Lecture Outline

- Automobile Manufacturing and Painting
- Energy Model Results
  - Energy Consumption, Costs, Environmental Impacts
- Energy Minimization Analysis Results
Overall Auto Assembly Plant Process Flow

Body Shop → Paint Shop → Final Assembly

T. Lawrence, U. GA
Paint Spray Booth General Design

T. Lawrence, U. GA
Process Flow Diagram for Automobile Assembly Painting

Exhaust 21°C
819,000 scfm

Ambient Air 11.1°C

351,000 scfm

Natl. Gas

Off Gas Generator 5.8×10^{10} kJ/yr

Carbon System

35,000 scfm

RTO 2.4×10^{11} kJ/yr

200,000 scfm

Natl. Gas

207°C

70%

30%

Phosphate

E-Coat Booth

E-Coat Oven

Sealer Booth

Sealer Oven

Prime Booth

Prime Oven

Basecoat/Clearcoat Booth

Basecoat/Clearcoat Oven

Painted Car Body

Unpainted Car Body

Booth Airhouse 3.0×10^{11} kJ/year

1,170,000 scfm

Ambient Air 11.1°C

130,000 scfm

Oven Airhouse 2.7×10^{11} kJ/year

Natl. Gas

Natl. Gas
Introduction and Background

Why Analyze Assembly Painting?
- Consumes 50% of assembly plant energy
- Approximately 10-20% of all energy used is for assembly plant painting

Future Paint Issues
- Solvent → Water-based → Powder
Phosphate Unit

- Purpose is to prepare body surface for painting
  - Cleaning solution
  - Rinse stages
  - Phosphate dip tank
  - Rinse stages
Electrocoating Tanks and Ovens

- Purpose is to prevent corrosion of body surfaces
  - Body is dipped into a tank
  - DC current is applied within tank
  - Washing step to remove excess solution
  - Drying oven (~215°C) removes excess solvents into an air stream that is directed to air pollution abatement equipment
Sealer Booths and Ovens

- **Purpose is to prevent rust**
  - joints between body parts
  - body surfaces near road surfaces
- **Booth where sealant is applied by robots**
- **Oven where sealant is cured**
  - Air stream in oven is directed to pollution abatement equipment
Prime Coat Booths and Ovens

- **Purpose is to provide a bonding surface between Electrocoat and the Basecoat**
  - Contains solids, fast volatilizing solvents, and slow volatilizing solvents
  - Fast volatilizing solvents removed in booths
  - Booths at 70°F and 70% relative humidity
  - Slow volatilizing solvents removed in ovens
  - Ovens at ~155°C
  - Oven air directed to pollution abatement equipment
Basecoat/Clearcoat Booths & Ovens

- Apply final color and clear coat overlay
  - Operation of ovens similar to prime coat
Paint Spray Booth General Design

Exhaust

Filter

Laminar downdraft

Paint spray

Sludge water to capture paint overspray

T. Lawrence, U. GA
The Carbon Wheel

- Concentrated VOC Air to RTC
- Hot Air Passes Over Paper
- Hot Desorption Air In
- Cleaned Booth Air Emitted Out
- Air Containers Activated Carbon Coated Paper
- Air From Booths

Wheel Rotates
Regenerative Thermal Oxidizer: VOC Abatement
Typical Booth Environmental Design Conditions

- Higher airflow for manual paint spray zones versus automatic (robotic) spray zones
- Typical paint booth conditions
  - Downdraft velocity
    - Manual zones = 100 fpm
    - Automatic zones: 60 to 80 fpm
  - Temperature: 75 to 78°F
  - Relative humidity: 60±10%
Energy Model Assumptions

- Steady-state analysis
- Assume booth conditions, 70°F, 70% RH
- Oven temperatures are specific to each oven
- Sensible heat and latent heat effects
- 1,300,000 scfm air flow rate
- 10% to ovens, 90% to booths
- 30% of booth air to Carbon Wheel system
- 6 RTO units, 88 scfm natural gas for each unit
## Energy Model Results

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Energy (kJ/yr)</th>
<th>Percent of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Booth Air</td>
<td>2.96E+11</td>
<td>28.6</td>
</tr>
<tr>
<td>RTO</td>
<td>2.40E+11</td>
<td>23.1</td>
</tr>
<tr>
<td>BC/CC Oven</td>
<td>1.10E+11</td>
<td>10.6</td>
</tr>
<tr>
<td>Booth Air Flow</td>
<td>7.62E+10</td>
<td>7.4</td>
</tr>
<tr>
<td>Prime Oven</td>
<td>7.45E+10</td>
<td>7.2</td>
</tr>
<tr>
<td>E-coat Oven</td>
<td>6.49E+10</td>
<td>6.3</td>
</tr>
<tr>
<td>Phosphate</td>
<td>5.92E+10</td>
<td>5.7</td>
</tr>
<tr>
<td>CW</td>
<td>5.84E+10</td>
<td>5.6</td>
</tr>
<tr>
<td>Sealer Oven</td>
<td>2.30E+10</td>
<td>2.2</td>
</tr>
<tr>
<td>RTO</td>
<td>1.49E+10</td>
<td>1.4</td>
</tr>
<tr>
<td>E-coat Booth</td>
<td>1.05E+10</td>
<td>1.0</td>
</tr>
<tr>
<td>Oven Air Flow</td>
<td>6.53E+09</td>
<td>0.6</td>
</tr>
<tr>
<td>Phosphate</td>
<td>9.53E+08</td>
<td>0.1</td>
</tr>
<tr>
<td>CW</td>
<td>8.58E+08</td>
<td>0.1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>1.04E+12</td>
<td>100</td>
</tr>
</tbody>
</table>
Environmental Impacts of Energy Use

- **Impacts of energy consumption**
  - Natural gas (NG) and electricity (assumed from coal)
  - Greenhouse gas emissions, CO2
  - Criteria pollutants: SOx, NOx, CO, VOC, PM10
  - Toxic (EPCRA) and hazardous (RCRA) pollutants

- **Impacts of producing NG and coal**
  - EIO-LCA web site at Carnegie Mellon University
  - www.eiolca.net
Impacts of Energy Consumption

\[
\text{Energy Consumption (kJ/yr)} \div \text{Fuel Value (kJ/kg fuel)} \div \text{Fuel Heating Efficiency} = \text{Pollutant Emission Rate (kg/yr)}
\]

- Toxics
- CO\textsubscript{2}
- SO\textsubscript{x}
- NO\textsubscript{x}
- CO
- VOC
- PM\textsubscript{10}
- RCRA
Impacts of NG/Coal Production

\[
\text{EIO-LCA} \rightarrow \frac{\text{Energy Consumption (kJ/yr)}}{\text{Fuel Value (kJ/kg fuel)}} \rightarrow \times \text{Fuel Cost ($/kg fuel)} \rightarrow \text{Pollutant Emission Rates (kg/yr)} \rightarrow \begin{align*}
\text{Toxics} & : \text{CO}_2, \text{SO}_x, \text{NO}_x, \text{CO}, \text{VOC}, \\
\text{PM}_{10} & : \text{RCRA}
\end{align*}
\]
Composite Environmental Index

- **Normalization:** use national emissions data
  - For each pollutant
- **Valuation:** weight each category of emission
  - EcoIndicator 95 method - European studies

<table>
<thead>
<tr>
<th>Environmental Index</th>
<th>Weight</th>
<th>National Inventory ($10^3$ kg/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toxics</td>
<td>5</td>
<td>$1.3\times10^6$</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>2.5</td>
<td>$5.5\times10^9$</td>
</tr>
<tr>
<td>SO$_x$</td>
<td>10</td>
<td>$1.8\times10^7$</td>
</tr>
<tr>
<td>NO$_x$</td>
<td>2.5</td>
<td>$2.1\times10^7$</td>
</tr>
<tr>
<td>PM$_{10}$</td>
<td>2.5</td>
<td>$2.8\times10^7$</td>
</tr>
<tr>
<td>VOC</td>
<td>2.5</td>
<td>$1.9\times10^7$</td>
</tr>
<tr>
<td>RCRA</td>
<td>5</td>
<td>$2.6\times10^8$</td>
</tr>
</tbody>
</table>
# Environmental/Cost Results

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Operating Cost per Year</th>
<th>% of Total Cost</th>
<th>% Env. Impact</th>
<th>Temperature In/Out</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Booth Air</td>
<td>Nat. Gas $1,968,777</td>
<td>21.2</td>
<td>3.9</td>
<td>11.1/21.1</td>
</tr>
<tr>
<td>Air Flow Booths</td>
<td>Electric $1,746,884</td>
<td>18.8</td>
<td>49.1</td>
<td></td>
</tr>
<tr>
<td>RTO</td>
<td>Nat. Gas $1,591,962</td>
<td>17.2</td>
<td>3.1</td>
<td>152/207</td>
</tr>
<tr>
<td>E-coat Booth</td>
<td>Electric $843,219</td>
<td>9.1</td>
<td>23.7</td>
<td></td>
</tr>
<tr>
<td>BC/CC Oven</td>
<td>Nat. Gas $729,593</td>
<td>7.9</td>
<td>1.4</td>
<td>11.1/177</td>
</tr>
<tr>
<td>Prime Oven</td>
<td>Nat. Gas $494,475</td>
<td>5.3</td>
<td>1.0</td>
<td>11.1/154</td>
</tr>
<tr>
<td>E-coat Oven</td>
<td>Nat. Gas $430,910</td>
<td>4.6</td>
<td>0.9</td>
<td>11.1/210</td>
</tr>
<tr>
<td>Phosphate</td>
<td>Nat. Gas $392,893</td>
<td>4.2</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>CW</td>
<td>Nat. Gas $387,833</td>
<td>4.2</td>
<td>0.8</td>
<td>11.1/127</td>
</tr>
<tr>
<td>RTO</td>
<td>Electric $341,513</td>
<td>3.7</td>
<td>9.6</td>
<td></td>
</tr>
<tr>
<td>Sealer Oven</td>
<td>Nat. Gas $152,727</td>
<td>1.6</td>
<td>0.3</td>
<td>11.1/138</td>
</tr>
<tr>
<td>Air Flow Ovens</td>
<td>Electric $149,733</td>
<td>1.6</td>
<td>4.2</td>
<td></td>
</tr>
<tr>
<td>Phosphate</td>
<td>Electric $21,850</td>
<td>0.2</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>CW</td>
<td>Electric $19,656</td>
<td>0.2</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$9,272,024</strong></td>
<td><strong>9.27E+6</strong></td>
<td><strong>100</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>
Energy Conservation Targeting: Pinch Analysis

- Graphical Pinch Analysis to examine the feasibility of waste energy recovery
- Only the RTO exhaust was used as hot stream
- All incoming air streams are combined into a composite cold stream
Pinch Analysis Results

- Energy transferred by a network of heat exchangers
- Energy transferred by external utilities
- All streams - Booth Air
- Booth Air + all streams

Heat Load (kJ/hr)

Temperature (°C)

0 4.0E+07 8.0E+07 1.2E+08

0 50 100 150 200 250

Energy transferred by external utilities

Cold (shifted)

Hot Stream
Heat Integration

- Encouraged by the pinch and energy flow found while modeling
- Two different approaches examined
  - Recycling of process material stream(s)
  - Heat integration using a heat transfer fluid (HEN: heat exchanger network)
Heat Integration via Recycle

- Maximum energy reduction of only 4%
- Environmental impact reduction of about 3%
- Economically feasible, and simple to accomplish

<table>
<thead>
<tr>
<th>CW clean air to booth robotic zones</th>
<th>Carbon Wheel to Ovens</th>
<th>Manual zones to Robotic zones</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Make up air</td>
<td>30 %</td>
<td></td>
</tr>
<tr>
<td>Air flow needed</td>
<td>351000 scfm</td>
<td>Air flow needed</td>
</tr>
<tr>
<td>Air available</td>
<td>351000 scfm</td>
<td>Air flow available</td>
</tr>
<tr>
<td>Fresh air added</td>
<td>105300 scfm</td>
<td>Energy Saved</td>
</tr>
<tr>
<td>Air recycled then</td>
<td>245700 scfm</td>
<td>Energy saved</td>
</tr>
<tr>
<td>Energy Saved</td>
<td>3.16E+10 kJ/yr</td>
<td>Money Saved</td>
</tr>
<tr>
<td>Money Saved</td>
<td>$110,918 per year</td>
<td>Money saved</td>
</tr>
<tr>
<td>Cost savings</td>
<td>$209,635 per year</td>
<td></td>
</tr>
<tr>
<td>Air flow needed</td>
<td>130000 scfm</td>
<td>Air flow needed</td>
</tr>
<tr>
<td>Air flow available</td>
<td>351000 scfm</td>
<td>Air flow available</td>
</tr>
<tr>
<td>Energy Saved</td>
<td>1.67E+10 kJ/yr</td>
<td>Energy saved</td>
</tr>
<tr>
<td>Money Saved</td>
<td>$299,478 per year</td>
<td>Money saved</td>
</tr>
</tbody>
</table>

Environmentally Responsible Design & Manufacturing (MEEM 4685/5685)
Dept. of Mechanical Engineering – Engineering Mechanics
Michigan Technological University

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HEN Economic Evaluation

- 10 year period
- 7 year MACRS depreciation scheme
- Income from reduction in energy cost
- Operating cost from pumping of heat transfer fluid and maintenance
- Sizing of exchangers uses constant value of the heat transfer coefficient
- Cost of exchangers uses a 0.6 exponential function
Economics & Env. Impact Reduction of HEN RTO to Booth, Recovery of $2.96 \times 10^{11}$ kJ/yr
Conclusions

- Over half of the process energy is lost through the RTO exhaust
- Heat integration using intermediate fluid appears to be economically feasible and reduces overall environmental impact

<table>
<thead>
<tr>
<th></th>
<th>IRR</th>
<th>Corporate Energy Recovered</th>
<th>Plant Env. Impact Reduction</th>
<th>Plant CO₂ Impact Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Booths set ambient &amp; recovery</td>
<td>0.4</td>
<td>6.51%</td>
<td>4.2</td>
<td>17.8</td>
</tr>
<tr>
<td>Booths seasonal</td>
<td>Econ:</td>
<td>0.317</td>
<td>5.65%</td>
<td>4.7</td>
</tr>
<tr>
<td></td>
<td>Env.:</td>
<td>0.306</td>
<td>6.34%</td>
<td>5.7</td>
</tr>
<tr>
<td>Ovens seasonal</td>
<td>Econ:</td>
<td>0.334</td>
<td>5.02%</td>
<td>6.0</td>
</tr>
<tr>
<td></td>
<td>Env.:</td>
<td>0.289</td>
<td>6.95%</td>
<td>7.8</td>
</tr>
</tbody>
</table>
ReCap

- Automobile assembly painting is an important energy consuming process in the manufacturing life-cycle.
- Environmental impacts are related to the energy consumption, wastewater, paint solids, and volatile organic compounds (VOCs).
- Heating of inlet air for booths and ovens is the major energy consuming element.
- Energy conservation alternatives can be evaluated using Pinch Analysis coupled with Heat Exchanger Network (HEN) synthesis.