Solar Reduction of CO_2

Group 9

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Project Goals

- Develop a process that uses solar energy to reduce CO_2 to CO and O_2
- Produce Viable Products
- Determine Applicability for Mars Exploration

Introduction

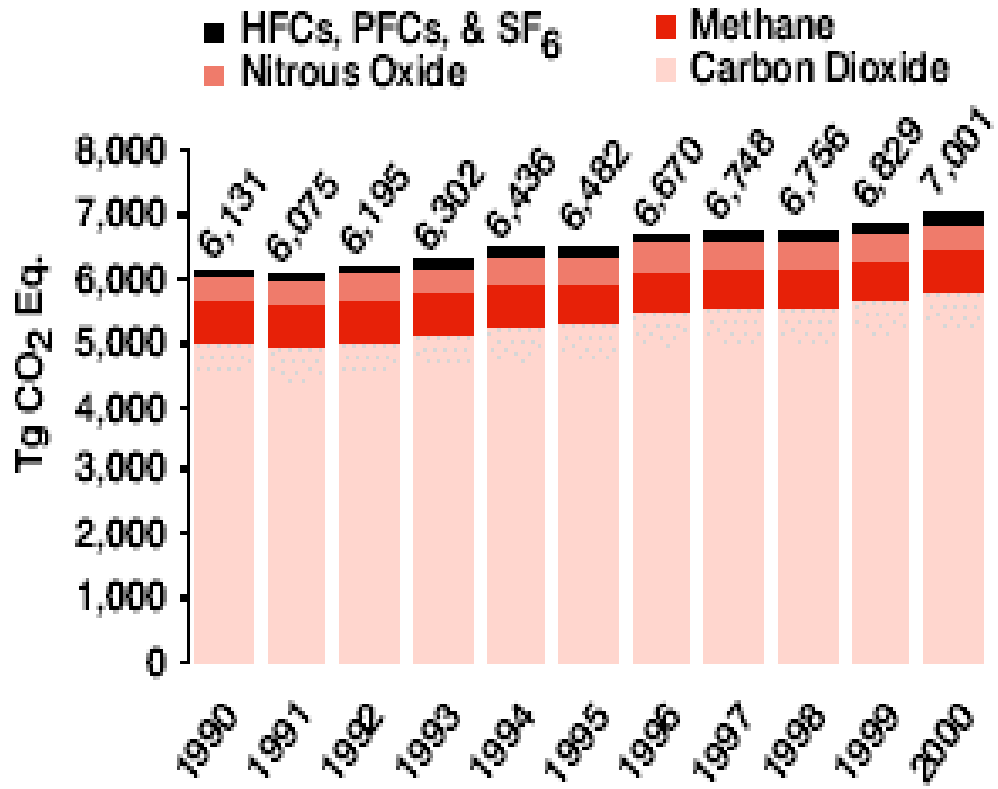
CO_2 Emissions

- Global Warming
  - Changes global climate
  - Melting of polar ice caps
  - Acidification of the oceans

Introduction

CO_2 Emissions

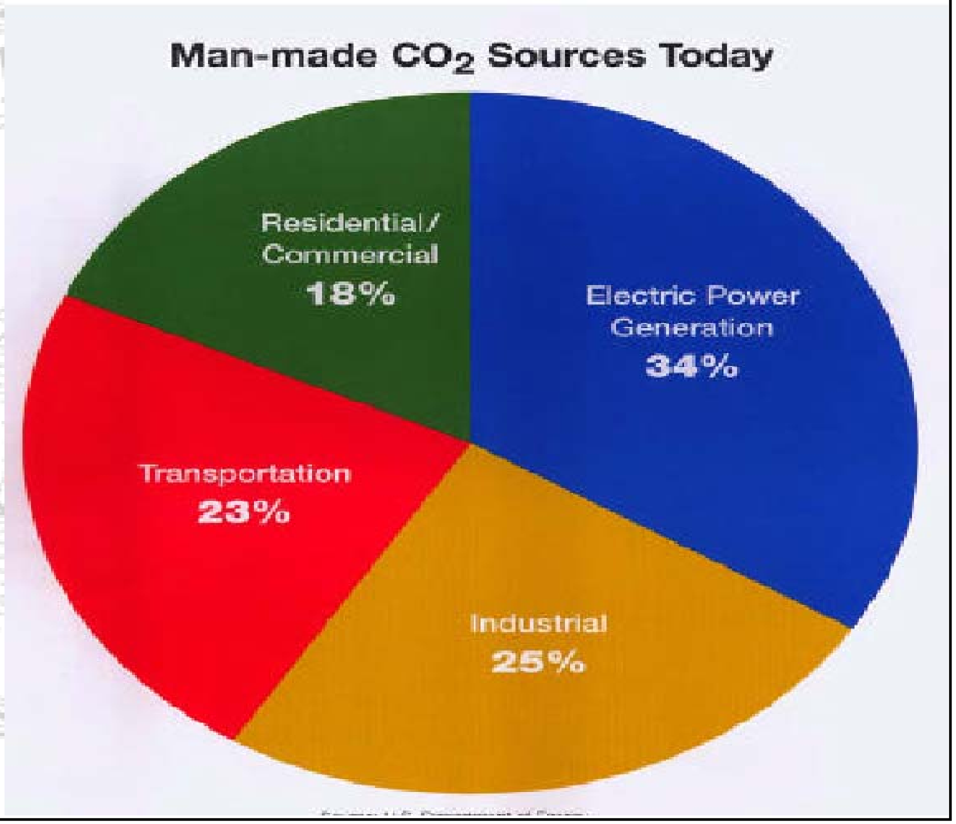
- 16.8% increase in CO_2
- constant increase since 1991



Introduction

CO_2 Emissions

- CO_2 Source
  - Industry
  - Energy
- U.S.A. Largest Producer



Background

CO_2 Mitigation Strategies

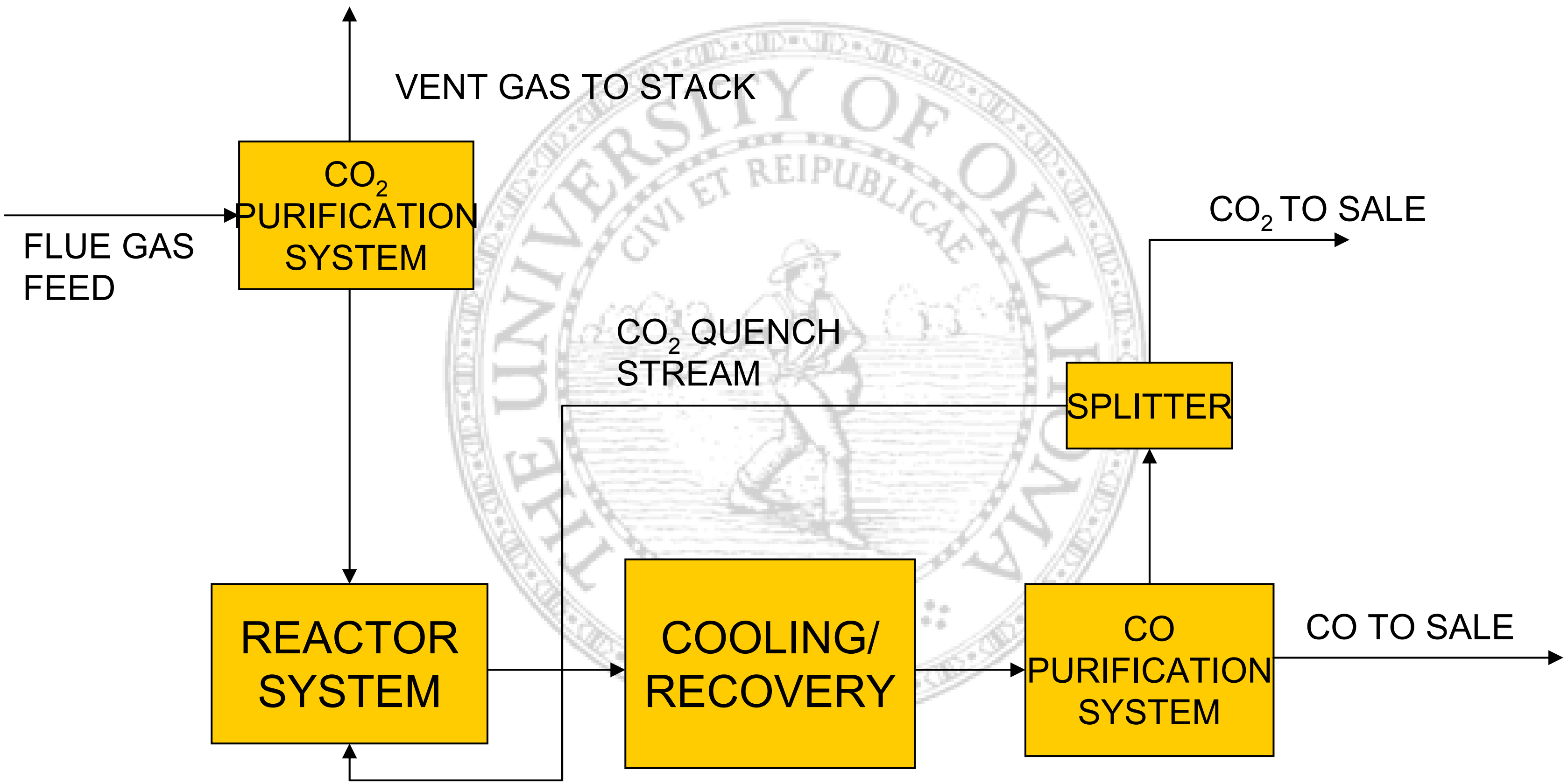
- Solar Reduction of CO_2
- Sequestration
- Artificial Rock Weathering
- “Scrubbing” the Atmosphere

Background

Solar Reduction

- Uses solar energy to convert CO_2 to CO and O_2
- Reduces the amount of CO_2 entering the atmosphere
- Marketable Products
  - CO
  - O_2
  - Energy

Process Overview



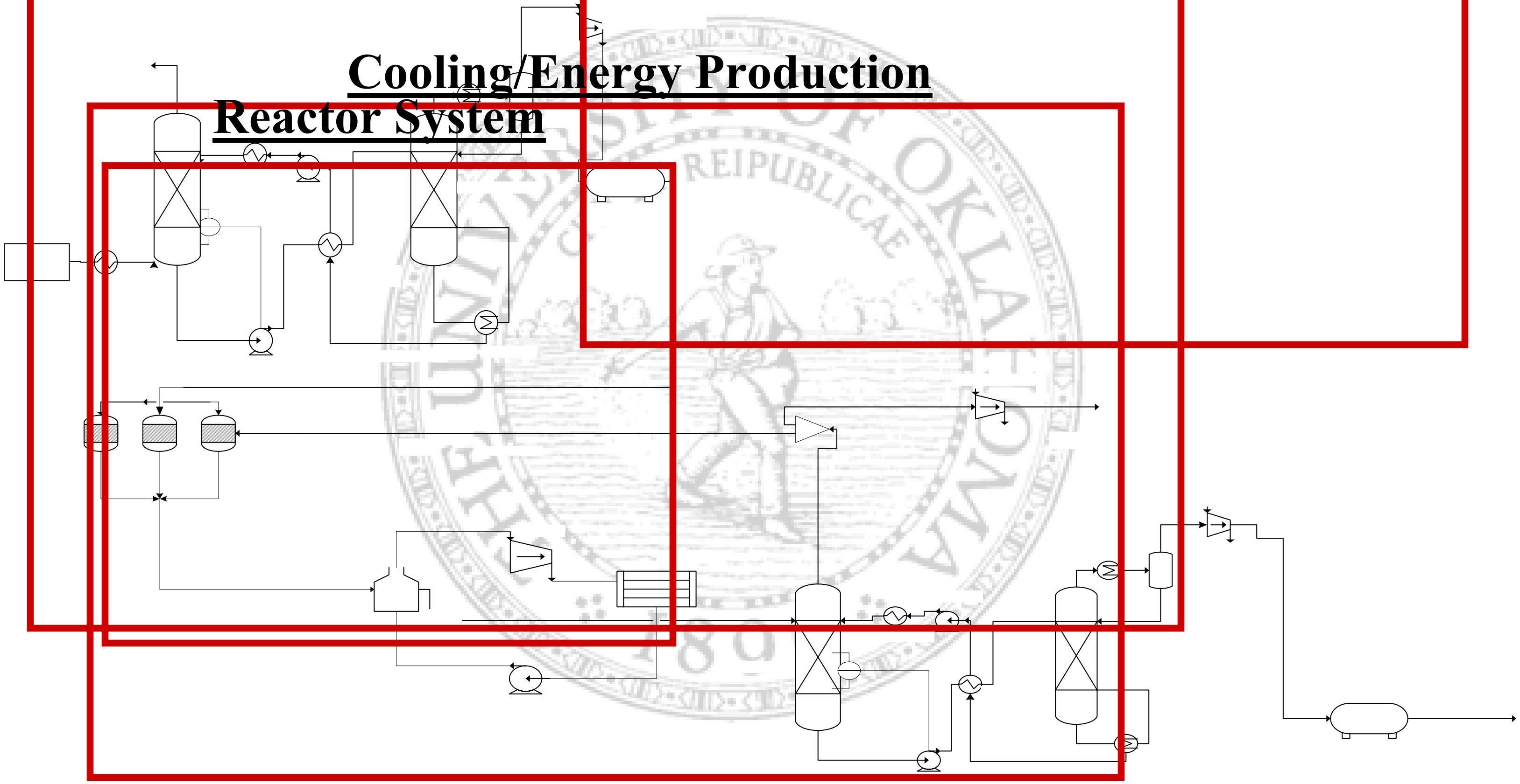
CO2 To Sale & Quench

CO Purification

CO_2 Purification

Cooling/Energy Production

Reactor System



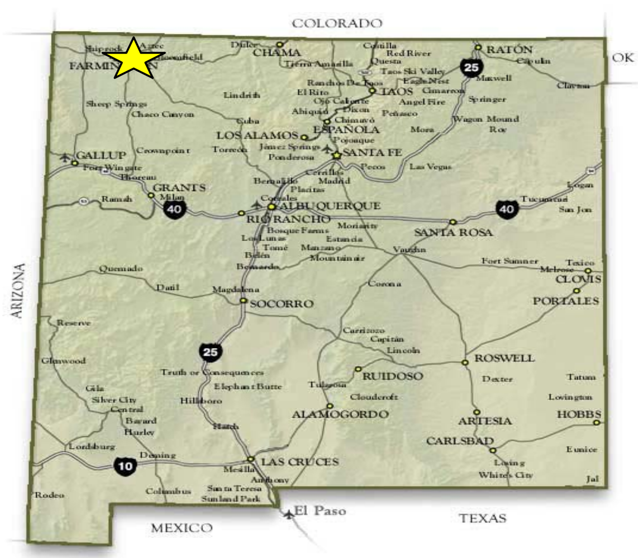
Process Location

San Juan Power Plant

Farmington, NM

CO_2 emissions from plant

~14.5 MM-ton/yr



Purification System

- Typical flue gas from coal fired boilers (dry basis):
  - 81% Nitrogen
  - 14 % Carbon dioxide (0.3 <pp<0.15 bar)
  - 5% Oxygen
  - Trace impurities SO_x (300-5000 ppmv), NO_x, Fly ash
- Pure CO_2 feed stream is needed for reaction process

Process Design

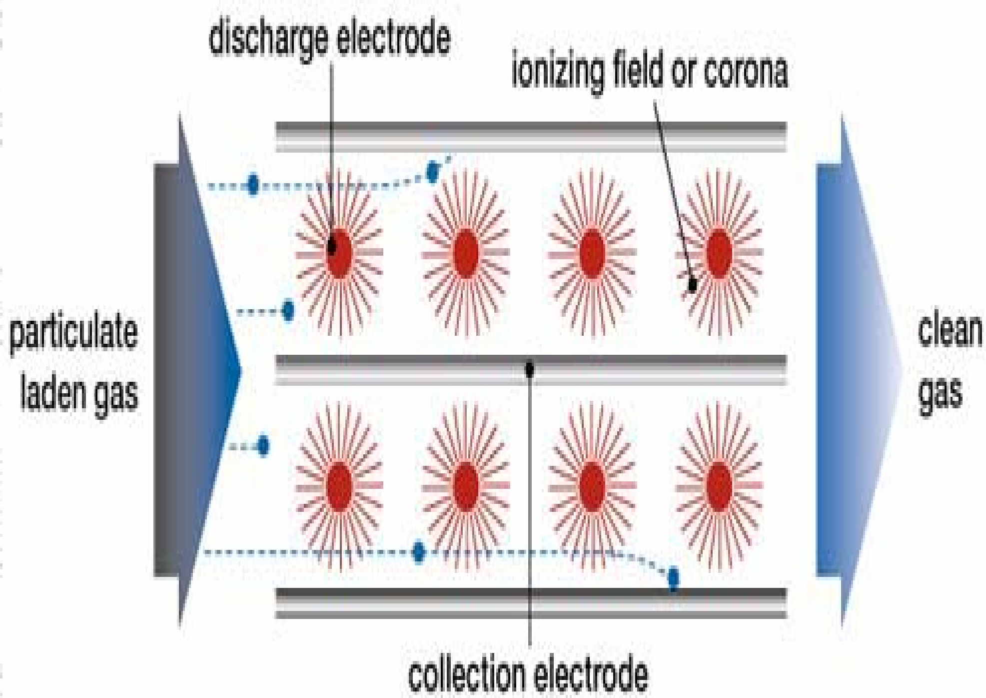
Purification System

- Produces 120 tons CO_2/day
  - Fly Ash Removal
  - Removal of NO_x & SO_x
  - Purification of CO_2

Process Design

Purification System

- Fly Ash Removal
- Electrostatic Precipitator
- Uses Electrostatic Charge



Process Design

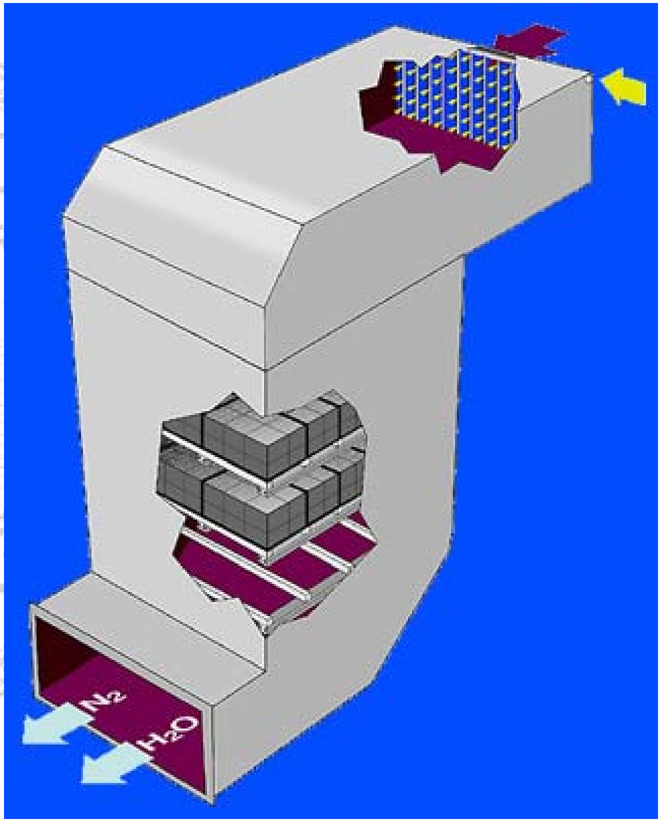
Purification System

NO_x Removal

- SCR DENOX(Haklor Topsoe) Process
- Catalytic reduction of NOx with NH_3

$$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O$$

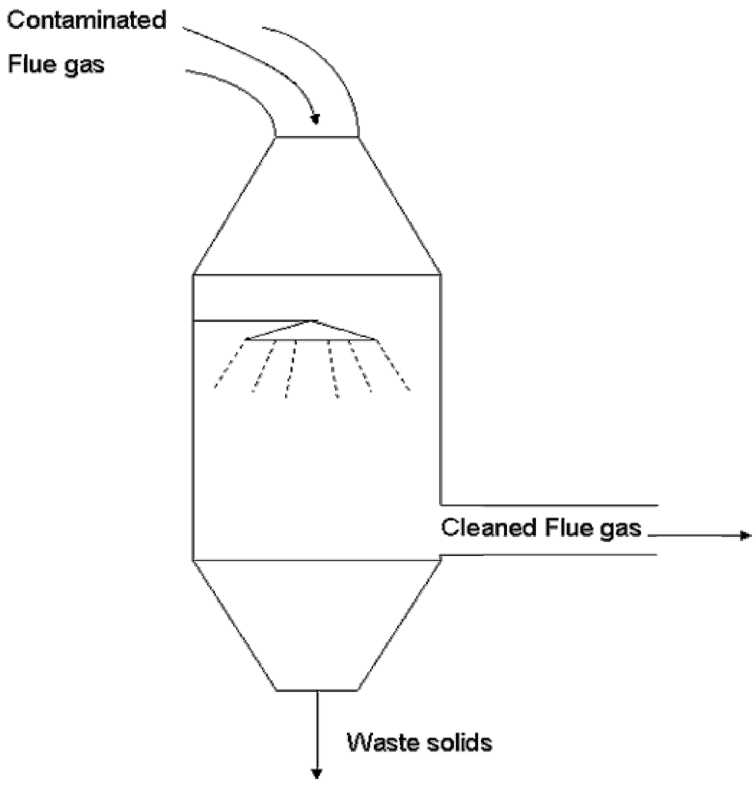
$$6NO_2 + 8NH_3 \rightarrow 7N_2 + 12H_2O$$



Process Design

Purification System

- SO_x Removal
- Utilizes Alkaline Compounds
  - Lime slurry
  - Soda ash
  - KOH or NaOH
- Can reduce SO_x to < 10 ppmv



Process Design

Purification System

- CO_2 Purification Methods
  - Membranes
  - Adsorption with Molecular Sieves
  - Cryogenic Processing
  - $Ca(OH)_2/Mg(OH)_2$ Scrubbing
  - Amine Scrubbing

Process Design

Purification System

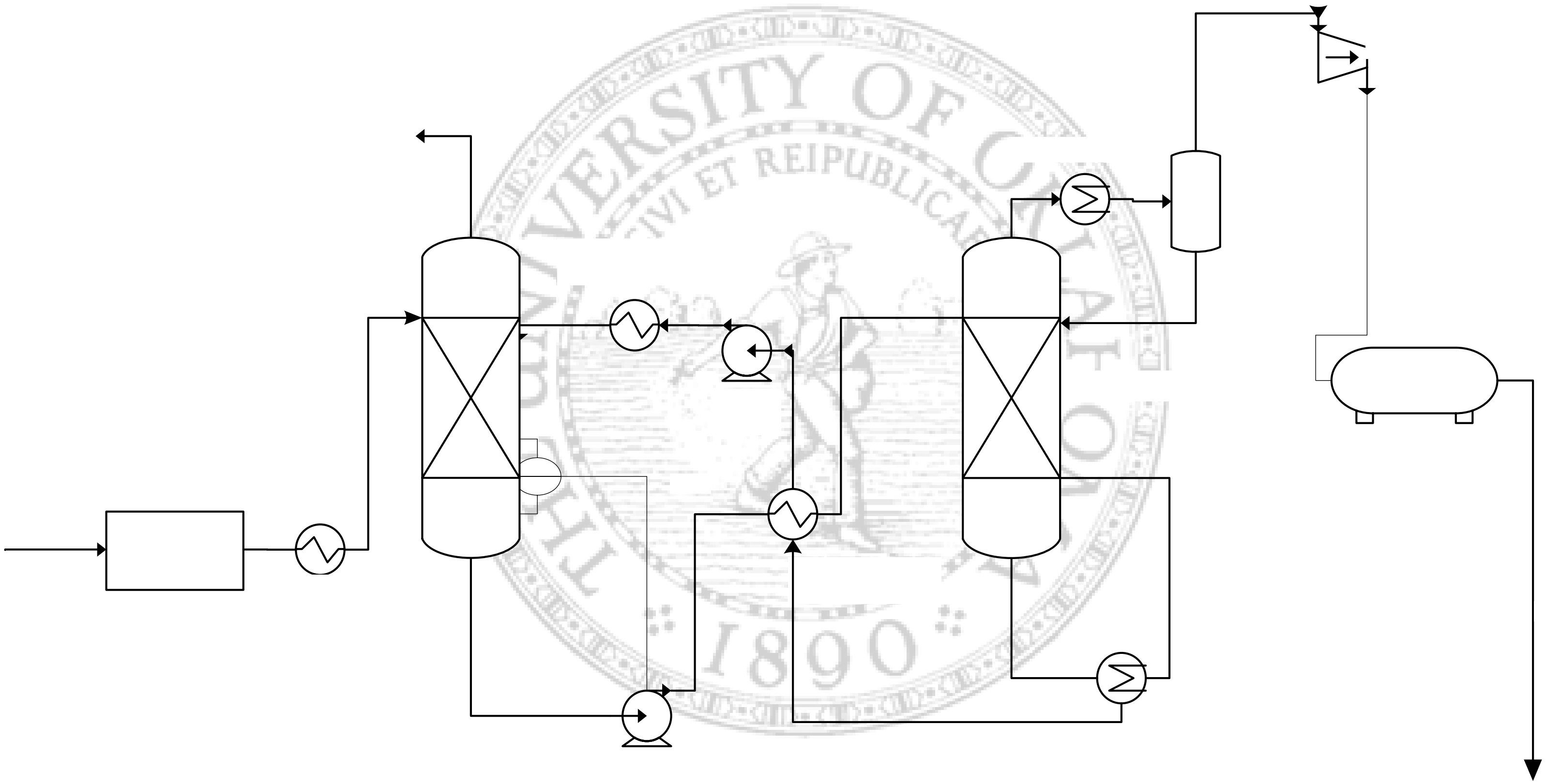
- Membranes
  - Require Additional Compression (Capital Cost)
  - Do Not Produce High Purity Products
- Adsorption
  - Use Molecular Sieves to Trap Gas
  - Regenerate Product
  - High Energy Requirements
  - Low Product Purity

Process Design

Purification System

- Cryogenic Processing
  - CO_2 separated by distillation
  - High energy requirements
  - Liquid CO_2 product
- $Ca(OH)_2/Mg(OH)_2$ Scrubbing
  - Compounds React Reversibly With CO_2
  - Both Compounds React Similarly With SO_2
  - Unproven on an Industrial Scale

Amine Separation Process



Process Design

Purification System

- AMINE SCRUBBING- (Absorption/ Stripping)
  - Absorber
    - $CH_3CH_2OHNH_2 + CO_2 \leftrightarrow CH_3CH_2OHNHCOO^- + H^+$
      (MEA) (Carbamate)
    - Econamine FG solvent
    - 30 wt. % MEA solution
    - 85-95% CO_2 recovery

Process Design

Purification System

- Stripper
  - CO_2 regenerated
  - $CH_3CH_2OHNHCOO^- + H_2O \leftrightarrow CH_3CH_2OHNH_2 + HCO_3$
  - Product purity 99.95%

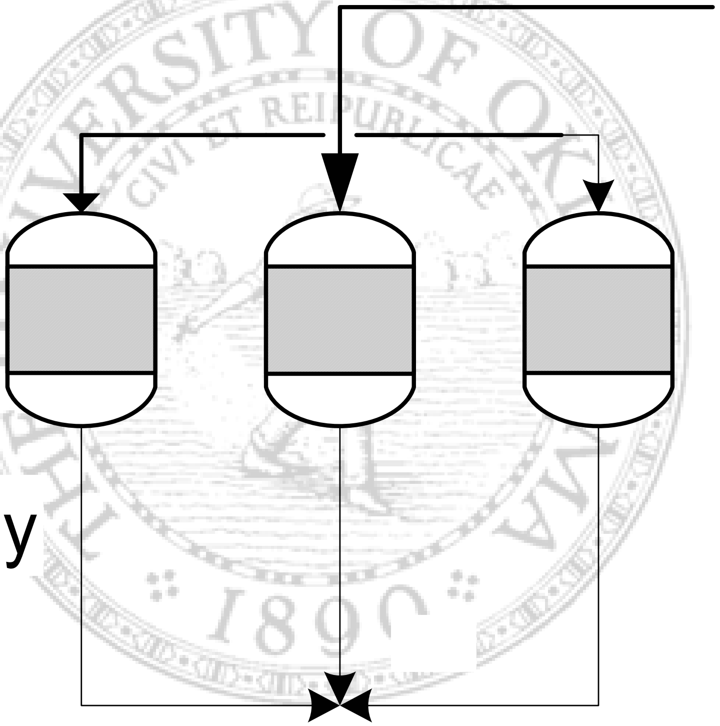
Process Design

Purification System

- Provided by The Wittemann Company
- Produces 120 tons CO_2 /day
- Capital Cost: $3.3 million

Process Design

Reaction



Reactor Array

Process Design

Reaction

- $$CO_2 + hv\&\ heat \leftrightarrow CO + \frac{1}{2}O_2$$
  - ΔH_R=1.2167x10^{5}BTU/lb-mol
- E_a = 1.44x10^5 BTU/lb-mol
  - Extremely High Temperatures Required

Process Design

Prototype Reactor

- Renewable Energy Corporation
- SOLAREC
  - Mirrors, Core, and Support
  - 10 L/min flow of CO_2
  - 6% Conversion

Process Design

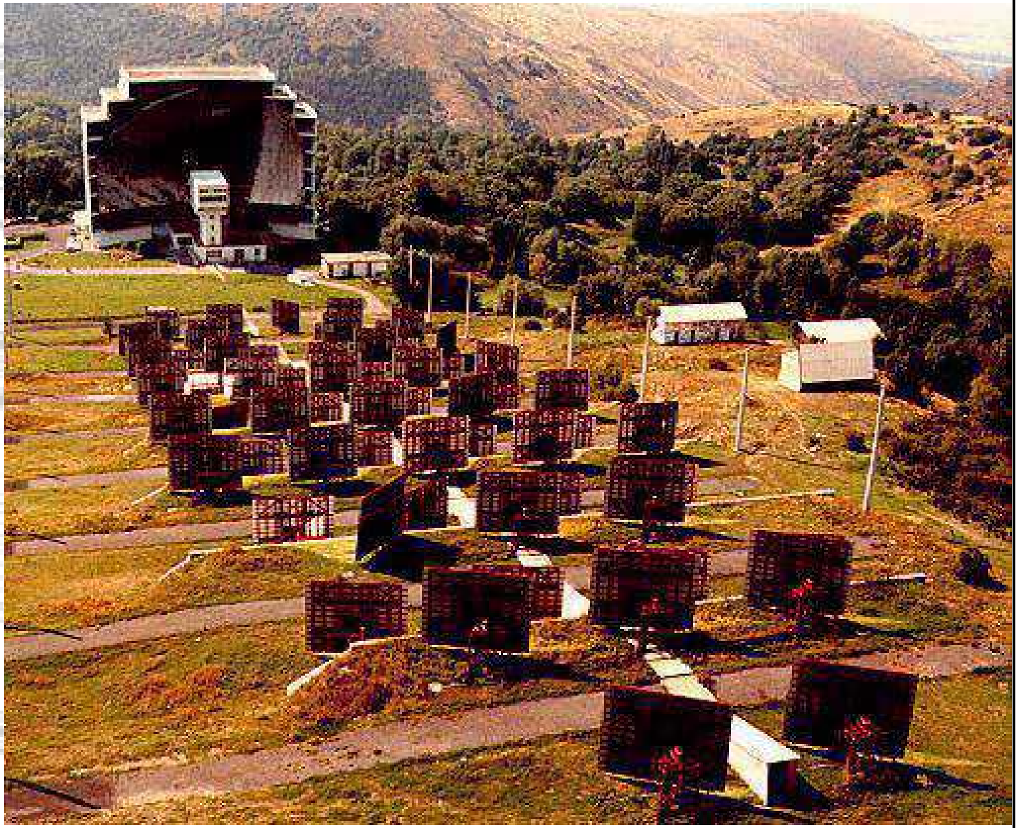
Reactor Scale Up

- Optimize Reactors
- Minimize Capital
- Intensive Properties
  - Temperature
  - Pressure

Process Design

Reactors

- Heliostat Array
- Solar Furnace



Process Design

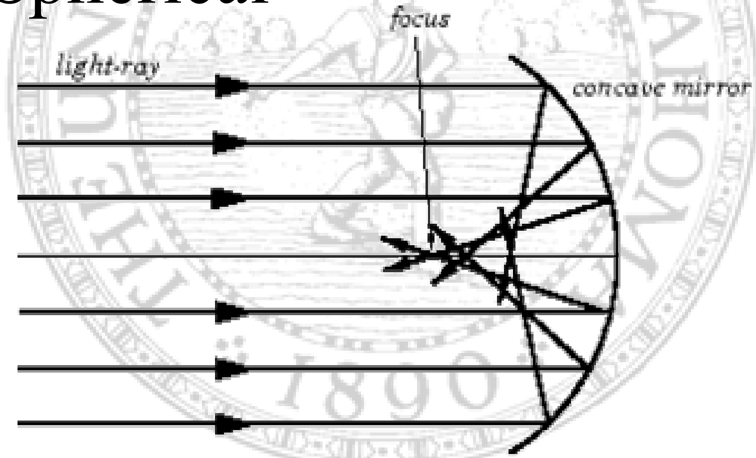
Reactor Scale Up

- Limitations
  - Physical Size
    - Reflective Surface Area (121 m^2)
    - Support Height (7.3 m)

Process Design

Scale Up Assumptions

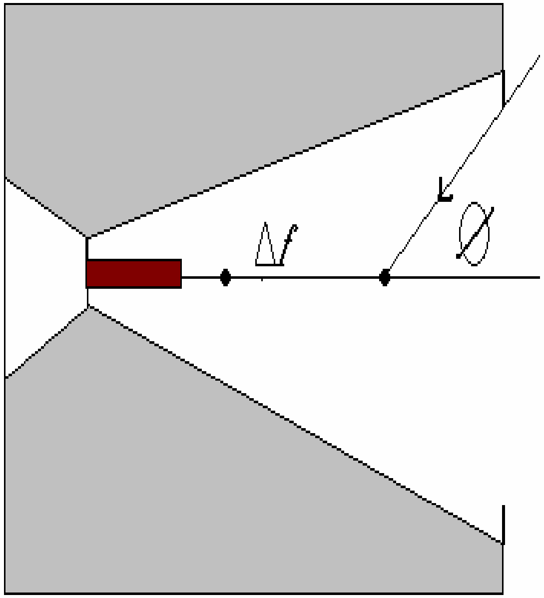
- Suns Rays are Parallel
- Mirror is Spherical

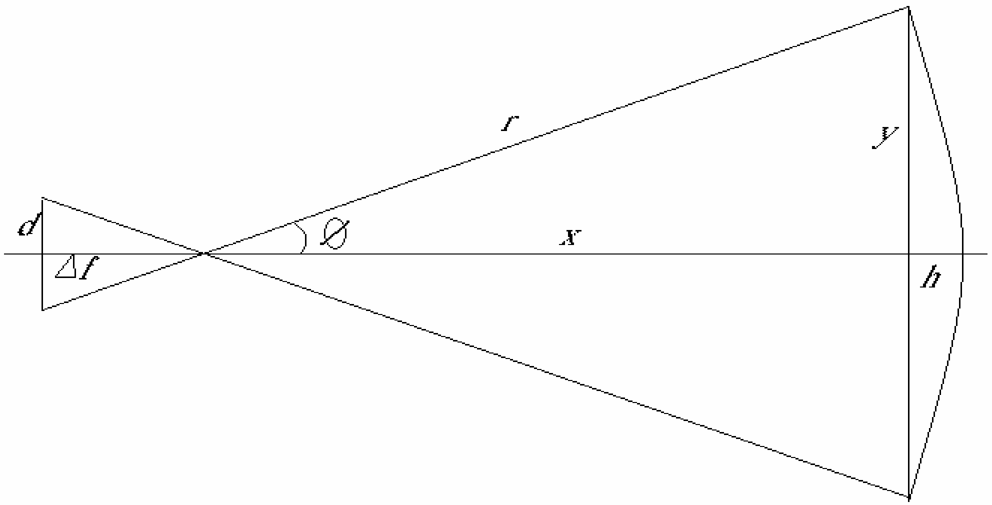


spherical aberration

Process Design

Scale Up Assumptions





Process Design

Scale Up Proportions

- $A = \pi \cdot R \cdot h$
- $A \propto \text{Radiant Energy}$
- $\text{RadiantEnergy} \propto \text{FlowRate}$
- $\text{Flowrate} \propto \text{Core Volume}$
- $\text{Pressure} \propto \text{Core Volume}$

Process Design

Reactor Cost

- 90% ~ Reflective Surface
- 10% ~ Unit and Structure
- Optimum Conditions
  - Maximum Size
  - Minimum Units

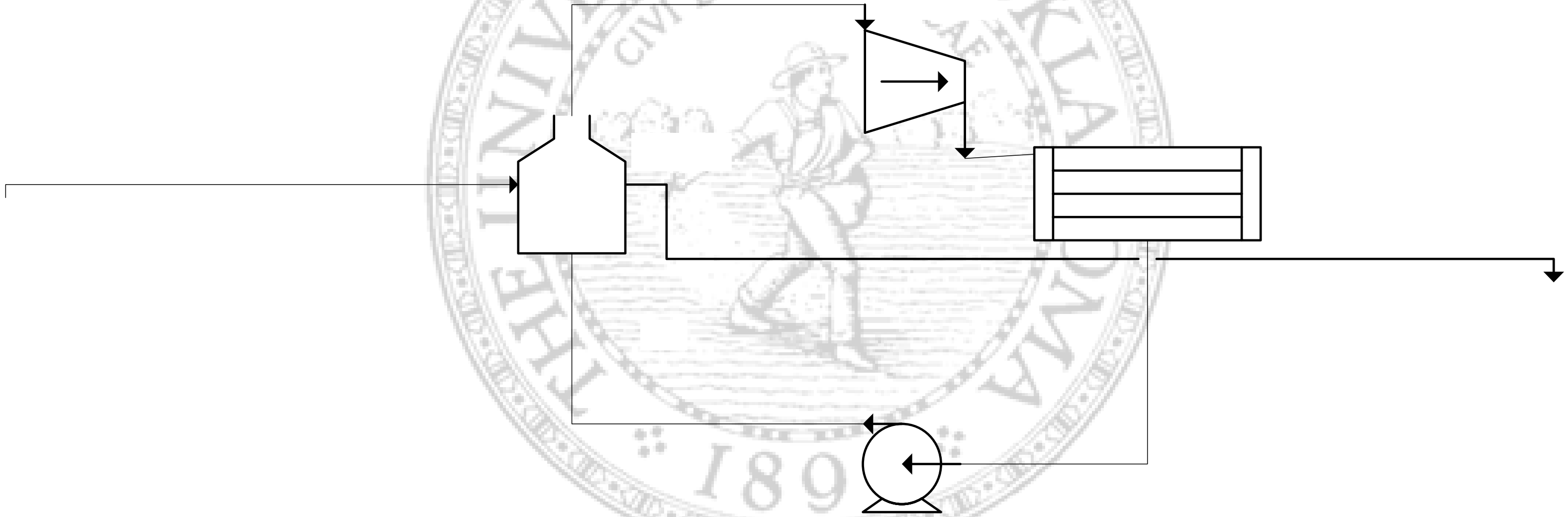
Process Design

Reactor Cost

- Optimum Conditions
  - 121 m^2 Surface Area
  - 28 Reactor Units
  - $3.64M for System

Process Design

Heat Removal System



Process Design

Thermal Energy

- Process stream leaves reactor at ~1350 ^oF
- COSORB requires stream at 85 ^oF
- Use energy to produce steam

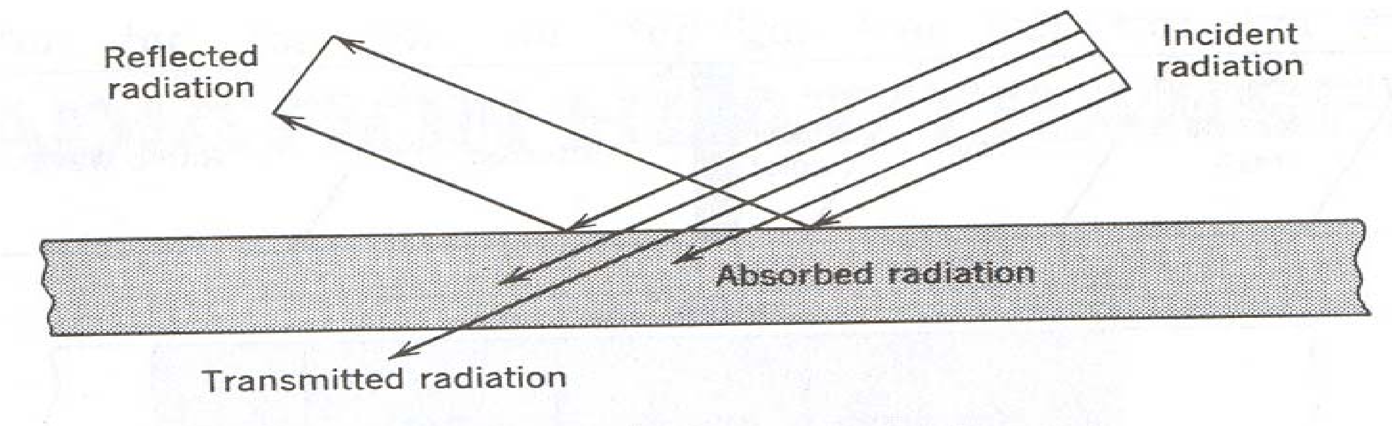
Process Design

Heat Transfer Equations

- Q= $\varepsilon \sigma A (T_i^4 - T_{wall}^4)$ Radiation
- Q= $A * K * \frac{\partial T}{\partial x}$ Conduction
- Q= $A * h * \partial T$ Convection

Process Design

Characteristics of radiation

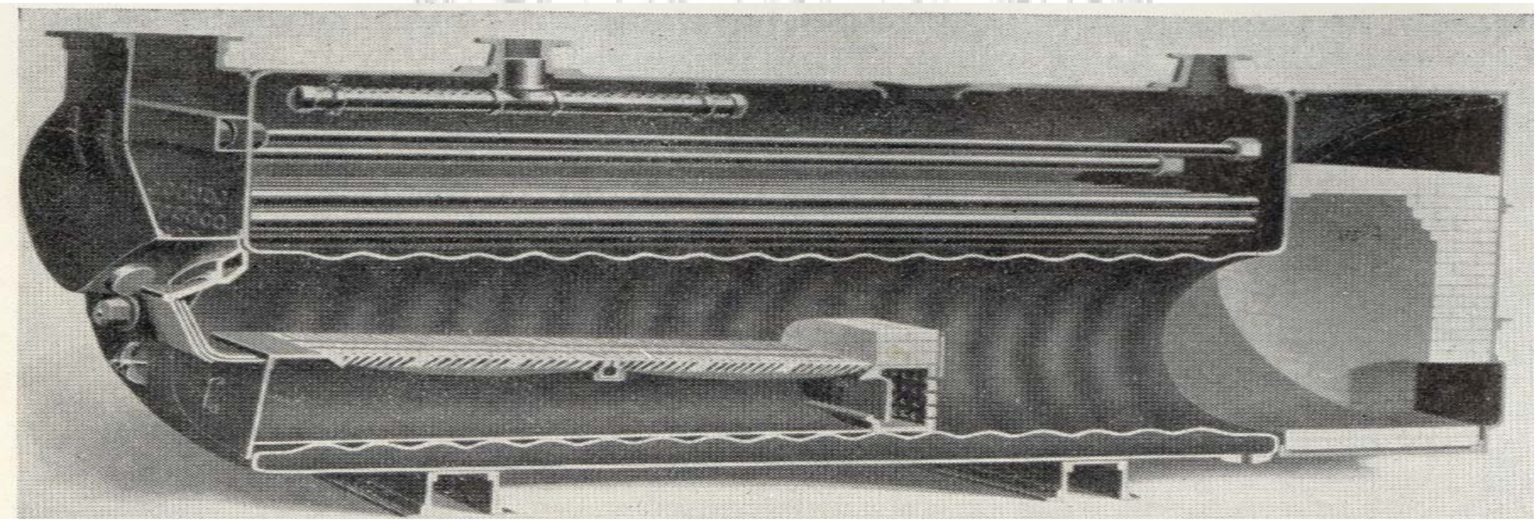


$$\rho + \alpha + \tau = 1$$

Process Design

Boiler furnace

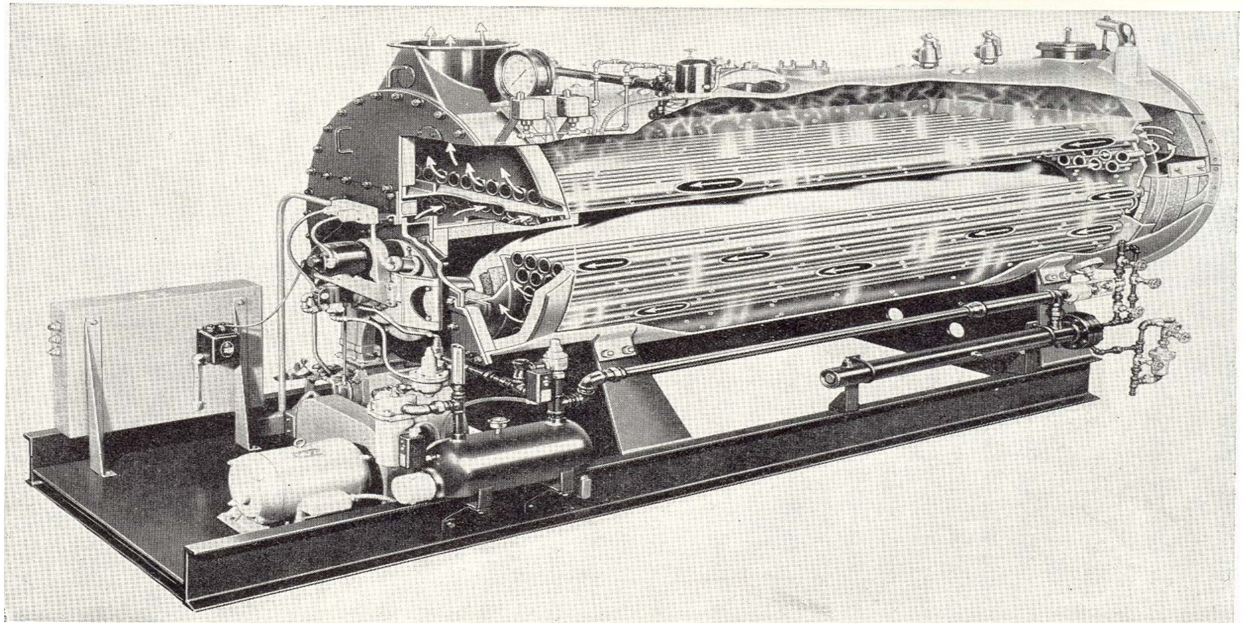
- **Heat Transfer Equipment**
  - **Fire-Tube Boiler**



Process Design

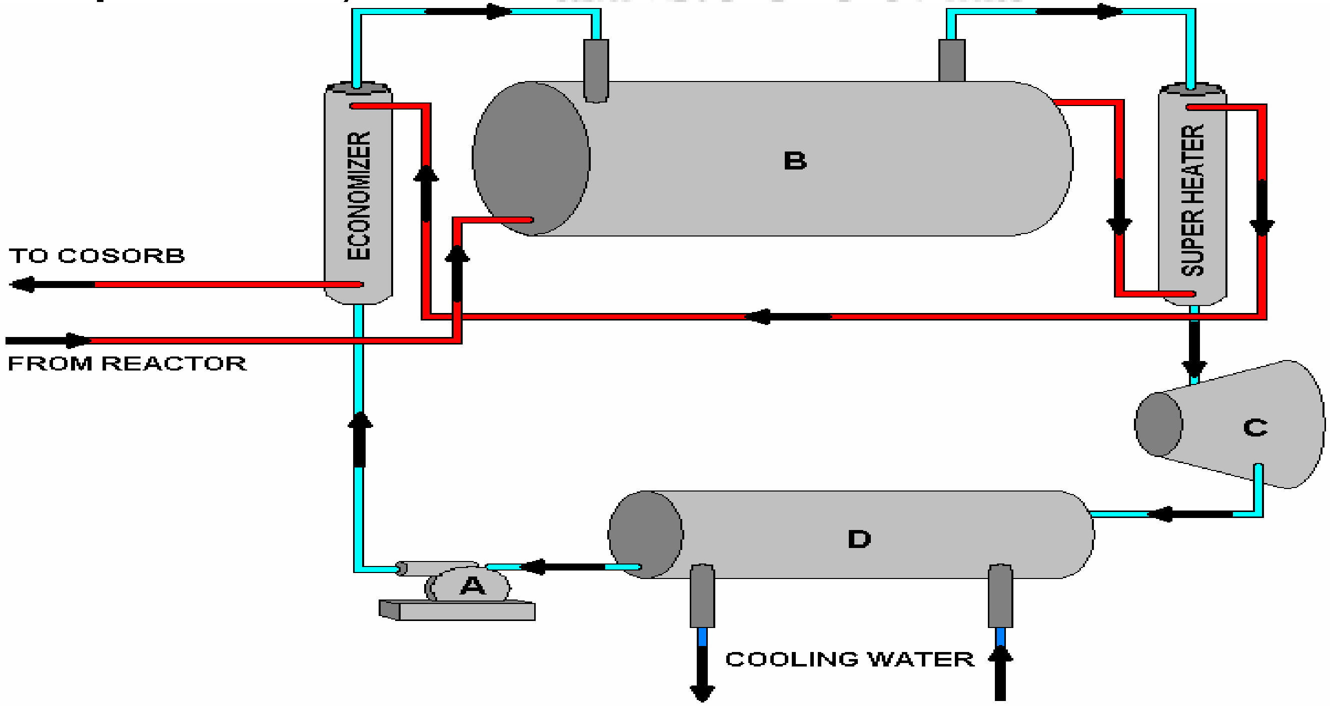
Characteristics of radiation

- Packaged Fire-Tube Boiler



Process Design

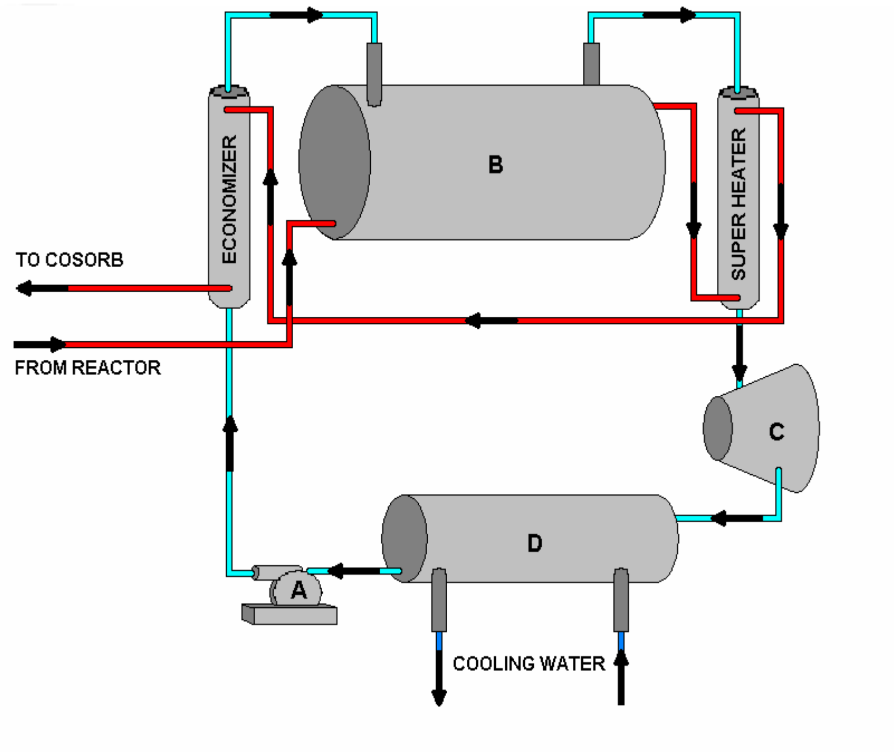
Proposed system



Process Design

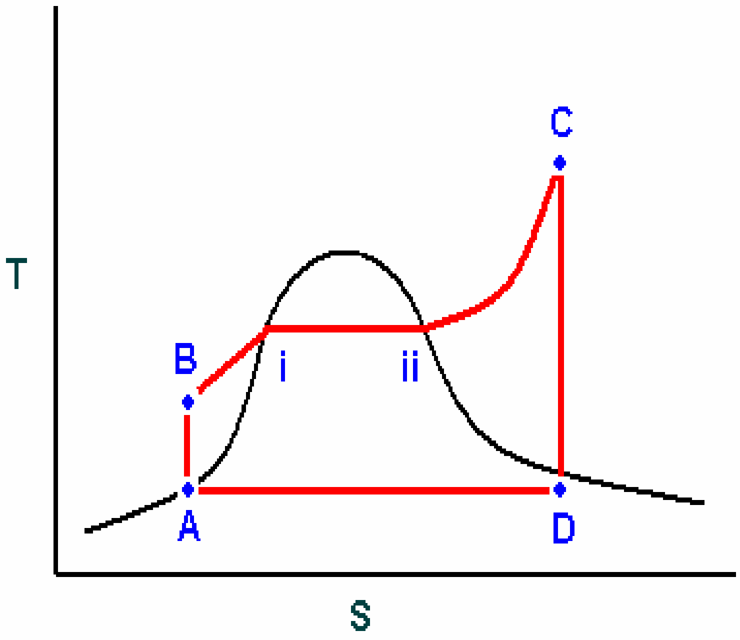
Proposed system

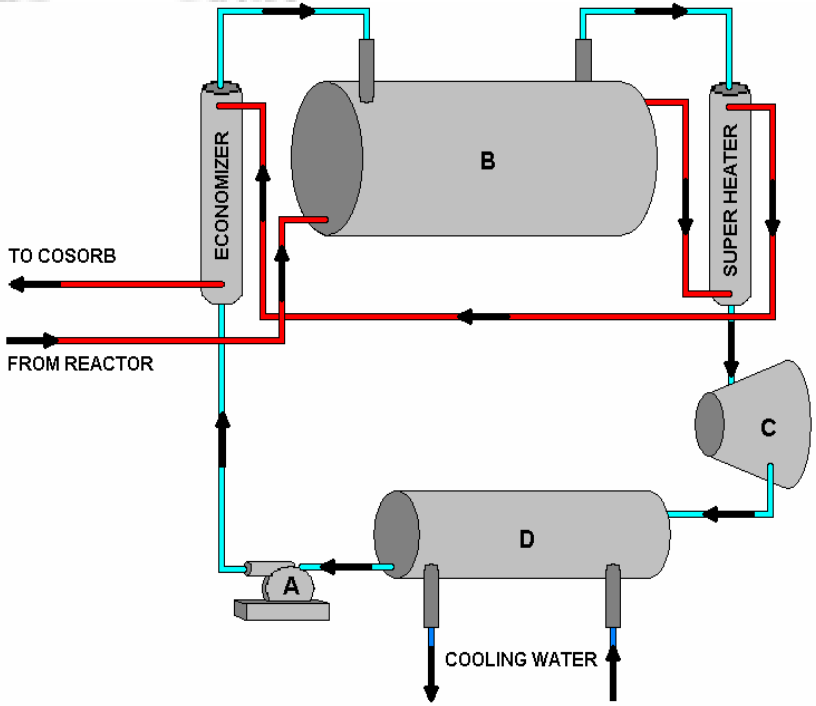
- 4 Tube pass
- 8 tubes, 12 ft length
- 2 ½ ′ OD
- 1 ½ psi pressure drop



Process Design

Proposed system





Process Design

Heat transfer

- Estimated 0.42 MW of thermal energy
- Produces ~36,000 lb/hr of steam

Process Design

Boiler Furnace Cost

- Boiler $145,000
- Cooling tower $2,000
- Pump $6,000

Process Design

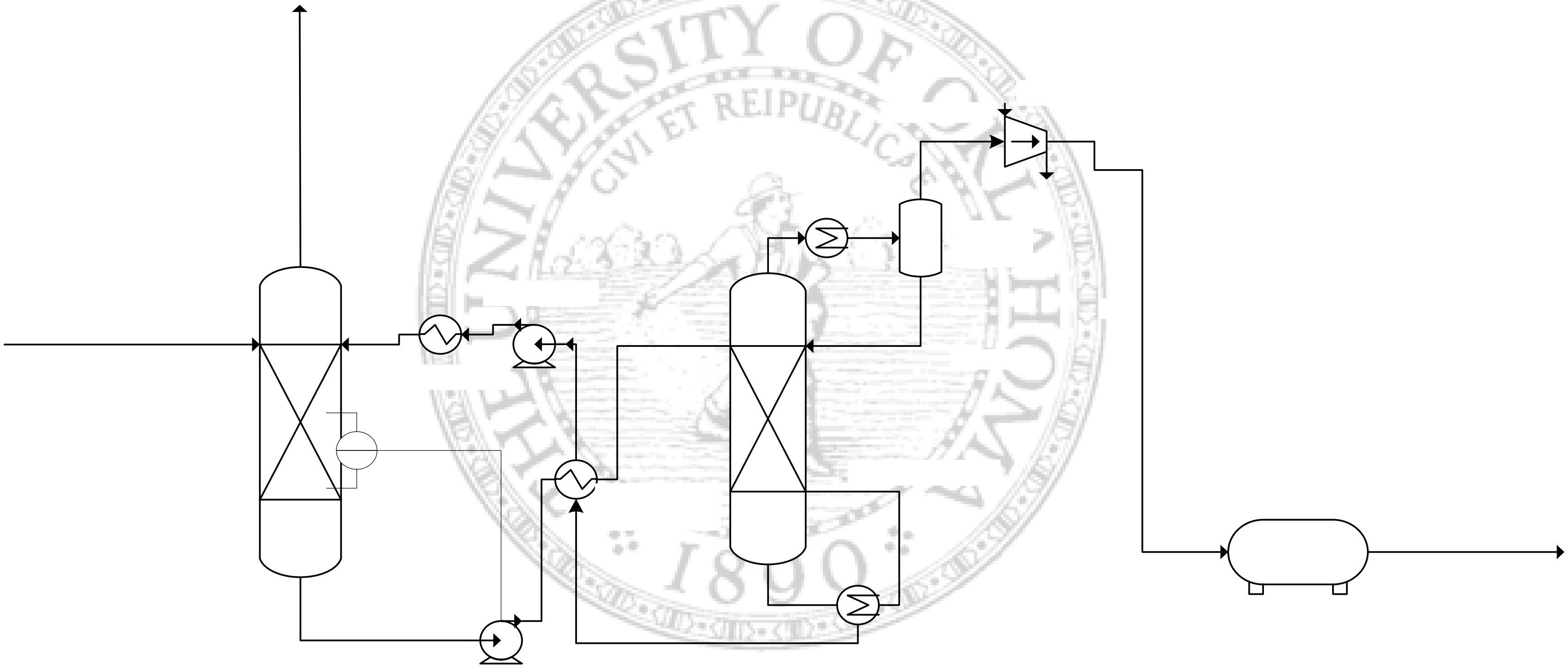
Product Recovery

- COSORB separation
- Iron reduction - thermodynamically unfavorable

$$Fe_2O_{3(s)} + 3CO_{(g)} \leftrightarrow 2Fe_{(l)} + 3CO_{2(g)}$$

Process Design

COSORB



Process Design

- COSORB - Selective absorption/desorption using $CuAlCl_4$ in organic solvent
  - Toluene
  - Monochlorobiphenyl

Process Design

- COSORB advantage
  - Low corrosion rate
  - Ability to separate CO in the presence of CO_2
  - Low energy consumption
  - Ability to produce high purity product (99.9%)

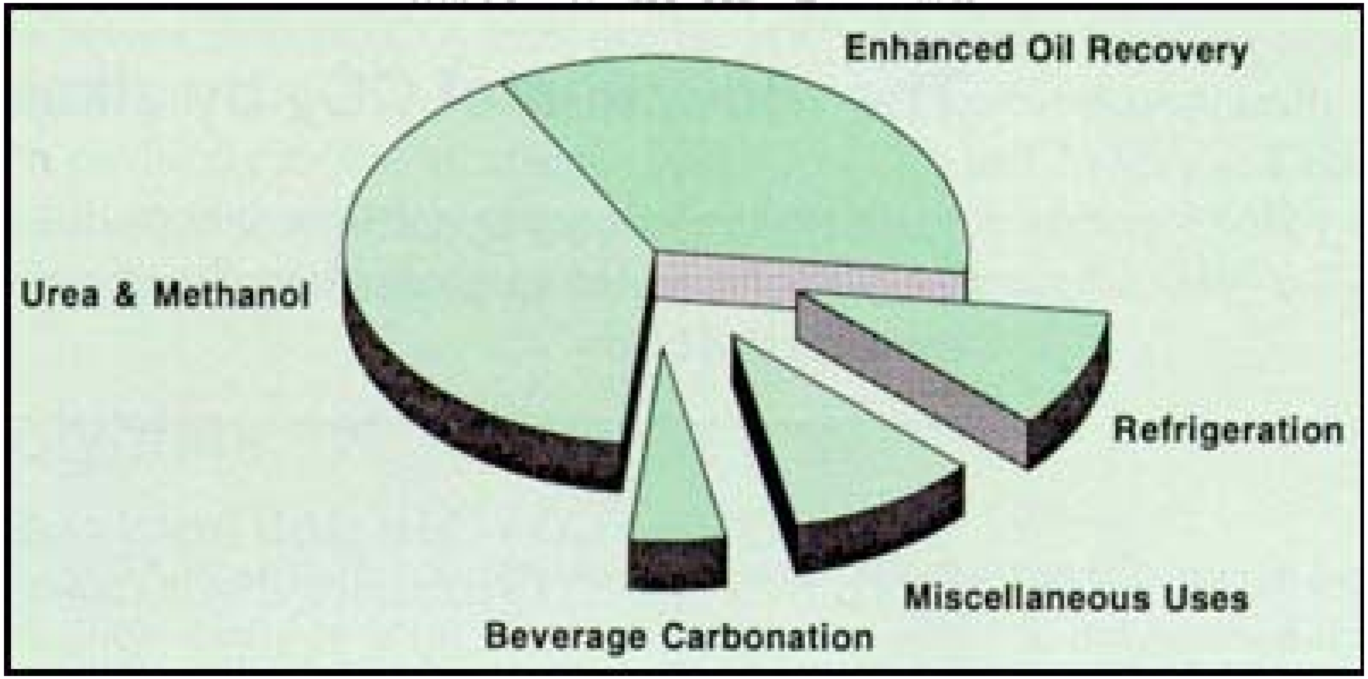
Process Design

CO_2 Recovery Options

- Separation system for CO_2 and O_2
  - High capital cost
  - Insignificant revenue generation
- Purge and recycle
  - Purge stream to sell for Enhanced Oil Recovery
  - Recycle stream to quench the reaction

Process Design

Industrial Uses of CO_2



Process Design

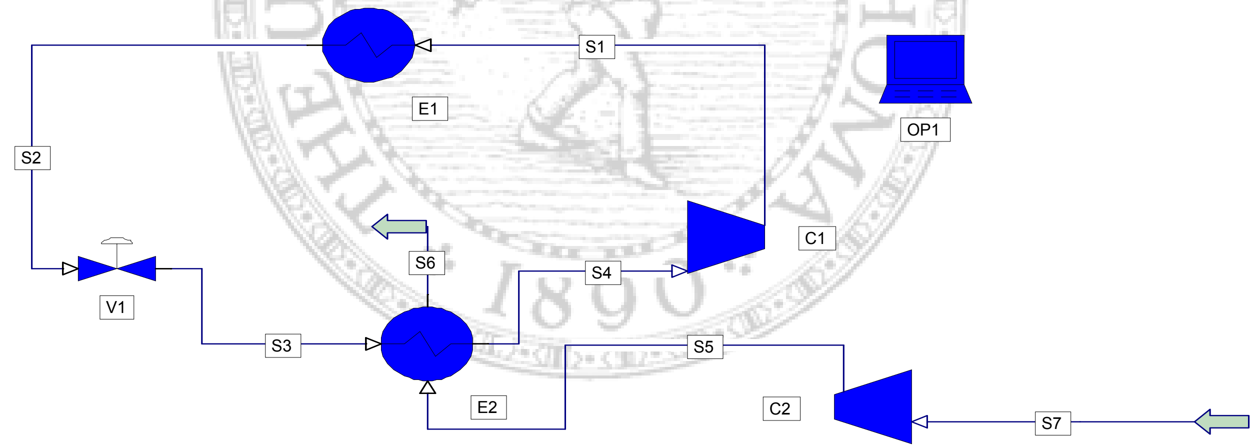
Storage

- Compressed Liquid CO_2
  - Wittemann MEA Freebee
- Compressed CO Gas
  - THT Cryogenics

Process Design

Storage

- Energy Requirements
  - PRO/ II
    - Compressor & Refrigeration Cycle



Process Design

Storage

- CO_2 Liquefaction
  - $0 capital cost
  - 170 KW
- CO compression
  - $200,000 capital cost
  - 27 KW

Safety

FOLLOW SAFETY PROCEDURES

- CO
  - TOXIC
    - Deadly at ~800ppm
  - Flammable
- CO_2
  - Pressurized CO_2 with trace O_2

Environmental Impact

CO_2 Reduction

- San Juan Produces 14500000 tons/yr
  - ~120 ton/ day processed
    - 5256 tons/yr reduction
    - 38544 tons/yr sold
  - 0.015% Chemically Reduced
  - 0.3% CO_2 Emissions Reduction

Environmental Impact

Energy Production

- San Juan
  - 1780 MW
    - ~22 tons CO_2 / KW Produced
- Solar Reduction
  - 0.42 MW
    - .05 lb CO_2 / KW Reduced

Economics

- Lifetime = 10yrs

Economics

Capital Investment

- Equipment Costs: $15.7m
  - Cosorb Unit - $11.7m
  - Boiler - $175,000
  - MEA system – $3.3m
  - Solar Reactor - $3.6m
- Land: royalties - $403,000
- TCI: $49m

Economics

Product Costs

- Operating Costs

Operating Costs	MMBtu/hr	$/yr	
MEA cooling water	8.02	$35,150.86	
MEA hot utility	4.58	$80,291.98	
Water from tower	1.60	$7,019.46	
COSORB cooling water	1.13	$4,952.68	
COSORB hot utility	0.21	$3,681.64	
Total power (MW)	0.5	$289,271.40	
Cost of water ($/MMBtu)	0.5	**$420,368.01**	Total
Cost of hotutility ($/MMBtu/hr)	2		
Cost of power ($/kWhr)	0.066		

Economics

Product Cost

- Labor, avg. 8hrs/day e.g.
  - Operators, maintenance workers
- Labor cost - $1.6m/yr
  - Wages obtained from Bureau of Labor Statistics
- Taxes – New Mexico
  - $56,000 + 7.6% of excess over $1m
  - Taxes - $2.6m/yr

Economics

Sales

- Commodities
  - CO - \$0.86/ft^3
    - 39mft^3/yr - \$33.5m\$/yr
  - CO2 - \$35/ton
    - ~17250ton/yr - ~\$604,000/yr
- Total Profit - \$34.2m/yr

Economics

Net Earnings, P

- Function of Sales, Product Cost, Depreciation.
  - P - ~$23.7m/yr
  - Cash flow - $18.6m/yr
- NPW - ~$78.5m
- ROI >46%
    - No risk
- POT – 1.65yrs

Economics

Risk Analysis

- Monte Carlo Method
  - Identify variables
    - FCI
    - Product Cost
    - Product Price
    - Conversion – 9.6%, 12% (base case), 14.4%
      - Based on $12\% \pm 20\%$

Economics

Risk Analysis

- Three Conversion scenarios
  - 9.6%, 12%, 14.4%
- Generate random numbers for all variables
  - Using mean and standard deviation

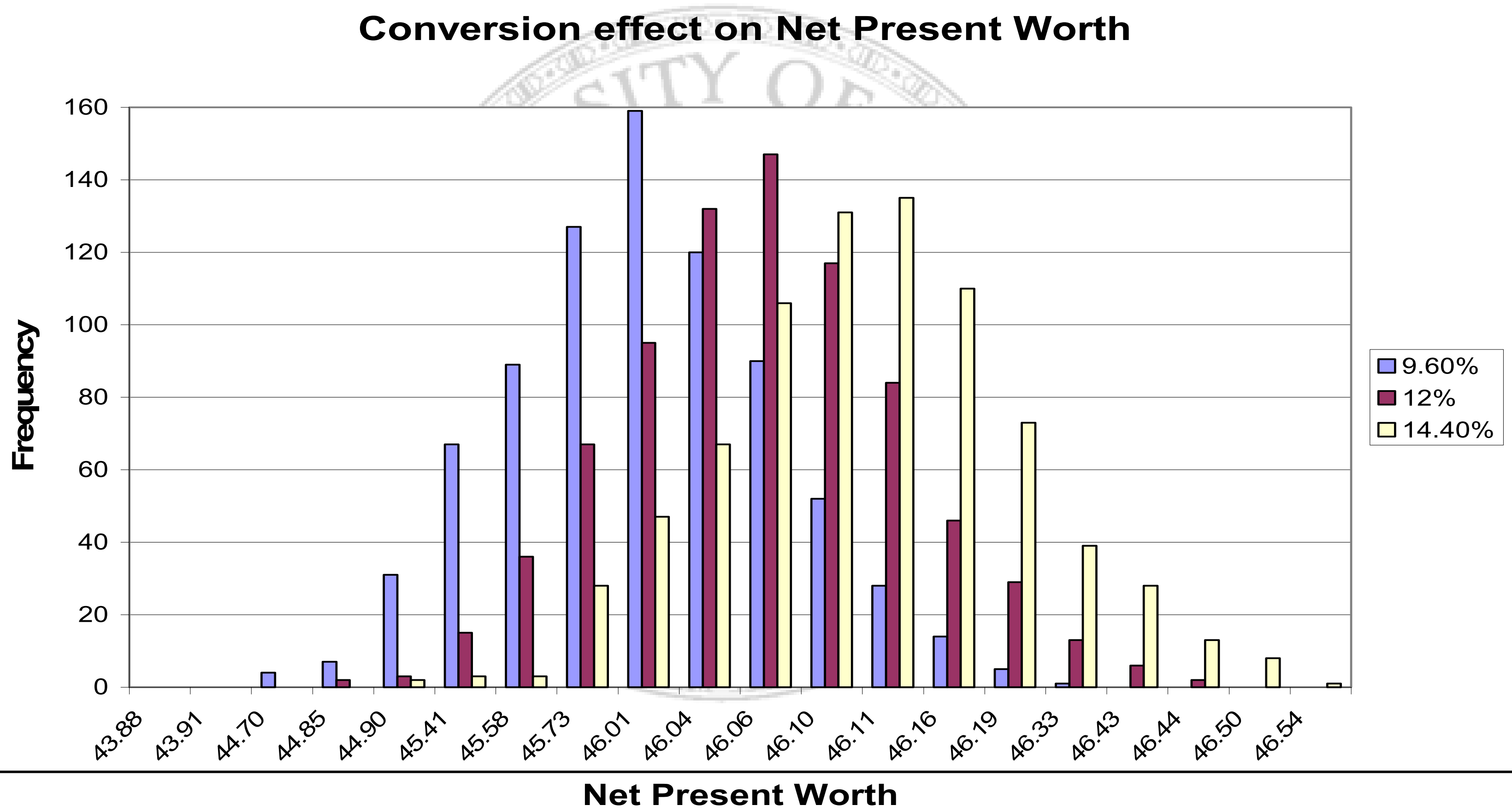
Economics

Risk Analysis

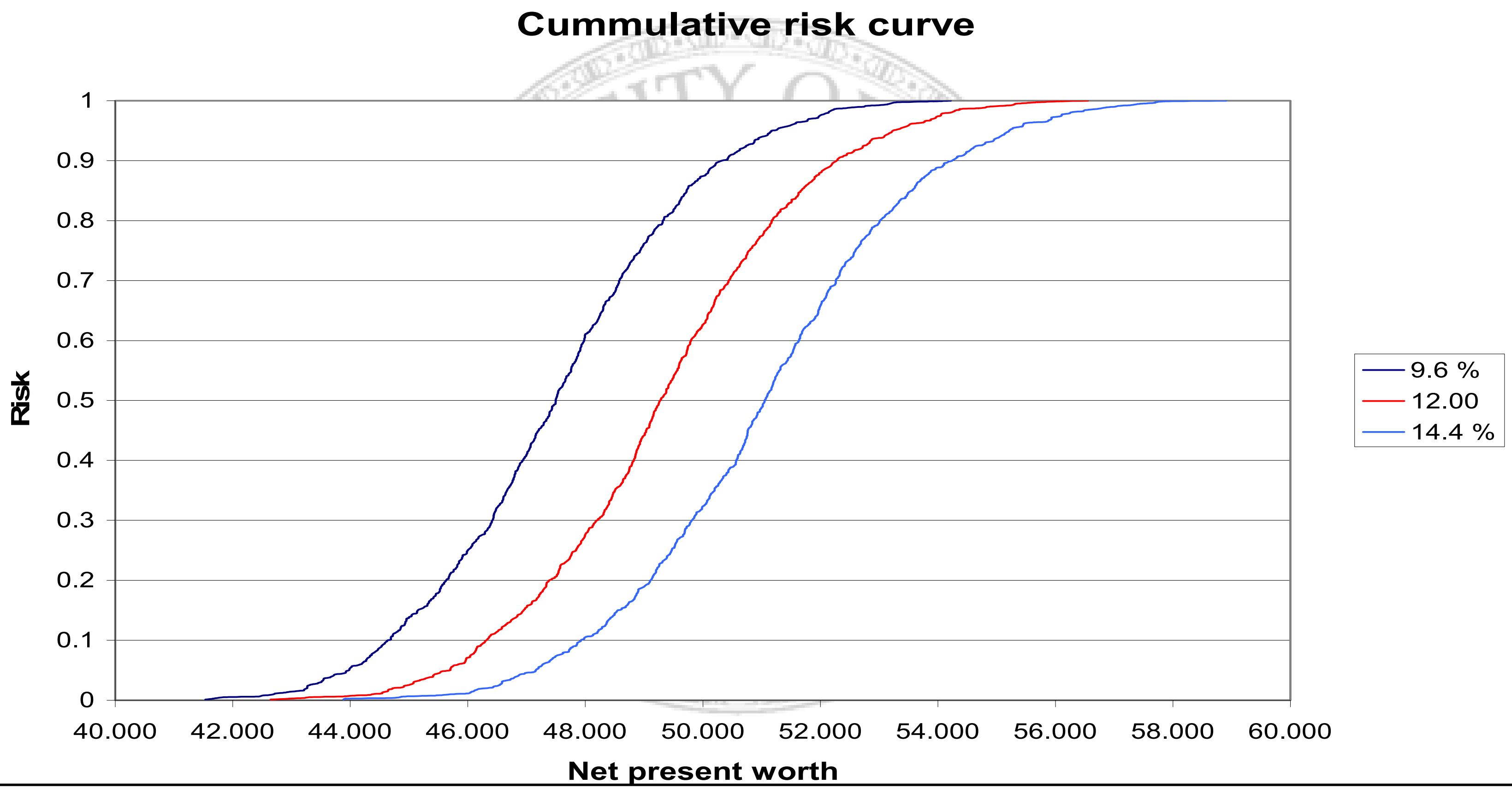
- Net Present Worth – affected by variables
  - Calculated by varying FCI, PC, PP
  - **Figure**: NPW over 10 yrs at each conversion

Net Present Value ($\$/10^6$)		
9.6 %	12%	14.4 %
45.42	47.27	48.84
48.24	49.61	51.92
50.73	53.08	55.27
50.85	52.68	54.40
49.49	51.85	53.44
44.00	45.96	47.51
48.73	50.80	52.28
48.19	49.64	51.19
49.05	50.85	52.84
45.04	46.26	47.93
46.85	49.37	51.00
49.75	51.16	53.32
45.54	47.57	49.94
45.72	47.64	49.44
45.00	46.71	48.21
48.12	50.64	52.33
49.53	51.19	52.69
43.22	44.54	45.73
43.08	44.58	46.04
43.27	44.92	46.55
46.89	48.70	50.44

Risk Analysis



Risk Analysis



Conclusions

- Project goal
  - Reduce CO_2 in atmosphere
    - 120tons/day removed by process

Conclusions

- Project is Profitable
- Further Research
  - Increasing Capacity of the System.
  - Conversion Rate

Conclusions

- We are the greatest group
  - In the history of Advanced Design!
- Questions?

Process Design

MARS – “The Next Real Frontier”

Process Design

Mars Application

- Pure Feed Source of CO_2
- Intensity of Solar Radiation on Mars
    - Atmosphere < 1 % of Earth's
    - No global magnetic field
    - Intensity 2.5 times greater
- Recovery of products
    - Pure CO for rocket fuel
    - Pure O_2 for sustaining life

Process Design

Mars Application

- Material Balance:
  - 10 million years of processing CO2
  - Production of 77 mi^3 of oxygen
- Not practical to Change the Atmosphere of Mars

$Ca(OH)_2$ Reactions

Absorption: $Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$

Regeneration: $CaCO_3 \xrightarrow{\Delta H} CO_2 + CaO$

Calcination: $CaO + H_2O \rightarrow Ca(OH)_2$

(Highly exothermic)