O_2n-Site Oxygen Production

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Outline

- Project Goal
- Brief Theory
- Progression of Project Design
- Design Conclusions
- Business and Economic Analysis

Problem Statement

- Develop a marketable oxygen generator for local onsite production in medical facilities
- This system should compete with current distribution prices

Recommendation

- Two adsorption system, incorporating both N_2 and Argon pressure swing adsorption, is the recommended system
- Onsite cryogenic distillation is not profitable

What We Need

- Hospital Need - Oxygen
  - 3000 liquid gallons per month (relatively small)
  - 1.24 lb-mol/hr
  - 99.2% Purity- FDA Standards
    - Dry
    - Remove impurities

Process Selection

- Criteria
  - Safety: NFPA 50 and NFPA 99
  - Purity: USP Standards
  - Space of system
  - *Cost of Equipment and Operations*

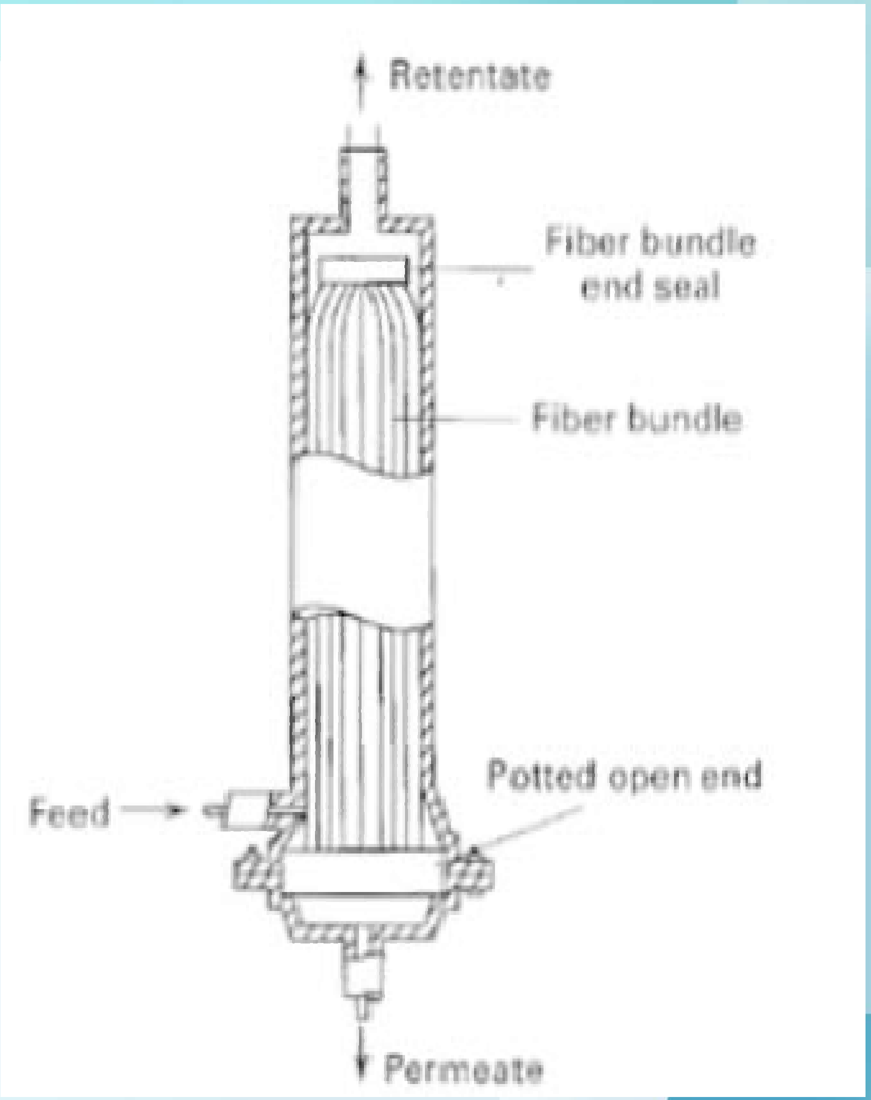
Optimization

- Criteria for optimization
  - Needs of hospital i.e. supply and storage
  - Low maintenance/high convenience
  - Process location and space availability
  - Economics

- Tools for optimization
  - Pro/II
  - Microsoft Excel

Options

- Membrane
  - High purity; still does not achieve needed purity

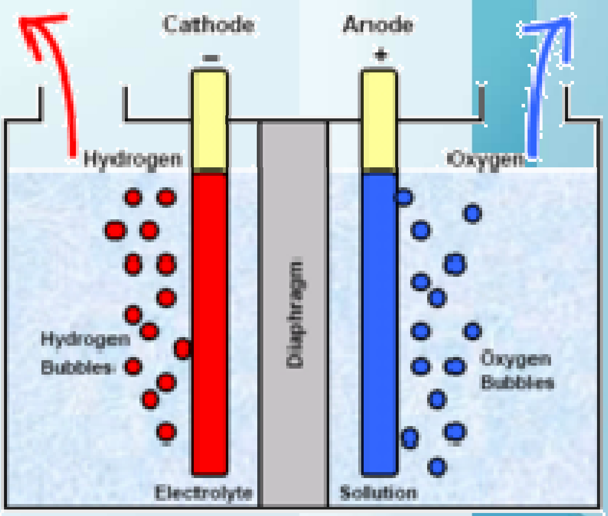


Hollow fiber membrane

Options

- Electrolysis
  - Process cost is expensive; electricity cost alone is more than twice the cost of buying

- Gibbs Free Energy
- $\Delta G = \Delta H - T\Delta S$
- 450 kJ/mol O_2
  →\$38,000/yr energy costs vs. \$19,000



Standard Electrolysis

Options

- Chemical
  - Utilization of a chemical reaction; unwanted product waste

$$F_2(g)+H_2O(l)\rightarrow O_2(g)+2HF(aq)$$

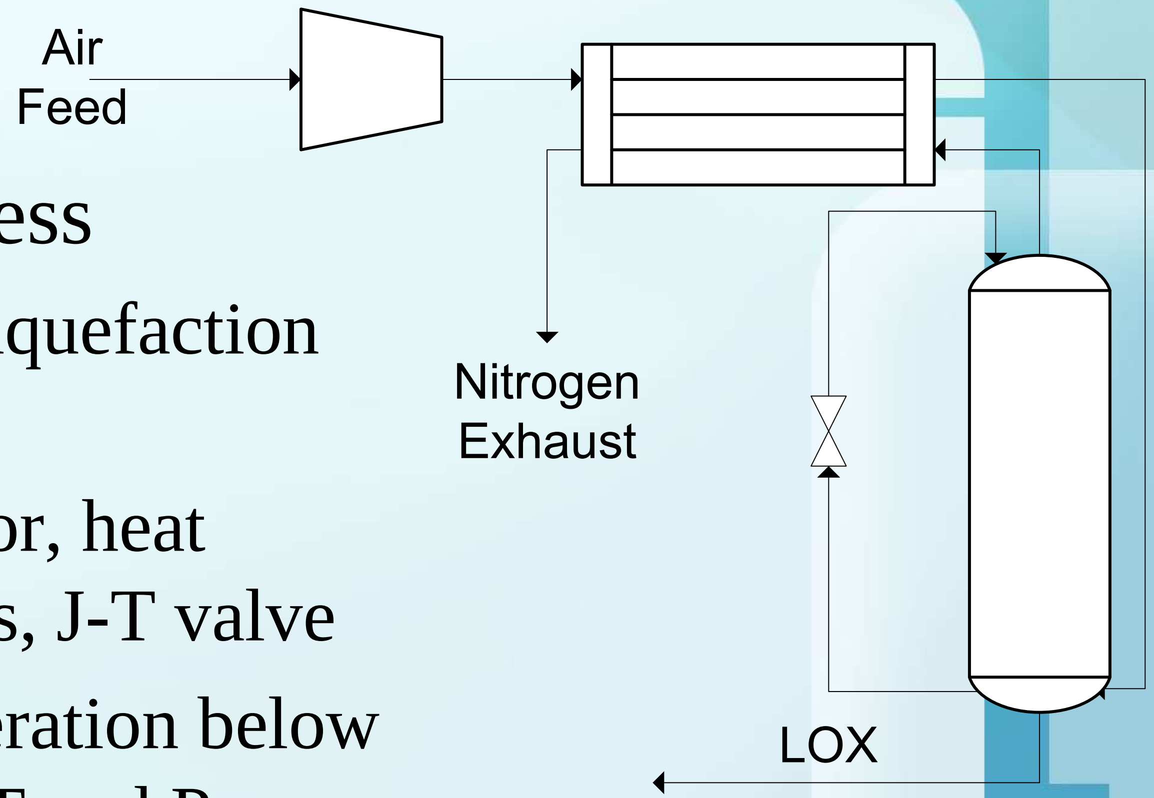
Options

- *Liquefaction*
  - *Can be used to achieve purity of 99.2%*
- *Pressure swing adsorption*

General Theory

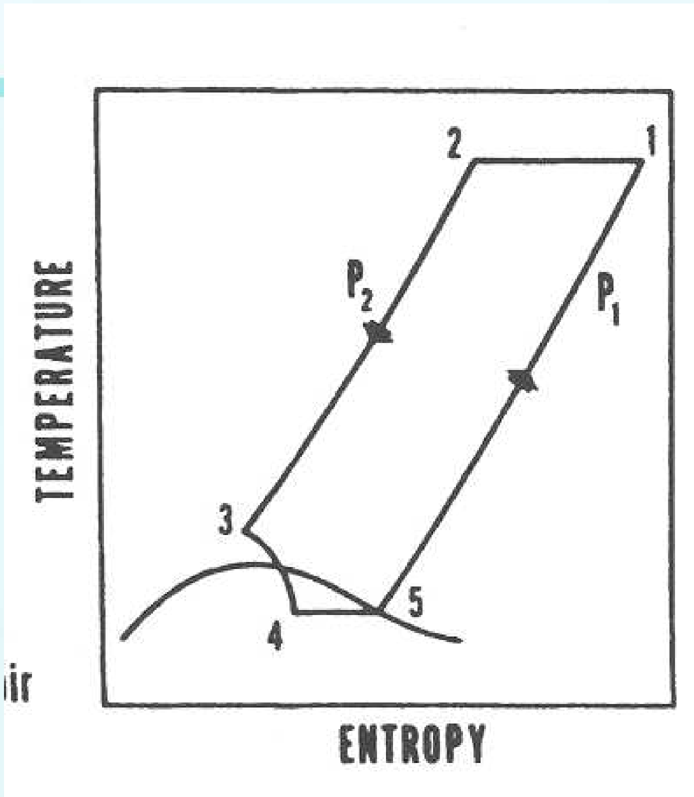
- What is cryogenics?
  - Nitrogen boils at -320 ^{o}F
  - Argon boils at -303 ^{o}F
  - Oxygen boils at -297 ^{o}F
- Carl von Linde, 1985

General Theory



Linde Process

- Simplest liquefaction cycle
- Compressor, heat exchangers, J-T valve
- Valve Operation below inversion T and P

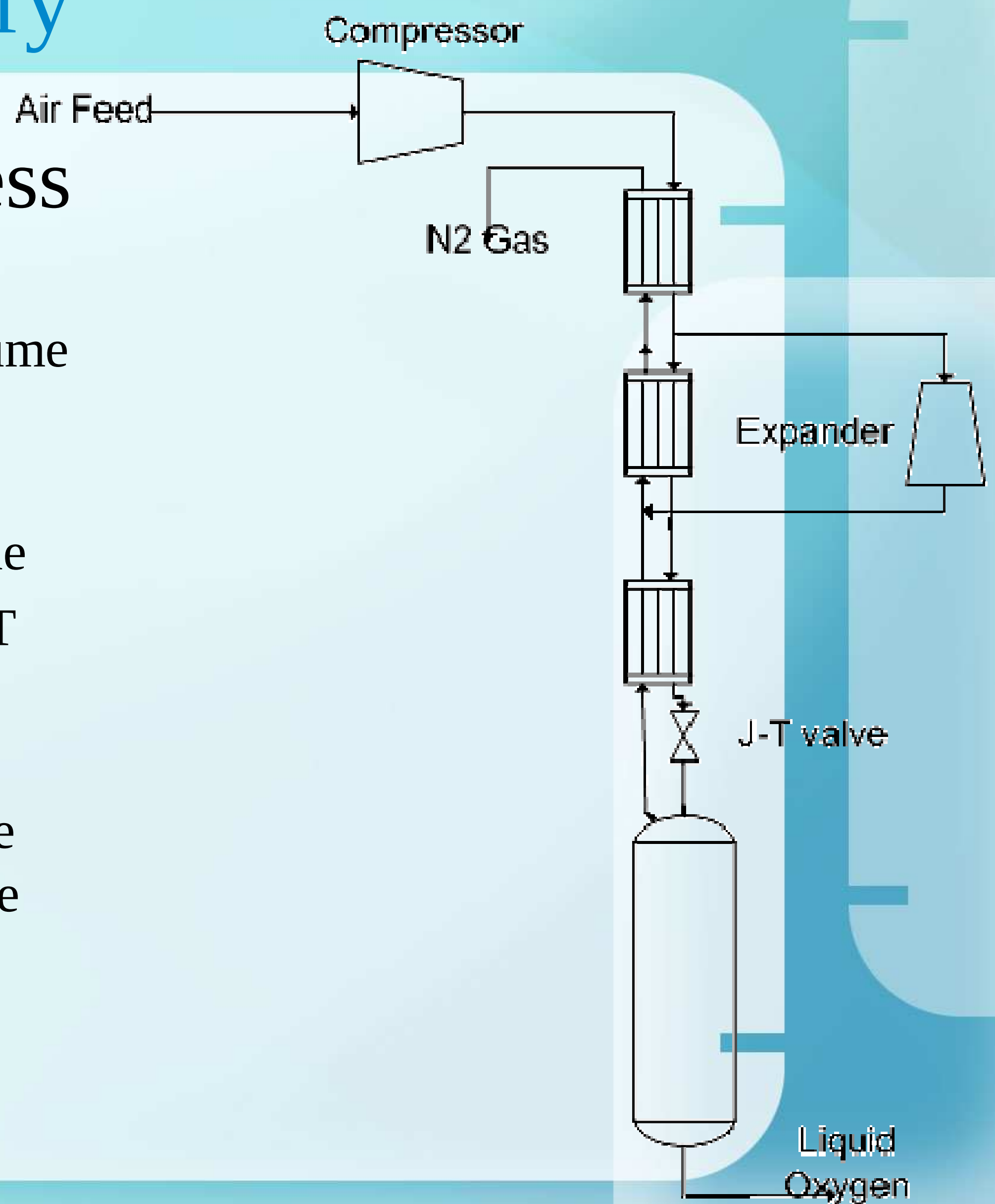


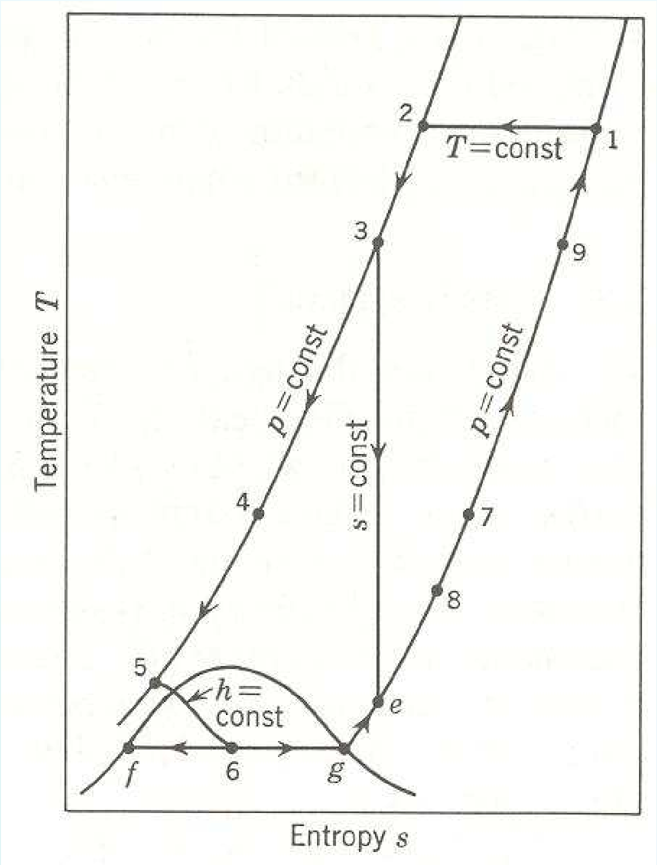
TEMPERATURE
ENTROPY
1
2
3
4
5
P2
P1
ir

General Theory

Claude Process

- Modern high volume Cryo-plants
- Compressor, HX, Expansion Turbine
- Below inversion T and P spec. not required
- Hybrid of both the Brayton and Linde Cycle

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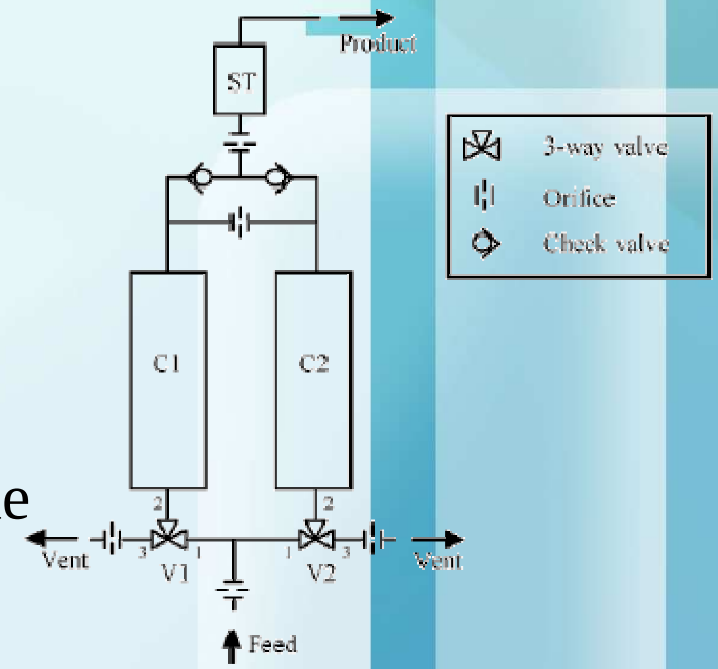
General Theory

Pressure Swing Adsorption

- A separation process through which a bed packed with molecular sieve or zeolite adsorbents are used to selectively adsorb a desired substance from a pressurized feed stream

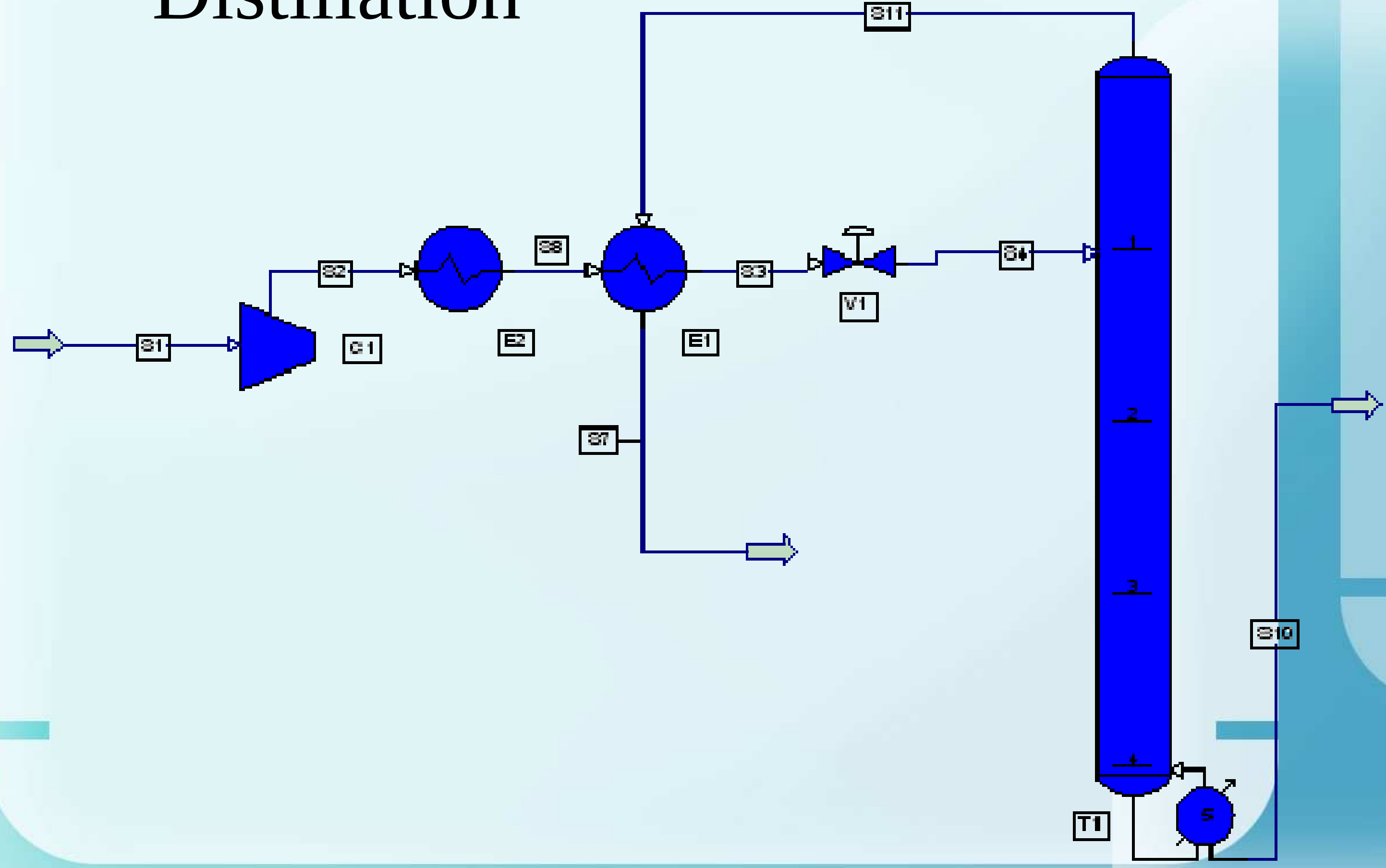
General Theory

- Two equal beds operate in alternating modes:
  1) adsorption
  2) desorption
  - this allows for continuous operation
- While one column is in mode 1 the other will always be in mode 2



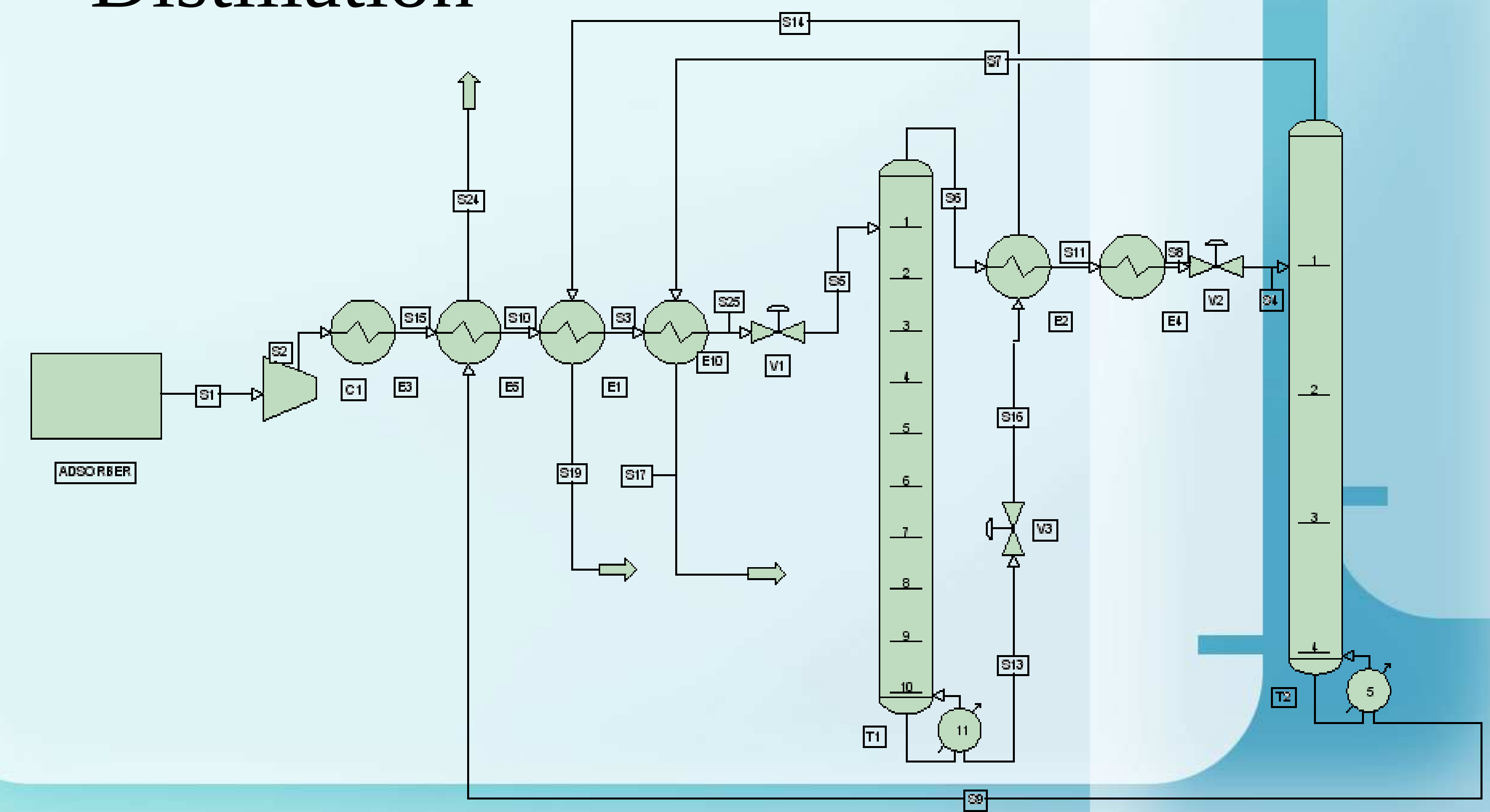
Three Options Considered

1. Air Feed into Cryogenic Distillation



Three Options Considered

2. Air Feed into an N_2 Adsorber followed by a Cryogenic Distillation



Three Options Considered

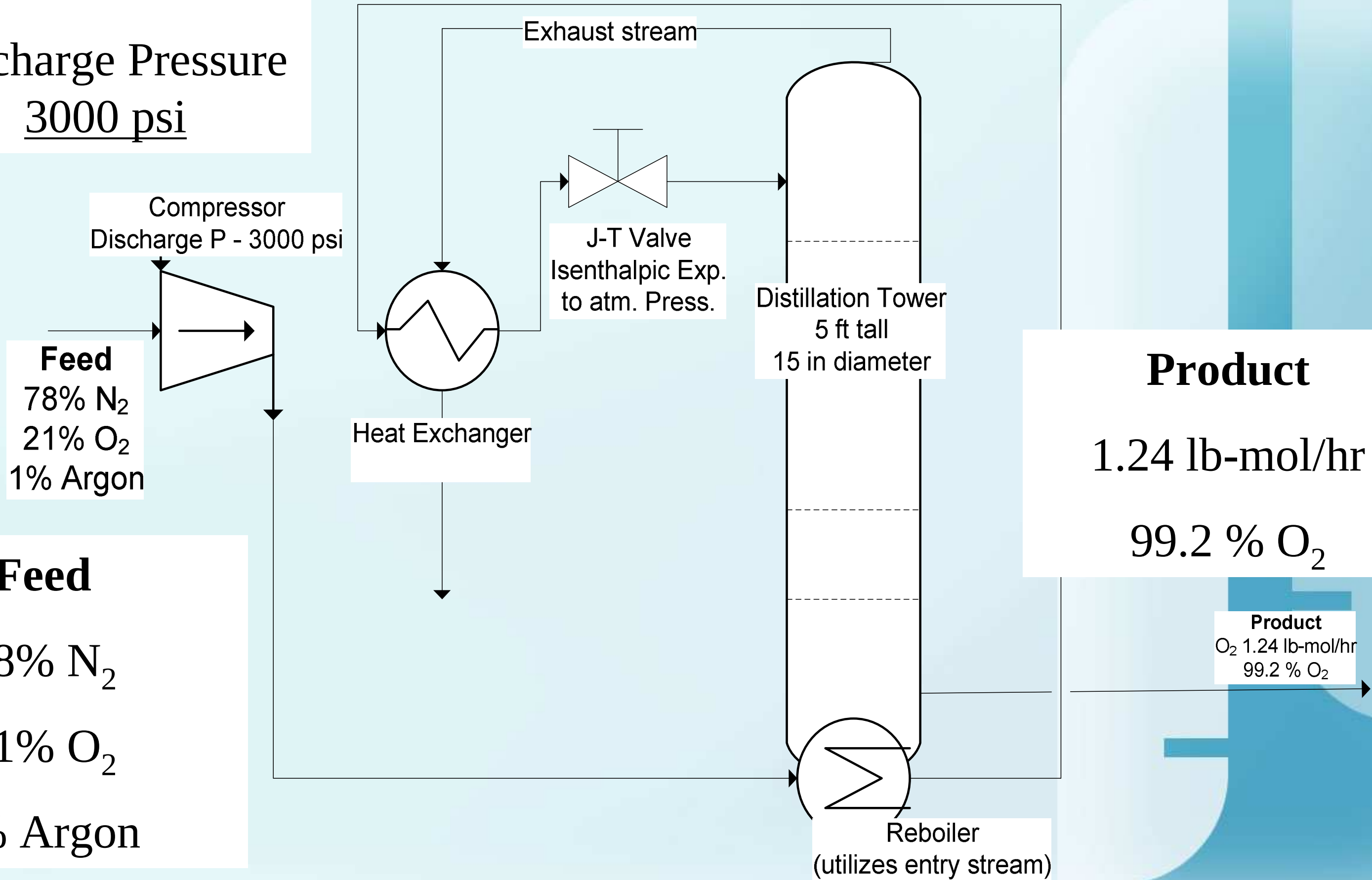
3. Air Feed into an N_2 adsorber followed by Argon removal

Air Feed into Cryogenic Distillation

Compressor

Discharge Pressure

3000 psi



Product

1.24 lb-mol/hr

99.2 % O_2

Feed

78% N_2

21% O_2

1% Argon

Air Feed into Cryogenic Distillation

- Required Flow Rate
  (for 1.24 lb-mol/hr 0_2)
  <u>95,000 ft³/hr</u>

- Requires unfeasible energy to compress

  Nearly 1,400 kW → $700,000/yr

Air Feed, N_2 Adsorber, Cryogenic Distillation

- Two Designs
  - With and Without Expander
- Results and conclusions

Air Feed, N_2 Adsorber, Cryogenic Distillation

- First Design

Expander

Expands to atmospheric

Product

1.24 lb-mol/hr

99.2 % O_2

Feed

21,000 ft³/hr

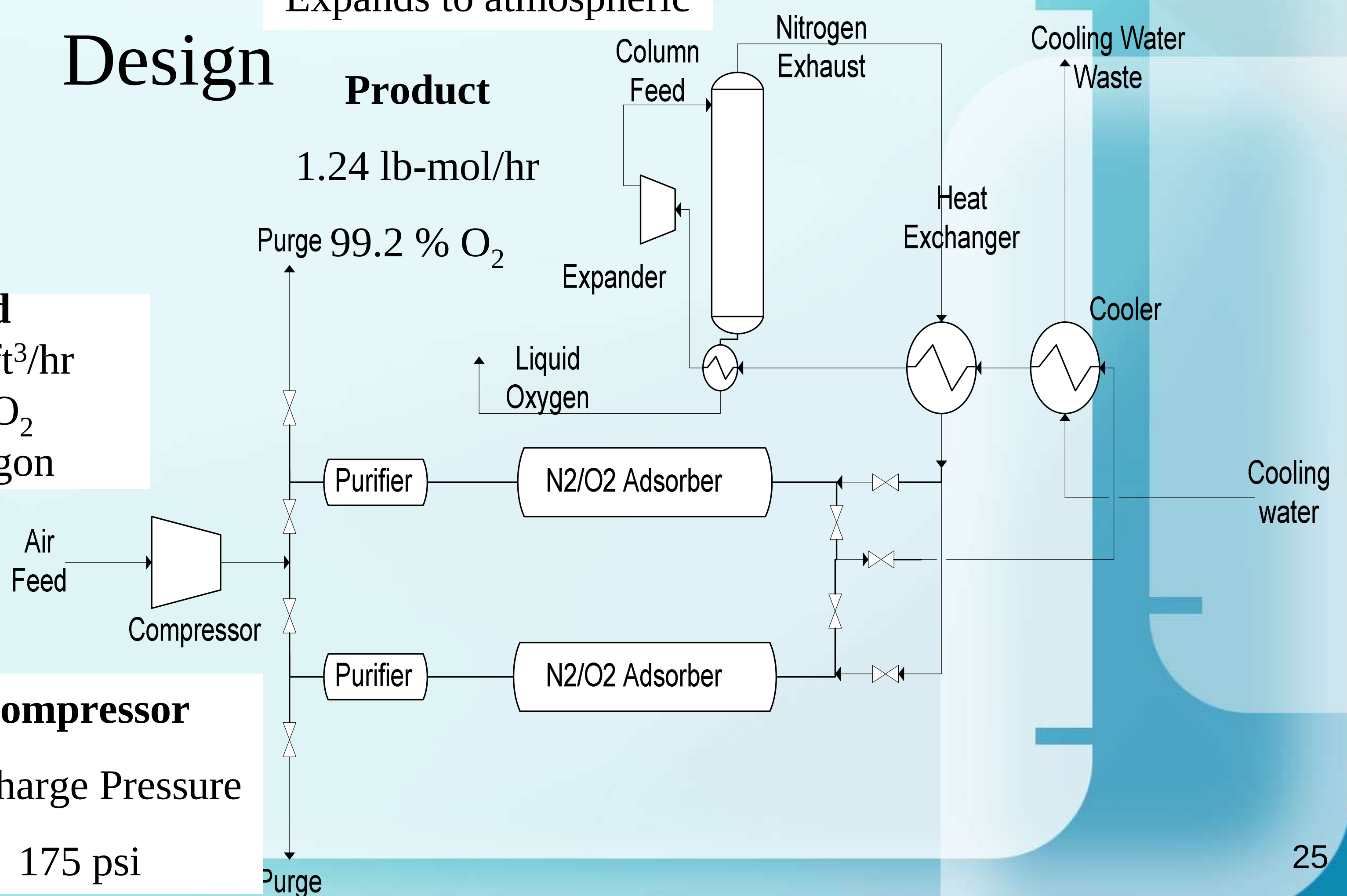
95% O_2

5% Argon

Compressor

Discharge Pressure

175 psi



Air Feed, N_2 Adsorber, Cryogenic Distillation

Column	$5,300
Cold Box	$34
Compressor	***$105,000***
Heat Exchangers	$14,560
Expander	***$105,000***
Pressure Swing Adsorber - O_2/N_2	$3,530
Pressure Swing Adsorber - Purifier	$1,900
Piping	$1,900
Total Equipment Cost	**$237,000**

Air Feed, N_2 Adsorber, Cryogenic Distillation

Operating Cost

Compressor Power	$35,300
Water	$900
Total	**$36,200**

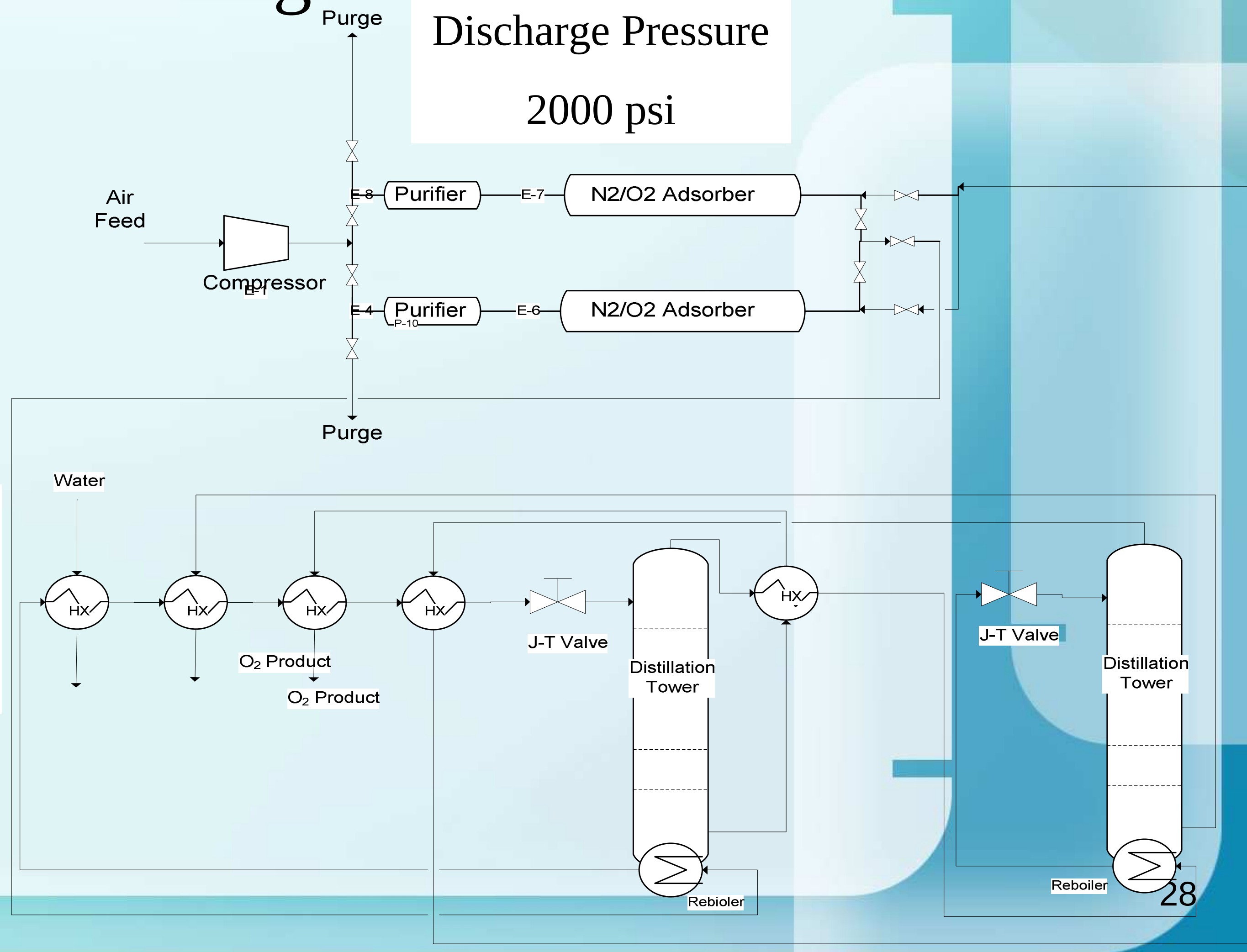
Air Feed, N_2 Adsorber, Cryogenic Distillation

- Second Design

Compressor

Discharge Pressure

2000 psi

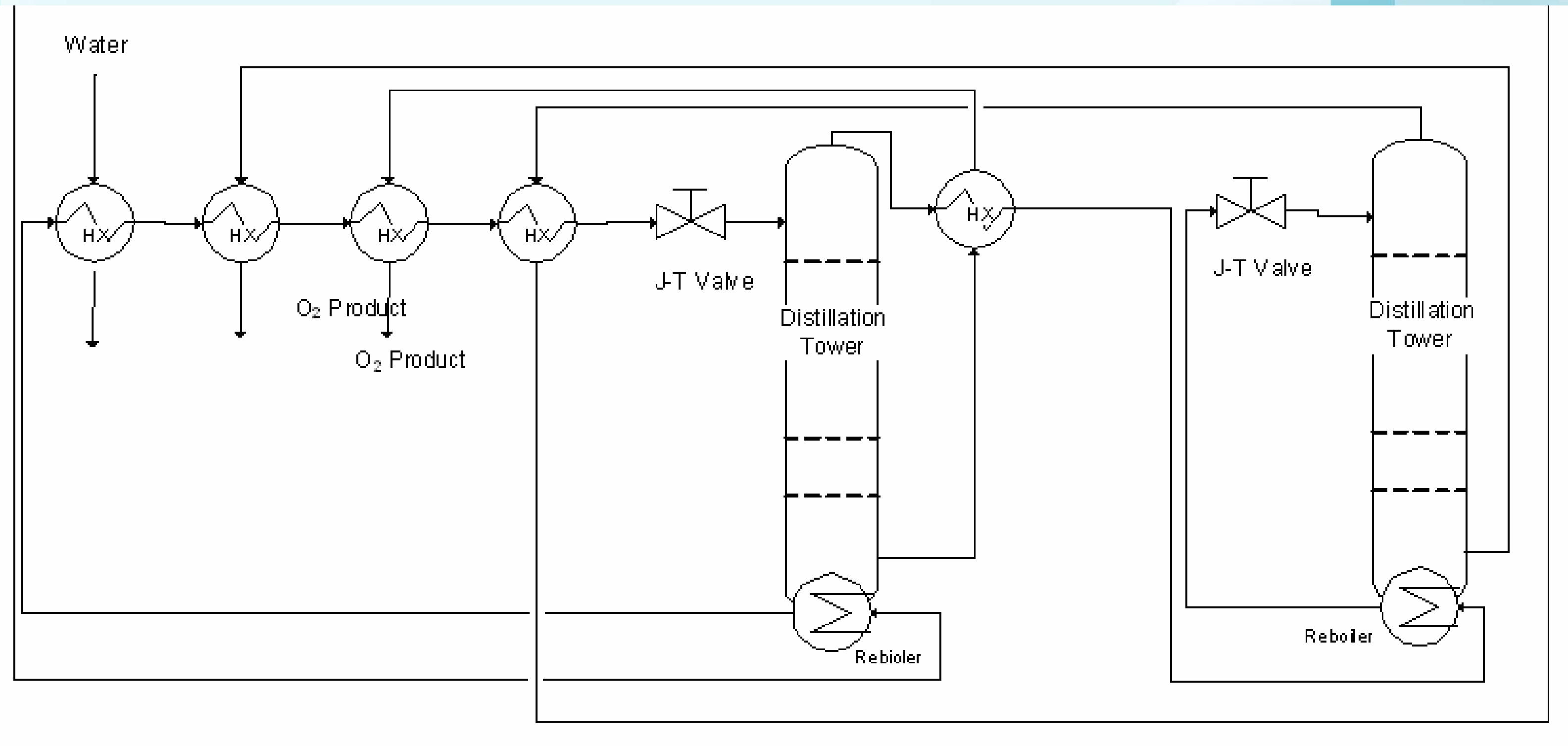


Feed (to cryo process)

8,000 ft^3/hr

95% O_2

5% Argon


Water
HX
HX
HX
HX
O2 Product
O2 Product
J-T Valve
Distillation
Tower
Rebioler
HX
J-T Valve
Distillation
Tower
Reboiler

Air Feed, N_2 Adsorber, Cryogenic Distillation

Equipment Costs

Column:	$10,600
Cold Box:	$100
Compressor:	*$200,000**
Heat Exchanger:	$4,000
Adsorber (O_2/N_2):	$3,500
Adsorber (Purifier):	$2,000
Piping:	$2,300
Total Capital Cost	**$222,500**

* RIX Industries, Rick Turnquist Sales Engineer

Air Feed, N_2 Adsorber, Cryogenic Distillation

Total Operating Cost	$/yr
Compressor Power (130 kW)	$70,000
Water	$5000
Total	**$75,000**

- OG&E Electricity: $0.058/kWh
- OKC Water: $0.255/1000 ft^3
  - 3000 ft^3/hr

Cost Comparison

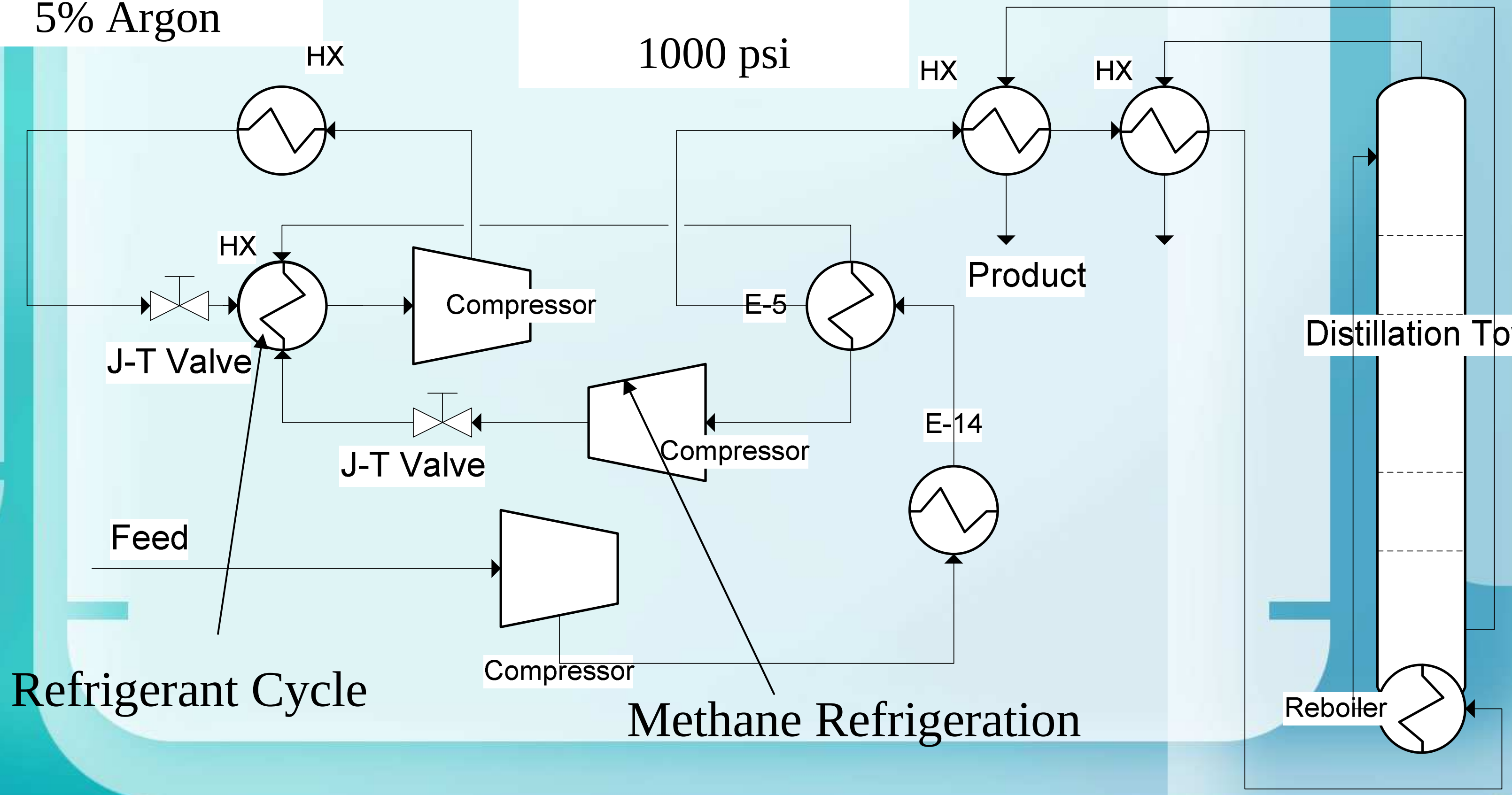
- Competitor
  - Delivered: ***$19,000 per year***
- Proposed first design
  - Total cost per year: $60,000
    - Operating cost: $36,000 per year
- Proposed second design
  - Total cost per year: $97,250
    - Operating cost: $75,000 per year

How Does a Plant Do It?

- Disregarding capital costs

Feed
1,800 ft^3/hr
95% O_2
5% Argon

Compressor
Discharge Pressure
1000 psi



How Does a Plant Do It?

- 20 kW energy
- Results in only $10,500/year energy costs
- Compared to $19,000/yr distribution price

Cryogenic Distillation Conclusions

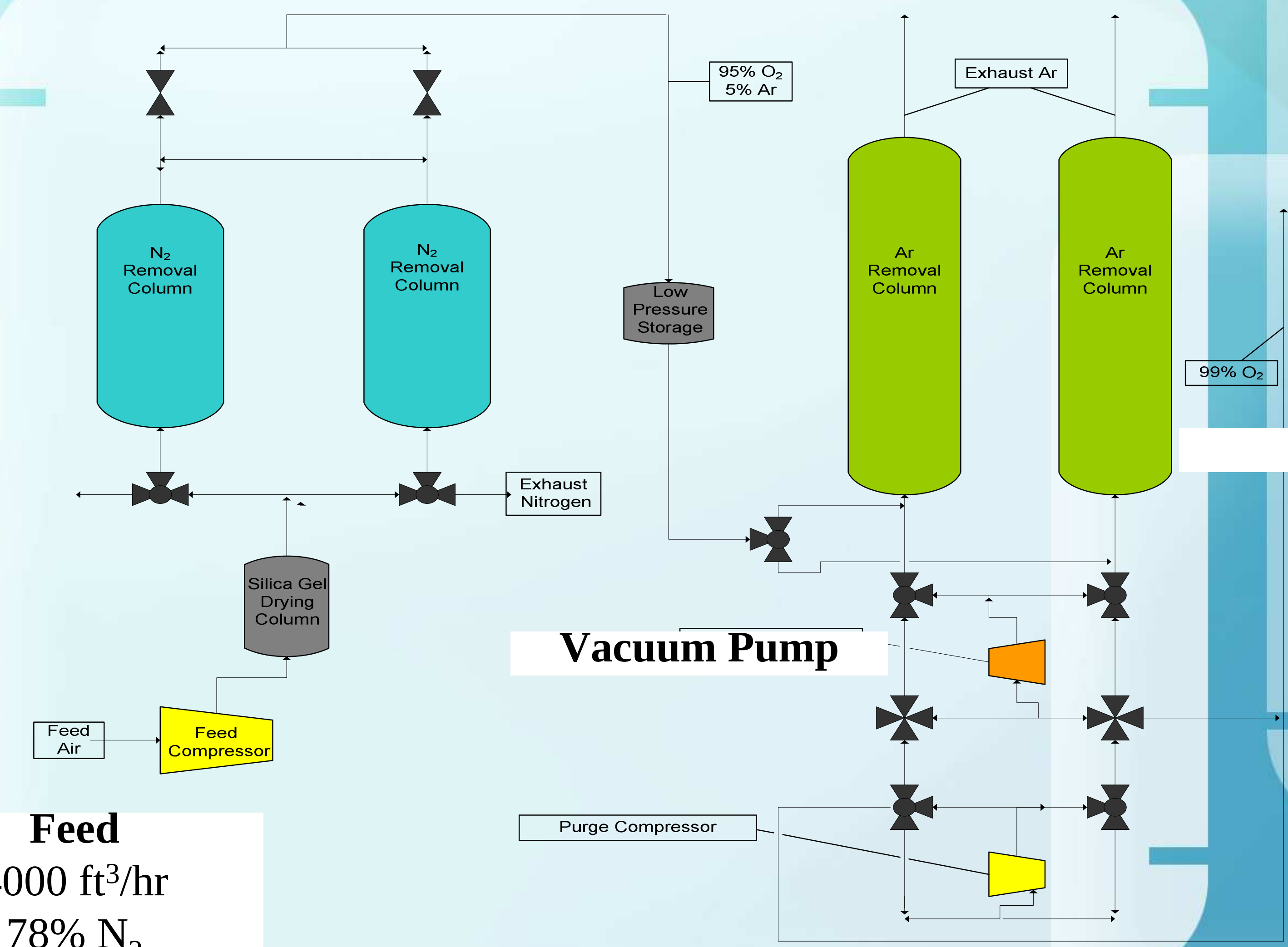
- The process is possible
- Energy costs are appeased by design incorporating more equipment
- Capital cost increase due to more equipment inhibits typical hospitals from making such large investments
  – Meaning → NO SAVINGS

Air Feed, N_2 Adsorber, Argon Adsorber

- Due to the infeasibility of the designed cryogenic system, a system utilizing Pressure swing adsorption to remove both N_2 and Argon removal was designed and examined

Air Feed, N_2 Adsorber, Argon Adsorber– PFD

Exhaust Argon



99% O_2

Vacuum Pump

Feed

4000 ft^3/hr

78% N_2

21% O_2

1% Argon

Nitrogen Removal

Langmuir isotherm for multi-component adsorption

$$q_i = Q_{\max} \frac{b_i P_i}{1 + \sum_{j=1}^{N} b_j P_j}$$

- q_i = loading (mol/kg) on the adsorbent
- Q_{max} = maximum loading (mol/kg) on the adsorbent
- N = the total number of components
- P_i = the partial pressure of component i
- Q_{max} and b_i are given for adsorbent Oxysiv 5

Nitrogen Removal

$$Q_F c_F t_x = q_F M L_x / L_B$$

(Equilibrium driven: mass transfer effects negligible)

Q_F: volumetric feed flowrate

c_F : solute feed concentration

t_x : time of the front at position L_x

M : adsorbent mass in bed

L_x : distance traveled by the front

L_b : length of the bed

q_F : loading per mass of adsorbent

Nitrogen Removal

- Column specifications (per column)
  - Height: 7.2 ft
  - Column diameter:1ft
  - Column volume: 5.6 ft^3
  - Adsorbent weight (Oxysiv 5): 109 kg (240 lbs.)

Argon Removal

Options

- Equilibrium PSA
- Rate based PSA

Argon Removal

- Equilibrium PSA
  - Operates similar to N_2 removal system
  - O_2 and Ar have similar physical properties and adsorption isotherms
  - Nearly equal amounts adsorbed resulting in lower yields

Argon Removal

Langmuir-Freundlich isotherms for O_2 and Ar

$$T = 30^\circ \text{ C.: } n_{Ar} = \frac{8.875 C_{Ar}}{1 + 0.0041 C_{Ar}}\ ;\ n_{O_2} = \frac{7.363 C_{O_2}}{1 + 0.00307 C_{O_2}}$$

$$T = 60^\circ \text{ C.: } n_{Ar} = \frac{5.222 C_{Ar}}{1 + 0.0025 C_{Ar}}\ ;\ n_{O_2} = \frac{4.155 C_{O_2}}{1 + 0.00166 C_{O_2}}$$

$$T = 90^\circ \text{ C.: } n_{Ar} = \frac{3.206 C_{Ar}}{1 + 0.00117 C_{Ar}}\ ;\ n_{O_2} = \frac{2.629 C_{O_2}}{1 + 0.00108 C_{O_2}}$$

Argon Removal

- Kinetic (rate based) separation
  - O_2 adsorbs at a much higher rate than Ar
  - Obtains 99% purity stream by the adsorption oxygen
  - BF-CMS (adsorbent) produces .01157 kg product/kg of adsorbent
  - 52.22% yield

Rege and Yang Kinetic Separation of Oxygen and Argon Using Molecular Sieve Carbon F

Argon Removal

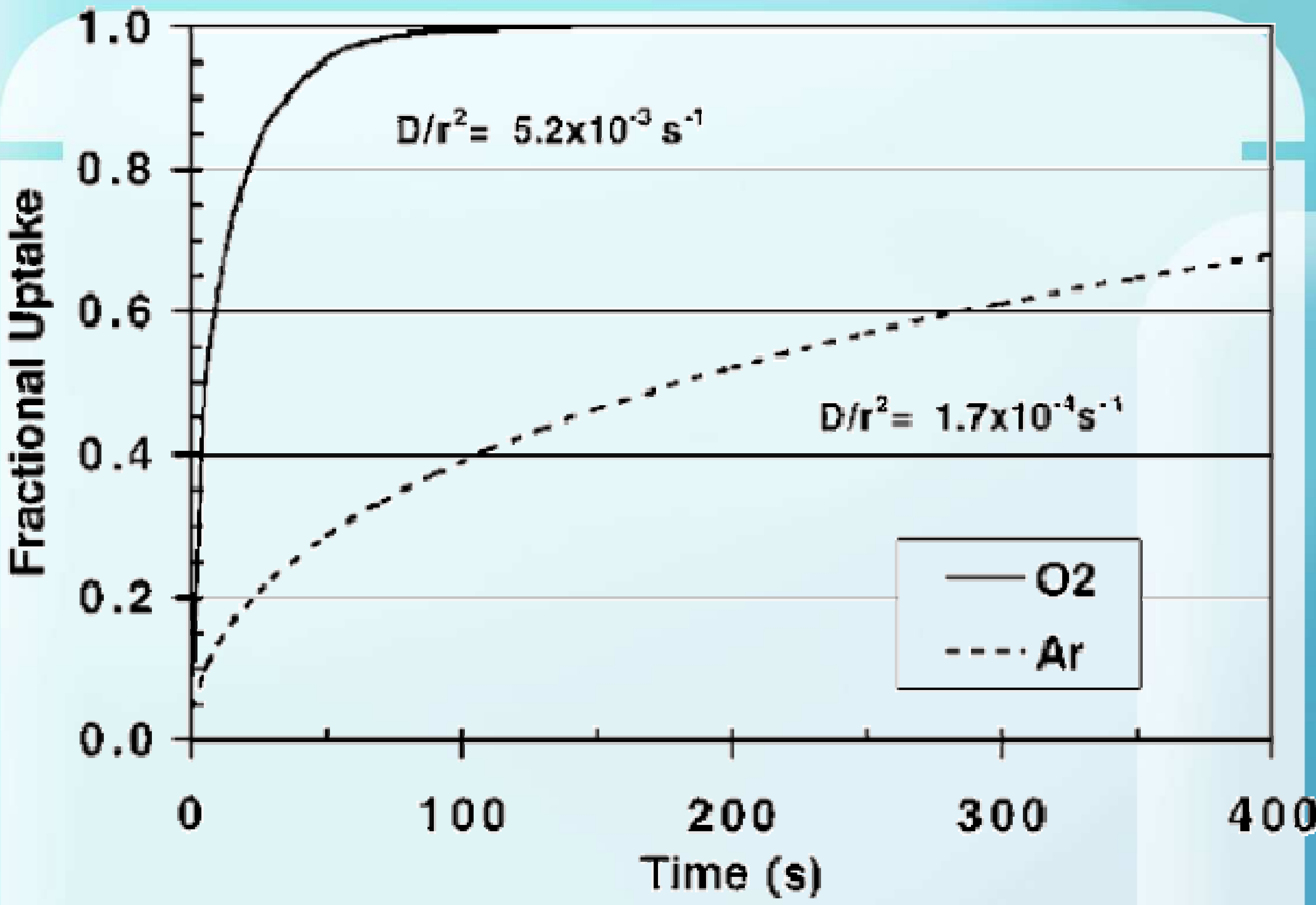
Rate based separation design equations

- Linear Driving Force Model

$$\frac{\partial \bar{q}}{\partial t} = \frac{15 D_e}{R_p^2}\left(q_{R_P} - \bar{q}\right)$$

- t = time
- D_e= effective particle diffusivity
- R_p = radius of a particle
- q_{Rp} = loading at particle surface
- $\bar{q}$ = average loading of component on adsorbent bed

Argon Removal



Fractional Uptake vs. time for Oxygen and Argon on Bergbau-Forschung CMS

Argon Removal

- Column specifications (per column)
  - Height: 16.4 ft
  - A Column diameter: 2.5ft
  - Column volume: 80.7 ft^3
  - Adsorbent weight (BF-CMS): 1554 kg (3425.9 lbs)

Operating conditions

- Nitrogen system
  - Inlet flowrate of 4000 ft^3/hr
  - Feed Air compression to 45 psia
  - Breakthrough time of 1 minute (cycle time of 2 min)
- Argon system
  - 1.24 lbmol/hr product flowrate
  - Air compressed to 2 atm
  - Desorption takes place at .2 atm
  - 99% product oxygen

Materials

	N_2	Ar
Metal	ft^2	ft^2
Adsorption Columns (Al) \$1.5 / ft^2	23	260
Low pressure storage tank (Al)	12	
Dryer Canister (Al)	24	
Frame (Steel) \$2 / ft^2	25	265
Adsorbents	lb	lb
Oxysiv 5 adsorbent \$5.5 / lb	480	
BF-CMS \$3 / lb		6850
Silica gel \$2 / lb	52	

Equipment Cost Summary

	Price	N_2	Ar
Piping	$ / ft	ft	ft
1/2" Sch. 40 Copper	3.61	6	10
Compressors	$	# of items	# of items
Feed	5365	1	
Purge	150		1
Other parts	$/item		
Vacuum pump	100		1
Fan	5	2	2
3-way solenoid valve	86	2	2
Check valve	20	2	2
Control Computer	1000	1	

System Equipment Costs

Final Cost	$31,600
Additional Costs (based on need)	
Tank fill Compressor	**$2,500.00**
High pressure storage tank	**$150.00**
Final Cost with Additions	$34,200

Results

- System occupies 20 by 20 ft^2 area
- Yearly energy costs- $8,500
- Average yearly cost of $15,150 over 10 year life of machine

Comparison

- Average yearly distribution costs

  $19,000

- Average yearly O$_2$n-site generator costs

  $8,500

- Average Yearly savings

  $4,000

Business Plan for Adsorption System

- Open market for this type of equipment
  - Hospital need
  - Dependence on distributors
  - Stability of product price
- Oklahoma
  - Approximately 350 medical facilities

Business Costs

Fixed Costs	
Tools	$10,000
Truck	$90,000
Trailer	$17,500
Clerical Supplies	$2,000
Total	$119,500

Operating Costs per year	
Salaries	$280,000
Insurance and Permits	$23,900
Equipment Maintenance	$11,950
Fuel	$39,000
Total	$354,850

Demand Model

- Factors include:
  - Convenience
  - Maintenance
  - Space
  - Reliability
  - Safety
- H is the product appeal determined on the demand factors

Demand Model

- β represents product preference
  - H_c is competitor appeal
  - H_d is new design appeal

$$\beta = \frac{H_c}{H_d} = .92$$

Factor	w_i	Y_d	y_d	Y_c	y_c
Convenience	0.40	9	0.90	7	0.70
Maint./Op. Cost.	0.20	6	0.60	7	0.70
Space	0.20	6	0.60	6	0.60
Reliability	0.10	9	0.90	8	0.80
Safety	0.10	7	0.70	8	0.80
Total=	1.00	$H_d=\Sigma w_i y_d=$	0.76	$H_c=\Sigma w_i y_c=$	0.70

Demand Model

- Consumer demand equation

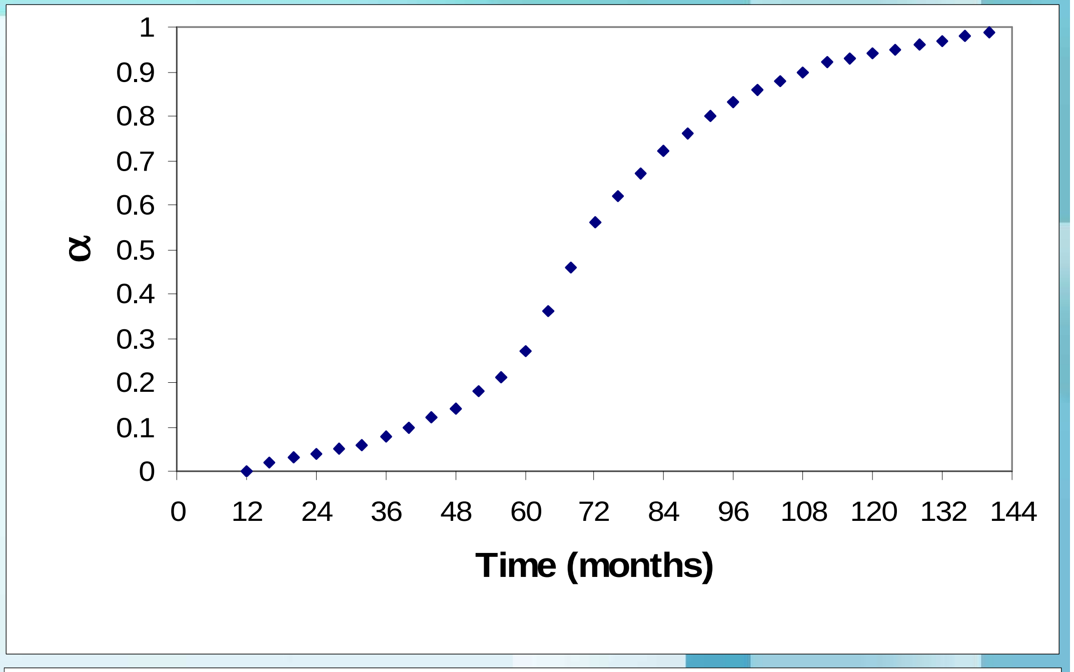
$$p_d d_d \beta = \alpha p_c d_c \frac{d_d{}^{\alpha}}{d_c{}^{\beta}}$$

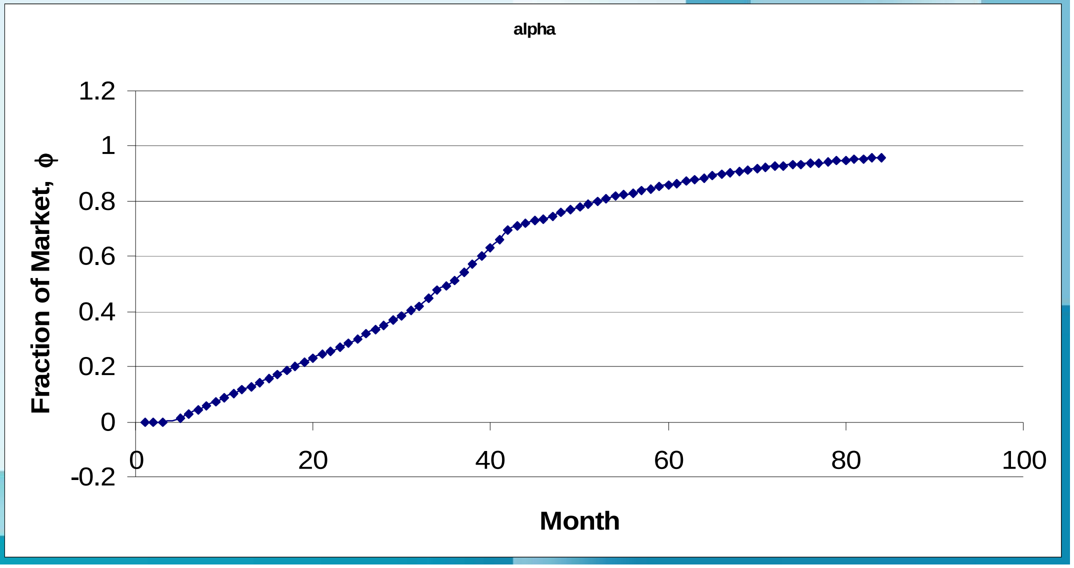
- Solve for new design demand, d_d

$$d_d = \frac{\alpha}{\beta} \frac{p_c}{p_d} (D - d_d)^{(1-\beta)} d_d{}^{\alpha}$$

Demand Based Sales Prediction

- α – The public knowledge of this product
- Varying Salespeople
- Responsibilities
  - Schedule meeting with potential clients
  - Repeat visits when requested or periodically
- Had to increase salespeople due to demand model behavior





Demand Based Sales Prediction

- Optimized selling price index
- Each selling price influenced demand of design
- Optimal selling price found
  - 1.9 times material costs
  - Upper limit for buy – gives yearly 20% savings
  - Gives total yearly customer cost of $15,150

Economic Analysis

- Sale Factor greater than 1.9 cost of equipment
- Seven year NPV $3.5 million
- Saturate market in
- Prediction
  - Total sale of 350 Systems

Conclusion

- Market does exist for on-site oxygen production
- On-site cryogenic oxygen production not feasible due to high capital costs
- *Adsorption system is economically feasible and is recommended*

Acknowledgements

- **Tom Reed**
- **Donovan Howell**

Questions