22.033 Design Course

Considerations in Designing a Nuclear Power Plant with a Hydrogen and Biofuels Facility
Why this project?

- Green energy policy climate
- Oil quickly depleting
- Nuclear high energy/electricity output versus maintenance costs
System Layout

22.033 NUCLEAR SYSTEMS DESIGN PROJECT 2011

- System Layout
- Storage Start-up For Heat Process
- Storage Loop
- Switchgrass Biomass
- Acid-Gas Removal
- Reactor
- Biofuels Distillation
- Biofuels Refining Process
Reactor Core
Outline

1. Goals
2. Overall Design of Reactor Core
3. Radial and Axial Overview of Core
4. Fuel
5. Heat Removal
6. Core Depletion
7. Secondary System
8. Turbines and Heat Exchangers
9. Future Work
Reactor Core Goals

• Provide enough electricity and process heat for hydrogen and biofuels production

• Choose and design a reactor that will operate at temperatures larger than what is in use

• Produce a unique and innovative reactor

• Final design must be feasible for electrical production
Core Designs Considered

- Supercritical $\text{H}_2\text{O}$
- Supercritical $\text{CO}_2$
- Traveling Wave Reactor
- Sodium-Cooled Fast Reactor (SFR)
- Lead-Cooled Fast Reactor (LFR) (LBEFR)
- CANDU Reactor
- Molten Salt Reactor
- Gas-Cooled Fast Reactor
- Pebble Bed Modular Reactor (PBMR)
- Very High Temperature Reactor (VHTR)
Major Reactor Design Choices

- **Lead-Bismuth Eutectic Cooled Fast Reactor (LBEFR)**
  - High heat capacity
  - Operates at ~ atmospheric pressure
  - High power density
  - Natural convection
  - Self-shielding
  - Essentially no coolant voiding possible

- **Supercritical Carbon Dioxide (S-CO₂) for Secondary Cycle**
  - Brayton cycle
  - Single phase working fluid
  - Smaller turbines
  - Higher cycle efficiency
Reactor Core Final Design

• Lead-Bismuth Eutectic (LBE) Cooled Fast Reactor with Supercritical CO$_2$ Secondary Loop

• 3575 MWt (1500 MWe)

  ➢ Limited by velocity of LBE (2.5 m/s) due to flow assisted corrosion

  ➢ Will provide only 1000 MWe to grid, remaining energy will be used for hydrogen and biofuel production
Core Overview

- LBE / CO₂ Heat Exchanger
- RPV
- Steel frame

Symbols:
- $T_{\text{hot}}$
- $T_{\text{cold}}$
Radial Overview of Core

X-Y view of core

- Fuel Regions (UN)
- Control Rods (B₄C)
- Reflector (MgO)
- Shield (B₄C)
- Coolant (LBE)
- Cladding
  (T91 stainless steel, protective outer layer)
Fuel Assembly and Zoning

Pitch/Pin = 1.6

Axial and Radial Zoning

<table>
<thead>
<tr>
<th></th>
<th>Rings 1-4</th>
<th>Rings 5-10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top</td>
<td>10%</td>
<td>12.5%</td>
</tr>
<tr>
<td>33%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lower</td>
<td>12.5%</td>
<td>15%</td>
</tr>
<tr>
<td>67%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parameter</td>
<td>Value</td>
<td></td>
</tr>
<tr>
<td>-----------------------------------------</td>
<td>-------------</td>
<td></td>
</tr>
<tr>
<td>Outlet Temperature</td>
<td>650°C</td>
<td></td>
</tr>
<tr>
<td>Inlet Temperature</td>
<td>484°C</td>
<td></td>
</tr>
<tr>
<td>Operating Pressure</td>
<td>Atmospheric</td>
<td></td>
</tr>
<tr>
<td>Full Power Operating Mass Flow Rate</td>
<td>143,600 kg/s</td>
<td></td>
</tr>
<tr>
<td>Max Fuel Enrichment</td>
<td>15%</td>
<td></td>
</tr>
<tr>
<td>Minimum Fuel Enrichment</td>
<td>10%</td>
<td></td>
</tr>
<tr>
<td>Linear Heat Rate BOL</td>
<td>74.3 kW/m</td>
<td></td>
</tr>
<tr>
<td>Fuel Material</td>
<td>UN</td>
<td></td>
</tr>
</tbody>
</table>
Reactor Core Final Design

K-effective vs. Rod Withdrawal Percentage

K-effective vs. Rod Withdrawal Percentage
Selected Temperatures Over a 1 Meter Active Fuel Height at 3575 MW

- Coolant Temp
- Max Clad Temp
- Centerline Temp
- Linear Heat Rate
## Comparison of UN and UO$_2$

<table>
<thead>
<tr>
<th></th>
<th>UN</th>
<th>UO$_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Thermal Conductivity</strong></td>
<td>21 W/mK</td>
<td>3-4 W/mK</td>
</tr>
<tr>
<td><strong>Melting Point</strong></td>
<td>2800°C</td>
<td>2800°C</td>
</tr>
<tr>
<td><strong>Uranium Metal Density</strong></td>
<td>13.60 g/cm$^3$</td>
<td>9.67 g/cm$^3$</td>
</tr>
<tr>
<td><strong>Other</strong></td>
<td>Need to enrich the nitrogen</td>
<td>Long and safe operating history</td>
</tr>
</tbody>
</table>
Natural Circulation

- Natural circulation appears sufficient for heat removal at full power.
- It is likely that pumping power/extra heat insertion from the PCM will be needed to maintain flow during shutdown.
- Further analysis needed to determine benefits of laminar vs. turbulent regimes.

Plot of mass flux vs. inlet temperature given an outlet temperature of 650° C for varying down channel diameters. $R = 3m$, $B = 2m$, $G = 1m$
Core Depletion

- Analysis done by comparison to previous cores: EISY, STAR & 2400MWt MIT design

- 24000 MWt achieved 1800 days lifetime with $k_{\text{eff}} = 1.02$ at BOL with rods removed.

- Likely that our reactor can achieve longer given greater fertile inventory and $k_{\text{eff}} = 1.04$ at BOL with rods removed.

- Needs formal core depletion code analysis

<table>
<thead>
<tr>
<th></th>
<th>Zone 1 (kg)</th>
<th>Zone 2 (kg)</th>
<th>Zone 3 (kg)</th>
<th>Total (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BOL Pu</td>
<td>3342</td>
<td>2807</td>
<td>1982</td>
<td>8131</td>
</tr>
<tr>
<td>EOL Pu</td>
<td>3375</td>
<td>2849</td>
<td>2044</td>
<td>8268</td>
</tr>
<tr>
<td>% change</td>
<td>0.99</td>
<td>1.50</td>
<td>3.13</td>
<td>1.68</td>
</tr>
<tr>
<td>BOL U</td>
<td>19356</td>
<td>16254</td>
<td>11476</td>
<td>47086</td>
</tr>
<tr>
<td>EOL U</td>
<td>17935</td>
<td>14568</td>
<td>10154</td>
<td>42657</td>
</tr>
<tr>
<td>% change</td>
<td>-7.34</td>
<td>-10.37</td>
<td>-11.52</td>
<td>-9.41</td>
</tr>
<tr>
<td>BOL MA</td>
<td>516</td>
<td>433</td>
<td>306</td>
<td>1255</td>
</tr>
<tr>
<td>EOL MA</td>
<td>423</td>
<td>316</td>
<td>214</td>
<td>953</td>
</tr>
<tr>
<td>% change</td>
<td>-18.02</td>
<td>-27.02</td>
<td>-30.07</td>
<td>-24.06</td>
</tr>
</tbody>
</table>

Estimated inventory changes from 2400MWt MIT core after 1800 days
Core Reactivity Coefficients

- Estimated again from ELSY, STAR and MIT cores

- Doppler coefficient was found to be \(-0.111+/-0.03\) for MIT core
  - Hard spectrum makes this less negative than other LMFBR cores

- Temperature coefficient was found to be \(+0.131+/-0.052\) for MIT core
  - Reactivity insertion at low lead densities not countered by increased scattering and leakage cross sections at higher temperatures.

- Needs to be explicitly calculated for our core. Use of MgO reflector has reduced our required enrichment which may change these values significantly based on work by Driscoll et al.
Outlays of the System

- Electric Power
  - 1000 MWe

- Plant Power
  - 500 MWe

- Process Heat
  - 315 MWt
Secondary System

S-CO2 Secondary Loop

**Efficiency: 42.2%**

Key:
- Heat Exchanger
- Reheater
- Condenser
- Turbine
- Compressor
- Pump
Secondary System

- Modeled in EES
  - Temperature and mass flow calculations
  - Allows for faster optimization
  - Database provided enthalpy information for S-CO$_2$
- Second turbine added to allow for greater efficiency
- Energy diverted to the Process Heat group does not significantly affect the secondary system (efficiency changes from 45.8% to 42.2%)
Shell and Tube Heat Exchanger

• Simple design (easy to make, low cost, etc.)

• Larger than PCHE

• Friction effects of LBE reduced
Turbines

• Compact due to Brayton Cycle

• Reduces size of turbomachinery

Future Work for Core

- Switch to alternate clad material or lower operating temperature OR both.
- Look at efficiency improvements in secondary system.
- Look at Uranium Carbide as alternate fuel.
- Full depletion and kinematic calculation.
- Determine if decay natural convection possible.
Process Heat
Outline

1. Goals
2. Heat Exchangers
3. Piping
4. Heat Storage
5. Future Work
Process Heat Goals

- Draw heat from the Core to provide steam to the Hydrogen and Biofuels plants
- Keep the LBE melted during reactor outage
- Design system for operation at high temperatures and pressures
System Layout
## System Pressure and Temperature Drops

<table>
<thead>
<tr>
<th>System component</th>
<th>Pressure drop [ kPa ]</th>
<th>Temperature change [ °C ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCHE1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hot side</td>
<td>8.043</td>
<td>-316</td>
</tr>
<tr>
<td>Cold side</td>
<td>23.749</td>
<td>+405.47</td>
</tr>
<tr>
<td>PCHE2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hot side</td>
<td>9.812</td>
<td>-388</td>
</tr>
<tr>
<td>Cold side</td>
<td>13.874</td>
<td>+518.67</td>
</tr>
<tr>
<td>Heat storage</td>
<td>1000</td>
<td>-1.5</td>
</tr>
<tr>
<td>Piping (30m)</td>
<td>2.047</td>
<td>-0.041</td>
</tr>
</tbody>
</table>
Heat Exchangers

\[ T_{\text{high}} = 630^\circ \text{C} \]
\[ P_{\text{high}} = 20 \text{ MPa} \]

PCHEs chosen for their:
• High operating temperatures
• Small volumes
• High effectiveness

Fig. 1 (pg. 218) from D. Southall and S. J. Dewson, “Innovative Compact Heat Exchangers.” Published in ICAPP 2010, San Diego, CA, June 13-17, 2010. © American Nuclear Society and the authors. All rights reserved. This content is excluded from our Creative Commons license. For more information, see http://ocw.mit.edu/fairuse.
### Working Fluid: Helium

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Dioxide (CO₂)</td>
<td>1079.5, 1237.8</td>
<td>2.337, 4.064 10⁻⁵, 10⁻⁵</td>
</tr>
<tr>
<td>Water/Steam (H₂O)</td>
<td>4476.1, 2351.5</td>
<td>1.35 10⁻⁴, 3.678 10⁻⁵</td>
</tr>
<tr>
<td>Helium (He)</td>
<td>5188.9, 5190.6</td>
<td>2.74 10⁻⁵, 4.533 10⁻⁵</td>
</tr>
</tbody>
</table>

***data from webbook.nist.gov***
PCHE Material: Alloy 617

Reasons for choosing Alloy 617:
• Tensile strength
• Thermal conductivity
• Thermal expansion
• Corrosion resistance
• Ease of manufacturing
• Design life of up to 60 years

PCHEs will operate well below design stresses at all points in system

Source: Li, Xiqing., et al. "Alloy 617 for the High Temperature Diffusion-Bonded Compact Heat Exchangers." Published in ICAPP 2008, Anaheim, CA, June 8-12, 2008. © American Nuclear Society and the authors. All rights reserved. This content is excluded from our Creative Commons license. For more information, see http://ocw.mit.edu/fairuse.
# Process Heat PCHEs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>PCHE1</th>
<th>PCHE2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat rate/unit</td>
<td>35 MW</td>
<td>26 MW</td>
</tr>
<tr>
<td>Number of units</td>
<td>9</td>
<td>12</td>
</tr>
<tr>
<td>Total heat rate</td>
<td>315 MW</td>
<td>312 MW</td>
</tr>
<tr>
<td>Hot fluid</td>
<td>S-CO₂</td>
<td>He</td>
</tr>
<tr>
<td>Cold fluid</td>
<td>He</td>
<td>H₂O</td>
</tr>
<tr>
<td>Channel configuration</td>
<td>zigzag</td>
<td>straight</td>
</tr>
<tr>
<td>location</td>
<td>S-CO₂ loop</td>
<td>Hydrogen plant</td>
</tr>
<tr>
<td>Total htc</td>
<td>1087.71 W/m²K</td>
<td>735 W/m²K</td>
</tr>
<tr>
<td>Volume</td>
<td>8.25 m³</td>
<td>15.6 m³</td>
</tr>
</tbody>
</table>

*HEATRIC's quote for steel $/kg cost used
PCHE1: Temperature and Heat Flux Profiles

- Zigzag flow channels
- Counterflow
- Single-phase forced convection
- No swings in temperature or heat flux
- S-CO$_2$: turbulent
- He: laminar
PCHE1: Temperature and Heat Flux Profiles

- Straight channels
- Counterflow
- Two-phase flow
- Unphysical behavior to the left of x=0.68m
- Exclude this region
- Both fluids laminar
- Large swings in temperature and heat flux!
- Design as three separate HXs?
Fouling and Design Life

Fouling affects heat rate and pressure drops

PCHE operation up to 500 – 660 hours:

• no change in effectiveness

• 55% increase in pressure drop!

18 month fuel cycle = ~12,960 hours

Solutions:

• Installation of redundant units

• Addition of Cl to fluid streams to reduce biofouling
Biofuels Heat Exchanger

- Recover heat from $\text{H}_2\text{O} + \text{H}_2$ and $\text{O}_2$ streams at the Hydrogen plant

- Produce steam at $182^\circ \text{C}$ and 0.1MPa for Biofuels

- Highly oxidative and reductive environment!

- Prospective materials: RBSiC and SiSiC

Courtesy of Acumentrics Corporation. Used with permission.

Ceramic monolith for a cross flow HX fabrication

Adapted from tests and design in “Conceptual Design for a High Temperature Gas Loop Test Facility.” Idaho National Laboratory Report INL/EXT-06-11648, 2006
### PCM: Lithium Chloride (LiCl)

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting Point</td>
<td>605° C</td>
</tr>
<tr>
<td>$\Delta h^\circ$ fusion</td>
<td>470 kJ/kg</td>
</tr>
<tr>
<td>$c_p$ (solid)</td>
<td>1.132 kJ/kg-K</td>
</tr>
</tbody>
</table>

**Containment Material: Alloy 20**

Nickel-Chromium-Molybdenum alloy

Resistant to chloride ion corrosion

MP >1380°C

k = 18.15 W/m-K

<table>
<thead>
<tr>
<th>Element</th>
<th>Min (%)</th>
<th>Max (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nickel</td>
<td>32.5</td>
<td>35.0</td>
</tr>
<tr>
<td>Chromium</td>
<td>19.0</td>
<td>21.0</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>2.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Copper</td>
<td>3.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Silicon</td>
<td>0.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Carbon</td>
<td>0.0</td>
<td>0.06</td>
</tr>
<tr>
<td>Sulfur</td>
<td>0.0</td>
<td>0.035</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>0.0</td>
<td>0.035</td>
</tr>
<tr>
<td>Niobium</td>
<td>1.0</td>
<td>none</td>
</tr>
<tr>
<td>Iron</td>
<td>0.0</td>
<td>balance</td>
</tr>
</tbody>
</table>

Storage – Heat Exchanger

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h_{\text{tank}}$</td>
<td>11.41 m</td>
</tr>
<tr>
<td>$d_{\text{PCM}}$</td>
<td>18 m</td>
</tr>
<tr>
<td>$t_{\text{PCM}}$</td>
<td>1.13 m</td>
</tr>
<tr>
<td>$t_{\text{wall}}$</td>
<td>1 cm</td>
</tr>
<tr>
<td>Length of tank</td>
<td>20 m</td>
</tr>
<tr>
<td>Gap height</td>
<td>1 cm</td>
</tr>
</tbody>
</table>

 Alloy 20

Lithium Chloride

He flow (into page)
Charging Layout

Charging Time (with 67 MW preheater): 33 days, 12 hours
Discharging Layout

Transmission Losses

Decay Heat

Primary Loop

140°C, m_dot(t) kg/s

150°C, m_dot(t) kg/s

Shell & Tube HX

550°C, 132 kg/s

T_out(t), 132 kg/s

Storage Loop

Helium

Energy Addition/Removal

Lead Bismuth

From Main Loop (shut off)

LiCl (3.447x10^6 MJ, 605°C)

To Main Loop (shut off)
Emergency Scenarios

Storage: LiCl leak

- Reroute He flow around storage and compressor

Heat Sink

- Average Decay Heat from core $\rightarrow$ process heat 1 hr after shutdown: 5MW
- Maximum temperature change of water: 10°C
- Volumetric flow rate of seawater: 455 gallons/second
- Ti plate type HX specifically for marine applications
- Outlet diffusers to reach thermal equilibrium quicker/minimize environmental impact
Future Work: Process Heat

• Compare PCHEs with Shell and Tube designs
• Split PCHE2 into multiple stages
• PCHE fouling factors
• Correction factors for determining CHF values for semi-circular channels
• $m_{\text{dot}}(t)$ of LBE
• Ensure that $\Delta T$ of $10^\circ$ C is enough to keep LBE molten even for lowest $m_{\text{dot}}$
• Effects of a support system on He flow
• Insulation: steady state and during shutdown
Hydrogen Production Plant
Outline

1. Engineering Objectives
2. Options for Hydrogen Production
3. UT-3
   • Plant Diagram
4. HTSE
   • Plant Diagram
   • Materials
5. Future Work
Engineering Objectives

• Meet biofuel’s hydrogen requirement
• Maximize use of process heat
• Minimize electricity use
• Zero greenhouse emissions
<table>
<thead>
<tr>
<th>Process</th>
<th>Materials</th>
<th>Temp [°C]</th>
<th>Efficiency [%]</th>
<th>Feasibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>ES</td>
<td>Water, Electrolytes, Anode/Cathode</td>
<td>~100</td>
<td>25-45</td>
<td>Drastic scaling required</td>
</tr>
<tr>
<td>HTSE</td>
<td>Solid Oxide Electrolysis Cell</td>
<td>&gt;500</td>
<td>90-95 (at 800°C)</td>
<td>Only small scale</td>
</tr>
<tr>
<td>SI</td>
<td>Ceramics</td>
<td>&gt;850</td>
<td>34-37</td>
<td>Commercially viable, but too high temp</td>
</tr>
<tr>
<td>SMR</td>
<td>Ni catalyst</td>
<td>700-800</td>
<td>60</td>
<td>Commercially viable, but polluting</td>
</tr>
<tr>
<td>UT-3</td>
<td>Ceramics, chemical reactants</td>
<td>760</td>
<td>&gt;40</td>
<td>Commercially viable</td>
</tr>
</tbody>
</table>

ES: Water Electrolysis  
HTSE: High Temperature Steam Electrolysis  
SI: Sulfur-Iodine Process  
SMR: Steam Methane Reforming  
UT-3: University of Tokyo-3  
(Ca-Br-Fe Thermochemical Cycle)
UT-3 Hydrogen Production Process

- Bromination of calcium oxide, acidity, leads to material concerns.

\[
\begin{align*}
\text{CaBr}_2(s) + H_2O(g) &\rightarrow \text{CaO}(s) + 2\text{HBr}(g) \quad (760 \degree C) \\
\text{CaO}(s) + \text{Br}_2(g) &\rightarrow \text{CaBr}_2(s) + 0.5\text{O}(g) \quad (571 \degree C) \\
\text{Fe}_3\text{O}_4(s) + 8\text{HBr}(g) &\rightarrow 3\text{FeBr}_2(s) + 4\text{H}_2\text{O}(g) + \text{Br}_2(g) \quad (220 \degree C) \\
3\text{FeBr}_2(s) + 4\text{H}_2\text{O}(g) &\rightarrow \text{Fe}_3\text{O}_4(s) + 6\text{HBr}(g) + \text{H}_2(g) \quad (560 \degree C)
\end{align*}
\]

UT-3 Hydrogen Production Process

Complications

• Necessary steam temperature could no longer be provided.

• Electric power required larger than reactor output.

• New hydrogen production design required
Solid Oxide Electrolysis Cell (SOEC)

Material Requirements

**Electrolyte:**
- Dense
- Chemically stable
- High ionic conductivity
- Gas-tight (no H-O recombination)
- Thin (minimize Ohmic resistance)

**Electrodes:**
- Porous, allows gas transportation
- Similar thermal expansion coefficient to electrolyte

# Electrolyte Material

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Ionic Conductivity (S/cm)</th>
<th>Optimal Temperature (K)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>YSZ</td>
<td>Stabilized zirconia</td>
<td>0.13</td>
<td>1273</td>
<td>Overall best choice</td>
</tr>
<tr>
<td>ScSZ</td>
<td>Stabilized zirconia</td>
<td>0.18</td>
<td>1273</td>
<td>Exorbitant cost</td>
</tr>
<tr>
<td>LSGM</td>
<td>Doped LaGaO$_3$</td>
<td>0.17</td>
<td>973</td>
<td>Requires reduced operating temperature; problematic reaction between LSGM and Ni</td>
</tr>
<tr>
<td>GDC</td>
<td>Ceria-based oxides</td>
<td>0.10</td>
<td>1073</td>
<td>Chemically unstable</td>
</tr>
<tr>
<td>SDC</td>
<td>Ceria-based oxide</td>
<td>0.08</td>
<td>1073</td>
<td>Chemically unstable</td>
</tr>
<tr>
<td>BaCeO$_3$</td>
<td>Proton-conducting electrolyte</td>
<td>0.08</td>
<td>1073</td>
<td>Low conductivity</td>
</tr>
</tbody>
</table>
HTSE with Regenerative Heating

Steam from Process Heat
\[ T = 559 \, ^\circ C, \, P = 0.105 \, MPa \]
\[ \text{mdot} = 88.07 \, \text{kg/s} \]

Start-Up Power Requirement
119.8 (47.9) MW

\( \text{O}_2(\text{g}) \)
\[ T = 71 \, ^\circ C \]
\[ P = 0.1 \, \text{MPa} \]
\[ \text{mdot} = 62.6 \, \text{kg/s} \]

\( \text{H}_2(\text{g}) \)
\[ T = 25 \, ^\circ C \]
\[ P = 0.1 \, \text{MPa} \]
\[ \text{mdot} = 7.9 \, \text{kg/s} \]
Future Work: Hydrogen Plant

• Determine electrical requirement to better accuracy.

• Possibly simulate HTSE plant to address efficiency.
Biofuels Production Plant
1. Goals
2. Overall Design of Biofuels Plant
3. Switchgrass
4. Gasification
5. Acid Gas Removal
6. Fischer-Tropsch Reactor
7. Distillation and Refining
8. Final Products and Concluding Thoughts
Biofuels Production Plant Goal

- Produce biofuels
- Large scale
- High quality
- Use nuclear power plant
  - Process heat
  - Electricity
- Hydrogen production plant
Biofuels Process Overview

Steam, Heated Air

Gasification

Acid Gas Removal

Fischer-Tropsch Reactor

Distillation & Refining

Hydrogen

Heat

Photo of switchgrass by Stephen Ausmus (USDA), public domain image.

Image by MIT OpenCourseWare.
## Choice of Biomass Feedstock Comparison

<table>
<thead>
<tr>
<th>Biomass</th>
<th>Current Cost ($/ton)</th>
<th>Energy Density (MJ/kg)</th>
<th>Agriculture Yield (tons/acre)</th>
<th>Food Source?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switchgrass</td>
<td>$40</td>
<td>17</td>
<td>11.5</td>
<td>no</td>
</tr>
<tr>
<td>Sorghum</td>
<td>$40</td>
<td>17</td>
<td>20</td>
<td>yes</td>
</tr>
<tr>
<td>Energy Cane</td>
<td>$34</td>
<td>13</td>
<td>30</td>
<td>no</td>
</tr>
<tr>
<td>Sugar Cane</td>
<td>$34</td>
<td>13</td>
<td>17</td>
<td>yes</td>
</tr>
<tr>
<td>Corn</td>
<td>$40-50</td>
<td>13.5</td>
<td>3.4</td>
<td>yes</td>
</tr>
<tr>
<td>Algae</td>
<td></td>
<td></td>
<td>58700 L/ha</td>
<td>no</td>
</tr>
</tbody>
</table>
Switchgrass
Optimal Growing Locations in U.S.

Map courtesy of Pacific Northwest National Laboratory, operated by Battelle for the U.S. Department of Energy.
Switchgrass
Optimal Growing Location in Texas

Map produced by the National Renewable Energy Laboratory for the U.S. Department of Energy.
Switchgrass

Growth and Transportation

• Outsource to local farmers → job creation

• Quantity: 2903 tons/day →
  • 85 flat bed trucks/day carrying 33.3 tons each
  • 13 closed hopper cars at full capacity

• Pelletize to 1300 kg/m³
Biofuels Process Overview

Steam, Heated Air

Gasification

Acid Gas Removal

Fischer-Tropsch Reactor

Distillation & Refining

Hydrogen

Heat

Image by MIT OpenCourseWare.

Photo of switchgrass by Stephen Ausmus (USDA), public domain image.
Gasification
Rentech Silvagas Dual Fluidized Bed Cycle
## Gasification

### Inputs and Outputs

<table>
<thead>
<tr>
<th></th>
<th>Mass flow (kg/s)</th>
<th>Temperature (° C)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Biomass In</strong></td>
<td>24.4</td>
<td>25</td>
</tr>
<tr>
<td><strong>Steam In</strong></td>
<td>2.6</td>
<td>182</td>
</tr>
<tr>
<td><strong>Air In</strong></td>
<td>11.9</td>
<td>354</td>
</tr>
<tr>
<td><strong>Syngas Out</strong></td>
<td>19.9</td>
<td>862</td>
</tr>
<tr>
<td><strong>Flue Gas Out</strong></td>
<td>19</td>
<td>916</td>
</tr>
</tbody>
</table>

### Composition of Syngas (by volume):

- **CO**
- **CO₂**
- **H₂**
- **CH₄**
- **C₂H₄**
- **Other**

Biofuels Process Overview

Steam, Heated Air

Gasification

Acid Gas Removal

Fischer-Tropsch Reactor

Distillation & Refining

Hydrogen

Heat

Photo of switchgrass by Stephen Ausmus (USDA), public domain image.

Image by MIT OpenCourseWare.
Acid Gas Cleanup Process

Cyclone Particulate Removal (682°C)

Syngas Cooling

Water Scrubber (107°C)

Compressor (1 bar to 30.7 bar)

Amine Acid Gas Removal

CO₂, H₂S

LO-CAT Acid Gas Removal

CO₂, H₂S

CO, H₂
Acid Gas Removal Output

Composition of Input to F-T Reactor

After gasification: 19.9 kg/s

After acid gas removal: 14.6 kg/s
Biofuels Process Overview

Steam, Heated Air

Gasification

Acid Gas Removal

Fischer-Tropsch Reactor

Distillation & Refining

Hydrogen

Heat

Photo of switchgrass by Stephen Ausmus (USDA), public domain image.

Image by MIT OpenCourseWare.
Fischer-Tropsch Reactor
Slurry Phase Bubble Column Design

\[ CO + 2H_2 \rightarrow -(CH_2) - + H_2O + 170 \, kJ \]

\[ H_2O + CO \rightarrow CO_2 + H_2 \]

- Fe catalyst
- Heat generated: 21.8 MW
Fischer-Tropsch Reactor

Product Selectivity

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### Fischer-Tropsch Reactor

#### Reactor Outputs

<table>
<thead>
<tr>
<th>Carbon Content</th>
<th>Product Classification</th>
<th>Mass Flow (kg/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(C_1 - C_5)</td>
<td>Light Gas</td>
<td>2.02</td>
</tr>
<tr>
<td>(C_5 - C_{12})</td>
<td>Naphtha (Gasoline)</td>
<td>5.09</td>
</tr>
<tr>
<td>(C_{12} - C_{20})</td>
<td>Distillate (Biodiesel)</td>
<td>2.65</td>
</tr>
<tr>
<td>(C_{20+})</td>
<td>Heavy wax</td>
<td>1.46</td>
</tr>
</tbody>
</table>
Biofuels Process Overview

1. **Steam, Heated Air**
2. **Gasification**
3. **Acid Gas Removal**
4. **Fischer-Tropsch Reactor**
5. **Distillation & Refining**
6. **Hydrogen**
7. **Heat**

Photo of switchgrass by Stephen Ausmus (USDA), public domain image.

Image by MIT OpenCourseWare.
### Distillation

<table>
<thead>
<tr>
<th>Fraction</th>
<th>Boiling Point (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light Gases</td>
<td>&lt; 40</td>
</tr>
<tr>
<td>Light Naptha</td>
<td>30-90</td>
</tr>
<tr>
<td>Heavy Naptha</td>
<td>90-200</td>
</tr>
<tr>
<td>Distillate</td>
<td>200-300</td>
</tr>
<tr>
<td>Heavy Wax</td>
<td>300-350</td>
</tr>
</tbody>
</table>

![Diagram of distillation process]

**Diagram Description:**
- **HEAT EXCHANGER:** Cooling, condensation
- **SEPARATOR:** Uncondensed gases
- **Reflux:** Reflux line
- **Trays:** 1 to 5
- **Reboil:** Heat exchanger, partial vaporisation
- **Bottom Product:**
Refining
Hydrogen Inputs
Biofuels Process Overview

Steam, Heated Air

Acid Gas Removal

Gasification

Fischer-Tropsch Reactor

Distillation & Refining

Hydrogen

Heat

Photo of switchgrass by Stephen Ausmus (USDA), public domain image.

Image by MIT OpenCourseWare.
## Final Products

<table>
<thead>
<tr>
<th>Product Classification</th>
<th>Mass Flow (kg/s)</th>
<th>Mass Flow (barrels/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light Gas</td>
<td>2.02</td>
<td>---</td>
</tr>
<tr>
<td>Diesel</td>
<td>2.87</td>
<td>1874</td>
</tr>
<tr>
<td>Gasoline</td>
<td>6.33</td>
<td>4780</td>
</tr>
<tr>
<td>Total Diesel and Gasoline</td>
<td>11.22</td>
<td>6654</td>
</tr>
</tbody>
</table>

- Expected revenue from: > $1.7 million/day
- Assuming 15 gal/tank, this amount of gasoline and diesel can fill over 18,500 cars/day
- Compare to U.S. 2011 demand of 9.12 million barrels/day

Carbon Sequestration

CO₂ management

• Options:
  • Recycle
  • Sell
  • Underground storage
  • Deep ocean dissolution

• CO₂ liquifies at 300kg/m³

• Compress to 20 MPa with in-line integrally geared compressor and DDHF multistage barrel pump
Future Work and Economics

• Potential improvements
  - scale up
  - use oxygen from H\textsubscript{2} plant in gasification step
  - recycle flue gas, H\textsubscript{2}S, CO\textsubscript{2} wastes

• Jobs generated: farmers, drivers, plant workers

• Total daily profit: $1.4 million/day

• Total profit selling only electricity: $0.83 million/day
Concluding Thoughts
Implications

- This facility design can feasibly produce green electricity, biodiesel, and biogasoline
- Minimal carbon emissions
- Nuclear reactor produces 1000 MWe to grid and powers hydrogen and biofuel plants
- Biofuels produces enough alternative fuels for 18,500 cars/day
Acknowledgments

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Questions & Discussion