APPENDICES

Appendix A

Biomass Co-firing Proposal

University of Utah

Technical Assistance in Support of Biomass Co-firing Demonstration

A Proposal to PacifiCorp

Introduction

PacifiCorp is considering the demonstration of biomass co-firing with pulverized coal at their Hunter plant as one of multiple CO_2 reduction strategies to be evaluated using legislative funding from SB115-54-20-104. This funding is specifically targeted for "a program to investigate, analyze and research clean coal technology."

Faculty members from the University of Utah have considerable experience with coal and biomass/coal co-firing, and are interested in providing technical assistance in support of the proposed biomass co-firing demonstration. Specifically, we are interested in assisting with the planning of the co-firing demonstration, as well as making measurements during the execution of the demonstration, and assisting in the analysis of data obtained during the testing. In addition, we envision several research tasks in support of the demonstration that can be carried out at our Industrial Combustion and Gasification Research Facility.

It is our understanding that the production of the required biomass fuel will be contracted directly with the two proposed suppliers, Amaron Energy and AEG/CoalSwitch. Therefore, our proposed efforts will focus only the technical support tasks. Brigham Young University will also participate in some of the proposed tasks, as well as potentially proposing an additional task, and these efforts will be incorporated into this proposal once they have been identified.

Project Objectives

The primary objectives for the University of Utah participation in the biomass co-firing demonstration are as follows:

1) Assess the mechanical stability and hydrophobicity or water resistance of the two candidate biomass fuels.
2) Perform on-site sampling of particulate matter (PM) in various size ranges during the Hunter plant demonstration. Other measurements may also be taken (e.g., deposition probes, Hg, etc.) if deemed feasible during the campaign.
3) Assist in the analysis of plant data relating to pollutant emissions, boiler performance
4) Perform laboratory studies of the combustion performance of the biomass/coal blends
5) Assessment of PM, CO_2 and other emissions avoided when burning forest biomass in the Hunter plant vs. a forest fire. What are the relative environmental impacts?

Detailed Work Plan

Tasks to be performed by University of Utah personnel, in collaboration with PacifiCorp personnel, are discussed in detail below. Since this proposal is a draft and the overall scope of work has yet to be finalized, limited detail is provided at this stage.

Task 1. Biomass Fuel Handling and Stability ***(UofU)***

This task will explore the potential hazards of the handling of the two different types of biomass fuels. Will the pellets be hydrophobic or at least water resistant? To what degree? Will dry storage facilities be required? How much dust is generated from each during handling (conveying/transfer points, movement around yard, off-loading from transport, etc.). What is the mechanical strength of the respective fuels (how much attrition/dust formation during handling)?

Some quantitative assessment of these attributes can be made prior to the full-scale demonstration using the material provided to the UofU for the milling trials, and this information could prove very helpful in preparing for the Hunter plant demonstration.

Task 2. On-site (Hunter Plant) Measurements During Co-firing Demonstration ***(UofU and BYU)***

In this task, the University of Utah and Brigham Young University will develop and adapt existing hardware for the measurement of particle size distribution and deposition rate during baseline operation and the biomass co-firing demonstration. U of U will build an isokinetic dilution sampling probe that will be long enough to extract particle samples from Hunter, Unit 3 boiler at a location near the primary superheat pendants. BYU will build two temperature controlled deposit sample probes to be installed at the same location in the furnace. Personnel from the U of U and BYU will travel to the plant and take particle size distribution and deposition rate data for several days before and during the biomass co-firing tests. The U of U will also take size segregated particle samples and will later analyze them for chemical composition. These data will be digested and a report will be written for PacifiCorp detailing the difference in mineral matter behavior between the baseline and demonstration periods. These data will also be available for comparison with pilot-scale data for similar operating conditions.

Task 3. Analysis of Boiler Operating, Emissions and Performance Data ***(BYU)***

BYU will visit Hunter, Unit 3 and collect operational data from PacifiCorp engineers and from the DCS system for the periods before and during the biomass co-firing demonstration. These data will be used to build a process model within Aspen of Hunter, Unit 3 for baseline operation and for the biomass co-firing test. This model will be used to evaluate differences in operation between the two period of operation and a report will be written for PacifiCorp detailing these results.

Task 4. Combustion Performance Evaluations ***(UofU)***

Laboratory-scale studies would be carried out to specifically target investigations of pollutant emission levels and ash/deposit properties for the two biomass co-fire blends, as compared to the baseline coal operation. We would use small-scale (100 KW) combustion tests to explore differences in the deposition behavior, flyash characteristics and NOx, SO_2, CO and CO_2 performance for the two different biomass fuels (after pulverizing). Operating conditions representative of Hunter plant operation would be used.

We would use a specially-designed deposition probe and our existing, state-of-the-art aerosol sampling and measurement equipment. We would follow up with similar measurements during the field trials, as described in Task 2.

A recent publication of a biomass co-firing study showed some reduction in NOx beyond that which can be attributed simply to fuel N reduction, or introduction of volatiles (they used biomass char). Thus, there may be an additional NOx benefit due to use of biomass, that could be assessed simultaneously with the ash/deposition study.

These two issues (deposition and NOx behavior) are the subjects of two new NSF grants on biomass co-firing awarded to the University of Utah, so we would be able to leverage those funds to make these studies relatively inexpensive. We could potentially measure other pollutant levels of interest to PacifiCorp at the same time, such as Hg, to quantify any differences between baseline coal firing and co-firing with the two different biomass fuels. We would also quantify LOI levels in flyash, as well as particle size distributions and elemental composition.

All of this information could be obtained in advance of the co-firing demonstration, and could provide guidance for test plans with the full-scale demonstration.

Task 5. Air Quality Assessment of Biomass Co-firing ***(UofU)***

One motivating factor for use of biomass from forest thinning operations is the perceived reduction in particulate matter pollution due to large-scale forest fires in overgrown areas, or from open burning of slash piles of cleared forest materials. This task will assess the environmental impact of displacing coal by burning this biomass in a controlled manner at the Hunter plant, as opposed to open burn or uncontrolled forest fires. Assessment will be made of the relative impact on particulate matter emissions, regional haze, CO_2, VOC, and NOx emissions, air toxics, or other environmental considerations.

The assessment will also consider the following life-cycle stages: extraction, transport, and combustion of the coal; harvesting, transporting, processing, and combustion of the biomass; and combustion of biomass by controlled burns. An overall evaluation of the differences in greenhouse gas emissions and net energy return will also be included.

Project Schedule:

Estimated timelines for each task are shown in the table below. The schedule assumes that the co-firing demonstration at the Hunter Plant would occur sometime in Q5 or Q6 of the program. The schedule can be flexible, to accommodate the needs and objectives of the program.

	Task Description	**Q1**	**Q2**	**Q3**	**Q4**	**Q5**	**Q6**	**Q7**	**Q8**
Task 1	Biomass Fuel Handling and Stability								
Task 2	On-site Measurements During Hunter Demonstration								

Task 3	Analysis of Boiler Operating, Emissions and Performance Data								
Task 4	Combustion Performance Evaluations								
Task 5	Air Quality Assessment of Biomass Co-firing								

Budget Estimates:

Estimated budget totals are provided for each task are provided below.

	Task Description	**UofU**	**BYU**	**Total Cost**
Task 1	Biomass Fuel Handling and Stability	$19,243		$19,243
Task 2	On-site Measurements During Hunter Demonstration	$41,785	$37,800	$79,585
Task 3	Analysis of Boiler Operating, Emissions and Performance Data		$25,100	$25,100
Task 4	Combustion Performance Evaluations	$73,864		$73,864
Task 5	Air Quality Assessment of Biomass Co-firing	$25,200		$25,200
Totals		**$160,092**	**$62,900**	**$222,992**

Appendix B

Cryogenic CO_2 Capture Testing Proposal

Sustainable Energy Solutions

Draft Cryogenic Carbon Capture Demonstration Budget

Overview

This document outlines a draft budget for Rocky Mountain Power's (RMP) involvement in the development of Cryogenic Carbon Capture. There are two phases to the proposed involvement, the first phase involves leveraging an existing test system to mature the technology for scale up to a larger pilot scale. This phase will involve some modifications to the existing system and extended testing at a RMP facility. The second phase will involve designing, engineering, building and testing a larger pilot system at a RMP facility. SES anticipates requesting about $1,174,857 from RMP of the total nearly $6 million project in 2017-2018 for the first phase project and up to $3 million in cost share from RMP of the total $20 million project in 2018-2021. The remaining funding for these projects will come from DOE, and other project partners including Tri-State Generation the Electric Power Research Institute and the National Rural Electric Coop Association.

Objective

This document outlines a rough draft of the budget we anticipate requesting from RMP for support in developing the promising Cryogenic Carbon Capture technology. This technology has many promising features including the potential to reduce the cost and energy requirements of carbon capture vs. existing technologies by more than 50%, easily retrofitting to existing plants, robustly handling contaminants like SOX, NOX, and Mercury, adding no additional water demand to the plant, and providing integrated energy storage for load leveling or improved intermittent renewable management. The purpose of this document is not to provide a detailed technology description, more information can be found at http://sesinnovation.com/.

The proposed budget is divided into two phases. The first phase leverages an existing field demonstration system as part of a proposed DOE project to mature the technology and gather critical information in preparation for a scale-up. This first phase will involve several project partners including SES, EPRI, Tri-State, and DOE. The second phase will be a collaborative project between SES, DOE, RMP and others to scale up the technology and demonstrate it at (5-10 MWe). Both of these phases represent significant steps in maturing the Cryogenic Carbon Capture Technology and preparing it for full-scale deployment by 2025.

Field Demonstration Phase

This phase involves improving and development of some key aspects of the technology to increase reliability, efficiency, and scalability of the process. This step also involves extending experimental continuous run times of the current 1 tonne/day demonstration system from about 50 hours to 500 hours in preparation for scale up and bringing cumulative run time up even higher. This step will also involve real-world case studies and refining the techno-economic analysis of the process. We are in agreement with DOE and other stakeholders that this is a critical step for advancing the technology and establishing the scalability and large-scale potential of the technology. Some pictures and diagrams related to this testing are found in the appendix.

The development work will take place during the end of 2016 and 2017 with the field testing being performed in 2018. The appendix contains a summary of the development tasks that will be performed as part of the larger project that will be funded mostly by the US DOE.

The total period of performance for this phase will be about 2.5 years. SES is proposing nine-months of on-site testing at a RMP Plant in Utah starting in 2018. The exact testing dates will be determined later as part of a collaborative pre-run phase and in conjunction with the larger project.

Field Demonstration Phase Budget

A separate proposal has been sent to DOE for the majority of the work required in this phase. While DOE will fund the majority of the development work, some RMP funds are being requested to help with development. Similarly, RMP will pay for the majority of the field testing, but DOE will also contribute a significant portion. The budget below outlines direct costs associated with that development and testing that we will request from RMP this budget of about $1,174,857 will be part of a larger roughly $6 million project funded mostly by DOE and will allow RMP to leverage its money to get a significant return on these research dollars. SES may adjust the scope of the RMP portion of the budget within the larger project if this is deemed beneficial to the overall project. This budget does not include the cost of utilities at the plant, or any modifications required at the plant. We anticipate the cost of connecting to electricity and flue gas will be minimal and don't anticipate needing any additional structural support in place for this small test system. There is a possibility for RMP to get involved to a greater extent in this phase if that is determined to be of benefit.

This budget is divided into a pre-run and development and a field test phase. The pre-run and development phase will begin in the first quarter of 2017 and will involve minor funding of the development work outlined in the appendix, planning with RMP, site visits to potential host sites, hazard and environmental identification and reviews with RMP, sharing of detailed information regarding flue-gas composition, permitting, etc. This phase will also involve pre-run preparations of the skid including any necessary modifications for pre-treatment of the flue-gas, preparing electrical, water, and flue-gas lines of appropriate lengths, and purchase of spare parts and equipment for the anticipated extended runs.

Cryogenic Carbon Capture Demonstration				
	Total	**2017**	**2018**	**2019**
Pre-Run and Development Budget	**$515,700**	$356,557	$159,144	
Field Test Run				
Lodging, M&I Expenses	**$76,190**		$ 76,190	
Transportation	**$17,100**		$ 17,100	
Salaries	**$255,487**		$255,487	
Loading & Transportation	**$7,000**		$ 7,000	
Liability Insurance	**$45,000**		$ 45,000	
Supplies & Consumables	**$0**		$ 0	
Temporary on-site work space	**$20,000**		$ 20,000	
Water Treatment & Disposal	**$10,000**		$ 10,000	
Overhead for Supplies and Travel	**$53,380**		$ 53,380	
Consulting	**$75,000**	$25,000	$25,000	$25,000
Capital Cost Assessment (Scale Up)	**$100,000**			$100,000
Total	**$1,174,857**	$381,557	$668,301	$125,000

Scaled-Up Pilot Phase

Following the Field Demonstration Phase, SES will be prepared to scale up the technology to a 5-10 MWe pilot demonstration. While the objective of the smaller-scale field demonstration phase will be to demonstrate the scalability of the technology, the scaled-up pilot phase will have the objective of showing better energy performance than currently available technology even at a full scale. This phase will involve designing, engineering, and building a new system at a scale that will be a slip stream from an existing plant, but will be commercial scale for many small industrial applications. This project will cost about $20-25 million total and will begin in 2018-2019. The majority of this funding will come from other sources, but SES will be looking for up to $3 million in funding from RMP as a partner in this project.

Appendix

Development Tasks

Task 2.0 – Drying

<u>Objective</u>

The objective of this task is to decrease the energy consumption and CO_2 absorption in the final flue gas drying stages of CCC.

<u>Planned Approach</u>

The Recipient will investigate state-of-the-art adsorption and phase change drying processes as well as alternative drying techniques. The Recipient will explore several approaches theoretically using its in-house software and process analysis system - Thermodynamic Analysis and Design Software (TAD) and Sustainable Thermodynamic Energy Process Software (STEPS), literature available from similar processes, and industrial experience. The Recipient will explore the most promising approach experimentally using the Cryogenic unit-operations bench (CUB) and compare the performance with the theoretical expectation. If necessary, the Recipient will explore some of the other approaches experimentally. The Recipient will strive to achieve agreement between theoretical and experimental analyses in determining the optimal solution.

Task 3.0 – Dissolved Carbon Dioxide

<u>Objective</u>

The objective of this task is to eliminate the accumulation of dissolved CO_2, solid CO_2, and other possible impurities in the CCC process.

<u>Planned Approach</u>

The Recipient will investigate options to mitigate potential heat exchanger fouling. The Recipient will explore each option theoretically using publicly available experimental data sets, its in-house software and process analysis system - TAD and STEPS, literature available from similar processes, and industrial experience. The Recipient will explore the most promising approach experimentally using the CUB, thermodynamic test cell (TTC), and small-scale flow reactor (SSFR) and existing heat exchanger systems and compare the performance with the theoretical expectation. If necessary, The Recipient will explore multiple approaches experimentally. The Recipient will strive to achieve agreement between theoretical and experimental analyses in determining the optimal solution.

Task 4.0 – Solid–Liquid Separation

<u>Objective</u>

The objective of this task is to improve the reliability and performance and to decrease the energy consumption of the solid–liquid separation process.

Planned Approach

The Recipient will investigate several alternative solid–liquid separation operations that could improve this unit operation. The Recipient will explore each alternative theoretically using its in-house software and process analysis system – TADS and STEPS, literature available from similar processes, and especially information from industrial applications of this equipment. The Recipient will explore the most promising approach experimentally using the CUB and the CCC-ECL™ skid and compare the performance with the theoretical expectation. If necessary, The Recipient will explore additional approaches experimentally. The Recipient will strive to achieve agreement between theoretical and experimental analyses in determining the optimal solution.

Task 5.0 – Heat Exchanger Testing

Objective

The objective of this task is to explore the relative merits of the three desublimating heat exchanger designs in a commercial-scale implementation of CCC.

Planned Approach

The Recipient will analyze the previously tested spray tower and fluid bed heat exchanger designs theoretically using its in-house software and process analysis system – TADS and STEPS. The existing versions of these heat exchangers will then be modified or replaced as needed. This also includes theoretical and experimental analyses of the patent-pending dynamic heat exchangers. All heat exchangers that show significant theoretical performance improvements will be tested using the CUB with CO_2-laden light gases. The CCC-ECL™ will provide the test bed if effective testing requires more integrated unit operations than are available in the CUB. All systems will be compared based on efficiency, reliability, and scalability and overall process techno-economics. Additional figures of merit for this task:

1. Footprint
2. Pressure drop
3. Complications to the balance of process

The Recipient will compare the performance with the theoretical expectation. The Recipient will strive to achieve agreement between theoretical and experimental analyses in determining the optimal solution.

Task 6.0 – Instrumentation and Controls

Objective

The objective of this task is to extend the skid testing time through improved controls, instrumentation, and unit operations.

Planned Approach

The Recipient will modify the CCC-ECL™ skid to implement measurements and controls that can be used to improve several aspects of the process, including:

1. solids loading in the slurry,
2. CO_2 content in the melter, and
3. pressure drop across the solids separator into the melter.

The Recipient will implement additional controls and measurement points as necessary to provide as complete automation as possible and to provide the data needed for detailed comparisons and forensic analysis with process simulation software. Additional figures of merit specific to this task include:

1. amount of operator attention/intervention required
2. ability to follow flow transients and upsets

Task 7.0 – Light-Gas Dispersal

Objective

The objective of this task is to explore issues with light-gas dispersal when the gas temperature is near room temperature.

Planned Approach

The Recipient will investigate several options for managing the light gas stream produced by the CCC process. The Recipient will explore each option theoretically using its in-house software and process analysis system – TADS and STEPS, and literature available from similar processes. The Recipient will explore the most promising approach experimentally using the CUB and compare the performance with the theoretical expectation. If necessary, the Recipient will explore some of the other approaches experimentally. The Recipient will strive to achieve agreement between theoretical and experimental analyses in determining the optimal solution.

Task 8.0 – Multi-Pollutant Capture

Objective

The objective of this task is to develop models that describe CCC capture of pollutants other than CO_2 and to validate these models with experimental data.

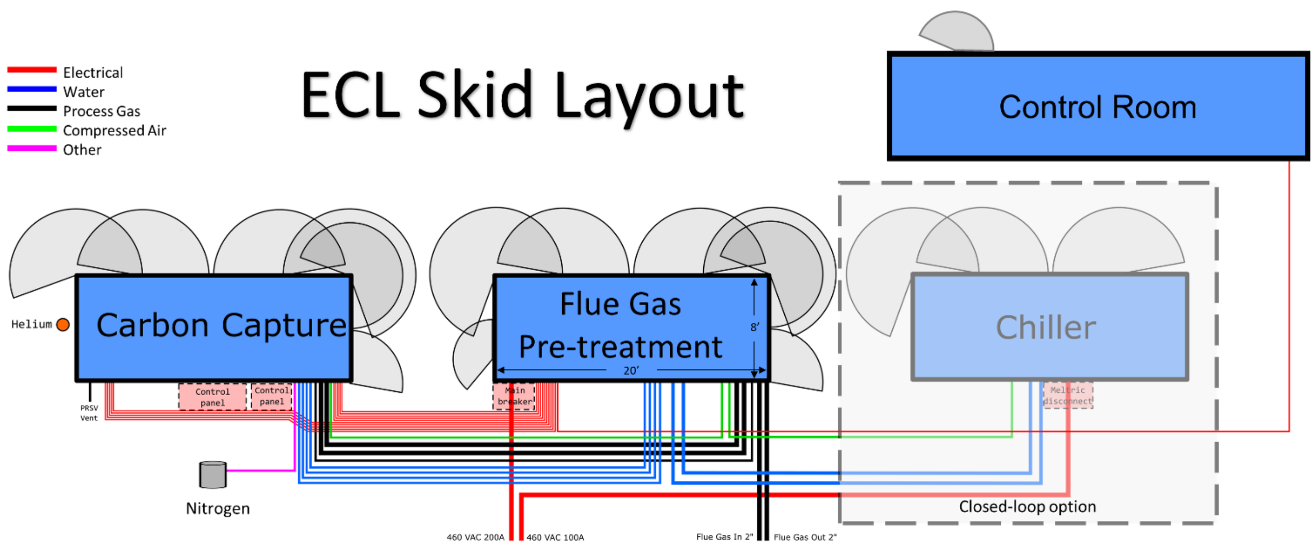
Planned Approach

The Recipient will develop predictive capability for the fate of sulfur dioxide (SO_2), nitrogen oxide (NO), nitrogen dioxide (NO_2), mercury (Hg), particular matter particles that are 2.5 to 10 micrometers in diameter (PM_{10}), particulate matter particles that are 2.5 micrometers in diameter or smaller ($PM_{2.5}$), and hydrogen chloride (HCl) that is verified by experimental measurements using the equipment discussed below and existing analyzers. The Recipient does not possess analyzers, nor does the Recipient believe analyzers exist anywhere, that can make on-line Hg measurements at the levels Hg should occur in the anticipated outlet stream. Even accumulation measurements have fallen short of detecting Hg. Therefore, the Hg data will be largely theoretical or extrapolations of higher concentration data.

The Recipient's analyses will be based on modifications to the exiting in-house process modeling software. Additionally, the Recipient will use a sub-Recipient to develop Aspen models to facilitate communication of results. Experimental data, which will include data from the Recipient's unit operations bench CUB and possibly the small-scale flow reactor at the sub-Recipient's facilities, will validate the analyses. Analyzers will include gas chromatograph (GC), mass spectrometer (MS), Fourier transform infrared spectroscopy (FTIR) spectrometer, nondispersive infrared sensor (NDIR) systems for composition and a Coriolis meter for determining solids loading in the slurry. These systems will provide species composition of the liquid and vapor phases, including possibly two liquid phases, at conditions of interest to the process. The solid phase is assumed to be pure CO_2 and has not yet been reliably sampled under pressurized, cryogenic conditions. It is not clear that solid sampling is necessary, but a measure of the amount of solids would be beneficial. The Recipient anticipates developing thermodynamic expressions for the multi-phase, multi-component analyses and chemical kinetic expressions for some of the gas species. The Recipient has already established miscibility gaps under some conditions in the solid–liquid-liquid-vapor hydrocarbon-CO_2 liquid system near the CO_2 melting point and pressure-sensitive kinetic constraints in the NO (but not NO_2) and possibly the SO_2 capture rates. These behaviors illustrate the potential complexity of both the thermodynamic and kinetic behavior of these systems.

Pictures and Diagrams

Pictures of Field Demonstration Unit and Diagram of 3-skids that house the field demonstration unit in addition to a mobile, temporary on-site work space.



Q&A from Previous Email

1. A brief description of what SES next development/pilot test steps would be to advance the technology?
    a. There are two development steps that we would like Pacificorp to consider:
        i. The near term step involves improving some key aspects of the technology to increase reliability, efficiency, and scalability of the process. This step also

involves extending experimental continuous run times of the current 1 tonne/day demonstration system from about 50 hours to 500 hours in preparation for scale up and bringing cumulative run time up even higher. This step will also involve real-world case studies and refining the techno-economic analysis of the process. We are in agreement with DOE and other stakeholders that this is a critical step for advancing the technology and establishing the scalability and large-scale potential of the technology.

ii. The following development step will be a 5-10 MWe pilot system that will demonstrate better energy performance than projections for full-scale amine systems and long-term performance and reliability.

2. Time required to perform additional pilot testing
   a. We are currently performing some design modifications and operational optimizations along with some short-term test runs for the current 1 tonne/day system, this will take about 12-months. Following these modifications we would like to perform field tests resulting in a minimum continuous demonstration of 500 hours, and many more cumulative hours of demonstration time. This will involve 6-9 months of testing on-site at a host power plant. All together phase will take about two years to complete.
   b. The 5-10 MWe pilot demonstration system will then take approximately 3 years with about 12-months of engineering and design work, 12-months of construction and fabrication, and 12-months for demonstration. The demonstration time could continue beyond this, but would not be necessary to evaluate the technology.
3. A summary of the costs to perform additional pilot testing to advance the technology?
   a. The modifications and additional testing for the 1-tonne/day system described above will cost about $3.5 million with some of this funding potentially coming from DOE or other sources.
4. The 5-10 MWe pilot project as described above will cost $15-25 million depending on the scope of the demonstration and size of the unit selected. We anticipate that a significant portion of this funding could also come from DOE, but will not be available until late 2018.

5. Physical requirements for the next stage of pilot testing:
   a. The table below outlines physical requirements for both systems:

	Skid-Scale 1-tonne/day system	**5 MWe Pilot Scale System**
Power Requirement	250 kVA peak @ 480 VAC	1.4 MW at 4700 VAC

	200A for the main system 100A for the water chiller	
Water requirements	None (closed loop)	700 GPM at 59 degF (Additional cooling water if temperature is higher)
Facility	None (operated from control room in skid)	TBD
Concrete Pad	Space for 3x 8’x20’ conex shipping containers weighing approximately 17,000 lbs each.	55’x55’ footprint <150 lb/ft^2

BYU:
350 Clyde Building
Provo, UT 84602

phone (801) 422-8616
email larry_baxter@byu.edu

SES:
1489 W 105 N
Orem, UT 84057

phone (801) 850-7091
email: l.baxter@sesinnovation.com

Larry L. Baxter

Education

1983 - 89 Brigham Young University Provo, UT

Ph.D. Chemical Engineering (major)

- Dissertation title: Turbulent Transport of Particles
- Outstanding Graduate Student Program at Sandia National Laboratories' Combustion Research Facility (6 months)

1977-78, 1980-83 Brigham Young University Provo, UT

BS Chemical Engineering (major), Chemistry (minor), Mathematics (minor) – graduate with high honors

- Kimball scholar (most prestigious academic scholarship offered at BYU)
- President of American Institute of Chemical Engineers student chapter – recipient of outstanding student chapter award
- Member of Tau Beta Pi and Sigma Xi

Professional experience

2000-present Brigham Young University Provo, UT

Professor, Chemical Engineering

- J. J. Christensen Professor for Thermochemical Sciences (2000-2005).
- Research focus: sustainable energy systems – includes substantial experimental and theoretical activities.
- $37M (PI) in research funding awarded including SES awards, 27 grad students, 330 UG students, > 100 journal papers, book chapters, encyclopedia articles, etc., 12 patents/patent applications

2007-present Sustainable Energy Solutions, LLC Orem, UT

Cofounder, Technical Director

- Developing carbon capture technology for CO_2-containing effluents that is approximately 50% cheaper and more energy efficiency than leading alternatives, as independently confirmed large international engineering firms and national labs.
- Demonstrated process at power plants at scales up to 1 ton CO_2 per day.

1987-2000 Sandia National Laboratories Livermore, CA

Member/Sr. Member/Principal Member of Technical Staff

- PI for Multifuel Combustor Laboratory – by far most frequently visited laboratory at Sandia's Combustion Research Facility
- Developed world-wide expertise in low-grade fuel experimental and theoretical combustion
- Hosted over 60 long-term visitors

Memberships

- ASME National Nominating Committee (2005-2008)
- Member AIChE (lifetime), ASME (lifetime), and ASTM

Volunteer

- 2 meetings/wk + 1 weekend a month with various youth groups (for 22 years)
- Helped organize 2-year "Introduction to Engineering" course in local high school
- Founding member of Computer Academy, Oakland Technical High School
- Precinct chairman for political party
- Member of lay ecclesiastical leadership

Courses Taught

Undergraduate: Fluid Mechanics, Separations, Career Skills, Freshman Seminar, Unit Operations Lab, Energy Engineering, Nuclear Engineering, Statistics for Engineers

Graduate: Combustion, Directed Studies (review of graduate thermodynamics, kinetics, and transport), Writing, Statistics for Engineers, Seminars

Recent Awards

Year	*Organization*	*Award*	*Citation*
2005	Western States Catalysis Club	1st Place Best Paper Award	Guo, X. C. Bartholomew, W. Hecker, and L. Baxter, Field and laboratory results of SCR deactivation suring low-rank coal and biomass-coal cofiring combustion, Feb, 2004
2005	Combustion Institute	Bernard Lewis Fellowship	Sustainable Energy and Biomass Combustion Visiting Lecturer Fellowship
2005	BYU College of Engineering and Technology	Outreach Award	UG Student-selected Education Award – College Level
2006	BYU College of Engineering and Technology	Outstanding Faculty Award	College/department-selected award – one per department
2008	BYU	Wesley P. Lloyd Outstanding Graduate Educator	University-wide award given annually to one faculty member for outstanding graduate education (course work, research, and thesis advising)
2008	Electric Power Conference	Invited US Keynote Speaker – Biomass Cofiring	Invited US speaker to international colloquium on biomass utilization
2008	American Association for the Advancement of Science	Invited Keynote Speaker – Gasification	Invited US speaker to international conference
2009	Brigham Young University College of Engineering and Technology	Outstanding Researcher	College-wide award for research accomplishments – one in the college
2009	Utah Technology Council	Innovation Award	1st place state-wide competition for innovative small businesses in energy
2009	Stoel-Rives	Concept to Company	2nd place state-wide competition for innovative small businesses
2009	Canadian Research Council	Keynote Speaker	Renewable Energy Options for Biomass
2010	Brigham Young University	Karl G. Maeser	Extraordinary research and creative work (campus wide)
2010	Korean Government	Keynote Speaker	Green Energy Conference (only US keynote speaker)
2013	Province of Alberta, Canada	DB Robinson Lecturer	Provincial award given to one person each year for contributions to engineering
2016	Utah Valley Magazine	Fab 40 Recipient	
2016	Edison Award (Edison Universe)	Gold (highest award, 1 given per category per year)	Cryogenic Carbon Capture™ nearly eliminates all emissions from fossil-fueled power plants at half the cost of alternatives while enabling greater adoption of solar and wind through built in, grid-scale energy storage.

Appendix C

CarbonSAFE Proposal

University of Utah

CarbonSAFE Rocky Mountains Phase I: Ensuring Safe Subsurface Storage of CO_2 in the Intermountain West

The Rocky Mountains of the western U.S. (Figure 1) contain and produce over 50% of all coal in the country (U.S. Energy Information Administration, 2014). Coal-fired power plants dominate the Rocky Mountain region (Figure 2), and that coal-power provides over **XX** GW of electricity for the intermountain west. Natural gas prices are low in 2016, but extensive pipeline networks will be required for switching fuels from coal to natural gas; and, prices for natural gas may not remain low. For the time being, perhaps decades to come, coal will be the least expensive option due to existing plants and coal transport systems, and extensive coal resources in the Rocky Mountain states.

Figure 1. Outline (red shade) of the Rocky Mountains in the western U.S. The focus of this proposal are power plants depicted in Figure 2, with the Hunter Plant as the prime example and case study site.

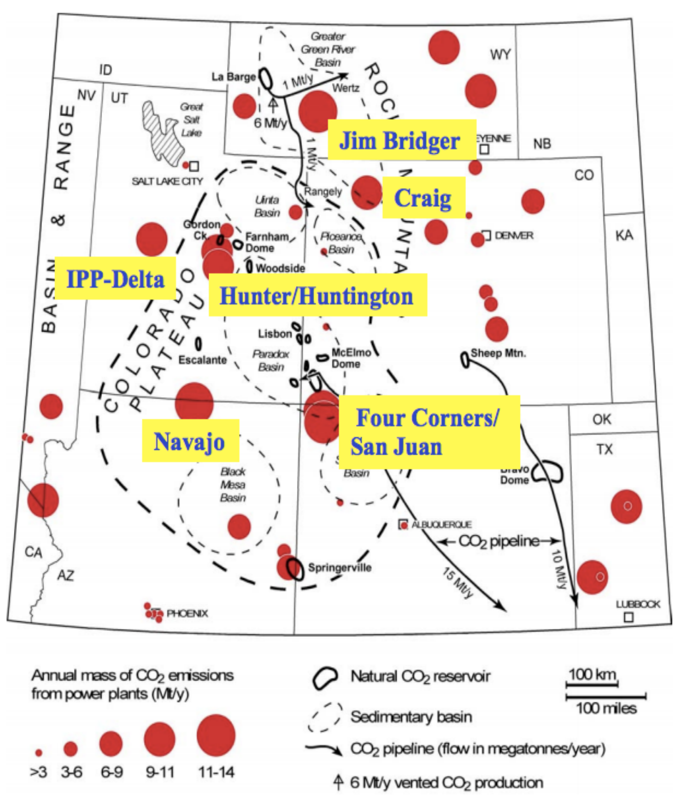


Figure 2. Location of major sources of CO2 emissions from fossil fuel power plants in the Southern Rocky Mountains-Colorado Plateau, with size of the red dots proportional to emissions (in millions tons/year, after Hovorka, 1999). The six largest power plant sites are labeled, including the Hunter Power Plant (near the Huntington Plant, also owned and operated by PacifiCorp and Rocky Mountain Power). Source of graphic: PacifiCorp, 2003.

CarbonSAFE Rocky Mountains Phase I will form of a CCS coordination team capable of addressing regulatory, legislative, technical, public policy, commercial, financial, and other challenges specific to commercial-scale deployment of CO_2 storage for both existing coal-fired power plants in the Rocky Mountain states as well as new plants powered either by coal or natural gas. CarbonSAFE Rocky Mountains Phase I will review and assert the best storage targets for power plants in the region. The project team will develop an optimized plan based on an operating power plant in central Utah, the Hunter Plant near Castle Dale, Utah, a 1.3 GW power plant owned and operated by PacifiCorp and Rocky Mountain Power. The plan will compare and contrast the range of possible injection sites and storage reservoirs, and identify those permutations with minimum risk, maximum storage efficiency, and minimum cost. The plan will include but not be limited to a strategy that would enable an integrated capture and storage project that is economically feasible and publicly acceptable. The CarbonSAFE Rocky Mountains Phase I CCS coordination team will conduct a high-level technical sub-basinal evaluation for potential storage sites near the Hunter plant. A major hypothesis of this proposal is that the optimum storage site for the Hunter plant is the power plant site itself, which would minimize CO_2 transport costs and optimize regulatory planning. However, all practical storage (injection) sites will be identified and compared using a state-of-the-art systems analysis of competing costs as well as regulatory and technical requirements including permitting, capture, compression, transport, injection and monitoring.

The primary outcome of the CarbonSAFE Rocky Mountains Phase I project will be a template protocol for existing and future coal-fired and natural-gas-fired plants in the Rocky Mountain states, with PacifiCorp's Hunter Plant as the representative example of a typical generating station in the Rocky Mountain west.

CarbonSAFE Rocky Mountains Phase I Team and Roles

PacifiCorp	Plant Operator and Power Sector Requirements
Utah Geological Survey	Geologic Characterization
New Mexico Tech	Seismic and Geologic Characterization
Los Alamos National Lab	Systems Analysis (Economic-Technical)
Sandia National Lab	Caprock Characterization
Schlumberger Carbon Services	Injection/Monitoring Well Design and Risk Assessment
University of Utah	Project Management, Simulation and Risk Assessment
University of Utah Law School	Legislative and Other Policy Requirements
Utah Department of Env. Quality	UIC and Other Permitting Requirements
Stakeholder Advisory Board (Under Assembly)	Advice on Non-technical CCS Requirements and Public Relations

References

U.S. Energy Information Administration, 2014, Annual Coal Report 2014, full text downloadable at http://www.eia.gov/coal/annual/pdf/acr.pdf.

PacifiCorp, 2003, http://www.pacificorp.com/content/dam/pacificorp/doc/Environment/Stakeholder_Groups/IGCC_1.pdf.

BRIAN J. O. L. MCPHERSON

Department of Civil and Environmental Engineering
University of Utah
Salt Lake City, Utah 84112
Email: b.j.mcpherson@utah.edu

EDUCATION and TRAINING

Ph.D. in Geophysics, *1996*, University of Utah, Salt Lake City.
Dissertation: *Three-Dimensional Model of the Geologic and Hydrodynamic History of the Uinta Basin, Utah: Analysis of Overpressures and Oil Migration*.
Advisors: David S. Chapman (University of Utah) and John D. Bredehoeft (USGS)
M.S. in Geophysics, *1992*, University of Utah, Salt Lake City,
Thesis: *Geothermal Analysis of the Powder River Basin, Wyoming*
Advisor: David S. Chapman
B.S. in Geophysics, *1989*, University of Oklahoma, Norman
Senior Thesis: *Annealing of etchable fission-track damage in F-, OH-, Cl- and Sr-apatite*
Advisor: Kevin D. Crowley

RECENT APPOINTMENTS
USTAR Professor of Civil and Environmental Engineering*, August, 2006 - Present***,** Department of Civil and Environmental Engineering, University of Utah (faculty post endowed by USTAR, the Utah Science, Technology and Research initiative).

TEN RELATED PUBLICATIONS

Dai, Z, R Middleton, H Viwanathan, J Fessenden-Rahn, J Bauman, R Pawar, S-Y Lee, and *B McPherson*. **2014**. "An integrated framework for optimizing CO2 sequestration and enhancing oil recovery." **Environmental Science and Technology Letters**, 1:49-54, American Chemical Society, http://pubs.acs.org/doi/abs/10.1021/ez4001033.

Tian, H., F. Pan, T. Xu, and *B.J. McPherson*, **2014**. Impacts of hydrological heterogeneities on caprock mineral alteration and containment of CO2 in geological storage sites. **International Journal of Greenhouse Gas Control,** 24: 30–42, http://dx.doi.org/10.1016/j.ijggc.2014.02.018.

Moodie, N., *McPherson, B*., Lee, S., and Mandalaparty, P., **2015**, Fundamental analysis of heterogeneity and relative permeability on CO2 storage and plume migration, **Transport in Porous Media, 104(2): 2-26***,* http://dx.doi.org/10.1007/s11242-014-0377-5.

Lee, S. J., *McPherson, B. J.,* Vasquez, F. G., **2015**, Leakage pathway estimation using iTOUGH2 in a multiphase flow system for geologic CO2 storage, **Environ Earth Sci** (2015) 74:5111-5128, http://dx.doi.org/10.1007/s12665-015-4523-3.

Han, W. S., *McPherson, B.J.*, **2009**, Optimizing geologic CO2 sequestration by injection in deep saline formations below oil reservoirs. *Energy Conversion and Management*, Vol. 50, No.10, 2570-2582, doi:10.1016/j.enconman.2009.06.008.

White, M.D., *B.J. McPherson*, R.B. Grigg, W. Ampomah, M.S. Appold, **2014**, Numerical Simulation of Carbon Dioxide Injection in the Western Section of the Farnsworth Unit, **Energy Procedia**, Volume 63, 2014, Pages 7891-7912, ISSN 1876-6102, http://dx.doi.org/10.1016/j.egypro.2014.11.825.

McPherson, B. J. O. L. and Sundquist, E. T., **2009**, editors, Carbon Sequestration and its Role in the Global Carbon Cycle, AGU Monograph Series, Publisher: American Geophysical Union, Washington, D.C., doi:10.1029/2009gm01308.
Weon Shik Han and *Brian J. McPherson*, **2008**, Comparison of Two Different Equations of

State for Application of Carbon Dioxide Sequestration, Advances in Water Resources, v. 31, p. 877–890, http://dx.doi.org/10.1016/j.advwatres.2008.01.011.

Han, Weon Shik, *McPherson, B.J*., P.C. Lichtner, Wang, F.P., **2010**, Evaluation of CO2 trapping mechanisms at the SACROC northern platform, Permian basin, Texas, site of 35 years of CO2 injection. American Journal of Science, 310, 282-324, doi:10.2745/04.2010.03.

Heath, J. E., Dewers, T. A., *McPherson, B. J. O. L*., Petrusak, R., Chidsey, T. C., Rinehart, A. J., and Mozley, P. S., **2011**, Pore networks in continental and marine mudstones: Characteristics and controls on sealing behavior, Geosphere, 7, 429–454, doi: 10.1130/GES00619.1.

SYNERGISTIC ACTIVITIES

Dr. McPherson is Director of the Southwest Regional Partnership on Carbon Sequestration. Dr. McPherson formed the Southwest Partnership project in 2003, one of seven regional partnerships funded by the U.S. Department of Energy to evaluate the science and technology of storage of atmospheric carbon in underground geological formations and in surface soil and vegetation. More information about the project is accessible online.

Appendix D

Application/Feasibility for Regional/Commercial Use of CO_2 for Enhanced Coal Bed Methane Recovery University of Utah -

Earth Geosciences Institute

Application/Feasibility for Regional/Commercial Use of CO2 for Enhanced Coal Bed Methane Recovery (Study)

Department of Chemical Engineering and Energy & Geoscience Institute
University of Utah

Synopsis:

Long-term sequestration is a desirable complement to above ground technologies for improving plant efficiency and highgrading carbon dioxide streams. CO2 has a preferential adsorptive affinity to methane that is present in coal below ground. If carbon dioxide is injected into unmineable coal seams in Utah, it preferentially displaces (and allows production) methane and replaces the methane within the coal. Methane is produced from - and carbon dioxide is sequestered in - deep, unmineable coals.

Objectives:

Evaluate opportunities in Carbon and Emery Counties to:

1. Use CO_2 or flue gas beneficially to produce natural gas from coalbed seams.
2. Concurrently, permanently sequester the carbon dioxide or flue gas that has been locally generated.

Background:

Coalbed methane has been a viable natural gas production string since the 1980s. Unlike conventional natural gas stored by compressibility in pore space, methane in coal is physically adsorbed to the surface of the coal. Following production of the water that is in the cleats in the coal, reduction in pressure will encourage the methane to desorb and be produced. Hydraulic fracturing is often required to provide conductive pathways for this desorbed gas to move to the wellbore. This is shown by the isotherm in Figure 1. That figure shows a reduced adsorptive capacity for methane as the pressure in the reservoir is reduced. This means that as the reservoir pressure depletes during production, methane will be produced.

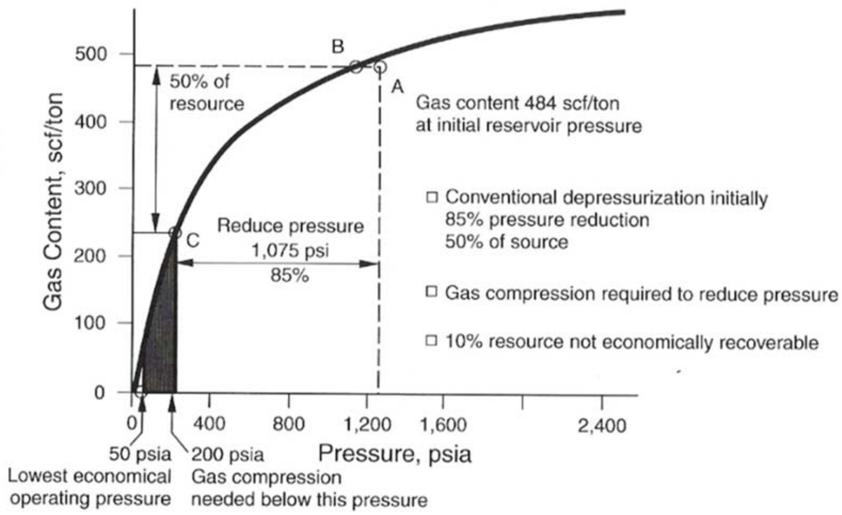


Figure 1. This is an example of an isotherm for methane stored by adsorption in a typical coal. As can be seen by the name the temperature is constant. In fact, the adsorptive potential reduces as temperature increases. At constant temperature 1) the amount of methane adsorbed increases as the pressure (representing the reservoir pressure) increases, and 2) reciprocally, as the pressure decreases methane will be produced because the reservoir's adsorptive capacity is reduced. Notice that a significant quantity of methane remains (and will not be produced) at lower pressures. (courtesy of Halliburton)

The bulk of the production requires significant drawdown (and ultimately depletion). In fact, the shaded area in Figure 1 schematically denotes the pressure in the wellbore below which artificial lift (pumping or compression) would need to be implemented to recover the substantial volumes of remaining gas – with attendant costs. Figure 2 shows an example of declining production in a prominent Utah coalbed methane play. Other examples throughout the state and the country are similar. One initial question to keep in mind is *"How can this residual gas be recovered more economically?"*

Insight into possible methods can be gained by comparing the adsorptive capacity of different gases. Figure 3 demonstrates that carbon dioxide has a greater affinity (more gas will be adsorbed at a particular temperature and pressure) than methane. In fact, carbon dioxide will displace methane from coal. This means that if you inject carbon dioxide into a methane-saturated coalbed, the carbon dioxide will be adsorbed and methane desorbed/produced.

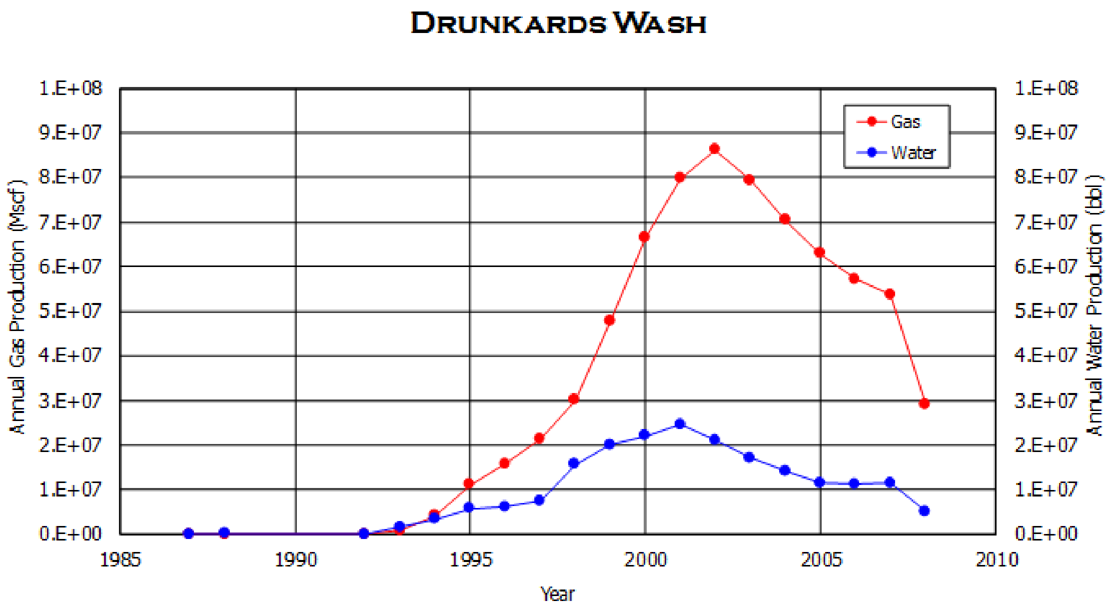


Figure 2. Quarterly production data from the Drunkard's Wash field in Carbon County Utah. There are various reasons for the decline some of them related to depletion, some related to gas pricing. Regardless, there is methane remaining in-situ.

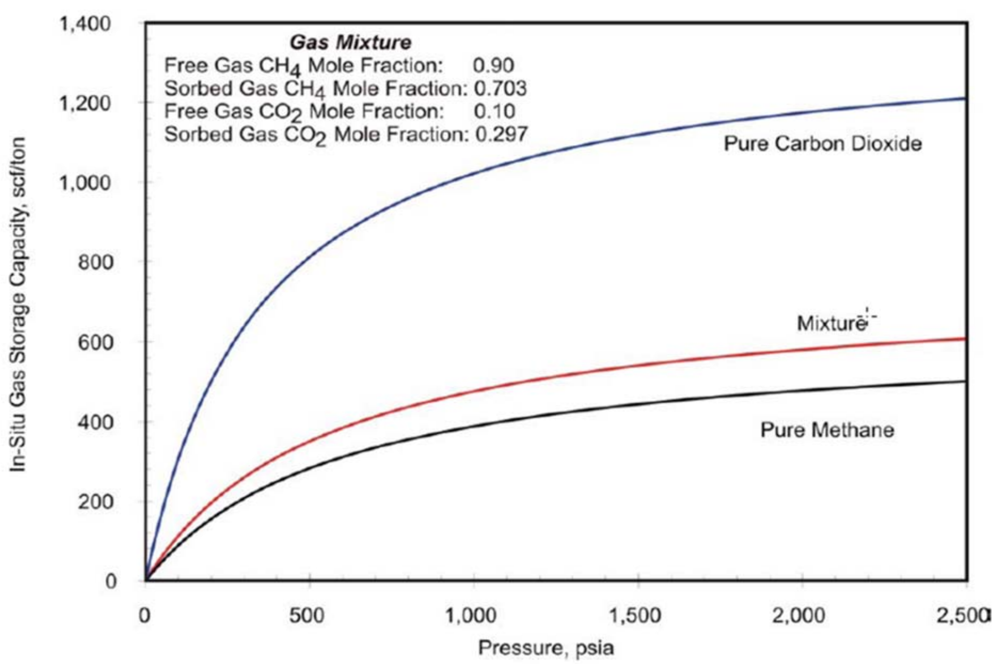


Figure 3. Isotherms on nominally equivalent samples where the sorbates varied from methane to carbon dioxide. A blend falls between the two extremes. Two features stand out. The first is that substantially more carbon dioxide is adsorbed in this coal than methane. The second aspect is that there is a tremendous affinity for carbon dioxide at low temperatures.

Recognizing the potential for carbon dioxide replacing methane in situ, pilot testing was undertaken several decades ago. For example:

- Burlington Resources (ConocoPhillips) carried out long-term CO_2/N_2 Injection into the Allison and Tiffany Units, San Juan Basin. Figure 4 shows data from the Allison pilot.
- Nitrogen functions somewhat differently than carbon dioxide. The process is methane stripping (partial pressure of methane reduced causing desorption to achieve partial pressure equilibration). Since nitrogen is not adsorbed, there is likely to be more rapid breakthrough of the injected gas from the injection well into the production well. This is undesirable because the pathway developed is a short circuit and less of the reservoir is exposed to the injectate (recovery of the methane is reduced. Data from the nitrogen pilot in the Tiffany unit are shown in Figure 5.
- Carbon Dioxide results in methane displacement by preferential adsorption.
- BP (Amoco) has strong patent positions (may have expired)
- ARC Alberta Innovates)– Fenn-Big Valley, Alberta; and China
- Southwest Partnership Fruitland Coal injection project
- Likely more recent pilots and testing programs.

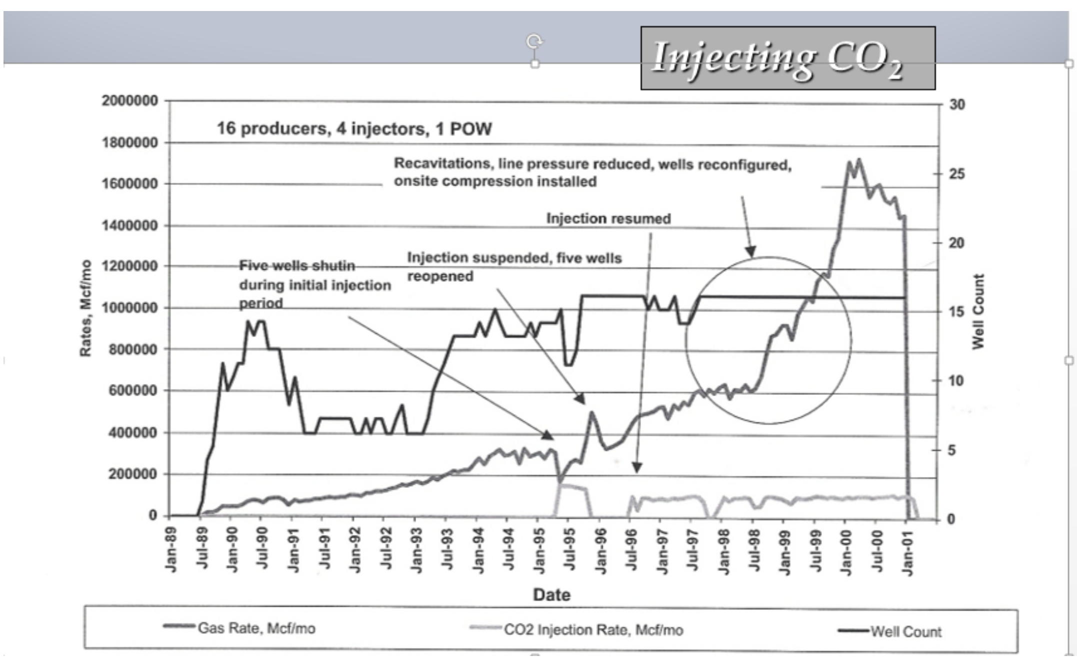


Figure 4. Over the course of 5 years, 4.7 Bcf of CO_2 were injected and there was an incremental recovery of 1.5 Bcf of natural gas. These data are from the Allison Unit and the $CO_2:CH_4$ ratio was 3.1:1.0.

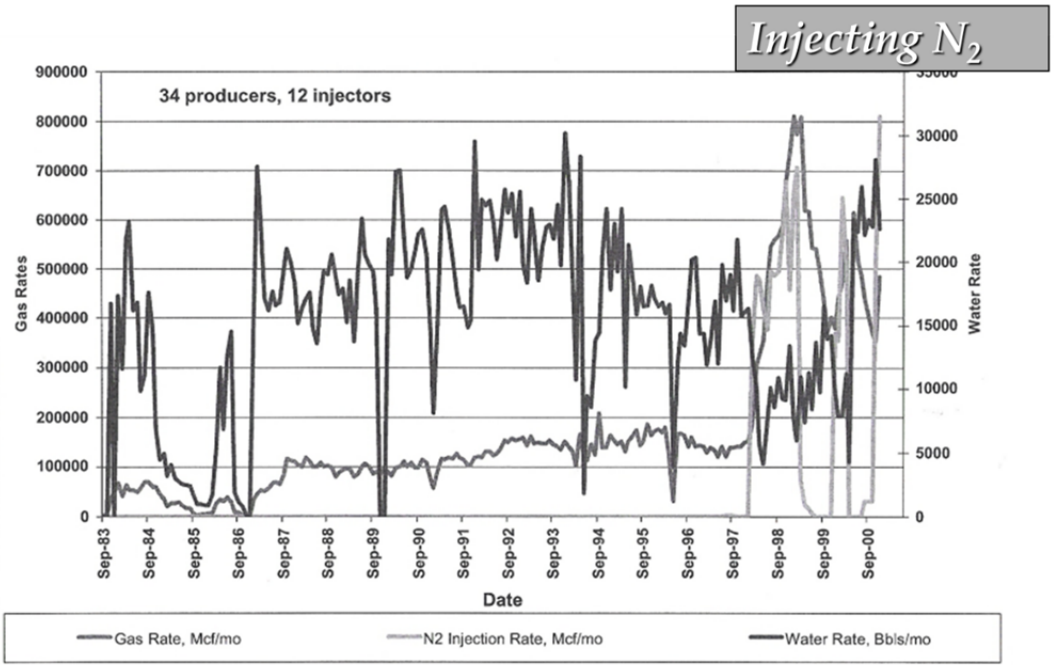


Figure 5. Nitrogen was injected into the Tiffany Unit. N2 injected over 4 years. There was a fivefold increase in methane production but early breakthrough occurred in 11 or 12 wells.

Challenges:

It seems that there is an elegant way – by injecting CO2 – to displace residual methane and sequester the CO2. This is true but there are some hurdles. The major hurdles are:

1. **Volumetrics:** The available subsurface volume will need to be assessed.
2. **Swelling:** CO2 adsorption causes the coal matrix to swell. Matrix swelling is accommodated by reduction in the cleat dimensions. The cleats provide permeability. The matrix swell therefore reduces the cleat permeability. Override may follow – the CO2 going elsewhere in a vertical setting. There are numerous possible mitigations to this and it is certainly not an insurmountable problem.
3. **Sequestration:** The CO2 in tertiary recovery programs like this is not permanently sequestered. If there is a wellbore penetration or a seal failure, it can be released. Hence, this activity needs to be hybridized with technology to permanently sequester the CO2. These include WAG stages (water after gas) where water is injected to inhibit or restrict desorption, injecting treated water

to encourage precipitation and cementation of cleat systems, and other methods.

4. **Induced Seismicity:** All injection zones will need to be certified to de-risk the occurrence of induced seismicity.
5. **Breakthrough:** The efficacy and sequestration potential of flue gas is uncertain.

Opportunities

A multi-task study program would be relevant. They can be sequential (some could logically be concurrent) and there would be logical Go-NoGo milestones.

Task	Description	Duration (person-months)	Amount
1	**Resource Evaluation:** From public domain sources (UGS data in particular) summarize the possible injection locations, capacities, advantages and challenges	6	$25,000
2	**Bench Scale Demonstrations:** Using CO2, flue gas (and N2 alone) carry out bench scale demonstration measurements to assess sorptive capacities and permeability modification in representative Utah coals.	12	$75,000
3	**Permanent Sequestration:** How can CO2 be more permanently be sequestered in coal seams?	12	$75,000
4	**Economic Viability:** First order estimate of economics of sequestration offset partially by methane production.	6	$25,000
5	**Simulations:** Based on Tasks 1 through 3 to confirm storage capacity	12	$50,000
6	**Pilot Program:** Five spot injection and monitoring program	TBD	TBD

Assessment of Benefits

This study will

1. Provide a complete **technical, economic and environmental study** on the costs and benefits including a specific CO2 source (power plant) with transportation to a specific coal bed methane source.

2. Determine whether **local coalbeds are conducive** to enhanced CO_2 methane recovery
3. Propose new technologies for **improving injection efficiency** and attempt to identify supplementary funding opportunities for field scale evaluation.
4. Confirm that the risk of **induced seismicity will be reduced** in comparison to carbon dioxide injection into deep saline aquifers (without "voidage/injectate" volume compensation).

Assessment of Costs

This study will provide cost estimates to install enhanced recovery injection and production facilities.

Assessment of Technical Challenges

This study will assess:

1. **Effectiveness of methane capture and purification** required of the gas stream prior to injection. If flue gas can be tolerated, there could be some advantages. The advantage being not necessarily that NOx can be sequestered but that the presence of nitrogen may enable moving CO_2 deeper into the coal (speculation at this point).
2. The true **capacity** for carbon dioxide storage in coals in-situ has not been established. Continuous injection below fracturing pressure may not be a realistic scenario. The potential for refined injection procedures including fracturing, water stages, and in particular horizontal wells, might alleviate the mismatch between a necessarily large and constant CO_2 supply and the sequestration volume in the coals.
3. **Seal integrity and permanence of sequestration** are always a concern for subsurface storage. Effective monitoring is required. Injection of water, particularly calcified water after periodic injection of carbon dioxide could afford mineralization and more permanent sequestration. Predicting, monitoring, and mitigating leakage is a common theme of all subsurface storage operations.
4. **Coal swelling** impacts on coal-bed methane production. The experience in the past has been that chemisorption and associated swelling have reduced cleat permeability. Tactical changes in the injection strategy – multiple horizontal wells, with water diversion stages and pressures above fracturing are envisioned to effectively provide conformal injection and storage of CO_2 through the bulk of the reservoir.
5. **Logistics and feasibility of piping CO_2** to injection equipment from a plant environment to the injection facility.
6. **A reviewer proposed a very perceptive question. "**Is this within the general scope of the STEP funding? This is a very large and broad area for R&D. Will having a

study done with these funds make much difference in the long run to the advancement of adsorption or methane recovery?" The point is well taken and a focused study can only accomplish so much. However, the physics of adsorption are fairly well understood, as are the limitations that have been demonstrated by previous pilots. The goal is to assess storage capacity and opportunities. To put this in context, horizontal drilling changed the perspective of shale gas and oil production. Similar arguments might be made for carbon dioxide sequestration in coal. Additionally, non-traditional injection technologies (injection above fracturing pressure, sequential injection of water, mineralization encouragement and others) are likely to dramatically increase storage capacity.

Milestones:

Milestone	**Date from Announcement of Award/Funding Available**
Contracts with PacifiCorp complete	1 month
Commence Task 1 (Resource Evaluation)	1 month
Draft Test Program Submitted	1 month
Revised Program Submitted Formalizing Experimental Matrix and Other Research Tasks	1.5 months
Annual Report I Presented/Submitted	13 months
Annual Report II Presented/Submitted	25 months
Annual Report III Presented/Submitted	37 months
Concept for Future In-Situ Pilot Testing	43 months
Final Report Presented/Submitted	49 months
Initiation of Proposal and Fund Raising for Future Five Spot Pilot Plant	49 months or sooner if appropriate

Summary

Since October 2009, John McLennan has been an Associate Professor in the Department of Chemical Engineering at the University of Utah. He is the ad hoc director of the Masters of Science degree program in Petroleum Engineering; a degree awarded through the Department of Chemical Engineering at the University of Utah. He has been a Senior Research Scientist at the Energy & Geoscience Institute and a Research Professor in the Department of Chemical Engineering at the University of Utah, since January 2008. He has a Ph.D. in Civil Engineering from the University of Toronto, in 1980.

He has more than thirty-five years of experience in geomechanics with petroleum service and technology companies. He worked nine years for Dowell Schlumberger in their Denver, Tulsa and Houston facilities. Later, with TerraTek in Salt Lake City, Advantek International in Houston, and ASRC Energy Services in Anchorage, he worked on projects concerned with coalbed methane recovery, rock mechanical properties determinations, produced water and drill cuttings reinjection, as well as casing design issues related to compaction. Recent work has focused on optimized gas production from shales and unconsolidated formations, fluid-rock interactions, geothermal energy recovery, in-situ microbial generation of natural gas and high temperature rock testing.

Experience

October 2009	**USTAR Associate Professor,** Department of Chemical Engineering, University of Utah and **Senior Research Scientist,** Energy & Geoscience Center, University of Utah
January 2008	**Research Professor,** Energy & Geoscience Institute, Departments of Civil and Chemical Engineering, University of Utah Within the Energy & Geoscience Institute promote geomechanics and fundamental research in unconventional hydrocarbons, and engineered geothermal systems. Within the Department of Chemical Engineering, participate in two RPSEA programs (one on gas production from low permeability sands and one on flow assurance).
2003 - 2008	**Technical Director,** ASRC Energy Services E & P Technology, Anchorage, AK
2001 - 2002	**Executive Vice President,** Advantek International Corporation, Salt Lake City, UT Involved with projects ranging from individual consulting efforts to participation in large consortium projects concerning produced water reinjection, compaction/subsidence and wellbore integrity. Central participant in corporate strategy to consolidate numerical and analytical tools, historical experience, correlations and risk analysis in overall knowledge-based packages for planning, drilling, completing, stimulating and managing reservoirs. Other projects encompass software development; evaluations, predictions, back-analyses and recommendations for exploitation strategies; and formulation of Best Practices.
1989 - 2001	**Executive Vice President,** TerraTek, Inc., Salt Lake City, UT Vice President — 1992-1999, Management of field and laboratory routine and special core analysis, geology, computerized tomography and

rock mechanics investigations for oil/gas, coal and civil construction projects. Supervision of approximately 25 scientists, engineers, technicians and support staff. Coordination of sales, marketing and relevant accounting/project tracking activities. Technical participation in high profile and new venture projects including multiple projects for the Gas Research Institute. Rock Mechanics Short Courses for clients.

Vice President, Engineering Testing and Simulations — 1989-1992
Management of field and laboratory rock mechanics investigations for oil/gas, coal, and civil construction projects.

1987 - 1989 **Program Leader, Rock and Fracture Mechanics,** Dowell Schlumberger Inc., Tulsa, OK

Manage rock and fracture mechanics development effort (4 scientists and 1 technician). Development of technology for production prediction from horizontal wellbores. Development of technology for fracturing and matrix acidizing deviated wellbores (theoretical, numerical and field validation). Supervise upgrade of laboratory testing and analysis capabilities for rock mechanics testing. Large-scale laboratory polyaxial testing for the assessment of deviated wellbore fracturing, acid fracturing and in-situ stress measurement. Interaction with development chemists for design of field-testing for product evaluation. Evaluation of the influence of perforations on hydraulic fracture initiation. Technical review of research efforts on wellbore stability, poroelasticity and fundamental fracture mechanics. Fracture design, back-analysis and trouble-shooting for high-profile field operations. Lecturer in Schlumberger Educational Services Advanced Reservoir Stimulation client schools.

1986 - 1987 **Technical Center Manager,** Dowell Schlumberger Inc., Denver, CO

Manage $1,000,000 customer service laboratory. Provide field support, including laboratory testing, treatment fluid design and formation evaluation for all of Dowell Schlumberger's North American operations. Fracture and acidizing design, back-analysis, trouble-shooting and customer interface for high profile field operations.

1981 - 1985 **Senior Research Engineer, Rock Mechanics,** Dowell Schlumberger Inc., Tulsa OK
Fundamental fracturing research on fluid loss during hydraulic fracturing. Fundamental research on correlation between static and dynamic mechanical properties with application to stress prediction. Develop a pseudo-three-dimensional hydraulic fracturing code, modeling fracture growth and proppant placement. Formation evaluations, treatment designs and optimizations. Dowell Schlumberger internal reports, client confidential reports; and public-domain publications as listed subsequently.

1980 - 1981 **Senior Engineer,** TTI Geotechnical Resources Ltd., Calgary, Alberta Canada
Open two-man Canadian office for U.S. Corporation. Field supervision and data analysis for four hydraulic fracturing stress measurement programs in Canada, and assistance on hydraulic fracturing stress measurements at two localities in the United States. Technical review of fracturing and stability response of oil sands.

EDUCATION

- B.A.Sc. Geological Engineering, University of Toronto, 1974
- M.A.Sc. Civil Engineering (Soil Mechanics), University of Toronto, 1976
- Ph.D. Civil Engineering (Rock Mechanics), University of Toronto, 1980

PUBLICATIONS

1. McLennan, J.D.: "Study and Analysis of Lateral Pressure in Two Granular Materials," M.A.Sc. Thesis, University of Toronto, Dec. 1975.
2. McLennan, J.D. and Roegiers, J-C.: "Stress Conditions Around the Niagara Gorge," Proc. 3rd Symp. Eng. Applications to Solid Mechanics, Toronto, 1976.
3. Roegiers, J-C. and McLennan, J.D.: "Rock Mechanics Problems Associated with Hot Dry Rock Geothermal Energy Extraction," Proc. Hot Dry Rock Geothermal Workshop, Los Alamos Scientific Laboratory, Los Alamos, New Mexico, LA-7470-C, April 1978.
4. Roegiers, J-C. and McLennan, J.D.: Numerical Modeling of Pressurized Fractures, University of Toronto, Department of Civil Engineering, ISBN 0316-7968, Pub 78-08, October 1978.
5. Roegiers, J-C., Thompson, and McLennan, J.D.: "Rock Movements Induced by the Construction of the Hamilton Mountain Trunk Sewer (Stage 4)," Canadian Geotechnical Journal, (1979) 16, 651-658.
6. Roegiers, J-C. and McLennan, J.D.: "Stress Determination at Great Depth of the Geothermal Well on the University of Regina Campus," Report to D.S.S., University of Toronto, Department of Civil Engineering, ISBN 0-7727-7003-4, Pub. 79-12, December 1979.
7. McLennan J.D. and Roegiers, J-C.: "A Synthesis of Hydraulic Fracturing Literature,"' University of Toronto, Department of Civil Engineering, ISBN 0-7727-7004-2, Pub. 79-13, December 1979.
8. McLennan, J.D.: "Hydraulic Fracturing: "A Fracture Mechanics Approach," Ph.D. Thesis, University of Toronto, Department of Civil Engineering, December 1980.
9. McLennan, J.D. and Roegiers, J-C.: "Do Instantaneous Shut-in Pressures Accurately Represent the Minimum Principal Stress," Workshop on Hydraulic Fracturing Stress Measurement, Monterey, CA, December 1981.
10. Roegiers, J-C. and McLennan, J.D.: "Factors Influencing the Initiation Orientation of Hydraulically Induced Fractures," Workshop on Hydraulic Fracturing Stress Measurement, Monterey, CA, December 1981.
11. McLennan, J.D., Elbel, J., Mattheis, E. and Lindstrom, L.: "A Critical Evaluation of the Mechanical Properties Log (MPL) on a Basal Quartz Well in the Caroline Area," 33rd Annual General Meeting of CIM, Calgary, June 1982.
12. Roegiers, J-C., McLennan, J.D. and Schultz, L.: "In-Situ Stress Determinations in Northeastern Ohio," 23rd U.S. Rock Mechanics Symposium, UCLA-Berkeley, August 1982.
13. McLennan, J.D. and Roegiers, J-C.: "How Instantaneous are Instantaneous Shut-in Pressures," paper SPE 11064 presented at the 1982 (57th) SPE Annual Fall Technical Conference and Exhibition, SPE/AIME, New Orleans, LA, September 1982.
14. Roegiers, J-C., McLennan, J.D. and Murphy, D.L.: "Influence of Preexisting Discontinuities on the Hydraulic Fracturing Propagation Process," First Japan-United States Symposium on Hydraulic Fracturing and Geothermal Energy, Tokyo, November 1982.
15. McLennan, J.D., Roegiers, J-C. and Marx, W.P.: "The Mancos Formation: An Evaluation of the Interaction of Geological Conditions, Treatment Characteristics and Production," SPE 11606, Low Permeability Symposium, Denver, 1983.
16. McLennan, J.D., Roegiers, J-C., Marcinew, R.P. and Erickson, D.J.: "Rock Mechanics Evaluation of the Cardium Formation," 34th Annual Meeting of CIM, Calgary, 1983.
17. Schuyler, J. and McLennan, J.D.: "The Interaction of Geology, Mechanical Properties and In-Situ Stresses in Hydraulic Fracturing," Proc. 25th U.S. Symposium on Rock Mechan-

ics, Evanston, IL, June 1984.
18. McLennan, J.D. and Picardy, J.C.: “Pseudo-Three-Dimensional Fracture Growth Modeling,” Proc. 26th U.S. Symposium on Rock Mechanics, Rapid City, SD, June 1985.
19. Detournay, E., McLennan, J. and Roegiers, J-C.: “Poroelastic Constants Explain Some of the Hydraulic Fracturing Mechanisms,” Proc. Unconventional Gas Technology Symposium, SPE 15262, Louisville, KY, May 1986.
20. McLennan, J.D., Hasegawa, H.S., Roegiers, J-C. and Jessop, A.M.: “A Hydraulic Fracturing Experiment at the University of Regina Campus: Geothermal and Seismotectonic Implications,” Canadian Geotechnical Journal, (November 1986) 23, 548-555.
21. Detournay, E., Cheng, A.H.-D., Roegiers, J-C. and McLennan, J.D.: “Poroelastic Considerations in In-Situ Stress Determination by Hydraulic Fracturing,” 2nd International Workshop on Hydraulic Fracturing Stress Measurement, Minneapolis, MN, June 1988.
22. Jeffrey, R.G., Hinkel, J.J., Nimerick, K.H. and McLennan, J.D.: “Hydraulic Fracturing to Enhance Production of Methane from Coal Seams,” Proc. 1989 Coalbed Methane Symposium, University of Alabama/Tuscaloosa, April 1989.
23. McLennan, J.D., Roegiers, J-C. and Economides, M.J.: “Extended Reach and Horizontal Boreholes,” in Reservoir Stimulation, Economides, M.J. and K.G. Nolte, ed., 1989.
24. Economides, M.J., McLennan, J.D., Roegiers, J-C. and Brown, E.: “Performance and Stimulation of Horizontal Wells,” World Oil, 1989.
25. Economides, M.J., McLennan, J.D., Roegiers, J-C. and Brown, E.: “Fracturing of Highly Deviated and Horizontal Wells,” paper 89-40-39 presented at the 1989 Annual Technical Meeting of the Petroleum Society of CIM, Banff, May 28-31.
26. Morales, R.H., McLennan, J.D., Jones, A.H. and Schraufnagel, R.A.: “Classification of Treating Pressure in Coal Fracturing,” 31st U.S Rock Mechanics Symposium, Boulder, CO, June 1990.
27. Detournay, E., Cheng. A.H.-D. and McLennan, J.D.: “A Poroelastic PKN Hydraulic Fracture Model Based on an Explicit Moving Mesh Algorithm,” J. En. Res. Tech.
28. Zheng, Z., McLennan, J.D. and Jones, A.H.: “Pore Volume Compressibilities Under Different Stress Conditions,” 1990 SCA Conference Paper No. 9005, Dallas, TX, August 1990.
29. Khodaverdian, M., McLennan, J.D. and Jones, A.H.: “Spalling and the Development of a Hydraulic Fracturing Strategy for Coal,” Final Report submitted to the Gas Research Institute (GRI) for Contract No. 5087-214-1460, TerraTek Report No. TR 91-111, April 1991.
30. Khodaverdian, M., McLennan, J.D., Jones, A.H. and Schraufnagel, R.A.: “Influence of Near Wellbore Effects on Treatment Pressure in Coal,” 1991 Coalbed Methane Symposium, Tuscaloosa, AL (May 13-16).
31. Khodaverdian, M., McLennan, J.D., Jones, A.H. and Schraufnagel, R.A.: “Examination of Near-Wellbore Effects on Hydraulic Fracturing of Coal,” Proc. 32nd U.S. Rock Mechanics Symposium, July 10-12, 1991, Norman, OK.
32. Mavor, M.J., Dhir, R., McLennan, J.D. and Close, J.C.: “Evaluation of the Hydraulic Fracture Stimulation of the No. 9 Well, San Juan Basin,” Coalbed Methane, (1991) Rocky Mountain Association of Geologists.
33. Zheng, Z., Khodaverdian, M.K. and McLennan, J.D.: “Static and Dynamic Testing of Coal Specimens,” paper SCA 9120, 1991.
34. Economides, M.J., McLennan, J.D., Brown, E. and Roegiers, J-C.: “Performance and Simulation of Horizontal Wells,” in World Oil’s Handbook of Horizontal Drilling and Completion Technology, Gulf Publishing Company, Houston, Texas (1991).
35. Van den Hoek, P.J., Kooijman, A.P., Kenter, C.J., Khodaverdian, M., Hyland, C.R. and McLennan, J.D.: “Size-Dependency of Hollow Cylinder Collapse Strength,” Proc. SPE 1992 Fall Meeting, SPE 24800, Washington, D.C.
36. Khodaverdian M.F. and McLennan, J.D.: “Hydraulic Fracturing Coalbed Methane Reser-

voirs: Obstacles and Solutions," Proc. 1992 International Gas Research Conference, Orlando, FL, November 16-18.

37. Zheng, Z., McLennan, J.D., Jones, A.H. and Spafford, S.: "Pore Volume Compressibility and Permeability of Coal Under Different Stress Conditions," Proc. 1992 International Gas Research Conference, Orlando, FL, November 16-18.
38. Khodaverdian, M.F. and McLennan, J.D.: "Cavity Completions: A Study of Mechanics and Applicability," Proc. 1993 International Coalbed Methane Symposium, Tuscaloosa, AL, May 17-21.
39. Greaves, K.H., Owen, L.B., McLennan, J.D. and Olszewski, A.J.: "Multi-Component Gas Adsorption-Desorption Behavior of Coal," Proc. 1993 International Coalbed Methane Symposium, Tuscaloosa, AL, May 17-21.
40. Olszewski, A.J., Zuber, M.D., Schraufnagel, R.A. and McLennan, J.D.: "Integration of Log, Core and Well Test Data Improves Coalbed Methane Reservoir Evaluation," presented at the 1993 International Coalbed Methane Symposium, Tuscaloosa, AL, May 17-21.
41. Khodaverdian, M.F., McLennan, J.D. and Jones, A.H.: "Hydraulic Fracture Stimulation for Enhanced Recovery of Coalbed Methane," 1994, 8th International Conference of the International Association for Computer Methods and Advances in Geomechanics, Morgantown, WV, May 22-28.
42. McLennan, J.D., Schafer, P.S. and Pratt, T.J.: A Guide to Determining Coalbed Gas Content, Gas Research Institute (1995) Chicago, IL.
43. Palmer, I.D., Vaziri, H.H., McLennan, J.D. and Khodaverdian, M.F.: "Openhole Cavity Completion in Coalbed Methane Wells – Modeling of Field Data," paper presented at the INTERGAS '95, Unconventional Gas Symposium, Tuscaloosa, AL, May 15-19.
44. Palmer, I.D., Vaziri, H.H., Khodaverdian, M.F. and McLennan, J.D., Prasad, K.V.K., Edwards, P., Brackin, C., Kutas, M. and Fincher, R: "Completions and Stimulations for Coalbed Methane Wells," paper SPE 30012 presented at the 1995 International Meeting on Petroleum Engineering, Beijing, China, November 14-17.
45. Palmer, I.D., Vaziri, H.H., McLennan, J.D. and Khodaverdian, M.F.: "Openhole Cavity Completion in Coalbed Methane Wells – Modeling of Field Data," paper presented at the INTERGAS '95, Unconventional Gas Symposium, Tuscaloosa, AL, May 15-19.
46. McLennan, J.D., Carden, R.S., Curry, D., Stone, C.R. and Wyman, R.E.: Underbalanced Drilling Manual, Gas Research Institute, GRI 97/0236 (1997) Chicago, IL.
47. Mitlin, V.S., Lawton, B.D. and McLennan, J.D.: "Improved Estimation of Relative Permeability from Displacement Experiments," paper SPE 39830 presented at the 1998 SPE International Petroleum Conference and Exhibition of Mexico, Villahermosa, Mexico, March 3-5.
48. Vásquez, A.R., Sánchez, M.S., McLennan, J.D., Guo, Q., Portillo, F., Poquioma, W., Blundun, M. and Mendoza, H.: "Mechanical and Thermal Properties of Unconsolidated Sands and its Application to the Heavy Oil SAGD Project the Tia Juana Field, Venezuela," paper SPE 54009 presented at the 1999 SPE Latin American and Caribbean Petroleum Engineering Conference, Caracas, Venezuela, April 21-23.
49. Khodaverdian, M.F., Abou-Sayed, A.S., Ramos, R., Guo, Q. and McLennan, J.D.: "Laboratory Simulation of Liner Loading and Near-Wellbore Permeability Variation in Poorly Consolidated Sandstones," paper SPE 47291 presented at the 1998 SPE/ISRM Eurock '98, Trondheim, Norway, July 8-10.
50. Palmer, I.D., McLennan, J.D. and Vaziri, H.H.: "Cavity-Like Completions in Weak Sands," paper SPE 58719 presented at the 2000 International Symposium on Formation Damage Control, Lafayette, LA, February 23-24.
51. Guo, Q., Dutel, L.J., Wheatley, G.B., McLennan, J.D. and Black, A.D.: "Assurance Increased for Drill Cuttings Re-Injection in the Panuke Field Canada: Case Study of Improved Design," paper IADC/SPE 59118 presented at the 2000 IADC/SPE Drilling Con-

ference, New Orleans, LA, February 23-25.

52. Abou-Sayed, A.S., Guo, Q., McLennan, J.D. and Hagan, J.T.: "Case Studies of Waste Disposal Through Hydraulic Fracturing," paper presented at the 2000 North American Rock Mechanics Symposium Workshop on Three-Dimensional and Advanced Hydraulic Fracture Modeling, Seattle, WA, July 29.
53. Vaziri, H.H., Palmer, I.D., McLennan, J.D., and Islam, R.: "How Can Sand Production Yield a Several-Fold Increase in Productivity: Experimental and Field Data?" paper SPE 63235 presented at the 2000 SPE Annual Technical Conference and Exhibition, Dallas, TX, October 1-4.
54. McLennan, J.D., Medley, G. and Veatch, R.: Underbalanced Completion Guide – A Technology Review, Gas Research Institute, GRI 00/0178 (2001), Chicago, IL.
55. Hagan, J.T., Murray, L.R., Guo, Q., McLennan, J.D., Abou-Sayed, A.S., Kristiansen, T.G. and Meling, T.: "Engineering and Operational Issues Associated with Commingled Drill Cuttings and Produced Water Re-Injection Schemes," paper SPE 73918 presented at the 2002 SPE International Conference on Health, Safety and Environment in Oil and Gas Exploration and Production, Kuala Lumpur, Malaysia, March 20-22.
56. McLennan, J.D. and Abou-Sayed, A.S.: "Some Advances in Near Wellbore Geomechanics," paper SPE/ISRM 78194 to be presented at the SPE/ISRM 2002 Rock Mechanics Conference, Irving, Texas, October 20-23.
57. Abou-Sayed, A.S., Guo, Q., Wang, G. and McLennan, J.D.: "Challenges for Monitoring and Verification of Drill Cuttings Reinjection Performance," paper SPE/ISRM 76796 to be presented at the 2002 SPE/ISRM 2002 Rock Mechanics Conference, Irving, Texas, October 20-23.
58. Palmer, I.D., Vorpahl, D.G., Glenn, J.M., Vaziri, H. and McLennan, J.D.: "A Recent Gulf of Mexico Cavity Completion," SPE 86462, SPE International Symposium and Exhibition on Formation Damage Control, held in Lafayette, Louisiana, U.S.A., 18-20 February 2004.
59. Suarez-Rivera, R., Green, S.J., McLennan, J.D. and Bai. M.: "Effect of layered Heterogeneity on Fracture Initiation in Tight Gas Shales," SPE 103327-MS, SPE ATCE, 2006.
60. Nagel, N. and McLennan, J.D. (ed.): *Cuttings Injection*, SPE Monograph, published 2010.
61. McLennan, J.D., Guo, Q., Wang, C., Geehan, T., Martin, W., and Marquardt, J.: "A Laboratory Study on Increased Assurance and Understanding Storage Mechanisms of E&P Waste Injection into an Unconsolidated Formation," SPE 111707, SPE International Conference on Health, Safety, and Environment in Oil and Gas Exploration and Production, 15-17 April 2008, Nice, France
62. McLennan, J.D., Green, S.J. and Bai, M.: 'Proppant Placement During Tight Gas Shale Stimulation: Literature Review And Speculation," ARMA-08-355, 42nd US Rock Mechanics Symposium and 2nd U.S.-Canada Rock Mechanics Symposium, held in San Francisco, June 29-July 2, 2008, San Francisco, CA.
63. Bai, M., Standifird, W., and McLennan, J.D.: "Modeling Fluid Mixture Transport and Cross-Flow in Layered Media," ARMA 09-33 for presentation at Asheville 2009, the 43rd US Rock Mechanics Symposium and 4th U.S.-Canada Rock Mechanics Symposium, Asheville, NC June 28th – July 1, 2009.
64. Bai, M., McLennan, J., and Standifird, W.: "An Alternative Method for Predicting Injectivity Decline in Produced Water Re-injection, SPE 120829, for presentation at the 2009 SPE European Formation Damage Conference, Scheveningen, The Netherlands, 27-29 May 2009.
65. McLennan, J., Tran, D., Zhao, N., Thakur, S. Deo, M., Gil, I., and Damjanac, B.: "Modeling Fluid Invasion and Hydraulic Fracture Propagation in a Naturally Fractured Rock, a Three Dimensional Approach," SPE 12788, 2010 SPE International Symposium and Exhibition on Formation Damage Control, Lafayette, Louisiana, USA, 10–12 February 2010.
66. Damjanac, B., Gil, I., Pierce, M., Sanchez, M., Van As A., and McLennan, J.: "A New

Approach To Hydraulic Fracturing Modeling In Naturally Fractured Reservoirs," 44th U.S. Rock Mechanics Symposium And 5th U.S.-Canada Rock Mechanics Symposium, June 27 - 30, 2010, Salt Lake City, Utah.

67. Stoddard, T., McLennan, J., Moore, J., Wagner, D.: "Fracture Conductivity of a Bauxite-Propped Geothermal System, GRC Transactions, 34, 457-461, 2010.
68. Brinton, D., Moore, J., McLennan, J, and Jones, C.: "Predicting Thermal Conductivity of Geothermal Reservoir Rocks," AIChE Annual Meeting, Salt Lake City, Utah, Nov. 8, 2010.
69. Dusseault, M., McLennan, J., and Jiang, S.: "Massive Multi-Stage Hydraulic Fracturing for Oil and Gas Recovery from Low Mobility Reservoirs in China," submitted to Petroleum Drilling Techniques, April 9, 2011.
70. Stoddard, T., McLennan, J. and Moore, J. 2012. Residual Conductivity of Bauxite-Propped Geothermal System- Influence of Self-Propping, Time, and Closure Stress, prepared for presentation at the 46th US Rock Mechanics / Geomechanics Symposium, Chicago, IL, USA, 24-27 June 2012.
71. Bhide, R.J., Zhao, N., McLennan, J.D. and Deo, M.D. 2012. Modeling Hydraulic Fracture Propagation in Low Permeability Reservoirs, ARMA 12-224, prepared for presentation at the 46th US Rock Mechanics / Geomechanics Symposium, Chicago, IL, USA, 24-27 June 2012.
72. Diek, A., Roegiers, J-C., Moore, J., and McLennan, J.D. 2012. Borehole Preconditioning Of Geothermal Wells For Enhanced Geothermal System Reservoir Development, Proceedings, Thirty-Seventh Workshop On Geothermal Reservoir Engineering, Stanford University, Stanford, California, January 30 - February 1, 2012, SGP-TR-194.
73. Nguyen, T., Abraham, J., Ramallo, M., Wagner, D., and McLennan, J. 2012. Formulation of Canola-Diesel Microemulsion Fuels and Their Selective Diesel Engine Performance, J. Am. Oil Chem. Soc., DOI 10.1007/s11746-012-2080-4.
74. Opara, O., Free, M.L., McLennan, J., Hamilton, J, and Adams, D.J. 2012. Microbial Production of Methane and Carbon Dioxide from Lignite, Bituminous Coal, and Waste Coal Materials, Int. J. Coal Geology.
75. Horton, B., Birgenheier, L., Johnson, C., Rowe, H., Kennedy, A. and McLennan, J. 2012. Litho- and Chemofacies of the Mancos Shale – Possible Predictors of Geomechanical Behavior of a Developing Shale Gas Play, AAPG ACE, Long Beach, CA April 22-25.
76. Bhide, R., Guilkey, J. and McLennan, J. 2012. Effect of Rotation on Cohesive Zone Implementation in Generalized Interpolation Material Point (GIMP) Method.
77. Bradford, J., McLennan, J., Moore, J., Glasby, D. Waters, D., Bailey, A., Rickard, W., Bloomfield, K., Kruwell, R., and King, D. 2013. Recent Developments at the Raft River Geothermal Field, Proc. Thirty-Eighth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 11-13, 2013, SGP-TR-198. Submitted, 01/2013.
78. McLennan, J.D. 2013. Geomechanics, Petrophysics and Isotherm Measurements for Selected Shale Samples, in China Shale Gas and Shale Oil Plays - Phase I, EGI Publication, S. Jiang (ed.), confidential to sponsors. Published, 02/2013.
79. Effective and Sustainable Hydraulic Fracturing, Edited by Andrew P. Bunger, John McLennan and Rob Jeffrey, ISBN 978-953-51-1137-5, Hard cover, 1000 pages, Publisher: InTech, Chapters published May 17, 2013 under CC BY 3.0 license, DOI: 10.5772/45724. Published, 05/17/2013.
80. Mao Bai, Arturo Diaz, John McLennan and Juan Reyna (2013). Importance of Fracture Closure to Cuttings Injection Efficiency, Effective and Sustainable Hydraulic Fracturing, Dr. Rob Jeffrey (Ed.), ISBN: 978-953-51-1137-5, InTech, DOI: 10.5772/56070. Published, 05/17/2013.
81. Hongtao Jia, John McLennan and Milind Deo (2013). The Fate of Injected Water in Shale Formations, Effective and Sustainable Hydraulic Fracturing, Dr. Rob Jeffrey (Ed.), ISBN: 978-953-51-1137-5, InTech, DOI: 10.5772/56443. Published, 05/17/2013.

82. Walter Glauser, John McLennan and Ian Walton (2013). Do Perforated Completions Have Value for Engineered Geothermal Systems, Effective and Sustainable Hydraulic Fracturing, Dr. Rob Jeffrey (Ed.), ISBN: 978-953-51-1137-5, InTech, DOI: 10.5772/56211. Published, 05/17/2013.
83. Ian Walton and John McLennan (2013). The Role of Natural Fractures in Shale Gas Production, Effective and Sustainable Hydraulic Fracturing, Dr. Rob Jeffrey (Ed.), ISBN: 978-953-51-1137-5, InTech, DOI: 10.5772/56404. Published, 05/17/2013.
84. McLennan, J.D. 2013. Chapter 14: Geomechanical Considerations for South American Shales, EGI Report I 01005 - South American Shale Gas & Shale Oil - Phase 1, Osborne, S. and Allen, R. (ed). Submitted, 06/2013.
85. Bhide, R., Gohring, T., McLennan, J. and Moore, J. Sheared Fracture Conductivity, Proc., Thirty-Ninth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 24-26, 2014, SGP-TR-202. Published, 02/2014.
86. Brauser, E.M. M.H. Bartl, P. Rose, J. Mclennan. Thermal Stability of CdSe/CdS Quantum Dots and their Application as a Novel Geothermal Tracer. Presented at 248th ACS National Meeting & Exposition, San Francisco, CA, United States, August 10-14, 2014.
87. Bradford, J., McLennan, J., Moore, J., Podgorney, R., Plummer, M., and Nash, G. 2015. Analysis of the Thermal and Hydraulic Stimulation Program at Raft River, Idaho, GeoProc 2015, Salt Lake City, February 27.
88. Bradford, J., Moore, J., Ohren, M., McLennan, J., Osborn, W.L., Majer, E., Nash, G., and Friefeld, B. 2015, Recent Thermal and Hydraulic Stimulation Results at Raft River, ID EGS Site, Fortieth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 2015, SGP-TR-202.
89. Brauser, E.M., Rose, P., McLennan, J., and Bartl, M.H. 2015. Optical Detection of Tracer Species in Strongly Scattering Media, Applied Spectroscopy, Volume 69, Number 3. March.
90. Rosen, P., Morris, A., Payne, G., Keach, B., Harvey, I., Richards-McClung, B., McLennan, J., Polson, R., Levey, R., Ring, T., Jurrus, E., and Jones, G.M. 2015. Klareco: An Indexing-based Architecture for Interactive Visualization of Heterogeneous Data Sources, 1st Workshop on Data Systems for Interactive Analysis (DSIA), October.
91. McLennan, J., Walton, I., Moore, J., Brinton, D. and Lund, J. (2015). Proppant Backflow: Mechanical and Flow Considerations, Geothermics, Volume 57, September, pp. 224-237.
92. Tran, T.Q. and McLennan, J.D. 2016. Evaluation of Mechanical and Transport Properties of In-Situ Processed Green River Oil Shale, in Utah Oil Shale: Science, Technology, and Policy Perspectives, Spinti, J.P. ed., CRC Press, July 20. Book Chapter
93. McLennan, J. 2016. Unconventional Natural Gas. Handbook of Combustion. 3:16:1–40, 01/2016. http://onlinelibrary.wiley.com/doi/10.1002/9783527
94. Allis, R., Moore, J., Gwynn, M., Hardwick, C., Kirby, S., McLennan, J., Pankow, K., Potter, S., and Simmons, S. 2016. EGS Concept Testing and Development at the Milford, Utah FORGE Site, Proceedings, 41st Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 22-24, 2016, SGP-TR-209.
95. Bradford, J., McLennan, J., Moore, J., Podgorney, R., and Nash, G. 2016. Numerical Modeling of the Stimulation Program at RRG-9 ST1, a DOE EGS, Proceedings 41st Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 22-24, 2016, SGP-TR-209.
96. Trang, T.Q., and McLennan, J. 2015. Evaluation of Mechanical and Transport Properties of In-Situ Processed Oil Shale, poster presented at Energy & Geoscience Institute Corporate Associates Meeting, Salt Lake City, UT.
97. Brauser, E.M., Hull, T.D., McLennan, J.D., Sly, J.T., and Bartl, M.H. 2016. Experimental Evaluation of Kinetic and Thermodynamic Reaction Parameters of Colloidal Nanocrystals, Chemistry of Materials, ACS.
98. Yang, X., Jin, X., Zhang, Y, Yin, Q., McLennan, J., Dai. C., Fan, W., and Xiao, Y. 2016.

Investigating the Fundamental Mechanisms Governing Solid Production in Superdeep Hot Tight Gas Reservoirs and Exploring Potential Solutions, SPE-181731-MS, prepared for presentation at the SPE Annual Technical Conference and Exhibition held in Dubai, UAE, 26–28 September 2016.

99. Jin, X., Shah, S., Roegiers, J-C., and McLennan, J. 2016. Weight Function of Stress Intensity Factor for Symmetrical Radial Cracks Emanating from Hollow Cylinder, Eng. Frac. Mech., Vol. 159, July, pp. 144-154.

100. Taylor, R., Tuttle, J., Nielsen, R., and McLennan, J. 2016Long Term Cement Damage from Pressure Cycling in Hydrocarbon Wells: Novel Method to Detect Permeability Changes along the Length of the Wellbore, ARMA, Houston, TX, June.

Disclosures

1. Diesel Microemulsion Biofuels. Status: Pending. Type: Parent/Utility. Inventors: Thu Thi Le Nguyen, Melisa Saleb Ramallo, John D. McLennan, Jacob Isaac Kalunakaahele Abraham. File date 05/10/2012. Assignee: The University of Utah. Country: United States.
2. Optimization of Biogenic Methane Production from Hydrocarbon Sources. Status: Pending. Type: Provisional. Inventors: D. Jack Adams, Michael L. Free, John D. McLennan, Jack (John R.) Hamilton. File date 04/10/2012. Assignee: The University of Utah. Country: United States.
3. Periodic Symmetry Defined Bioreactors. Status: Pending. Type: Provisional. Inventors: Leonard F. Pease, Swomitra K. Mohanty, John D. McLennan, Anthony Butterfield, Samuel Doane, Rete Browning, Tyler Lee. File date 02/18/2014. Assignee: The University of Utah. Country: United States.
4. Encapsulation and Time Release of Microbe Loaded Porous Proppant, U-6049. 11/02/2015. Inventors: Taylor David. Sparks, John D. McLennan, Kyu-Bum Han, John Fuertez, Assignee: The University of Utah. Country: United States.
5. Porous Proppant for Delivering Bacteria, U-6110. 02/22/2016. Inventors: Taylor David. Sparks, John D. McLennan, Kyu-Bum Han, Assignee: The University of Utah. Country: United States.

Organizations and Societies

- Society of Petroleum Engineers, Member and 2007 Chairperson of Salt Lake Section, Currently Program Chair
- Society of Professional Well Log Analysts, Member
- American Institute of Chemical Engineers, Member
- American Rock Mechanics Association, Board of Directors, President

Graduate Students

Joshua Thompson	MS Chemical Engineering	2010
John Gregory	ME Chemical Engineering	2011
Chad Wilding	ME Chemical Engineering	2011
Trevor Stoddard	MS Chemical Engineering	2011
Dan Brinton	MS Chemical Engineering	2011

Eric Brauser	Ph.D. Chemical Engineering	2015
Walter Glauser	MS Chemical Engineering	2015
Alan Walker	MS Petroleum Engineering	2015
Jacob Abraham	MS Petroleum Engineering	2015
Jacob Bradford	Ph.D. Chemical Engineering	2016 Summer
Thang Tran	Ph.D. Chemical Engineering	2016 Winter
Eric Edelman	MS Petroleum Engineering	2016 Spring
Shuo Zhang	MS Petroleum Engineering	2016 Spring
Yili Zhao	MS Petroleum Engineering	2016 Spring
Bryan Forbes	MS Petroleum Engineering	2016 Spring
John Fuertez	Ph.D. Chemical Engineering	2016 Winter
Raili Taylor	Ph.D. Chemical Engineering	2017
Joshua Zannoni	Ph.D. Chemical Engineering	2017
David Shaw	Ph.D. Chemical Engineering	2017
Jeff Easton	Ph.D. Chemical Engineering	2018
Shashank Tiwari	Ph.D. Chemical Engineering	2019
David Brown	MS Petroleum Engineering	
Brandon Palmer	MS Petroleum Engineering	
Kevin Kincaid	MS Petroleum Engineering	
James Schloss	MS Petroleum Engineering	
Arturo Acosta	MS Petroleum Engineering	
Garrett Schultz	MS Petroleum Engineering	
Joel Tetteh	MS Petroleum Engineering	

Appendix E

Solar Thermal Integration, Hunter Plant

Brigham Young University

Solar Augmentation of Coal-Fired Power Plant

Brian Iverson, BYU
Kody Powell, U of U

The Hunter power plant, located near Castledale, UT burns approximately 4.5 million tons of coal/year to operate as a 1.32 GW_e power plant. PacifiCorp has expressed interest in considering the costs and benefits to offsetting some of the coal energy source with solar-thermal energy. This preliminary outline provides a possible framework for solar augmentation of PacifiCorp's plant. Solar augmentation of existing coal-fired power plants is a topic that has been researched by U.S. national laboratories [1]. For existing coal or natural gas combined cycle power plants in UT, it has been shown that 1.4 GW_e of energy could be created through solar-augmentation (neglecting sites that have only fair potential).

We propose the study of solar-augmentation to the Hunter plant through the use of parabolic trough or power tower solar collection. Figure 1 illustrates two potential locations where thermal energy from solar-augmentation may integrate with an existing steam power cycle for coal. The locations differ when considering the type of solar energy collection (trough, tower) due to different max temperatures achievable from the collection mechanism. Typically, a max collection temperature near 380 °C for parabolic trough and 540 °C for power towers is expected with increases achieved in the recent 5 years.

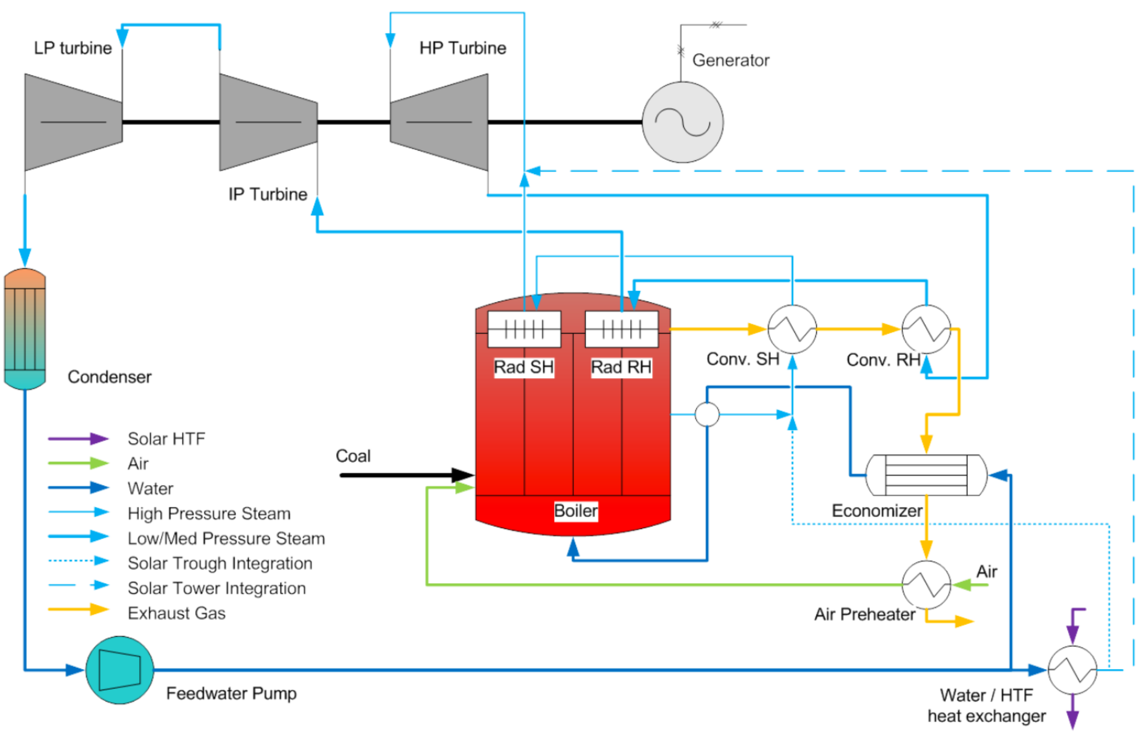


Figure 1. Schematic of solar steam integration into coal plant by solar trough or tower concentration platforms. SH = superheater, RH = reheater (from [1])

The proposed work will investigate the following aspects of solar integration at Hunter:

- Solar resource: Direct normal insolation (DNI) is the primary energy source for solar thermal energy collection and average DNI values at or above 7 kWh/m^2/day have the highest possible potential for solar-augmentation. A plant with a DNI below 4 $kWh/m^2/day$ may not be worth considering.

- Land resource: Previous work has shown that existing fossil plants can accept a design-point maximum of between 10% and 20% of their total plant output from solar steam before reaching equipment or other design limitations [1]. Based on the assumption that 1 MW_e of solar requires 5 acres of land, a 100 MW plant could accept up to 10 to 20 MW_e of solar generation, which would require 50 to 100 acres of land or 0.5 to 1 acres per fossil plant megawatt. Further, land with a less than 3-5% slope is preferred for solar-augmentation or extensive grating is required.
- Efficiency: Solar-use efficiency is the measure of how many megawatts of solar electricity are generated per solar thermal megawatt integrated into the fossil plant. Solar-use efficiency can decrease with increasing solar contribution. Conditions up to the maximum amount of solar integration will be considered. A power plant model will be generated or NREL's System Advisor Model (SAM) will be used for evaluating performance.
- Type of solar augmentation: Trough and tower methods of solar thermal energy collection will be considered to determine optimum solar-integration conditions.
- Costs: Costs associated with additional hardware or plant subsystems will be provided and analyzed in a cost/benefit study.

Additional aspects may also be considered with planning development. However, the above encompasses the major points of understanding required to advise on the usefulness of augmenting the Hunter plant with a solar resource.

Some initial questions to be answered:

- What is the age of the Hunter plant?
- What is the current capacity factor of the Hunter plant?

Budget:

Student (2 years): $38k
Summer internship at National Lab (student): $7k
Tuition (2 years): $11k
Faculty (summer month each year for 2 years): $30k
Supplies (databases, computer programs): $3k
Travel (lab site visit, conference attendance): $6.5k
Indirect costs: $41.5k
Optional national lab support (NREL, Sandia): $15k
Total: $150k

Bio: Brian Iverson completed his PhD at Purdue University in 2008 and currently teaches at Brigham Young University. His area of specialty is heat transfer. Brian worked as a part of the concentrating solar power team at Sandia National Laboratories from 2009-2012 and has published extensively in several aspects of solar power generation from collection [2-4], to storage [5-11], to system performance [4, 12-14].

References

[1] Turchi, C., Langle, N., Bedilion, R., and Libby, C., 2011, "Solar-augment potential of U.S. fossil-fired power plants," NREL/TP-5500-50597, February 2011, National Renewable Energy Lab, Golden, CO.

[2] Iverson, B. D., Andraka, C. E., Yellowhair, J., and Ho, C. K., 2010, "Optical error impacts on flux distribution for a dish concentrator using probabilistic modeling," SolarPACES, September 21-24, 2010, Perpignan, France.

[3] Andraka, C. E., Yellowhair, J., and Iverson, B. D., 2010, "A parametric study of the impact of various error contributions on the flux distribution of a solar dish concentrator," ASME Energy Sustainability, May 17-22, 2010, Phoenix, AZ, USA.

[4] Ho, C. K. and Iverson, B. D., 2014, "Review of high-temperature central receiver designs for concentrating solar power," *Renewable & Sustainable Energy Reviews*, Vol. 29, pp. 835-846.

[5] Flueckiger, S. M., Iverson, B. D., and Garimella, S. V., 2013, "Simulation of a concentrating solar power plant with molten-salt thermocline storage for optimized annual performance," Energy Sustainability, July 14-19, 2013, Minneapolis, MN.

[6] Iverson, B. D., Flueckiger, S. M., and Ehrhart, B. D., 2011, "Trough heat collection element deformation and solar intercept impact," SolarPACES, September 20-23, 2011, Granada, Spain.

[7] Kolb, G. J., Ho, C., Iverson, B. D., Moss, T. A., and Siegel, N. P., 2010, "Freeze-thaw tests of trough receivers employing a molten salt working fluid," ASME Energy Sustainability, May 17-22, 2010, Phoenix, AZ.

[8] Iverson, B. D., Broome, S. T., and Siegel, N. P., 2010, "Temperature dependent mechanical property testing of nitrate thermal storage salts," SolarPACES, September 21-24, 2010, Perpignan, France.

[9] Flueckiger, S. M., Iverson, B. D., Garimella, S. V., and Pacheco, J. E., 2014, "System-level simulation of a solar power tower plant with thermocline thermal energy storage," *Applied Energy*, Vol. 113, pp. 86-96.

[10] Flueckiger, S. M., Iverson, B. D., and Garimella, S. V., 2014, "Economic optimization of a concentrating solar power plant with molten-salt thermocline storage," *Journal of Solar Energy Engineering*, Vol. 136, pp. 011016.

[11] Iverson, B. D., Broome, S. T., Kruizenga, A. M., and Cordaro, J. G., 2012, "Thermal and mechanical properties of nitrate thermal storage salts in the solid-phase," *Solar Energy*, Vol. 86, pp. 2897-2911.

[12] Gary, J. A., Ho, C. K., Mancini, T. R., Kolb, G. J., Siegel, N. P., and Iverson, B. D., 2010, "Development of a power tower technology roadmap for DOE," SolarPACES, September 21-24, 2010, Perpignan, France.

[13] Dunham, M. T. and Iverson, B. D., 2014, "High-efficiency thermodynamic power cycles for concentrated solar power systems," *Renewable and Sustainable Energy Reviews*, Vol. 30, pp. 758-770.

[14] Iverson, B. D., Conboy, T. M., Pasch, J. J., and Kruizenga, A. M., 2013, "Supercritical CO2 Brayton cycles for solar-thermal energy," *Applied Energy*, Vol. 111, pp. 957-970.

Brian D. Iverson

Home
1522 Oak Lane
Provo, UT 84604
(801) 636-8912

bdiverson@byu.edu

Brigham Young University
435 CTB
Provo, UT 84602
(801) 422-7514

Education

Ph.D. Mechanical Engineering, 2008
Purdue University, West Lafayette, IN
Thesis: "Traveling-Wave Electrohydrodynamic Micropumping in a Temperature Gradient"
Advisor: Suresh V. Garimella

M.S. Mechanical Engineering, 2004
Purdue University, West Lafayette, IN
Thesis: "Heat and Mass Transport in Heat Pipe Wick Structures"
Advisor: Suresh V. Garimella

B.S. Mechanical Engineering – Magna Cum Laude, 2002
Brigham Young University, Provo, UT
Research: "Thermally Developing Electroosmotic Convection in Rectangular Microchannels"
Advisors: Brent W. Webb and R. Daniel Maynes

Professional Positions

Assistant Professor, Nov 2012 – present
Brigham Young University, Provo UT
Exploit high aspect ratio structures for enhancement and control of heat and mass transport.
Graduate committee member.
Mentor student research.
Conduct undergraduate and graduate courses in thermal science.

Senior Member of Technical Staff, 2009 – 2012
Sandia National Laboratories, Albuquerque NM
Investigate alternative power cycles and compatible collection and storage of solar thermal energy.
Characterize behavior of freeze event recovery for deployment of molten salt in trough CSP.
Analyze molten salt feasibility in line-focus concentrated solar power systems.
Examine the effects of trough receiver tube bending on solar intercept.
Measure solid-phase, thermal and mechanical properties of thermal energy storage salts.
Identify thermal ratcheting scenarios and bed properties for thermocline thermal storage tanks.
Model flux sensor for solar tracking; implement design and characterize transient solar response.
Administer seminar series for staff education, collaboration, awareness and preparedness.
Provide technical monitoring and support for DOE's Funding Opportunity Announcements (FOA).
Examine thermal energy storage for power tower and dish-based concentrated solar energy systems.
Model optical error sources and relative impact on flux distributions

Post-Doctoral Researcher, January 2009 – August 2009
NSF Cooling Technologies Research Center, Purdue University
Investigate thin-film thermal transport for organic/Si interfacial contact resistance.

Perform local thermal measurements with a modified scanning thermal microscopy technique.
Characterize composites, thin-films and embedded structures with thermal imaging.
Explore separation mechanisms and membrane technology for biological and energy applications.

Research Assistant, 2002 - 2008
NSF Cooling Technologies Research Center, Purdue University
Conduct electronics cooling research with industry leaders at pre-competitive level.
Perform finite element modeling of micropump with moving boundaries and ion generation.
Present at NSF Industry/University Cooperative Research Center (I/UCRC) conferences.
Design and fabricate integrated electrohydrodynamic micropumps.
Test wicking capabilities of flat heat pipes wick structures.
Analyze/characterize benefits of wick design from testing results.
Perform literature searches and publish research findings.

Teaching Assistant, Heat and Mass Transfer, January – May 2008
Purdue University
Prepare lectures and teach course material in the absence of the professor.
Hold regular office hours for student consultation and one-on-one instruction.
Prepare exam material and grade exams.

Visiting Researcher, May 2007 – August 2007
Research Triangle Institute International, NC
Fabricate solution-based organic photovoltaic cells and identify improvement mechanisms.
Develop processing steps and construct PbS quantum dot solution photovoltaic cells.
Establish Streptavidin/Biotin binding force measurement methodology for microcantilevers.
Measure piezoelectric response signals in vibrating microcantilever devices.

Research Assistant, Thermal Science, 2001 - 2002
Brigham Young University
Obtain analytical solution for thermally developing flow in electroosmotic pumping.
Design and implement testing apparatus for electroosmotic flow in microtubules.
Collect research results and publish findings.

Teaching Assistant, Applied Thermodynamics, Summer 2001
Brigham Young University
Conduct student laboratory sessions for diesel and refrigeration cycles.
Assist students in analyzing experimental data.
Compile existing lab knowledge and write TA training manual.

Engineering Intern, 2000 - 2001
Geneva Steel, Vineyard UT
Plan preliminary stages of new projects including walking beam furnace.
Design and revise parts/machinery using CAD tools, manage project prints.

Tutor, 1996 - 1997
Utah Valley State College Partnership, UT
Tutor “at-risk” high school students in English, Math, History, and supporting coursework.
Monitor student academic progress.
Coordinate communication with parents, education leaders and student.

Publications

*Advised student

Books

1. Iverson, B. D. and Garimella, S. V., Integrated Micropumping: Traveling-wave electrohydrodynamics induced in a temperature gradient, Saarbrücken, LAP Lambert Academic Publishing, 2010.

Journal Articles

1. Blanc, M. J.*, Mulford, R. B.*, Jones, M. R., and Iverson, B. D., 2016, "Infrared visualization of the cavity effect using origami-inspired surfaces," *Journal of Heat Transfer*, Vol. 138, pp. 020901.
2. Mulford, R. B.*, Jones, M. R., and Iverson, B. D., 2016, "Dynamic control of radiative surface properties with origami-inspired design," *Journal of Heat Transfer*, Vol. 138, pp. 032701.
3. Marr, K. M.*, Chen, B., Mootz, E., Geder, J., Pruessner, M., Melde, B., Vanfleet, R. R., Iverson, B. D., and Claussen, J. C., 2015, "High aspect ratio, carbon nanotube membranes decorated with Pt nanoparticle urchins for small scale underwater vehicle propulsion via H_2O_2 decomposition," *ACS Nano*, DOI: 10.1021/acsnano.5b02124.
4. Iverson, B. D., Bauer, S. J., and Flueckiger, S. M.*, 2014, "Thermocline bed properties for deformation analysis," *Journal of Solar Energy Engineering*, Vol. 136, pp. 041002.
5. Ho, C. K. and Iverson, B. D., 2014, "Review of high-temperature central receiver designs for concentrating solar power," *Renewable & Sustainable Energy Reviews*, Vol. 29, pp. 835-846.
6. Flueckiger, S. M.*, Iverson, B. D., Garimella, S. V., and Pacheco, J. E., 2014, "System-level simulation of a solar power tower plant with thermocline thermal energy storage," *Applied Energy*, Vol. 113, pp. 86-96.
7. Flueckiger, S. M.*, Iverson, B. D., and Garimella, S. V., 2014, "Economic optimization of a concentrating solar power plant with molten-salt thermocline storage," *Journal of Solar Energy Engineering*, Vol. 136, pp. 011016.
8. Dunham, M. T.* and Iverson, B. D., 2014, "High-efficiency thermodynamic power cycles for concentrated solar power systems," *Renewable and Sustainable Energy Reviews*, Vol. 30, pp. 758-770.
9. Iverson, B. D., Conboy, T. M., Pasch, J. J., and Kruizenga, A. M., 2013, "Supercritical CO2 Brayton cycles for solar-thermal energy," *Applied Energy*, Vol. 111, pp. 957-970.
10. Iverson, B. D., Broome, S. T., Kruizenga, A. M., and Cordaro, J. G., 2012, "Thermal and mechanical properties of nitrate thermal storage salts in the solid-phase," *Solar Energy*, Vol. 86, pp. 2897-2911.
11. Iverson, B. D., Blendell, J. E., and Garimella, S. V., 2010, "Note: Thermal analog to atomic force microscopy force-displacement measurements for nanoscale interfacial contact resistance," *Review of Scientific Instruments*, Vol. 81.
12. Iverson, B. D., Cremaschi, L., and Garimella, S. V., 2009, "Effects of discrete-electrode configuration on traveling-wave electrohydrodynamic pumping," *Microfluidics and Nanofluidics*, Vol. 6, pp. 221-230.
13. Iverson, B. D. and Garimella, S. V., 2009, "Experimental characterization of induction electrohydrodynamics for integrated microchannel pumping," *Journal of Micromechanics and Microengineering*, Vol. 19.
14. Icoz, K., Iverson, B. D., and Savran, C., 2008, "Noise analysis and sensitivity enhancement in immunomagnetic nanomechanical biosensors," *Applied Physics Letters*, Vol. 93.
15. Iverson, B. D. and Garimella, S. V., 2008, "Recent advances in microscale pumping technologies: A review and evaluation," *Microfluidics and Nanofluidics*, Vol. 5, pp. 145-174.
16. Iverson, B. D., Davis, T. W., Garimella, S. V., North, M. T., and Kang, S. S., 2007, "Heat and mass

transport in heat pipe wick structures," *Journal of Thermophysics and Heat Transfer*, Vol. 21, pp. 392-404.

17. Iverson, B. D., Maynes, D., and Webb, B. W., 2004, "Thermally developing electroosmotic convection in rectangular microchannels with vanishing Debye-layer thickness," *Journal of Thermophysics and Heat Transfer*, Vol. 18, pp. 486-493.

Journal Articles in Review

Conference Papers and Refereed Publications

1. Blanc, M. J.*, Mulford, R. B.*, Jones, M. R., and Iverson, B. D., 2015, "Visualization of the cavity effect present for origami-inspired surfaces with IR imaging," Heat Transfer Gallery, ASTFE Thermal and Fluids Engineering Summer Conference, August 15-20, 2015, New York, NY.
2. Mulford, R. B.*, Jones, M. R., and Iverson, B. D., 2015, "Net radiative heat exchange of an origami-inspired, variable emissivity surface," ASTFE Thermal and Fluids Engineering Summer Conference, August 9-12, 2015, New York, NY.
3. Mulford, R. B.*, Christensen, L. M.*, Jones, M. R., and Iverson, B. D., "Dynamic control of radiative surface properties with origami-inspired design," ASME International Mechanical Engineering Congress and Exposition, Montreal, Canada, November 14-20, 2014.
4. Flueckiger, S. M.*, Iverson, B. D., and Garimella, S. G., "Simulation of a concentrating solar power plant with molten-salt thermocline storage for optimized annual performance," Energy Sustainability, Minneapolis, MN, July 14-19, 2013.
5. Iverson, B. D., Flueckiger, S. M.*, and Ehrhart, B. D.*, 2011, "Trough heat collection element deformation and solar intercept impact," SolarPACES, Granada, Spain, September 20-23, 2011.
6. Iverson, B. D., Cordaro, J. G., and Kruizenga, A. M., 2011, "Thermal property testing of nitrate thermal storage salts in the solid-phase," ASME International Conference on Energy Sustainability, Washington D.C., August 7-10, 2011.
7. Iverson, B. D., Broome, S.T., and Siegel, N. P., 2010, "Temperature dependent mechanical property testing of nitrate thermal storage salts," SolarPACES, Perpignan, France, September 21-24, 2010.
8. Iverson, B. D., Andraka. C. E., Yellowhair, J. and Ho, C. K., 2010, "Optical error impacts on flux distribution for a dish concentrator using probabilistic modeling," SolarPACES, Perpignan, France, September 21-24, 2010.
9. Ho, C. K., Mancini, T. R., Kolb, G. J., Siegel, N. P., Iverson, B. D. and Gary, J., 2010, "Development of a power-tower technology roadmap for DOE," SolarPACES, Perpignan, France, September 21-24, 2010.
10. Andraka, C. E., Yellowhair, J. and Iverson, B. D., 2010, "A parametric study of the impact of various error contributions on the flux distribution of a solar dish concentrator," ASME International Conference on Energy Sustainability, Phoenix, AZ, May 17-22, 2010.
11. Kolb, G., Ho, C., Iverson, B. D., Moss, T., and Siegel, N., 2010, "Freeze-thaw tests of trough receivers employing a molten salt working fluid," ASME International Conference on Energy Sustainability, Phoenix, AZ, May 17-22, 2010.
12. Iverson, B. D. and Garimella, S. V., 2008 "Performance characterization of a traveling-wave electrohydrodynamic micropump," ASME International Mechanical Engineering Congress and Exposition, Boston, MA, October 31 – November 6, 2008.
13. Cremaschi, L., Iverson, B. D., Garimella, S. V., 2006, "Enhanced electrohydrodynamic pumping for the microscale," ASME International Mechanical Engineering Congress and Exposition, Chicago, IL, November 5-10, 2006.
14. Iverson, B. D., Singhal, V., and Garimella, S. V., 2006, "Micropumping technologies for electronics cooling," Electronics Cooling, Vol. 12, No. 2.
15. Acikalin, T., Iverson, B. D., Garimella, S. V., Raman, A. and Petroski, J., 2004, "Numerical

investigation of the flow and heat transfer due to a miniature piezoelectric fan," ASME International Mechanical Engineering Congress and Exposition, Anaheim, CA, November 2004.

16. Iverson, B. D. and Garimella, S.V., 2004, "Experimental measurements of heat and mass transport in heat pipe wicks," ASME Heat Transfer/Fluids Engineering Summer Conference, Charlotte, NC, July 11-15, 2004.

Abstract Reviewed Conference Presentation Only

1. Brownlee, B. J.*, Marr, K. M.*, Claussen, J. C., and Iverson, B. D., 2016, "Enhancement of rransport-limited chemical reactions via functionalized carbon nanotube microarray membranes," ASME International Conference on Nanochannels, Microchannels and Minichannels, July 10-14, 2016, Washington, DC.
2. Lee, M. L., Ghosh, A., Tolley, L. T., Hawkins, A. R., Iverson, B. D., and Tolley, H. D., 2016, "Microchip Thermal Gradient Gas Chromatography," 40th Intern. Symp. on Capillary Chromatography, May 29-June 3, 2016, Riva del Garda, Italy.
3. Mulford, R. B.*, Blanc, M. J.*, Jones, M. R., and Iverson, B. D., 2015, "Total heat emission from an origami-inspired variable emissivity device," ASME International Mechanical Engineering Congress and Exposition, Houston, TX, November 13-19, 2015 (Poster).
4. Stevens, K. A.*, Maynes, D. R., Crockett, J., Iverson, B. D., "The effect of superhydrophobicity on two-phase channel flow," American Physical Society, 68th Annual DFD Meeting, Boston, MA, November 22-24, 2015.
5. Cowley, A.*, Maynes, D., Crockett, J., Iverson, B. D., "Inertial effects on heat transfer in superhydrophobic microchannels," American Physical Society, 68th Annual DFD Meeting, Boston, MA, November 22-24, 2015.
6. Lund, J. M.*, Syme, D. B.*, Vanfleet, R. R., Davis, R., Jensen, B. D., and Iverson, B. D., "Carbon Nanotube-Templated, Porous Films for Thermal Isolation," AVS 62nd International Symposium and Exhibition, October 18-23, 2015, San Jose, CA.
7. Boyer, N.*, Syme, D.*, Rowley, J.*, Davis, R. Vanfleet, R., Iverson, B. D., Harker, M., and Creighton, R., "Carbon Nanotube Sheets from Horizontally Aligned Carbon Nanotubes," AVS 62nd International Symposium and Exhibition, October 18-23, 2015, San Jose, CA.
8. Mulford, R. B.*, Jones, M. R., and Iverson, B. D., 2015, "Dynamic radiative surface properties with origami-inspired topography," NASA Thermal & Fluids Analysis Workshop, August 3-7, 2015, Silver Spring, MD.
9. Marr, K. M.*, Claussen, J. C., and Iverson, B. D., "Enhanced Monopropellant Fuel Decomposition by High Aspect Ratio, Catalytic CNT Structures for Propulsion of Small Scale Underwater Vehicles," American Physical Society, 67th Annual DFD Meeting, San Francisco, CA, November 23-25, 2014, DFD14-2014-002818.
10. Mulford, R. B.*, Christensen, L. G.*, Iverson, B. D., Jones, M. R., and Howell, L. L., "Dynamic Thermal Management of Radiation through Origami-Inspired Design," Spacecraft Thermal Control Workshop, Aerospace Corporation, El Segundo, CA. March 25-27, 2014.
11. Park, J.*, Delimont, I.*, Mulford, R.*, Christensen, L.*, Howell, L., Iverson, B. D., and Jones, M., "Dynamic control of radiation-based thermal management through origami-inspired design," International Mechanical Engineering Congress and Exposition, November 15-21, 2013 (Poster).
12. Marr, K. M.*, and Iverson, B. D., "High aspect ratio sensing platforms for flowing environments," International Mechanical Engineering Congress and Exposition, November 15-21, 2013 (Poster).
13. Iverson, B. D., and Garimella, S. G., "Induction Electrohydrodynamic Pumping in a Temperature Field," Frontiers in Scalable Nanostructured Materials and Interfaces, West Lafayette, IN, March 10-12, 2009 (Poster).

Invited Talks

1. Iverson, B. D., "Education for Life: Faith in Scholarship," Brigham Young University, ME Graduate Seminar, April 4, 2016.
2. Iverson, B. D., "Transport Enhancement of Rate-Limited Chemical Reactions *via* Pt-Decorated, Carbon Nanotube Microarray Membranes," Utah State University, December 3, 2015.
3. Iverson, B. D., "Context is Everything - Literature Reviews and Writing," ME Graduate Student Seminar, Brigham Young University, October 26, 2015.
4. Iverson, B. D., "Transport Enhancement of Rate-Limited Chemical Reactions *via* Pt-Decorated, Carbon Nanotube Microarray Membranes," Purdue University, October 5, 2015.
5. Iverson, B. D., "Context is Everything - Literature Reviews and Writing," ME Graduate Student Seminar, Brigham Young University, March 30, 2015.
6. Iverson, B. D., "Introduction to Microfluidics," Mechanical Engineering 550 Guest Lecture, Brigham Young University, December 5, 2014.
7. Iverson, B. D., "Solving Proximity Challenges of Sensor Miniaturization through High Aspect Ratio, Carbon Nanotube Scaffolds," NASA Goddard, Greenbelt MD, October 8, 2014.
8. Iverson, B. D., "Solving Proximity Challenges of Sensor Miniaturization through High Aspect Ratio, Carbon Nanotube Scaffolds," Army Research Lab, Adelphi MD, October 8, 2014.
9. Iverson, B. D. and Zuber, P., "Literature Reviews," Brigham Young University, ME Graduate Student Seminar, joint presentation, March 10, 2014.
10. Brigham Young University, Energy Portfolio Panel Discussion, December 12, 2013. Panel member.
11. Iverson, B. D., "Thermal Energy Storage in Concentrating Solar Power Systems," Brigham Young University, Department of Mechanical Engineering, February 27, 2012, Provo UT.
12. Iverson, B. D., Garimella, S. G., and Blendell, J. "Thermal Contact Resistance at Silicon-Organic Material Interfaces," Intel Thermal Work Group, July 28, 2009, Chandler, AZ.
13. Iverson, B. D., "Integrated Micropumping for Thermal Management and Microfluidic Biodevices," Texas A&M University, June 25, 2009, College Station, TX.
14. Iverson, B. D., "Integrated Micropumping for Thermal Management and Microfluidic Biodevices," Sandia National Laboratories, Solar Thermal Test Facility, February 17, 2009, Albuquerque, NM.
15. Iverson, B. D., "Enhanced Electrohydrodynamic Micropumping," Research Triangle Institute International, Group Seminar, August 8, 2007, Durham, NC.
16. Iverson, B. D. and Garimella, S. G., "Enhanced Electrohydrodynamic Micropumping," Indiana Chapter of International Microelectronics and Packaging Society (IMAPS) Vendor's Day and Mini-Symposium, April 30, 2007, Indianapolis, IN.
17. Iverson, B. D., and Garimella, S.G., "Heat Pipes for Heat Spreading," Japan Society of Mechanical Engineering Project Meeting 2003, October 13-17, 2003, Tokyo, Japan. Heat sink conference fostering international thermal management interaction.

Non-Refereed Publications

1. Stevens, K. A.*, Crockett, J., Maynes, D. R. and Iverson, B. D., "Two-phase pressure drop in superhydrophobic channels," Utah NASA Space Grant Consortium, May 2015.
2. Mulford, R. B.*, Jones, M. R. and Iverson B. D., "Dynamic control of radiative surface properties with origami-inspired design," Utah NASA Space Grant Consortium, May 2015.

Patent and Provisional Patent Submissions

1. Vanfleet, R. R., Davis, R. C., Syme, D., and Iverson, B. D., Aligned and laterally oriented, carbon nanotube thin films, Provisional Patent, submitted March 2015.
2. Iverson, B. D., Marr, K. M., Convective Enhanced Sensing with High Surface Area Flow Structures, Convective enhanced sensing with high surface area flow structures, Provisional Patent, submitted November 2014.
3. Claussen, J. C., and Iverson, B. D., A micro-scale vehicle having a propulsion device, Provisional

Patent, submitted October 2014. Patent Application No. 14/877,594.

4. Howell, L. L., Iverson, B. D., and Jones, M. R., Dynamic Control of Spectral Radiative Properties through Compliant Surfaces, Provisional Patent, submitted November 2013.

Honors and Awards

Professional

- Advances in Engineering featured our work as a key scientific article (September 2014), from: Iverson *et al.*, 2014, *Journal of Solar Energy Engineering*, Vol. 136, pp. 041002. https://advanceseng.com/mechanical-engineering/thermocline-bed-properties-deformation-analysis/
- Renewable Energy Global Innovation Series featured our work as a key scientific article (January 2014), from: Iverson, B. D., Conboy, T. M., Pasch, J. J., and Kruizenga, A. M., 2013, "Supercritical CO_2 Brayton cycles for solar-thermal energy," *Applied Energy*, Vol. 111, pp. 957-970. http://reginnovations.org/key-scientific-articles/supercritical-co2-brayton-cycles-solar-thermal-energy/
- New Mexico Small Business Assistance Program outstanding innovation award supporting SAVSU Technologies (May 2012)
- One of the top 5 cited articles from Microfluidics and Nanofluidics from 2008-2009 (July 2011): Iverson, B. D. and Garimella, S.V., 2008 "Recent advances in microscale pumping technologies: a review and evaluation," Microfluidics and Nanofluidics, Vol. 5, No. 2, pp. 145-174.
- Spot Award, performance award for significant accomplishment, Sandia National Laboratories (December 2010)
- Best Paper/Presentation of Session Award, Indiana Chapter of International Microelectronics and Packaging Society Vendor's Day and Mini-Symposium (April 30, 2007)
- Best Poster, Cooling Technologies Research Center review meeting (2005, 2006, 2009)
- National Defense Science and Engineering Graduate Fellowship Honorable Mention (2003)
- National Science Foundation Graduate Research Fellowship Honorable Mention (2003)
- Perfect score on GRE Quantitative (2002)
- Professional Nominations: Tau Beta Pi, Golden Key Honor Society, Phi Kappa Phi (2000-2001)

Academic

- Winkelman Fellowship for PhD studies, Purdue University (2005-2007)
- Ingersoll Rand Fellowship for graduate studies, Purdue University (2002-2004)
- Magna Cum Laude distinction, Brigham Young University, Provo UT (2002)
- Karl G. Maeser Scholarship, Brigham Young University, Provo UT (2001-2002)
- Alvina S. Barrett Scholarship, Brigham Young University, Provo UT (2000-2001)
- University Scholarship, Brigham Young University, Provo UT (1996-1997, 1999-2000)

Regional/Local

- Academic All-State Soccer Team, Division 5A, UT (1996)
- Sterling Scholar, West Jordan High School, UT (1996)
- Eagle Scout, Boy Scouts of America (1996)

Visibility

- ACS Nano podcast, August 20, 2015, Topic: Micro Underwater Vehicle Propulsion
  - Link: http://pubs.acs.org/subscribe/journals/ancac3/audio/ancac3-0815.mp3
- Guest on "Top of the Mind," with Julie Rose, BYU Radio, July 13, 2015. Topic: Micro Underwater Vehicle Propulsion.

- Link: http://www.byuradio.org/episode/b980e1ac-e5d0-4619-b3e0-f4d2cee375f3?playhead=5189&autoplay=true

Advisement

Graduate Student Advisement

- Ben Brownlee, PhD thesis in progress, Brigham Young University, 2015-
- Kimberly Stevens, PhD thesis in progress, Brigham Young University, 2014-
- Derric Syme, MS thesis in progress, Brigham Young University, 2014-
- Rydge Mulford, PhD thesis in progress, Brigham Young University, 2014-
- Kevin Marr, MS, Brigham Young University, 2013-2015

Undergraduate Student Advisement

- Taylor Davis, "Microfabrication and device construction," Brigham Young University, March 2016 - present.
- Chad Gudmendsen, "Electrodeposition and biofunctionalization," Brigham Young University, January 2016 – present.
- Courtney Nordgran, "Superhydrophobic two-phase flow measurements," Brigham Young University, September 2015 – April 2016.
- Michael Farnsworth, "3D control of origami surfaces", Brigham Young University, July 2015 – May 2016.
- Shane Rahrle, "3-omega measurement techniques for thin-films," Brigham Young University, July 2015 – May 2016.
- Mitchell Blanc, "Origami-based, radiative surface property control," Brigham Young University, May 2015 – April 2016.
- Jonathan Erickson, "Two-phase flow visualization," Brigham Young University, September 2014 – June 2015.
- Ben Brownlee, "Detection of low H_2O_2 concentrations," Brigham Young University, September 2014 – May 2015.
- Carson Storey, "Through flow experimental setup for chemical sensing," Brigham Young University, July 2014 – June 2015.
- Bennett Myres, "Thermal conductivity detectors for gas chromatography," Brigham Young University, January – April 2014.
- Derric Syme, "Aligned CNT composites," Brigham Young University, November 2013 – May 2014
- Luke Christensen, "Dynamic radiation control with origami-based surfaces," Brigham Young University, Sept 2013- May 2014.
- Rydge Mulford, "Dynamic radiation control with origami-based surfaces," Brigham Young University, Sept 2013- May 2014.
- Isaac Delimont, "Dynamic radiation control with origami-based surfaces," Brigham Young University, June-Aug 2013.
- Jared Park, "Dynamic radiation control with origami-based surfaces," Brigham Young University, June-November 2013.
- Kevin Marr, "Porous anodic alumina templates," Brigham Young University, Jan-April 2013.

Project-Related Student Advisement

- Marc T. Dunham, "High-efficiency thermodynamic power cycles for concentrated solar power systems" Graduate Student Intern, Stanford University, 2012-2013.
- Scott M. Flueckiger, Freeze event recovery in parabolic trough, thermocline-bed property characterization and thermocline storage, Graduate Student Intern, Purdue University, 2011-2013.

- Brian D. Ehrhart, Critical Skills Master's Program, Sandia National Laboratories, 2011.

Student Awards

- Ben Brownlee, Utah NASA Space Grant Consortium Fellowship, $6k, 2016-2017.
- Kim Stevens, Utah NASA Space Grant Consortium Fellowship, $6k, 2016-2017.
- Ben Brownlee, NSF Fellowship Honorable Mention, 2016.
- Michael Farnsworth, ORCA Fellowship, BYU, $1.5k, 2016.
- Kim Stevens, Utah NASA Space Grant Consortium Fellowship, $7k, 2015-2016.
- Ben Brownlee, College of Engineering and Technology Fellow, BYU, $10k, 2015-2016.
- Rydge Mulford, NASA Space Technology Research Fellowship, $200k, 2015-2018.
- Ben Brownlee, ORCA Fellowship, BYU, $1.5k, 2015.
- Carson Storey, ORCA Fellowship, BYU, $1.5k, 2015.
- Rydge Mulford, 3-Minute Thesis Department and College Winner, BYU, $1.5k, 2015.
- Rydge Mulford, Utah NASA Space Grant Consortium Fellowship, $4k, 2014-2015.

Thesis Committee Advisement

- David Miller (Julie Crockett), July 2015-
- Alden Yellowhorse (Larry Howell), April 2014-
- Adam Cowley (Dan Maynes), April 2013-
- Matthew Searle (Dan Maynes), April 2013-
- Cristian Clavijo (Dan Maynes), April 2013-
- Jason Lund (Brian Jensen), January 2013-
- David Clark (Matthew Jones), February 2013-
- John Sessions (Brian Jensen), PhD Defense, March 2016
- Tyler Macbeth (Matthew Jones), Masters Defense, August 2015
- Daniel Ellis (Dale Tree), Masters Defense, July 2015
- Kim Stevens (Scott Thomson), Masters Defense, June 2015
- Travis Moore (Matthew Jones), PhD Defense, September 2014
- Jeremy Osguthorpe (Matthew Jones), Masters Defense, August 2013
- Daniel Tovar (Dale Tree), Masters Defense, August 2013

Funding Activities

Awarded

1. Co-PI for "Passive Inspection CubeSat (PIC)," NASA Undergraduate Student Instrument Project (USIP) Student Flight Research, $200,000 over 2 years, submitted November 2015 (Long, D., <u>Iverson, B. D.</u>, Warnick, K., Wilde, D., Wirthlin, M.).
2. Co-PI for "Carbon Nanotube Fabrication Approaches Enabling Portable Gas Chromatography Systems," Brigham Young University Mentoring Environment Grant (MEG), $20k over 2 years, awarded December 2015 (Jensen, B., <u>Iverson, B. D.</u>, Vanfleet, R. R.).
3. Co-PI for "Experimental Analysis of Fluid and Thermal Transport on Superhydrophobic Surfaces," Brigham Young University Mentoring Environment Grant (MEG), $19,950 over 2 years, awarded December 2015 (Crockett, J., <u>Iverson, B. D.</u>, Maynes R. D.).
4. PI for "High Aspect Ratio CNT Structures for Electrode Sensors," Iowa State University, $7,000 over 6 months, awarded November 2015 (<u>Iverson, B. D.</u>)
5. Co-PI for "Droplet Formation and Removal Characteristics on Superhydrophobic Nano and Microstructured Surfaces," Moxtek, $35,348 over 1 year, awarded June 2015, (Crockett, J., <u>Iverson B. D.</u>, Maynes, D.).
6. PI for "Dynamic Control of Radiative Surface Properties with Origami-Inspired Design," NASA

Space Technology Research Fellowship for Rydge Mulford, $30,000 over 3 years (Faculty Advisor Allowance; total award worth $222,000 over 3 years), awarded April 2015, (Mulford, R. B., Iverson, B. D.).

7. PI for "Dynamic Control of Surface Radiative Properties through Actuation of Origami-Inspired Surface Topographies," NASA EPSCoR of Utah, $24,851 over 1 year, awarded October 2014, (Iverson, B. D., Jones, M. R.).
8. PI for "Increasing Sensor Signal Strength of Glucose Detection in Amperometric Sensors, Research Initiation Grant, Brigham Young University, $10k over 1 years, awarded July 2014, (Iverson, B. D.)
9. Co-PI for "Droplet Mobility in Superhydrophobic Channels," Utah NASA Space Grant Consortium, Faculty Research Infrastructure Award Program, $21,500 over 1 year, awarded May 2014, (Crockett, J., Iverson, B. D., Maynes, D.).
10. PI for "Dynamic control of radiative absorption and emission through tunable, origami-based geometries," New Faculty Research Proposal, College of Engineering and Technology, Brigham Young University, $10,000 over 1 year, awarded August 2013 (Iverson, B. D.).

Previous to BYU

- Sunshot Lab Proposal Development Process (2012)
  PI for: "Heat exchangers for efficient thermal to electric conversion at high-temperature"
- Sunshot FOA, Department of Energy (2011)
  PI for: "High-temperature enabling receivers for advanced solar-thermal power cycles"
- High Energy Advanced Thermal Storage, ARPA-E (2011)
  Contributed as sub-PI for the following two submissions (both accepted for full-proposals):
  "High performance thermal storage solutions for dish-Stirling systems"
  "Thermal-wave energy storage system"
- Annual Operating Plan, Sandia National Laboratories (2010-2011)
  Prepared sections for submission to the U.S. Department of Energy.
- Indiana 21st Century Microscale Cooling Extension (2006-2007)
  Assisted in a successful $2M grant proposal submitted to the state of Indiana for extension funding of a microscale cooling joint project with Delphi Electronics, Kokomo, IN.
- Cooling Technologies Research Center (2005-2007)
  Proposed new and continuing projects for this NSF funded Industry/University Cooperative Research Center (I/UCRC) in the areas of heat pipe technology and micropumping.
- Air Force Research Lab (2006)
  Prepared supporting material for an AFRL Power Center grant.
- Multidisciplinary University Research Initiative (2006)
  Submitted supporting documents and data for this collaborative grant proposal.
- Office of Naval Research Proposal Abstract (2006)
  Prepared a white paper for submission to ONR regarding an EHD micropump for integrated electronics cooling.

Professional Activities

Courses Taught

- Heat Transfer ME EN 340 (W13, F13, Sp14, F14, Sp15, F15, Sp16)
- Convective Heat Transfer ME EN 643 (W14, W16)
- Intermediate Heat Transfer ME EN 540 (W15)
- Mentored Projects ME EN 497R (W13, F13, W14, Su14, F14, W15, Sp15, F15, W16)
- Capstone Senior Design Coach 475/476
  - 2015-2016 Stryker Plasma Stability Fixture

- 2014-2015 Union Pacific Refrigerated Boxcar Airflow Distribution

Skills

- Device Fabrication and Characterization: Atomic force microscopy, scanning electron microscopy, mask design, lithography, cleanroom safety and procedures, isotropic/anisotropic etching, RIE etching, solution processing, glove box organic processing, thin-film deposition, oxidation
- Software: SolTRACE, CIRCE, Fluent, Gambit, Comsol, AutoCAD, MATLAB, Engineering Equation Solver, Mathcad
- Other: Proficient Japanese, interpersonal skills

Professional Training (Life-Long Learning)

- Speed Networking, August 25, 2015, Brigham Young University
- BYU Grant Writing Bootcamp, May 2015
- BYU Teaching and Learning Seminar
  - "Confessions of a converted lecturer," Eric Mazur, Harvard, March 4, 2015
  - "Teaching the truth," February 3, 2015
  - "Why motives matter," "Increasing Autonomy," December 12, 2014
  - "Homework sized projects, real-world practice," November 4, 2014
  - "Rethinking Exams – Assessing our Assessment," March 4, 2014
  - "Course Organization," February 12, 2014
  - "Conditioning and Retention," December 13, 2013
  - "Partial Credit," November 5, 2013
  - "Communicating expectations and assessment," March 5, 2013
  - "Immediacy," February 5, 2013
- MATLAB for Data Processing and Visualization, April 14, 2010

Professional Societies

- American Society of Thermal and Fluid Engineers
- American Society of Mechanical Engineers
  - Committee Member of Heat Transfer in Energy Systems (K-6)
  - Committee Member Elect of Nanoscale Transport Phenomena (K-9)
- Golden Key National Honor Society
- Tau Beta Pi, Engineering Honor Society

Consulting Activities

- Infinia Corporation, Ogden UT, May 2013. Reviewed thermal energy storage proposal and identified concerns using mineral oil as a heat transfer fluid and highly conductive materials in thermocline beds.

Service

Professional

- Sweet Talk seminar, mentoring freshman mechanical engineering students, March 25, 2016.
- Heat Transfer ME 340 Course Committee Chair, 2015-present
- BYU ORCA Grant Reviewer, 5 proposals, December 2015.
- Grad Expo 2015, graduate student recruiting fair, October 4-5, 2015.
- Session Chair (2 sessions), ASTFE Thermal and Fluids Engineering Summer Conference,

August 9-12, 2015.

- BYU Graduate Studies Fellowship Reviewer, 2 proposals, March 2015.
- Sweet Talk seminar, mentoring freshman mechanical engineering students, February 20, 2015.
- BYU Mechanical Engineering Department 3-Minute Thesis Competition, Organizer
  Held January 26, 2015.
- BYU writing group participant, 2013-present
- BYU ORCA Grant Reviewer, 10 proposals, November 2014.
- Heat Transfer Qualifying Exam Committee, Fall 2014.
- Sweet Talk seminar, mentoring freshman mechanical engineering students, September 5, 2014.
- BYU Graduate Studies Graduate Fellowship Reviewer, 2 proposals, March 2014
- Heat Transfer Qualifying Exam Committee, Winter 2014.
- BYU College of Engineering and Technology 3-Minute Thesis Competition, Judge
  Held January 30, 2014
- BYU Mechanical Engineering Department 3-Minute Thesis Competition, Organizer
  Held December 9, 2013
- BYU ORCA Grant Reviewer, 10 proposals, November 2013.
- Graduate committee, BYU Mechanical Engineering, 2013 – present
  Organized Graduate Seminar Series
  Instituted online community for reporting
  Facilitated schedule and hosted speakers
  Evaluated graduate student applicants twice yearly
  Advised on department fellowship selection
- Curriculum Development Committee, 2013-present
  Engineering practice, 1 credit junior course
- Heat Transfer Qualifying Exam Committee, Fall 2013.
- Sweet Talk seminar, mentoring freshman mechanical engineering students, September 27, 2013.
- Sweet Talk seminar, mentoring freshman mechanical engineering students, April 12, 2013.
- Session Chair, CSP Storage Technologies, ASME Energy Sustainability, July 14-19, 2013.
- Made from Concentrate, CSP seminar chair, Sandia National Laboratories, (2012)
- Session Chair, CSP Power Tower Technologies, ASME Energy Sustainability (2011)
- Equipment and Process User Program "Super User," Birck Nanotechnology Center (2009)
  Advise users and staff of equipment function for training and troubleshooting.
- Volunteer and lab tour guide for Purdue University graduate student recruiting weekends (2003-2008)
- Professional Development Committee Chair for the Nanotechnology Student Advisory Council, Birck Nanotechnology Center, Purdue University (2006-2007)
  Organized resume and curriculum vitae workshop, February 15, 2007.
  Organized industry and faculty career path seminar, April 12, 2007.
- Volunteer Birck Nanotechnology Center escort and lab tour guide, Purdue University (2006-2007)
- Tau Beta Pi, Membership Committee Chair for Utah, Beta Chapter (2001-2002)
- Paper/Funding Reviews:
  Applied Physics Letters, 1 paper, June 2016.
  Journal of Heat Transfer, 1 paper, May 2016.
  International Journal of Heat and Mass Transfer, 1 paper, May 2016.
  Journal of Heat Transfer, 1 paper, April 2016.
  Energy, 1 paper, February 2016.
  ACS Applied Materials and Interfaces, 1 paper, February 2016.
  Solar Energy, 1 paper, November 2015.
  Journal of Heat Transfer, 16 photogallery submissions, September 2015.
  Applied Thermal Engineering, 1 paper, September 2015
  Journal of Heat Transfer, 1 paper, August 2015.
  ASTFE Thermal Fluids Engineering Summer Conference, 2 papers, April 2015.

DOE SBIR/STTR Grant Applications, 2 papers, March 2015.
Journal of Solar Energy Engineering, 1 paper, March 2015.
ACS Applied Materials and Interfaces, 1 paper, March 2015.
Applied Energy, 1 paper, January 2015.
Journal of Electronic Packaging, 1 paper, August 2014.
ACS Applied Materials and Interfaces, 1 paper, August 2014.
International Journal of Heat and Mass Transfer, 1 paper, August 2014.
Journal of Electronic Packaging, 1 paper, July 2014.
Experimental Heat Transfer, 1 paper, June 2014.
Journal of Fluids Engineering, 1 paper, June 2014.
International Journal of Electrical Power and Energy Systems, 1 paper, May 2014.
ASME International Mechanical Engineering Congress and Exposition, 2 papers, May 2014.
Sensors and Actuators B: Physical, 1 paper, March 2014.
International Journal of Heat and Mass Transfer, 1 paper, March 2014.
Journal of Solar Energy Engineering, 1 paper, January 2014.
ASME Turbo Expo 2014, 1 paper, November 2013.
Journal of Fluids Engineering, 1 paper, November 2013.
Energy Conversion and Management, 1 paper, September 2013.
Solar Energy, 1 paper, August 2013.
Solar Energy, 1 paper, June 2013.
ASME International Mechanical Engineering Congress and Exposition, 1 paper, May 2013.
Renewable and Sustainable Energy Reviews, 1 paper, May 2013.
ASME Summer Heat Transfer Conference 2013, 1 paper, March 2013.
DOE SBIR/STTR Grant Applications, 1 paper, March 2013.
ASME Turbo Expo 2013, 1 paper, December 2012.
Energy Sustainability 2012, 1 paper, March 2012.
Materials Science and Engineering B, 1 paper, September 2011.
Applied Energy, 1 paper, September 2011.
International Journal of Heat and Mass Transfer, 1 paper, August 2011.
Energy Sustainability 2011, 2 papers, April 2011.
Journal of Solar Energy Engineering, 1 paper, January 2011.
SBIR/STTR Grant Applications, 3 papers, January 2011.
Journal of Micromechanics and Microengineering, 1 paper, May 2010.
Journal of Heat Transfer, 1 paper, February 2010.
Solar Energy, 1 paper, February 2010.
Journal of Micromechanics and Microengineering, 1 paper, June 2009.
International Journal of Refrigeration, 1 paper, May 2009.
Journal of Fluids Engineering, 1 paper, December 2008.
Electronics Packaging Technology Conference, 1 paper, October 2008.
Journal of Electronic Packaging, 1 paper, July 2008.
Journal of Heat Transfer, 1 paper, June 2008.
Microfluidics and Nanofluidics, 1 paper, May 2008.
ITherm 2008 Conference, 1 paper, January 2008.
Microfluidics and Nanofluidics, 1 paper, November 2007.
ASME International Mechanical Engineering Congress and Exposition, 1 paper, 2005.

Outreach

- Utah STEM Fest, hands on experiences with science and technology to encourage young interest, February 2-4, 2016.

- Wasatch Elementary Science Presentation, Provo School District, "Why is that bugs can stand on water? – surface tension and hydrophobicity," November 17, 2014.

Community

- AYSO Soccer Coach, Albuquerque, NM (2011-2012)
- AYSO Referee, Albuquerque, NM (2010-2011)
- Webelos Den Leader, Boy Scouts of America (2010-2011)
- Premier Soccer Academy Coach, Albuquerque, NM (Spring 2010)
- English Conversation Facilitator, Daily Dose Program, NC (Summer 2007)
- Volunteer missionary, Okayama, Japan, The Church of Jesus Christ of Latter-Day Saints (1997-1999)
- BYU Honor Code Committee Volunteer (1996-1997)

Appendix F

Advanced Neural Net Controls

University of Utah

Research Proposal

CLEAN COAL ENABLED BY ARTIFICIAL INTELLIGENCE

A research project for the Utah Sustainable Transportation and Energy Plan

PacifiCorp Contact
Glenn Pinterich (Project Manager)
PacifiCorp
Huntington Power Station
Huntington, Utah 84528
glenn.pinterich@pacificorp.com

University Contact
Prof. Kody Powell (Principal Investigator)
The University of Utah
Department of Chemical Engineering
50 S Central Campus Dr., Rm 3290G
Salt Lake City, Utah 84112
801-581-3957
kody.powell@utah.edu

Participating Members

Participant	Organization	Role
Glenn Pinterich	PacifiCorp – Huntington Power Station	Project Manager
Michael Dayton	PacifiCorp – North Temple Office	Technical Advisor
Ian Andrews	PacifiCorp – North Temple Office	Project Oversight
Prof. Kody Powell	U. of Utah Dept. of Chemical Engineering	Principal Investigator
Jake Tuttle	U. of Utah Dept. of Chemical Engineering	Graduate Researcher
Brad Radl	Taber International / Griffin Open Systems	Vendor/Tech. Support
Prof. John Hedengren	BYU Dept. of Chemical Engineering	Technical Advisor

Proposed University of Utah Budget: **$395,205**

Contents

Project Summary 3
Background 3
Overview of Artificial Neural Networks in Coal Combustion Optimization 3
ANNs for NOx Emissions Minimization and Efficiency Improvements 4
Overview of Research Challenges 5
Objectives and Deliverables 6
1. Install and Support Artificial Intelligence Software 7
2. Document Emissions Reductions and Heat Rate Improvements 7
3. Address Fundamental Research Challenges 7
Project Deliverables by Organization 8
Timeline 9
Budget 11
Project Team 11
Conclusion 12
References 13

PROJECT SUMMARY

The University of Utah will partner with PacifiCorp's Huntington power station and Taber International/Griffin Open Systems to install, demonstrate, and fundamentally research artificial intelligence technologies to improve emissions of coal-fired power systems. The software-based technology provided by Griffin Open Systems™ is primarily based on artificial neural networks (ANNs), which are proven data-driven modeling techniques used to mathematically describe complex processes, such as coal combustion for power generation. ANNs are used to mathematically "learn" the process, particularly the relationships between inputs (e.g., valve positions, flow rates, damper positions, etc.) and important outputs (e.g., NO_x generation rate, plant efficiency, power output, etc.), through a mathematical model-fitting routine. Using this empirical mathematic model of the process, rigorous optimization routines can be used to determine the optimal combination of inputs to give a desired change in an output (e.g., finding the conditions that minimize NO_x emissions, maximize efficiency, or a combination of both). Because the process is continually changing as conditions change, the software is used to continuously update the model and re-solve for optimality.

The proposed project is ideal in a number of ways: 1) The project has an assurance of success as the base technology has been commercially demonstrated and will have the engineering support of a vendor with decades of experience in coal plant optimization. 2) There are many research opportunities to improve the technology on the topics of intelligent model fitting and dynamic optimization through transient operation due to fast ramping of the plant (caused by increased renewables on the grid). 3) The project is extremely low cost as it is completely software-based and does not require a large capital project to retrofit the plant. 4) The technology is immediately scalable to other units. 5) The technology will have an indefinite emissions benefit if the plant chooses to extend to a permanent software license. 6) The primary research team members are experienced in neural networks and process optimization and are local to Emery County (home of the plant site). They have a vested interest in the plant's performance and will spend a significant amount of time on-site to ensure the project's success.

BACKGROUND

Overview of Artificial Neural Networks in Coal Combustion Optimization

Optimizing a process entails selecting the best combination of input (decision) variables that give an optimal value of an output variable (i.e., maximizing efficiency, maximizing profit, or minimizing cost). Real-time optimization (RTO) is commonly used in many industries and is an ideal technology to implement because of its high benefit-to-cost ratio, as it only requires software while using existing plant instrumentation and control systems [1–3]. RTO requires the use of an accurate mathematical model of the process so that the model can be solved in real-time to determine the optimal operating conditions of the plant. The process of coal combustion for power generation is so complex that physics-based models are too computationally intensive to be solved in real-time. Because of this, data-driven, empirical models (such as ANNs) are typically used for RTO of coal plants [4–7]. ANNs have proven to be very effective at predicting plant performance, with studies indicating an **average error of 1.35% or less for prediction of output variables** [8].

An artificial neural network is a type of mathematical modeling structure. ANNs are designed to mimic the human brain's mechanism for learning and retaining information by storing it in chemical and electrical signals, which increase in response to environmental stimulii. A simplified structure of an ANN is shown in Figure 1. In this figure, *u* represents the inputs (e.g., valve positions, temperature set points, excess O_2, etc.) and *y* represents the output, of which there can be many (NOx emissions, heat rate, etc.). The greek letters (ϕ and Ω) are mathematical "activation" functions, which produce a certain response to the inputs and the weighting parameters (*w* and *W*). When given a set of real data from the plant, the weighting parameters can be adjusted using a rigorous mathematical model-fitting routine so that the model's outputs (*y*) closely match the plant data, which the model is trying to predict [9]. As the process changes, new weighting parameters can be found so that the model stays accurate, despite an ever-changing process. While the figure shows a very basic representation of a neural network model structure (known as a three layer perceptron), there are many different types and configurations of neural network models, depending on the application. The models can also be combined with other types of models or algorithms in a hybrid configuration.

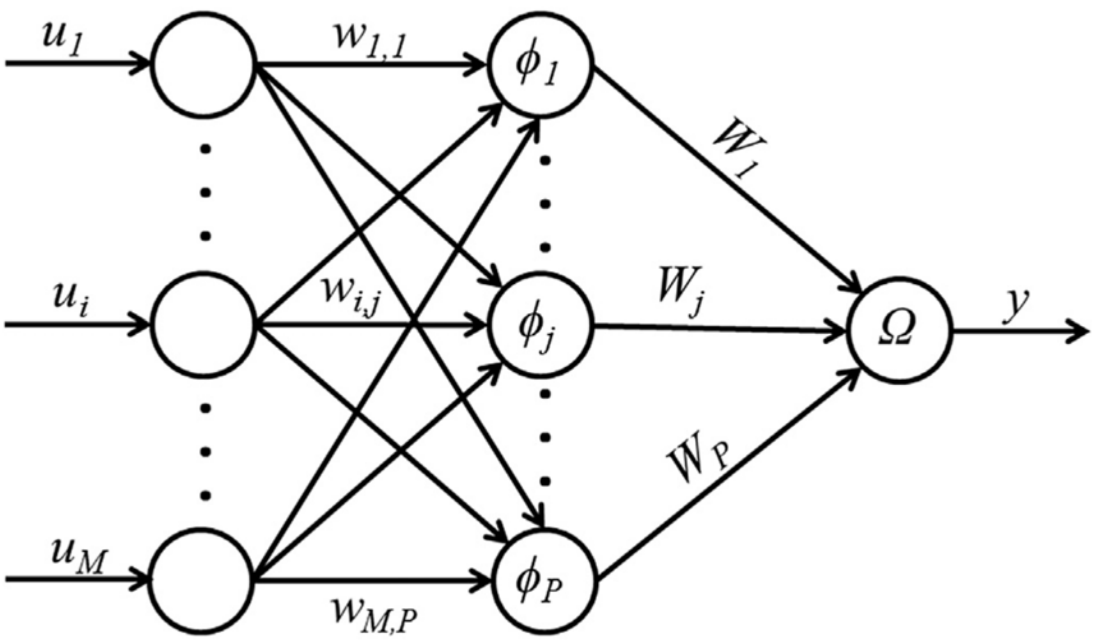


Figure 1: A visual representation of an artificial neural network (ANN). The ANN takes in inputs (*u*) to predict a specified output (*y*) using groups of mathematical functions (ϕ and Ω). The weights (*w* and *W*) are adjusted algorithmically so that the output matches plant data as closely as possible. Figure available from Powell et al. [9]**.**

ANNs for NOx Emissions Minimization and Efficiency Improvements

Once an accurate model of the process is found, the model is solved using a mathematical optimization routine to determine the set of inputs (*u*) that give the best output (*y*). If the objective is to mimizine NOx in a coal plant, for example, the ANN model can be solved to determine the optimal process inputs that give minimal NOx, given the current set of environmental conditions. This has been done with much success industrially. **Studies have shown NOx reductions of up to 48% and CO reductions of 75%** [10].

Similarly, neural network optimizers focused on **heat rate improvements save an estimated 0.5-1.5%**, which means a proportional amount of fuel and CO_2 emissions savings [11]. A preliminary estimate of the savings that could be achieved by a typical coal power plant using neural network optimization technology is summarized in Table 1. These projections for the Huntington Plant are for two units operating at full load, so it should be noted that the initial research project will only focus on a single unit. However, the results would be scalable by deploying the software to multiple units in the future. The software application must also be tuned so that it achieves an ideal balance between NOx emissions minimization and efficiency maximization, whose optimal solutions may not perfectly coincide.

Table 1: Preliminary estimates of anticipated annual savings for two units at full load at the Huntington plant using by neural network RTO with heat rate minimization as the primary objective.

Description	**Quantity**
Plant Output	895 MWe
Heat Rate [12]	10080 Btu/kWh
Fuel cost per unit energy [13]	$1.63 per MMBtu
Fuel cost per year	$130,000,000 per year
Projected heat rate improvement [11]	0.5-1.5 %
Projected savings for full-load operation	$650K-$1.9M per year
Projected CO_2 savings [14]	40,000-122,000 tons/yr

Overview of Research Challenges

Although neural network optimization technology has proven to be an effective and low cost clean coal technology, there are still many opportunities to improve the technology. One of the key issues is that the process can drift over time, which makes the model less accurate and the optimization results less relevant. Although the existing technology employs methods to continuously update the model, changes in the process, such as the loss of sensors or actuators or sudden shifts in operating conditions can cause adversely impact the model's accuracy. This in turn causes deactivation of the software application by plant operators, which eliminates any potential emissions benefit. To keep the model evergreen and ensure long-term operator adoption, intelligent model adaptation routines are needed. These routines would continuously monitor the process's health, statistically detect anomalies, and systematically make changes to the process inputs so that the model can "re-learn" the response. Currently, the technology requires a trained engineer to initialize the model, including finding the best model structure, given the current set of functioning sensors and actuators. Continuous re-fitting of the model can change the model parameters to keep the model accurate, but it generally does not change the model's structure. Methodologies for continuously monitoring the health of the process, the model, and any instrumentation are needed. By keeping the model up to date by re-fitting, intelligently updating the model structure, or alerting an engineer or operator when the process needs physical maintenance, the software can have long-term operator adoption and require minimal manpower to sustain.

Another critical research topic has a arisen as a result of increased penetration of variable renewable power sources on the grid in recent years. Solar and wind energy are intermittent in nature and their fluctuations generally cause fuel-based power plants to ramp up and down to maintain the frequency on the grid. In California, major grid instabilities are projected as a result of unprecedented amounts of renewables on the grid, which will cause fuel-based plants to ramp up and down at somewhat extreme ramp rates [15,16]. Projections show that increased penetration of intermittent renewables causes (what once were considered) baseload power sources (coal and nuclear) to change loads with rapid ramping in order to enable renewables, as Figure 2 demonstrates [17]. From an optimization point of view, extreme ramping like that shown in the figure makes it much more difficult to optimize. Real-time optmization is generally based on the idea of steady-state operation of a process, which is the assumption that the process is relatively constant for at least a short period of time. A dynamically-changing process is more difficult to optimize as the operating conditions of the plant are always shifting. By extending the neural network model to be dynamic, optimization can be performed over a time horizon, rather than at a single instance in time. The proposed researchers have expertise in dynamic optimization [18–21] and believe this is an area where a significant impact can be made in research and in efficient grid operation. Dynamic optimization of a ramping coal plant would become a renewable energy-enabling technology because it could be used to maintain grid stability even under extreme ramping conditions.

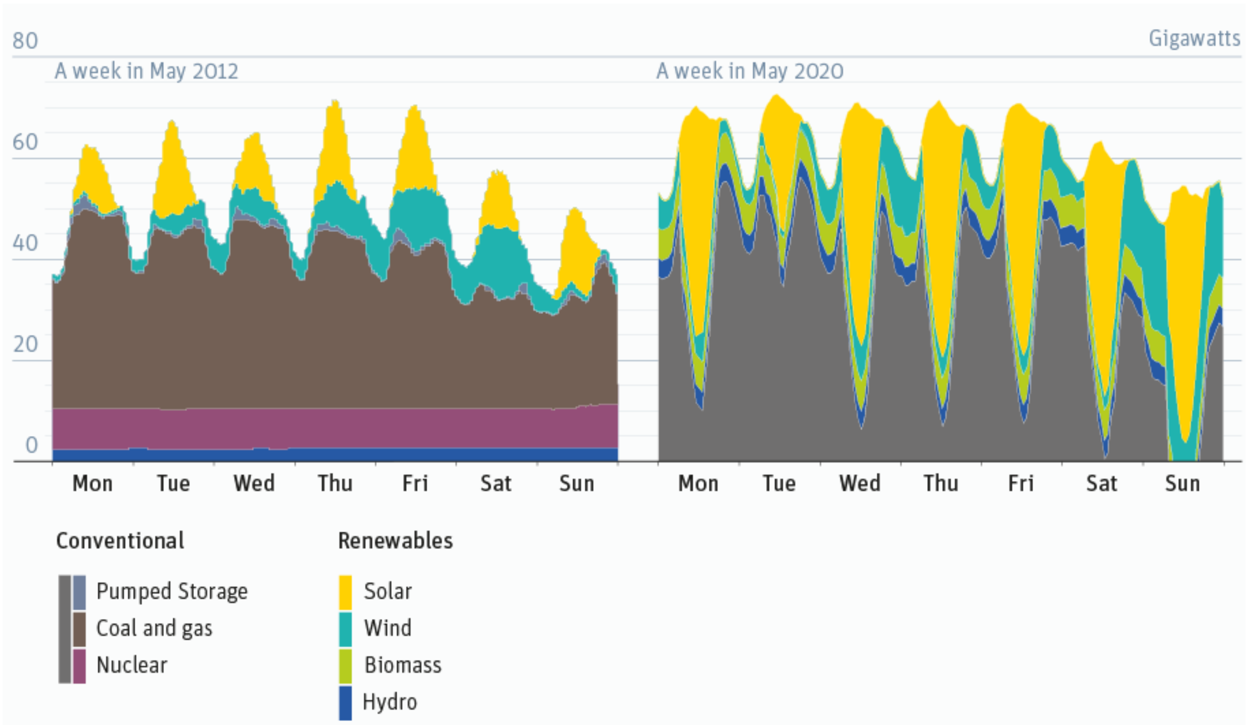


Figure 2: Load profiles for 2012 and projected in 2020 with high renewable penetration. Optimization under rapid ramping conditions is a key research objective. Figure available from [17]**.**

Another major opportunity for improving plant operations is in optimizing the many auxiliary processes required for power generation. While neural network optimization technology is predominantly used for combustion optimization in the boiler, auxiliary units such as cooling towers, scrubbers, the generator, etc, can also be optimized to improve the efficiency of the entire operation, not only the boiler. At low load, auxiliary power consumption can increase heat rate by up to 21% compared to full-load operation [22]. Modeling and optimizing these auxiliary processes via neural network technology, therefore, will provide additional opportunities to improve the overall efficiency of the plant.

OBJECTIVES AND DELIVERABLES

The proposed project represents an ideal combination of safe and potentially transformative. It will leverage existing, proven technology to ensure measurable emissions reductions, but will also explore cutting-edge research topics to improve the software in the face of new operational challenges. The objectives of the project are summarized in the following sections.

1. Install and Support Artificial Intelligence Software

The primary objective of the project will be to successfully deploy the neural network software application as well as the Griffin Intelligent Sootblowing application and ensure their adoption and long-term use. This will be accomplished by working with Taber International, who will provide up-front engineering services to install the Griffin Open Systems neural network optimization software and work through any technical issues related to its deployment. The sub-contract to Taber/Griffin will include maintenance and licensing fees and ensure their ongoing support of the software application. The University of Utah researchers will work closely with Taber to master the software so that they can provide additional support to maintain and improve the application. The University of Utah researchers will spend a significant amount of time on-site at the Huntington Plant to become well-acquainted with the process and the personnel. A graduate student researcher will spend the summer months working full-time at the site and will also work full-time at the site once graduate coursework has been completed. University personnel will provide ongoing training to plant personnel on how to use the software. They will also continually monitor the application (on site or remotely) and implement modifications and improvements as they are developed. For the duration of the project, university personnel will be on call to ensure a high service factor and long-term adoption for the software.

2. Document Emissions Reductions and Heat Rate Improvements

As a clean coal research and development project, a critical objective will be to measure and document the emissions and heat rate improvements that can be attributed to the use of the neural network software. Using previous years as a baseline, the plant's performance will be tracked and reported on each year. As the implementation of optimization software is a learning process (for the personnel as well as for the software), a gradual improvement in plant emissions are anticipated as recommendations and improvements are progressively implemented. Research personnel will formally report to PacifiCorp management from the plant and from the North Temple Office on a quarterly basis to present recent results and discuss ongoing improvement recommendations. The research team will also release a final report at the project's conclusion to report on the progress made during the three-year research project.

3. Address Fundamental Research Challenges

At its core, the research project is an artificial intelligence project, which presents many fundamental research challenges. Specific to coal-fired power, some of the key research issues to be addressed are finding methods to keep the model evergreen using intelligent model adaptation as the plant's processes drift or change over time. While the Griffin software currently has a continuous "learning" feature where the model is re-fit periodically every few hours, long-term issues may arise as sensors or actuators degrade and become unreliable or new instrumentation is added. Fundamental process changes like these would typically require a new model structure to account for more or fewer inputs. During the project, intelligent methods for finding a new model structure and fitting the model will be explored on a simulation basis by the research team. These may be tested in the live plant application pending a thorough review process and approval from plant personnel.

A related key research objective will be intelligent process and application health monitoring. To address this objective, the researchers will explore statistical methods to detect when the process or the model have faults that may be caused by malfunctioning equipment or performance degradation over time. In these instances, action taken by plant engineering or maintenance personnel would be required and an automated response by the software would not be sufficient. Upon development and inclusion of adequate fault detection methods, the research team will explore automated alerting of plant personnel and study the impact this might have on efficiency and equipment lifetime.

The research team will go beyond neural network optimization of the combustion process in the boiler and will explore opportunities to improve overall efficiency by applying the neural network optimization technology to the plant's auxiliary processes, including pumps, fans, and compressors. Where variable frequency drives (VFDs) are available, the team will explore optimization of these process components to determine the optimal speed that results in reduced overall power consumption. Major auxiliary process equipment that the team will explore optimizing includes cooling towers, the flue gas desulphurization unit (scrubber), electrostatic precipitators, and the generators. Working with the Griffin Intelligent Sootblowing application, the project team will also study optimal sootblowing so that the boiler process efficiency is maximized while minimizing the use of auxiliary steam to accomplish this periodic maintenance task.

Another major challenge facing the coal power plants worldwide is the rapid ramping that is required as intermittent renewable energy becomes more and more prevalent on the grid. Dynamic optimization so that a plant can still perform optimally even during changing load will be addressed by the research team. These potential enhancements to the software will be developed offline in a simulation environment and will be introduced to the plant only if success at the simulation level proves to be effective. This will also require approval from plant personnel before any modifications are implemented.

As in any process automation application, the more sensor data that is available, the better. As the team works to install and develop the optimization application, they will also explore the use of additional or upgraded sensors to improve plant operations. Where appropriate, recommendations including a detailed cost/benefit analysis will be made to plant personnel.

While challenging, the research that emerges as a result of approaching these problems could have an impact far beyond a single power plant. With fuel-fired power plants around the world facing similar issues with transient operation due to intermittent renewables on the grid, solutions to these problems have the potential to have a substantial impact on society.

Project Deliverables by Organization

Table 2: Description of deliverables from each participating entity.

PacifiCorp
• *Provide project oversight* • *Provide training/guidance on utility-scale coal combustion optimization* • *Provide guidance on performance metrics to be monitored and the direction of the optimizer implementation* • *Provide feedback on report conclusions.* • *Establish KPI's for success, e.g., NOx <0.15 lbs/mmbtu, CO less than Permitted value, 0.75% Net Unit Heat Rate (NUHR) reduction, etc.* • *Provide office for U of U student/faculty* • *Provide and prepare server for optimizer, communication link, DCS modifications*
University of Utah

- *Perform parametric study of the test unit throughout the entire process; prior to installation of the optimizer, during the installation, during the learning phase and after the optimizer is online to test the effectiveness of the various inputs. This study would at a minimum identify the most effective control loops to be available for the neural network combustion optimizer. It will also identify the need of additional instrumentation and controls.*
- *Assist PacifiCorp and Taber Int. personnel with the installation/implementation of the optimizer. Evaluate the neural network in operation and provide recommendations for improvement and process control expansion e.g., adding additional control loops, expand usage to include auxiliary plant processes like; cooling tower fan control, scrubber control, or any process that has remotely controlled parameters. In that vein also evaluate which process might benefit for the addition of remote control that could be optimized.*
- *Assist PacifiCorp (and possibly 3rd party tuners) personnel with unit optimization and evaluate the effects of that optimization and how the optimizer responds to that optimization.*
- *Evaluate factors that may discourage system usage e.g., poor human machine interface, excessive maintenance, lack understanding or distrust of "intelligent" control, insufficient instrumentation and or controls. Where possible identify mitigation opportunities for the identified problems and aid in their implementation.*
- *Provide additional ongoing training to plant operators and other plant personnel in the operation of neural network optimization*
- *Help to establish KPI's for success, e.g., NOx <0.15 lbs/mmbtu, CO less than Permitted value, 0.75% Net Unit Heat Rate (NUHR) reduction, etc.*
- *Report on the performance of the neural network optimizer with regard to usage level, benefit received, benefits lost and improvement recommendations*
- *Provide year round onsite coverage (have personnel on site at least two days a week once application has been commissioned)*

Taber International

- *Provide software*
- *Provide engineering support for installation*
- *Provide engineering product support*
- *Provide best practice guidance based on installed base experience*
- *Provide training for software implementation and modification*

Brigham Young University

- *Provide additional technical guidance on research aspects of project*

TIMELINE

The proposed project is for a duration of three years, which will be required to reach the above-specified objectives. While the software can be installed in a matter of weeks, optimizing its usage may take years. This includes a long run-time to ensure that plant operations personnel become comfortable with its use through training and troubleshooting, identifying opportunities to improve the software's functionality through improved sensors and actuators in the process, and exploring techniques to better model and optimize the process. The fundamental research objectives are also challenging problems that are long-term in nature and will require multiple years to develop and possibly implement.

For the duration of the project, the research team will prioritize spending as much time on site as possible. When project personnel are not living in proximity of the plant (primarily due to required university coursework in Salt Lake City), they will continue research including providing remote support, on call support, and will make regularly scheduled visits to the plant site. An approximate schedule is included in Table 3.

Table 3: An approximate project schedule indicating the anticipated number of days on site per month in each period.

Period	***Approximate Days On Site/Month***	***Objectives***
Preparation Work		
Jan. 2017 – Apr. 2017	2	• Student learns Griffin Open Systems Software and develops test applications for simulated processes • Plant repairs/installs instrumentation + server and prepares for software installation • Scheduling with Taber/Griffin for engineering services is complete • Multiple visits by student researcher and adviser to get acquainted with process, site personnel, and installation progress • Possible Ameren site visit by U of U and PacifiCorp
Installation and initial data collection		
May 2017- Aug. 2017	20	• Installation of Griffin Combustion Optimization and Intelligent Sootblowing applications completed in mid-May • Student researcher is on site 40 hrs/wk to oversee installation, work with operators to identify any adoption issues, begin data collection, and identify any potential issues with software application
Ongoing research project		
Sept. 2017- Apr. 2018	8	• Remote monitoring / on call application support • Continuous improvement of application through programming enhancements, instrumentation improvement recommendations, operator training, interface enhancements • Documentation of improvement for emissions, fuel savings, etc. • Research into dynamic optimization through plant power set-point transitions • Final report on project
May 2018- Aug. 2018	20	
Sept. 1 2018- Apr. 2019	8-20	
May 2019- Dec 2019	10-20	

BUDGET

The University of Utah portion of the budget for the project is $395,205 and is summarized in Table 4. The budget includes salaries for university personnel including one-month of salary per year for the project PI and eighteen months per year for graduate researchers. Travel, living, and per diem costs are also included. The researcher support and travel funds will assure that university personnel can spend an adequate amount of time on site to develop and support the application for the duration of the project.

Table 4: The University of Utah budget summary for the project, which includes university personnel salaries and benefits, travel costs, and all overhead charges.

	2017	*2018*	*2019*	***Total***
Salaries w/ overhead	$90,985	$92,805	$94,661	**$278,451**
Travel, living expenses, and per diem w/ overhead	$37,698	$37,698	$41,358	**$116,754**
Total	**$128,683**	**$130,503**	**$136,019**	**$395,205**

The comprehensive budget will be managed and distributed by PacifiCorp and also includes $320,000 in up-front costs for Taber International for engineering services ($160,000) and a single unit license ($160,000) and a total of $96,000 for three years of licensing fees for the software from Griffin Open Systems. Engineering services entail multiple trips to the site from Taber personnel to install the software and ensure that everything is running correctly. Return trips will be made to make adjustments as necessary and will include training for plant personnel. These upfront costs ensure turnkey use of the software. Annual maintenance fees of $32,000 per year will be distributed to Griffin Open Systems for use of the Griffin neural network Combustion Optimization and Intelligent Sootblowing software applications. At the end of the project, the licensing fee may be applied toward a permanent corporate license, which has a cost total of $1,000,000 (PacifiCorp would be required to supply the remaining $840,000).

PROJECT TEAM

PacifiCorp engineering personnel, led by Glenn Pinterich at the Huntington Plant, will provide project management and oversight. PacifiCorp's engineering team will provide technical expertise in the process and will have responsibility for all final decisions on the project.

In addition to PacifiCorp personnel, the proposed project team has both the expertise and vested interest in the project to ensure success. The Principal Investigator, Prof. Kody Powell, has worked previously for ExxonMobil Research and Engineering as an expert in advanced control and optimization of utility networks. His background includes developing model predictive control (MPC) and real-time optimization (RTO) applications for combined heat and power systems for ExxonMobil refineries and chemical plants across the country. Prof. Powell has developed neural network models used for predicting energy demands for a district energy system [9] and he also has expertise in dynamic optimization, with research focused on developing novel dynamic optimization algorithms to take advantage of energy storage [18,21,23]. Prof. Powell is a native of Huntington, Utah and has a strong desire to do research projects which can benefit the people of Emery County.

Jake Tuttle is a student researcher in the Department of Chemical Engineering at the University of Utah and is committed to pursuing a Ph.D. Jake is also a native of Emery County and is excited about the prospect of living in Emery County while completing his graduate research work. Jake is currently near the top of his class in chemical engineering and holds a 3.92 GPA. He has experience in Java Programming (which Griffin Open Systems is based on).

Brad Radl is the founder, President, and Chief Technology Officer of Taber International and Griffin Open Systems. His companies have decades of experience in coal power plant optimization. His companies, based in Chardon, Ohio, provide engineering services, installation, licensing, and maintenance of their software products. Griffin Open Systems Combustion Optimization is based on neural network technology, but provides an open platform that can be easily customized by plant personnel. His software products have proven to be very effective at reducing NOx and improving heat rate and plants for decades [24].

Prof. John Hedengren is a professor in Chemical Engineering at Brigham Young University. He has worked for ExxonMobil Chemical and PAS, Inc. as an advanced control and optimization expert. Prof. Hedengren's research is focused on advanced control and optimization of upstream oil operations, unmanned aerial vehicles, and energy systems. Prof. Hedengren has developed his own dynamic optimization software, which has been used in a number of industrial and research application areas [21]. Prof. Hedengren will serve on the project as an additional technical advisor.

CONCLUSION

The proposed project is an ideal opportunity to deploy and demonstrate clean coal technology with a high probability of success and a very high benefit-to-cost. This software-based technology does not require major capital expenses, as most clean coal technologies would, and can be permanently adopted by the Huntington Plant and easily scaled across the entire PacifiCorp fleet. Although the technology is essentially turnkey, there are still many improvements to be made in a research project, including documenting the emissions benefits and improving the technology with intelligent model-fitting routines for long-term operator adoption and optimizing under ramping conditions to better enable renewable energy technologies on the grid. The technology has proven to be effective at reducing both NOx and CO_2 emissions and will make a positive impact on plant operations. Because the research project is focused on artificial intelligence in a power generation facility, the research has potential to extend beyond coal plants and be applied to combined cycle power generation processes and even technologies outside of the power industry.

Members of the project team have deep roots in Emery County and will be able to spend large portions of the project actually working in the plant. This will ensure that the software is effective and that plant operators are comfortable using the technology, so that high service factors can be achieved to reduce emissions to the fullest extent possible. The project team will have a vested interest in doing whatever they can to improve operations at the Huntington plant.

REFERENCES

[1] Adamson R, Hobbs M, Silcock A, Montague G. Real Time Optimisation of Industrial Gas Supply Networks. IFAC-PapersOnLine 2015;48:355–60. doi:10.1016/j.ifacol.2015.08.207.

[2] Acevedo P. AM, Graciano JEA, Liporace FDS, Vianna AS, Roux GAC Le. Decomposition Techniques for the Real-time Optimization of a Propylene Production Unit. Comput. Aided Chem. Eng., vol. 37, 2015, p. 893–8. doi:10.1016/B978-0-444-63578-5.50144-4.

[3] Bindlish R. Power scheduling and real-time optimization of industrial cogeneration plants. Comput Chem Eng 2016;87:257–66. doi:10.1016/j.compchemeng.2015.12.023.

[4] Wang X, Ma L, Wang B, Wang T. A hybrid optimization-based recurrent neural network for real-time data prediction. Neurocomputing 2013;120:547–59. doi:10.1016/j.neucom.2013.04.016.

[5] Zhu Q, Jones J., Williams A, Thomas K. The predictions of coal/char combustion rate using an artificial neural network approach. Fuel 1999;78:1755–62. doi:10.1016/S0016-2361(99)00124-6.

[6] Cheng J, Wang X, Si T, Zhou F, Wang Z, Zhou J, et al. Maximum burning rate and fixed carbon burnout efficiency of power coal blends predicted with back-propagation neural network models. Fuel 2016;172:170–7. doi:10.1016/j.fuel.2016.01.035.

[7] Cheng J, Wang X, Si T, Zhou F, Zhou J, Cen K. Ignition temperature and activation energy of power coal blends predicted with back-propagation neural network models. Fuel 2016;173:230–8. doi:10.1016/j.fuel.2016.01.043.

[8] Smrekar J, Assadi M, Fast M, Kuštrin I, De S. Development of artificial neural network model for a coal-fired boiler using real plant data. Energy 2009;34:144–52. doi:10.1016/j.energy.2008.10.010.

[9] Powell KM, Sripasad A, Cole WJ, Edgar TF. Heating, cooling, and electrical load forecasting for a large-scale district energy system. Energy 2014;74:877–85. doi:10.1016/j.energy.2014.07.064.

[10] Rambalee P, Gous G, de Villiers PG., McCulloch N, Humphries G. Control and Stabilization of a Multiple Boiler Plant: An APC Approach. IFAC Proc Vol 2010;43:109–14. doi:10.3182/20100802-3-ZA-2014.00027.

[11] Sargent & Lundy LLC. Report to EPA: Coal-Fired Power Plant Heat Rate Reductions. 2009.

[12] EIA. Average tested heat rates by prime mover and energy source 2007-2014. Energy Inf Adm 2016. http://www.eia.gov/electricity/annual/html/epa_08_02.html (accessed March 14, 2016).

[13] EIA. Coal Markets 2016. http://www.eia.gov/coal/markets/#tabs-prices-2 (accessed March 11, 2016).

[14] EIA. U.S. Energy Information Administration: Carbon dioxide emissions from different fuels n.d. https://www.eia.gov/tools/faqs/faq.cfm?id=73&t=11.

[15] CAISO. What the duck curve tells us about managing a green grid. Calif ISO, Shap a Renewed Futur 2012;Fact Sheet:1–4. doi:CommPR/HS/10.2013.

[16] Crawford J. The California `Duck Curve' That Will Jolt Its Power Grid. Bloom Bus 2015. http://www.bloomberg.com/news/articles/2015-10-21/california-s-duck-curve-is-about-to-jolt-the-electricity-grid (accessed February 3, 2016).

[17] Bertram R. Renewables Need Flexible Backup, Not Baseload. Energy Transit 2015.

[18] Powell KM, Hedengren JD, Edgar TF. Dynamic optimization of a hybrid solar thermal and fossil fuel system. Sol Energy 2014;108:210–8. doi:10.1016/j.solener.2014.07.004.

[19] Powell KM, Hedengren JD, Edgar TF. Dynamic optimization of a solar thermal energy storage system over a 24 hour period using weather forecasts. 2013 Am. Control Conf., IEEE; 2013, p. 2946–51. doi:10.1109/ACC.2013.6580282.

[20] Powell KM, Cole WJ, Ekarika UF, Edgar TF. Optimal chiller loading in a district cooling system with thermal energy storage. Energy 2013;50:445–53. doi:10.1016/j.energy.2012.10.058.

[21] Hedengren JD, Shishavan RA, Powell KM, Edgar TF. Nonlinear modeling, estimation and predictive control in APMonitor. Comput Chem Eng 2014;70:133–48. doi:10.1016/j.compchemeng.2014.04.013.

[22] IEA. Power Generation from Coal Measuring and Reporting Efficiency Performance and CO 2 Emissions. 2010.

[23] Kim JS, Powell KM, Edgar TF. Nonlinear model predictive control for a heavy-duty gas turbine power plant. 2013 Am. Control Conf., IEEE; 2013, p. 2952–7. doi:10.1109/ACC.2013.6580283.

[24] Radl B. Neural networks prove effective at NOx reduction. Mod Power Syst 2000.

KODY M. POWELL, PH.D.

Salt Lake City, UT | kody.powell@utah.edu | kodypowell.che.utah.edu | 801-581-3957

WORK EXPERIENCE

The University of Utah Department of Chemical Engineering, SLC, UT 2016-Present
Assistant Professor in Energy Systems Research
Research in energy systems with a specialty in modeling, optimization, advanced control, and energy storage

ExxonMobil Research and Engineering, The Woodlands, TX 2015
Real-Time Optimization Research and Development Engineer
Real-time optimization development and global support for refining and chemical plant utility networks, first principles process modeling and estimation for fault detection

ExxonMobil Refining and Supply, Baytown, TX 2013-2015
Senior Engineer in Advanced Control and Optimization
Model predictive control, real-time optimization, and distributed control system development for refinery-wide utilities, gasoline blending, environmental

The University of Texas at Austin – Utilities and Energy Management 2012 – 2013
Project Leader for Large-Scale Utilities Optimization Project
Dynamic real-time optimization of campus-wide utilities (electricity heating, and cooling), energy demand forecasting, model development for gas and steam turbines, waste heat boilers, centrifugal chillers, cooling towers, energy storage system

ExxonMobil Research and Engineering, Baytown, TX 2011
Internship in Model Predictive Control and Real-Time Optimization
Evaluated advanced control software packages, developed algorithms for model predictive control and state estimation

Fairchild Semiconductor, West Jordan, UT 2006 – 2009
Process Engineering Co-Op
Planned and executed projects and experiments related to diffusion and chemical and physical vapor deposition processes

TEACHING

The University of Utah

Heat Transfer (anticipated)	2016
Advanced Data Analytics in Smart Manufacturing (anticipated)	2017

The University of Texas at Austin

Teaching Assistant – Optimization 2013

Co-Instructor – Senior Unit Operations Lab 2009-2012

Teaching Assistant – Energy Technology and Policy 2011

EDUCATION

The University of Texas at Austin, Austin, TX

Ph.D. in Chemical Engineering 2013

Dissertation: "Dynamic Optimization of Energy Systems with Thermal Energy Storage"

The University of Utah, Salt Lake City, UT

B.S. in Chemical Engineering, Chemistry Minor 2009

Magna cum Laude

AWARDS

Cockrell School of Engineering Fellowship 2009-2013
The University of Texas at Austin

Graduate Research Fellowship 2009-2012
The National Science Foundation

Oblad Silver Medal of Excellence 2009
The University of Utah Department of Chemical Engineering

Outstanding Senior Award 2009
AIChE University of Utah Chapter

Presidential Scholarship and Oblad Energy Scholarship 2002-2009
The University of Utah

PEER-REVIEWED JOURNAL PUBLICATIONS

[13] "Thermal energy storage to minimize cost and improve efficiency of a polygeneration district energy system in a real-time electricity market"
K.M. Powell, A. Sriprasad, W.J. Cole, T.F. Edgar
Energy, In Press 2016

[12] "A continuous formulation for logical decisions in differential algebraic systems using mathematical programs with complementarity constraints"
K.M. Powell, A.N. Eaton, J.D. Hedengren, T.F. Edgar
Processes, Volume 4, pp. 7 2016

[11] "Energy intensification using thermal storage"
T.F. Edgar, **K.M. Powell**
Current Opinion in Chemical Engineering, Volume 9, pp. 83-88 2015

[10] "Heating, cooling, and electrical load forecasting for a large-scale district energy system"
K.M. Powell, A. Sriprasad, W.J. Cole, T.F. Edgar
Energy, Volume 74, pp. 877-885 2014

[9] "Nonlinear modeling, estimation, and predictive control in APMonitor"
J.D. Hedengren, R.A. Shishavan, **K.M. Powell**, T.F. Edgar
Computers and Chemical Engineering, Volume 70, pp. 133-148 2014

[8] "Dynamic optimization of a hybrid solar thermal and fossil fuel system"
K.M. Powell, J.D. Hedengren, T.F. Edgar
Solar Energy, Volume 108, pp. 210-218 2014

[7] "Reduced-order residential home modeling for model predictive control"
W.J. Cole, **K.M. Powell**, E.T. Hale, T.F. Edgar
Energy and Buildings, Volume 74, pp. 69-77 2014

[6] "Turbine inlet cooling with thermal energy storage"
W.J. Cole, J.D. Rhodes, **K.M. Powell**, T.F. Edgar
International Journal of Energy Research, Volume 38, pp. 151-161 2014

[5] "An adaptive-grid model for dynamic simulation of thermocline energy storage systems"
K.M. Powell, T.F. Edgar
Energy Conversion and Management, Volume 76, pp. 865-873 2013

[4] "Optimal chiller loading in a district cooling system with thermal energy storage"
K.M. Powell, W.J. Cole, U.F. Ekarika, T.F. Edgar
Energy, Volume 50, pp. 445-453 2013

[3] "Improved large-scale process cooling operation through energy optimization"
K. Kapoor, **K.M. Powell**, W.J. Cole, J.S. Kim, T.F. Edgar
Processes, Volume 1, pp. 312-329 2013

[2] "Modeling and control of a solar thermal power plant with thermal energy storage"
K.M. Powell, T.F. Edgar
Chemical Engineering Science, Volume 71, pp. 138-145 2012

[1] "Optimization and advanced control of thermal energy storage systems"
W.J. Cole, **K.M. Powell**, T.F. Edgar
Reviews in Chemical Engineering, Volume 28, pp. 81-99 2012

SELECT CONFERENCE PRESENTATIONS

"Thermal energy storage to enhance hybrid energy systems"
K.M. Powell
Nuclear Hybrid Energy Systems CORE Workshop, INL, Idaho Falls, ID 2013

"Dynamic optimization of a solar thermal energy system using weather forecasts"
K.M. Powell (presenter), J.D. Hedengren, T.F. Edgar
*Proceedings of the 2013 American Control Conference**, Washington DC 2013

"Nonlinear model predictive control for a heavy-duty gas turbine power plant"
J.S. Kim, **K.M. Powell** (presenter), T.F. Edgar
Proceedings of the 2013 American Control Conference,* Washington DC 2013

"A process systems approach to teaching distillation"
K.M. Powell (presenter), T.F. Edgar
AIChE Annual Meeting, Pittsburgh, *PA* 2012

"Dynamic optimization of solar thermal systems with storage"
K.M. Powell (presenter), J.D. Hedengren, T.F. Edgar
AIChE Annual Meeting, Pittsburgh, *PA* 2012

"Control of a large-scale solar thermal energy storage system"
K.M. Powell (presenter), J.D. Hedengren, T.F. Edgar
Proceedings of the 2011 American Control Conference,* San Francisco, CA 2011
*includes peer-reviewed paper

GRANTS

National Science Foundation Graduate Research Fellowship Program, "Measurement Techniques and Improved Control Systems for Rapid Thermal Annealing Processes Used for Printed Thin Film Solar Cells", 2009-2012, K.M. Powell (PI), $121,500.

The University of Texas at Austin Office of Sustainability, "Optimization of the Campus Cooling System to Reduce Energy Usage" 2012-2013, K. M. Powell (PI), T. F. Edgar, K. Kuretich, W. J. Cole, R. Thompson, J. Hedengren, K. Kapoor, J. Mojica, A. Sripasad, J. Kim (co-PI's), $36,930

Appendix G

Clean Coal Research Team Members

APPENDIX G
Clean Coal Research Team

The following individuals and their respective organizations listed below participated in the Clean Coal Research development phase to identify candidate Areas of Research, research objectives and to prioritize candidate projects/studies:

Brad Adams, Brigham Young University
Foster Agblevor, Utah State University
Morris Argyle, Brigham Young University
Larry Baxter, Brigham Young University
Alair Emory, Utah Governor's Office of Energy Development
Eric Eddings, University of Utah
Kevin Fry, Reaction Engineering Inc.
Andrew Fry, University of Utah (now with Brigham Young University)
Alex Hietsoi, Utah State University
Brian Iverson, Brigham Young University
John McLennan, University of Utah – Earth Geosciences Institute
Brian McPherson, University of Utah - USTAR
Kody Powell, University of Utah
Andrew Sweeney, USTAR
Phil Smith, University of Utah
Dale Tree, Brigham Young University
Tyson Todd, USTAR
Jost Wendt, University of Utah
Kevin Whitty, University of Utah
Ian Andrews, Rocky Mountain Power
Larry Bruno, Rocky Mountain Power
Ken Clark, Rocky Mountain Power
Mike Dayton, Rocky Mountain Power
Glen Pinterich, Rocky Mountain Power
Laren Huntsman, Rocky Mountain Power
Greg Hunter, Rocky Mountain Power

Participation also by: Jeff Caldwell (Amaron), Ralph Coates (Amaron), Russ Taylor (AEG Coalswitch), Phil Scalzo (AEG Coalswitch), Kyler Stitt (Sustainable Energy Solutions); Burdick Trapper (Rocky Mountain Power) and Jake Tuttle (University of Utah)

Appendix H

Major Project Milestones

Appendix A - Biomass Co-Firing Test

Entity	Milestone Title/Description	Estimated Date
UofU	Contracts with PacifiCorp complete with UofU	Jan-17
PacifiCorp	Contracts with fuel suppliers complete	Feb-17
PacifiCorp	Owner's Engineer selected	Feb-17
UofU	Test Plan – Lab-scale Combustion Performance Evaluation	Mar-17
UofU	Draft Report on Biomass Fuel Handling and Stability	Apr-17
UofU	Complete Design & Construction of Isokinetic Particle Sampling Probe	Jun-17
BYU	Complete Design & Construction of Temperature-controlled Deposit Sample Probes	Jun-17
Fuel Suppliers	Delivery of processed Biomass Fuel	Jul-17
PacifiCorp	Testing acknowledgement from Utah DAQ	Jun-17
UofU	Lab-scale Combustion Performance Interim Report	Jul-17
PacifiCorp	Perform Biomass Testing at Hunter Unit 3	Aug-17
UofU/BYU	Draft Report – Analysis of Measurements from Hunter Plant Testing	Dec-17
UofU	Lab-scale Combustion Performance Draft Final Report	Nov-17
UofU	Air Quality Assessment Draft Report	Sep-17
Owner's Engineer	Draft Assessment Report Issued	Sep-17
Owner's Engineer	Final Assessment Report Issued	Nov-17
BYU	Draft Report on Analysis of Boiler Operating, Emissions and Performance Data	Jun-18

Appendix B - Cryogenic Carbon Capture Testing

	Milestone Title/Description	Start Date	Planned Completion Date
	Planning Phase		
	Site selection	1/1/2017	3/15/2017
Major Milestone	Contract with PacifiCorp complete		**2/1/2017**
	Draft Test Program Development	2/2/2017	3/1/2017
Major Milestone	Final Test Program	3/1/2017	**3/15/2017**
	Development Phase		
	Development Work (in conjunction with NETL Phase I plan)	3/1/2017	10/1/2017
Major Milestone	Phase I development completed		**10/1/2017**
Major Milestone	Testing acknowledgement from Utah DAQ		**12/15/2017**
	Mobilization for demonstration (on-site electrical and flue gas access)	10/1/2017	2/15/2018
	Field Demonstration Phase		
Major Milestone	SES Demonstration Unit setup on site	3/15/2018	**4/15/2018**
	Site Testing	4/15/2018	12/1/2018
Major Milestone	Site Testing Completed		**12/1/2018**
	SES Demonstration Unit Demobilization	12/1/2018	12/15/2018
	Reporting Phase		
Major Milestone	Draft Report		**2/15/2019**
Major Milestone	Final Report Submitted		**2/28/2019**

Appendix C - CarbonSAFE Pre-Feasbility Study

Milestone Title/Description	Planned Completion Date
CCS Team Commitments	3/1/2017
Catalog of Project Challenges	3/1/2017
Update Project Management Plan	4/1/2017
Update Data Management Plan	4/1/2017
Project Kickoff Meeting	2/1/2017
Project Review Meeting	Once Annually
Quarterly Progress Reports to DOE	Quarterly
Data Submission to NETL-EDX	Quarterly
Final Report	6/20/2018
Feasibility Sub-Plan for Practical Challenges	1/1/2018
Feasibility Sub-Plan for Public and Economic Acceptability	1/1/2018
Detailed Plan for Long-Term Liability for Stored CO_2	5/1/2018
Finalize Ranked List of Site Options	5/1/2018
Compile Initial Area of Review	9/1/2017
Initial MVA Plan	5/1/2018
Compile Risk Registry	3/1/2018
Initial Risk Mitigation Plan	5/1/2018
Compile Catalog of Accessible Information (Data) and Resources	2/1/2017
CO_2 Source Assessment	5/1/2018
Initial CO_2 Management Strategy	5/1/2018
CarbonSAFE Rocky Mountains Phase II Proposal	12/1/2017

Appendix D - CO_2 Enhanced Coal Bed Methane Study

Milestone Title/Description	Date from Announcement of Award/Funding Available
Notice to Proceed Start Date (Assumed)	1/1/2018
Contracts with PacifiCorp complete	1/31/2018
Commence Resource Evaluation	1/31/2018
Draft Test Program Submitted	1/31/2018
Revised Program Submitted Formalizing Experimental Matrix and Other Research Tasks	2/15/2018
Annual Report I Presented/Submitted	1/31/2019
Annual Report II Presented/Submitted	1/31/2020
Annual Report III Presented/Submitted	1/30/2021
Develop Concept for Future In-Situ Pilot Testing	7/1/2021
Final Report Presented/Submitted	10/31/2021

Appendix E - Solar Thermal Assessment (Hunter Plant)

Milestone Title/Description	Date from Announcement of Award/Funding Available
Contract between BYU and PacifiCorp complete (Assumed start date)	1/1/2019
Contract between Owner's Engineer and PacifiCorp complete	3/2/2019
Commencement of study	5/1/2019
Draft of proposed study objectives	5/31/2019
Final proposed study objectives	6/30/2019
Solar resource study draft complete	7/31/2019
Land resource study draft complete	12/30/2019
Select steam/feedwater injection points	4/30/2020
Cycle efficiency draft calculations complete	6/29/2020
Coal consumption offset and solar augmentation cost estimates draft complete	12/29/2020
Draft final report submitted	2/28/2021
Final report submitted	6/29/2021

Appendix F - Neural Net Optimization Implementation

Milestone Title/Description	Estimated Completion Date
Contracts with PacifiCorp complete (U of U and Griffin/Taber)	1/15/2017
Project Kick off Meeting	1/20/2017
Instrumentation upgrades complete	4/30/2017
Unit base line optimization and parametric study begins	5/1/2017
Combustion optimization and intelligent soot-blowing software installation with Taber begins	6/1/2017
Base line data collection complete	7/31/2017
Initial installation period complete	8/31/2017
Annual progress report complete for Year 1	1/31/2018
Operator Training	5/31/2018
Parametric study on optimization of auxiliary systems complete	8/31/2018
Annual progress report complete for Year 2	1/31/2019
Exploratory study on dynamic optimization with set point ramping complete	8/31/2019
Final study on impact on emissions complete	12/31/2019
Final report complete and submitted to PacifiCorp	1/31/2020

Appendix G - Low NOx Technology Testing

Milestone Title/Description	Estimated Completion Date
Assumed Start Date	1/15/2017
Contract for Owner's Engineer	3/1/2017
Preparation of Baseline Information Complete	2/14/2017
Prepare Assesment Criteria and Testing Criteria	3/16/2017
Boiler CFD model Complete	5/1/2017
Preparation of Request for Information	5/1/2017
Issue Request for Information	5/16/2017
RFIs received and Assessment Complete	7/16/2017
RFP Commercial documents Complete	7/1/2017
Issue Request for Proposal	7/24/2017
RFP Responses Received	9/22/2017
RFP Proposals Assessment	10/8/2017
Economic/Technical Feasibililty of Technologies	12/7/2017
Prepare List of Recommended Technologies and Test Program	12/23/2017
Execute Commerical Documents with selected technologies	2/6/2018
Testing acknowledgement from Utah DAQ	2/22/2018
Site Mobilization (as required)	3/9/2018
Site Testing	9/7/2018
Technology Assessment Complete	11/7/2018
Draft Report-Technology Recommendations issued	12/23/2018
Final Report Issued	2/22/2019