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# IMPROVEMENTS IN FUEL FLEXIBILITY AND OPERATING COST REDUCTION AT CSU DRAKE STATION WITH TARGETED IN-FURNACE INJECTION™ TECHNOLOGY

**James Towell; Tom Martinez; David Hightower; Richard Maxey**
Colorado Springs Utilities
Colorado Springs, Colorado, USA

**Gerry Snow, PE; Hector Gonzalez; Robert Rians**
Fuel Tech, Inc.
Warrenville, Illinois, USA

## ABSTRACT

Power generating stations are under continuous pressure to achieve maximum availability, highest efficiency, and minimum environmental emissions at the lowest possible cost. In recent years, increased fuel flexibility has become more critical financially and operationally than ever before. Colorado Springs Utilities (CSU) has been very progressive in adopting and implementing benchmark technologies and operating strategies to help achieve these goals across their diversified generation portfolio, and in particular at four operating coal units representing 462 megawatts in the system. One key strategy employed at CSU's Martin Drake Station has been to continuously evaluate and test alternative coal feedstocks which have potential to reduce cost while maintaining capacity, fuel supply security, availability, and efficiency. These tests would not have been possible without the use of Fuel Tech's Targeted In-Furnace Injection™ (TIFI®) technology to control slagging and fouling, reduce forced outages and load drops, and enhance unit efficiency. The TIFI process involves the use of two different forms of fluid dynamics modeling coupled with a virtual reality engine. Together, these simulation methods create a running duplicate of a given furnace with injection overlays and dosage maps to predict the precise trajectory of an injected chemical, helping to ensure as close to 100% coverage of the targeted zones as possible. With TIFI installed on Units 6 and 7 at Martin Drake Station, the operators were able to blend Powder River Basin coal with design fuel up to double the percentages previously achievable. Using TIFI, the plant was able to maintain full load generation, better control slagging deposits, show improvements in heat absorption, and reduce attemperator spray flows over previous blend trials. Including the cost of the TIFI program, the station has demonstrated a potential annual operating cost reduction approaching $4.9 million. Effective return on TIFI program investment is 4:1.

## INTRODUCTION

The Martin Drake Power Plant comprises Units 5, 6, and 7. Units 5 and 6 are wall-fired boilers rated at 46 MW and 77 MW, respectively. The Martin Drake Power Plant is shown in Figure 1.

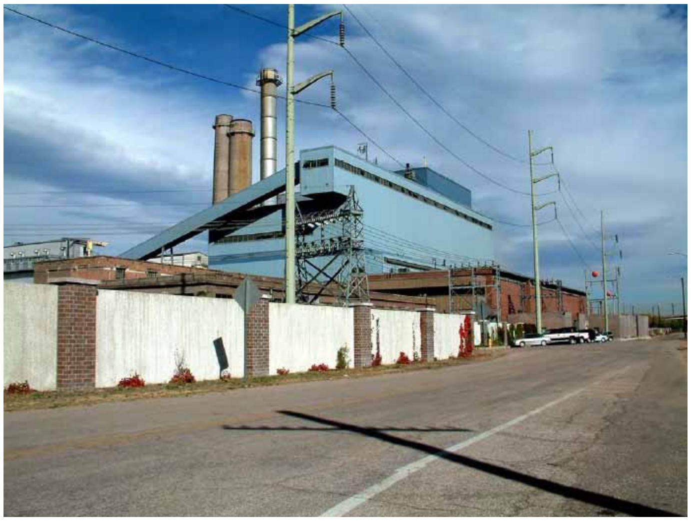

**Figure 1. Martin Drake Power Plant**

Drake Unit 7 is a 1,336 MMBtu/hr (nameplate) Babcock & Wilcox wall-fired, dry bottom, coal-fired boiler rated at 131

MW (net). Unit 7 entered commercial operation on June 14, 1974. A reverse-air fabric filter baghouse was placed in service on Drake Unit 7 in November 1993. Low NOx burners were installed in October 1999.

## FUEL BLENDS

Design fuels fired at Drake Station are bituminous coals sourced from mines located in western and northwestern Colorado. All three units are able to burn 100% of either of these fuels. From early 2005 through 2007, various blends of PRB were tested in Unit 7. The unit was able to maintain full load up to a 30% PRB blend; however slag deposits quickly formed on the waterwalls causing increased furnace exit gas temperatures. Characteristics of both the baseline design coal from Colorado and the tested PRB coal are shown in Table 1.

**Table 1. Drake Unit 7 Coal Options**

| | | | **Colorado Coal Composite Sample** | **PRB Coal Composite Sample** |
|---|---|---|---|---|
| **Proximate Analysis (As Received)** | | | | |
| Moisture | $H_2O$ | (%) | 9.21 | 25.24 |
| Ash | Ash | (%) | 9.31 | 5.46 |
| Volatile Matter | VM | (%) | 37.23 | 38.94 |
| Fixed Carbon | C | (%) | 44.25 | 30.35 |
| Total | | (%) | 100 | 99.99 |
| Total Sulfur | S | (%) | 0.53 | 0.20 |
| lb $SO_2$/MMBtu | | (lb/MMBtu) | 0.93 | 0.54 |
| lb Ash/MMBtu | | (lb/MMBtu) | 8.16 | 5.58 |
| Ash to Sulfur Ratio | | | 17.57 | 27.3 |
| **Ultimate Analysis (As Received)** | | | | |
| Moisture | $H_2O$ | (%) | 9.43 | 26.16 |
| Carbon | C | (%) | 66.29 | 53.03 |
| Hydrogen | H | (%) | 4.47 | 3.35 |
| Nitrogen | N | (%) | 1.62 | 0.73 |
| Sulfur | S | (%) | 0.5 | 0.15 |
| Ash | Ash | (%) | 9.45 | 5.05 |
| Oxygen | O | (%) | 8.24 | 11.53 |
| Total | | (%) | 100 | 100 |
| Higher Heating Value | HHV | (Btu/lb) | 11,411 | 8,993 |
| Higher Heating Value (MAF) | | (Btu/lb) | 12,568 | 12,851 |
| Hardgrove Grindability Index | HGI | | 46 | 49 |
| **Mineral Analysis of Ash** | | | | |
| Silicon Dioxide | $SiO_2$ | (%) | 54.79 | 38.95 |
| Aluminum Oxide | $Al_2O_3$ | (%) | 26.91 | 17.2 |
| Titanium Dioxide | $TiO_2$ | (%) | 0.71 | 1.15 |
| Iron Oxide | $Fe_2O_3$ | (%) | 4.67 | 5.62 |
| Calcium Oxide | CaO | (%) | 3.99 | 18.6 |
| Magnesium Oxide | MgO | (%) | 1.4 | 4.74 |
| Potassium Oxide | $K_2O$ | (%) | 1.29 | 0.58 |
| Sodium Oxide | $Na_2O$ | (%) | 1.02 | 1.51 |
| Sulfur Trioxide | $SO_3$ | (%) | 2.46 | 7.89 |
| Phosphorus Pentoxide | $P_2O_5$ | (%) | 1.13 | 1.17 |
| Total | | (%) | 98.37 | 97.41 |
| **Ash Fusion Temperatures - Oxidizing** | | | | |
| Initial Deformation | IT | ($^oF$) | 2622 | 2193 |
| Softening | ST | ($^oF$) | 2670 | 2200 |
| Hemispherical | HT | ($^oF$) | 2690 | 2206 |
| Fluid | FT | ($^oF$) | 2700 | 2215 |
| **Ash Fusion Temperatures - Reducing** | | | | |
| Initial Deformation | IT | ($^oF$) | 2548 | 2078 |
| Softening | ST | ($^oF$) | 2595 | 2120 |
| Hemispherical | HT | ($^oF$) | 2631 | 2138 |
| Fluid | FT | ($^oF$) | 2656 | 2145 |

Related to increased FEGT and due to ash fusion characteristics of the PRB coal, the secondary superheat and pendant reheat surfaces also became heavily slagged and fouled. These deposits have been a key contributor to increased tube leaks through tube metal corrosion, requirements for increased soot blowing and aggressive cleaning measures, and flow channeling and increased gas flow velocities leading to tube erosion and wastage.

Comparing analysis details between the two coal types, we conclude that slagging and fouling with even modest blends of PRB would be expected in this unit. Firstly, the ash fusion temperatures (ST and HT) for PRB are 450$^o$F – 500$^o$F lower than Colorado coal under both oxidizing and reducing conditions. Evaluation of slagging indices also indicates the potential for heat transfer surface fouling. Calculation of slagging and fouling indices is based on classification of the ash (Babcock & Wilcox Company 1992). From mineral analysis of the ash, lignitic ash is defined as having more (CaO + MgO) than $Fe_2O_3$. Bituminous ash is defined as having more $Fe_2O_3$ than the sum of CaO and MgO. Lower rank Western coals typically have lignitic ash. The ratio of $Fe_2O_3$ to (CaO + MgO) for Colorado coal is 0.86, and for PRB it is 0.24. Both of these coals therefore can be classified as having lignitic ash. The slagging index for lignitic ash is based on ASTM ash fusion temperatures. The index is a weighted average of the maximum hemispherical temperature (HT) and the minimum initial deformation temperature (IT), as given by:

$$R_s = \frac{(\text{Max HT}) + 4(\text{Min IT})}{5}$$

where: Max HT = higher of the reducing or oxidizing hemispherical softening temperatures ($^o$F)
Min IT = lower of the reducing or oxidizing initial deformation temperatures ($^o$F)

For the two fuels, the slagging indices are calculated as:

Colorado Coal, $R_s = 2576$

PRB Coal, $R_s = 2104$

Based on the Babcock & Wilcox ranking of slagging potential, these indices would rank the Colorado coal as having a low slagging potential, whereas the PRB coal would have a high to severe potential.

During the 2005 – 2007 PRB blending test burns, large clinkers were observed growing on the upper waterwall surfaces and pendant superheat surfaces, even with PRB blends of less than 30%. Falling slag occasionally bridged the bottom of the boiler. All of these issues required load sheds and forced outages to remove and clean slag accumulations.

In order to consistently fire PRB blends higher than about 10% or 20% in Drake Unit 7, CSU worked with Fuel Tech to design a Fuel Chem® Targeted In-Furnace Injection™ (TIFI®) program to reduce or eliminate slagging and fouling and eliminate forced load drops and outages so that the Martin Drake Power Plant could take full advantage of cost savings associated with utilizing the maximum blend of PRB coal.

## TARGETED IN-FURNACE INJECTION™

Fuel Tech has been applying and optimizing the Fuel Chem® Targeted TIFI® program since the early 1990s. Details of TIFI technology, ash deposit chemistry, and modification of slag crystalline structure have been presented previously (Smyrniotis 2003, Schulz and Smyrniotis 2006). TIFI systems are currently installed on over 100 combustion units burning a wide variety of fuels including coal, heavy oil, biomass, and municipal waste. Identified benefits fall into five broad categories: availability and reliability gains, efficiency gains, maintenance benefits, fuel flexibility, and environmental improvements.

The TIFI slag and fouling control program involves targeting areas of the radiant and convection sections of a boiler with chemicals designed to control these problems. By targeting the problem areas of the furnace instead of simply putting additives in the fuel, performance and cost effectiveness are significantly improved. Chemicals are mixed with air and water and then injected into the flue gas stream. The areas that are targeted are based on Computational Fluid Dynamics (CFD) models to ensure maximum coverage where the problem areas are known to exist.

TIFI technology involves using two different forms of fluid dynamics modeling and a virtual reality engine. Together, these create a running duplicate of a given furnace with injection overlays and dosage maps to analyze where chemical distribution and to achieve maximum possible coverage of the targeted areas. The most common application of TIFI technology utilizes brine derived magnesium hydroxide slurry diluted with water and then atomized with air. This mixture is sprayed into the furnace at optimized port locations as determined by the models.

The first step with the CFD process is to create a geometrically correct, three-dimensional model based on all internal boiler dimensions and structures. Burner and overfire air configurations, tube spacing, geometries, and materials are taken into account to provide an accurate representation of the combustion zone and convective passes. Combustion air flows, fuel flows, and fuel properties are then included to build a mass and energy balanced model. Field measurements of furnace temperatures and combustion gas concentration profiles are usually taken to verify and calibrate the model. Figure 2 shows an image taken from the virtual reality model and details the gas flow dynamics using vectors that are coded for velocity (length), temperature (color), and direction.

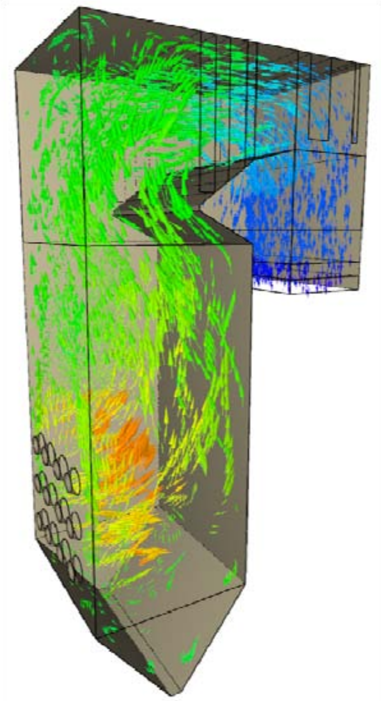

**Figure 2. Drake Unit 7 Gas Flow Vectors**

Once the fluid dynamic model is constructed, a very useful visualization tool is an isosurface to show where ash softening temperatures are expected to occur in the unit. Generally, temperatures are hotter upstream of the surface and cooler downstream. The ash will tend to stick to surfaces that are encountered in regions where the gas temperature is hotter than the softening temperature. Figure 3 shows an isosurface for baseline Colorado coal at 2,595°F, which is the ash softening temperature under reducing conditions (see Table 1). Reducing condition temperatures are used here to show potential worst case circumstances. As illustrated, semi-molten or sticky ash is unlikely to reach the superheat pendants above the bull nose of the furnace. This is consistent with normal operating conditions with design coal where routine soot blowing is sufficient to keep waterwall and superheat surfaces relatively free of slag and fouling deposits. With PRB coal however, the situation is quite different. Ash softening temperature under reducing conditions for PRB is much lower at 2,120°F. Figure 4 shows an isosurface at 2,120°F for boiler operation on 100% PRB coal. This image illustrates the predicted sticky ash and a high potential for slagging and fouling on radiant zone and superheat pendant surfaces with use of PRB.

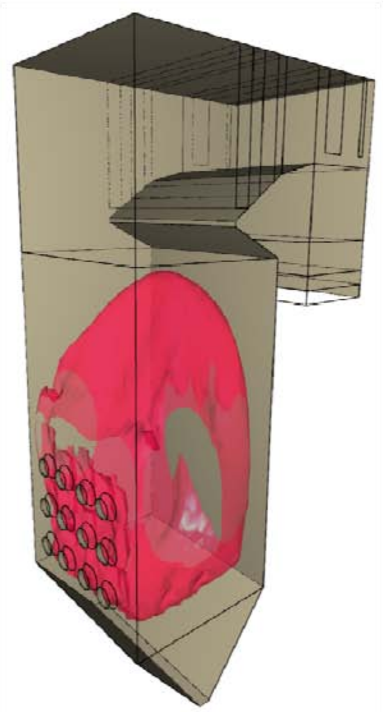

**Figure 3. Temperature Isosurface Showing Colorado Coal Ash Softening Temperature Location (2,595$^{o}$F – Reducing)**

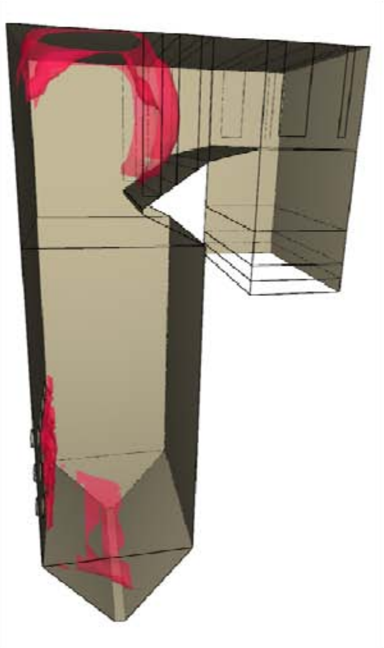

**Figure 4. Temperature Isosurface Showing PRB Coal Ash Softening Temperature Location (2,120$^{o}$F – Reducing)**

Following the completion of the CFD model and operating case studies, an injection design model is then developed to simulate and optimize the TIFI injector array. The model allows the design team to test various combinations of injector locations along with variable droplet size, distribution, and velocity. Best candidate solutions are then modeled with CFD coupled with injector placement and flows. Concentration contours showing chemical distribution are used to evaluate the effectiveness of possible injector arrays. Figure 5 shows the optimized injector placement for Drake Unit 7. There are 22 injectors distributed over four levels and six feed manifolds. Chemical streamlines from the bottom level of injectors are also shown in Figure 5. Figure 6 shows TIFI chemical coverage in the radiant and convective zones of the unit, and Figure 7 shows a cross-sectional concentration profiles entering the superheat pendants. Green and light blue shades indicate more concentrated coverage of the targeted surfaces. Figure 6 shows that in addition to good coverage in the ash hopper, good chemical distribution is evident around the bull nose and into the superheat pendants. Figure 7 shows good uniform coverage across the superheat pendants, with a slightly higher concentration bias towards the bottom of the pendants. During the PRB test burns conducted in 2005 and 2007 without TIFI slag control, these are exactly the regions where large clinkers accumulated requiring load sheds and cleaning outages. As indicated in these figures, the models predict efficient chemical coverage in the problem areas.

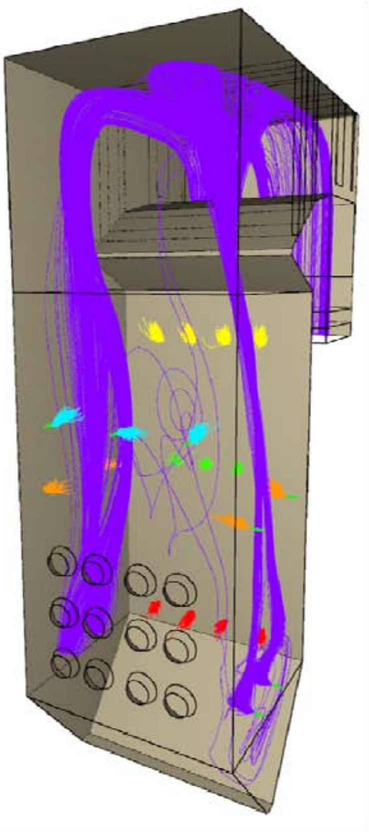

**Figure 5. Drake Unit 7 TIFI Injector Placement Showing Predicted Chemical Streamlines From Bottom Row**

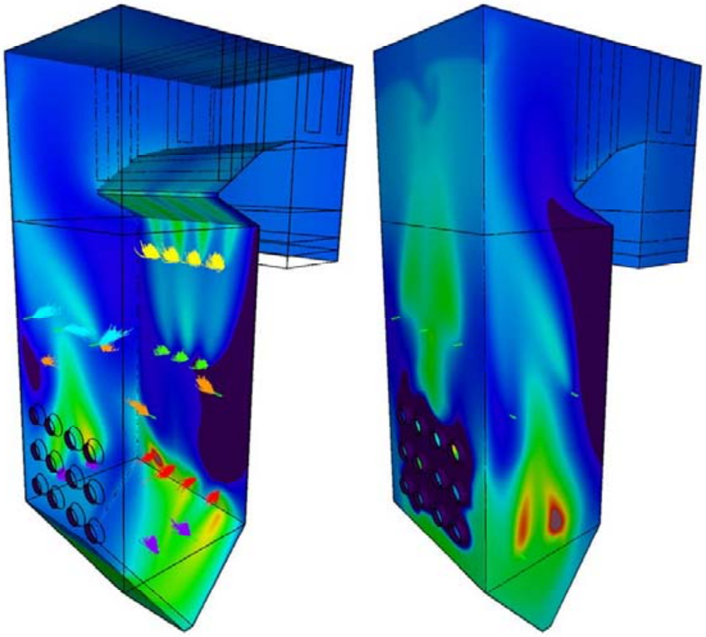

**Figure 6a** **Figure 6b**

**Drake Unit 7 TIFI Chemical Coverage**

(Figure 6a Shows Rear & Left Wall
Figure 6b Shows Front & Right Wall)

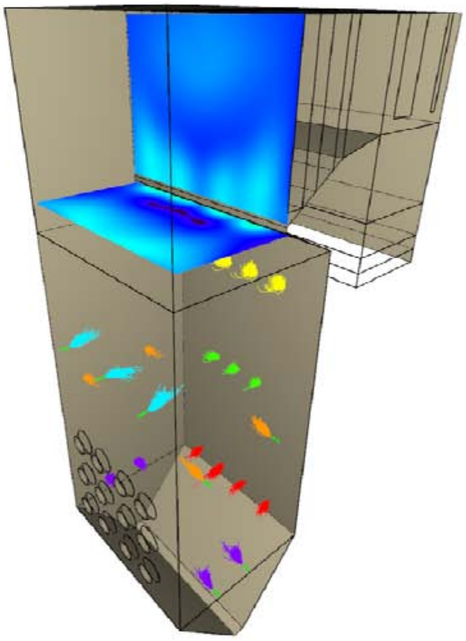

**Figure 7. Drake Unit 7 TIFI Injector Placement Showing Predicted Chemical Streamlines From Bottom Row**

## UNIT 7 PERFORMANCE ANALYSIS

Figure 8 shows the timeline of the Fuel Chem TIFI program implementation at Drake Unit 7 and illustrates the PRB blends fired during this period. As indicated, the PRB blend was increased from the previous average of about 10% up to 30%, and soon to 50% with the start-up of the slag control program. PRB blend was maintained at 50% for at least four months during the five month program. Following the run period with high PRB blends, usage of this coal was reduced back to about 10 – 15% and the TIFI program was put on standby. Current status and future plans are discussed at end of this paper.

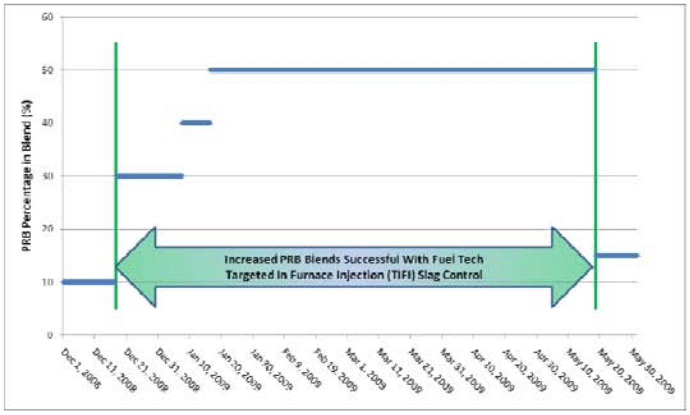

**Figure 8. Drake Unit 7 PRB Blends During**

Overall thermal absorption across the waterwalls and over the secondary superheat circuits are shown over the operating load range in Figures 9 and 10, respectively. In these graphs, baseline operation with Colorado coal is shown in blue. Heat transfer performance for the five month operation with PRB blends and TIFI slag control is indicated by the red data points. These trends show that heat transfer performance could be maintained with TIFI together with good combustion practice and soot blowing measures as implemented by the Drake operations team.

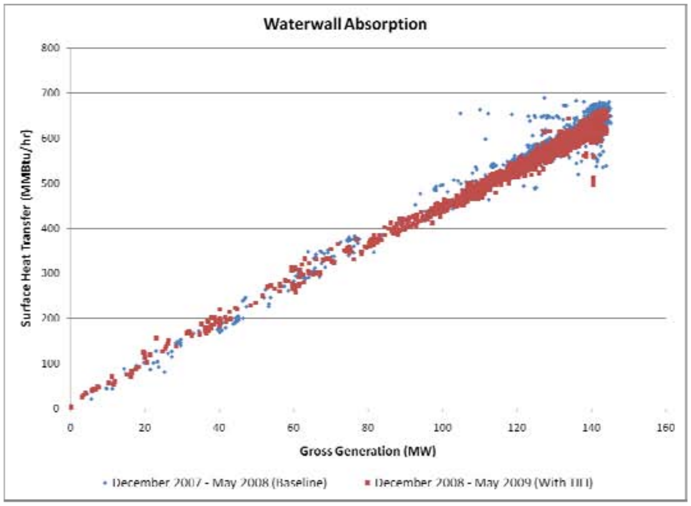

**Figure 9. Drake Unit 7 Waterwall Absorption vs. Load**

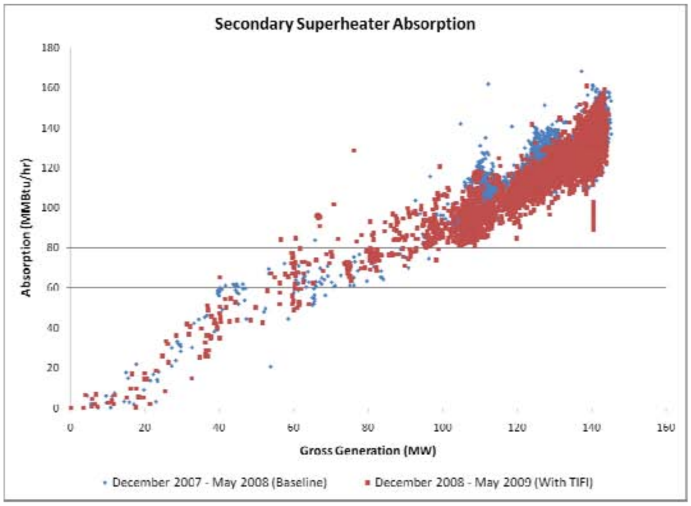

**Figure 10. Drake Unit 7 SSH Absorption vs. Load**

Efficient combustion practice and slag management procedures have also allowed the unit to maintain design steam temperature, even with PRB blends up to 50% as shown in Figure 11.

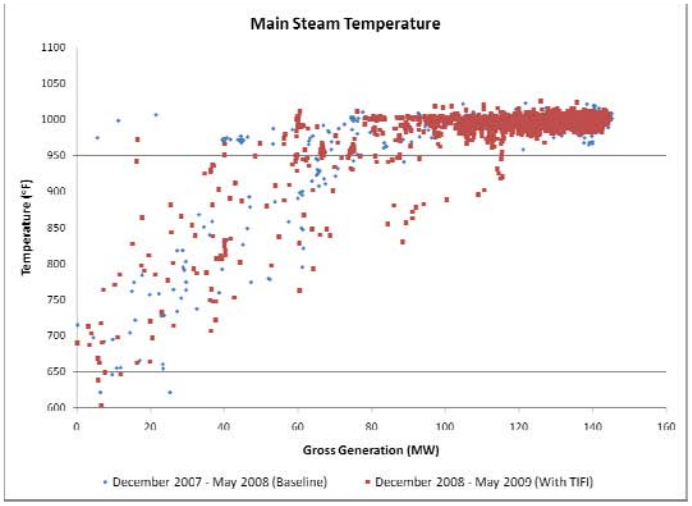

**Figure 11. Drake Unit 7 Main Steam Temperature vs. Load**

Figure 12 presents superheater attemperator spray flow time trends for the Colorado coal baseline and 30% to 50% PRB blends with TIFI. The time periods are five months in 2008 (baseline) and five months in 2009 (PRB with TIFI). Again, blue and red data points are used to distinguish between baseline operation and PRB operation. Gaps in the data occurring in March are scheduled outages (6 weeks in 2008, 11 days in 2009). This graph shows that superheat spray flow rates during PRB operation with TIFI were generally similar, if not less than baseline operation. This finding indicates that heat transfer distributions in the unit were not substantially upset with the fuel switch. The drop in spray flows seen following the March 2008 outage was primarily the result of refurbishment and return to service of the top high pressure feedwater heater. This allowed a slight reduction in furnace firing and furnace exit gas temperature.

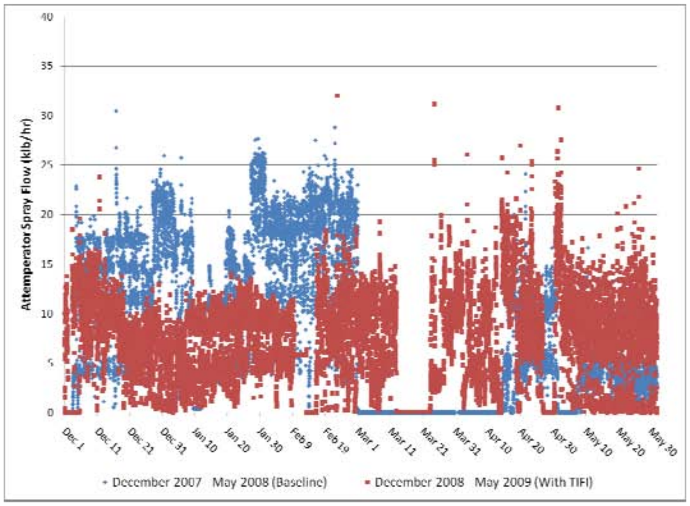

**Figure 12. Drake Unit 7 Desuperheater Spray Flows**

A histogram showing relative operation across three ranges (or "bins") of generation is shown in Figure 13. This graph reveals that with all of the operating measures and slag management tools employed during the five month PRB run with TIFI, the station was actually able to slightly increase generation on Unit 7 over previous baseline operation. Summing the operating time percentages in the top two bins, we see that the PRB/TIFI run achieved an operating time of 77% at or above 130 MW versus about 59% for the baseline period.

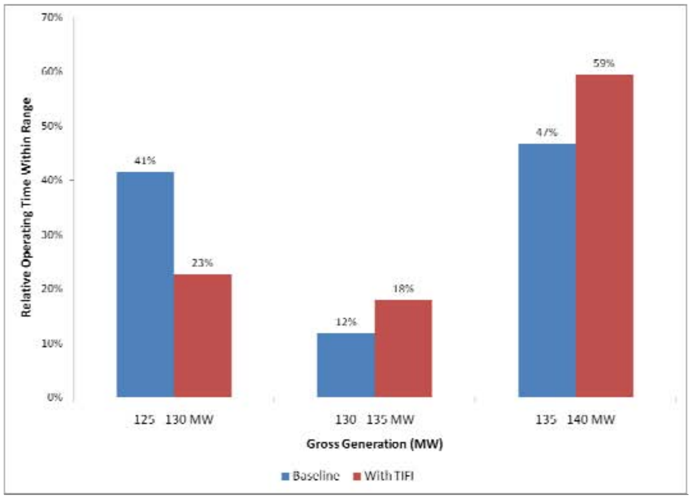

**Figure 13. Drake Unit 7 Generation Histogram**

## FINANCIAL ANALYSIS

Table 2 presents Drake Unit 7 Site Conditions, together with Operating Parameters and Annual Cost summaries for three operating cases:

- Case I: Baseline Operation, Colorado Coal
- Case II: 30% PRB / 70% Colorado, w/o TIFI
- Case III: 50% PRB / 50% Colorado, with TIFI

Averages for coal heating value, delivered price, and electric power pricing appear under Site Conditions. Average Operating Parameters for the three cases are shown next. The data are based on historic, average operation with the baseline Colorado coal, test burn experience with PRB blends between 2005 and 2007, and information collected during the five month TIFI program conducted from December 2008 through May 2009. As a result of additional unscheduled outages and slag induced derates, the effective annual capacity factor drops by 5% to about 87% for Case II (PRB blends up to 30% without TIFI slag control). Based on five months of operating experience under Case III (up to 50% PRB blend, but with TIFI slag control), we see no forced outages, slag related derates, off-line explosive cleaning requirements, or pressure part failures beyond normal baseline, design coal operation.

Using Case I as the baseline, costs for boiler cleaning and tube leak repairs are added to lost revenue due to forced outages and derates under Annual Cost Impacts. The Annual Fuel Cost row shows the operating cost reductions coming from higher percentages of PRB. In Case III, the fuel cost savings are offset by the average annual TIFI program cost for Drake Unit 7. The small loss in boiler thermal efficiency resulting from the addition of dilution water and atomizing air in the 22 TIFI injectors is included in unit heat rate and effective fuel consumption. Total savings (compared to Case I) are summarized below these rows. Including the cost of the TIFI program, the station has demonstrated a potential annual operating cost reduction approaching $4.9 million. Effective return on TIFI program investment (ROI) is 4.2 to 1. When the Drake Power Plant resumes operation on PRB blends, the project team will continue to fine tune TIFI chemical coverage and utilization. With close monitoring of key unit performance indicators and fuel properties, we expect to increase this ROI value even further.

## CURRENT STATUS AND FUTURE PLANS

Following five months of operation with increased PRB blends and Fuel Chem TIFI slag control, Unit 7 was returned to Colorado design coal with minimal PRB blends. This decision was based on changes in coal market pricing that have temporarily eliminated the financial advantage for Drake Station to blend higher PRB percentages. As a result, the TIFI system is currently off line and remains in standby. These market driven changes are expected to reverse in early 2011, and will once again provide Drake a significant financial advantage in resuming the TIFI system. These circumstances illustrate a key feature of Fuel Chem TIFI technology. Equipment and capital expenditures to install the injection equipment are minimal and boiler pressure part intrusion is rarely required. Chemical metering, control systems, injection probes, and related equipment are provided by Fuel Tech under the program, so there is no need for the plant to carry unused capital equipment during standby periods. As market and operational circumstances shift, the flexibility of the TIFI system allows utilities to quickly leverage the benefits and financial advantages accordingly.

## REFERENCES

Babcock & Wilcox Company. *Steam, Its Generation and Use. 40th Edition.* Barberton, Ohio, 1992.

Schulz, K.W. and Smyrniotis, C.R. "Analyzing the Use of Chemical Technology for Controlling and/or Influencing Opacity, Fouling, and Slagging in Coal-Fired Utility Boilers." *Presented at the Clean Coal Conference.* Clearwater, Florida, 2006.

Smyrniotis, C.R. "Novel Method for Controlling Fouling & Slagging in Coal & Other Solid Fuel Fired Boilers/Furnaces." *Presented at the 28th International Technical Conference on Coal Utilization & Fuel Systems.* 2003.

**Table 2. Drake Unit 7 Coal Blend and TIFI Treatment Case Study**

| Site Conditions | Units | Value |
|---|---|---|
| Colorado Coal Higher Heating Value | Btu/lb | 11,411 |
| Colorado Coal Delivered Price | $/ton | $50.00 |
| PRB Higher Heating Value | Btu/lb | 8,993 |
| PRB Delivered Price | $/ton | $21.00 |
| Retail Power at Busbar | $/MWh | $30.00 |

| Operating Parameters | Units | Case I: Baseline Operation Colorado Coal | Case II: Test Burn w/o TIFI 30% PRB / 70% Colorado | Case III: Operation w/TIFI 50% PRB / 50% Colorado |
|---|---|---|---|---|
| Gross Generating Capacity | MW Gross | 142 | 142 | 142 |
| Net Generating Capacity | MW Net | 131 | 131 | 131 |
| Scheduled Outages per Year (Average) | Days/Year | 10 | 10 | 10 |
| Unscheduled Outages per Year | Days/Year | 1 | 8 | 1 |
| Slag Shed Derates per Year | Events/Year | 4 | 48 | 4 |
| Lost Net Generation for Slag Sheds [1] | MWh/Year | 2,400 | 28,800 | 2,400 |
| Dispatched Load Reductions | MWh/Year | 60,000 | 60,000 | 60,000 |
| Effective Annual Capacity Factor [2] | % | 92 | 87 | 92 |

| Annual Cost Impacts | Units | Case I: Baseline Operation Colorado Coal | Case II: Test Burn w/o TIFI 30% PRB / 70% Colorado | Case III: Operation w/TIFI 50% PRB / 50% Colorado |
|---|---|---|---|---|
| Blasting & Cleaning Costs [3] | $/Year | ($20,000) | ($80,000) | ($20,000) |
| Tube Leak Repairs [4] | $/Year | ($50,000) | ($200,000) | ($50,000) |
| Lost Revenue due to Unscheduled Outages and Slag Derates | $/Year | ($166,320) | ($1,618,560) | ($166,320) |
| Annual Fuel Cost | $/Year | ($26,699,416) | ($22,089,186) | ($20,631,252) |
| TIFI Program Cost [5] | $/Year | $0 | $0 | ($1,172,589) |
| **Fuel Savings (Compared to Baseline)** | $/Year | $0 | $4,610,230 | $6,068,164 |
| **Total Savings (Compared to Baseline)** | $/Year | $0 | $2,947,990 | $4,895,575 |
| **Return on TIFI Program Investment** | ROI | N/A | N/A | 4.2 |

Notes:

[1] Based on 6 hours with net generation reduced to 100 MW.

[2] Including dispatched generation, scheduled & unscheduled outages, and slag related derates.

[3] Based on 1 cleaning per year for Cases I and III, 4 off-line cleanings per year for Case II.
Average maximum of $20,000 per day for off-line cleaning by explosive cleaning contractor.

[4] Based on 1 tube leak repair per year for Case I and III, 4 tube leak repairs per year for Case II.
Average of $50,000 for labor and materials for each tube leak repair.

[5] Based on TIFI Slag Control injection of 3 lb chemical per ton of coal.