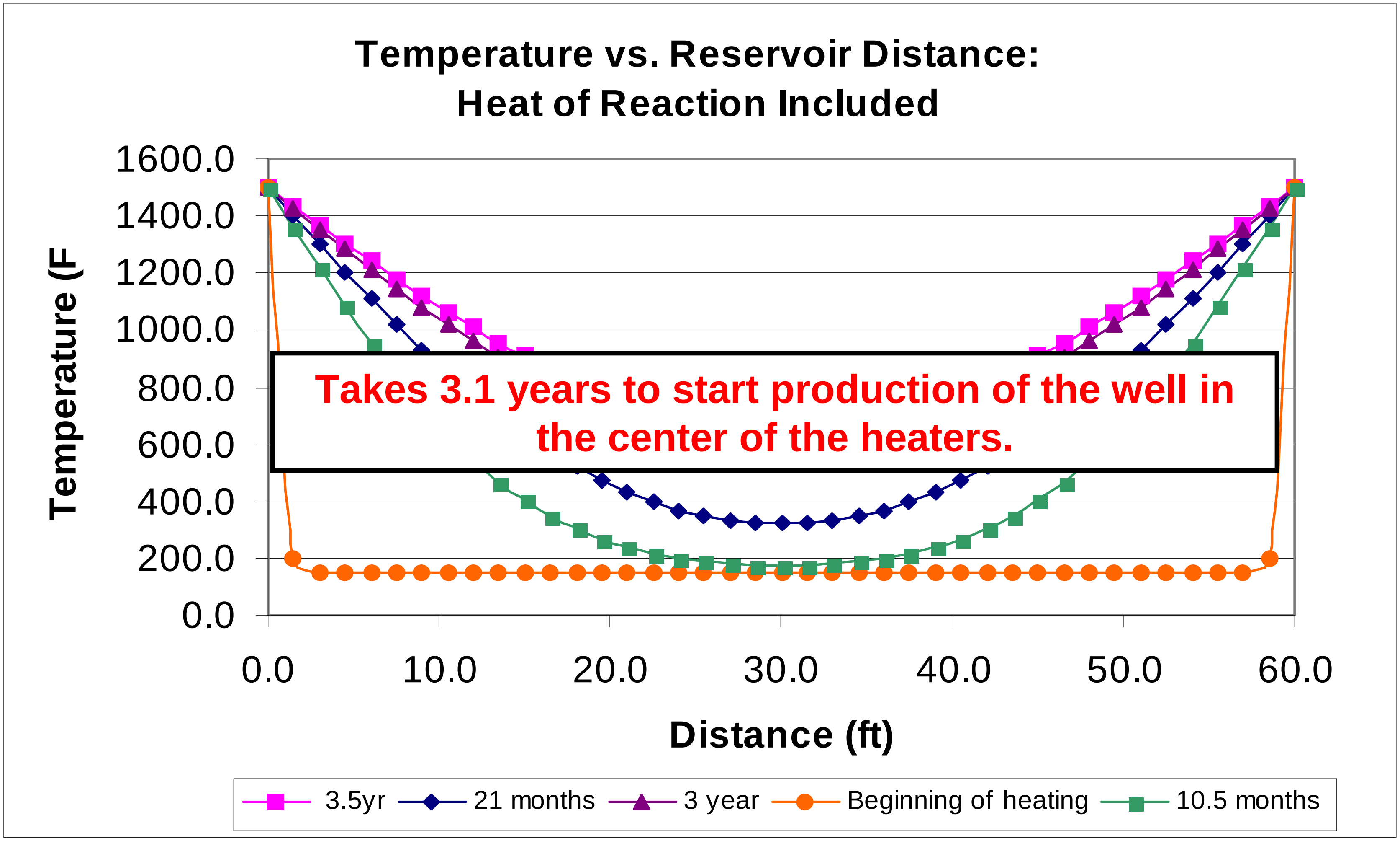
Accounts for heat spreading linearly away from each heater into the reservoir rock

Accounts for heat of reaction due to cracking of kerogen

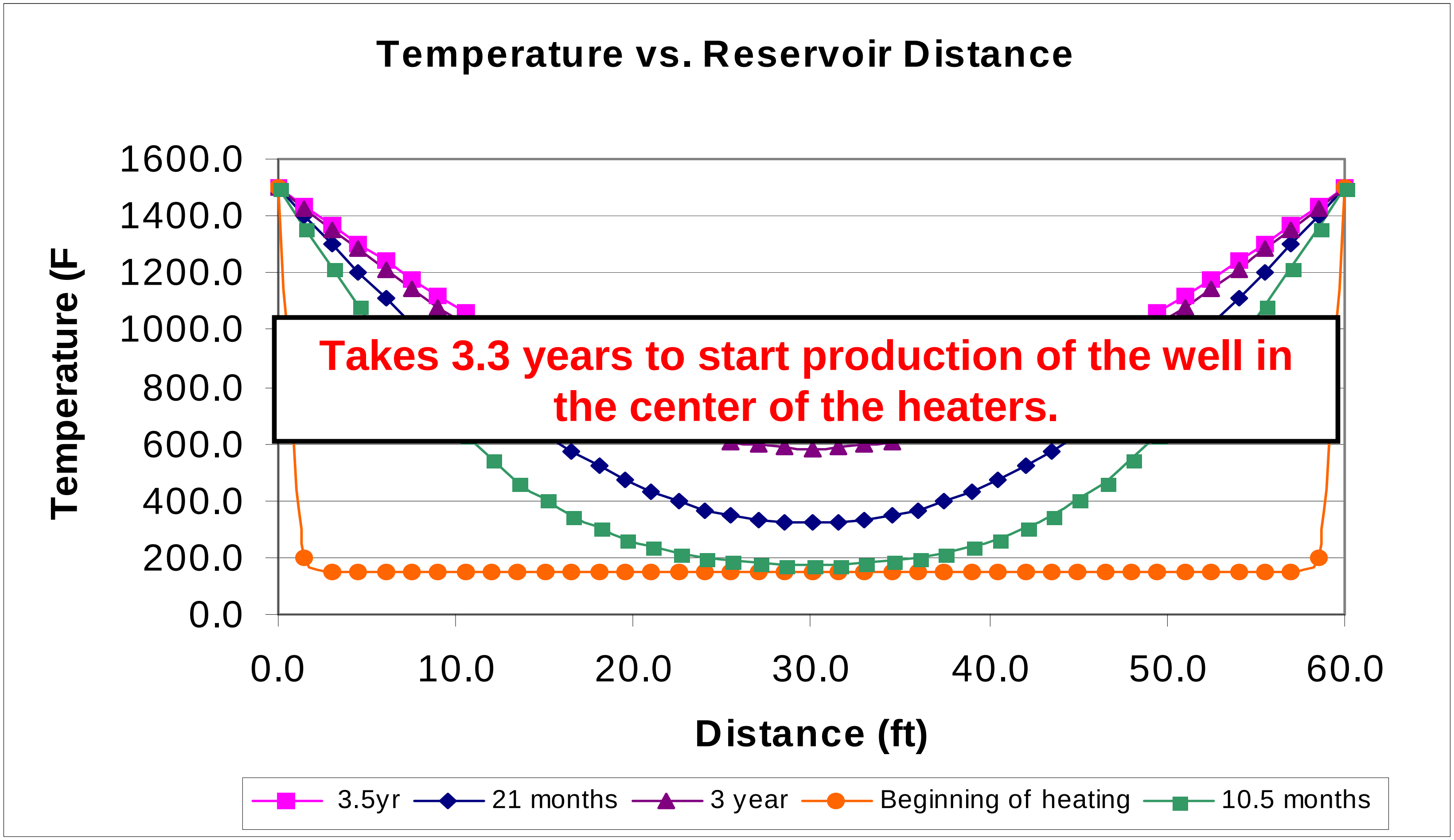
Reservoir Temperature Profile Assumptions

- Thermal diffusivity assumed constant
- Models only include periods of time when no fluid flow is occurring in reservoir
- Heaters assumed to be in a hexagonal pattern in the earth
- Heat generation from reaction is calculated from average kinetic values of kerogen cracking
- Heat lost to overburden by heaters not considered

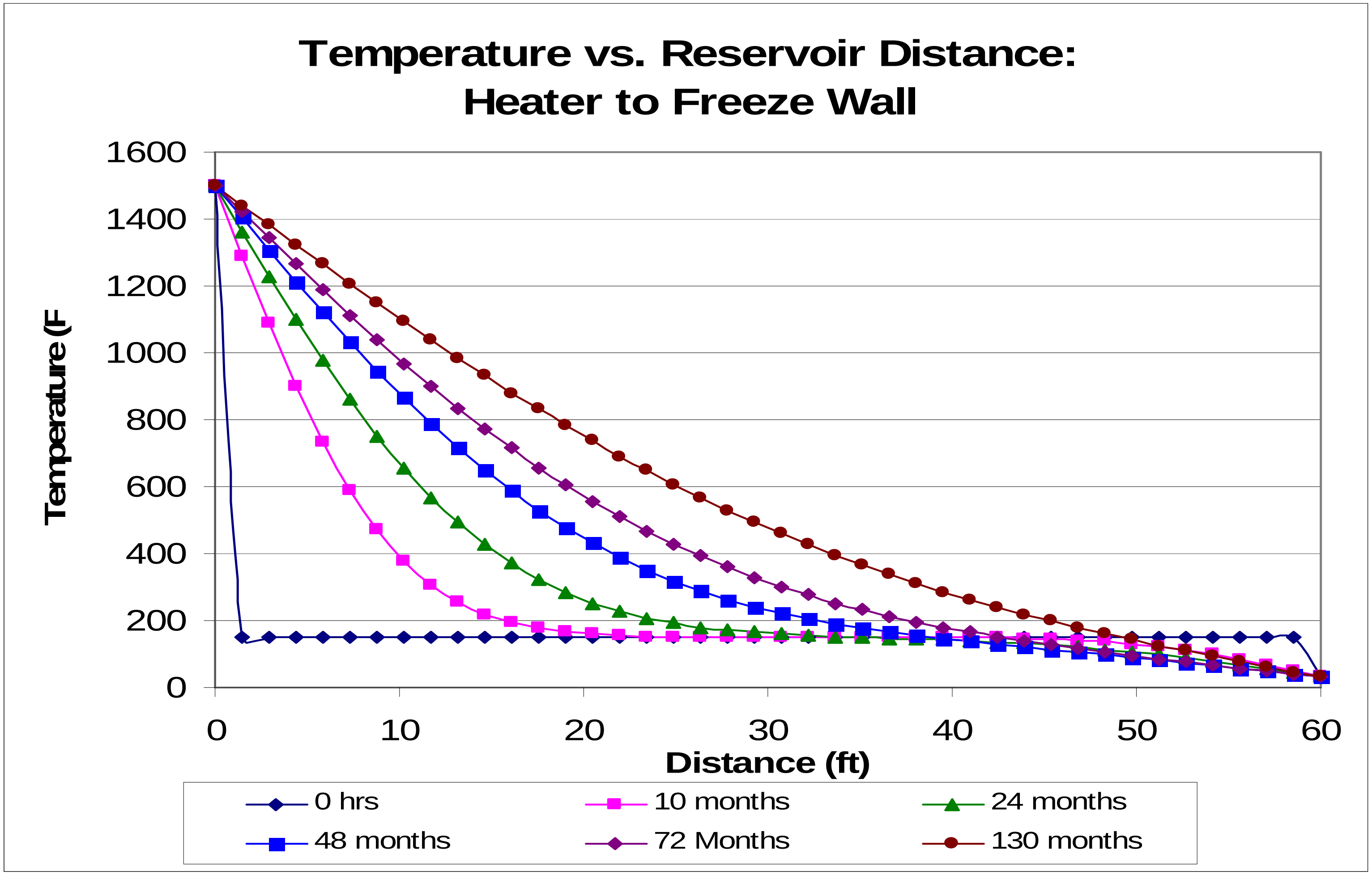
Reservoir Temperature Profile



Reservoir Temperature Profile: No Heat from Reaction

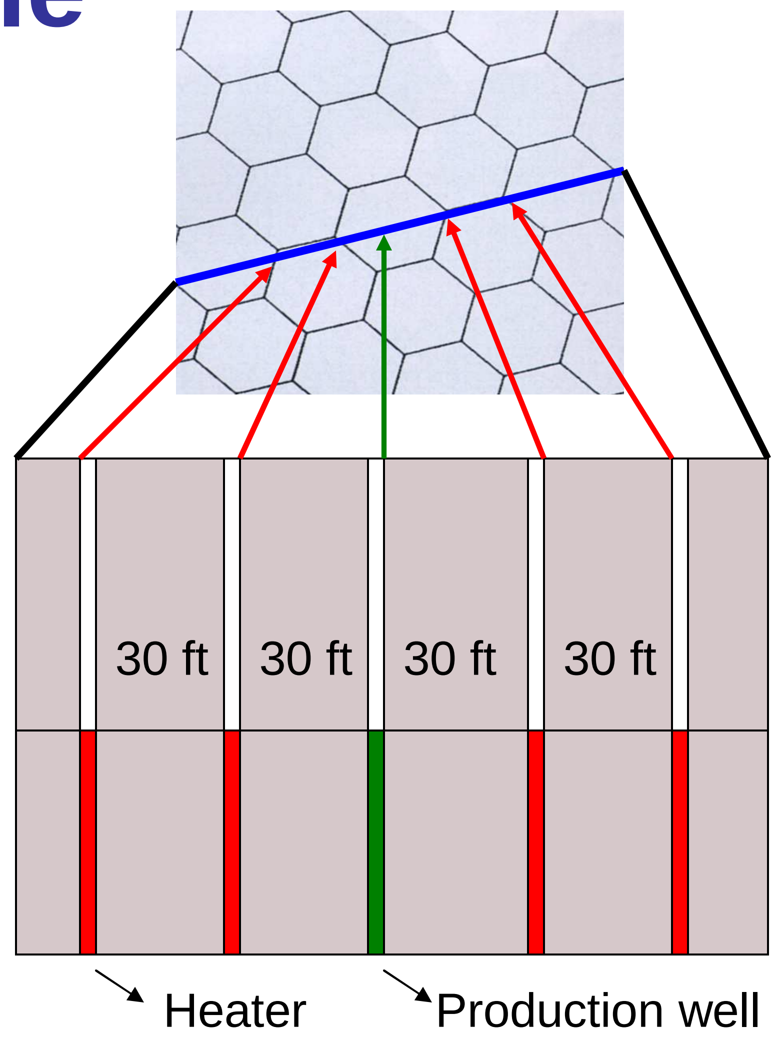


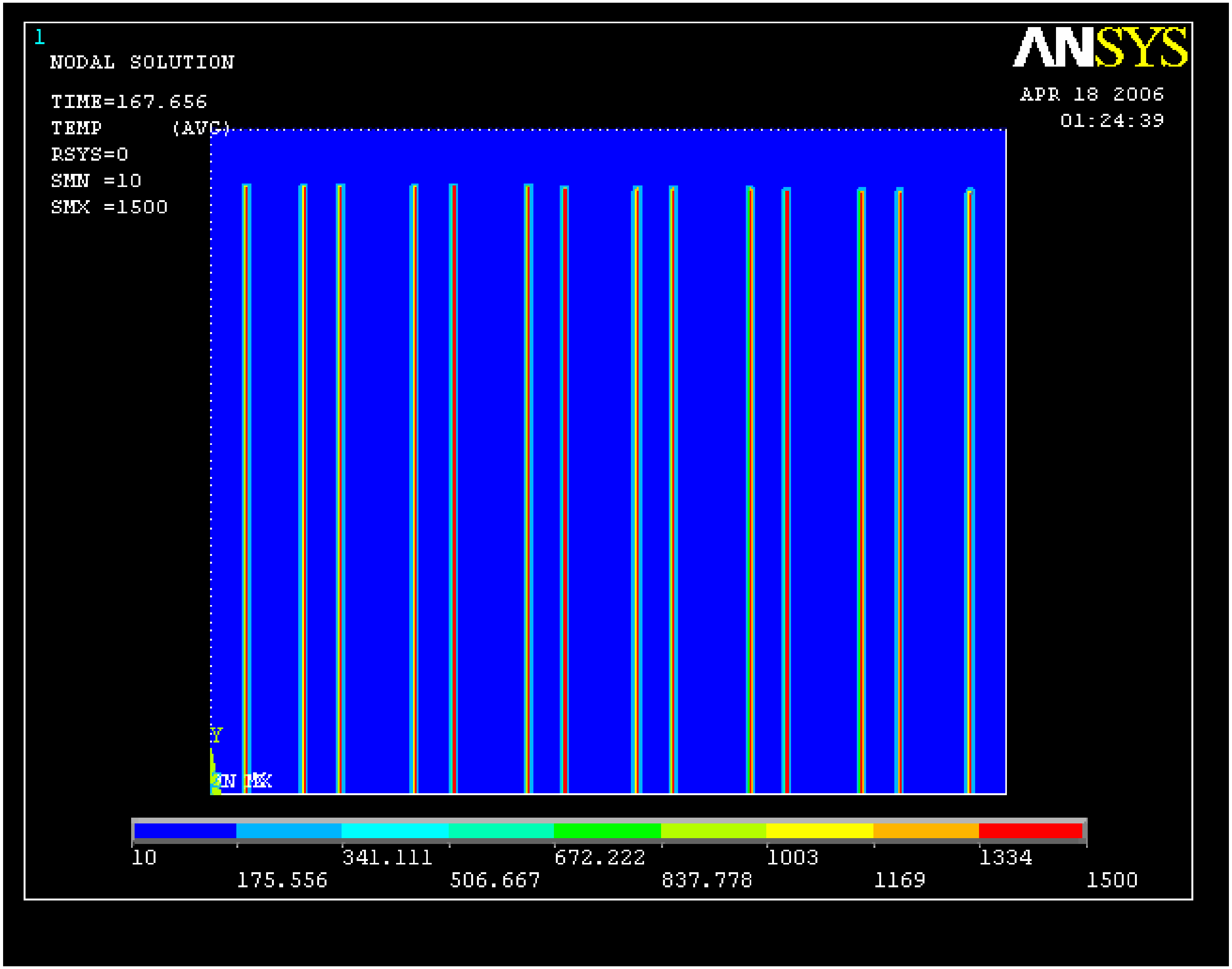
Reservoir Temperature Profile: Heater to Freeze Wall



2D Reservoir Temperature Profile

- Developed using ANSYS
- Initial reservoir temperature 150^{o}F
- Freeze walls included as boundary condition.





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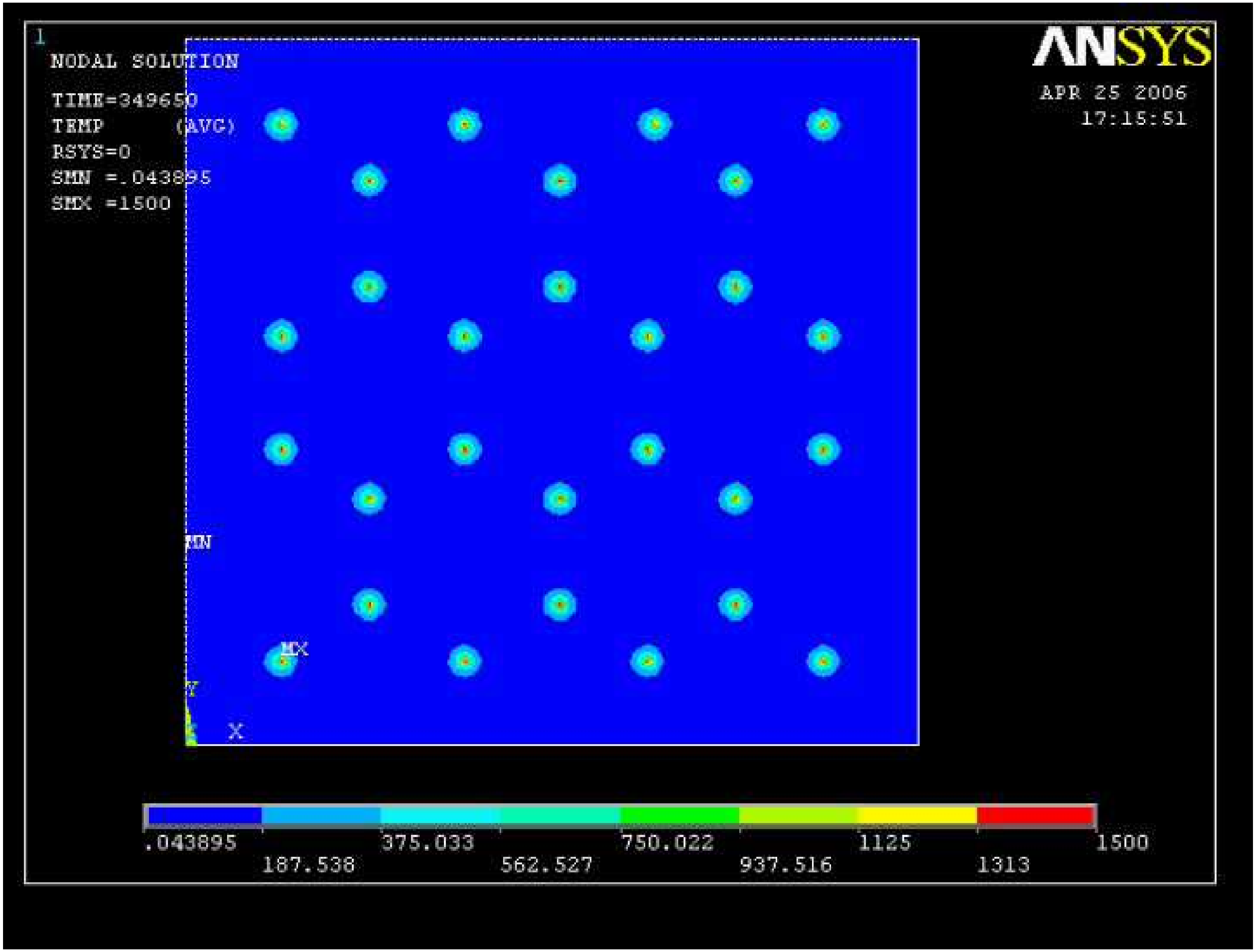
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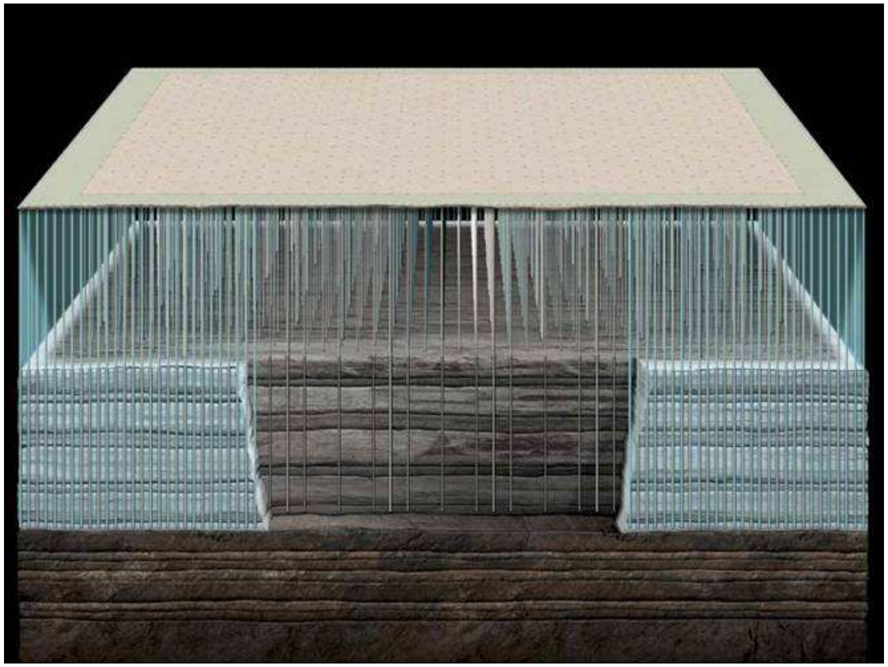
Shale Oil:
Subsurface Operations

- Drilling costs
- Refrigeration costs
- Pumping costs
- Heating costs



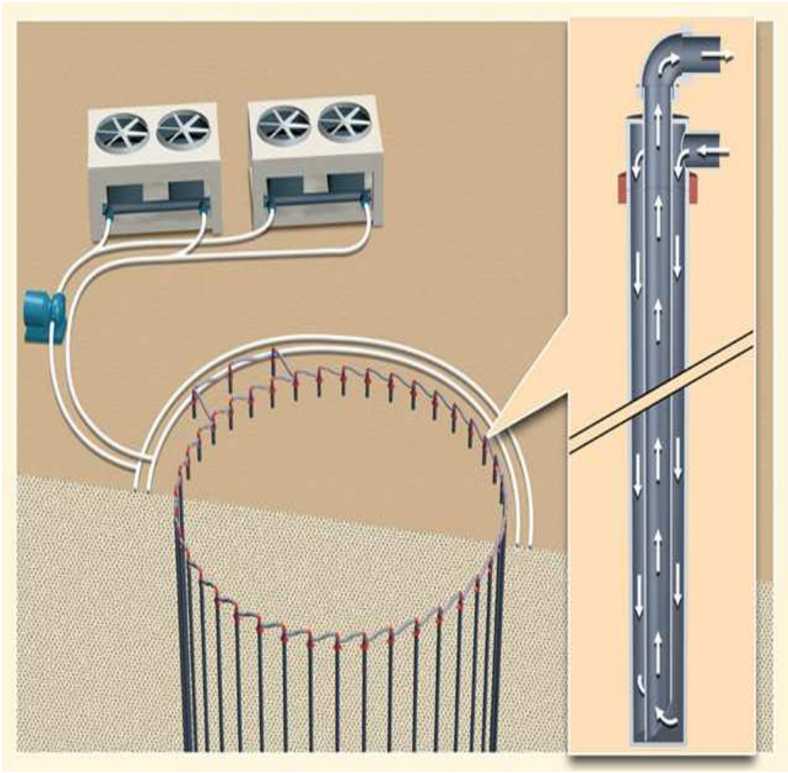
Drilling Costs

- Consists of wells for heaters and producers
  - 250 wells for heaters per 10 acre plot
  - 80 producer wells
- Total well costs of $26.4 million.
  - $80,000[2] per well.

2. Brown, Randy. Field Engineer XAE inc.

Freeze Wall Construction

- Constructed of double wall pipes placed 8 ft. apart
- Calcium chloride brine at -10 degrees F is circulated.
- Water in the soil freezes creating an impermeable barrier.



*Soil freeze technologies

Freeze Wall: Duty & Costs

During freezing:

$$Q = M * C_p * (T_{final} - T_{initial}) + \Delta\mathrm{H}_{\mathrm{freezing}} * \mathrm{M}_{\mathrm{water}}$$

$$Q = 5.0 * 10^6 \ \mathrm{K}W$$

During production:

$$Q = -k \frac{\partial T}{\partial z}$$

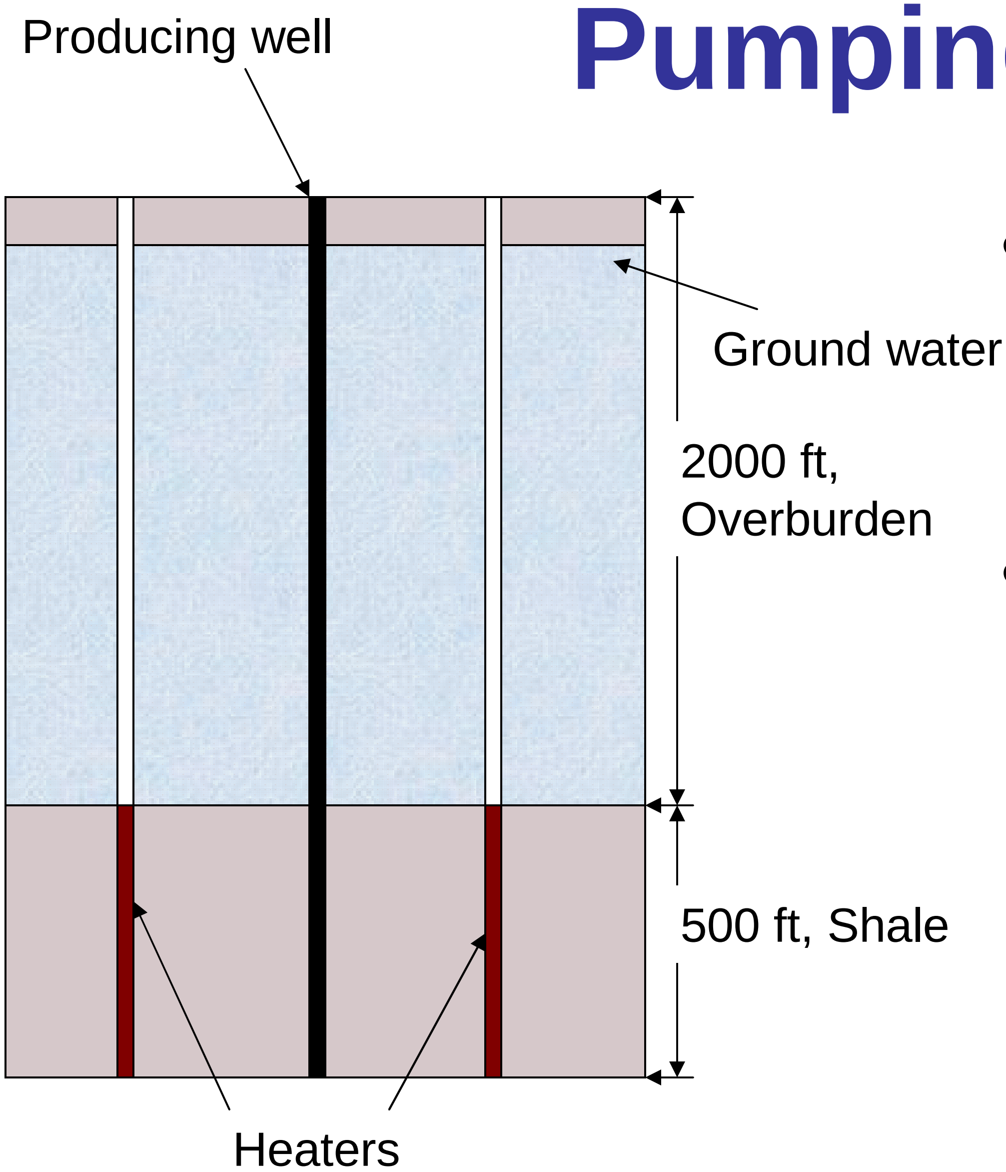
$$Q = 8.7\,KW$$

Purchase cost for $5.0*10^6$ KW of refrigeration[1]: $12.5 million

Operating Cost[2]: $3.2 million per day

1. Peters et al p.894 fig. B-7
2. Peters et al p.898 table B-1

Pumping



- Ground water trapped within freeze wall
- Must be removed to prevent contamination

Pumping Costs

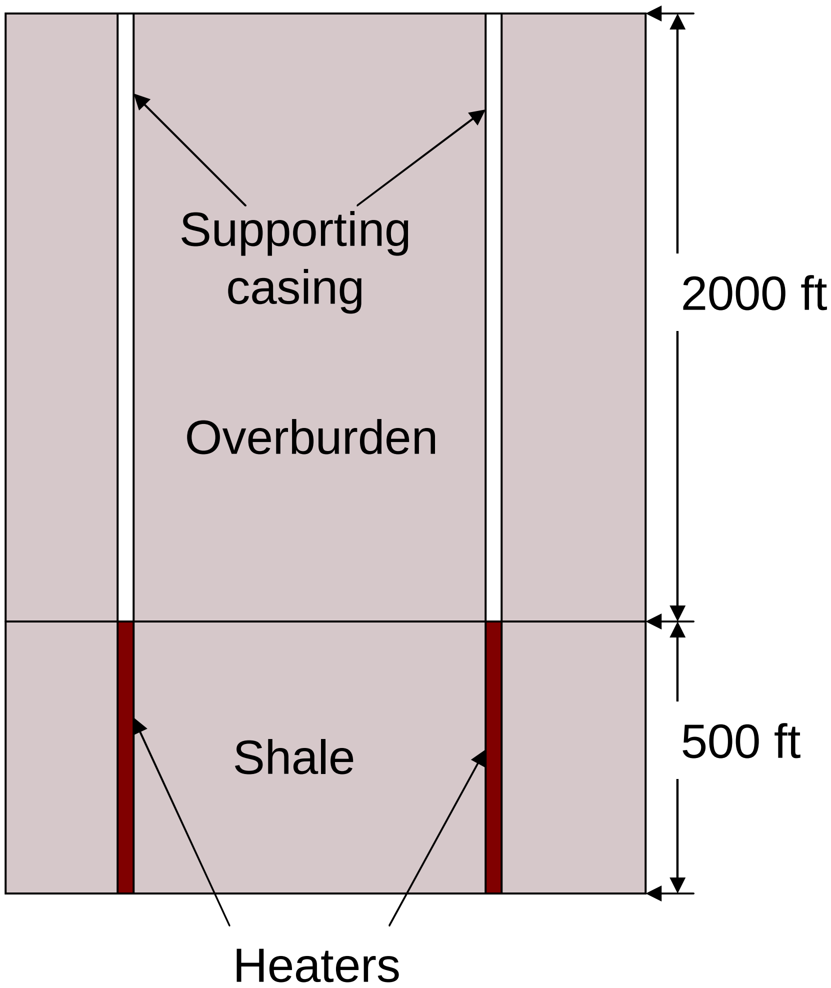
- A pump is needed to remove water from within the freeze wall.
  - 2 barrels of water for every barrel of oil[6]
  - Pumps must handle 1.6 million gallons per hour to remove the water in 2 weeks.
    - Centrifugal pumps
    - 80 pumps, $23,000 per pump[7]
    - $120,000 electricity needed per day

6. Bartis et. al. *Oil Shale Development in the United States*. p. 50. Rand Santa Monica, California: 2005
7. Peters et. al. *Plant Design And Economics For Chemical Engineers*. P. 516, Mcgraw-Hill: New York 2003.

Heating: Challenges

- Challenges
  - Regulated at a constant temperature
  - Must operate at high temperatures
  - Must have a large power output.

Heating: Solution



- Electric heaters lowered to the bottom of well hole
- Extends the entire length of the shale layer

Heating Element

- Chromel AA* heating element
  - 68% nickel
  - 20% chromium
  - 8% iron
  - Self regulating: 1500 ^{o}F

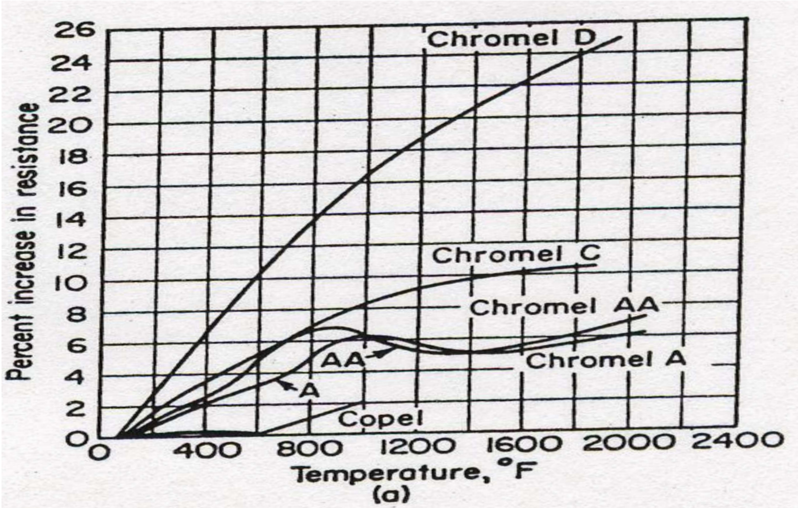


FIG. 4-15*a*. Temperature-resistance relationship for Chromel AA, A, C, D and Copel wire.

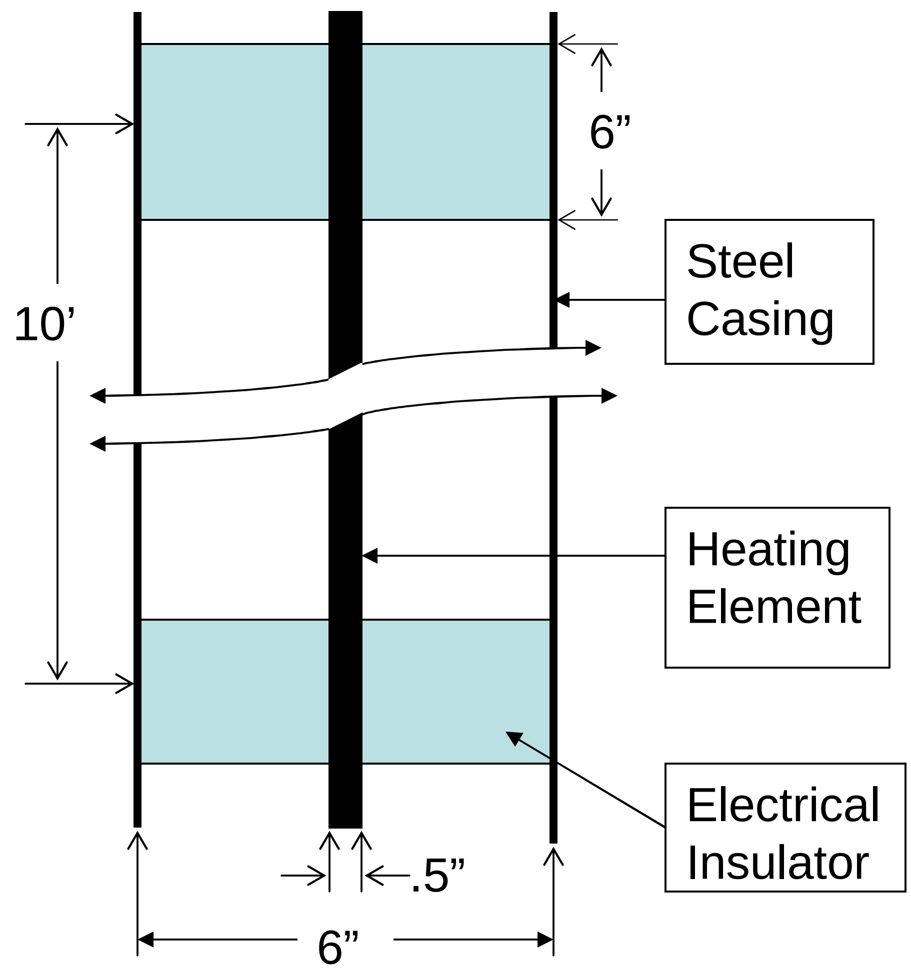
2

*Trademark of Hoskins Manufacturing

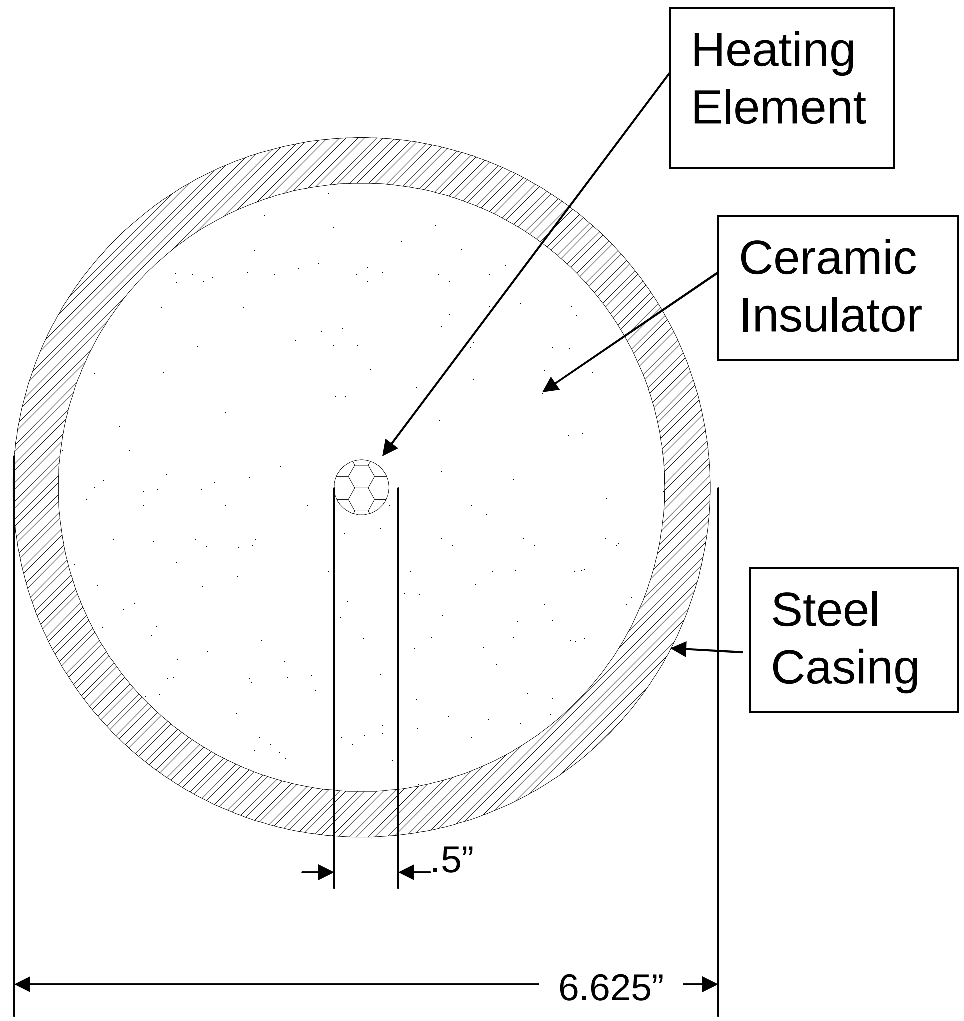
2 Handbook of chemical engineers, p. 4-201 8th ed.

Heater Design

- Cylindrical design
- Electric heating element suspended in the center.
- Spaced from the casing by electrical insulators



Heater Design



Heating Costs

Electrical

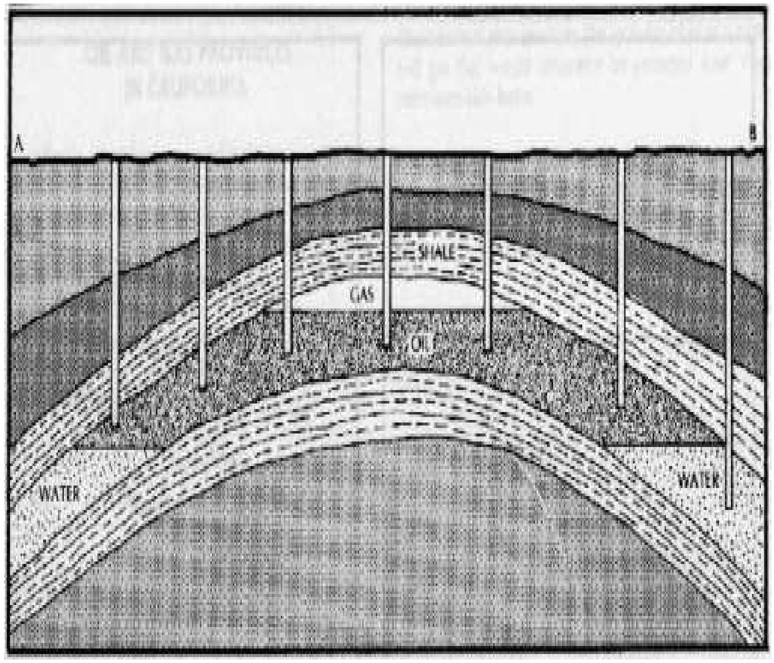
- 165 KW per heater
- Operating at 480 V AC and 350 amps
- Electrical costs heating:
  - $.08 per KW-hr[4] $80,000 per day total

Materials

- Steel Casing
  - $10 per foot
- Heater element
  - $20 per foot
- Porcelain insulator
  - $14 each, 250 per heater
- Total material cost: $80,000 per heater

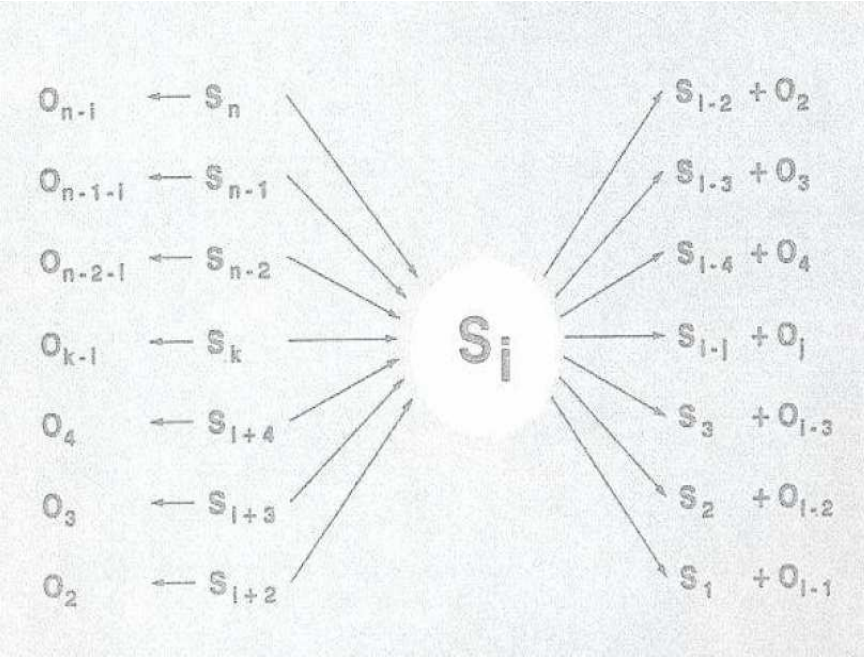
Reservoir Composition Study

- Heating process causes cracking of kerogen.
- Estimation of composition of products in reservoir needed.
- A temperature profile is necessary for composition computation
- Ultimately, reservoir characteristics will allow design of processing facilities.



Reservoir Composition Model

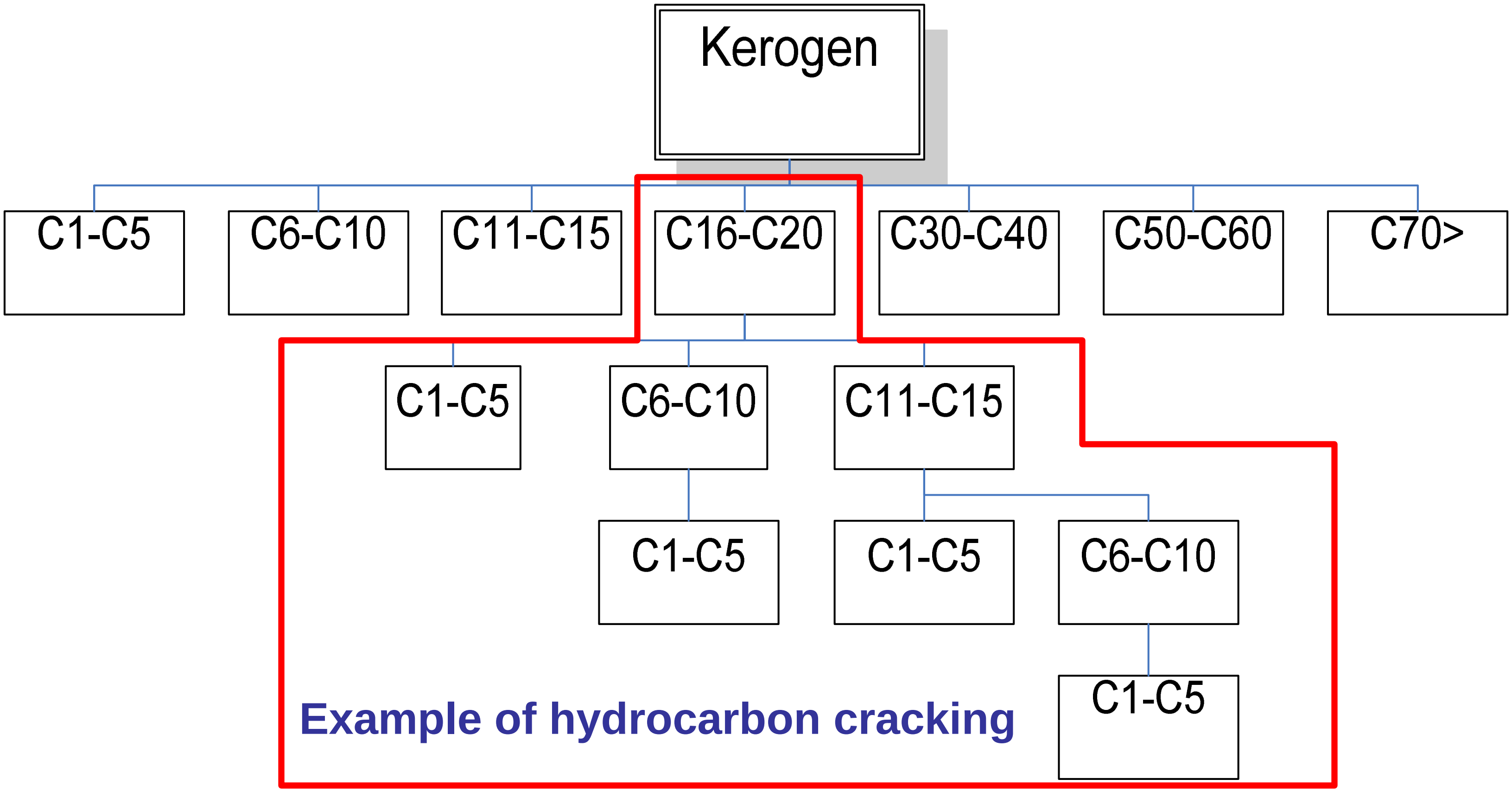
- Cracking process under the earth
  - Kerogen:
    - $MW_{avg.}$=3000
    - Approximate formula $C_{200}H_{300}SN_5O_{11}$
- Modeled using visbreaking model
- Using temperature profile, predicts concentrations of hydrocarbons in reservoir



Reaction depiction for thermal cracking[1]

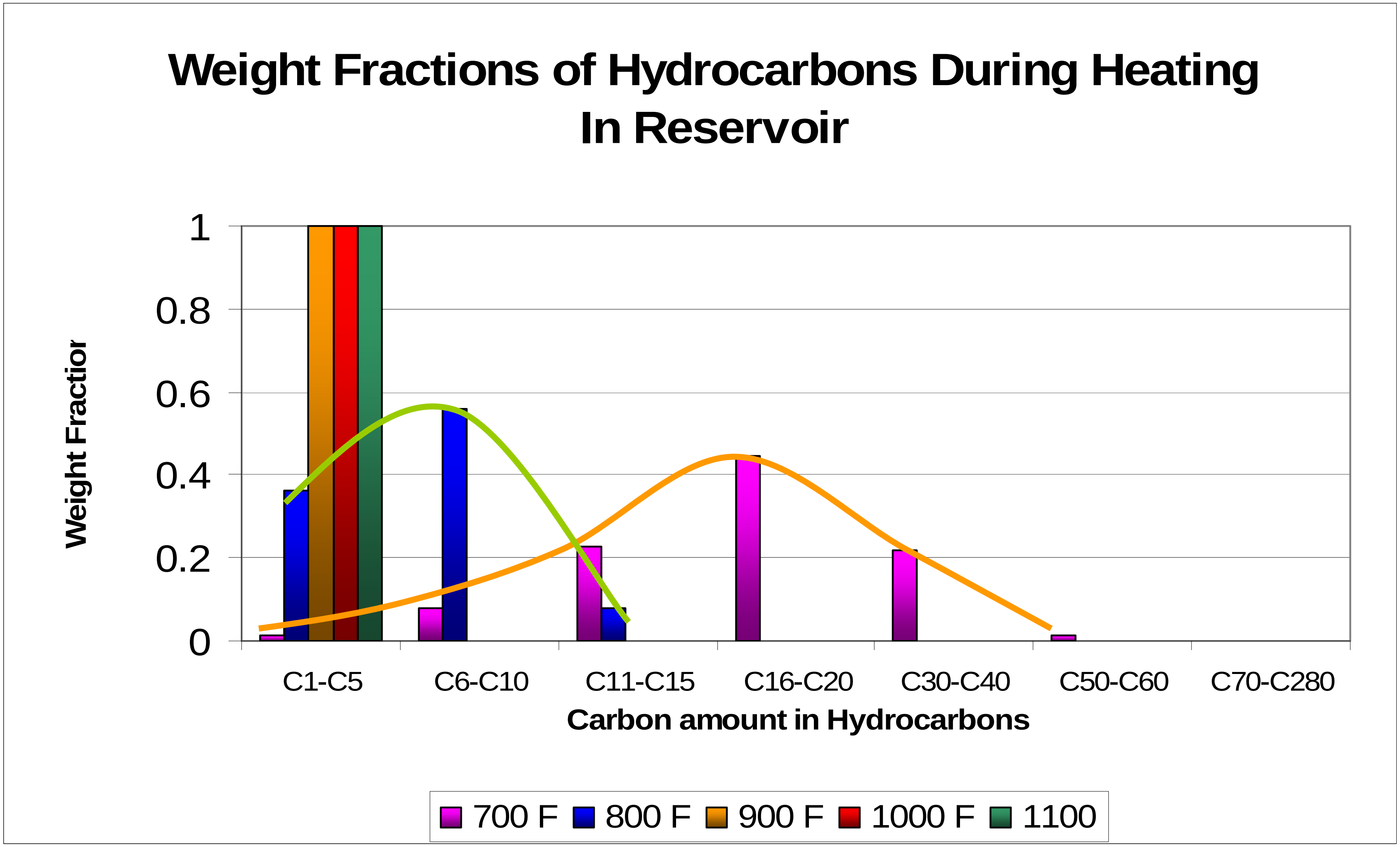
1. Castellanos, Julian. *Visbreaking Yields*. Encyclopedia of Chemical Processing and Design vol. 62. Marcel Dekker: New York. P411,

Composition Model



$$\frac{dC_{Si}}{dt} = \sum_{k=i+2}^{n} K_{k,i} Cs_{k} - Cs_{i} * \sum_{j=1}^{i-2} K_{i,j}$$

Reservoir Composition



Problems With Composition Model

- Averaged K-Values must be used due to the large amounts of data
- Parameters are fit to laboratory data that may not be similar to reservoir
- Does not account for coking in reservoir
- Results are not close to reported results from experimental site

Suggested Solution for Composition Model

- Use a tool with a larger capacity than excel

- Use a model specifically developed to calculate products from kerogen
  - Example: Braun and Burnham’s model of decomposition of kerogen

Oil Processing Design

Specifications

Oil composition

1. **No significant sulfur content**
2. **Carbon solid from cracking is not produced**
3. **Heavy hydrocarbons are not produced**
4. **TBP curve of a sample light sweet crude oil is being used currently.**
   - **Update with compositional model results**

Production

1. **20 acres produced from one facility**
2. **Water treatment will function ¼ of the time of the oil treatment**

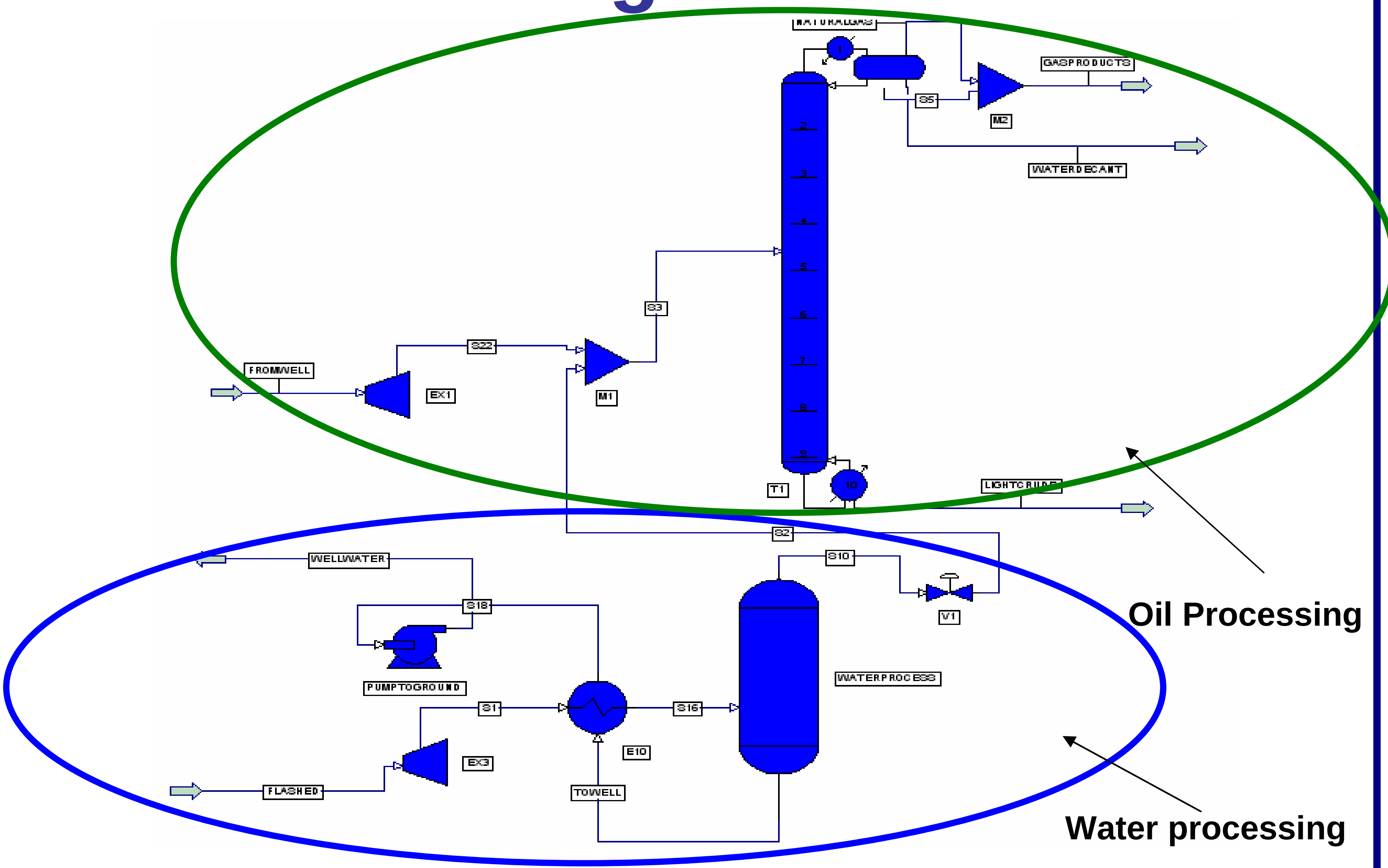
1. Bartis et. al. *Oil Shale Development in the United States*. p. 50. Rand Santa Monica, California: 2005

Oil Surface Facilities Considerations

Experimental project site

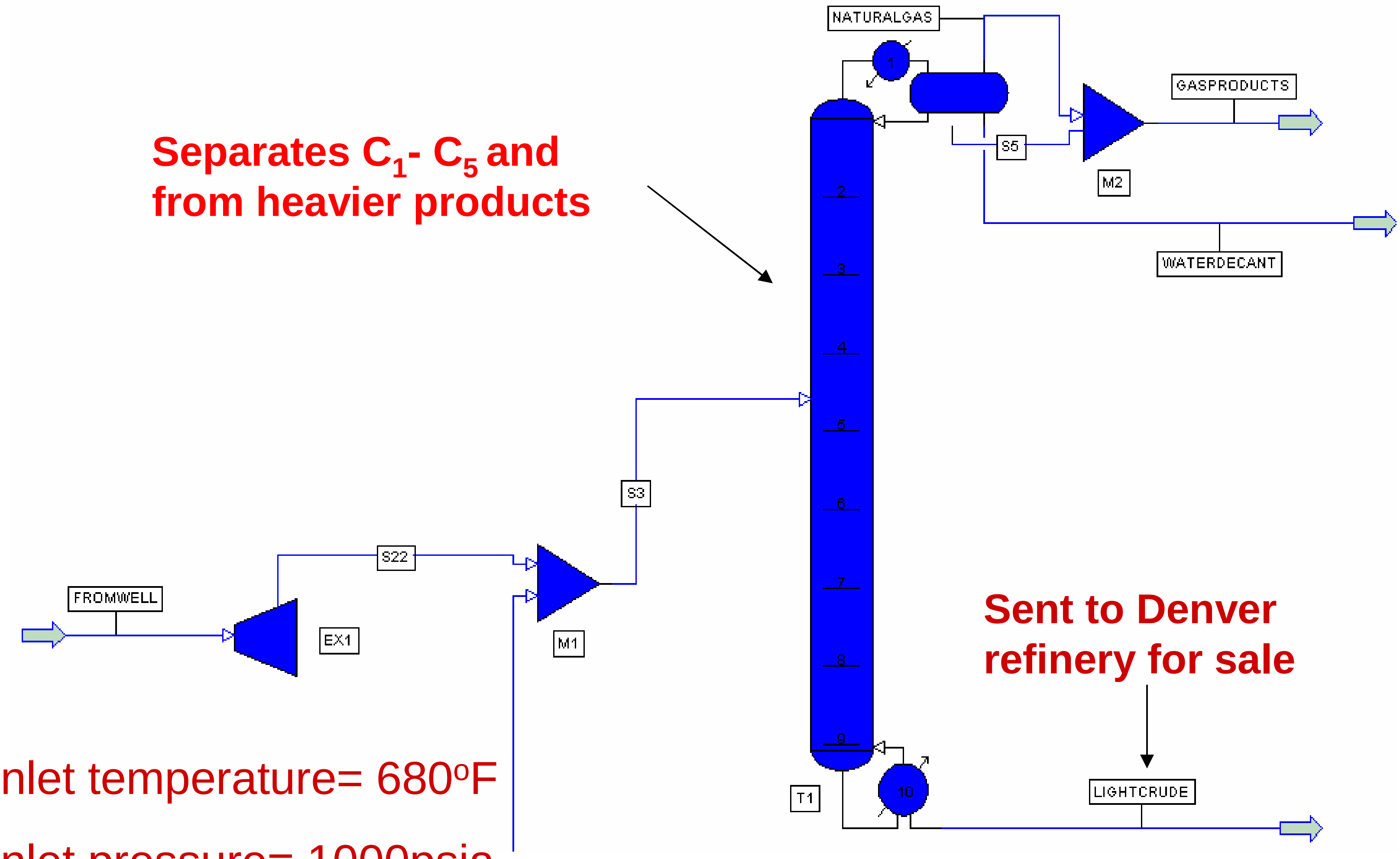
- Elevation changes
- High temperature fluid
- Piping will be above ground
- Two different transportation routes for oil and gas
- Some gas will be used for running electricity plant

Oil Processing Skeleton Model



Oil Processing Facilities

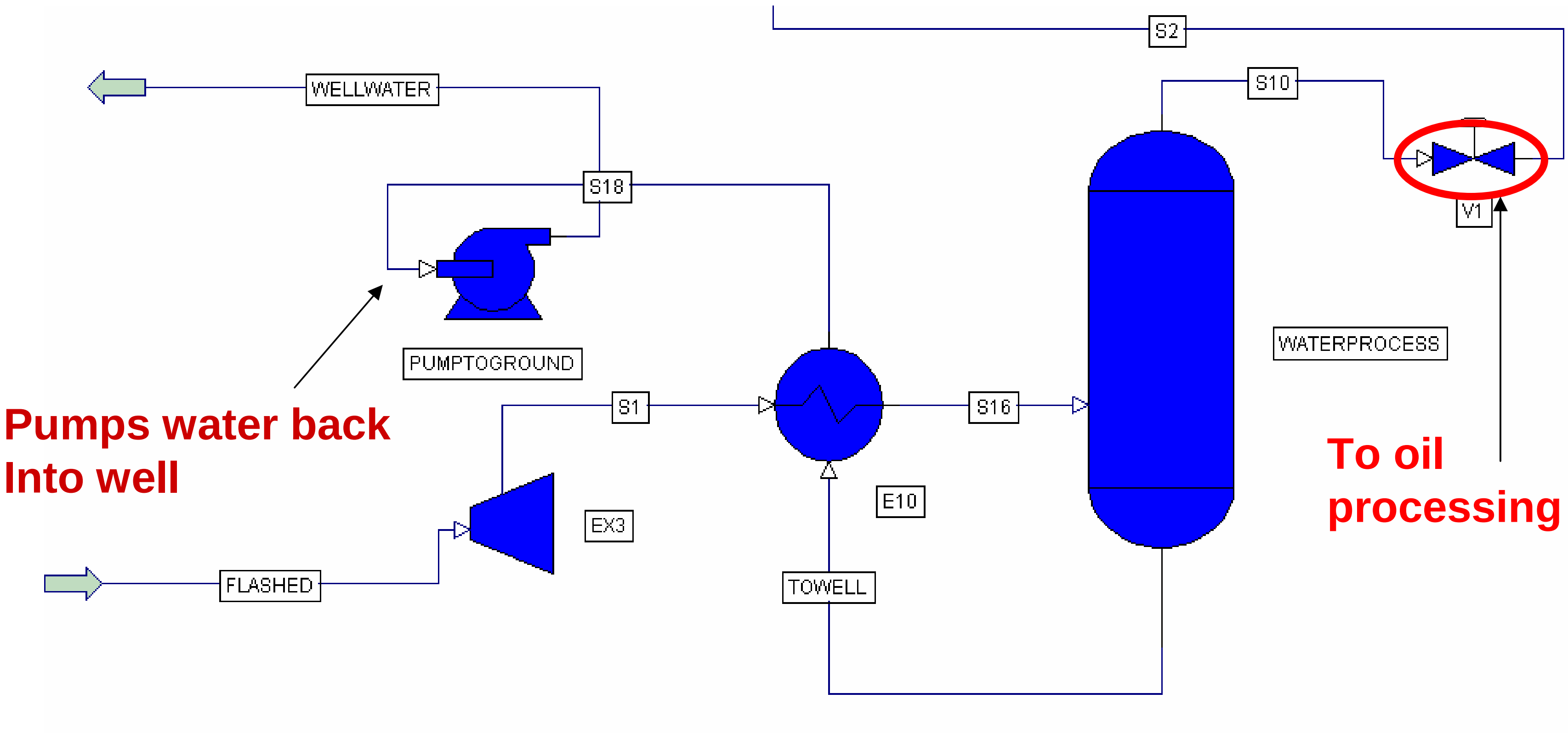
Separates C_1- C_5 and from heavier products



Sent to Denver refinery for sale

- Inlet temperature= 680^{o}F
- Inlet pressure= 1000psia

Water Processing Facilities



- Inlet temperature = 680ºF
- Inlet Pressure= 1000psia

Processing Facilities

- Future options for gas treatment
  - Create a gas plant on site
  - Use ethane to make ethylene on site
  - LPG to market with oil
  - Burn gas production for power generation

Power Plant Options

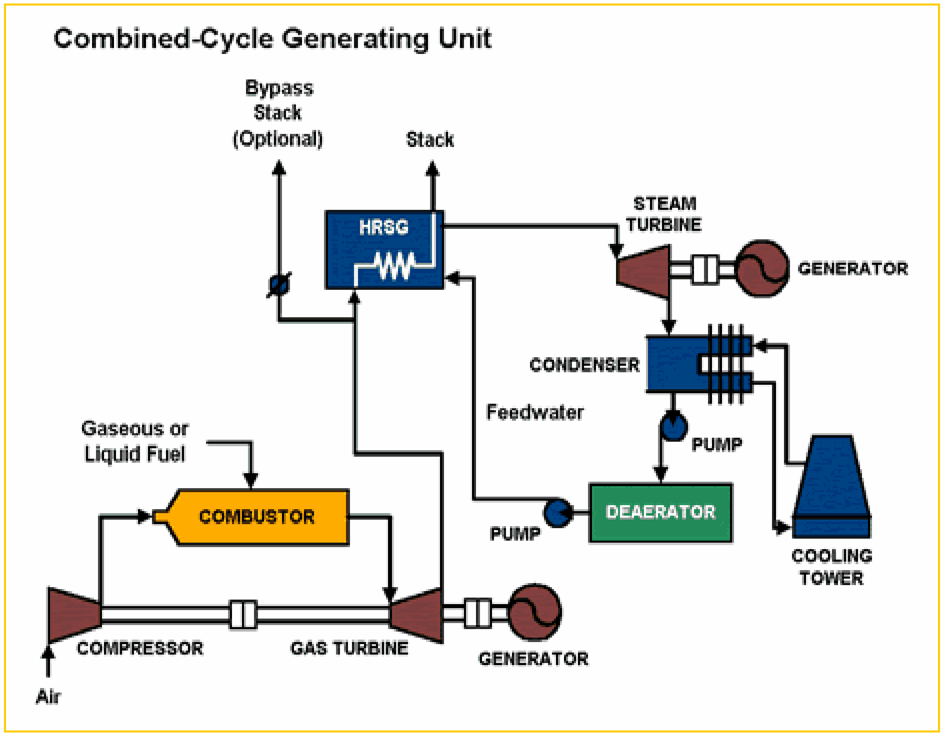
Nuclear Power Plant
- Bad public opinion
- Low emissions

Gas Powered Plant
- Methane is priced high
- Producing methane on sight

Coal Powered Plant
- High emissions
- Coal supply needed

Power Plant

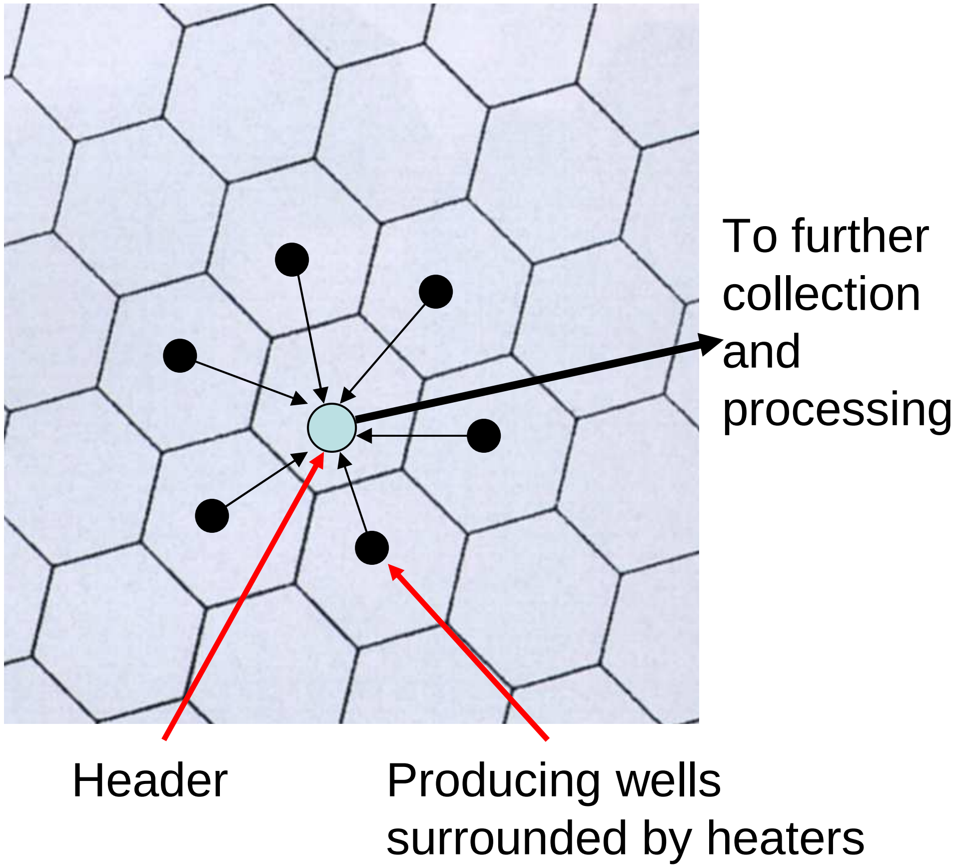
- Combined Cycle
  - Capital Cost, $500M
  - Operating Cost, $60,000/day
  - Natural Gas Required, 110M ft^3
  - Electricity Generated, 800 MW
  - Efficiency, 57%



R.H. Kehlhofer, et al., Combined-Cycle Gas & Steam Turbine Power Plants

Gathering Pipelines

- Well to Header
  - 4” Schedule 80, Carbon Steel
  - Oil & Gas
- Header to Main Gathering Pipe
  - 8” Schedule 80, Carbon Steel
  - Oil & Gas
- Main Gathering Pipe to Processing Facility
  - 20” Schedule 80, Carbon Steel
  - Oil & Gas



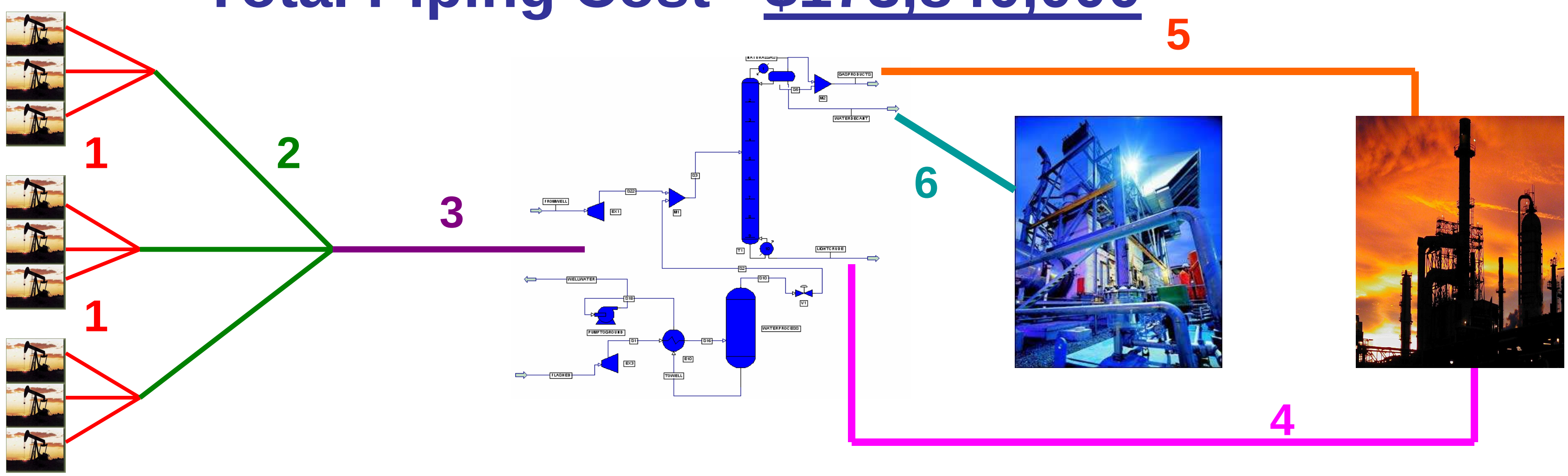
Sell Pipelines

- Gas to/from Market
  - 8” Schedule 80, Carbon Steel
- Oil to Market
  - 12” Schedule 80, Carbon Steel
- Gas to Power Plant
  - 16” Schedule 80, Carbon Steel

Pipeline Costs

Pipe Description	Contents	D (in)	Schedule	Length (ft)	$/foot	Total Cost
1. From Well	Oil & Gas	4	80	400000	$ 10	$ 4,000,000
2. From 1 Acre	Oil & Gas	8	80	100000	$ 30	$ 3,000,000
3. From 10 Acres	Oil & Gas	20	80	1000	$ 100	$ 100,000
4. Crude Oil to Sell	Oil	24	80	1188000	$ 110	$ 130,680,000
5. Gas to sell	Gas	8	80	1188000	$ 30	$ 35,640,000
6. Gas to Power Plant	Gas	10	80	10500	$ 40	$ 420,000

Total Piping Cost= $173,840,000



Production Schedule

- Ten acre tracts
- 40,000 BPD per tract
- A new tract every year

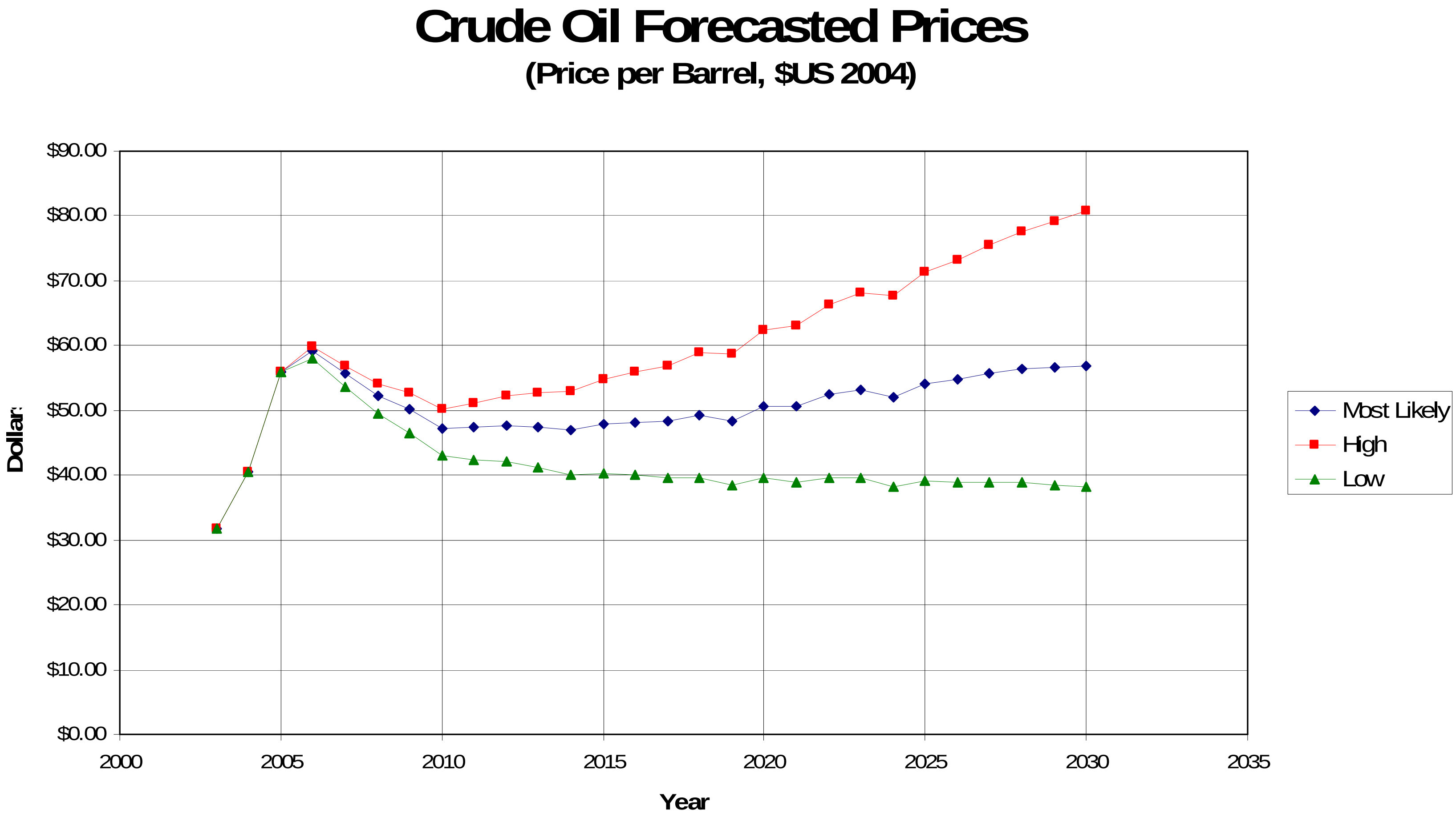
Schedule Table

- (grey) site preparation: drilling wells, freeze wall formation, water removal
- (red) heating only
- (blue) Production: refrigeration and heating continues
- (green) water injection
- (yellow) site reclamation

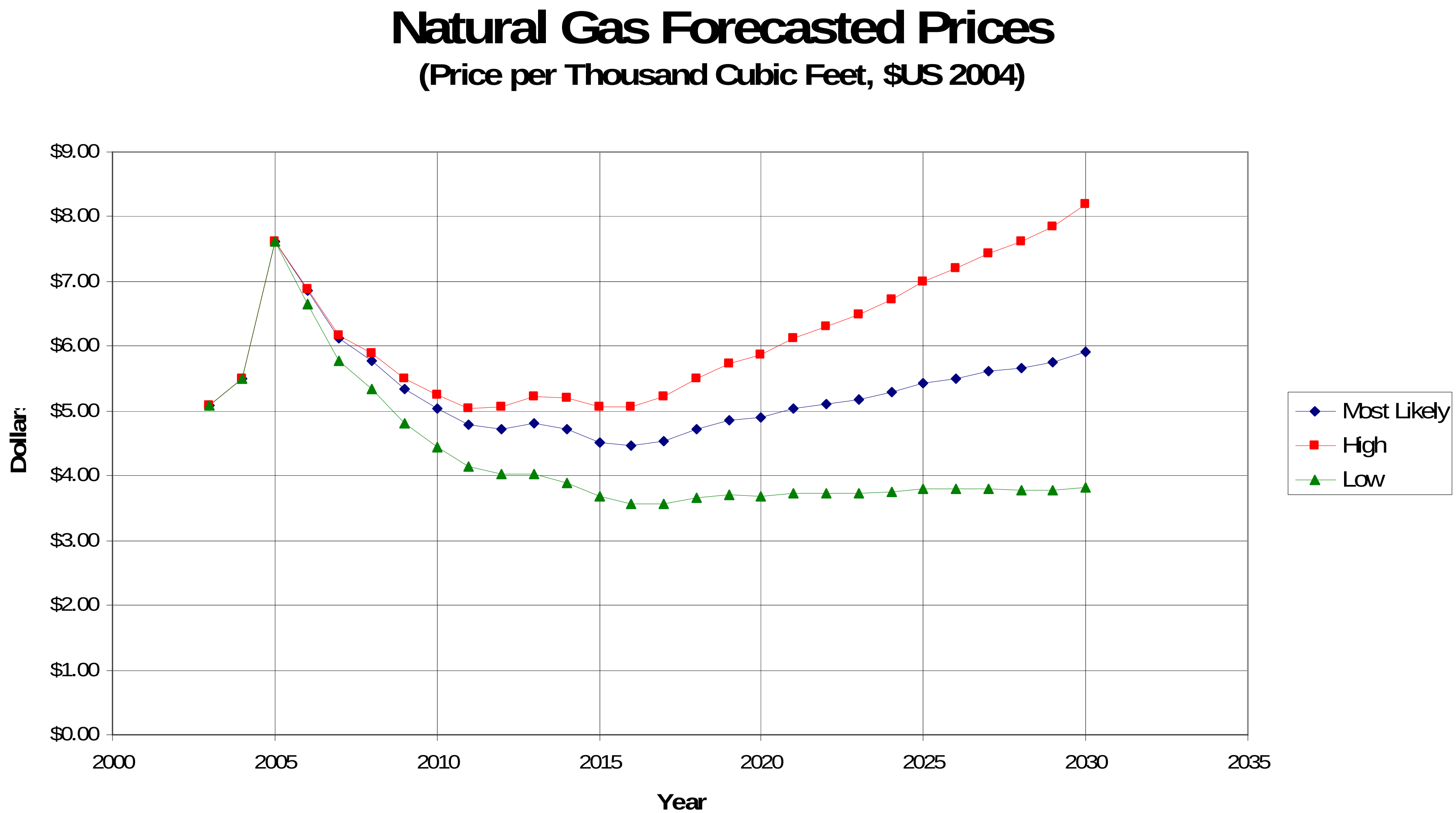
Environmental Effects

- Location
  - Colorado Rocky Mountains
  - Lack of infrastructure
  - Low population
  - Natural habitats affected largely
- Ground Coverage
  - Drilling cannot occur on slope
  - Wells spaced 30-60 ft apart
  - Large land clearings necessary
- Emissions
  - Choice of power plant
  - Processing on site

Crude Oil Price Forecast



Natural Gas Price Forecast



Pricing Estimations

- **Includes**
  - Equipment costs
  - Heating
  - Cooling
  - Power Plant
  - Drilling
  - Production taxes
  - Operating costs
- **Excludes**
  - Logistical costs
    - Extensive Road building
    - Transporting materials
    - Relocating employees
  - Research costs
  - Reclamation costs

Processing Equipment Costs

Component	Basis of Estimation	Cost
a. Heat Exchangers	5 @ $15,867	$80,000
b. Distillation	D=3m, H=6m, 10 trays	$87,000
c. Mixer #2	D=.508	$16,000
d. Mixer #1	D=.4572m	$14,000
e. Flash #1	D=1m, H=10m	$15,000
f. Pump	.0544 m3/s, 6800 kPa	$40,000
g. Pumps (piping)	2 w/ .151 m3/s, 1035 kPa	$32,000
h. Heat Exchangers	3 w/ SA= 100 ft2	$3,600
i. Expander	P=1932 kW	$235,000
j. Expander #2	P=552 kW	$105,000
k. Compressor	5800 kW, centrifugal-rotary	$1,100,000
	Processing Equipment Costs	$1,727,600

Extraction Equipment Costs

Component	Basis of Estimation	Cost
a. Heaters	25/acre @ $100,000	$25,000,000.00
b. Refrigeration plant	800 KW capacity	$12,500,000.00
c. Pump	80, 1.6M gal/hr water, 2 weeks	$1,840,000.00
d. Power Plant	Combined Cycle, $400/kWh	$500,000,000.00
	Extraction Equipment Costs	$541,067,000

Total Capital Investment = $867 million

Annual Costs

Component	Basis for Estimate	Cost Per Year
I. Manufacturing Cost		
A. Direct Production Costs		
1. Raw Materials		
a. Cooling Water	178M lb/hr $0.08/1000kg	$1,650,000
2. Operating Costs		
a. Drilling Costs (contract)		$22,400,000
		00
		00
		00
3. Di		00
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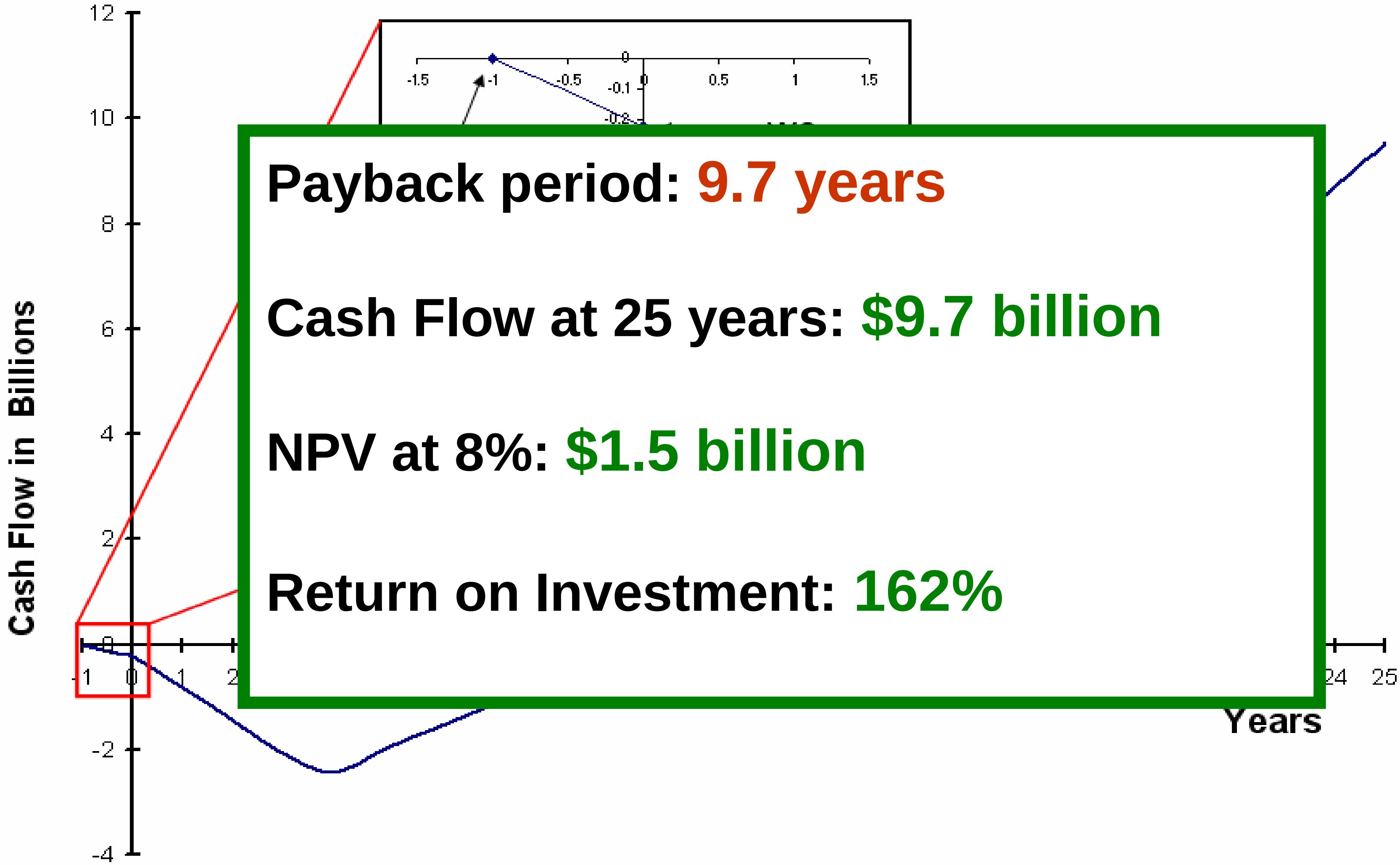
		00
		00
4. Ma		00
5. Op		00
6. La		00
7. Pa		$0
B. Fixed Charges		
1. Capital Costs	Straight Line Depreciation, 25 years	$33,027,000
a. BLM Production Tax	12.5% of Gross	$228,617,750
b. Insurance	.7% of FCI	$5,780,000
c. State Production Tax	1% of Gross	$18,289,420
C. Overhead Costs	10% of the Total Product Cost	$56,000,000
II. General Expenses		
A. Administration Costs	20% of Operating labor and maintenance	$11,960,000
	Total Annual Cost	**$677,800,000**

Cost per barrel: <u>*$23.21*</u>

Profit Estimates



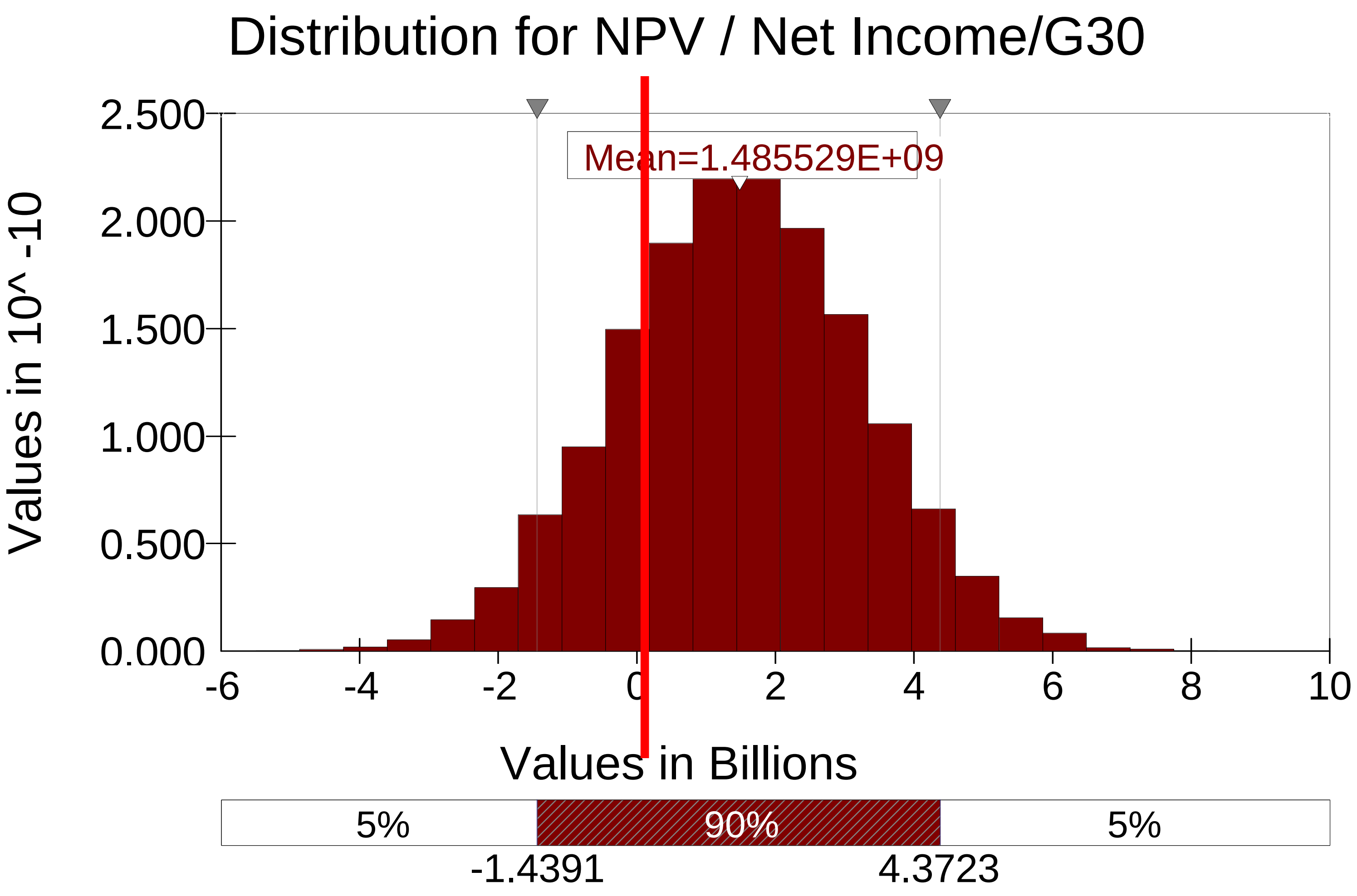
Payback period: 9.7 years

Cash Flow at 25 years: $9.7 billion

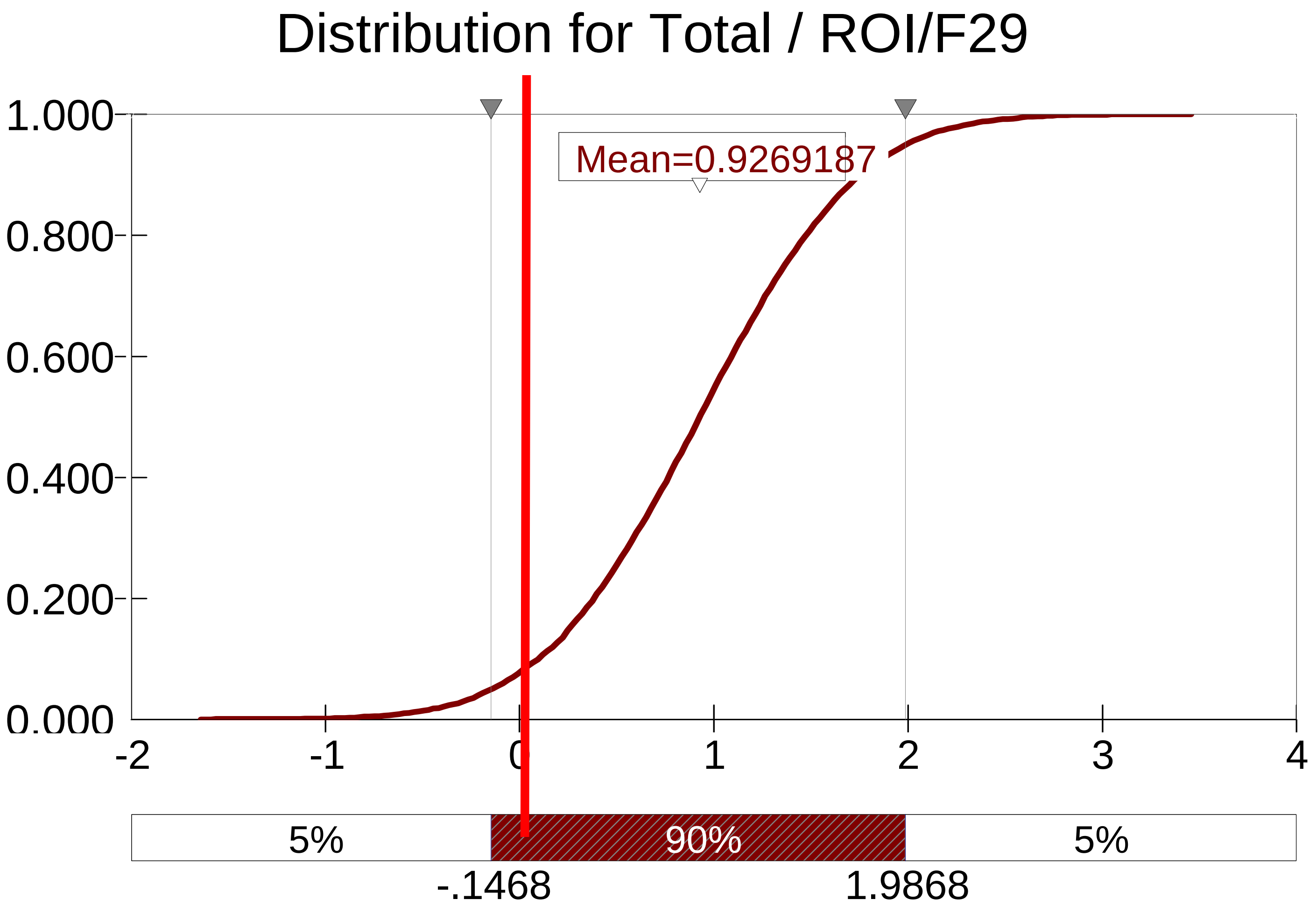
NPV at 8%: $1.5 billion

Return on Investment: 162%

Risk Assessment



Risk Assessment



Future Work

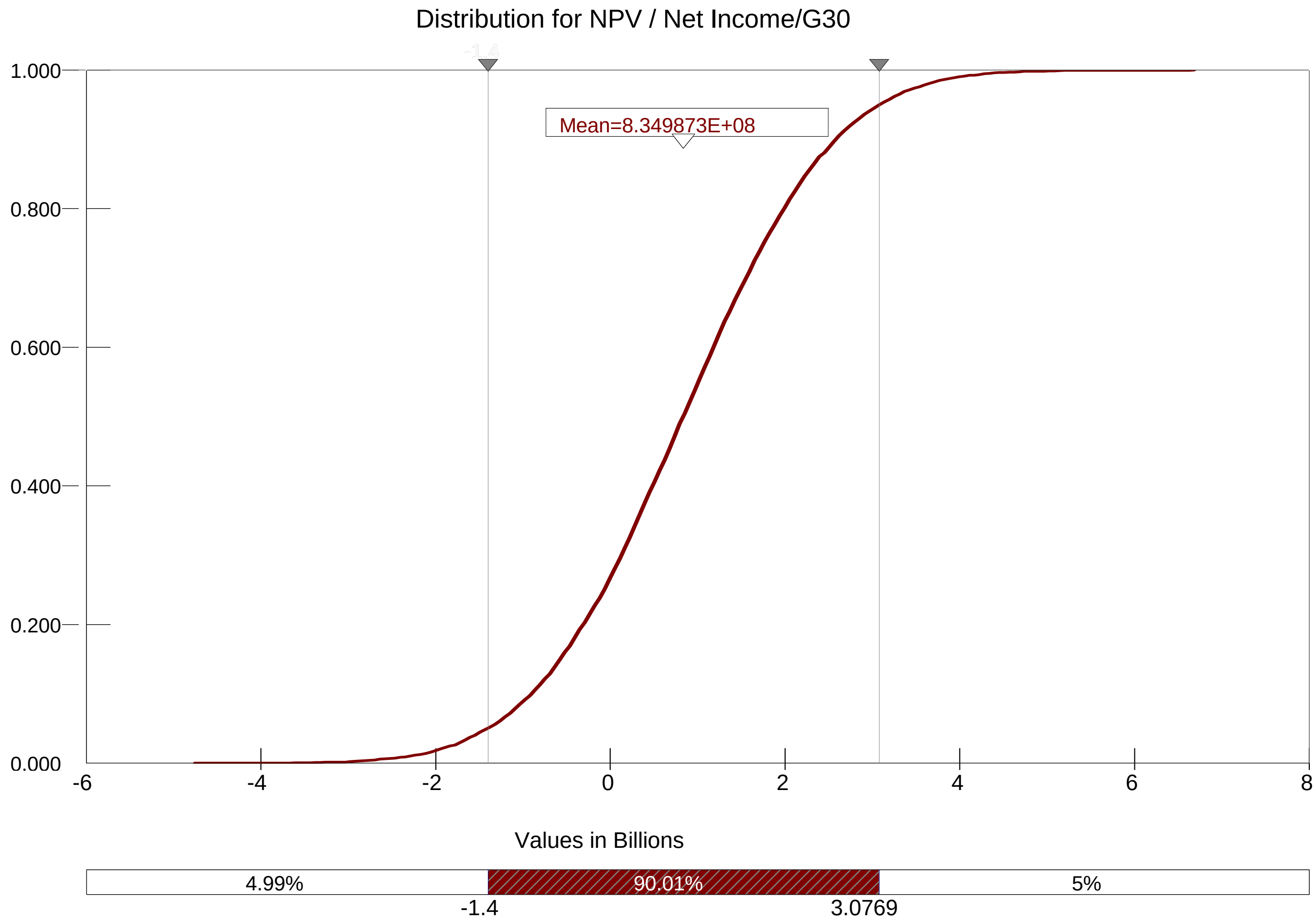
- Logistics
  - Transportation of materials
  - Drilling complications
  - Reclamation Process
  - Work Force
- Optimizations
  - Heater to heater distances
  - Heater temperature
  - Heater material
  - Composition of reservoir
- 3D temperature profile
- Detailed project risk assessment


Questions?

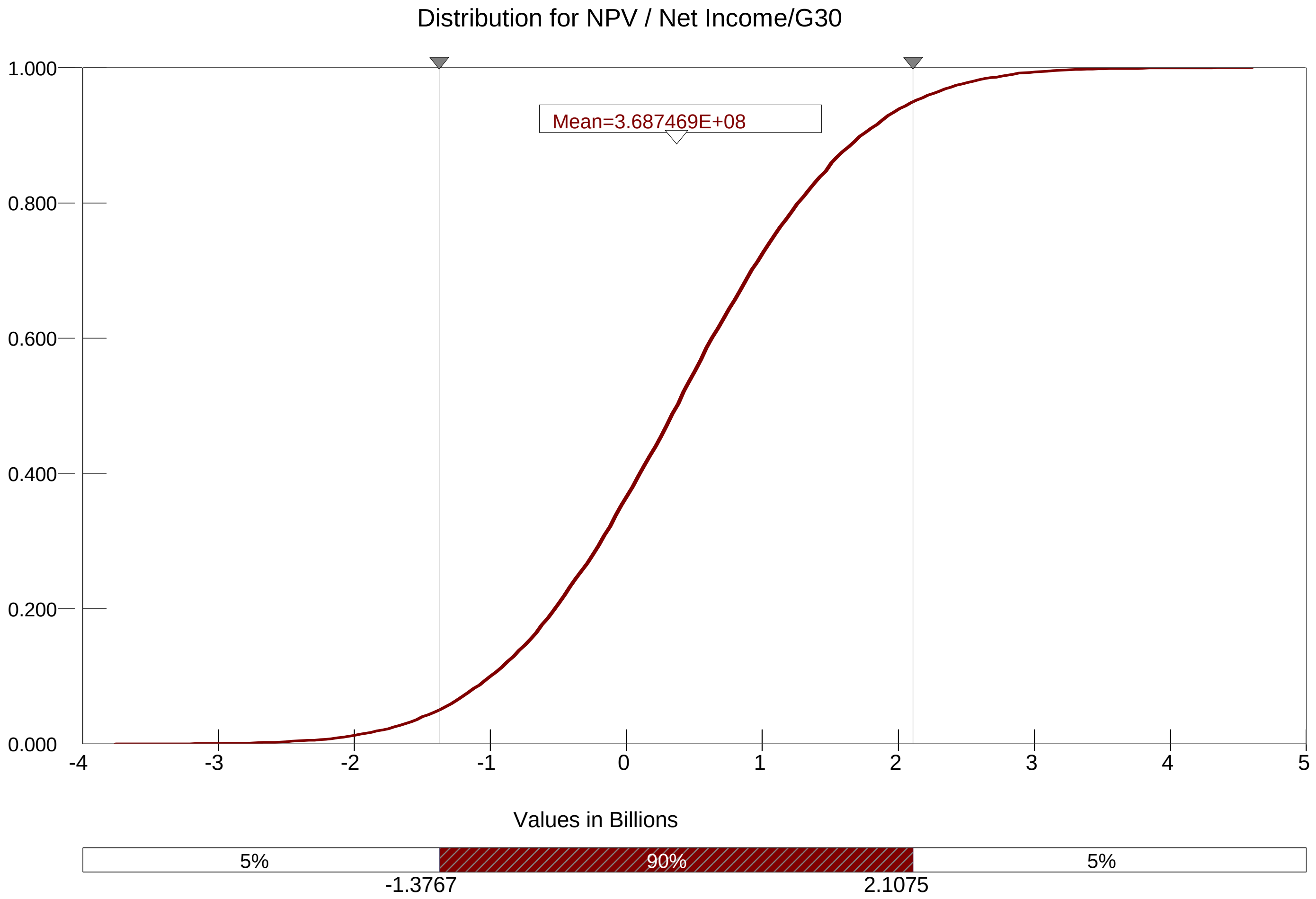
Net Present Values: Varied Rates

Rate	NPV (25 years)
0.08	$1.5 billion
0.10	$0.8 billion
0.12	$0.4 billion
0.15	$-0.1 billion

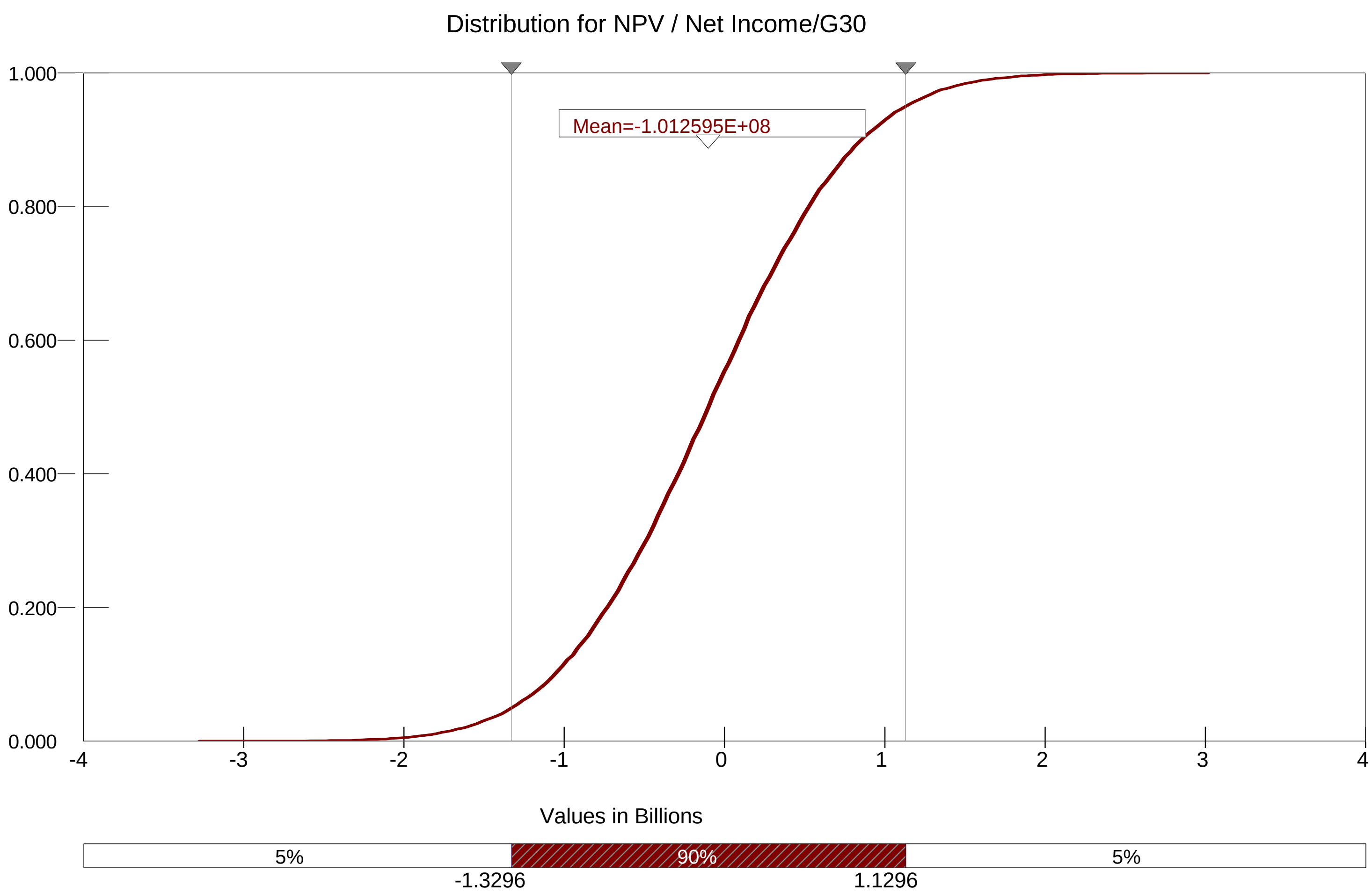
Risk Assessment:
NPV with Rate=10%



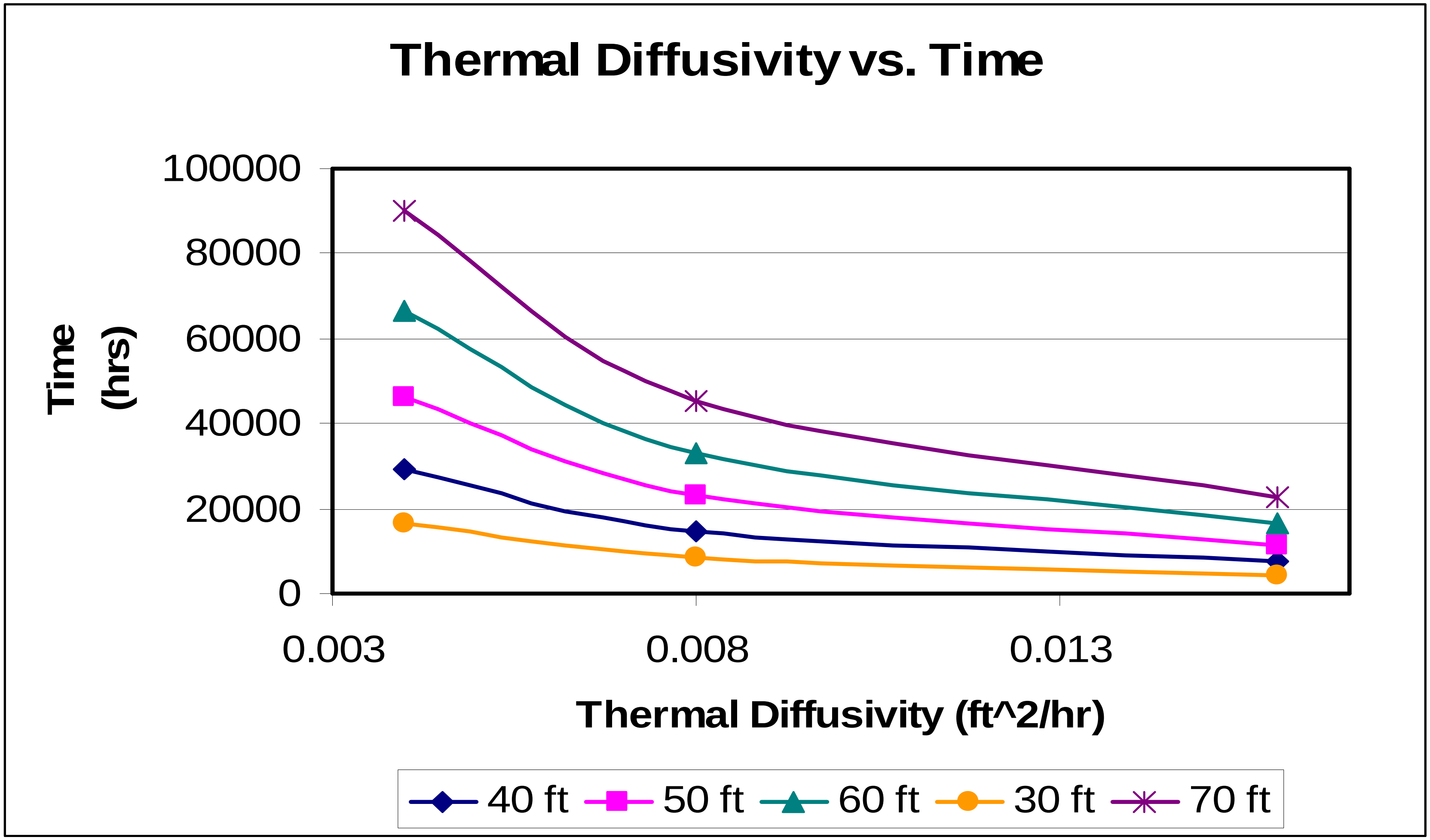
Risk Assessment: NPV with Rate=12%



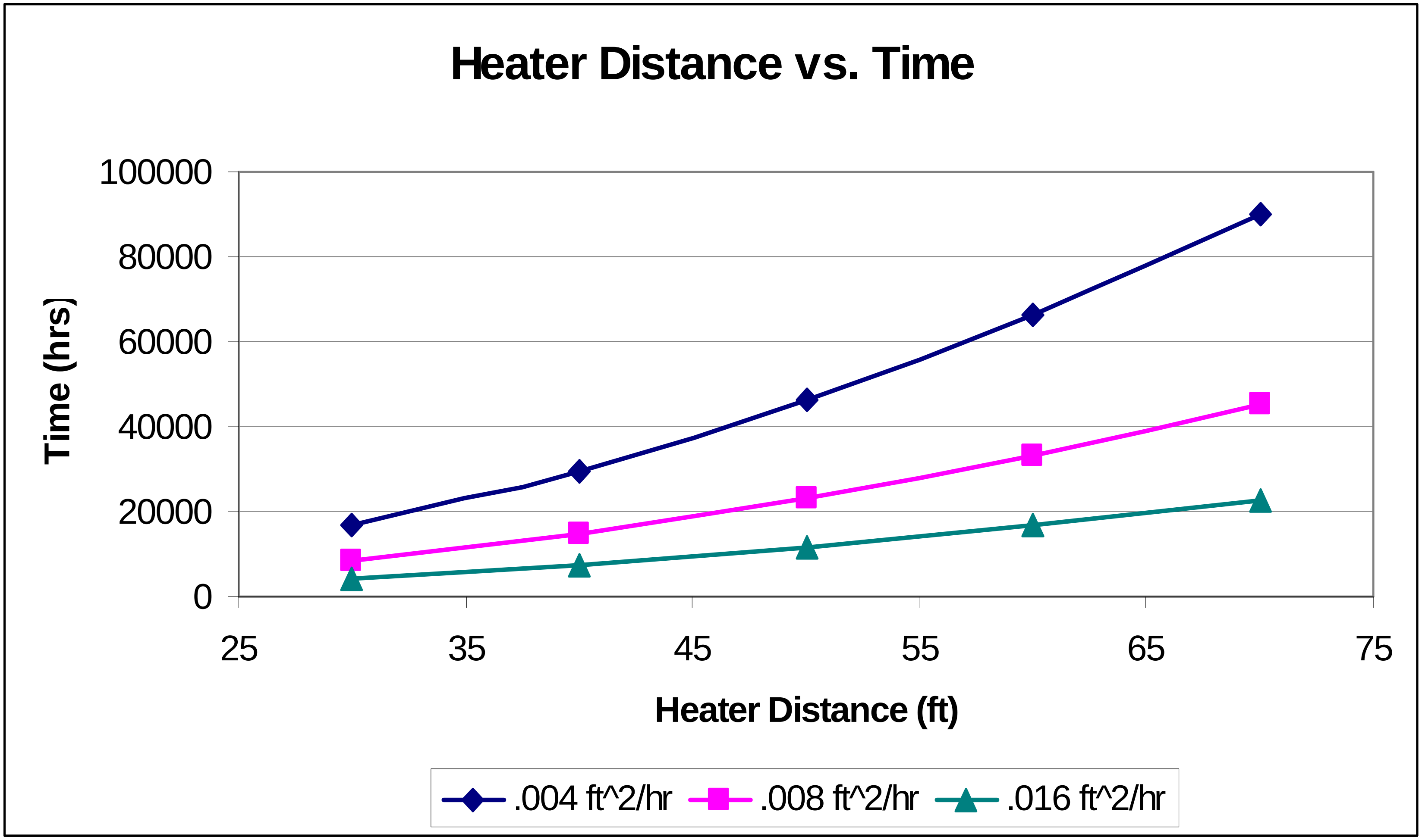
Risk Assessment: NPV with Rate=15%



Temperature Profile: Affect of Thermal Diffusivity



Temperature Profile: Affect of Heater Distance



Reservoir Production: Fracturing