

An Investigation of the Performance of a Re-Aeroed Turbocharger on Unit 9A at El Paso's Station 32 & The Development of a Predictive Waste Gate Model

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*Presented at the Gas Machinery Conference in Atlanta, GA.
October 5-7, 2009*

ABSTRACT

This paper presents a follow-up study on the ability to turbocharge low-BMEP two-stroke cycle engines. A Worthington LTC two-stroke cycle engine was upgraded with a re-aeroed turbocharger to provide additional waste gate margin at high ambient temperatures and at degraded engine operating conditions. Described herein are the engineering and diagnostic tools that were used, including engine modeling software and historical turbocharger performance data, to ultimately design and commission the re-aeroed turbocharged engine system. The paper includes data collected prior to and after the upgrade. One of the key performance indicators was the forecasted waste gate margin before and after the upgrade at various ambient temperatures. The authors show that by using engineering models and key performance data, a performance matrix modeling the excess turbine power at different ambient conditions and engine operating parameters could be created. This information was then used to determine the necessary turbocharger performance parameters. This paper investigates the modeling process and discusses the results used to evaluate the ability of the turbocharger to effectively increase waste gate margin.

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1.0 Project Background

This paper is a follow-on to the paper presented by Beshouri, Chapman, and Goss at the 2006 Gas Machinery Conference. They described the historical perspective of the Worthington LTC engines at Station 32 and the subsequent engineering effort that led to the successful upgrade of those engines in March 2006. Of note is the difficulty in turbocharging engines, such as the LTC, that operate with a significantly lower brake mean effective pressure (BMEP) than that of other turbocharged engines. This BMEP constraint translates into the following physical facts, which are described in more detail in the 2006 paper:

1. Engine
 - a. The low BMEP indicates a relatively low trapped fuel mass in the cylinders.
 - b. The ignition system is designed to ignite an air/fuel mixture that is greater than a specific lean limit.
 - c. The relatively low OEM boost level of about 6 inHg created by the scavenger pump most undoubtedly created a specific trapped equivalence ratio within the engine cylinders.
 - d. This trapped equivalence ratio was in the range where combustion would occur with the OEM ignition system.
 - e. Increasing the boost level traps additional air inside the cylinders, but the trapped fuel mass does not increase. This leads to a leaner trapped equivalence ratio. At some increased boost level, the trapped equivalence ratio would decrease (become more lean) to a point where the ignition system would not reliably ignite the mixture.
2. Turbocharger
 - a. The sustainability of any turbocharger is a function of turbocharger efficiency, boost level, turbine inlet temperature, and the pressure decrease across the engine cylinders.
 - b. Typical emissions-constrained turbocharged engines have a boost level that represents at least a factor of 1.7 times barometric pressure. This is a boost level of at least 21 inHg, which is over three times the OEM boost level of the LTC engines.
 - c. For a given turbocharger efficiency and pressure decrease across the engine, a decrease in the boost level from 21 inHg to 10 inHg, for example, physically requires an increased turbocharger turbine inlet temperature (blowdown/exhaust gas energy). This requirement is based on the thermo- and fluid-dynamic relationship between the engine and turbocharger components. This thermodynamic relationship is well-described in the PRCI report by Grauer and Chapman (2009).
 - d. The turbine inlet temperature is constrained by the NO_x constraint. Increased turbine inlet temperature (engine exhaust temperature) increases NO_x emissions.

These facts clearly point to a trade-off between the minimum trapped equivalence ratio in the cylinder and the minimum boost level that still permits the turbocharger to sustain itself. Following a series of

modeling investigations by ScavengeTech, a pilot test was conducted on engine 9A in March 2006 to assess the feasibility of operating the engine in a pure turbocharger mode with OEM pistons and liners. The results of that testing are discussed after first reviewing the unique aspects of performance modeling with T-RECS and testing of the turbocharger and engine liners at the NGML. The results from the pilot test showed that the pure turbocharged engine could be operated over a range of speeds and torques within the CO and NO_x compliance window. However, because of the relatively low boost level of approximately 12 inHg, operating flexibility was sacrificed.

The key result from the 2006 effort was that software and hardware engineering tools that were developed over the last several years by AETC, K-State's NGML, and ScavengeTech, many of which were funded through research supported by the Pipeline Research Council International, can be decisively used to develop an engineered solution for a very difficult engine upgrade project. The project team brought to bear a multitude of tools to ensure that the final engine system specification was accurate and met the emissions requirements. While some may consider the use of these tools and the design time costly, the end result is that the engine operated the first time as forecasted by the project team. There were no hardware/field iterations necessary. The cost-savings in reduced time spent on-site by the contractors greatly outweighed the cost of creating the engine system design.

A second key result is that the project team treated the engine, turbocharger, intake, and exhaust systems as one coupled engine system. For example, modifications to a cylinder port impacted the performance of the entire system, not just the engine itself. Port modifications affect the trapped mass inside the cylinder, which impacts the power produced by the engine as well as the NO_x and CO emissions. Additionally, the impact on the trapped mass affects the turbocharger turbine inlet turbine, which in turn affects the ability of the turbocharger compressor to provide air to the engine.

While the 2006 upgrade was a success, there was very little margin for engine and/or turbocharger degradation. In the time since the 2006 upgrade, intake port carboning was found to increase the engine differential pressure, which lowered the available energy at the turbine inlet enough to jeopardize the ability of the turbocharger to sustain itself. Consequently, as an alternative to constant port cleaning, El Paso embarked on a second turbocharger upgrade project that would increase the engine operating margin such that the turbocharged engine system could continue to operate in a slightly degraded condition.

2.0 Design Point Selection and Validation

During the 2006 engine upgrade, three engines were outfitted with turbocharger management systems, i.e., TuMS, to continuously measure turbocharger performance and quantify engine/turbocharger degradation. During the summer of 2008, the historical data from the TuMS units and other engine operating data clearly showed during times of high ambient temperatures the LTC engines at Station 32 operated with little to no waste gate and emissions compliance margin. Team members from El Paso, ScavengeTech, and Globe, investigated the possibility of increasing waste gate and emissions compliance margins by re-aeroing the 2006-version turbochargers at Station 32 in a way that increased overall turbocharger efficiency.

The team analyzed the TuMS (now Turbo Shield) turbocharger data and engine performance data collected in March 2006 during initial commissioning of the engines to develop a new design point. The design point was developed from this data set for the following reasons:

- Station personnel: the LTC engines operated and performed the best during and just after initial commissioning; and
- Pilot study data collected by AETC: the LTC engines operated below emissions levels and with sufficient emissions margin.

From the March 2006 data, ScavengeTech developed a design point that would allow the engines to operate with improved waste gate and emissions compliance margins. The design point specifications shown in Table 1 were reviewed by El Paso and then sent to Globe Turbocharger to re-aero one of the LTC turbochargers.

Table 1: Turbocharger Design Point Specifications

Ambient Temperature	100°F
Barometric Pressure	14.88 psia
Compressor Inlet Pressure	1 inH ₂ O below ambient
Compressor Discharger Pressure	22.95 psia
Turbine Inlet Pressure	21.544 psia
Turbine Discharge Pressure	15.413 psia
Turbine Inlet Temperature	965°F
Engine Fuel Flow Rate	10.943 mscfh (0.14 lbm/s)
Compressor Air Flow Rate	5.3233 lbm/s
Differential Pressure	2.863 inHg
Turbocharger Speed	Approx. 11,517 RPM

Once re-aeroed, the turbocharger was tested at the K-State National Gas Machinery Laboratory in November, 2008. The test plan fully verified turbocharger mechanical integrity and the turbocharger could achieve the design point specified in Table 1. During the test, the design point was first collected after the turbocharger was thermodynamically stable. A load valve on the test cell is positioned to achieve the design compressor pressure ratio and the differential pressure between the compressor discharge and the turbine inlet. Once positioned, the load valve emulates the flow restriction of the engine. After reaching thermodynamic stability¹, a complete 2.5 minute averaged data set is collected. Included in the data set are oil, cooling water, turbocharger speed, air stream, and exhaust stream flow rates, temperatures, and pressures. Additionally, a complete vibration spectrum is recorded to verify rotor balance, shaft alignment, and overall mechanical integrity of the turbocharger. With the exception of the surge point, the remaining data points are collected without changing the load valve position.

The NGML mechanical and performance tests showed the following:

- The turbocharger compressor performed almost the same as the turbocharger designed in 2006;
- The turbine efficiency increased from 66% to 76%, which is a significant improvement over the 2006 version;
- The surge margin was 20.7%, indicating there will be no surge issues;
- The turbocharger met, and even exceeded, the design point specifications;
 - The required turbine inlet temperature was more than 150°F lower than specified;
 - The lower turbine inlet temperature equates to increased waste gate margin.

Table 2: Turbocharger Test Results Corrected to 100°F and 14.7 psia

	Design Specifications	Corrected Test Values
Ambient Temperature	100°F	100°F
Barometric Pressure	14.88 psia	14.7 psia
Compressor Inlet Pressure	1 inH ₂ O below ambient	14.47 psia
Compressor Discharger Pressure	22.95 psia	22.5 psia
Compressor Pressure Ratio	1.54	1.55
Turbine Inlet Pressure	21.544 psia	21.06 psia
Turbine Discharge Pressure	15.413 psia	14.71 psia
Turbine Inlet Temperature	965°F	736°F
Compressor Air Flow Rate	5.3233 lbm/s	5.224 lbm/s
Differential Pressure	2.863 inHg	2.932 inHg
Turbocharger Speed	Approx. 11,517 RPM	11,564 RPM

¹ Thermodynamic stability is quantified by continuously monitoring and calculating the rate of change of the compressor and turbine discharge temperatures. The turbocharger is considered thermodynamically stable once the rate of change is less than 1°F over a five minute period. Experience at the NGML clearly shows that thermodynamic stability must be verified to accurately determine turbocharger performance.

As shown in Table 2, the turbocharger met the design point requirements to a very high accuracy. The tested air flow rate, when corrected to 100°F and 14.7 psia, was 5.224 lbm/s, less than 2% off of the design specification of 5.3233 lbm/s. The differential pressure tested value of 2.932 inHg was also very close to the design specification of 2.863 inHg a difference of less than 2.5%. In addition, the required turbine inlet temperature during the test was well below the design specifications of 965°F.

Figure 1 compares the 2006 turbocharger compressor with the newly re-aeroed turbocharger compressor. The test results showed the compressor performance changed very little during the re-aero. As illustrated in Figure 1, the compressor pressure ratio of the re-aeroed turbocharger was very similar to the 2006 designed turbocharger at the same corrected mass flow rate.

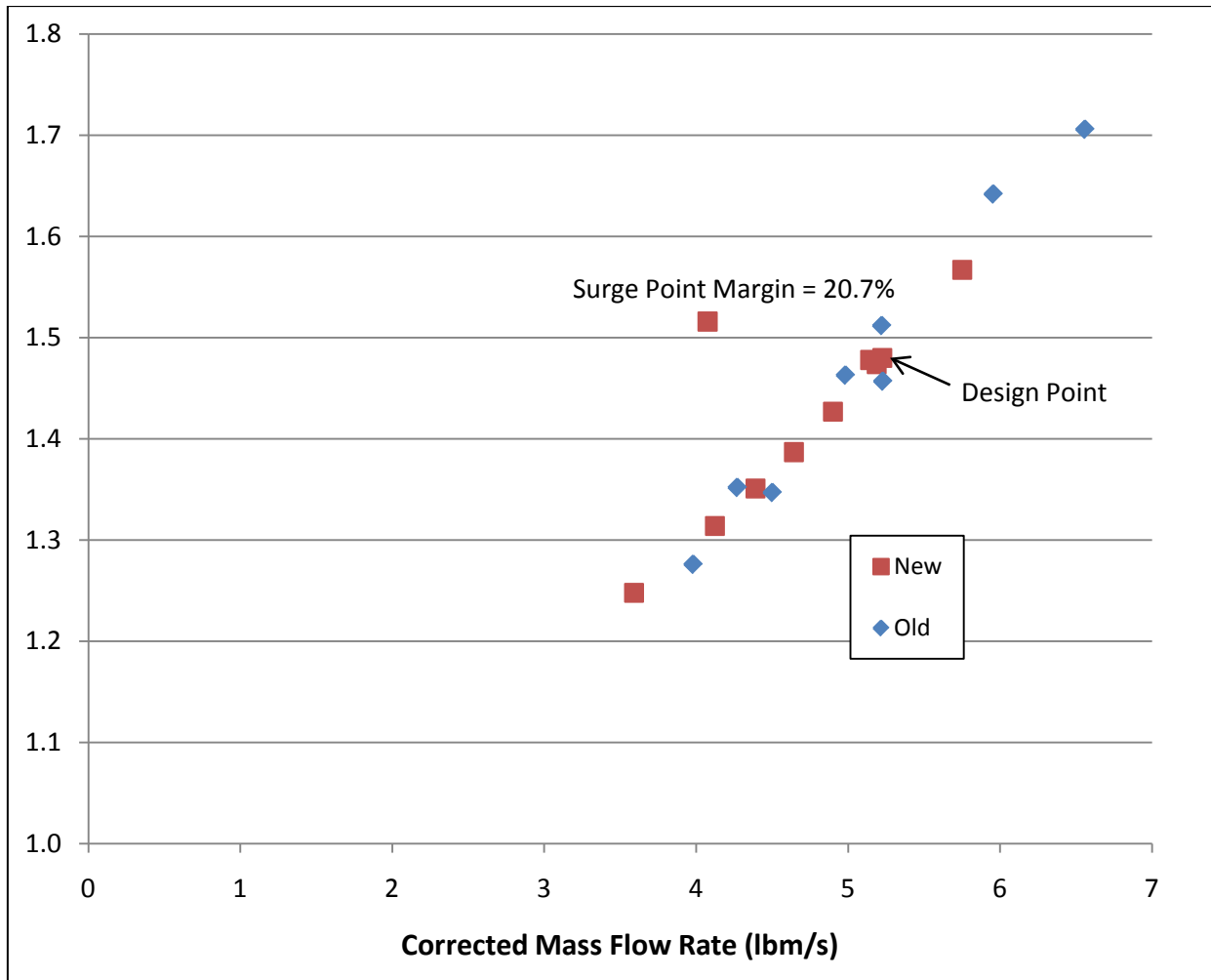


Figure 1: Turbocharger Test Results Compressor PR v Corrected Air Flow Rate

Not only were the compressor pressure ratios very similar, but as shown in Figure 2, the compressor performed at efficiencies very similar to the previous turbocharger design. Both the 2006 turbocharger and the re-aeroed turbocharger operated at a compressor efficiency of approximately 75 percent. As illustrated in Figure 2 and Figure 3, the compressor of the 2006 turbocharger operated 10 percent more efficiently than the turbine. Therefore, improving the turbine would have a greater impact than trying to improve the compressor.

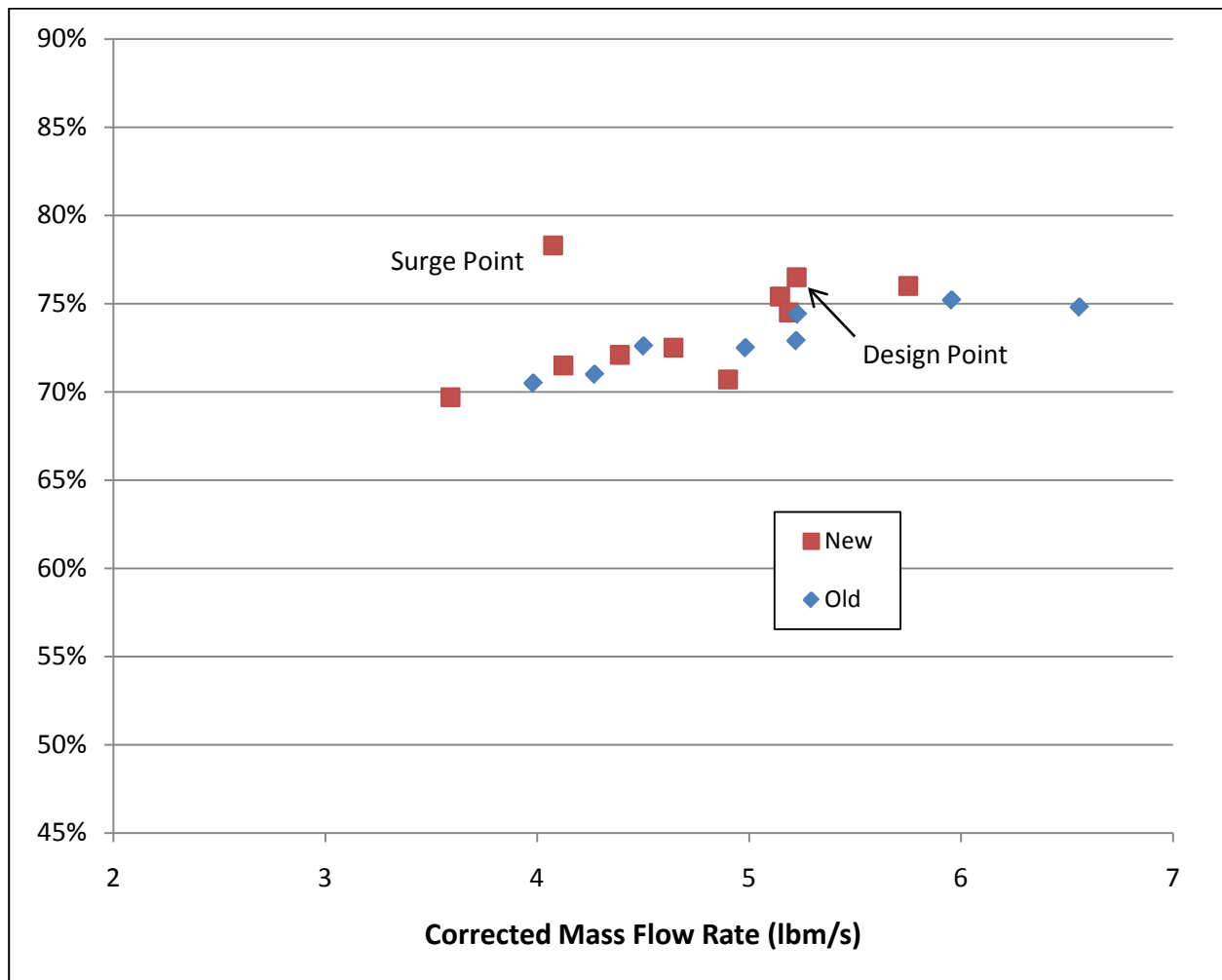


Figure 2: Turbocharger Test Results Compressor Efficiency v Corrected Air Flow Rate

The largest improvements to the re-aeroed turbocharger came from changes in the turbine. As show in Figure 3, the efficiency of the turbine increased approximately 10 percentage points after the redesign process. With a higher turbine efficiency, less energy is required to operate the re-aeroed turbocharger at the same flow rate as the 2006 turbocharger.

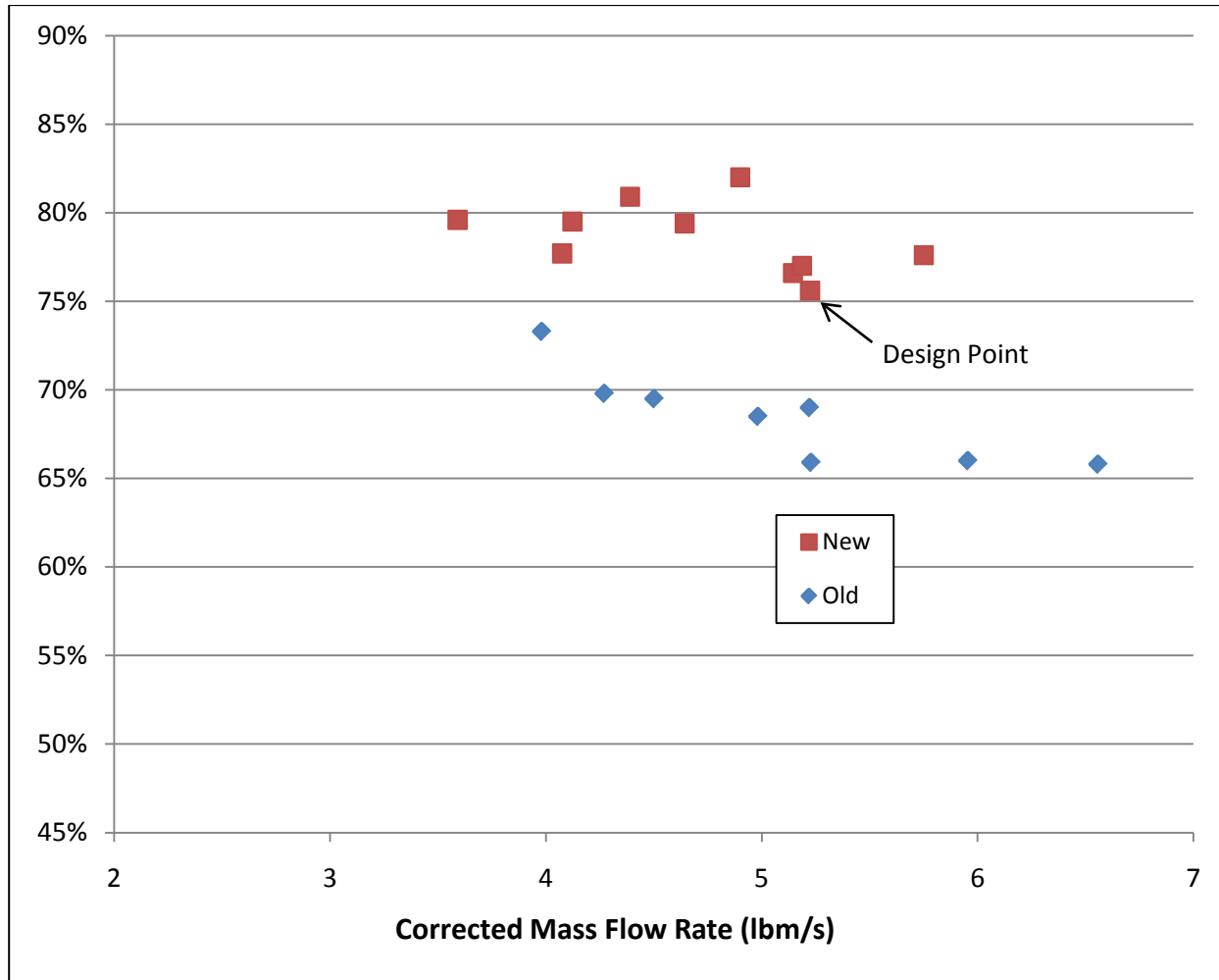


Figure 3: Turbocharger Test Results Turbine Efficiency v Corrected Air Flow Rate

The lower energy need to operate the turbine translated into a lower required turbine inlet temperature. As shown in Figure 4, the required turbine inlet temperature of the re-aeroed turbocharger decreased by approximately 100°F over the turbocharger tested in 2006. This increase in turbine efficiency also led to an improved overall turbocharger efficiency of approximately 8 percentage points as shown in Figure 5. This higher efficiency and lower required turbine inlet temperature will translate, in turn, into additional waste gate margin on the engine.

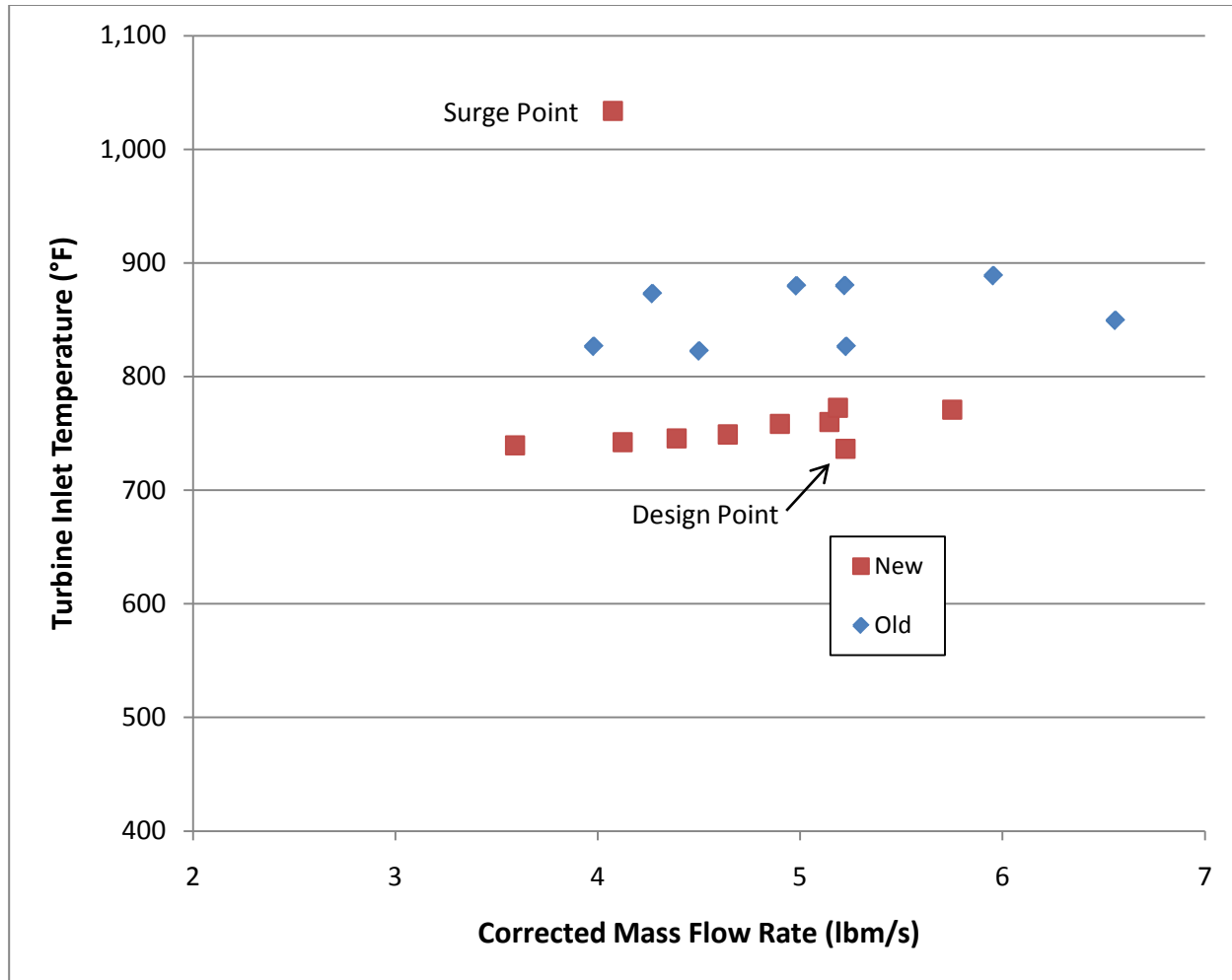


Figure 4: Turbocharger Test Results Turbine Inlet Temperature v Corrected Air Flow Rate

The turbocharger testing at the NGML verified the re-aeroed turbocharger would operate as designed and would meet or exceed the design specifications. The next step was to install the re-aeroed turbocharger on the engine. Prior to installation on the engine, pre-installation test data were collected from the engine to ensure a true comparison between the 2006 turbocharger and the re-aeroed turbocharger.

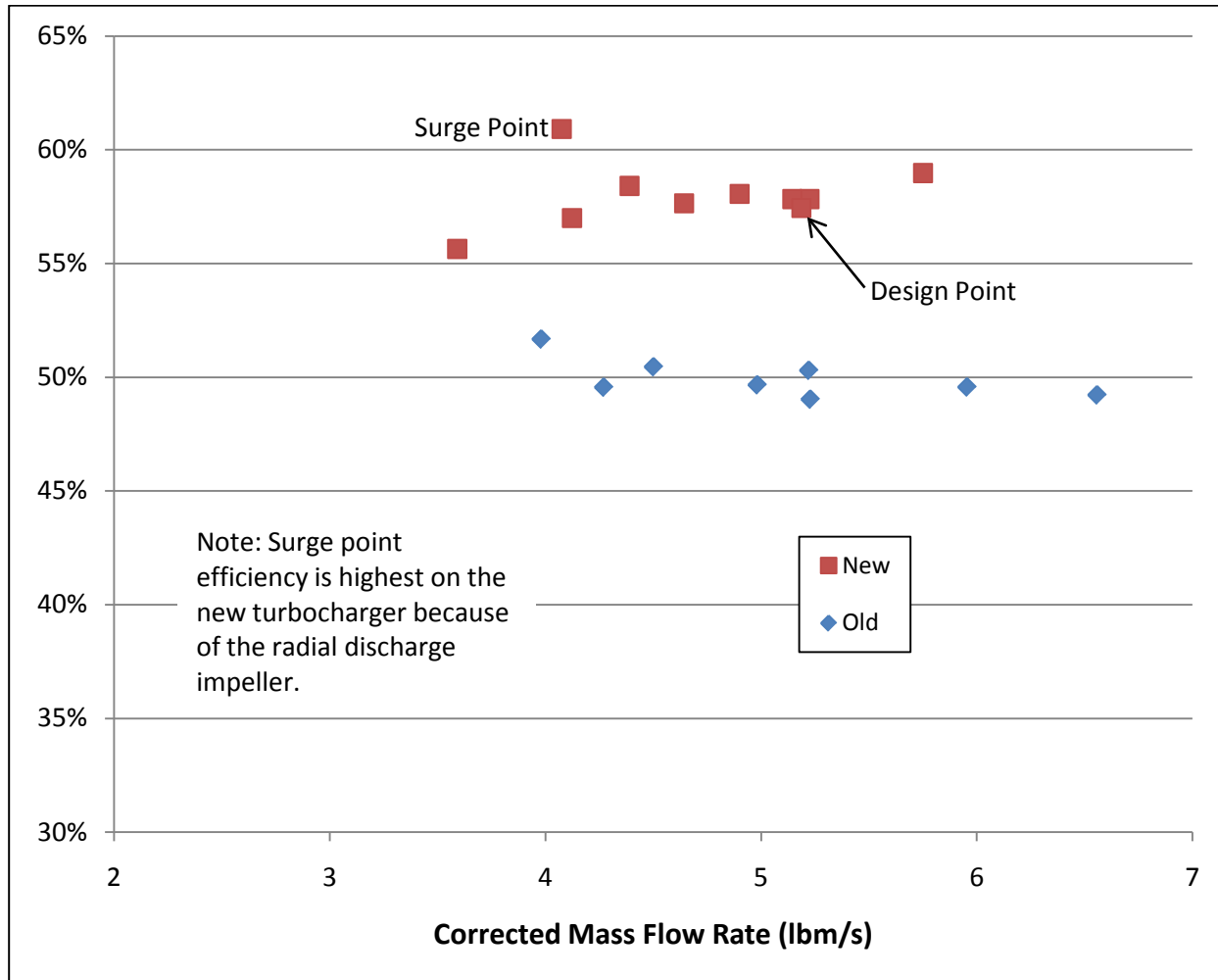


Figure 5: Turbocharger Test Results Overall Turbocharger Efficiency v Corrected Air Flow Rate

3.0 On Engine and Field Testing of Re-Aeroed Turbocharger

Before installing the new turbocharger on an engine, the 2006 turbocharger-engine system needed to be tested and data collected to establish a baseline for comparison. The team analyzed historical performance data collected by turbocharger management systems installed on Unit 9A and Unit 11A to determine which engine would provide the best testing platform. The performance parameters gathered from the historical data were compared to the 2006 design point as well as the re-aeroed turbocharger design point.

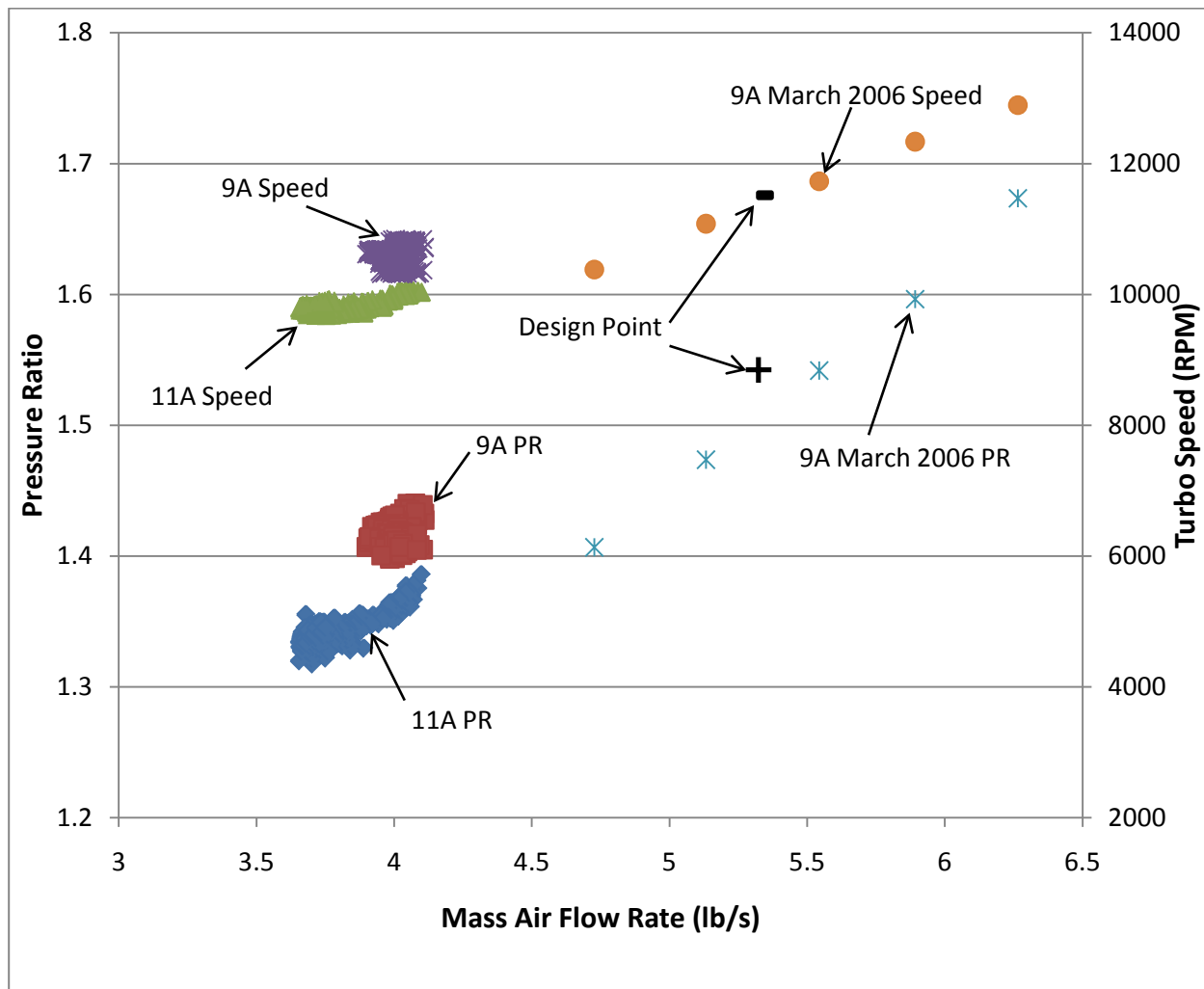


Figure 6: Engine 9A and 11A Turbocharger Performance Comparison - Pressure Ratio and

Figure 6 and Figure 7 show historical data from the Turbo Shield units installed on engines 9A and 11A. The Turbo Shield units measure and record the following parameters:

- Compressor air flow rate
- Turbocharger speed
- Compressor air inlet temperature and pressure
- Compressor air outlet temperature and pressure
- Turbine exhaust gas inlet temperature and pressure
- Turbine exhaust gas outlet temperature and pressure
- Engine differential pressure by subtracting the turbine inlet pressure from the compressor outlet pressure

Figure 6 compares data that is typically shown on a turbocharger compressor map. The compressor pressure ratio and turbocharger speed are plotted as functions of the air mass flow rate through the compressor. The March 2006 data were measured and recorded during the commissioning test of engine 9A. The design point specification is also shown in the figure. The other data on the figure represents the air flow rate, pressure ratio, and turbocharger speed continuously collected by the Turbo Shield units between the dates of March 1, 2008 and March 3, 2008.

Figure 7 shows the air manifold pressure and engine differential pressure as functions of the air flow rate through the compressor for each of these engines. As in Figure 6, the 2006 data were collected during the commissioning test of engine 9A.

The following key observations were made:

- Both units operated at a point where the air flow rate, pressure ratio, and turbocharger speed were significantly lower than the design point;
- The differential pressure across engine 9A was approximately the same as during the 2006 test, but at an air flow rate that was approximately 27% less than during the 2006 test. The only explanation was that the flow restriction had significantly increased since the 2006 data were recorded;
- The data comparison in Figure 6 and Figure 7 shows the turbochargers on engines 9A and 11A did not operate similarly. They both, however, were operating with degraded engine and/or turbocharger performance and significantly below both the 2006 design point and re-aeroed design point; and
- While both engines operated at degraded levels and off of design point conditions, engine 11A operated with a lower air flow restriction than engine 9A. This is shown by the higher engine differential pressure of 9A in Figure 7 at approximately the same air flow rate through the engine.

The higher flow restriction on engine 9A would prove to be a more rigorous test of the re-aeroed turbocharger. Therefore, the field testing of the re-aeroed turbocharger would be done on engine 9A.

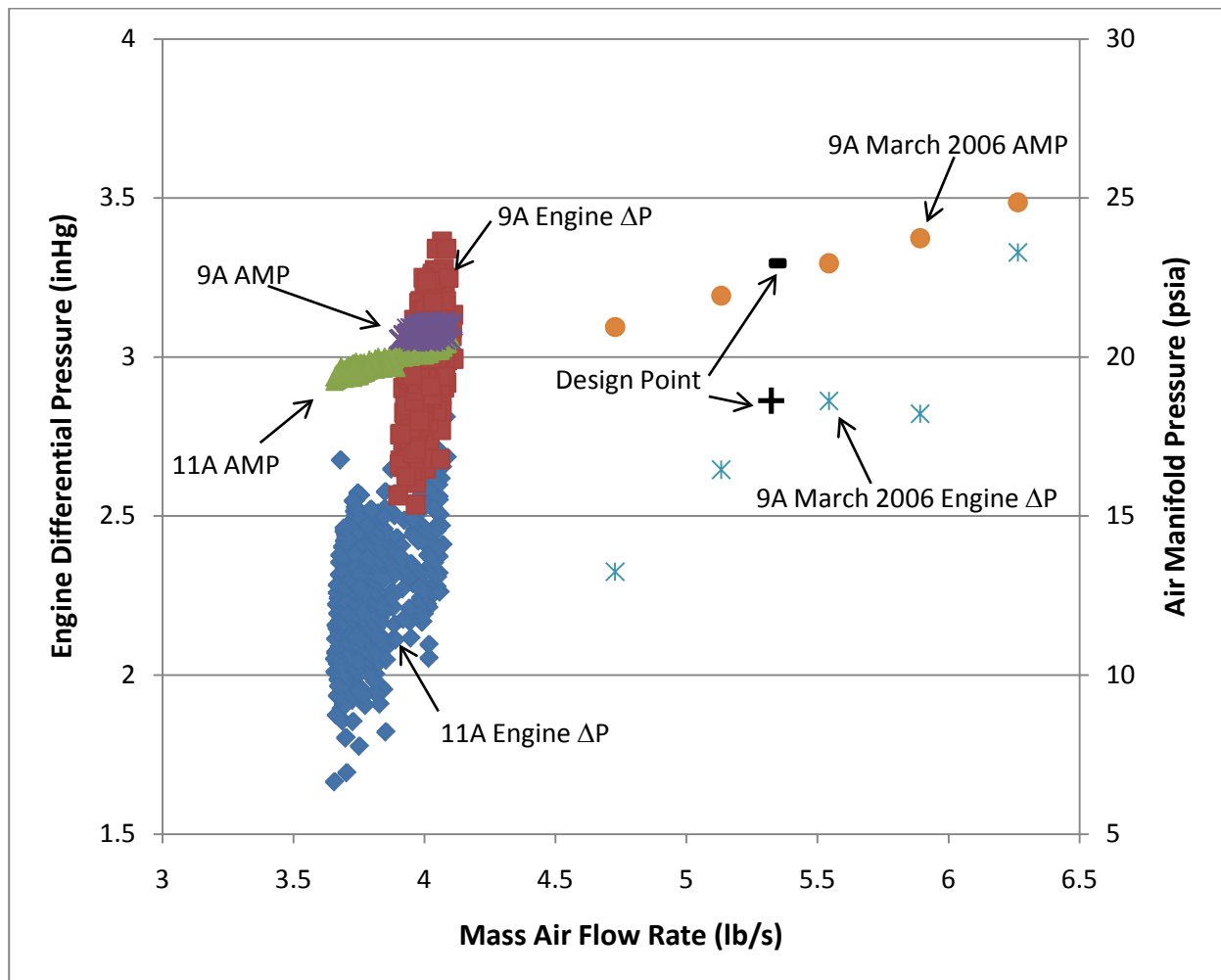


Figure 7: Engine 9A and 11A Turbocharger Performance Comparison - Engine Differential and AMP

Before installing the re-aeroed turbocharger on 9A, the engine was inspected, and repairs were made to ensure the engine would operate at top performance. These repairs included cleaning the cylinder intake ports of any carbon buildup. As carbon starts to accumulate, it begins to block the ports, increasing the flow restriction across the engine and dramatically changing the performance of the engine and the turbocharger.

In addition to inspecting and repairing the engine, engine and turbocharger data were collected prior to installation of the re-aeroed turbocharger. Engine emissions and operating data were collected by Mr. Ron Wachowiak of El Paso, and turbocharger data were collected from the turbocharger management system by Eric Dufur of ScavengeTech. The engine and turbocharger data sets were collected during the same time intervals to assure the operation of the unit at that time was accurately represented by the data. When the engine and turbocharger data sets are taken at different times or even days, it is much more difficult to accurately match data sets and create a robust model of the entire system. By taking

the engine and turbocharger data at the same time, an accurate and more robust model of the turbocharged engine system could be created.

Because the re-aeroed turbocharger was installed and tested in December, the data by itself was not a good test of how well the re-aeroed turbocharger would operate during the hot summer months. To assess the re-aeroed turbocharger, ScavengeTech used the pre-installation data sets to create a model of the system using the Turbocharger-Reciprocating Engine Computer Simulation (T-RECS) software. This model was then used to forecast how the 2006-version of the engine would operate over a range of operating and ambient conditions.

Once the re-aeroed turbocharger was installed, a second comprehensive data set was collected from the turbocharger and engine. A T-RECS model was also created for this data set. At this point, tuned T-RECS models were available for the pre- and post-installation engine configurations, as well as for the 2006 commissioning test.

Comparing these three data sets; March 2006, just prior to the upgrade, and just after the upgrade, the team was able to quantify changes in engine performance and operating flexibility from the time the engine was commissioned in 2006 to just before and after the turbocharger upgrade. In addition to comparing the T-RECS models, an excess turbine power model was developed by ScavengeTech. This excess turbine power model allowed the team members to quantify the operating flexibility improvements made available by redesign of the turbocharger, and to forecast the performance during times of high ambient temperatures. The development of this model is explained in the following section.

4.0 Development of an Excess Turbine Flow Model

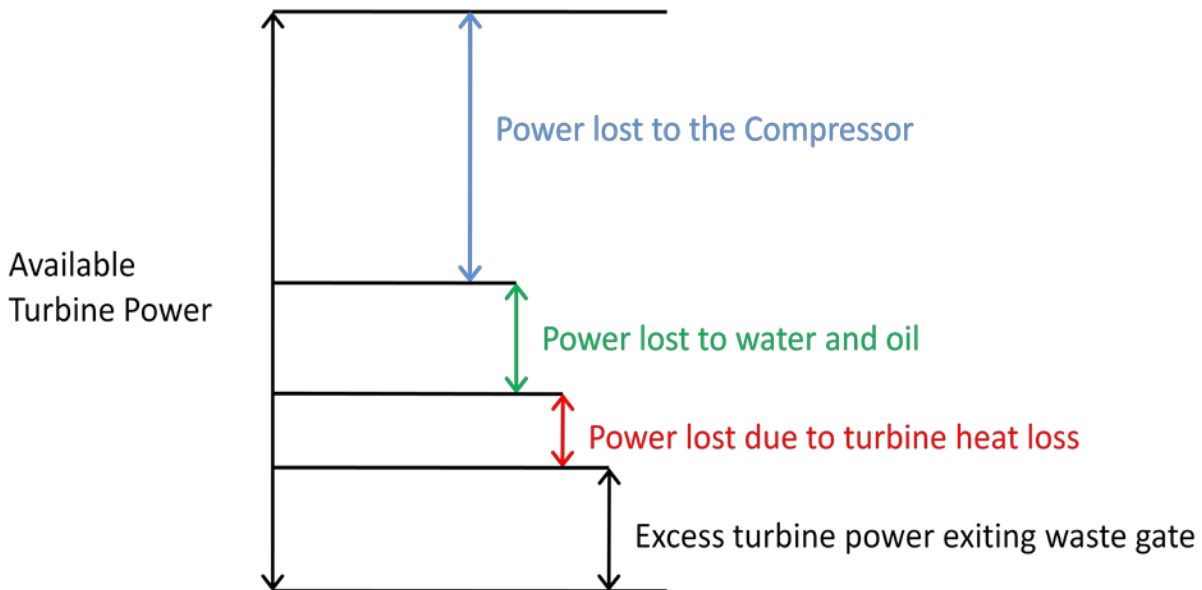


Figure 8: Turbine Power Distribution Diagram

The amount of waste gate margin a turbocharger has depends greatly on the amount of energy available to the turbine. Figure 8 illustrates the turbocharger power balance. Based on the total exhaust flow rate from the engine, the turbine has the potential to produce a specific amount of power. This specific amount of power is shown as the “Available Turbine Power” in Figure 8. From this Available Turbine Power, a portion is consumed by the compressor, a portion is transferred to the oil and water systems via heat transfer, and a portion is transferred to the surroundings via heat transfer from the turbocharger case. Any remaining Available Turbine Power represents the waste gate margin. As the ambient temperature increases, the portion of the Available Turbine Power required to drive the compressor increases, while the portions transferred to the oil, water, and surroundings stays approximately the same. Consequently, because the Available Turbine Power remains approximately constant, the waste gate margin is reduced. The ability to forecast excess turbine power at high ambient conditions is a valuable asset to maintaining engine performance and emissions compliance. Having this ability was the purpose for developing the excess turbine flow model.

One of the key engineering tools used during this project was the excess turbine flow model developed by ScavengeTech. The excess turbine flow model is schematically illustrated in Figure 9. Using this excess turbine flow model in conjunction with the performance modeling capabilities of T-RECS, a matrix was developed that forecasted the amount of excess turbine power available over a range of ambient conditions. The development of the excess turbine flow model was accomplished using test data from the NGML turbocharger test and turbocharger field data collected on December 17, 2008, immediately after the re-aeroed turbocharger was installed on engine 9A. The enthalpy change across and the rate of energy loss from the turbine was calculated from the test call test data, and a correlation was developed between the two. This correlation is shown in Figure 10.

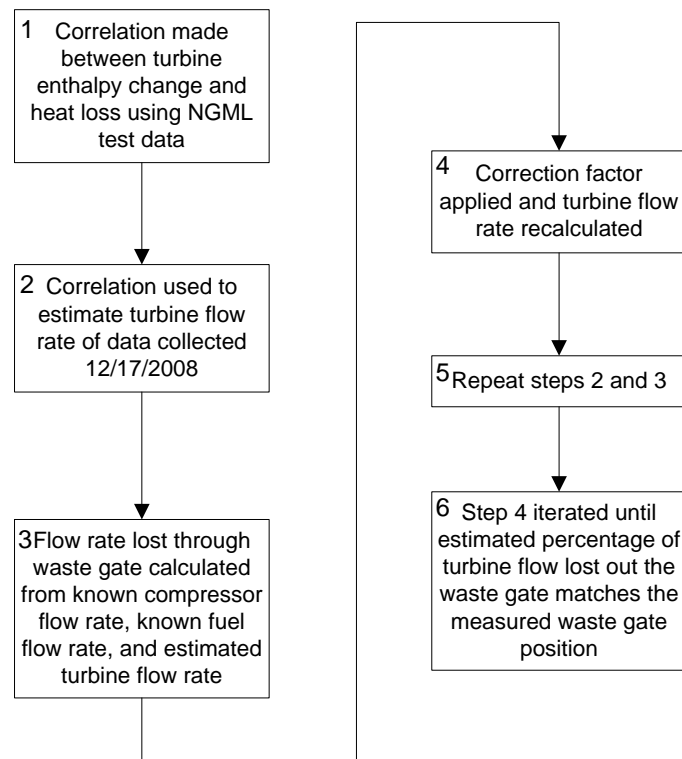


Figure 9: Process outline for excess turbine flow model

The enthalpy change in Figure 10 is calculated by:

$$\Delta H_{turbine} = \dot{m} c_{p,turbine} (T_{inlet,turbine} - T_{outlet,turbine}) \quad (1.1)$$

The turbine energy loss, expressed as a rate of energy transfer from the turbine via heat transfer, was calculated by subtracting the turbine enthalpy change from the power produced by the turbine:

$$\dot{Q}_{turbine} = \dot{W}_{turbine} - \underbrace{\dot{m}_{turbine} c_{p,turbine} (T_{out} - T_{in})_{turbine}}_{-\Delta H_{turbine}} \quad (1.2)$$

The excess turbine flow model uses the correlation created between the Enthalpy change and the turbine energy loss to estimate a turbine flow rate. Once a turbine flow rate has been estimated, the flow rate lost through the waste gate is calculated. This is done by subtracting the turbine flow rate from the sum of the known compressor flow rate and the known fuel flow rate:

$$\dot{m}_{wastegate} = \dot{m}_{compressor} + \dot{m}_{fuel} - \dot{m}_{turbine} \quad (1.3)$$

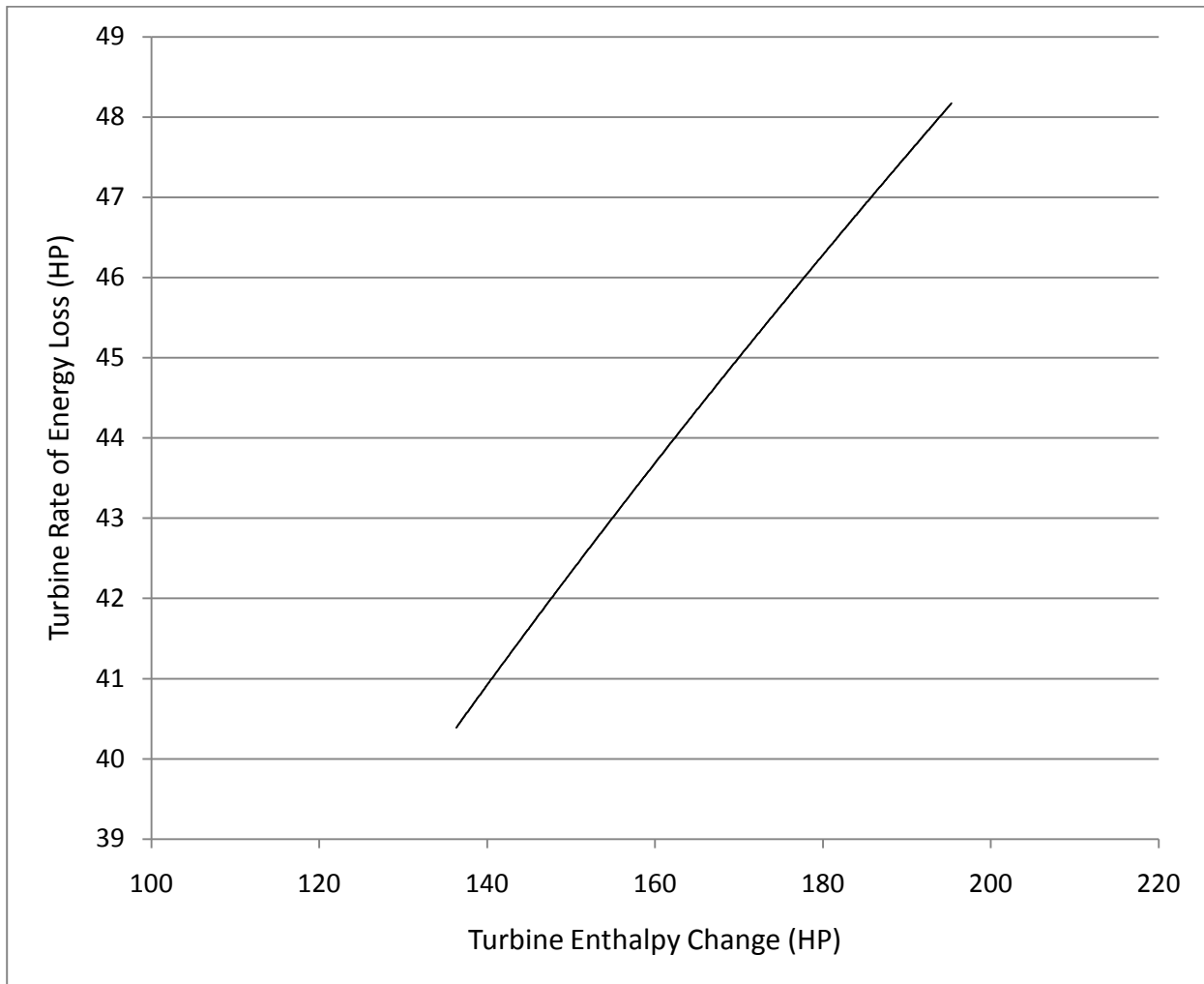


Figure 10: Correlation of Turbine Enthalpy Change and Rate of Energy Loss

The total mass flow rate available to the turbine is the sum of the compressor air flow rate and the fuel flow rate from the engine. A portion of this total flow rate passes through the turbine and the remainder passes through the waste gate. Based on equation (1.2), the rate of energy loss from the turbine is a function of the mass flow rate through the turbine. Because of this functionality, an iterative solution must be used to determine the true mass flow rate through the turbine, which is step 2 in Figure 9. Once the true turbine mass flow rate is calculated, the portion of the total available flow rate that passes through the waste gate is calculated using equation (1.3).

5.0 Matrix Development for Forecasting Excess Turbine Flow

As discussed earlier, a T-RECS model of engine 9A was created using four different data sets. Each of these data sets was collected during varying levels of performance.

1. The first model was developed using operating data from March 2006 at the time when the 2006-version of the turbocharger was installed. Because the re-aeroed turbocharger design point was based on data from this test, this model was to provide the baseline for performance and operation.
2. The second model was developed from test data collected during May 2007. This was during a time period well before the turbocharger upgrade and prior to the engine being inspected and cleaned. This was also a point in time where there were known issues with the operation of the engine such that it would provide a good model for "worst-case scenario" operation.
3. The third model was created from data collected on December 17, 2008, just after engine 9A had been cleaned and inspected and just after the re-aeroed turbocharger was installed. This model was developed to show the improved performance of the re-aeroed turbocharger and to portray the ideal, or "best-case scenario", operation.
4. The final model was created from data collected in February 2009, two months after the re-aeroed turbocharger had been installed. This model would show the effect that port carboning has on the performance of the engine system with the re-aeroed turbocharger, and the ability of the re-aeroed turbocharger to meet the design requirements even with the engine and/or turbocharger in a degraded state.

Each of the four T-RECS models was individually tuned to match the operating data from the respective data sets. After each model was properly tuned, and the corresponding flow coefficients and operating parameters set, the models were exercised to develop a performance matrix for each case. The performance matrix varied air manifold pressure, engine ignition timing, and ambient temperature as shown in Table 3.

Table 3: T-RECS Performance Matrix Parameters and Ranges

Performance Parameter	Range	Increment
Air Manifold Pressure	5 to 8 psig	0.5 psi
Engine Ignition Timing	-6 to -14 °BTDC	-2°
Ambient Temperature	50 to 100 °F	25°F

The input parameters needed to run the excess turbine flow model were extracted from the matrix output to calculate the excess turbine flow for each of the 4 cases that were examined. This process was done for each of the four T-RECS matrix models. The resulting excess turbine flow over the range of the matrix was plotted for each data set and the results were compared. The following figures are the result of the entire modeling process.

The colored bars in Figure 11 represent the air manifold pressure as it ranges from 5 psig to 8 psig. Each grouping of bars represents a different ignition timing that ranges from -14°BTDC to -6°BTDC. Along the vertical axis is the calculated percent excess turbine flow. As the air manifold pressure is increased, the percent of excess turbine flow increases substantially, by as much as approximately 15%. The change in ignition timing, shown along the horizontal axis, has a much lower impact on the percent excess turbine flow, less than 5%. Because the ignition timing has an almost insignificant impact on the excess turbine flow, the four data sets were compared at the common ignition timing of -10°BTDC.

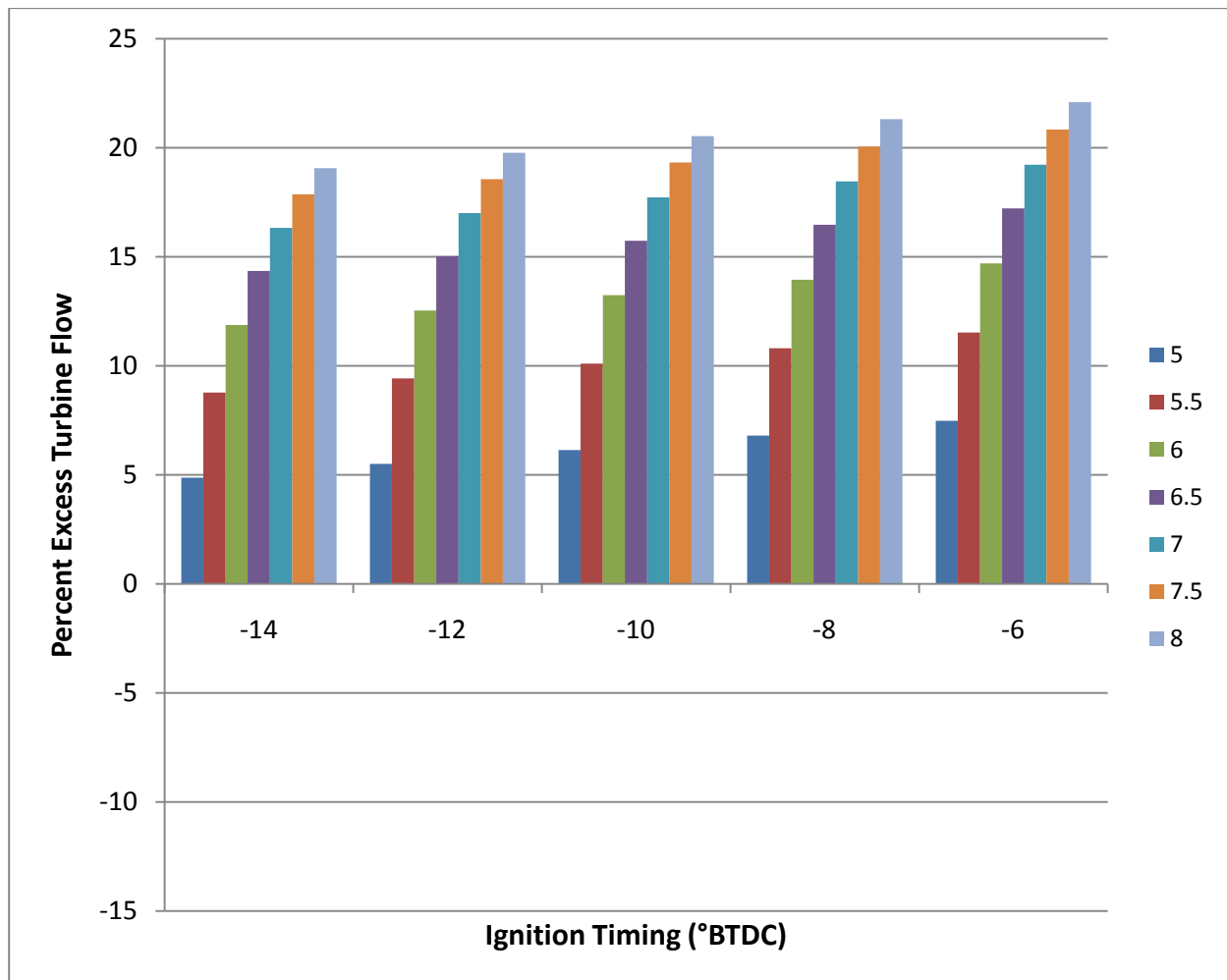


Figure 11: March 2006 Data Excess Turbine Flow at 50°F

The goal of the modeling was to quantify the impact of ambient temperature on the excess turbine flow rate. As shown in Figure 12, and as expected, the ambient temperature has a large impact on the excess turbine flow rate. As the temperature increases from 50°F to 100°F, the amount of excess turbine flow can decrease by almost 10%. The key observation from this figure is if the turbocharger is operating with a waste gate margin of less than 10% during the winter, this decrease in excess turbine flow as the temperature begins to warm can lead to unexpected and costly events during the summer. The turbocharger may begin to operate without any waste gate margin, causing less air to be delivered to the engine, increasing the emissions, and ultimately leading to operating out of compliance. The second key observation is that the excess turbine flow rate strongly depends on the air manifold pressure.

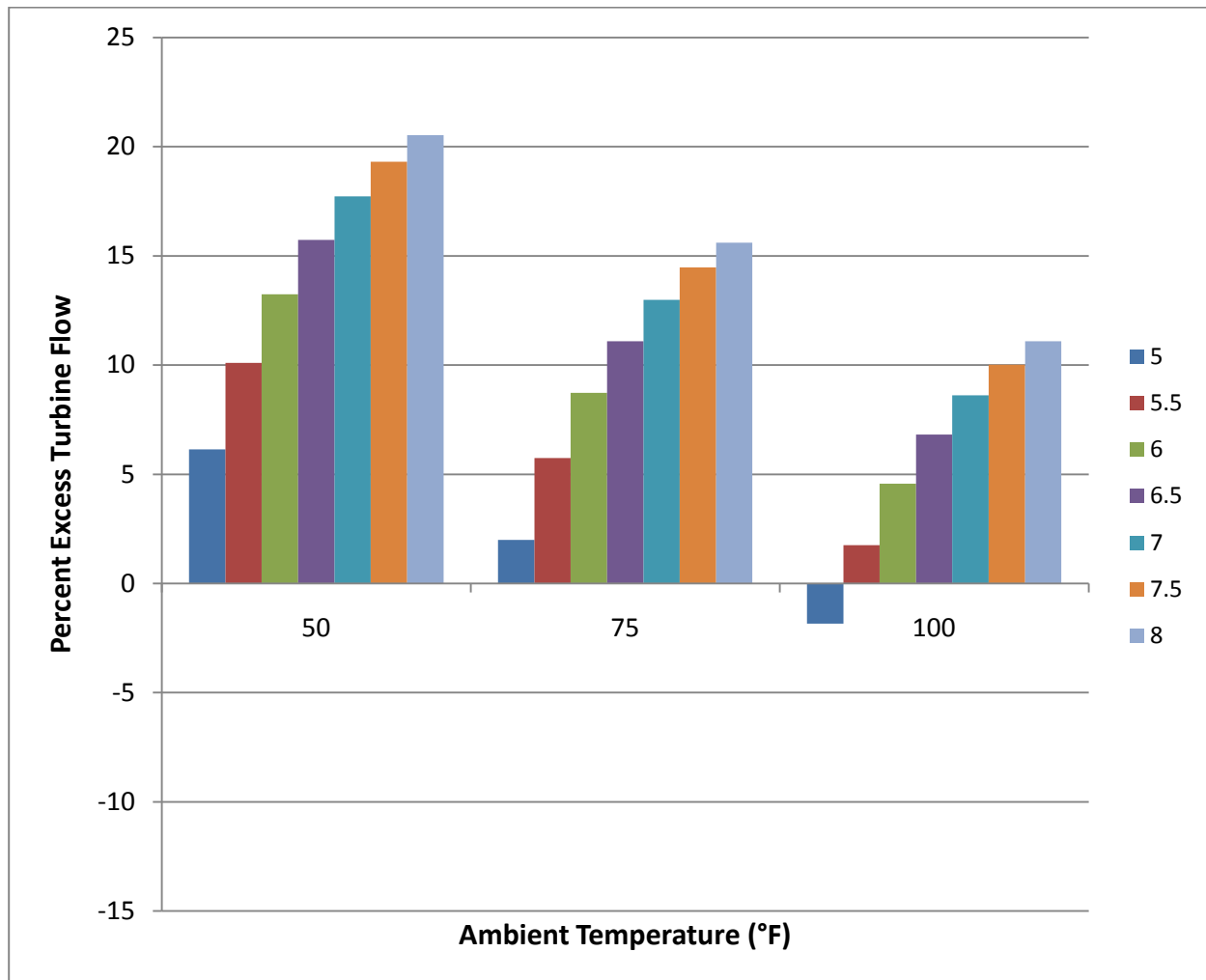


Figure 12: March 2006 Data Excess Turbine Flow at -10°BTDC IT

The modeling results of the May 2007 data set are shown in Figure 13. This is a direct comparison to the March 2006 data shown in Figure 12. As the figures show, the excess turbine flow decreased significantly between March 2006 and May 2007, especially at the higher ambient temperatures. During May 2007, when the outside temperatures were beginning to increase, there was very little to no excess turbine flow. For the turbocharger to provide enough air to the engine, the engine would have to constantly operate at a higher air manifold pressure. Even while operating at a higher air manifold pressure, there was very little excess turbine flow. The reason for the reduced excess turbine flow rate was due to intake port carboning. As the intake port carboning increased, the available energy at the turbine inlet decreased. When the available energy decreases, the total enthalpy across the turbine decreases, which, in turn, decreases the excess turbine flow rate.

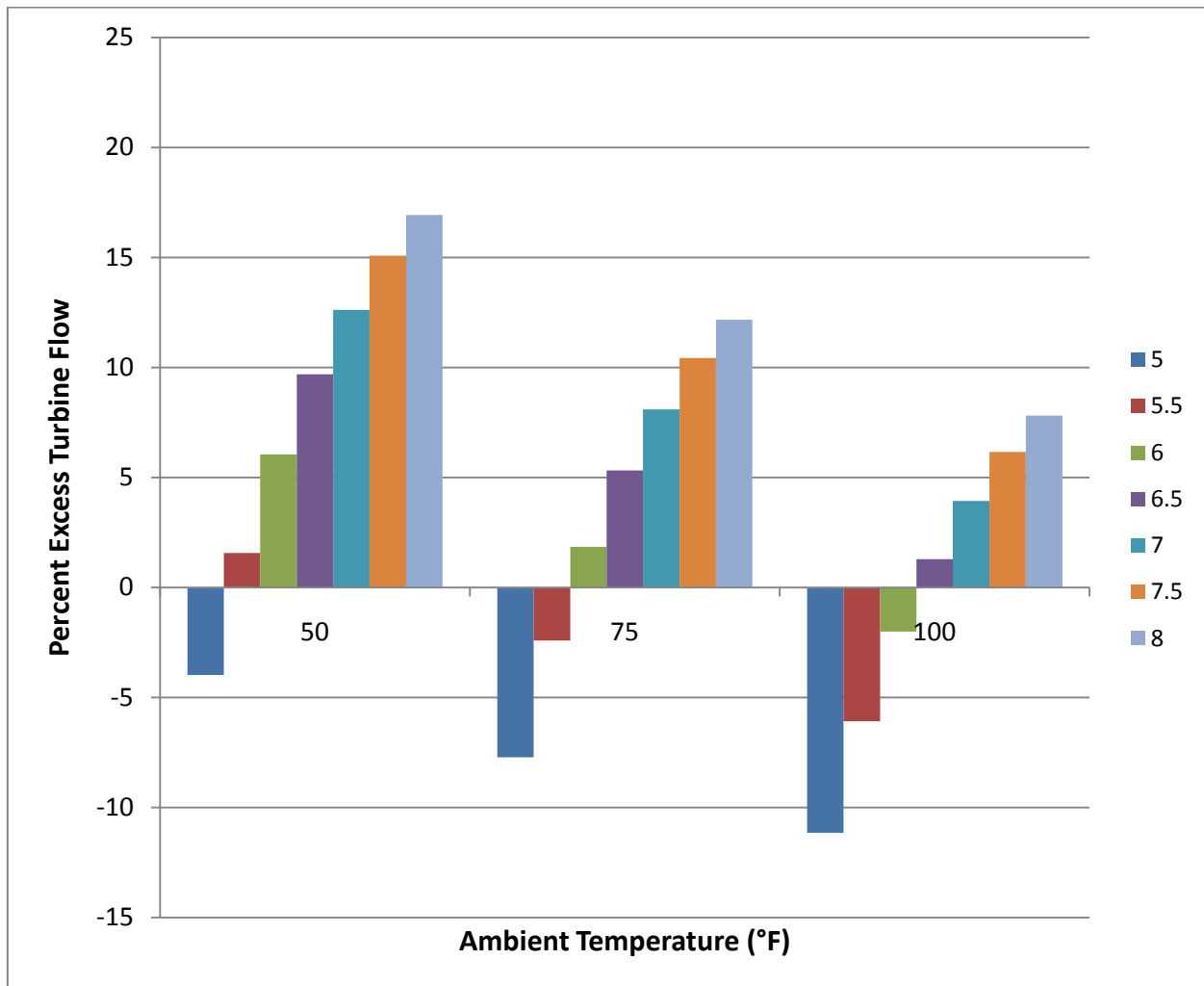


Figure 13: May 2007 Data Excess Turbine Flow at -10°BTDC

The modeling results shown in Figure 14 are from the data set taken just after the re-aeroed turbocharger was installed. The re-aeroed turbocharger provided excess turbine flow at the lower ambient temperature. At high ambient temperatures, the model simulated excess turbine flow, even with the lower air manifold pressures. Consequently, the re-aeroed turbocharger should, and has, operated with excess turbine flow, i.e., waste gate margin.

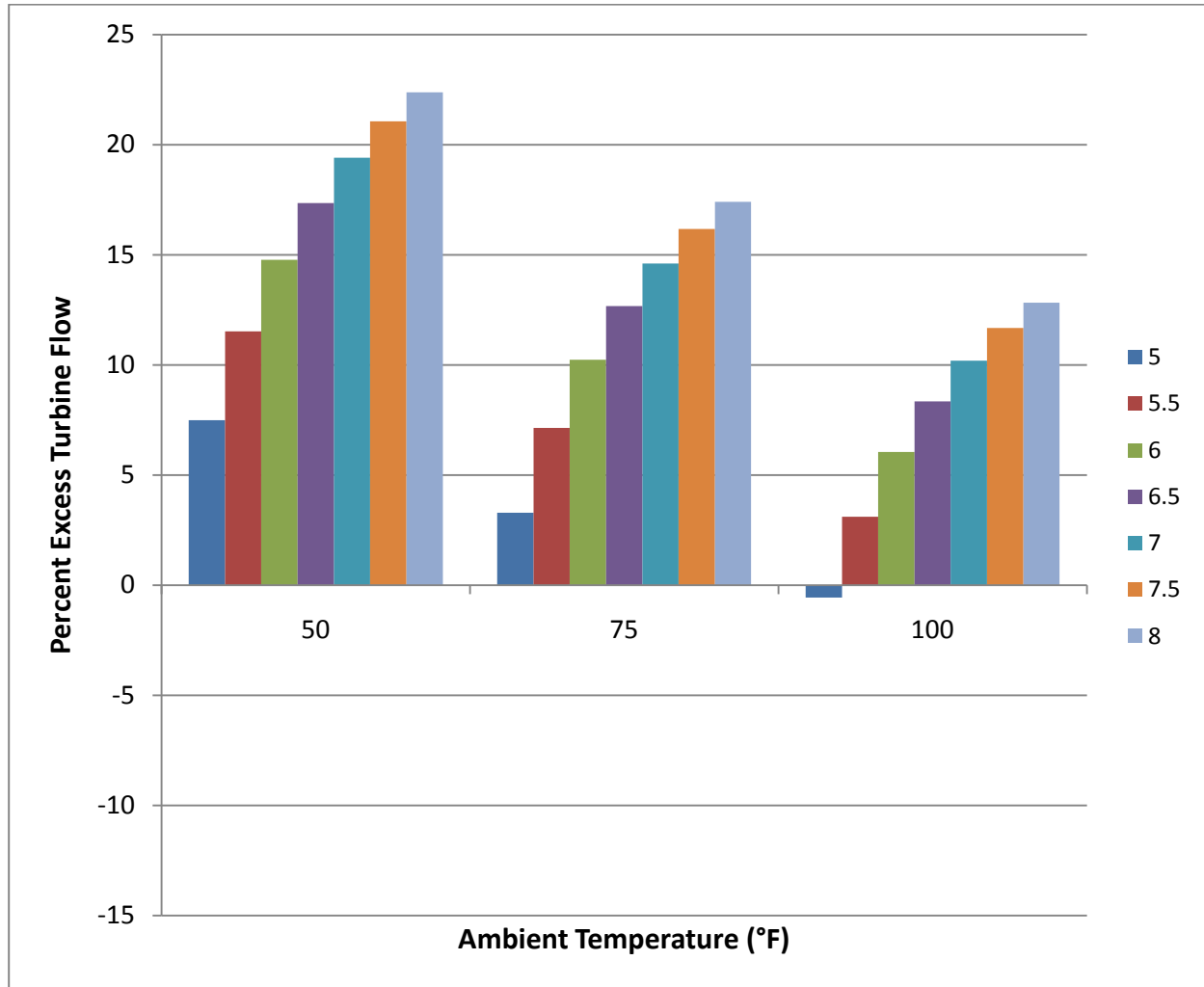


Figure 14: December 2008 Data Excess Turbine Flow at -10°BTDC

The final model created was from data collected after the re-aeroed turbocharger had operated on the engine for two months. The results from the model are shown in Figure 15. The excess turbine flow had decreased slightly between December 2008 and February 2009, but the turbocharger data did not show any signs of degradation. Since the turbocharger had not degraded, the decrease in excess turbine flow had to be contributed to some other part of the system.

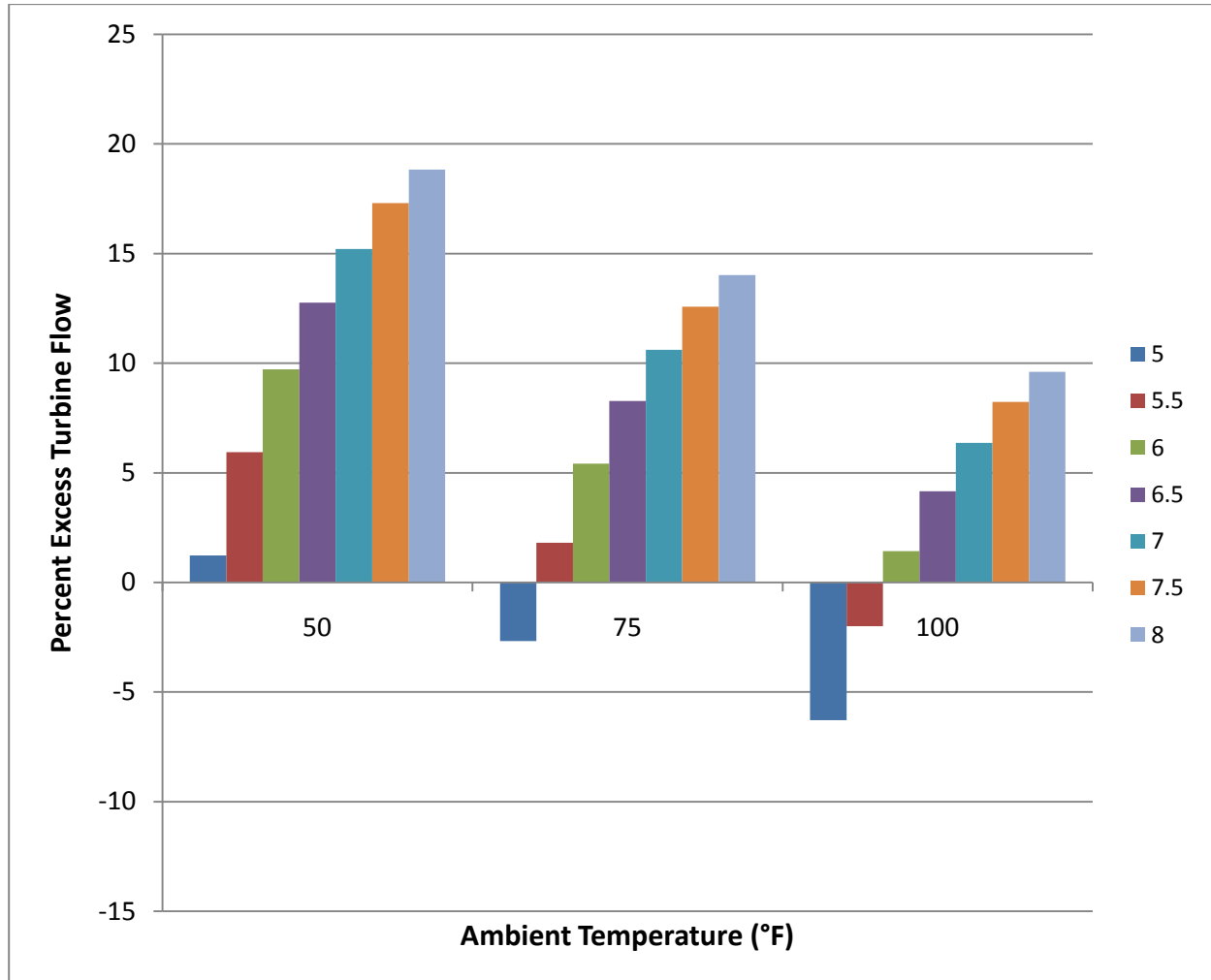


Figure 15: February 2009 Data Excess Turbine Flow at -10°BTDC

After inspecting the engine, a “small” amount of carbon build up was found on the engine intake ports. This slight carbon build up, not degrading turbocharger performance, led to the decrease in excess turbine flow. The increase in the flow restriction caused by the carbon buildup is evident in the higher engine differential pressure shown in Figure 16. Even with the flow restriction caused by the carbon buildup, at air manifold pressures above 6 psig, excess turbine flow is available at higher ambient temperatures.

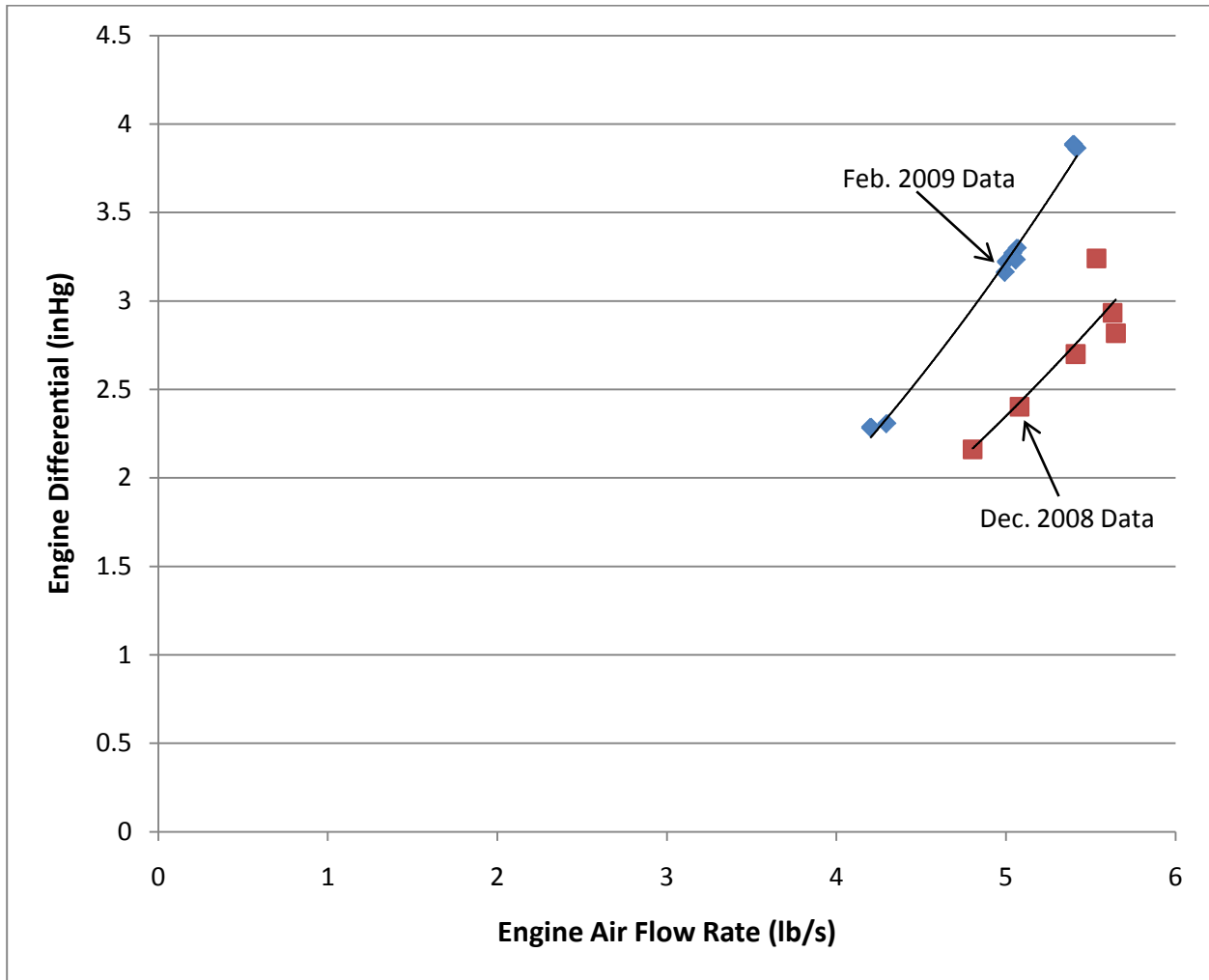


Figure 16: Flow Restriction Increase between December 2008 and February 2009

6.0 Results and Conclusions

The team examined the results of the modeling to determine if the performance of the re-aeroed turbocharger was sufficient enough to put the same turbocharger design on the remaining engines at Station 32. The conclusions from the modeling study are:

- Carbon buildup:
 - Occurred between December 2008 and February 2009.
 - Resulted in a 16% increase in flow restriction.
- There were no signs of turbocharger degradation.
- Even with port carboning:
 - There is excess turbine flow available at 100°F ambient.
 - Operators may need to slightly retard ignition timing to achieve excess turbine flow.
- Test data shows engine meets emissions at any tested operating condition.
- Symptoms of port carboning show up as reduced waste gate margin. Unfortunately, this symptom is oftentimes mis-diagnosed as a “turbocharger problem.” Instead, the larger differential pressure across the engine erodes the available energy at the turbocharger turbine inlet, which then leads to reduced waste gate margin.
- Port carboning has a much more significant impact when the air manifold pressure is relatively low. This will always be the case in low-BMEP engines.
- Developing a solution that used the same turbocharger cases, as opposed to installing new turbochargers, ultimately saved approximately \$2 million. The use of historical turbocharger data made this savings possible.

With these conclusions, El Paso decided to implement the re-aeroed turbocharger design on the remaining engines at Station 32. Future inspections and testing of the engines are planned to assure the turbochargers continue to operate with available excess turbine flow. Since the decision to place the re-aeroed turbocharger on the remaining engines at Station 32, three additional turbochargers have been tested at the NGML, and all three have been installed on LTC engines.

7.0 Acknowledgements

The authors thank the Station 32 personnel at Jasper, TX for their cooperation and work throughout the project. Also, the authors would like to thank Damian Kuiper for his technical expertise and advice during the project.

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