“Green is Seen in Fertilizers”
Municipal Solid Waste Management

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University of Oklahoma
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MSW Overview

EPA 2005 Facts and Figures

U.S. Waste Produced = 245.7 million ton

- Other wastes: 21%
- Yard trimmings: 7%
- Food wastes: 17%
- Paper & paperboard: 26%
- Glass: 6%
- Metals: 7%
- Plastics: 16%
Municipal Solid Waste

- Composition is highly variable
- Poor quality fuel
  - Low heating value
  - High moisture content
- Difficult to handle and feed to process equipment
Landfilling

- Waste is deposited and buried
  - Produces leachate
    - Groundwater pollutant
  - Greenhouse gas emissions
    - Methane and CO$_2$
  - Costs cities $10 to $70 per ton
  - Reduces nearby land property value
  - 2005: Landfill Waste
    - 133.3 million tons
Municipal solid waste has steadily increased throughout the past 45 years.

The number of landfills has steadily decreased throughout the past 17 years.
Incineration

- Waste is completely combusted
  - Minimizes land required by landfills
    - Reduces weight by up to 90%
  - Waste-to-energy
  - Pollutants
    - Greenhouse gases
    - Toxic ash
  - High operation costs
  - 2005: Waste combusted with energy recovery
    - 33.4 million tons
Pyrolysis/Gasification

- Partial combustion
  - Limited (less than stoichiometric) amount of oxygen
  - Thermally self-sustaining
    - Combust a small portion of the feed to generate heat for pyrolytic reactions

\[
\begin{align*}
C + O_2 & \rightarrow CO_2 & \Delta H = -406 MJ/\text{kmol} \\
C + H_2O & \rightarrow CO + H_2 & \Delta H = 131 MJ/\text{kmol} \\
C + CO_2 & \rightarrow 2CO & \Delta H = 173 MJ/\text{kmol}
\end{align*}
\]
Benefits of Pyrolysis/Gasification

- Potential to be profitable
  - Produce fuel or chemicals
- Reduce quantity and improve quality of solid discards
  - Remedy municipal solid waste management problems
Pyrolysis Mass Balance

- **Metals**: 8.93 tons/unit time
- **MSW**: 100 tons/unit time
- **Front-End Sorting and Shredding**
- **Refuse Feed**: 91.07 tons/unit time
- **Oxygen**: 20.62 tons/unit time
- **Pyrolysis Reactor**
- **Syngas**: 66.15 tons/unit time
- **Water**: 26.63 tons/unit time
- **Slag**: 20.63 tons/unit time
Pretreatment Processing

- Shredding to reduce MSW particle size
- Air/density separator
  - Heavy fraction exits bottom
    - 90% of ferrous removed in magnetic separator
    - 66% of aluminum removed in eddy current aluminum separator
  - Light fraction, mostly organic, exits the top
    - Cyclone removes particulates
Pyrolysis/Gasification

- Exothermic reactions in oxidative zone
- High temperature endothermic reactions in the reduction zone
  - In the absence of oxygen
- Produces two products
  - synthetic gas
  - slag
Synthesis Gas

- Molar composition
  - Carbon monoxide – 40%
  - Hydrogen – 24%
  - Carbon dioxide – 24%
  - Other gases – 12%
- Typically produced from coal or hydrocarbons
- Syngas composition can be altered depending on desired end product
Product Options

- Synthesis Gas
  - Ammonia
  - Hydrogen
  - Methanol
  - Synthetic Fuel
    - Urea
    - Acetic Acid
    - Formaldehyde
    - Dimethyl Ether
Product Selection

• Criteria
  • Profitability based on NPW and IRR
    • Varied MSW capacity
  • Current and Future Market

• Estimated using information in literature and current journals
  • Total Capital Investment
  • Product Price
  • Operating Cost
Economic Assumptions

- Total Capital Investment
  \[ C_{New} = C_{Old} R^{0.65} \]
- Operating Cost and TCI scaled up using cost indices
- Product Price
  - Most Current Available Prices
- Neglected
  - Front End Processing
  - Waste Revenue
  - Taxes, Depreciation, Inflation
## Economic Model: Acetic Acid Production

### Total Capital Investment

- **Acetic Acid Production**: 177,294,150 lbs/year
- **Inflation**: 0.00%

### Operating Cost

- **Acetic Acid Price**: $0.31/lb
- **Inflation**: 0.00%

### Tax Rate

- **0%**

### Main Display Discount Rate

- **10%**

### Calculations

<table>
<thead>
<tr>
<th>Year</th>
<th>Total Capital Investment</th>
<th>Acetic Acid Production (lbs)</th>
<th>Acetic Acid Price ($/lb)</th>
<th>Gross Revenue</th>
<th>Annual Product Cost</th>
<th>Net Profit After Taxes</th>
<th>Depreciation</th>
<th>Annual Cash Flow</th>
<th>Cumulative Cash Flow</th>
<th>10% Discounted Cash Flow</th>
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### Economics Summary

#### Net Present Worth Table:

- **0%**: $57,052,907
- **5%**: $14,308,944
- **8%**: ($4,671,324)
- **10%**: ($15,281,293)
- **15%**: ($36,403,105)
- **20%**: ($51,905,774)
- **30%**: ($72,561,062)

#### Economics Information:

- **Payout Time**: 6.96 years
- **Rate of Return**: 7.20%
- **Return on Investment**: 0.44
- **Disc. Return on Investment**: -0.12
## Product Comparison – 1500 TPD

<table>
<thead>
<tr>
<th>Product</th>
<th>Production</th>
<th>Price</th>
<th>Operating Cost</th>
<th>Net Revenue</th>
<th>Total Capital Investment</th>
<th>Net Present Worth</th>
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<td>Methanol (gal)</td>
<td>39,212</td>
<td>$1.02</td>
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<td>$5,555,679</td>
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<td>Acetic Acid (lb)</td>
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<td>Formaldehyde (lb)</td>
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<td>$6,736,810</td>
<td>$90,784,183</td>
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<td>Ammonia (ton)</td>
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<td>$275</td>
<td>$7,204,301</td>
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<td>Urea (ton)</td>
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<td>Hydrogen (m³)</td>
<td>549,732</td>
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<td>Synthetic Fuel</td>
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<td>($22,701,754)</td>
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<td>Diesel (gal)</td>
<td>16,312</td>
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<td>$11,565,243</td>
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<td>Naphtha (gal)</td>
<td>8,341</td>
<td>$1.63</td>
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</table>
Product IRR vs. MSW Capacity
Future Urea Market

- U.S. fertilizer usage to increase 10-15% in 2008
- Dependent on Crops
  - Corn – 41% of usage

**U.S. Urea Demand**

<table>
<thead>
<tr>
<th>Year</th>
<th>Demand (MM tons)</th>
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<td>1999</td>
<td>12</td>
</tr>
<tr>
<td>2000</td>
<td>12</td>
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<td>2001</td>
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<td>2002</td>
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<td>2003</td>
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<tr>
<td>2004</td>
<td>12</td>
</tr>
<tr>
<td>2005</td>
<td>12</td>
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</tbody>
</table>

"Future demand for crops will be higher... and fertilizer demand will climb even higher"
Urea Production Reactions

Water Gas Shift
\[ CO + H_2O \rightarrow CO_2 + H_2 \]

Ammonia Synthesis
\[ 3H_2 + N_2 \rightarrow NH_3 \]

Urea Synthesis
\[ 2NH_3 + CO_2 \rightarrow NH_2COONH_4 \rightarrow NH_2CONH_2 + H_2O \]
Syngas to Ammonia

Compressed Synthesis Gas
2.55 x 10^6 moles/unit time
From Pyrolysis Unit

Sulfur Removal

Compression

Water-Gas Shift Conversion

Ammonia
1.09 x 10^6 moles/unit time
To Urea Reactor

Compression Ammonia Synthesis

Methanation

CO₂ Removal

N₂
5.44 x 10^6 moles/unit time
From Air Separation Unit

CO₂
1.63 x 10^6 moles/unit time
To Urea Reactor

H₂O
Ammonia to Urea

Ammonia
1.09 x 10^6 moles/unit time
From Ammonia Production Unit

Carbon Dioxide
3.11 x 10^5 moles/unit time
From Ammonia Production Unit

Urea Reactor

Decomposition and Recirculation

Ammonia and Carbamate Recycle

Finishing

Evaporation

Urea
5.44 x 10^5 moles/unit time

Wastewater
## Operating Cost

<table>
<thead>
<tr>
<th>Direct Cost</th>
<th>$/ton of Urea</th>
</tr>
</thead>
<tbody>
<tr>
<td>Utilities</td>
<td></td>
</tr>
<tr>
<td>steam ($10^3$-$10^4$ kPa), m³</td>
<td>12.84</td>
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<tr>
<td>cooling water, m³</td>
<td>13.95</td>
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<tr>
<td>Labor, personnel shift ($28/h)</td>
<td>5.72</td>
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<tr>
<td>Supervision</td>
<td>0.86</td>
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<tr>
<td>Catalyst cost</td>
<td>2.31</td>
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<tr>
<td>Maintenance and Repairs</td>
<td>14.92</td>
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<tr>
<td>Operating Supplies</td>
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<tr>
<td>Laboratory Charges</td>
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<tr>
<td>Fixed Cost</td>
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<td>Insurance</td>
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<td>Property Taxes</td>
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<td>Overhead</td>
<td>12.90</td>
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<td>General Cost</td>
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<td>Administrative Costs</td>
<td>4.30</td>
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<td>Distribution and Marketing Costs</td>
<td>5.4</td>
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<tr>
<td>Total Operating Cost</td>
<td>89.74</td>
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</tbody>
</table>
Plant Location: New York City

- Generates about 25,000 TPD waste
- Contains no landfills, incinerators or resource recovery facilities
  - All MSW is transferred out of the city
    - About 70% is sent to out-of-state landfills
    - Costs up to $70/ton
- Growing population
Waste Disposal Contracts

- Waste dropped at transfer station, then transported to landfills or incineration facilities
  - 3 year contracts
  - Option for two 1 year extensions

<table>
<thead>
<tr>
<th>Available TPD from Expiring Contracts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year</td>
</tr>
<tr>
<td>Available Capacity (TPD)</td>
</tr>
<tr>
<td>Average</td>
</tr>
<tr>
<td>Standard Deviation</td>
</tr>
<tr>
<td><strong>Annual Expansion Opportunity</strong></td>
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</tbody>
</table>
*Current Urea Demand: 11.6 MMtons/year
Urea Profitability Sensitivity

Sensitivity to MSW Capacity

\[ y = 0.078x - 107.3 \]
\[ R^2 = 0.996 \]

Sensitivity to Urea Price

\[ y = 1.664x - 210.8 \]
\[ R^2 = 1 \]
Urea Regret Analysis

- **Prices**
  - 2006 average = $223/ton
  - 2000-2004 average = $121/ton
  - 2006 August Spot Price = $267/ton

- **2005 Urea Market**
  - 1.4% (1200 TPD)
  - 4.0% (3500 TPD)
  - 6.8% (6000 TPD)
## Regret Analysis

### NPW

<table>
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<th>Average</th>
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### Regret

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Min

Optimum Capacity = 6000 TPD MSW
**Economic Model: Urea Production**

3/7/2007 1:44

Total Capital Investment $417,978,064

Fixed Capital Investment $355,246,112

Working Capital $62,731,952

Tax Rate 35%

Main Display Discount Rate 10%

Urea Production 1,957 tons/day

Urea Price $223/ton 0.00% Inflation

Municipal Solid Waste 6,000 tons/day

MSW Charge $40/ton

Operating Cost $85/ton Urea 0.00% Inflation

<table>
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<tr>
<th>Year</th>
<th>Total Capital Investment</th>
<th>Urea</th>
<th>MSW</th>
<th>Gross Revenue</th>
<th>Annual Product Cost</th>
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<th>Annual Cash Flow</th>
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<td>714,243</td>
<td>$223</td>
<td>2,190,000</td>
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<td>$1,150,082,090</td>
<td>$732,104,026</td>
<td>$732,104,026</td>
<td>$239,271,486</td>
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**Economics Summary**

**Net Present Worth Table:**

<table>
<thead>
<tr>
<th>Rate</th>
<th>Present Value</th>
<th>Discount Rate</th>
<th>Discounted Cash Flow</th>
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</thead>
<tbody>
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<td>($207,514,262)</td>
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<td>$438,572,962</td>
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<td>8%</td>
<td>$310,284,627</td>
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<td>($289,089,502)</td>
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<td>10%</td>
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<td>70%</td>
<td>($312,193,777)</td>
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<td>$99,754,422</td>
<td>80%</td>
<td>($329,109,814)</td>
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<tr>
<td>20%</td>
<td>($649,784)</td>
<td>90%</td>
<td>($341,895,234)</td>
</tr>
<tr>
<td>30%</td>
<td>($130,651,434)</td>
<td>100%</td>
<td>($351,818,533)</td>
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**Economics Information:**

- **Payout Time:** 4.53 years
- **Rate of Return:** 19.96%
- **Return on Investment:** 1.75
- **Disc. Return on Investment:** 0.57
Economic Conclusion

- Plant Size = 6,000 tons MSW/day
- TCI = $418,000,000
- NPW = $239,000,000  @ 10% discount
- IRR = 20%
- Urea Break-even Price = $65/ton
Questions?
Pyrolysis Reactor

- Vertical shaft reactor
  - Solid waste enters through the top
  - Purified oxygen from air separator fed through the bottom
- Solid waste dried by upward flowing gases at top of reactor
  - Exiting gas therefore cooled to between 93°C and 315°C
- Pyrolysis occurs in the middle zone at temperatures above 1500°C
  - Combustion of char in oxidative zone at the bottom of the reactor produces the heat necessary for the pyrolytic reactions
- Operates between 2100 and 2200 psia
Gas Cleaning

- Syngas flows through spraying water scrubber
- Electrostatic precipitator removes particulates and pyrolytic oils
  - These components are recycled back to the reactor
- Water removed in a shell and tube condenser
Operating Cost

- Utilities, labor and catalyst costs estimated from data in the *Encyclopedia of Chemical Technology*
- Other operating costs estimated from reasonable percentages in *Plant Design and Economics for Chemical Engineers*
  - Supervision: 15% of labor
  - Maintenance and repairs: 3% of FCI
  - Operating supplies: 15% of maintenance and repairs
  - Laboratory charges: 15% of labor
  - Insurance: 0.7% of FCI
  - Property taxes: 2% of FCI
  - Overhead: 60% of labor, supervision, and maintenance and repair costs
  - Distribution and marketing: 6% of total operating cost
Carbon Dioxide

- Process produces 4,305 tons/day
- Urea synthesis requires 3.5:1 ratio of ammonia to urea in the reactor feed
  - Process uses 820 tons/day carbon dioxide
- Net carbon dioxide production: 3,485 tons/day
  - Implementation of $25/ton carbon tax would increase operating cost by $45/ton urea
  - CO$_2$ sequestration estimated at $35/ton would increase operating cost by $62/ton urea
- Reduces project profitability but does not change project results
Methanol

\[ 2H_2 + CO \rightarrow CH_3OH \]
\[ 3H_2 + CO_2 \rightarrow CH_3OH + H_2O \]

- Reactant Ratio: \[ \frac{H_2}{2CO+3CO_2} = 1 \]
- Low Temperatures and High Pressures favor Methanol formation
- Methanol can be sold as a product or used as an intermediate to produce alternative products
Ammonia

\[ 3H_2 + N_2 \rightarrow 2NH_3 \]

- Reactant Ratio: \( \frac{H_2}{N_2} = 3 \)
- Used in fertilizers and refrigeration
- Reaction occurs at high temperature and pressure
Synthetic Fuel

\[ 2H_2 + CO \rightarrow -CH_2 - + H_2O \]

- Reactant Ratio: \( \frac{H_2}{CO} = 2 \)
- Fischer-Tropsch synthesis
- Converts H\textsubscript{2} and CO into straight chain hydrocarbons using metal catalysts
  - Diesel and naphtha
Hydrogen

\[(1) \quad H_2O + CH_4 \rightarrow 3H_2 + CO\]
\[(2) \quad H_2O + CO \rightarrow H_2 + CO_2\]

- Reactant Ratio: \( \frac{H_2O}{CO + CH_4} = 1 \)
- Steam reformation (1) is used to convert methane into CO and \( H_2 \)
- Water gas shift reaction (2) is used to produce additional \( H_2 \)
- Main fuel source for Hydrogen fuel cells
### Economic Model: Urea Production

**3/6/2007**

<table>
<thead>
<tr>
<th>Total Capital Investment</th>
<th>$169,751,842</th>
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</thead>
<tbody>
<tr>
<td>Fixed Capital Investment</td>
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<td>Working Capital</td>
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<td>Tax Rate</td>
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<td>Main Display Discount Rate</td>
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<table>
<thead>
<tr>
<th>Urea Production</th>
<th>489 tons/day</th>
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<tr>
<td>Urea Price</td>
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<tr>
<td>Municipal Solid Waste</td>
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<tr>
<td>MSW Charge</td>
<td>$40 /ton</td>
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<tr>
<td>Operating Cost</td>
<td>$112 /ton Urea</td>
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<td>0.00% Inflation</td>
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<tr>
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<th>Urea Yearly Production (tons)</th>
<th>Urea Price ($/ton)</th>
<th>Urea Gross Revenue ($/ton)</th>
<th>Urea Annual Production Cost ($/ton)</th>
<th>Urea Net Profit After Taxes ($/ton)</th>
<th>Urea Annual Cash Flow ($/ton)</th>
<th>Cumulative Cash Flow ($/ton)</th>
<th>Total Yearly MSW Production (tons)</th>
<th>MSW Charge ($/ton)</th>
<th>MSWNet Annual Cash Flow ($/ton)</th>
<th>10% Discounted Cash Flow ($/ton)</th>
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**Economics Summary**

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<thead>
<tr>
<th>Net Present Worth Table:</th>
<th>Economics Information:</th>
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<tbody>
<tr>
<td>0% $140,687,089</td>
<td>Payout Time: 5.73 years</td>
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<td>5% $67,323,430</td>
<td>Rate of Return: 12.24%</td>
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<td>30% ($77,342,317)</td>
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