Carbon Nanotubes Plant

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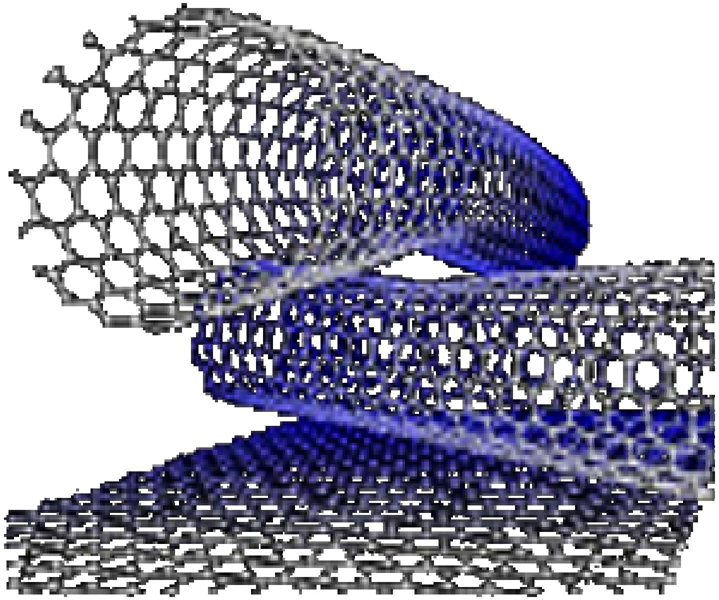
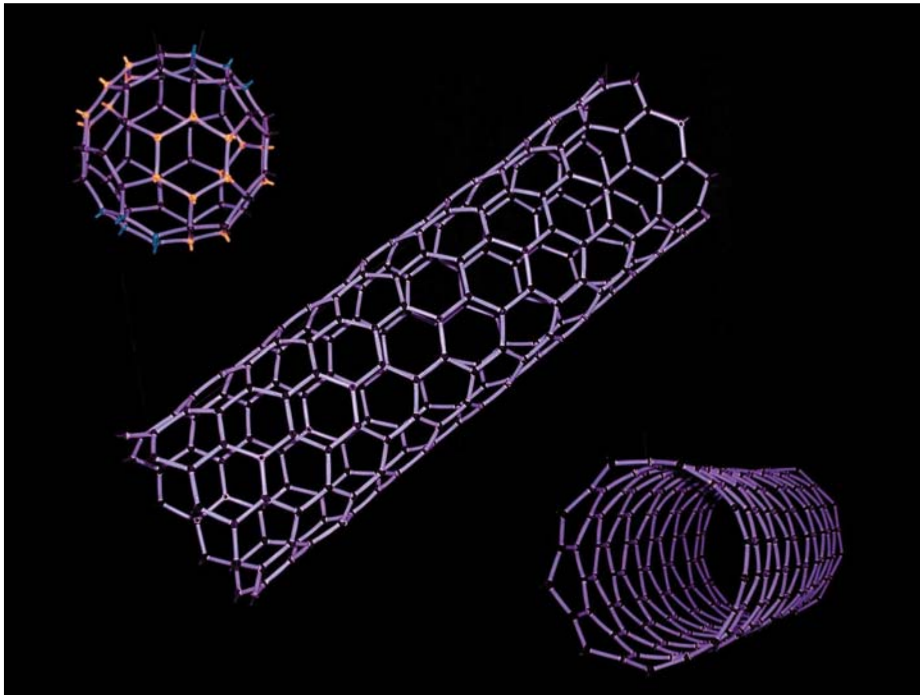


Presentation Outline

- Carbon nanotube history
- Production methods
- Economic Forecast
- HiPCO plant design
- CoMoCat plant design
- Plant Capacity and Location
- Business Plan

History

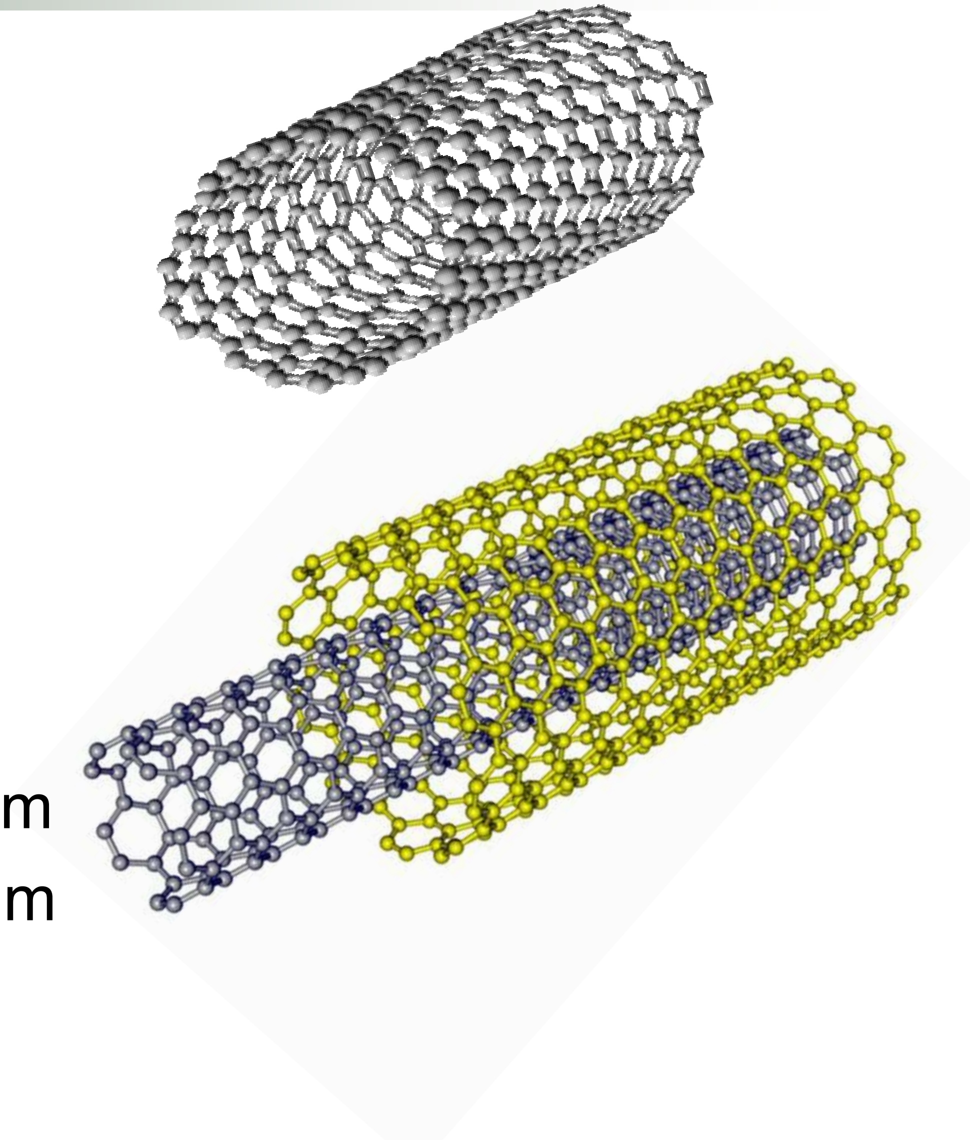
- The discovery of nanotubes comes from the Buckyball in 1980
- Nanotubes discovered in 1991 by S. Iijima



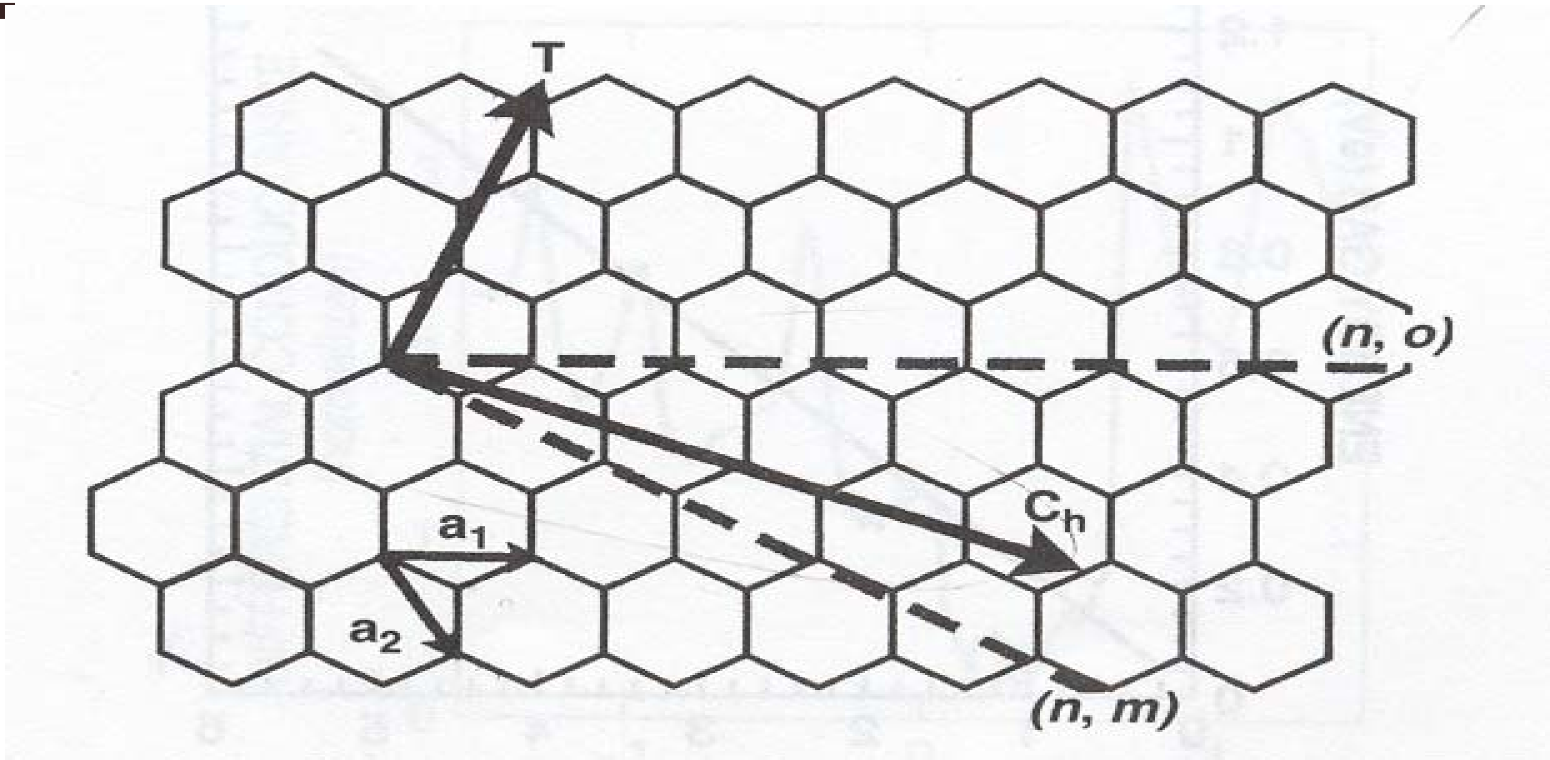
(http://www.slb.com)

Types of CNT’s

- Single wall (SWNT)
  - single layer wall
  - diameter 0.7-5 nm
- Multi-wall (MWNT)
  - concentric tubes
  - inner diameter: 1.5-15 nm
  - outer diameter: 2.5-30 nm



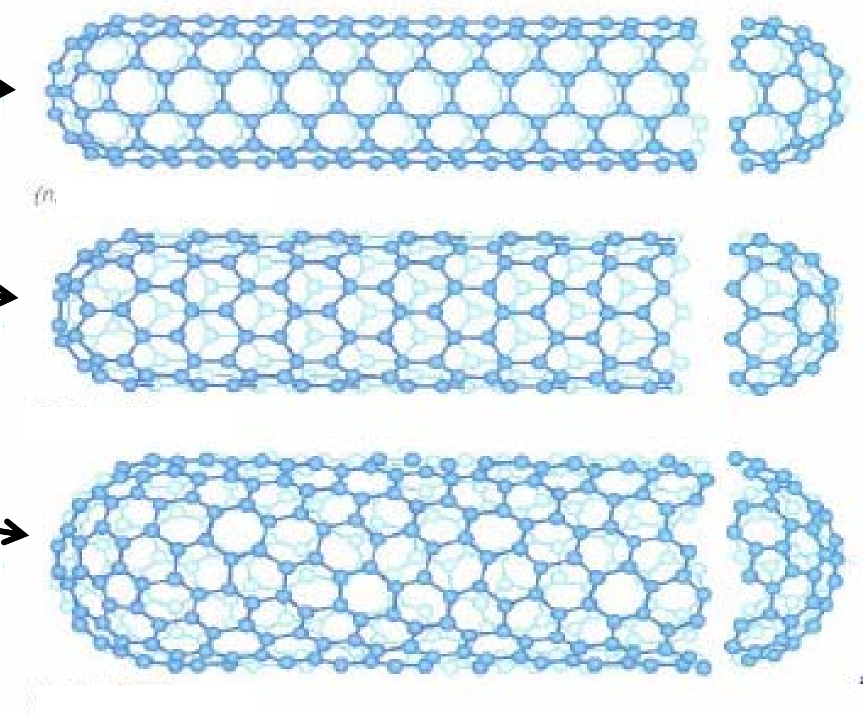
Orientation and Properties



All possible structures of SWNTs can be formed from chiral vectors

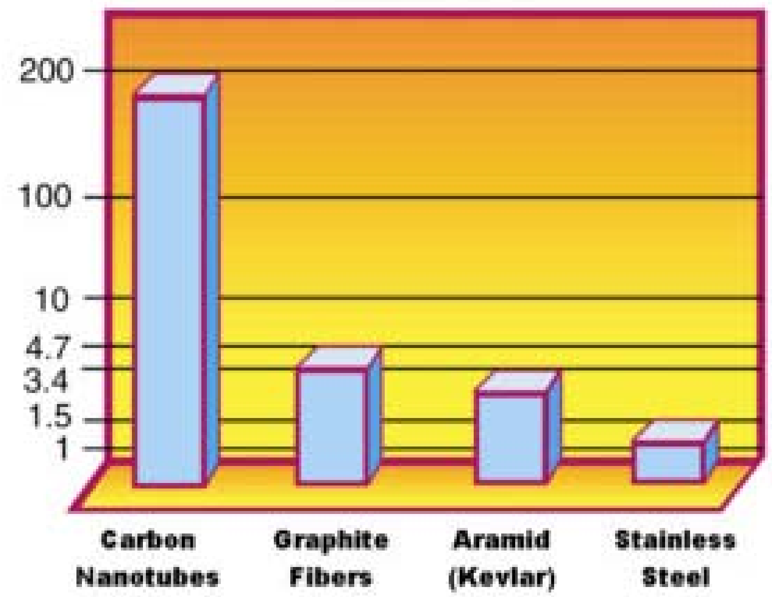
Bond Types

- Armchair (conductor)
- Zigzag (semiconductor)
- Chiral (semiconductor)



Properties

- The chart compares the tensile strength of SWNT's to some common high-strength materials.
- Electrical conductivity is as high as copper
- Thermal conductivity is as high as diamond
- Strength 100 times greater than steel at one sixth the weight



SWNT Applications

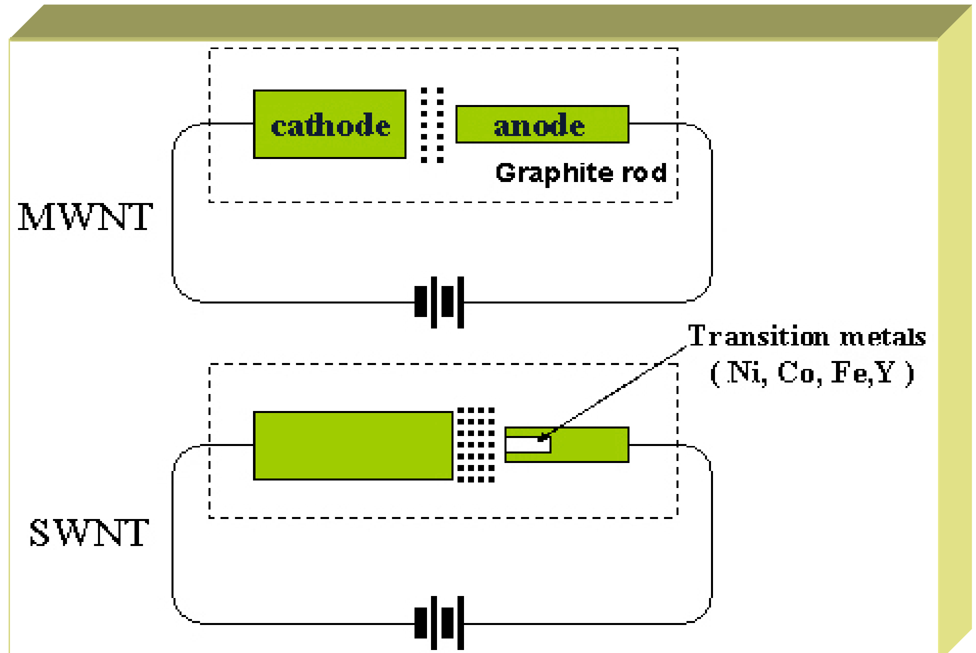
Application	Diameter (nm)	Length (μm)	Desired Form
Lithium batteries	0.7- 1.4	5. -40.	Defects
Chemical sensors	1.4 - 2.3	20. - 40.	Higly aligned carbon nanotubes
Flat panel displays	1.0 - 5.0	5. - 100	Highly ordered arrays on substrate
Hydrogen storage	1.85 - 5.0	10.-50	Produced by Ar and H_2 arc method
AFM tips	1.0 - 2.0	18. - 35.	Grown directly by CVD onto Si tips (can be attached later)

Production Methods

- Arc discharge
- Laser ablation
- Chemical Vapor Deposition (CVD)

Arc–Discharge Process

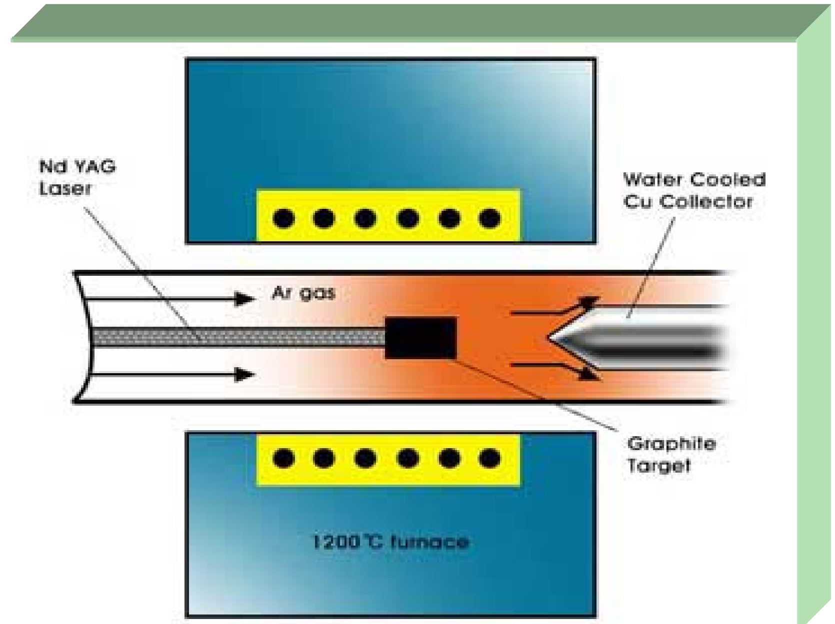
- High-purity graphite rods under a helium atmosphere.
- T > 3000^{o}C
- 20 to 40 V at a current in the range of 50 to 100 A
- Gap between the rods approximately 1 mm or less
- Lots of impurities: graphite, amorphous carbon, fullerenes



Arc-discharge apparatus

Laser Ablation Process

- Temperature 1200^{o}C
- Pressure 500 Torr
- Cu collector for carbon clusters
- MWNT synthesized in pure graphite
- SWNT synthesized when Co, Ni, Fe, Y are used
- Laminar flow
- Fewer side products than Arc discharge



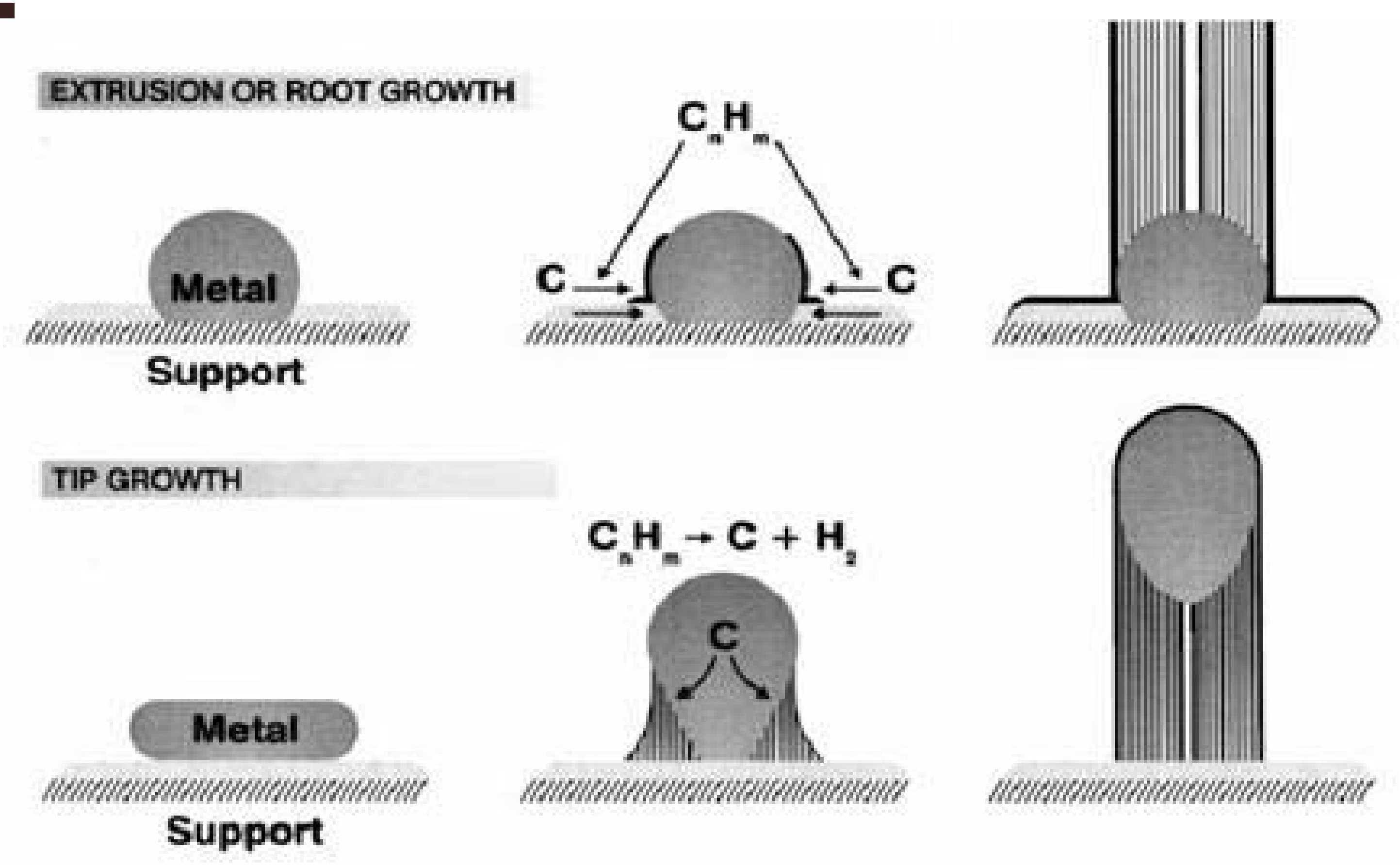
Laser ablation apparatus

Chemical Vapor Deposition

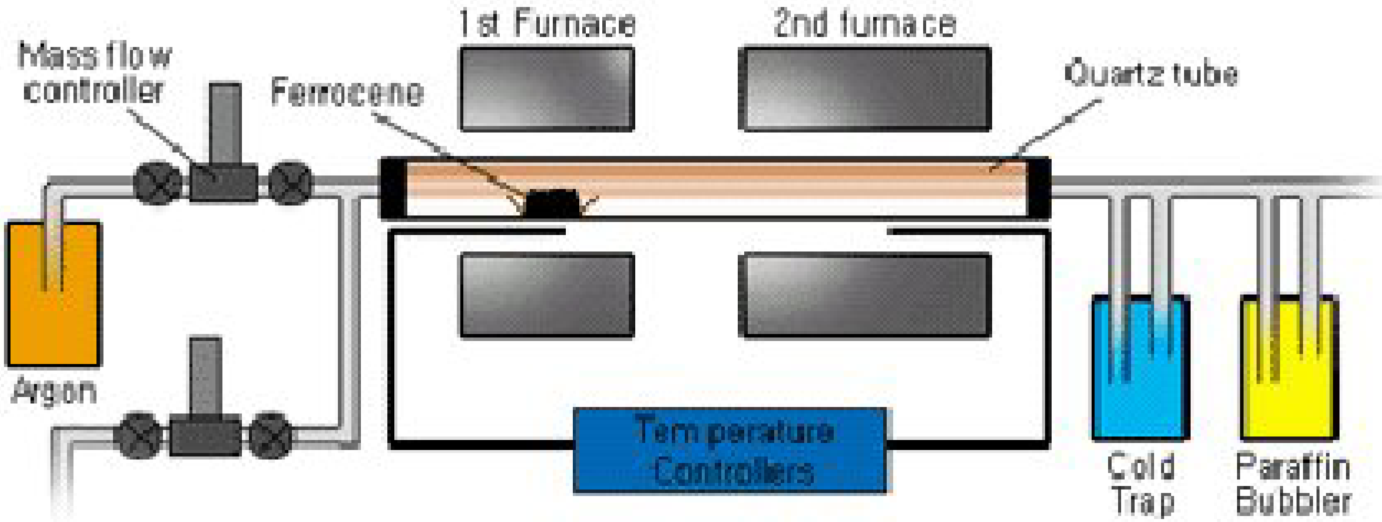
CVD

- **Gas phase process**
  No substrate
- **FROM CARBON MONOXIDE**
  - **(HiPCO®)**
  - **(CoMoCat®)**

Growth Mechanism



CVD in Gas Phase Process



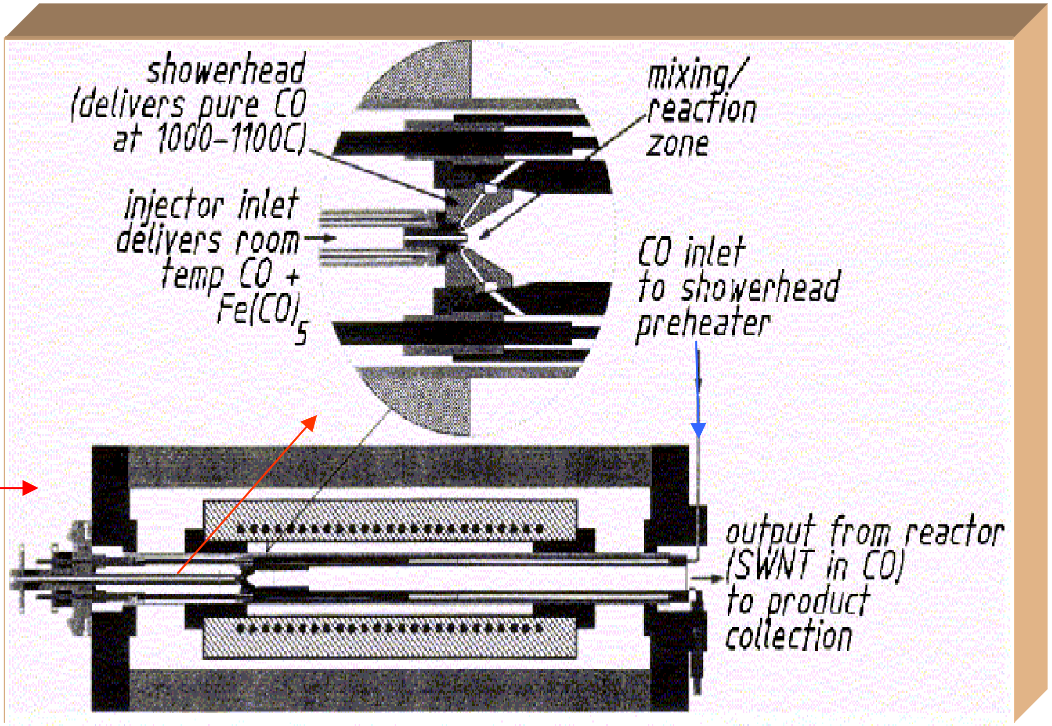
- Catalysts: Fe, Ni, Co, or alloys of the three metals
- Hydrocarbons: CH_4, C_2H_2, etc.
- Temperature: First furnace 1050^{o}C
  Second furnace: 750^{o}C
- Produce large amounts of MTWNs

CVD of Carbon Monoxide

- Thermal decomposition of iron pentacarbonyl in a flow of CO
- Temperature ~1050°C
- Pressure ~10 atm

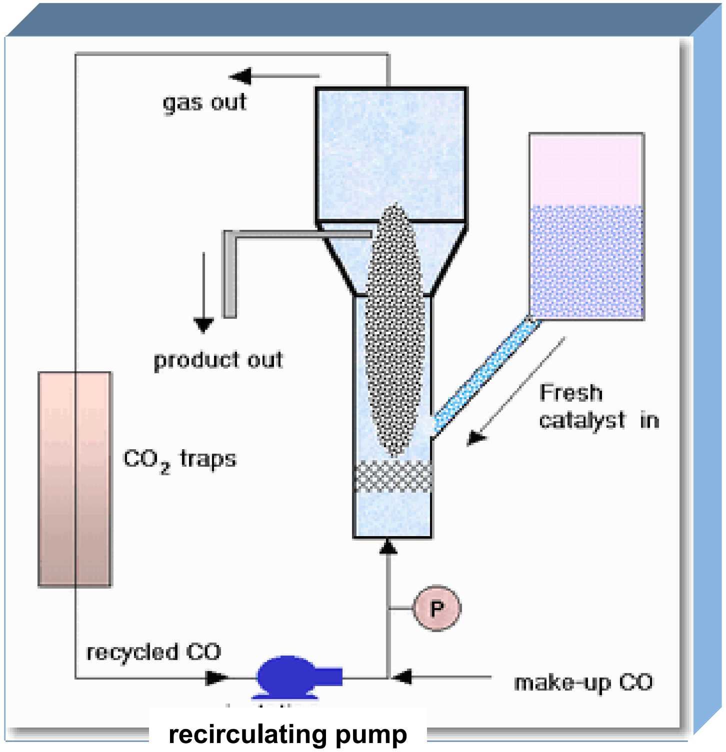
$$2CO(g) \xrightarrow{Fe(CO)_5} C(s) + CO2(g)$$

HiPCO® PROCESS



CVD of Carbon Monoxide

CoMoCat® PROCESS



- Disproportionation of CO over a Co/Mo, silica supported catalyst
- Temperatures 700-950^{o}C
- Pressure (1–10 atm)

$$2CO(g) \xrightarrow{Co\,:\,Mo} C(s) + CO_2(g)$$

Comparison of Nanotube Production Technology

Table 1. Comparison of Nanotube Production Technology

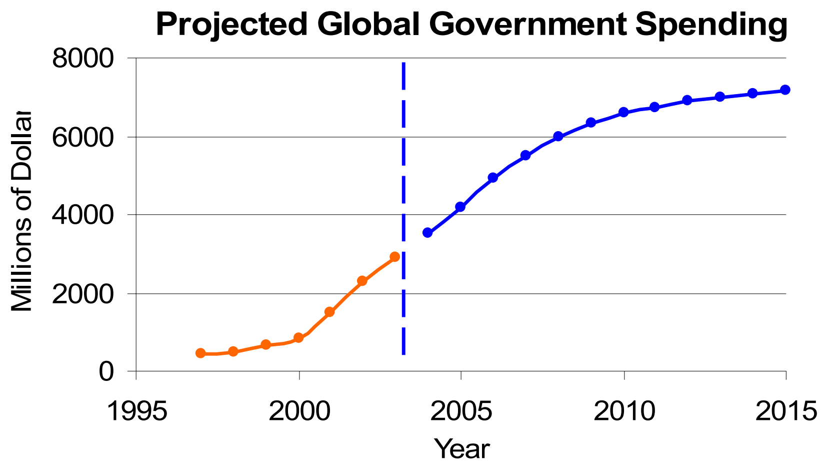
Properties	Arc Discharge	Laser Ablation	Gas Phase Process	Vapor Deposition
Nanotube Generator	Requires high voltage arc discharge.	Requires expensive high energy lasers.	Catalytic particles.	Catalytic particles.
Process	Batch.	Batch.	Continuous.	Continuous or Semi Batch.
Diameter of SWNT Nanotubes	1.2-1.4 nm	1.2-1.4 nm	0.8-1.4 nm	0.8-1.4 nm
Length of Nanotubes	1-10 microns	1-10 microns	Micron or longer	20 cm
Yields	~50%	~70%	50%	~97-99%
Quality of nanotubes	Produces largely defect free nanotubes.	Produces defect free nanotubes. Considered highest quality nanotubes.	Produces MWNT and SWNT; hard to separate. Semi Conductor	Produces tubes with some defects. Number of defects declining. Semi Conductor
Production Quantities	Could exceed 10g/day.	Less than 1g/day.	In full operation, 500-2,000 kg per day.	Theoretically can produce kg or more per day.

Source: BCC, Inc.

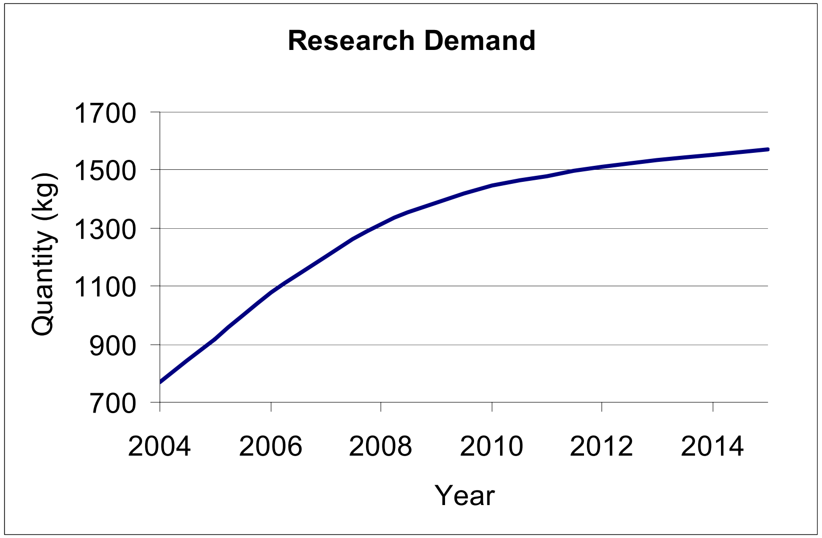
Market Forecast

- Derived from information and news sources
- Two sectors: Research and Commercial
- Research demand assumed to increase in proportion to government spending
- Commercial demand evaluated for 6 applications:
  - Batteries
  - Flat Panel Displays
  - AFM Probe Tips
  - Chemical Sensors
  - Hydrogen Storage
  - Fibers and Composites

Research Demand

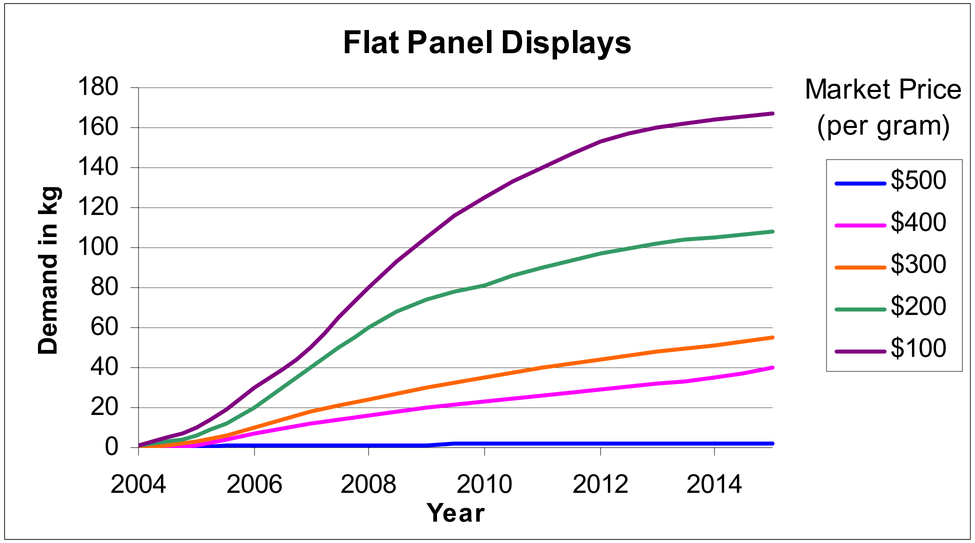


- Government spending was estimated from the National Nanotechnology Initiative
- Largest spenders: U.S., Japan, W. Europe
- Research demand was assumed to increase at the same rate as government spending
- Research demand is essentially independent of price



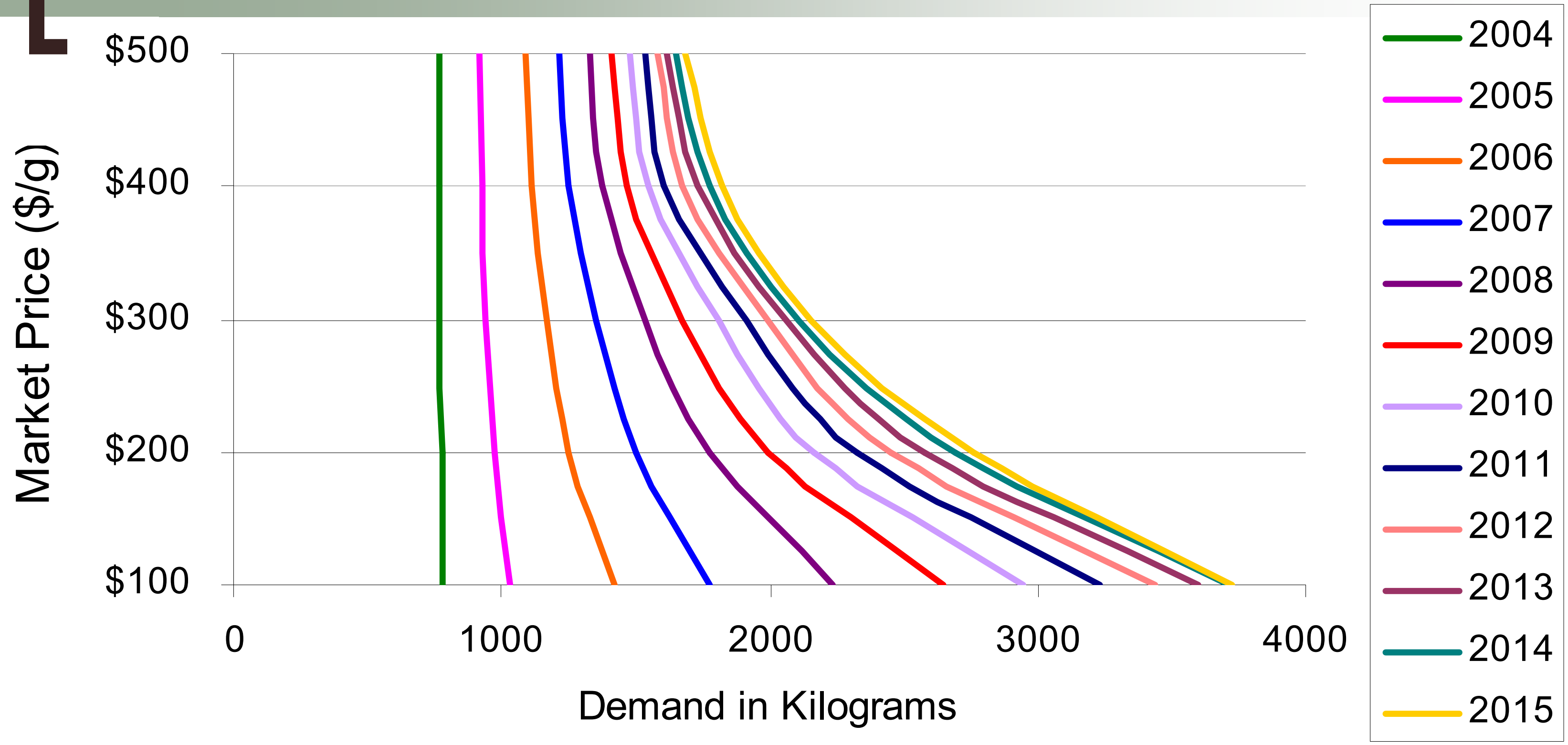
Commercial Demand

- Flat Panel Display market
- Based on Applied Nanotech Inc. estimates on timeline and market share
- Average display size and nanotube quantity determined from technical papers
- Demand varies with market price and time



- Evaluated for 5 other applications

Forecasted Demand Curves

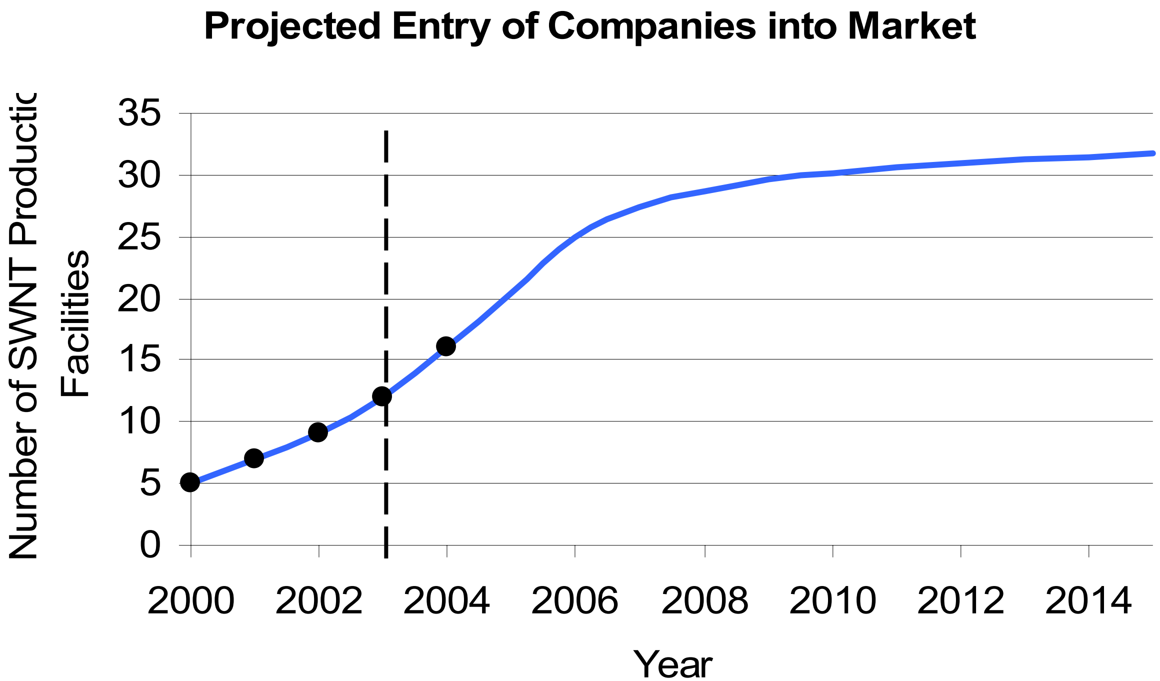


- Total demand in both research and commercial sectors
- Demand curves shift to the right with time
- Demand becomes less inelastic with time and at lower price

Companies

Company	Production (g/day)
Carbolex	35
Carbon Solutions Inc.	50
CNI	500
IIJIN	200
MER	10
Nanocarblab	3
Nanocyl	20
Nanolab	50
NanoLedge	120
NanoAmor	50
Shenzhen Nanotech	200
SouthWest	500
AVERAGE	145
TOTAL	1738

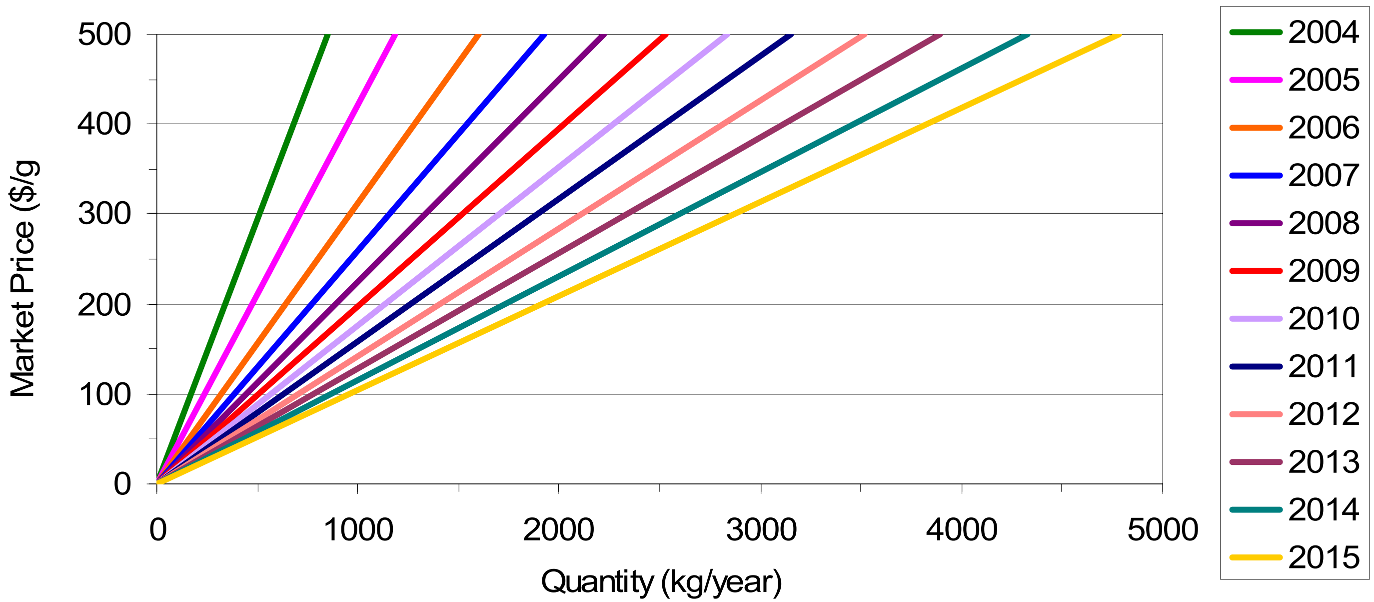
Companies



- The projected number of companies in the market was estimated based on the past trend
- Average production rate determined from market research

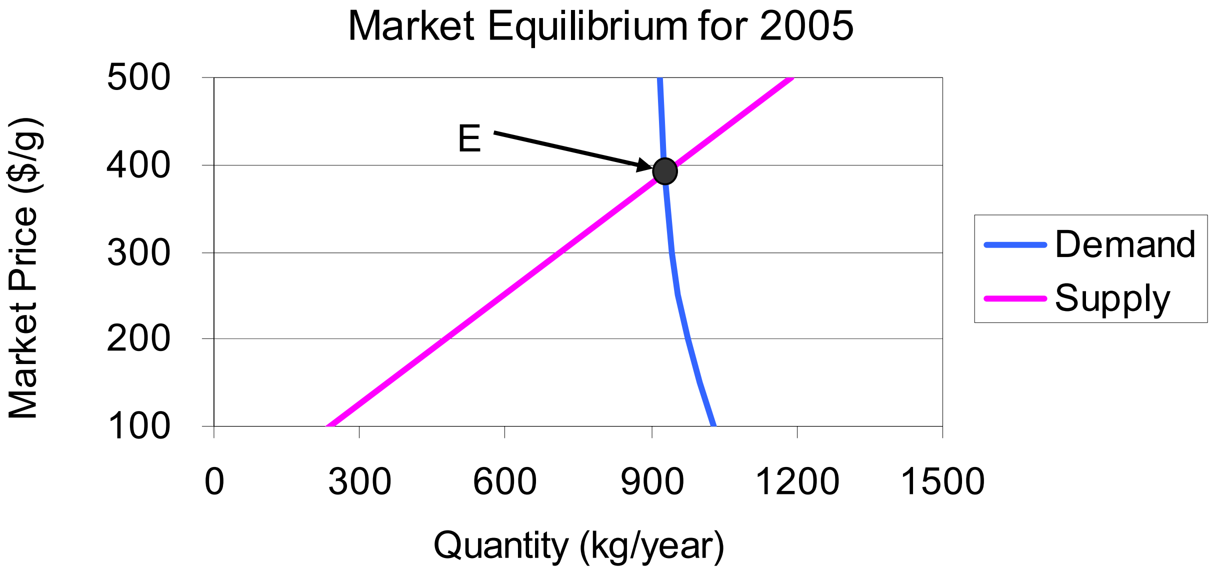
Supply Forecast

- Based on projected number of companies
- Average production rate to increase at a maximum of 10% per year
- Supply curves were assumed to be linear



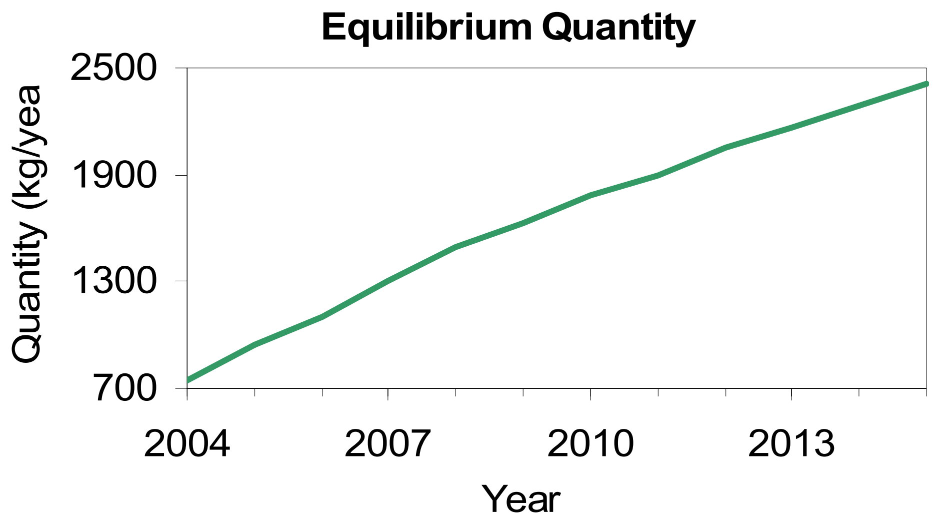
Market Equilibrium

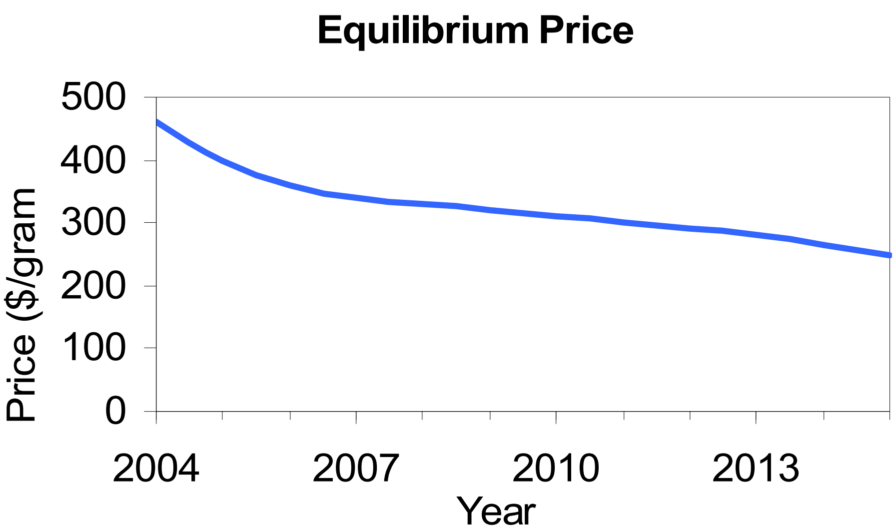
- Intersection of supply and demand curves
- Price and quantity determined for each year



Equilibrium

- Equilibrium quantity will increase at a nearly linear rate



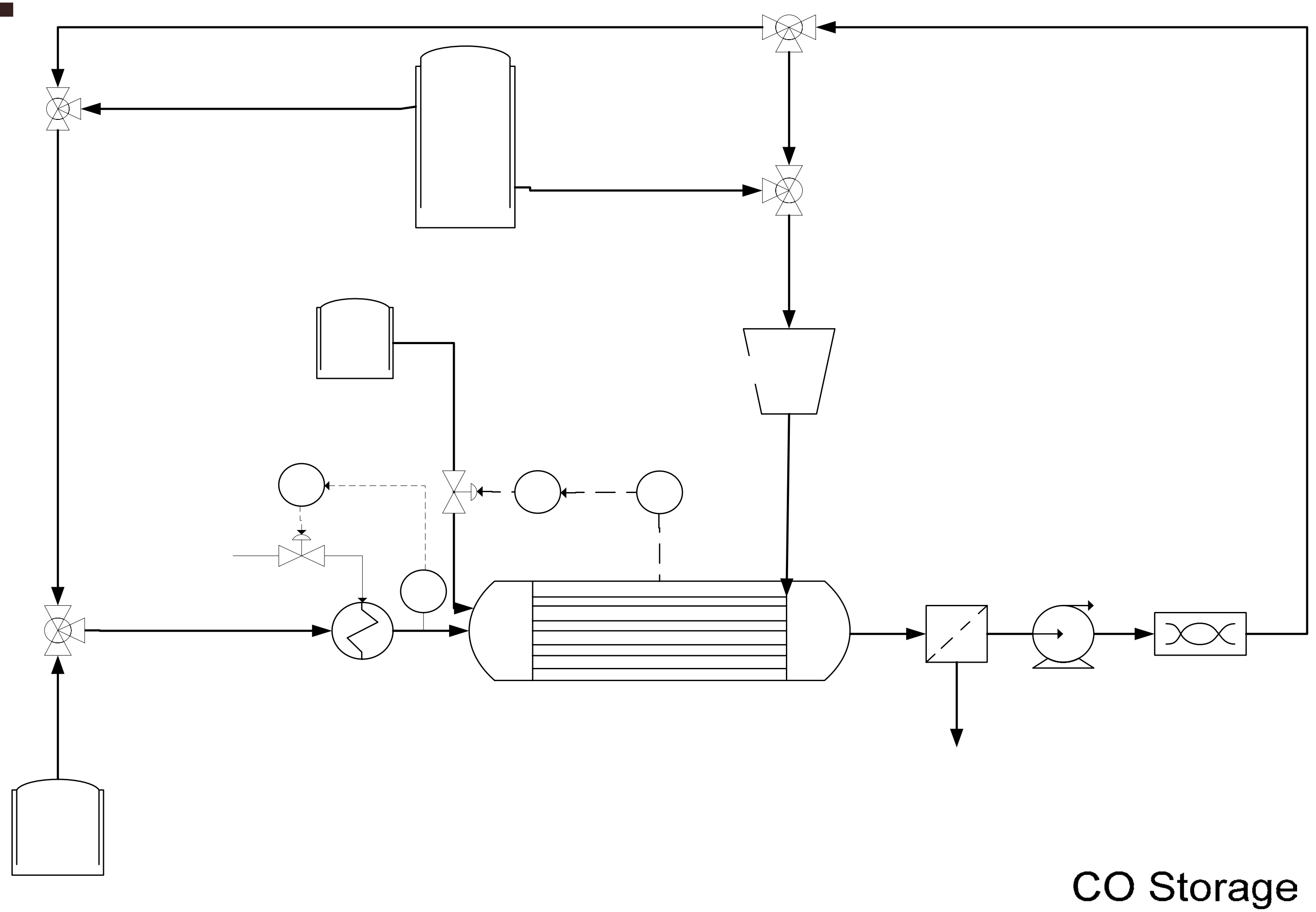


- Equilibrium price will decrease over the next ten years

Production Method

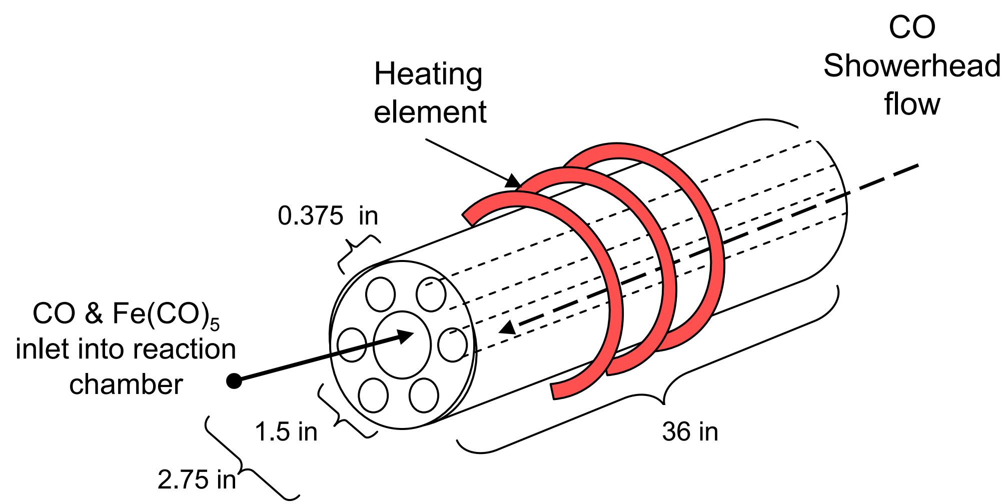
- HiPCO and CoMoCat were analyzed to determine better option
- Process designs
- Initial cost estimates
  - Equipment
  - Raw materials
  - Operating costs

HiPCO Process

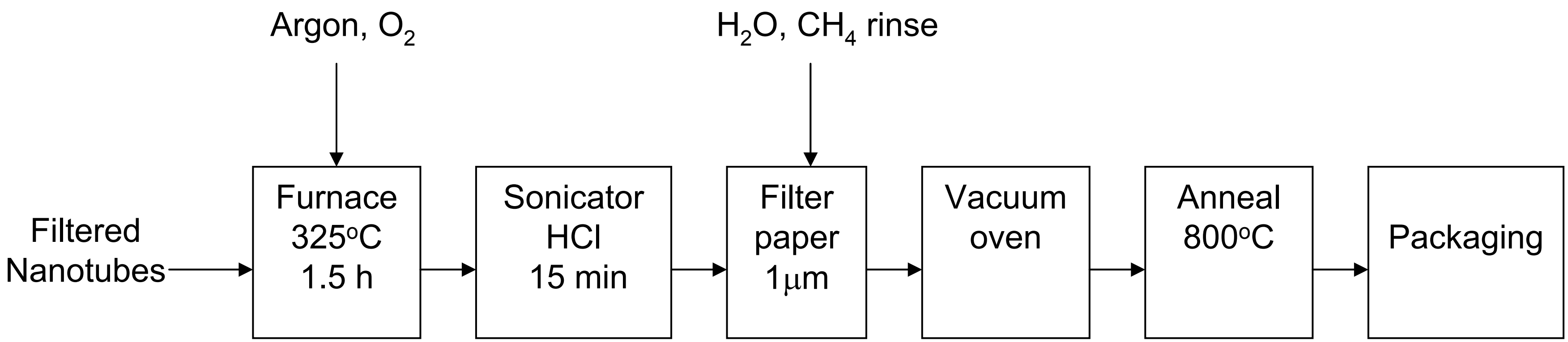


HiPCO Reactor

- Scaled-up from pilot as bundle of tubes
- Stainless steel tubes with heating elements
- Channels bored in tube wall
- Tube cost: $225



Purification Process



- Heat in furnace
- Sonicate in concentrated HCl
- Filter and dry in vacuum oven
- Anneal at 800^{o}C

Cole Parmer Furnace
1200^{o}C, 1000W

Cole Parmer
Ultrasonic Processor
1000W, 300^{o}C

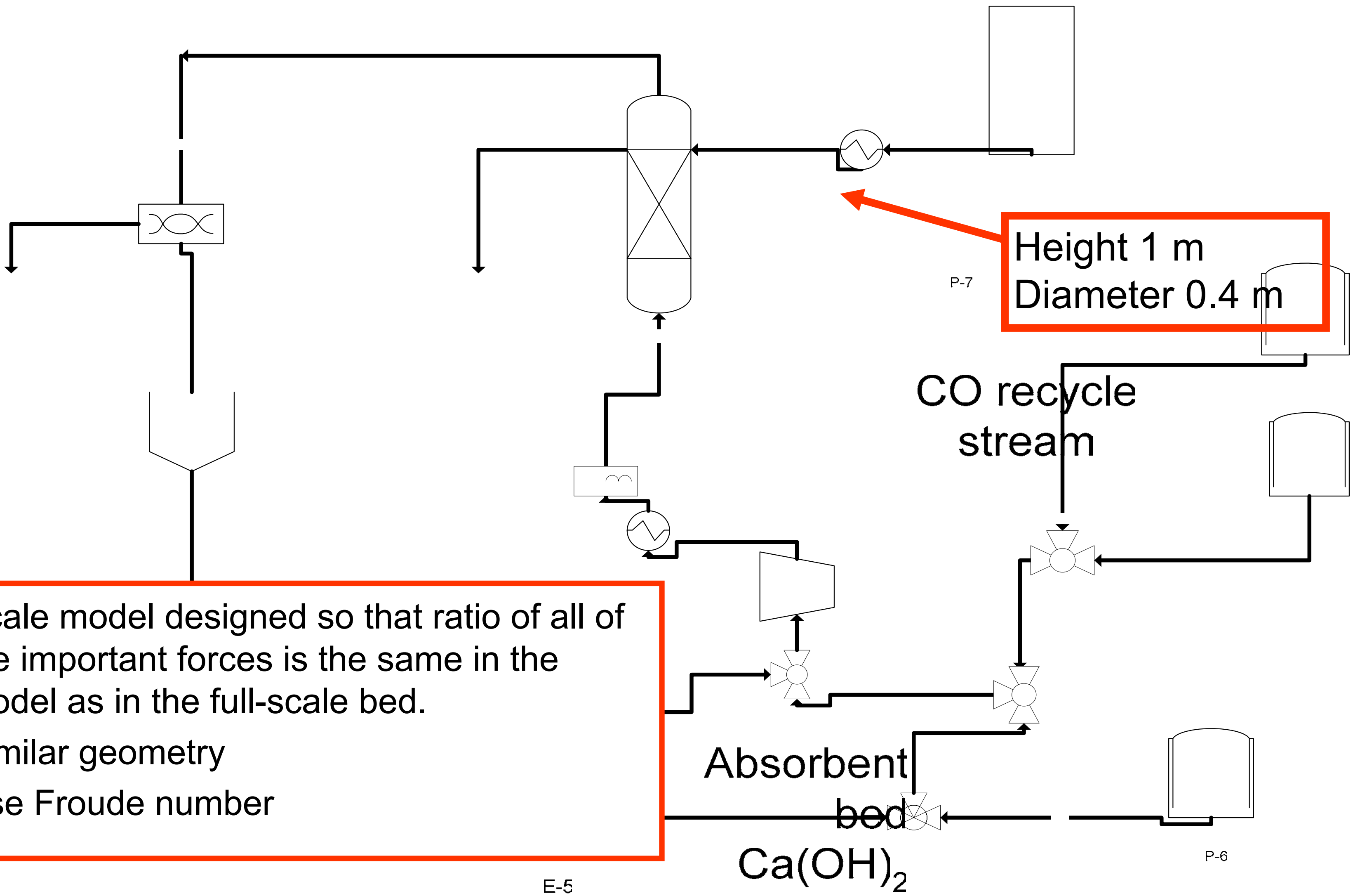
Cole Parmer Vacuum Oven
10L, 100L/hr, 1500 W

HiPCO Equipment Costs

Equipment	Cost ($)
Reactor	25,050
Compressor	60,000
Molecular sieve	10,000
Nanotube filter	1,300
Vacuum oven	2,700
Furnace	2,000
Ultrasonic processor	7,940
Vacuum pump	500
Total	109,490

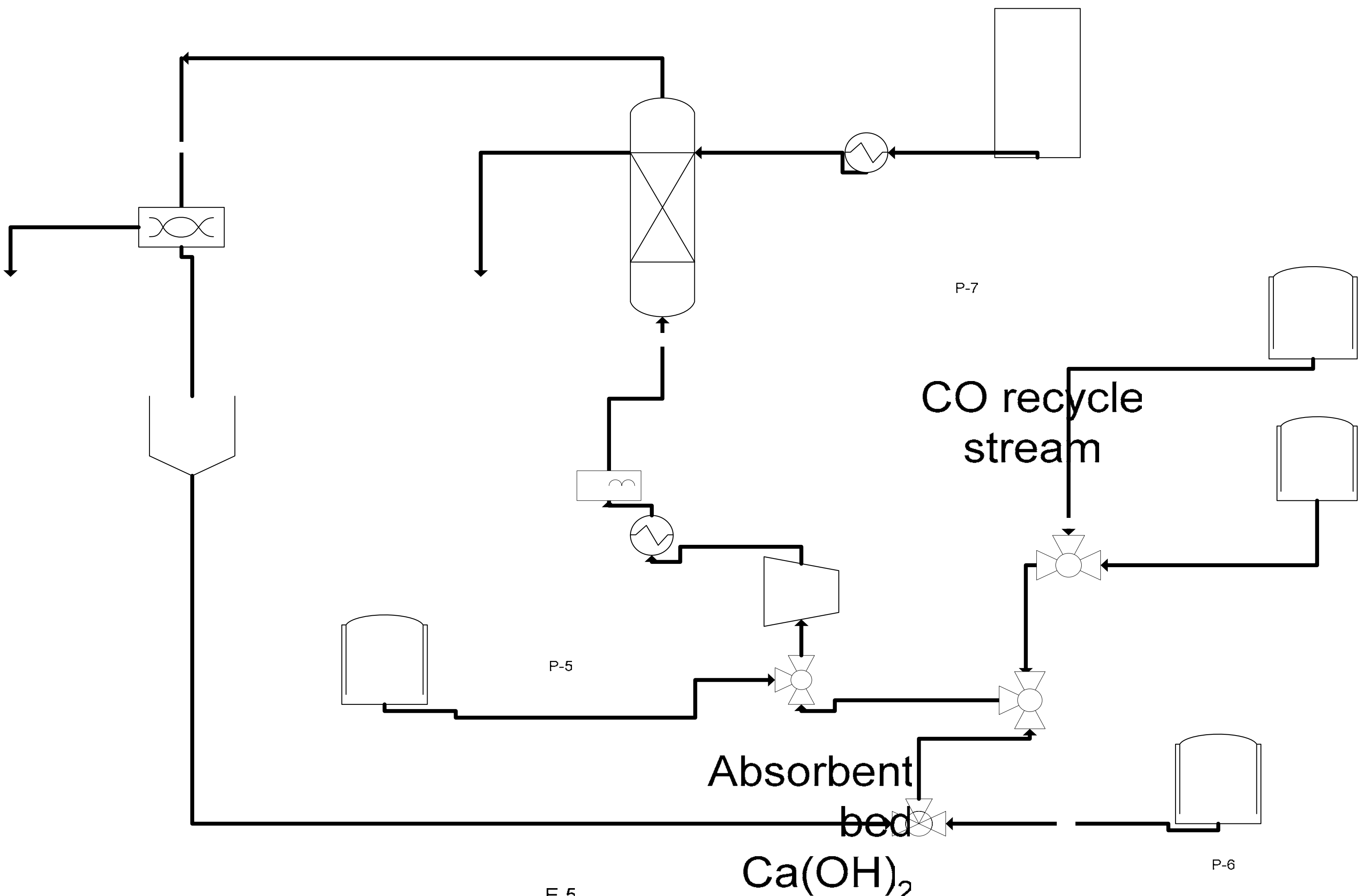
- Shown for a capacity of 360 kg per year

CoMoCat Flow Diagram

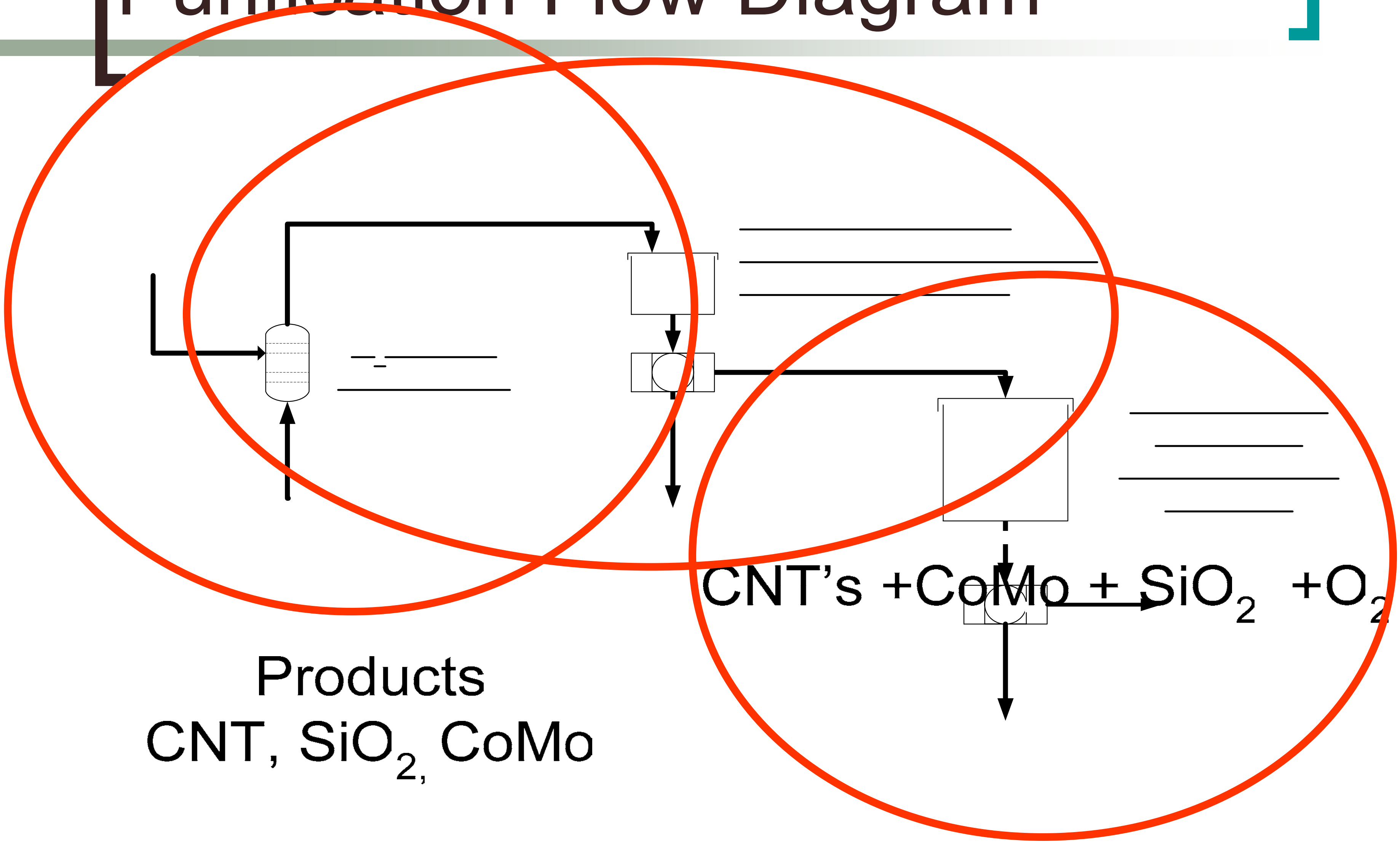


- Scale model designed so that ratio of all of the important forces is the same in the model as in the full-scale bed.
- Similar geometry
- Use Froude number

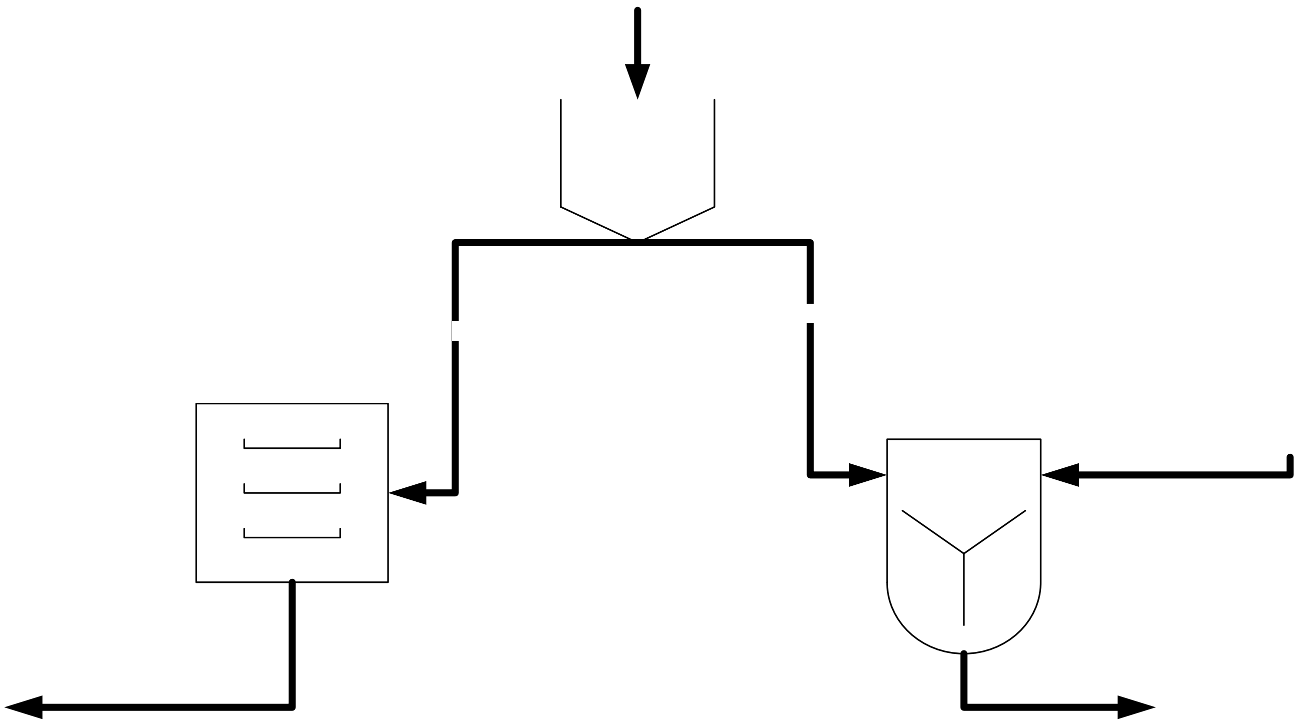
CoMoCat Flow Diagram



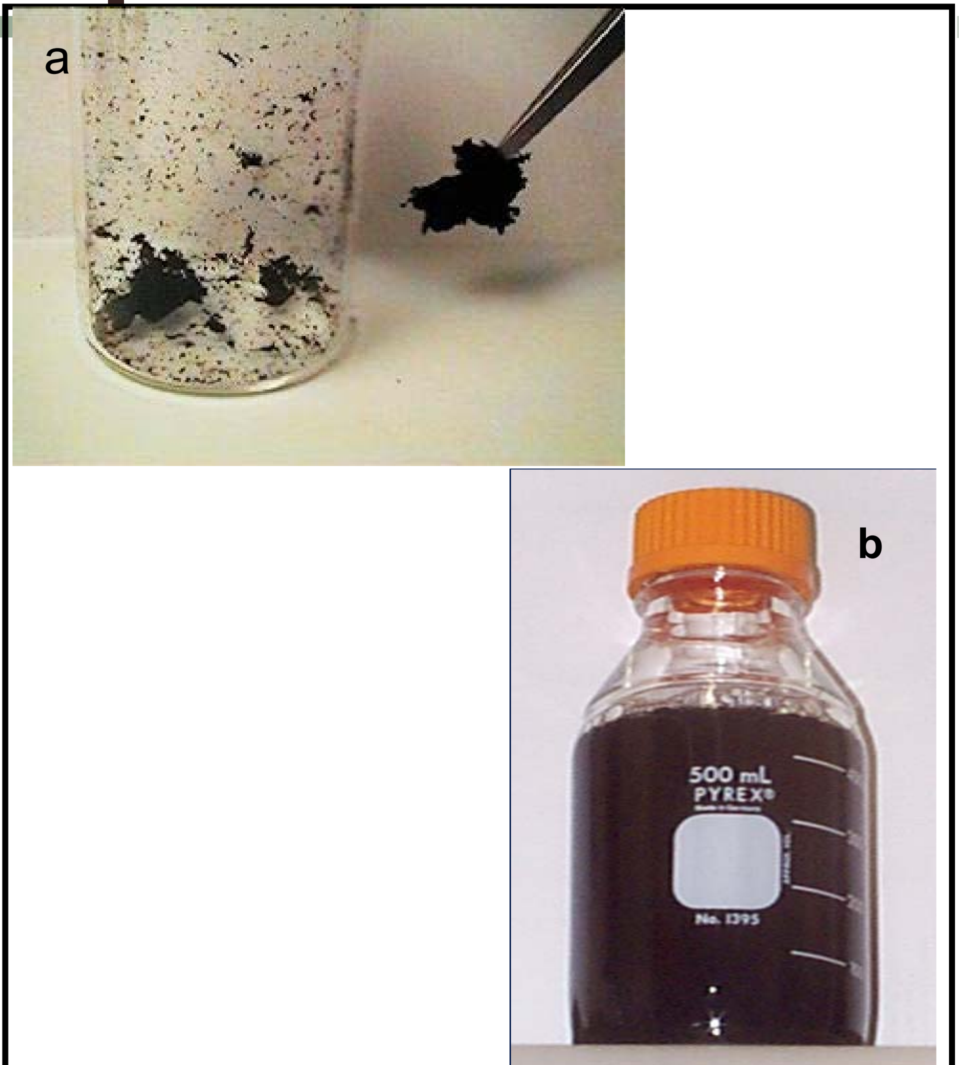
Purification Flow Diagram



CNT Handling Diagram



Delivering Forms



Forms of delivering the nanotubes :

- *a) freeze-dried web*
- *b) stable suspension*

CoMoCat Equipment Costs

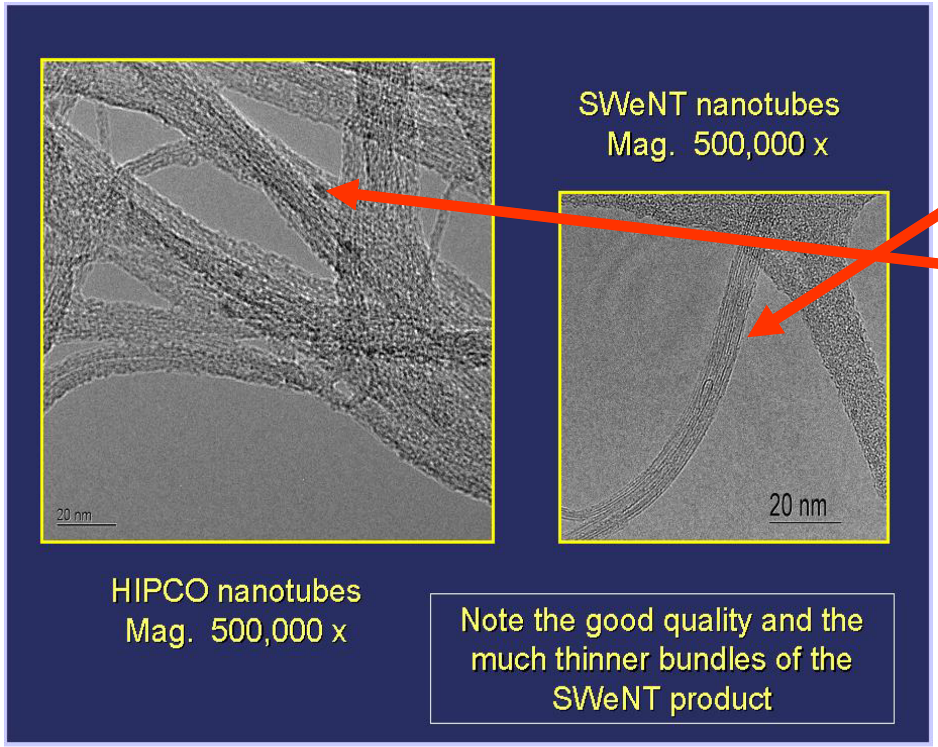
Equipment	Cost ($)
Reactor	35,800
Compressor	50,300
Molecular sieve	10,000
Filters	1,300
Gas heater	11,000
Catalyst heater	15,000
Gel Drying bed	10,000
Sonicating Beds	11,500
Total	144,900

- Shown for a capacity of 360 kg per year
- Pricing info: Matches & T.P.McNulty Associates
  M.S. Peters and K.D. Timmerhaus, Plant Design & Economics for Chemical Engineers

Production method comparisons

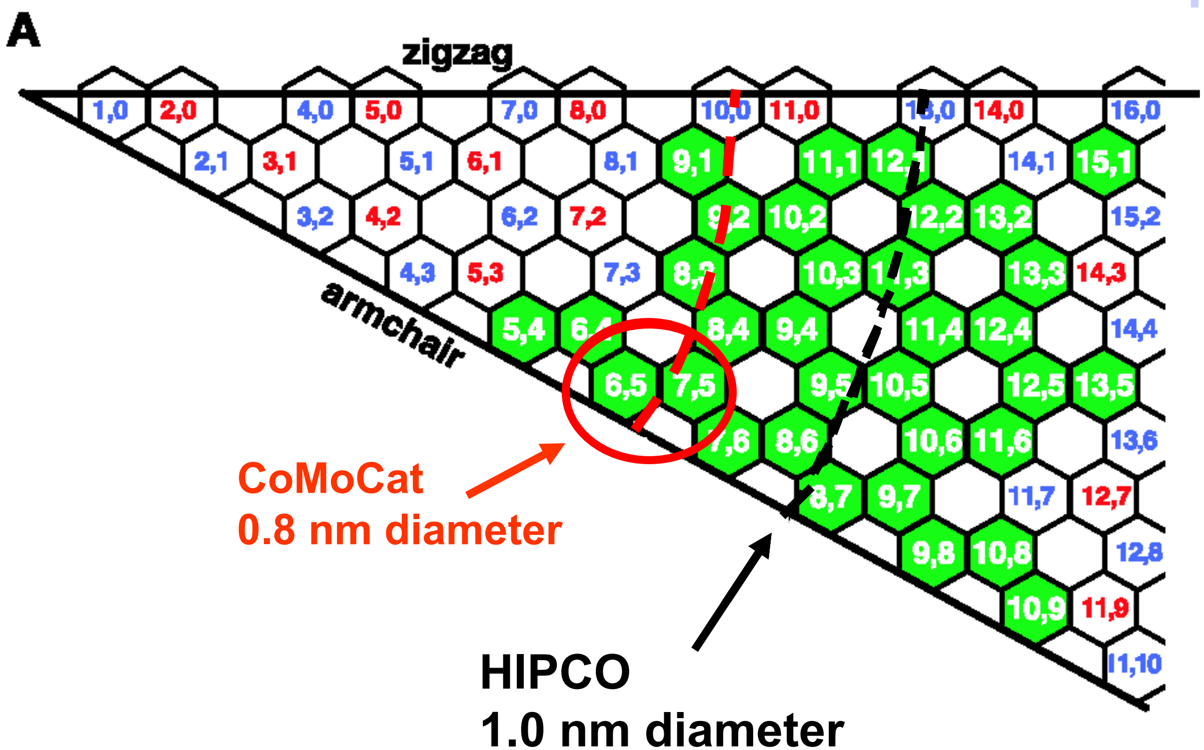
- Quality
- Technology
- Potential Market
- Fixed Capital Investment
- Operating Cost

Comparison of Quality



- Bundle size
  - CoMoCat (10-20 CNT's)
  - HIPCO (50-100 CNT's)
- Impurities
  - CoMoCat: less by wt%
  - HiPCO: fewer types

Comparison of Quality



- *Distribution of semiconducting nanotubes (Chiral).*
- *The diameter of the nanotubes increases to the right.*

Technology Comparisons

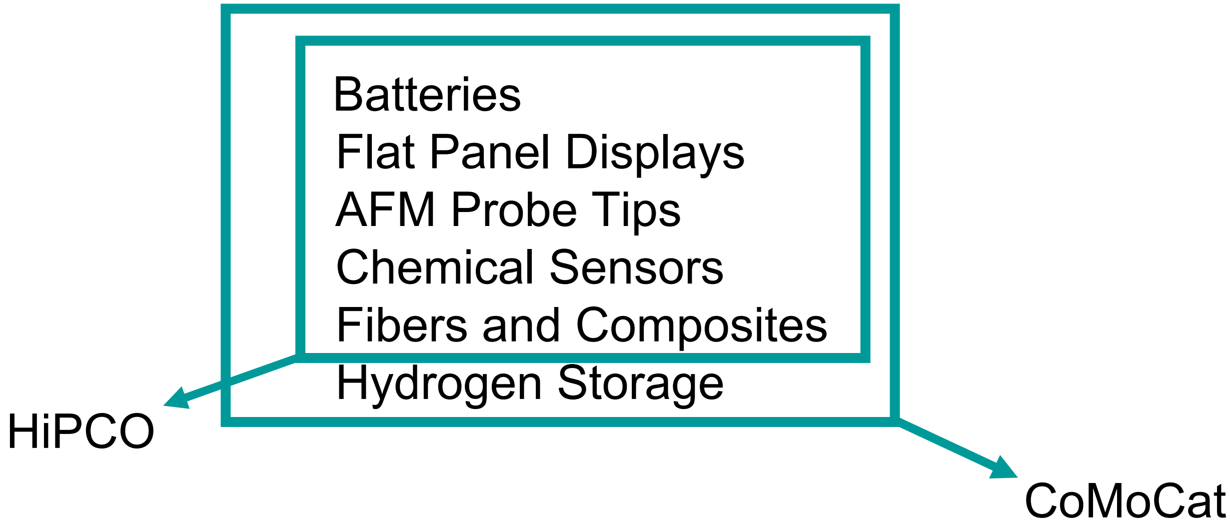
HiPCO

- Plug flow reactor
- Laminar flow
- Simple catalyst
- Yield
  - 50wt% SWNT
  - 50wt% Fe impurities
- Lower Selectivity
- Bigger bundles (50-100 CNTs)

CoMoCat

- Semi Batch reactor
- Turbulent flow
- Complicated catalyst
- Yield
  - 10wt% SWNT
  - 90wt% impurities
- Higher Selectivity
- Smaller bundles (10 – 20 CNTs)

Potential Market



- Potential market for both processes are essentially the same
- Processes were evaluated on a cost basis

Operating Cost Analysis

HiPCO		CoMoCat
2,589,499	Annual utility cost ($/ year)	2,230,000
596,000	Annual raw material cost ($/year)	2,020,000
1,000,000	Labor cost ($/year)	1,000,000
4,185,500	Annual Operating Costs	5,250,000

•Shown for a capacity of 360 kg per year

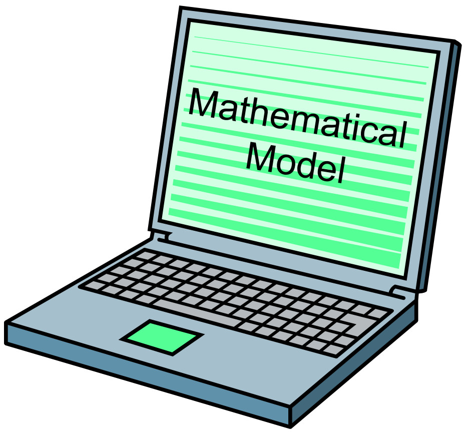
Fixed Cost Analysis

Technology	HiPCO	CoMoCat
Purchased equipment	$159,490.00	$169,490.00
delivered equipment	$23,923.50	$25,423.50
pruchased equiment installation	$63,796.00	$67,796.00
instrumentation$Controls(installed)	$95,694.00	$101,694.00
Piping(isntalled)	$49,441.90	$49,441.90
Electrical systems(installed)	$39,872.50	$39,872.50
Buildings(land and constructions)	$639,593.50	$639,593.50
Yard improvements	$39,872.50	$39,872.50
Service facilities	$87,719.50	$87,719.50
Total direct cost	$1,199,403.40	$1,220,903.40
Engineering and supervision	$100,000.00	$100,000.00
Construction expenses	$250,000.00	$250,000.00
Legal expenses	$9,170.68	$9,170.68
Contractor's fee	$150,000.00	$150,000.00
Contingency	$80,701.94	$80,701.94
Advertising	$10,000.00	$10,000.00
Marketing	$5,000.00	$5,000.00
Total indirect costs	**$604,872.62**	**$604,872.62**
FCI	**$1,804,276.02**	**$1,825,776.02**

- **Shown for a capacity of 360 kg per year**

Mathematical Model

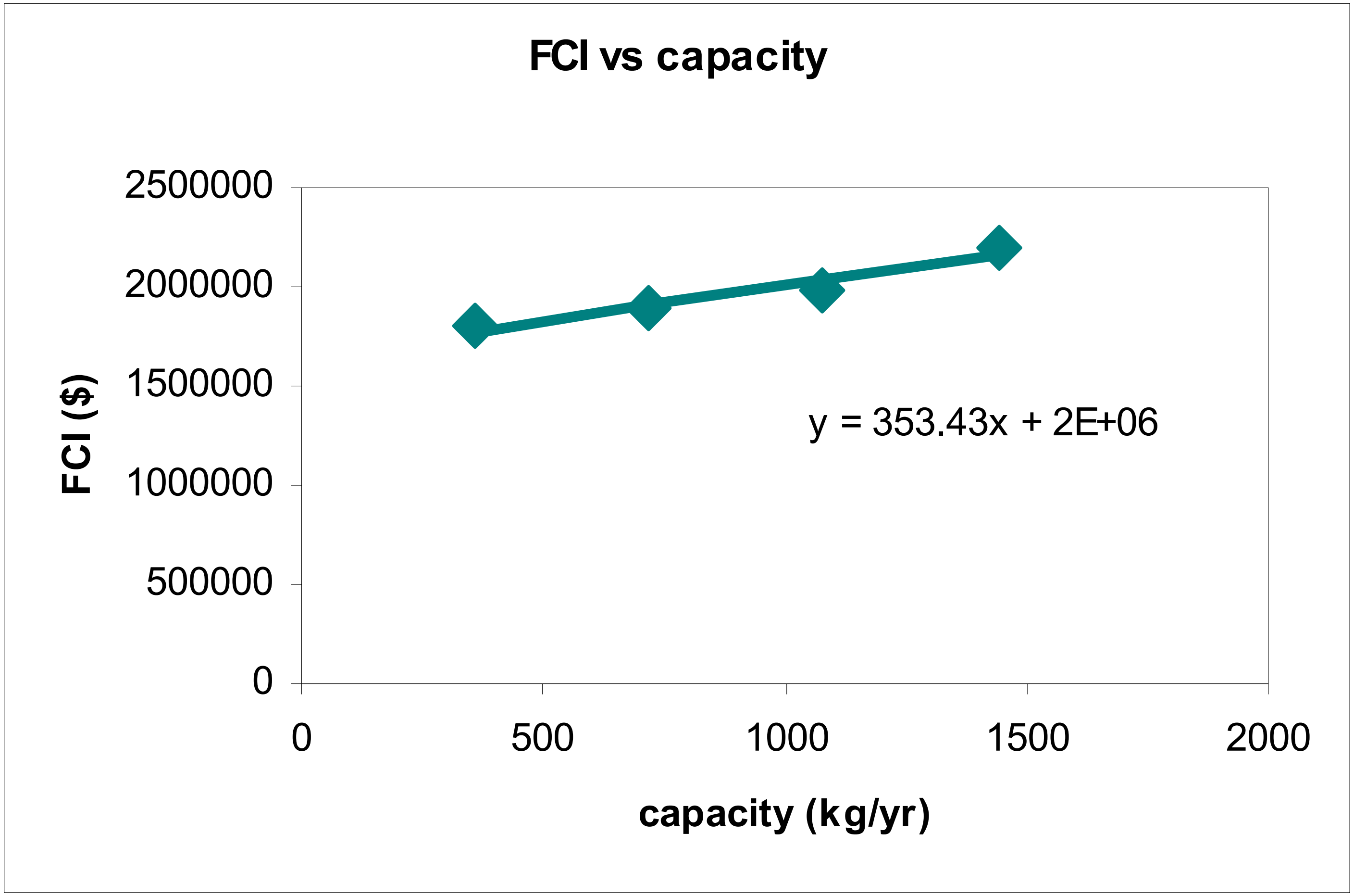
- Input:
  - FCI vs. Capacity
  - Operating Costs
  - Raw materials
  - Locations
  - Taxes
  - Labor wages
  - Demand
- Output:
  - Net present value
  - Plant location
  - Product market



FCI vs. Capacity

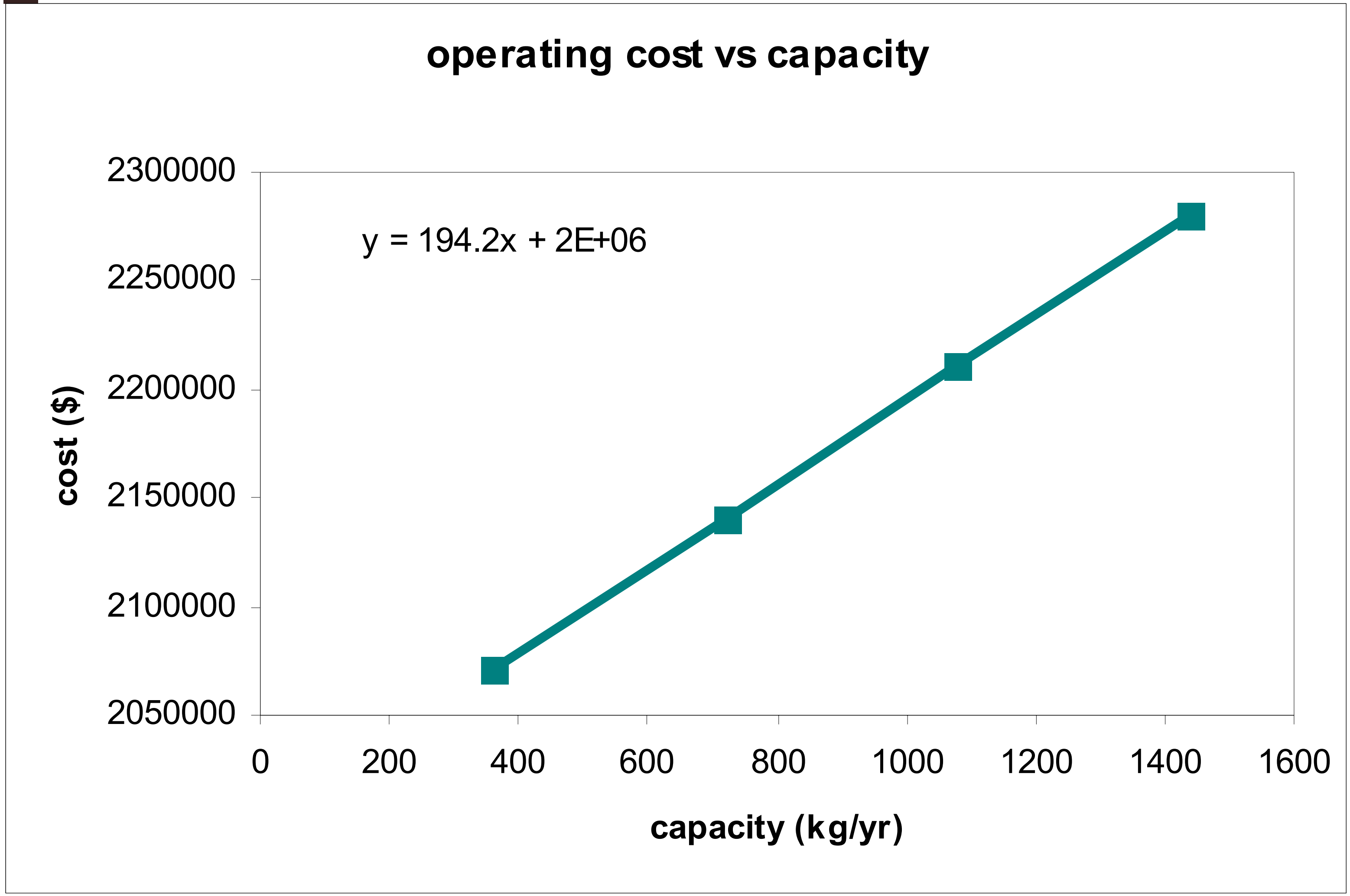
Capacity (kg/yr)	360	720	1080	1440
Purchased equipment	$159,490.00	$182,741.00	$205,992.00	$259,243.00
delivered equipment	$23,923.50	$27,411.15	$30,898.80	$38,886.45
pruchased equiment installation	$63,796.00	$73,096.40	$82,396.80	$103,697.20
instrumentation$Controls(installed)	$95,694.00	$109,644.60	$123,595.20	$155,545.80
Piping(isntalled)	$49,441.90	$56,649.71	$63,857.52	$80,365.33
Electrical systems(installed)	$39,872.50	$45,685.25	$51,498.00	$64,810.75
Buildings(land and constructions)	$639,593.50	$639,593.50	$639,593.50	$639,593.50
Yard improvements	$39,872.50	$45,685.25	$51,498.00	$64,810.75
Service facilities	$87,719.50	$100,507.55	$113,295.60	$142,583.65
Total direct cost	$1,199,763.40	$1,281,734.41	$1,363,705.42	$1,550,976.43
Engineering and supervision	$100,000.00	$100,000.00	$100,000.00	$100,000.00
Construction expenses	$250,000.00	$250,000.00	$250,000.00	$250,000.00
Legal expenses	$9,170.68	$10,507.61	$11,844.54	$14,906.47
Contractor's fee	$150,000.00	$150,000.00	$150,000.00	$150,000.00
Contingency	$80,701.94	$92,466.95	$104,231.95	$131,176.96
Advertising	$10,000.00	$10,000.00	$10,000.00	$10,000.00
Marketing	$5,000.00	$5,000.00	$5,000.00	$5,000.00
Total indirect costs	**$604,872.62**	**$602,974.55**	**$616,076.49**	**$646,083.43**
FCI	**$1,804,636.02**	**$1,884,708.96**	**$1,979,781.91**	**$2,197,059.86**

Model Input

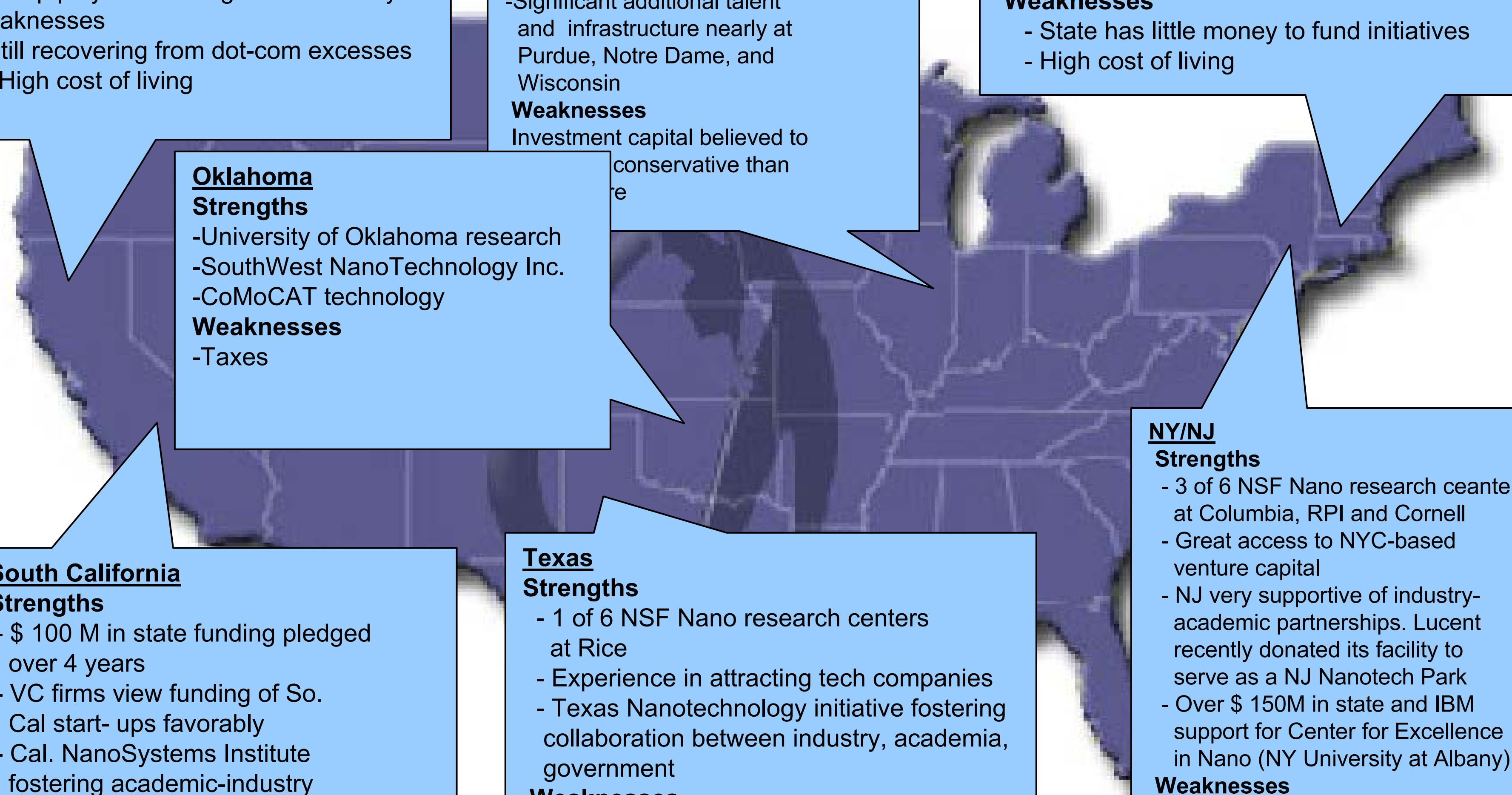


FCI vs capacity
2500000
2000000
1500000
1000000
500000
0
FCI ($)
y = 353.43x + 2E+06
0
500
1000
1500
2000
capacity (kg/yr)

Model Input



operating cost vs capacity
y = 194.2x + 2E+06
2300000
2250000
2200000
2150000
2100000
2050000
cost ($)
0
200
400
600
800
1000
1200
1400
1600
capacity (kg/yr)



Silicon Valley

Strengths
- $100M in state funding pledged over 4 years
- Tech-focused infrastructure, with myriad Of top players from high-tech industry

Weaknesses
- Still recovering from dot-com excesses
- High cost of living

Illinois

Strengths
- 2 of 6 NSF Nano research centers at Northwestern and UIUC (including RPI's center, due to NSEC grant partnership)
- Strong nano research base
- Significant additional talent and infrastructure nearly at Purdue, Notre Dame, and Wisconsin

Weaknesses

Investment capital believed to … conservative than … re

Massachusetts

Strengths
- 1 of 6 NSF nano research centers at Harvard
- Track record of establishing new industries
- Abundant entrepreneurship

Weaknesses
- State has little money to fund initiatives
- High cost of living

Oklahoma

Strengths
- University of Oklahoma research
- SouthWest NanoTechnology Inc.
- CoMoCAT technology

Weaknesses
- Taxes

NY/NJ

Strengths
- 3 of 6 NSF Nano research ceanters at Columbia, RPI and Cornell
- Great access to NYC-based venture capital
- NJ very supportive of industry-academic partnerships. Lucent recently donated its facility to serve as a NJ Nanotech Park
- Over $ 150M in state and IBM support for Center for Excellence in Nano (NY University at Albany)

Weaknesses
- No coordinated effort yet
- High cost of living

South California

Strengths
- $ 100 M in state funding pledged over 4 years
- VC firms view funding of So. Cal start- ups favorably
- Cal. NanoSystems Institute fostering academic-industry collaboration

Weaknesses
- Competitive entrepreneurial environment can make funding difficult
- High cost of living

Texas

Strengths
- 1 of 6 NSF Nano research centers at Rice
- Experience in attracting tech companies
- Texas Nanotechnology initiative fostering collaboration between industry, academia, government

Weaknesses
- Austin- Huston – Dallas cluster is geographically dispersed
- No concrete state funding or initiative yet

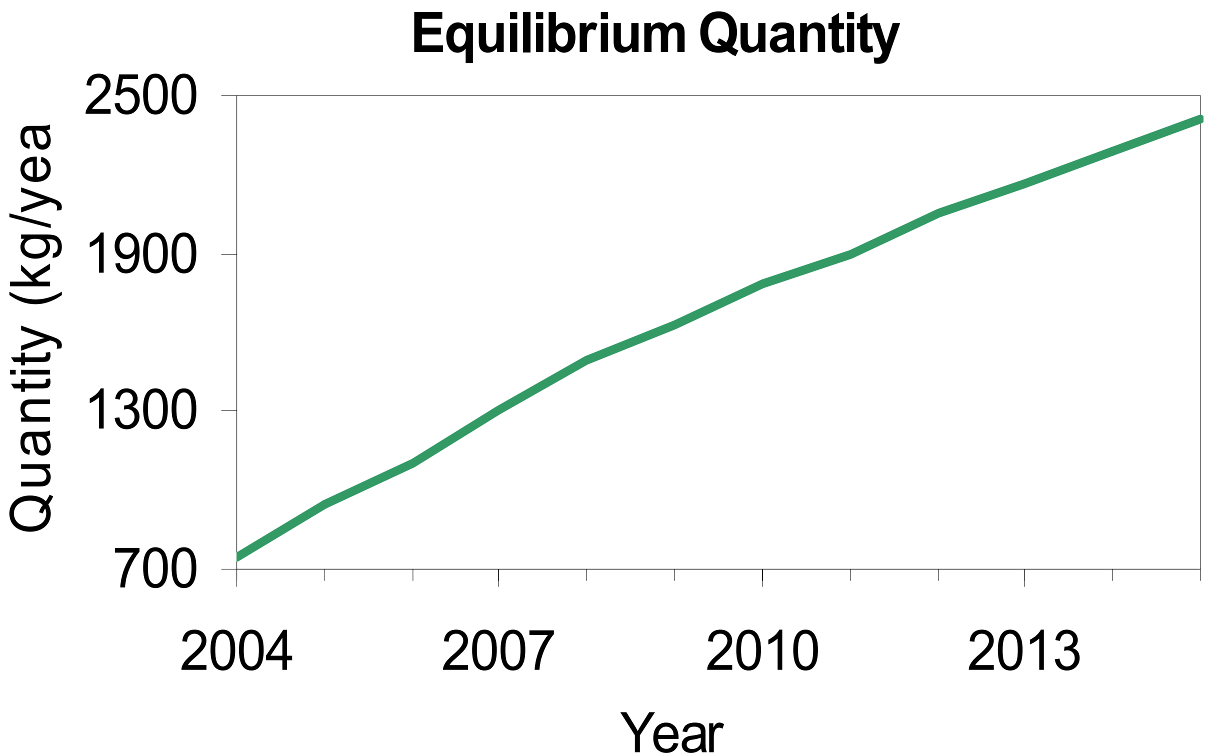
Taxes and Labor

States	State Income Tax	State Sales Tax	Property Tax
California	1% - 9.3 %	6%	30%
Texas	0%	6.25%	25%
NY/NJ	1.4 % - 6.37 %	6%	34%
Massachusetts	5.30%	5%	30%
Illinois	3%	6.25%	33.33%
Oklahoma	0.5 % - 7 %	4.50%	15%

- Total staff : 22
- Total wage paid per year: $ 1,000,000

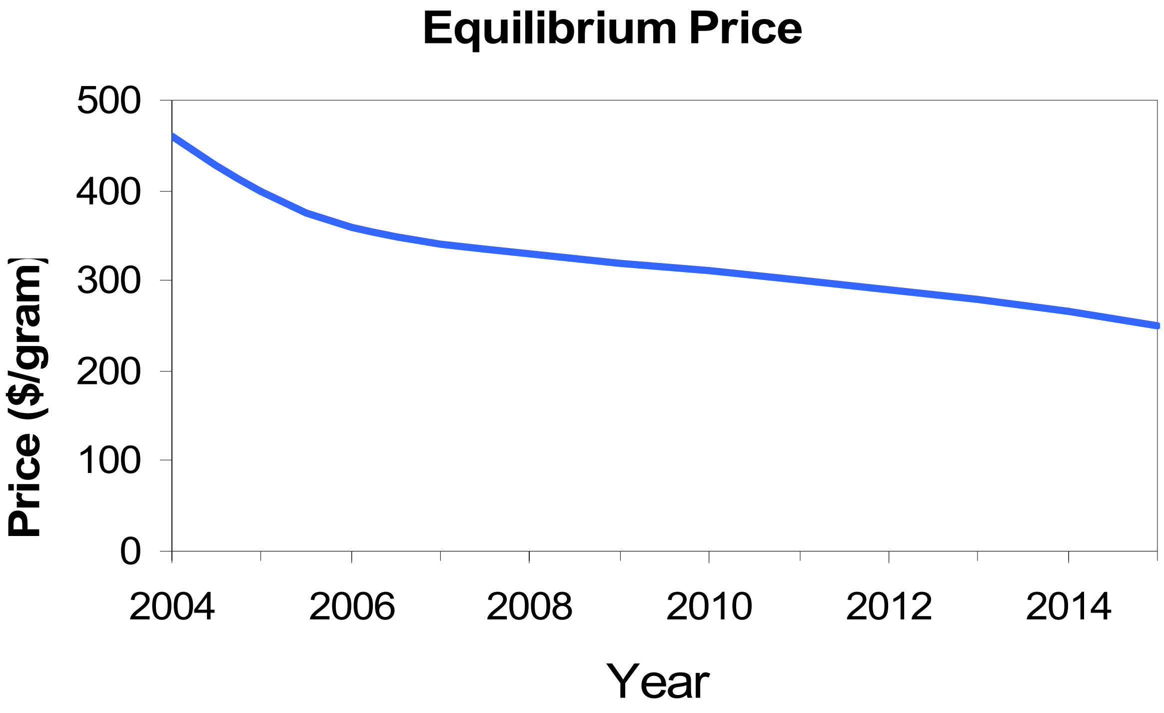
Model Input

- Forecasted demand for nanotubes



Model Input

- Forecasted price



Equations

Binary Variables

bi = 1 if constructed

bc = 1 if expanded

$$FCI_i = A * bi_i + B * bc_i + C * Capacity_i$$

$$CF_{i,tp} = \mathrm{Re}venue_{i,tp} - (\mathrm{Re}venue_{i,tp} - d * FCI_i) * taxprop_i$$

Amount taken directly from revenues to pay for capital investment

$$TotalCosts_{i,tp} = RawMatCost_{i,tp} + OperatingCosts_{i,tp} + Capimprove_{tp}$$

Equations

$$TCI_i = FCI_i / 0.85$$

Objective Function to be MAXIMIZED

$$NPW = \sum_i \left(\sum_{tp} \frac{CF_{i,tp}}{(1+i)^{tp}} + \frac{(V_s + I_w)}{(1+i)^{tp}} \cdot FCI_i - TCI_i \right)$$

Constraints

$$NumPlants = \sum_i bi_i$$

$$Capacity_i * bi_i \geq \sum_j x_{i,j,tp}$$

Percentage of targeted market

$$Demand_{j,tp} * (PM) \geq \sum_i x_{i,j,tp}$$

$$MaxCap_i \geq Capacity_i$$

$$\sum_j x_{i,j,tp=1} = 0$$

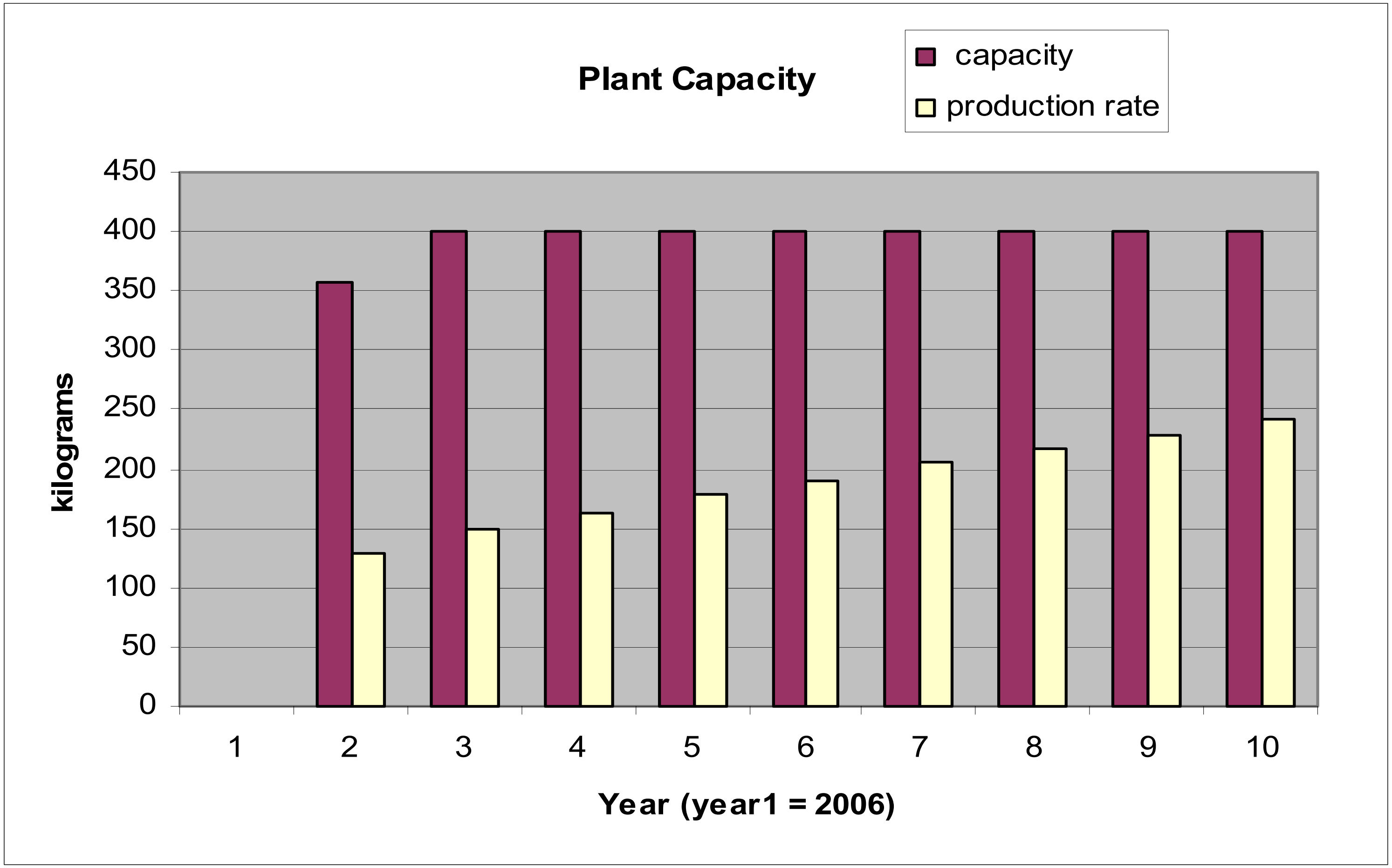
Sensitivity Analysis

Raw materials	Current price	+ 50%
NPW (million$)	18	0.745

Model Output

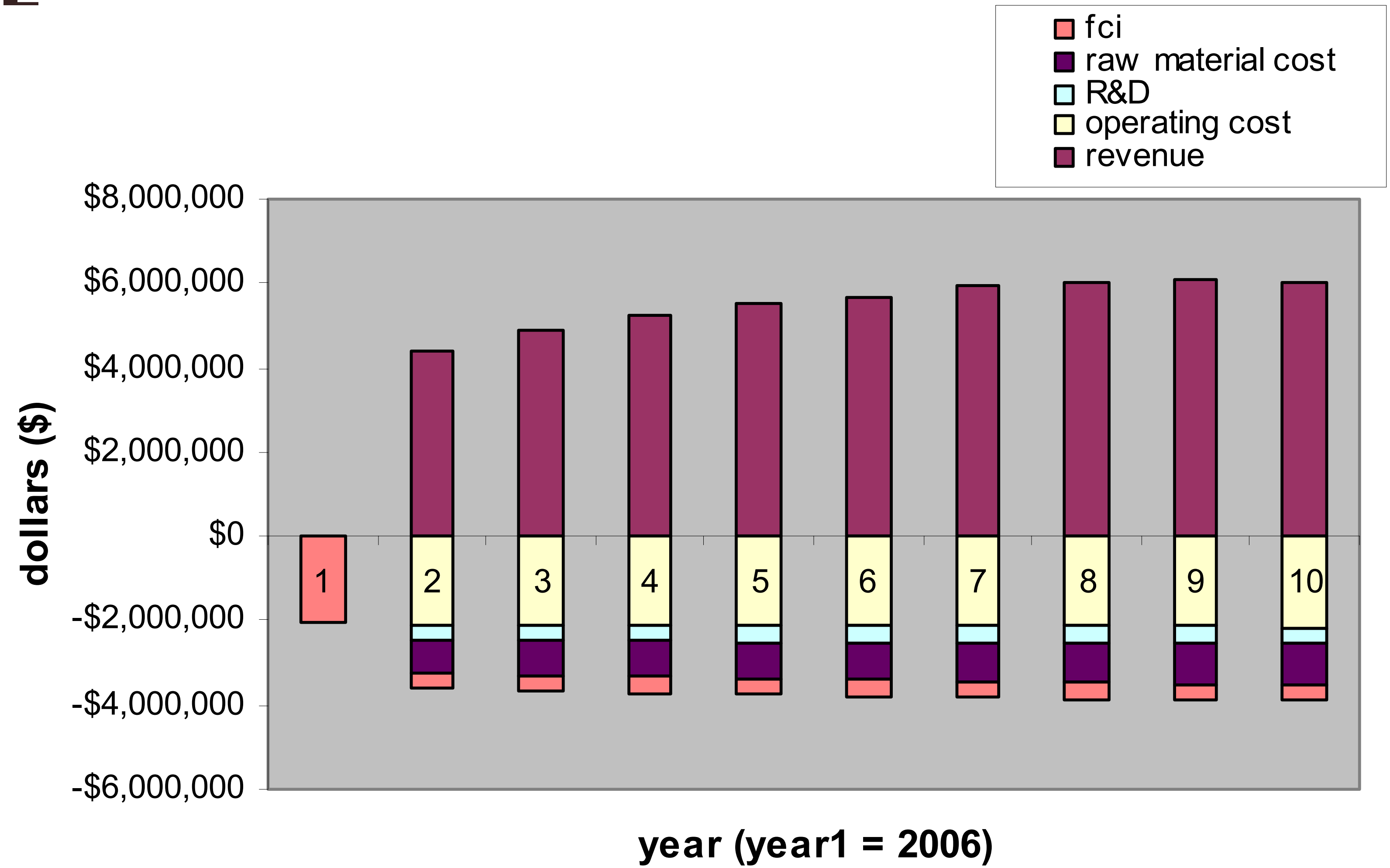
- Net present value over 10 years: $18 million
- TCI = 2.5 million
- Plant Location: Oklahoma
- Plant Capacity: 241 kg/year
- ROI = 46%

Plant Capacity

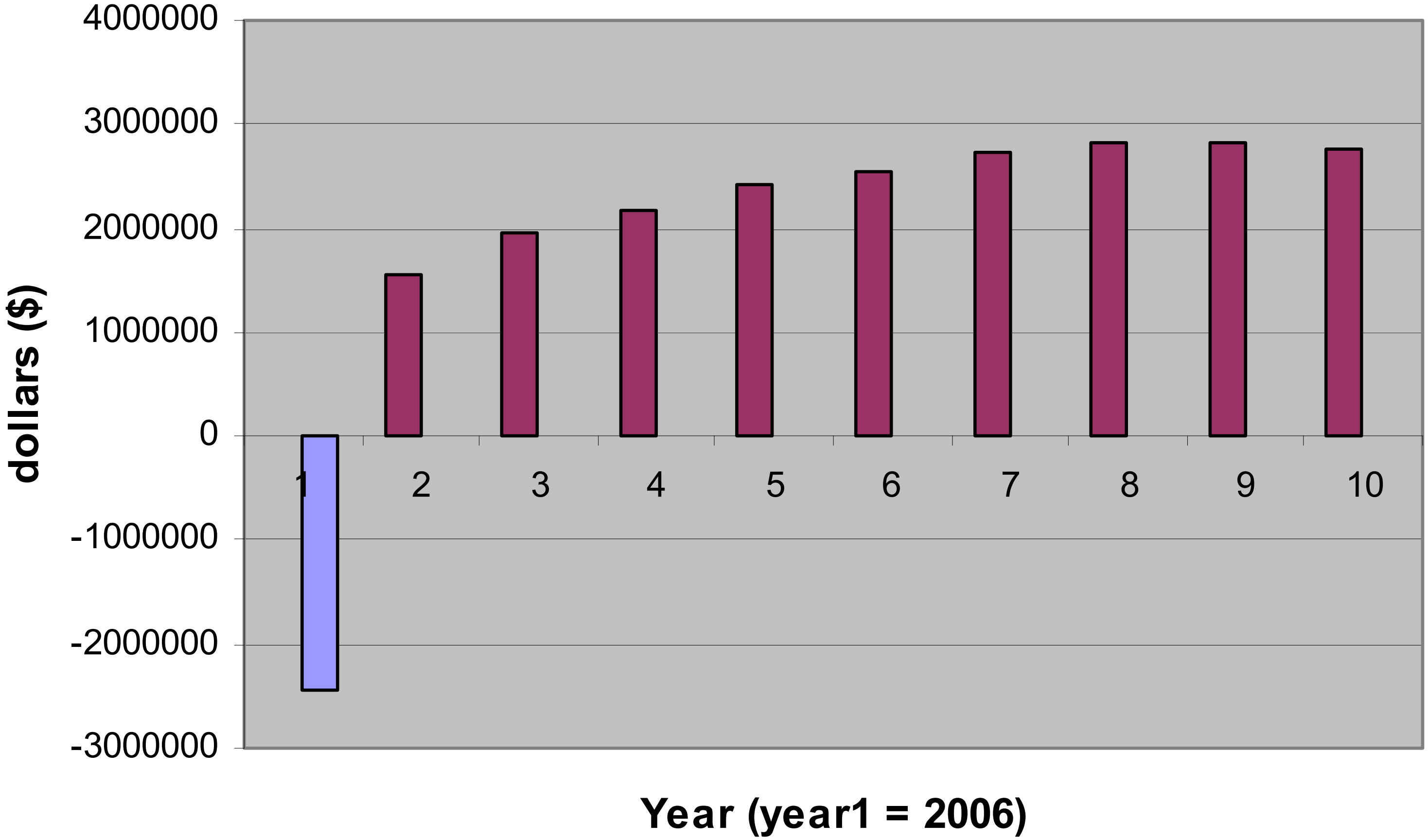


- For $2.5 million total capital investment

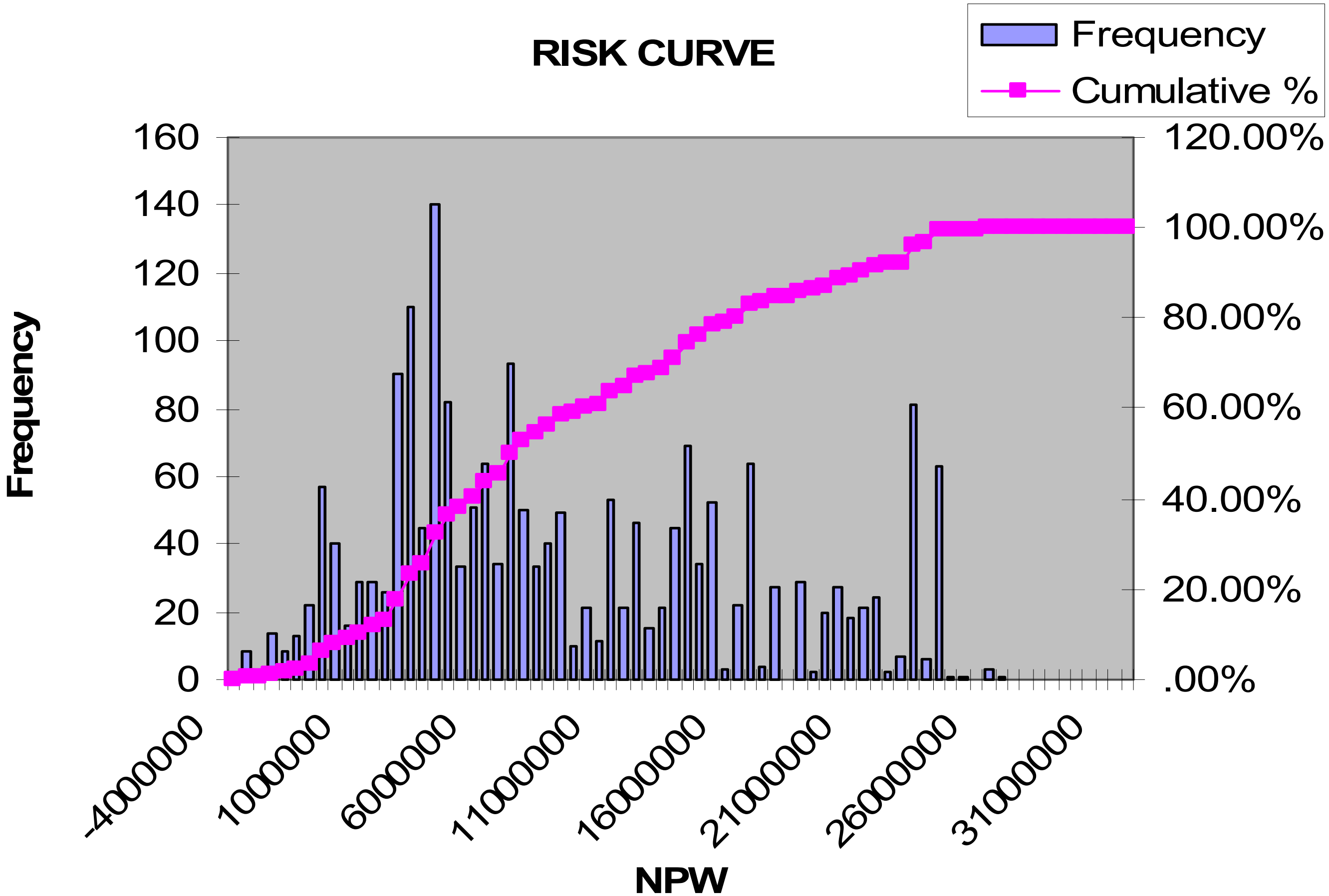
Revenue and Costs



Annual Cash Flow



Risk analysis

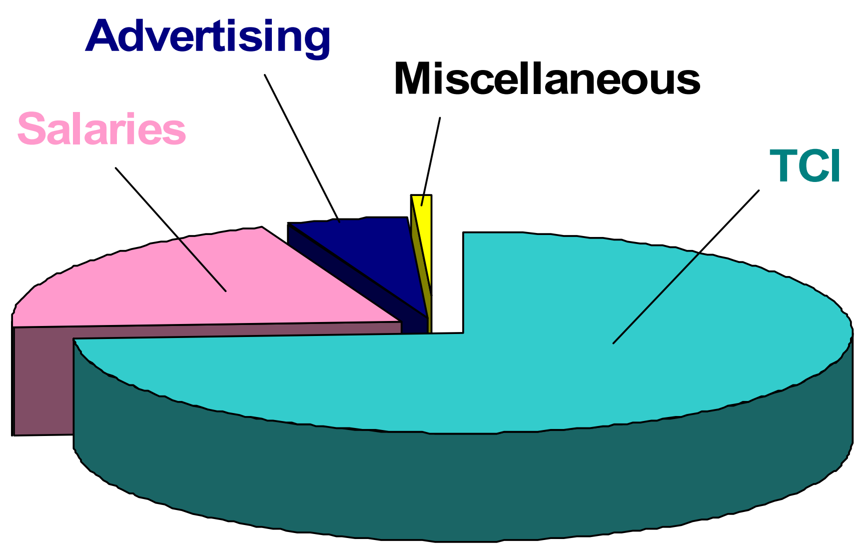


Business Plan

- Plan to capture 10% of the market
  - Competitive production rate of 1kg/day
  - Advertising and promotion
  - Low product cost allows to undersell competition
- Market product to research sectors until commercial applications develop
- Largest commercial sectors are fibers and composites and flat panel displays

Funding Requirement

- Seeking a backer to provide financial investment of $2.5 million
- Investor will receive 15% ownership of the company



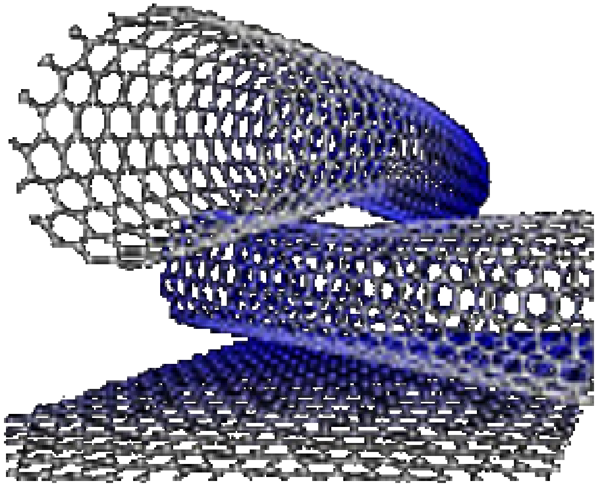
Conclusions

- Construct facility with HiPCO process
  - Capacity: 241 kg/year
  - Location: California
- Total capital investment: $2.5 million
- Expected net present worth: $18 million
- Return on investment: 46 %

Future Considerations

- Expand plant to include functionalization
- Apply profits toward research facility
- Seek contracts with large companies

Questions?



Fluidized bed Reactor scale up

- Scale model designed so that ratio of all of the important forces is the same in the model as in the full-scale bed.
- Similar geometry
- Use Froude number

$\rho_s U_o d_p / \mu$	Particle inertia/ gas viscous force
$\rho_f U_o L / \mu$	Gas inertia/ Gas viscous force
U_o^2 / gL	Inertia /gravity force
ρ_s / ρ_f	Solid inertia/ Gas inertia force
$G_s / \rho_s U_o$	Solid recycle volumetric flow /Gas volumetric flow
L/D	Bed height/ bed diameter

Fluidized bed Reactor scale up

- Froude number

$$(D_m/D_c) = ((V_f)_m/(V_f)_c)^{2/3}$$

$$((V_f)_m/(V_f)_c)^{1/3} = (G_s/\rho)_m/(G_s/\rho_s)_c$$

Wen-Ching Yang, *Handbook of Fluidization and Fluid-Particle Systems,2003*