IPRO 302

CO_2 Mitigation: A Techno-Economic Assessment

Midterm Report

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Sponsor: Sargent & Lundy

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1.0 Revised Objectives

To design a carbon dioxide removal system as an addition to an existing pulverized coal-fired power plant located in Council Bluffs, Iowa. Using computer models to simulate the processes involved for the appropriate scales of carbon dioxide removal, an analysis will be performed to determine all costs associated with implementing the selected technologies. These costs will include considerations of real-estate, operation, capital investment, and sequestration.

No changes have been made to the objectives.

2.0 Results to Date

1. Current Results

Steam Team Results

Although not too much has been accomplished in terms of achieving numerical results, there has been progress in the preliminary stages and in the overall understanding of both the processes and the problem. Initially, very little was understood of the power plant steam cycle and the general function of the plant. However, now the exact path of the steam and the flue gas in completely understood by all members, which is absolutely necessary for proper analysis. Upon understanding the problem and the goals to be achieved, the next step was to choose a means to solve it. As Professor Don Chmielewski had available a MATLAB code which appeared to be useful, it was decided to utilize a MATLAB simulation of the steam stream and flue gas. The code was modeled for a sub-critical plant which utilized a wet scrubber pollution control device. However, for these purposes, it is necessary to modify the code for a dry scrubber simulation and supercritical situation.

Currently our MATLAB code works on a step by step basis, analyzing the flue and steam after each step in the power plant process. The various heat requirements for all the steps are known and used to calculate temperatures throughout the components. Furthermore, a simple mass balance system is used throughout each step to tabulate values of certain elements or components within the flue gas. Through use of all this information, analysis will provide information such as flue and steam flow rates, flue composition, steam and flue temperatures, all throughout each step of the power plant.

Current work underway in adapting for the dry scrubber device is proving difficult due to temperature and pressure dependencies. The dry scrubber operates through the mixing of the flue gas with a water and lime slurry. The water and lime slurry is fed in at specific flow rate, which we do not know. The key is that upon entering, the water immediately undergoes a phase change and a saturated steam mixture results. Both the resultant temperature of the flue gas exiting and the necessary flow rate of water/lime need to be calculated. To do this, a water mass balance equation, energy balance equation, and Antoine's Equations' are being utilized. Combination of these three equations will result in a function which may be graphed, and upon analysis, the proper temperature flow rate data set found. Although the process is straightforward, there has been difficulty in properly combining all three equations to achieve a numerical value.

Through further exploration, various factors were determined to be of extreme importance. The sulfur dioxide removal rate of the dry scrubber, for example, is of great importance as remaining sulfur dioxide will affect the carbon dioxide removal process. This value, however, is not to be calculated, as the project sponsor is planning on releasing this information for analysis.

Flue Crew's Technical Achievements

The CO_2 scrubbing process that the flue crew is designing takes the flue gas that would normally go into the atmosphere and remove a desired amount of CO_2 from it. Six designs need to be made with CO_2 removal percentages of 25, 50, and 90 and inlet flue gas temperatures of 30°F and 100°F. An absorption tower removes CO_2 from the gas with a 25% ammonia and 75% water mixture. The solution containing the CO_2 is then sent to the stripper tower where the CO_2 is removed from the solution into a gas and sent to a compressor which pressurizes it for sequestration.

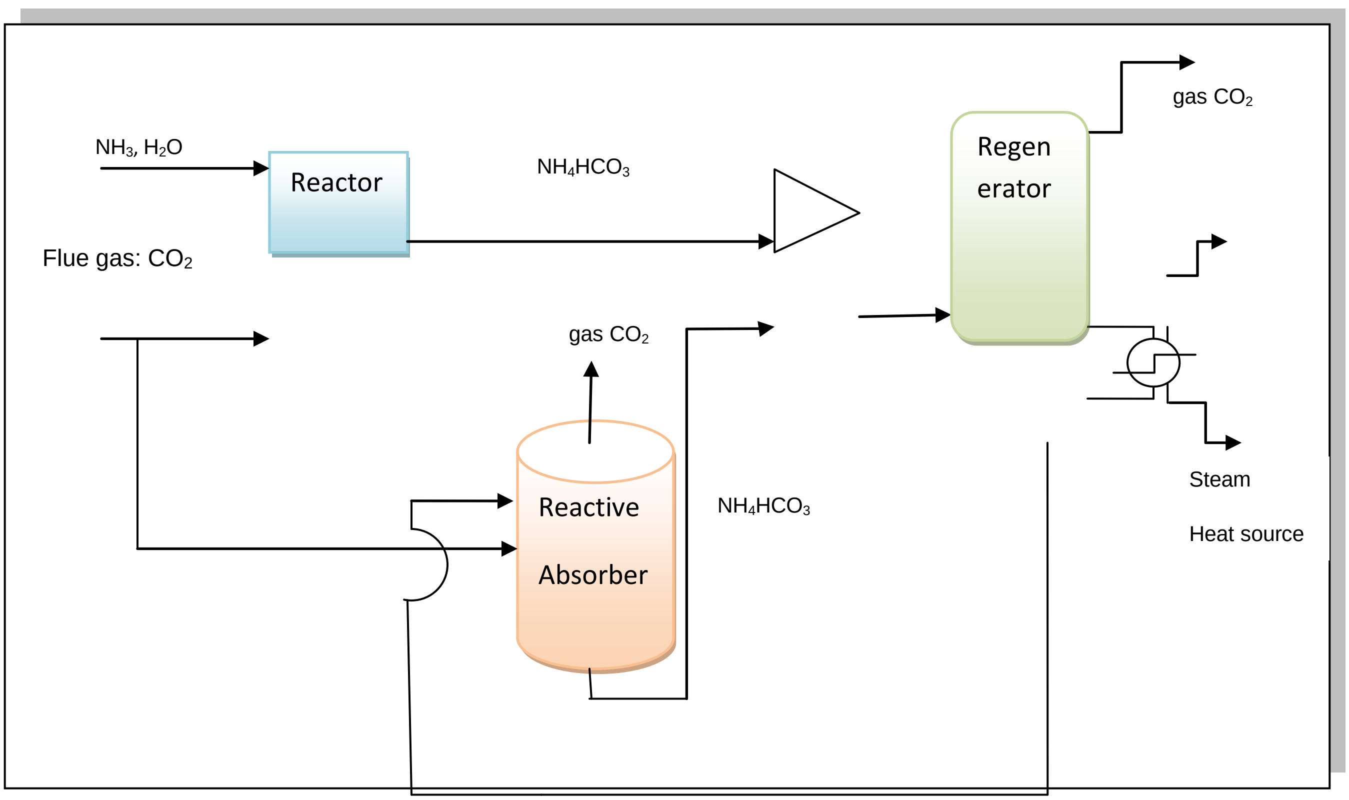
When the flue crew started the design process, they assumed that no chemical reactions occurred in the system. However, their research and communications with Sargent & Lundy indicated that the removal mechanism is a series of chemical reactions and that side reactions occur within the system which cause the solvent to degrade. This made the design more complicated than originally thought and required the team to take a new approach to the design. The following reactions were found to occur in the system.

$NH_3 + H_2O + CO_2 \rightarrow NH_4HCO_3$ $SO_2 + H_2O \rightarrow H_2SO_4$

$2NH_4HCO_3 \Leftrightarrow (NH_4)_2CO_3 + CO_2 + H_2O$ $H_2SO_4 + 2NH_3 \rightarrow (NH_4)_2SO_4$

The modeling software available does not implement these reactions in absorption and stripping units, so a new modeling approach has been made where the absorber and stripper are both modeled as series of equilibrium reactors with pressure drops, temperature changes, and the appropriate volume to simulate an equilibrium stage in the absorber and stripper units.

Some simple calculations were made so that the flue crew could get an idea on what types of properties the final design will have. The following diagram shows the simplified process model used for these calculations.



The flue gas enters the simulation where the degradation reaction between the SO_2 gas and ammonia solution is simulated in a reactor at the entrance. Then, that product is sent to the reactive absorber where some CO_2 is absorbed into the solvent. The solvent is then sent to the regenerator, which is the stripper, and pure CO_2 is recovered from there. The solvent is then sent back to the absorber to collect more CO_2. The flue gas is released into the atmosphere after it has gone through the absorber. Steam which comes from a turbine in the power plant is used as a heat source on the regenerator.

Because the equilibrium reaction between the CO_2 gas and ammonia bicarbonate in the ammonia solution limits the mass transfer between the two phases, calculations were performed based upon equilibrium discluding mass transfer between the two phases. The final result of the calculations showed that 1.294 pounds of CO_2 is removed for every pound of ammonia in solution. This calculation provides a starting point for the complex model of the process.

2. ***Current or potential products or outputs resulting from research and testing***

The project will result in a report given to the sponsor at the end of the semester, which explains the selected design and cost of all processes associated with the implementation. This design will offer Sargent & Lundy a basis for comparison of their existing research. The sponsor might implement a form of our design in the coal power plant in Council Bluffs, Iowa.

3. ***Deliverables that will be produced by the project team due to current results***

We have completed some basic modeling of the processes. The models are still in their preliminary stages and require further refinement and verification to yield the desired information.

4. ***Do current results address the problem of the sponsor?***

Yes, the current results address the problem of the sponsor, but not entirely. A detailed economic analysis and complete model of all processes has yet to be developed.

5. ***How will the current results be incorporated into proposed solution or solution framework?***

Hopefully, the knowledge gained from the research will provide sponsors with a solid understanding of the energy and monetary costs associated with the selected carbon dioxide removal processes for various requirements of carbon dioxide removal.

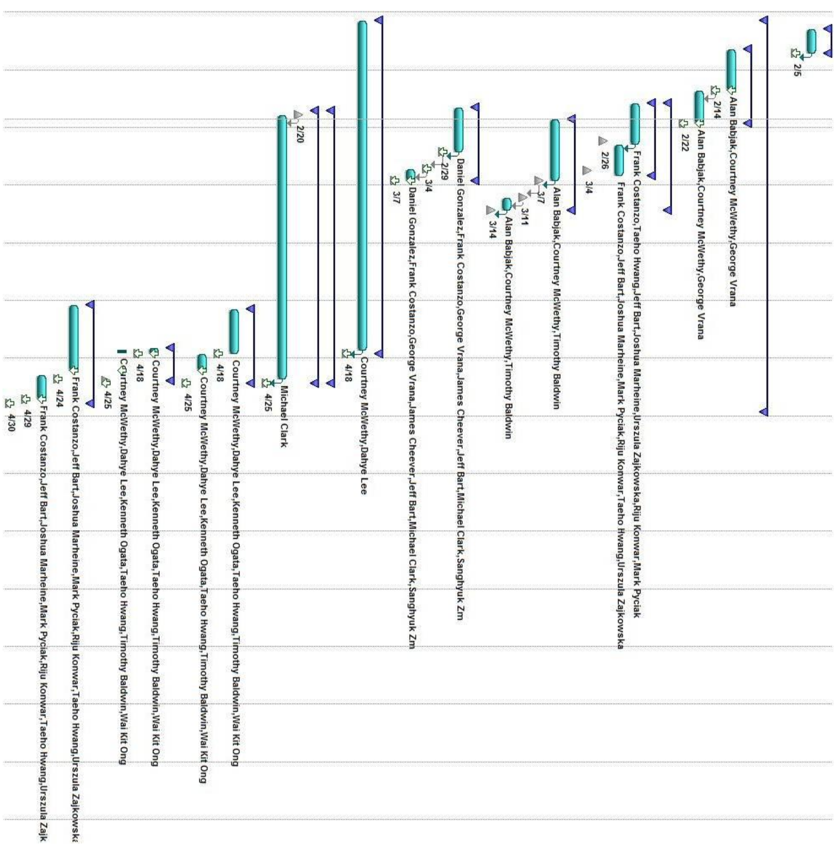
3.0 Revised Task / Event Schedule

1. Describe any changes in project tasks pertaining to the problem solution or project design.

After two meetings with the sponsor, it has been established that the boiler portion of the pulverized coal-fired plant can in no way be modified, as this would require the complete redesign of the existing equipment. It had previously been assumed that the amount of coal fed into the system to provide power for all processes, could be varied. Therefore, instead of performing complex iterations of economic energy dispatch in order to determine optimal coal input rates, a fixed rate of coal consumption will be assumed. In addition, the team will need to determine the amount of SO_2 remaining in the flue gas after desulphurization stages in order to account for the ammonia degeneration within the stripper and absorption column. Additional side reactions were clarified by Sargent & Lundy and added to the process model.

2. ***Changes to summary tasks or sub-tasks pertaining to IPRO project deliverables and list all associated due dates and start dates.***

Task Name	Duration	Start	Finish	Predecessors
Project Organization	**4 days?**	**Thu 1/31/08**	**Tue 2/5/08**	
Discuss Team Structure	4 days?	Thu 1/31/08	Tue 2/5/08	
Determine Team Structure	1 day?	Tue 2/5/08	Tue 2/5/08	2
Deliverables	**70 days?**	**Tue 1/29/08**	**Fri 5/2/08**	
Project Plan	**14 days?**	**Tue 2/5/08**	**Fri 2/22/08**	
Work on Project Plan Rough Draft	8 days?	Tue 2/5/08	Thu 2/14/08	
Get Input From Team about Project Plan	1 day?	Thu 2/14/08	Thu 2/14/08	
Make Corrections to Project Plan	6 days?	Fri 2/15/08	Fri 2/22/08	8
Project Plan Due	1 day?	Fri 2/22/08	Fri 2/22/08	
Midterm Deliverables	**20 days?**	**Mon 2/18/08**	**Fri 3/14/08**	
Midterm Progress Report Presentation	**.71 days?**	**Mon 2/18/08**	**Thu 3/6/08**	
Work on Midterm Progress Presention	8 days?	Mon 2/18/08	Wed 2/27/08	
Do Corrections on Midterm Progress Presentation	5.71 days?	Thu 2/28/08	Thu 3/6/08	13
Midterm Progress Presentation Practice	1.14 days?	Tue 2/26/08	Wed 2/27/08	
Midterm Progress Report Presentation Due Date	1.14 days?	Tue 3/4/08	Wed 3/5/08	
Midterm Progress Report Paper	**16 days?**	**Fri 2/22/08**	**Fri 3/14/08**	
Work on Midterm Progress Report Paper Rough Draft	11 days?	Fri 2/22/08	Fri 3/7/08	
Post Midterm Progress Report for Input	1 day?	Fri 3/7/08	Fri 3/7/08	18
Get input from team for corrections to the paper	1 day?	Tue 3/11/08	Tue 3/11/08	19
Do Corrections on Midterm Progress Report Paper	3 days?	Wed 3/12/08	Fri 3/14/08	20
Turn in Midterm Progress Report	1 day?	Fri 3/14/08	Fri 3/14/08	21
Ethics Paper	**14 days?**	**Tue 2/19/08**	**Fri 3/7/08**	
Work on Ethics Presentation Rough Draft	9 days?	Tue 2/19/08	Fri 2/29/08	
Post Ethics Paper Rough Draft for Input	1 day?	Fri 2/29/08	Fri 2/29/08	24
Get input from team for corrections on paper	1 day?	Tue 3/4/08	Tue 3/4/08	25
Make corrections to ethics paper	3 days?	Wed 3/5/08	Fri 3/7/08	26
Turn in Ethics Paper	1 day?	Fri 3/7/08	Fri 3/7/08	
Meeting Minutes	**59 days?**	**Tue 1/29/08**	**Fri 4/18/08**	
Take meeting minutes/post on igroups	58 days?	Tue 1/29/08	Thu 4/17/08	
Meeting Minutes Due	1 day?	Fri 4/18/08	Fri 4/18/08	30
IPRO Day Deliverables	**49 days?**	**Wed 2/20/08**	**Fri 4/25/08**	
Web Site	**49 days?**	**Wed 2/20/08**	**Fri 4/25/08**	
Put up initial web site design	1 day?	Wed 2/20/08	Wed 2/20/08	
Periodically update website	47 days?	Thu 2/21/08	Thu 4/24/08	34
Final web site due	1 day?	Fri 4/25/08	Fri 4/25/08	35
Exhibit/Poster	**15 days?**	**Tue 4/8/08**	**Fri 4/25/08**	
Design Exhibit/Poster rough draft	9 days?	Tue 4/8/08	Fri 4/18/08	
Post design for input	1 day?	Fri 4/18/08	Fri 4/18/08	
Get input from team for corrections on paper	3 days?	Sat 4/19/08	Tue 4/22/08	
Exhibit/Poster Due	1 day?	Fri 4/25/08	Fri 4/25/08	
Abstract/Brochure	**.67 days?**	**Thu 4/17/08**	**Fri 4/25/08**	
Design Abstract/Brochure	1.5 days?	Thu 4/17/08	Fri 4/18/08	
Post design for input	).17 days?	Fri 4/18/08	Fri 4/18/08	
Get input from team for corrections on paper	0.5 days?	Fri 4/18/08	Fri 4/18/08	
Abstract/Brochure Due	).17 days?	Fri 4/25/08	Fri 4/25/08	
Final Presentation	**19 days?**	**Mon 4/7/08**	**Wed 4/30/08**	
Make final presentation rough draft	13 days?	Mon 4/7/08	Tue 4/22/08	
Practice presentation	1 day?	Thu 4/24/08	Thu 4/24/08	
Make corrections to presentation	4 days?	Thu 4/24/08	Tue 4/29/08	
Practice presentation 2	1 day?	Tue 4/29/08	Tue 4/29/08	
Give presentation	1 day?	Wed 4/30/08	Wed 4/30/08	



Task Name	Duration	Start	Finish	Predecessors
Final Report w/ Table of Contents	**22 days?**	**Thu 4/3/08**	**Thu 5/1/08**	
Make final report rough draft	4.13 days?	Thu 4/3/08	Wed 4/9/08	
Post final report rough draft for input	1 day?	Fri 4/18/08	Fri 4/18/08	54
Get input from team for corrections on paper	1.88 days?	Wed 4/23/08	Thu 4/24/08	55
Make corrections on final report	1.88 days?	Fri 4/25/08	Mon 4/28/08	56
Final report due	3.38 days?	Thu 5/1/08	Thu 5/1/08	57
IPRO CD	**36 days?**	**Mon 3/17/08**	**Fri 5/2/08**	
Submit IPRO CD	1 day?	Fri 5/2/08	Fri 5/2/08	
Spring Break!	5 days?	Mon 3/17/08	Fri 3/21/08	
Design	**39 days?**	**Tue 2/19/08**	**Fri 4/11/08**	
Steam Team	**34 days?**	**Tue 2/19/08**	**Fri 4/4/08**	
Present overview of design to IPRO group	1 day?	Tue 2/19/08	Tue 2/19/08	
Make base model of first case	16 days?	Tue 2/19/08	Tue 3/11/08	
Model Integration of the First Case	4 days?	Wed 3/12/08	Mon 3/17/08	67
Integrate models for the last 5 cases	9 days?	Tue 3/25/08	Fri 4/4/08	68
Flue Crew	**39 days?**	**Tue 2/19/08**	**Fri 4/11/08**	
Present overview of design to IPRO group	1 day?	Tue 2/19/08	Tue 2/19/08	
Make base model for first case	16 days?	Tue 2/19/08	Tue 3/11/08	
Model Integration of the First Case	5 days?	Tue 3/11/08	Mon 3/17/08	73
Integrate models for the last 5 cases	9 days?	Tue 3/25/08	Fri 4/4/08	74
Economic analysis of first case	6 days?	Tue 3/25/08	Tue 4/1/08	74
Economic analysis of last 5 cases	8 days?	Wed 4/2/08	Fri 4/11/08	76
Research teams	**44 days?**	**Tue 2/5/08**	**Fri 4/4/08**	
Research background for project plan	3.17 days?	Tue 2/5/08	Mon 2/18/08	
Research for flue crew team	33 days?	Wed 2/20/08	Fri 4/4/08	80
Research for steam team	33 days?	Wed 2/20/08	Fri 4/4/08	80
Research for team leader	33 days?	Wed 2/20/08	Fri 4/4/08	80

The Gantt chart shows that the only major dates changed in the project plan have been the technical team schedules. These dates were changed due to underestimation of time necessary to complete the deliverables and design work.

4.0 Changes in Task Assignments and Designation of Roles and Team Organization

1. ***Discuss changes to team organization.***

Due to a surplus of sophomore students on this project, 5 have been selected to research current and future environmental regulations in Iowa with attention to carbon dioxide sequestration and storage. The most feasible carbon dioxide use in Iowa will be suggested enabling the team to incorporate this option in their detailed economic analysis for consideration of carbon dioxide sequestration and storage costs. Furthermore, another four sophomore students have been assigned to select the most appropriate compressor design after carbon dioxide separation, in order to pressurize the carbon dioxide to needed pressure for the most feasible sequestration option, with minimal energy penalties.

2. ***Define sub team or individual sub team task assignments and responsibilities.***

The technical tasks are divided among all of the people in the IPRO project. The two main sub-teams are the Flue Crew and the Steam Team. The Flue Crew is entrusted to develop a reliable CO2 removal unit. The Steam Team is working to model the power plant operation and determine the energy requirements of the CO2 removal processes. The chemical engineering sophomore students are separated into different groups based upon the task that is assigned to them. One group of two chemical engineering sophomores are responsible for finding equipment information and choosing appropriate equipment materials for the flue crew's designs. Five of the sophomores are responsible for finding sequestration and storage costs. Another four sophomores are assigned to design a compressor which will pressurize the CO_2 for the desired sequestration method. A few sophomores are involved in helping the steam team with MATLAB code and background research.

Everyone in this IPRO team is also in a deliverable team. The following deliverable teams have been formed in the group: reports, presentations, ethics, abstract and poster, and web site.

These teams did not require any reforming since they were made in the beginning of the IPRO project.

3. ***Describe any changes made since the beginning of the semester in sub-team roles.***

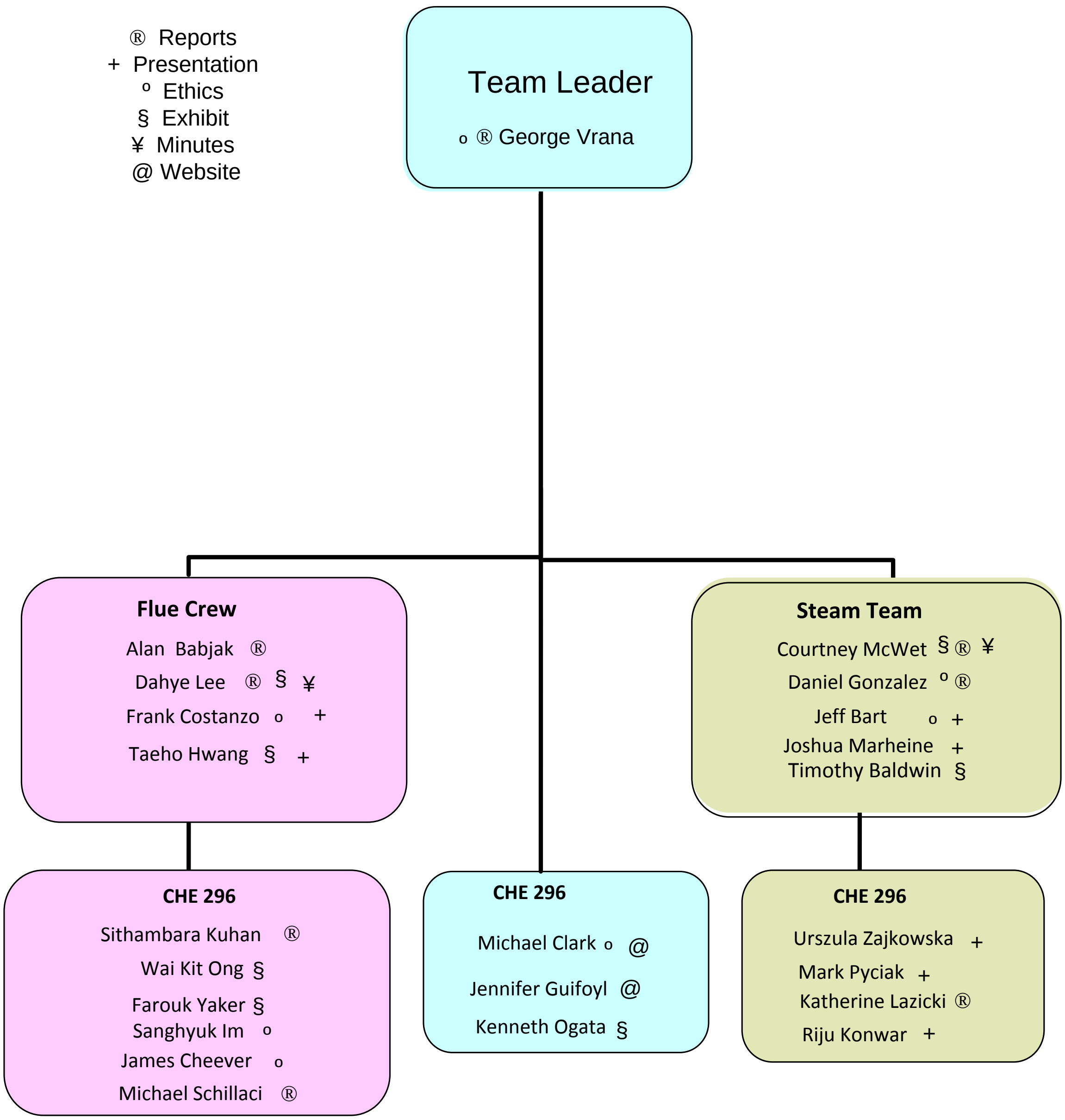
Since the beginning of the semester, changes were made in the way that the steam team and flue crew work together. The two teams now meet on a regular basis to do their technical work. While particular roles in each group have not changed since the beginning of the semester, the steam team is now encouraged to help the flue crew with any technical hurdles they might face and the reverse is also true. One person on the flue crew and one sophomore chemical engineering student are now charged with helping the steam team with MATLAB coding.

While roles within the deliverables team have not changed, the whole IPRO team is now charged with the task of proof-reading and critiquing rough drafts of deliverables coming from each team. This change makes sure that the deliverables are high quality.

4. ***If appropriate, explain how and why team organization has changed since the project plan was first formulated.***

The sophomore team members were reallocated into separate subgroups according to our current needs. One of these groups will research the environmental regulations in Iowa with special attention to sequestration. The other group is charged with the selection of an appropriate compressor to meet the needs of the selected CO2 storage option.

5. Team Structure



5.0 Barriers and Obstacles

1. Describe any obstacles encountered while completing the planned tasks for the project.

The complex team organization and deliverable requirements prior to the start of technical design have delayed the progress of the technical sub-teams. The amount of time originally allocated to completing the deliverables was much less than was actually required. Additionally, difficulty was encountered in finding the correct assumptions for the technical models and implementing the complexity of the systems under study into MATLAB and HySys. Also, the students that were not majoring in chemical engineering weren't knowledgeable in chemical reaction thermodynamics, absorbers, and strippers. This made them less capable of making contributions to the CO_2 scrubber design.

2. ***Explain how the team or sub-team resolved these obstacles.***

People outside of the different deliverables teams critiqued the rough drafts of the deliverables and helped producing those deliverables so that the deadlines would be met and that quality deliverables were produced. The flue crew obtained advice about how to implement their models in HySys from various professors in the chemical engineering department and performed rough calculations to get a feel for how the system should perform once the chemical reactions are implemented. More people where assigned to help with MATLAB code in the steam team so that the power plant model would develop faster. The steam team watched the flue crew give a presentation explaining the CO_2 removal process, read some materials on thermodynamics, and asked the flue crew questions so that they could have a good understanding of the CO_2 removal technology.

3. ***Identify any remaining barriers or obstacles that need to be addressed before the team can successfully complete the planned work.***

The flue crew needs to find a way to implement thermodynamic equation of state models for chemicals which are not present in HySys before they can simulate the process. The steam team needs to learn how to fully implement the model of the power plant in MATLAB.

4. ***Discuss how the team intends to deal with the identified barriers and obstacles.***

The flue crew will research and take tutorials on how to implement these unrecognized chemicals in the HySys simulation over the spring break so that the technical design schedule will be followed after spring break. The steam team will devote more time into learning MATLAB and debugging the code so that a full model can be developed soon after spring break. This model will also more accurately account for the dry scrubber for the process unlike the wet scrubber which the model currently contains.

In addition, most teams will collaborate on a more frequent basis in order to become fully aware of future challenges so that they might be resolved in a timely manner.

6.0 Midterm Presentation Slides

Objectives

- Analysis of CO_2 removal system
  - Computer models of power, steam and flue gas cycles
- Economic analysis
  - Capital and operation costs.
  - Sequestration costs.

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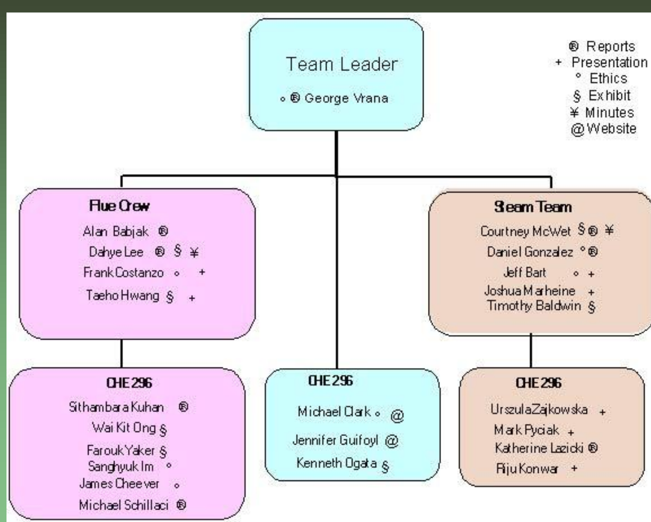
Team



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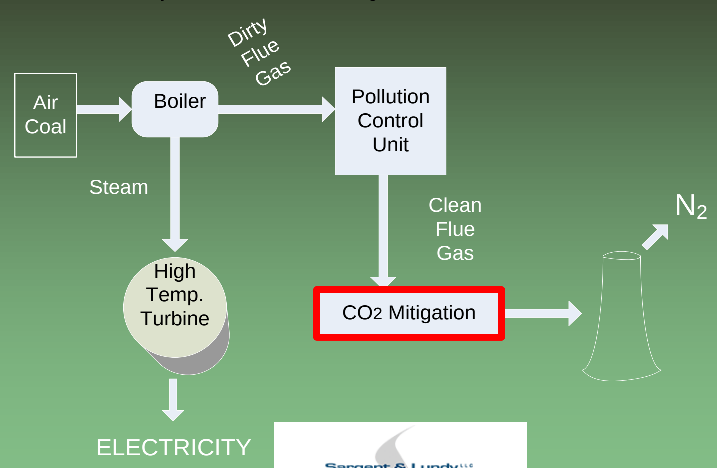
Team Structure



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Steam Side

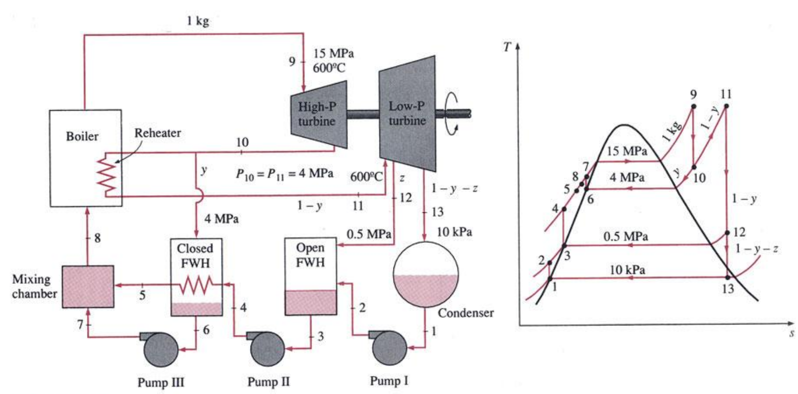

FIGURE 9-19
Schematic and *T-s* diagram for Example 9-6.

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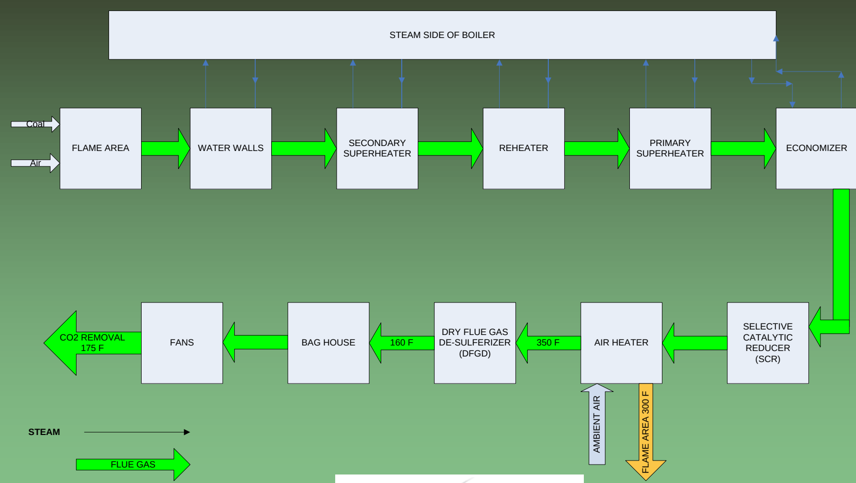
Steam/Flue Gas Flow



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- Absorber
  - Absorption is when liquid & gas phases come into contact
  - Diffusion or mass transfer of solute to Solution
  - Solute : CO_2 – absorbed from flue gas into flowing liquid
- Stripper
  - Separate and regenerate CO_2 from solution
  - Separation Property : Relative Volatility --- CO_2 is 30 times more volatile than Ammonia
- Reaction

absorber

$$(NH_4)_2CO_3 + H_2O + CO_2 \rightleftarrows 2\,NH_4HCO_3$$

stripper

Ammonia Carbonate — Ammonia Bicarbonate

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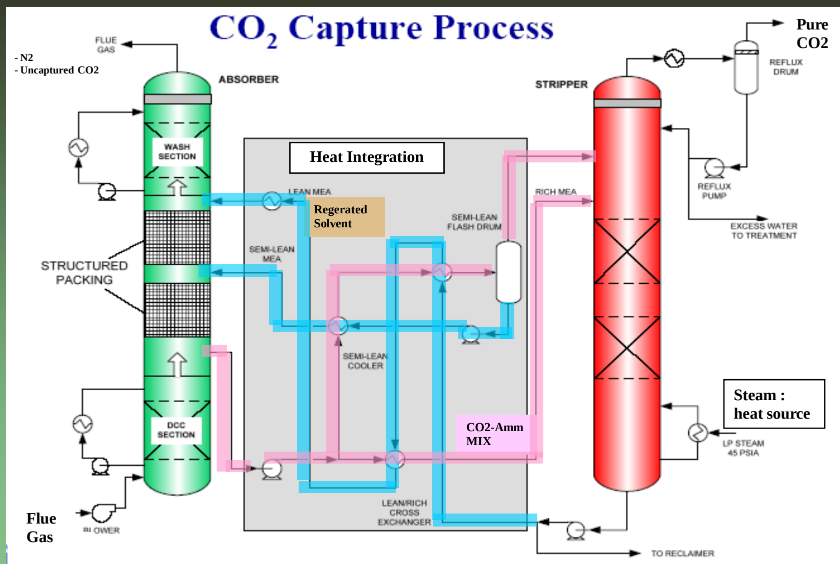

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Accomplishments

- Developed an understanding of processes involved.
- Completed Project Plan deliverable
  - Identified member strengths and weaknesses
  - Developed complete team structure
- Two Meetings with Project Sponsor
- Initial Simulations in Matlab and Hysys

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What's Next?

- Hysys computer models
- Matlab computer models
- Current and Future Regulations research
- Economic Analysis

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