Technologies to Enhance Operation of the Existing Natural Gas Compression Infrastructure

Quarterly Technical Progress Report

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ABSTRACT

This report documents work performed in the fifth quarter of the project entitled: *Technologies to Enhance Operation of the Existing Natural Gas Compression Infrastructure*. The project objective is to develop and substantiate methods for operating integral engine/compressors in gas pipeline service, which reduce fuel consumption, increase capacity, and enhance mechanical integrity. The report describes the following work: completion of analysis of data from first visit to second site; preparation for follow-up testing.

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1. INTRODUCTION

This report documents work performed in the fifth quarter (October 1, 2003 through December 31, 2003) of the project entitled: *Technologies to Enhance Operation of the Existing Natural Gas Compression Infrastructure*.

The project objective is to develop and substantiate methods for operating integral engine/compressors in gas pipeline service, which reduce fuel consumption, increase capacity, and enhance mechanical integrity.

The project has been structured in three phases – the first to last eighteen (18) months, with nine (9) tasks. These tasks, with their objectives, are as follows:

1. **Research Management Plan:** To define a work breakdown structure and supporting narrative that addresses the overall project objectives.

2. **Technology Status Assessment:** To describe current and competing technologies for pipeline compression, with strengths and weaknesses.

3. **Industry Advisory Committee (IAC):** To interact with industry advisors and their suppliers and, thereby, focus the work and help transfer knowledge into practice.

4. **Test Plan:** To develop a test plan which addresses project objectives, and which will serve as a basis for tests to be performed at various industry sites.

5. **Data Acquisition System (DAS):** To develop a data system which will support project objectives and acquire all needed data with appropriate format, data rates, and display.

6. **Test Program:** To perform tests on a representative series of engine/compressors; gather data to develop required relationships for efficiency, capacity, and mechanical integrity.

7. **Data Analysis:** To relate power cylinder standard deviation, balancing process, and compressor cylinder operation to fuel flow, compression efficiency, and crankshaft strain through models.

8. **Methods for Optimized Operation:** To apply the models and develop optimized methods for balancing and operating engine/compressors.

9. **Program Management:** To perform planning, administrative, and technical direction functions to achieve project objectives; to communicate with and report to the DOE and other co-funding organizations.

So far, progress has been made under all of Tasks 1 through 9, and is discussed in the subsequent sections of this quarterly report.

In the first quarter, Task 1 was completed, and progress was made on Tasks 2, 3, 4, 5, and 9.

In the second quarter, Tasks 2, 4, and 5 were completed; further progress was made on Tasks 3 and 9, and initial progress was made on Task 6 (calibration and site visit for first test site).

In the third quarter, the initial test at the first site was completed (Task 6) and data analysis was started (Task 7).

In the fourth quarter, the initial test at the second site was completed (Task 6), and data analysis was started on this data (Task 7). Analysis of data from the first site was completed (Task 7). Operational optimization plans (Task 8) were prepared for the return to site 1.

In the fifth quarter, a presentation of results was made at the DOE-NETL Research Review session held during the Gas Machinery Conference (October 6-8, 2003). Analysis of data for the second site was completed. Plans were prepared and distributed to the Industry Advisory Committee (IAC) for follow-up testing on two test series initiated at two industry hosted sites. Preparation was made for these follow-up tests.

2. EXECUTIVE SUMMARY

Tasks 1, 2, 4, and 5 were completed prior to this quarter.

An Industry Advisory Committee (IAC) was formed in the first quarter. A first IAC meeting was held January 14, 2003, and provided valuable project direction. A second IAC meeting was held June 24, 2003, and provided further focus to the direction of the project. An informal IAC meeting was held following the DOE Research Review session at the Gas Machinery Conference (October, 5, 2003). This activity falls under project Task 3.

Following an initial site visit, the first field test was held at El Paso Corporation's Station 823 in Kinder, Louisiana on a Clark HBA-6T, April 15-17, 2003. This was the first major activity under Task 6, and the data was reported in the previous quarterly report. A separate data report was delivered.

Since the initial field test, significant analysis of data obtained during the test has been performed, as part of Task 7, and has been presented in the previous quarterly report.

Following an initial site visit, the second field test was held at Williams (Transco) Station 40 at Sour Lake, near Beaumont, Texas (August 26-28, 2003). This is the second major activity under Task 6. The majority of data analysis from this test was completed in the preceding quarter and is summarized in this quarterly report. Additional analysis of rod load monitor results and load step effects are presented in this report.

Work has continued on plans to implement follow-up tests, which will evaluate operational optimization methods based on previous tests at two industry hosted sites. The following plans have been prepared and distributed to the Industry Advisory Committee (IAC):

1. Plan for second test series at El Paso Station 823 (Kinder, Louisiana).
2. Plan for follow-up before and after testing for high-pressure fuel injection.

3. EXPERIMENTAL

According to the Test Plan, the following data channels were to be acquired simultaneously and processed as part of the testing:

- *Compressor Cylinder Dynamic Pressure* - used for compressor horsepower and flow determination (Sensotec piezo-restrictive transducer).
- *Engine Dynamic Cylinder Pressure* - used for engine horsepower determination, engine balance, and engine statistics (Kistler quartz piezoelectric transducer).
- *Engine Intake and Exhaust Dynamic Pressure Measurements* - used to correlate acoustic dynamic effects to engine statistics (Kistler piezo-resistive transducer (water-cooled)).
- *Torsional Vibrations (IRV)* - used as a surrogate for mechanical integrity (BEI 512 pulse encoder).
- *Bearing Centerline Vibration Measurements* - used as a surrogate for mechanical integrity (PCB velocimeters).
- *Crankshaft Dynamic Strain* - acquired using SwRI's Strain Data Capture Module (SDCM). Used as a direct measurement of shaft loading, and used to provide link between engine statistical quantities (PFP), and crankshaft fatigue damage [1].
- *Engine Fuel Flow* - used to document overall engine efficiency (AGA3 method using Emerson Flobas 103).
- *Suction Header and Discharge Header Pressures and Temperatures* - used for installation efficiency determination (Sensotec piezo-restrictive transducer).
- *Engine Exhaust NO_X and O_2 Levels* - used for input into an engine performance model (NGK fast-response transducer).
- *Compressor Rod Load* - used for both mechanical integrity and loading optimization (strain gage-based; bridged to cancel bending).

For the first test at TGP's Kinder, Louisiana station (April 15-17, 2003), the majority of these channels were successfully acquired as a coherent data set for every test condition. All channels were calibrated prior to the tests. In addition to the channels listed above, a portable emissions analyzer (an ECOM A+) was used to measure concentration of NO, NO_2, NOx, O_2, and CO in the exhaust.

A few of the channels listed above gave problems at the first site. The engine fuel flow meter was calibrated prior to the test, but it was discovered during the test that it was set for a much higher flow rate than was needed and did not give useful data. The rod load monitor RF transmitter drifted too much. This is a development device and the underlying problem has now been corrected. The power cylinder #1 pressure transducer gave suspect data.

At the second test site (Transco Station 40, Sour Lake, Texas, August 26-28, 2003), the fuel flow was successfully measured throughout the test series. The rod load monitor worked successfully. Exhaust manifold dynamic pressure was acquired, as well as air manifold pressure. Station records were used for suction and discharge pressure and temperature for the compressor. All cylinder pressure transducers functioned satisfactorily.

For the follow-up on the first site tests, it is planned to obtain the fuel flow and rod load data not obtained at the first tests in April 2003. Figure 3-1 shows the self-powered rod load monitor (RLM) configured specifically for the HBA-6T crosshead, which has been assembled for this follow-up test. (RLMs for the preceding tests have been battery powered.)

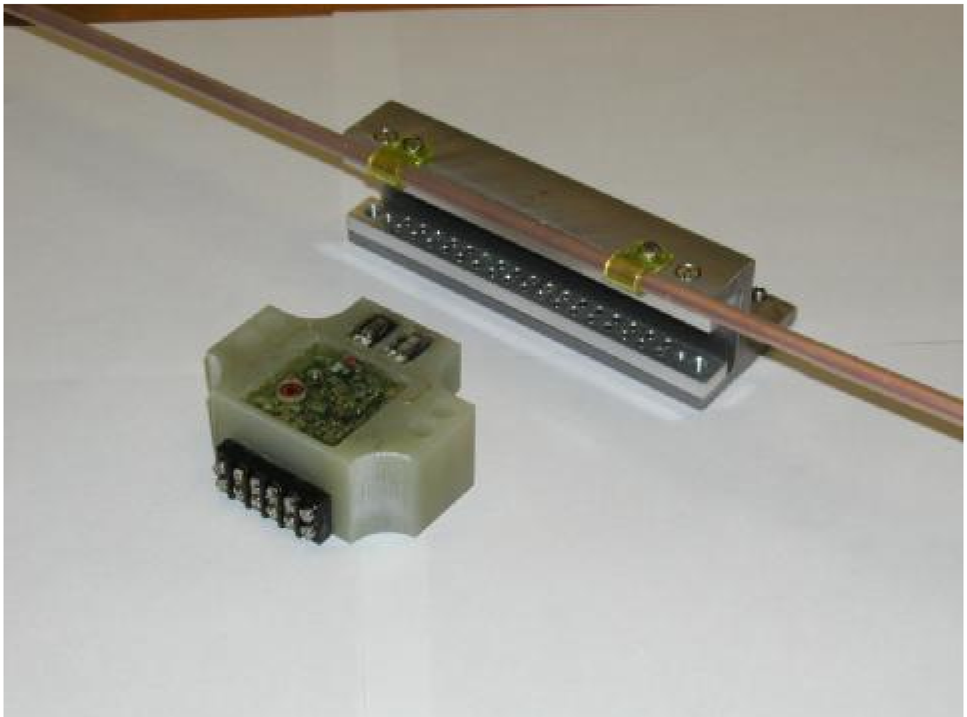

Figure 3-1. Self-Powered Rod Load Monitor (RLM)

4. RESULTS AND DISCUSSION

4.1 INDUSTRY ADVISORY COMMITTEE (IAC) TASK

An informal meeting of most IAC members was held following the DOE Research Review at the Gas Machinery Conference. There has been subsequent interaction with IAC members regarding plans for follow-up testing.

4.2 TEST PROGRAM (TASK 6)

The first test at the second site (Williams Transco's Station 40 at Sour Lake, Texas) was completed in August 2003. Data was acquired as described in the experimental section of this report. Tests were performed to investigate how compressor operation and engine balancing affect integrity and performance of the engine.

The test unit was a GMW10 with three compressor cylinders - one of six similar units at the station. It has a nominal power of 2500 HP (1865 MW) and a nominal speed of 250 RPM. Figure 4-1 shows the test unit and its three compressor cylinders. Figure 4-2 shows five power cylinders, the left bank.

This engine has recently been retrofitted with high-pressure fuel injection (Enginuity's HPFI™ System) and a turbocharger, which replaces the previous scavenging system.

The last quarterly report provided further photographic records and descriptive details of the instrument installations, test results, and data analysis. Table 4-1 summarizes the results of this data analysis.

Table 4-1. Summary of Sour Lake Data Analysis Results

Dynamic Variation Range for Air Manifold Pressure	17 to 22% of Average
Dynamic Variation Range for Exhaust Manifold Pressure	48 to 70%
Rod Load Range	-47,000 lb. to +55,000 lb.
Typical Compression Power during Tests	2375 HP
Compressor Thermal Efficiency	85% to 86%
Engine Heat Rate	7200 to 7300 BTU/HP-Hr.
Increase in Ratio of Compressor to Engine Power during 5 Hours of Tests - As an Apparent Increase in System Mechanical Efficiency as Oil Heats Up	2 to 2.5%
Corresponding Decrease in Fuel Flow	1.5%
Corresponding Decrease in Heat Rate	1.25%
Heat Rate Reduction by Advancing Timing from 8.5 to 11 Degrees BTDC	Reduction from 7250 to 6950 BTU/HP-Hr.
System Thermal Efficiency with "As Found" Timing	29.8%
System Thermal Efficiency with 11 Degrees Timing	31%
Typical Range of Peak-Firing Pressure in 20 Successive Cycles	362 Minimum to 594 Maximum (PC7)
Range of Crankshaft Dynamic Strain during Tests	Between 50 and 60 Microstrain Peak-to-Peak
Typical Spread in Power Cylinder Compression Pressure Over 10 Cylinders	From 244 to 275 PSI
Typical Spread in Average Peak-Firing Pressure Across 10 Power Cylinders	35 PSI
Typical Instantaneous Spread	175 PSI

Figure 4-1. Williams Sour Lake Station, Unit 6

Figure 4-2. Power Cylinder, Left Bank

5. DATA ANALYSIS

The following addresses some items of data analysis from the tests at Sour Lake (Transco Station 40) not addressed in the previous quarter.

5.1 INFLUENCE OF TIMING AND AIR MANIFOLD PRESSURE

Figures 5-1 and 5-2 show how timing and air manifold pressure (AMP) influence heat rate and system thermal efficiency. The points at 8.5° before top dead center (BTDC) for timing and at 12.5 inches of Mercury (Hg) for AMP represent the nominal condition (resulting in 7250 BTU/HP-hr. and 29.8% efficiency). The points at higher and lower timing (6° BTDC, 11° BTDC) and at higher and lower AMP (10 inches, 14 inches Hg) represent independent perturbations in timing and AMP about this nominal condition. They quantify how heat rate falls as timing is increased and how heat rate rises as AMP is increased (making the combustion leaner). Figures 5-3 and 5-4 quantify how NOx follows opposite trends to the heat rate. This opposing trend is sometimes referred to as the NOx-heat rate trade-off. Figure 5-5 presents a plot of heat rate as a function of NOx with all the data from Figures 5-1 through 5-4 on it. Figure 5-5 shows, for example, that heat rate can be substantially reduced from 7250 to 6950, with a 20% NOx increase, by an increase in timing to 11° BTDC.

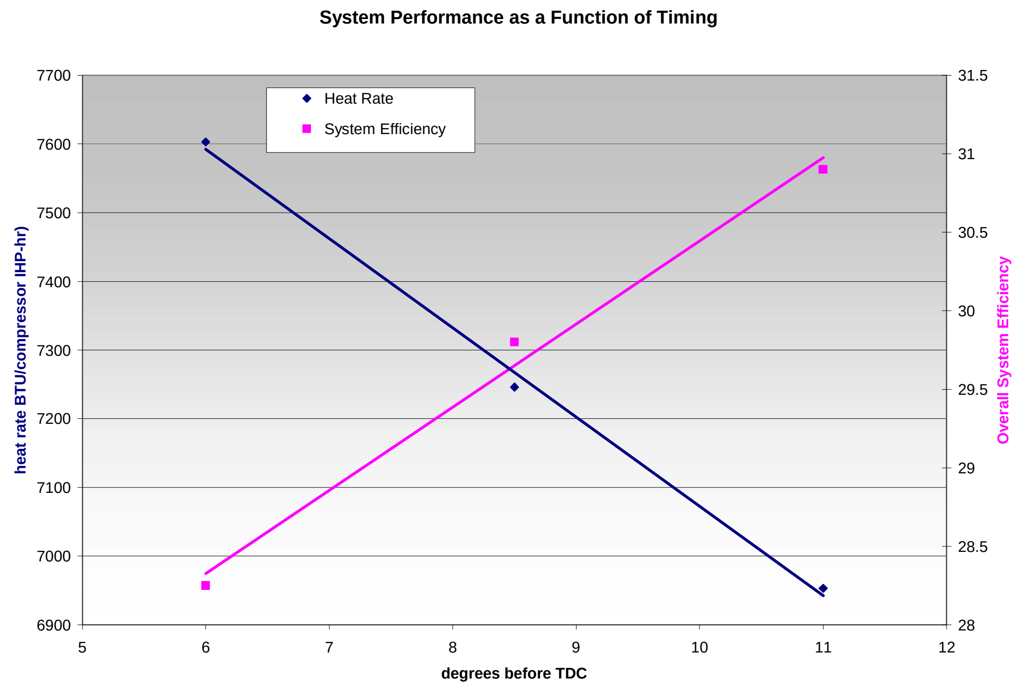

Figure 5-1. Heat Rate and System Efficiency as a Function of Timing

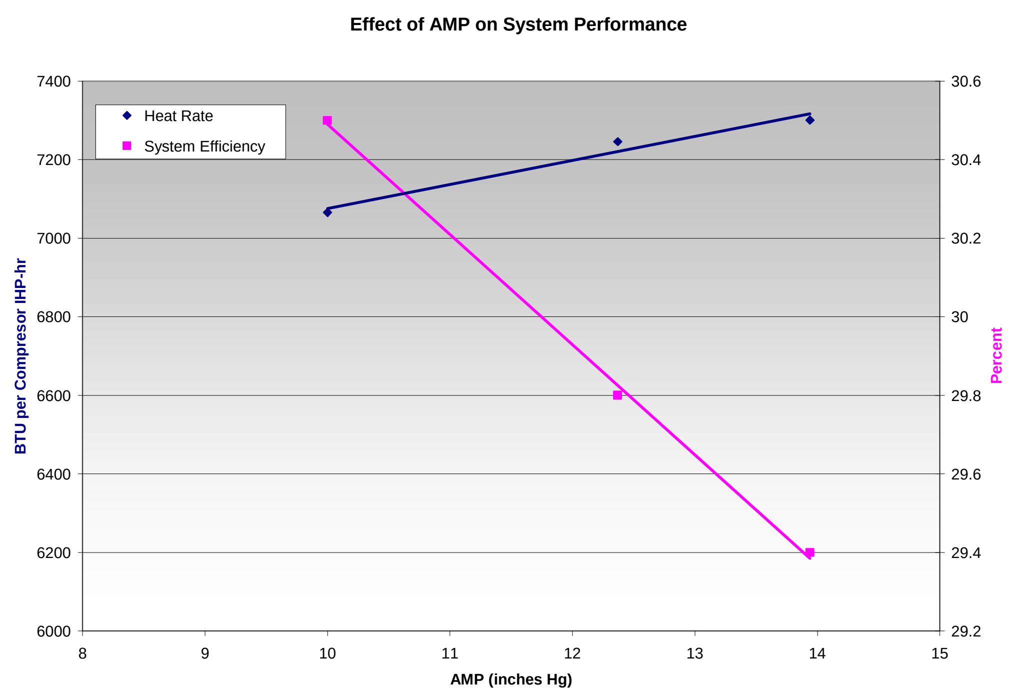

Figure 5-2. Heat Rate and System Efficiency as a Function of Air Manifold Pressure

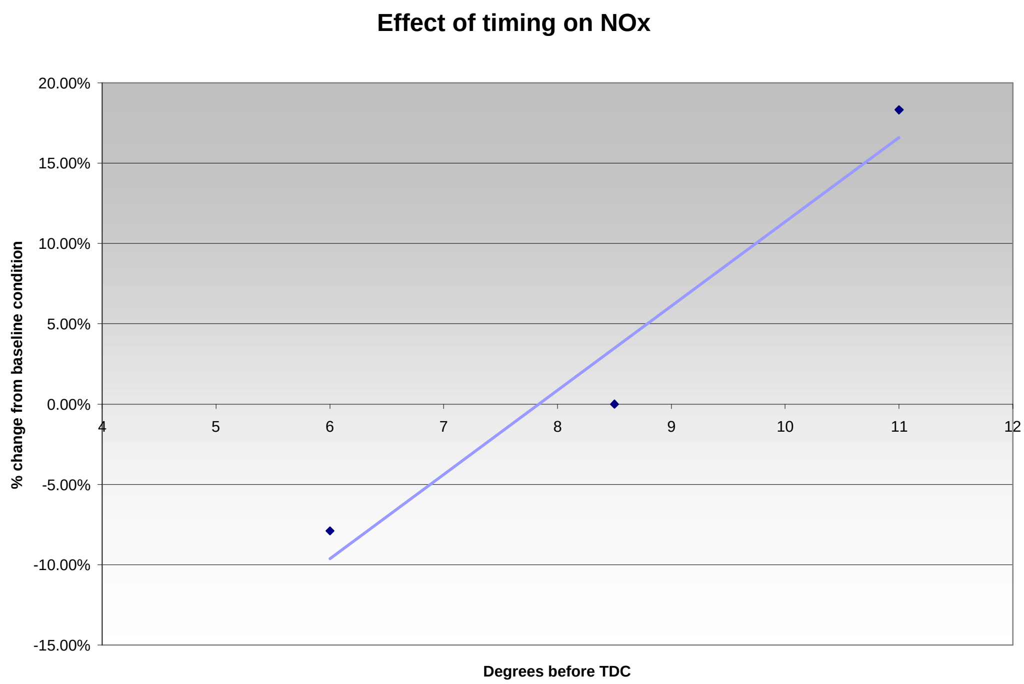

Figure 5-3. Change in NOx as a Function of Timing

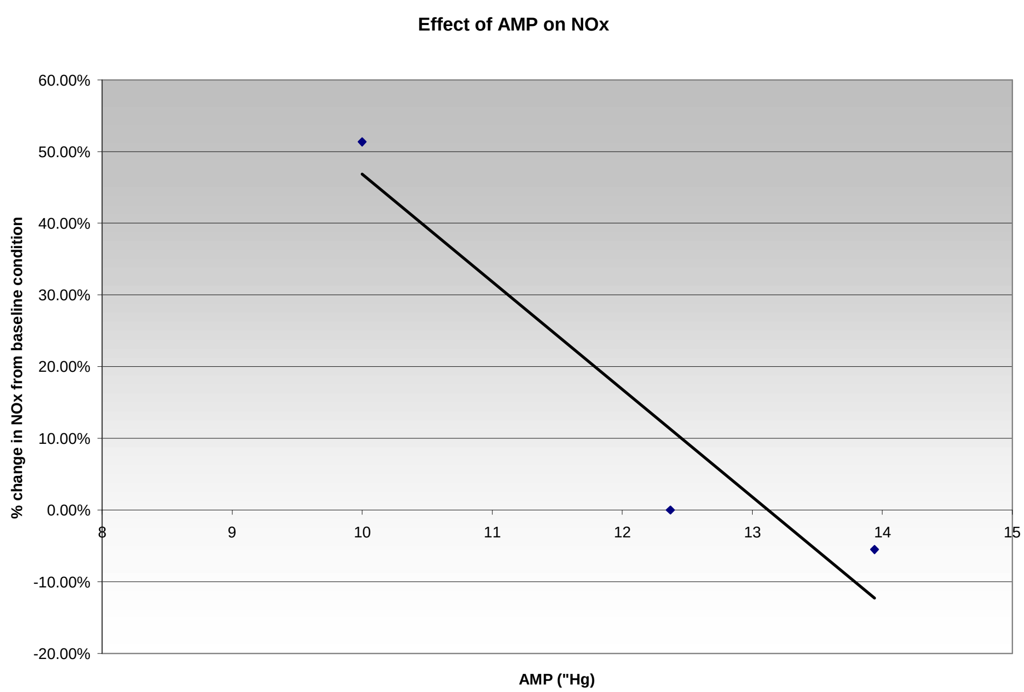

Figure 5-4. Change in NOx as a Function of Air Manifold Pressure

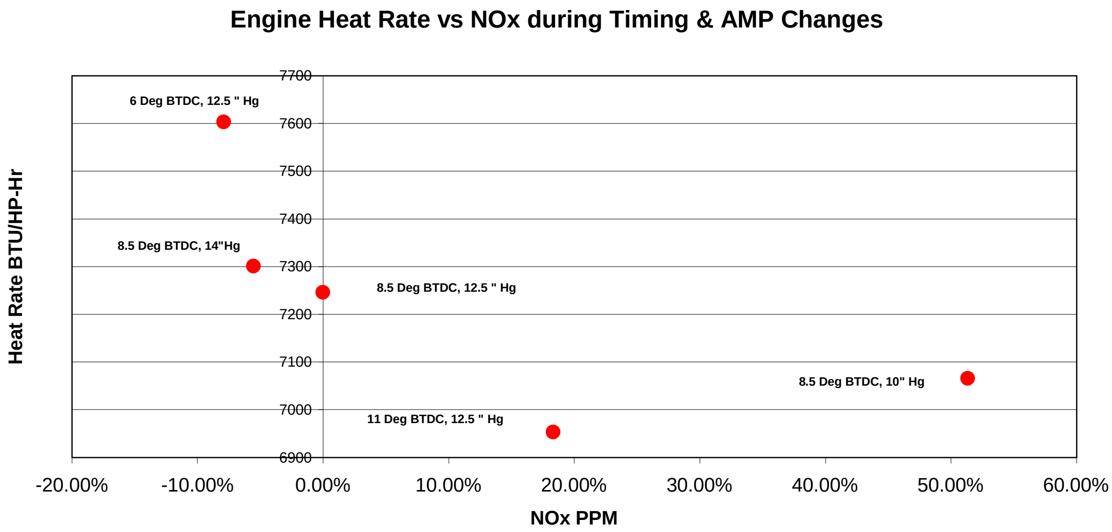

Figure 5-5. Trade-off between Head Rate and NOx

5.2 ROD LOAD MONITOR EVALUATION

During the Sour Lake tests, data was obtained on compressor cylinder #3 with cylinder pressure and with the rod load monitor (RLM). However, when compared, the ratio between cylinder pressure indicated horsepower and the horsepower determined from the RLM varied strongly during the day. The sensitivity of the RLM appeared to be changing during the day, and since it has already been observed that there is an increase in oil temperature over the day, a temperature effect was suspected. Tests in the laboratory following the Sour Lake tests confirmed a distinct increase in the ratio of volts per 1000 microstrain, as shown in Figure 5-6. Based on this, an effort was made to correct the data. Figure 5-7 presents the variation of oil inlet and outlet temperature during the test day, and the increase in outlet temperature is clear. As the best information available on temperature variation, the outlet temperature data of Figure 5-7 has been combined with the sensitivity correction of Figure 5-6, as expressed in the equation on the chart ($y = 0.0016x + 0.8571$, where y is volts/1000 microstrain and x is temperature), to come up with a corrected horsepower based on the RLM. The correction is not perfect, because the oil temperature would not be expected to provide a precise measurement of rod temperature.

The result is shown two ways. Figure 5-8 presents the horsepower determined from cylinder pressure (compressor IHP) and from the RLM (corrected), as they varied during the day. Figure 5-9 presents the ratio of the two horsepowers. Clearly, the correction is imperfect, and is not a long term satisfactory way to determine horsepower from the rod load measurement. Based on these results, the component in question in the RLM has been replaced and the sensitivity now does not vary with temperature. We plan to test the refined RLM on the return to El Paso Station 823.

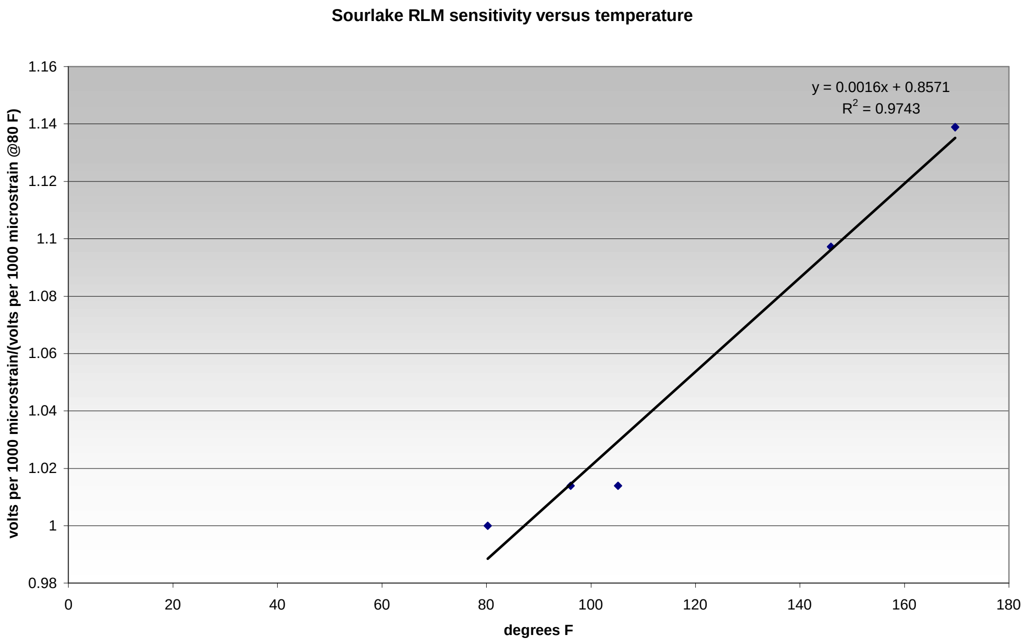

Figure 5-6. Post Test RLM Temperature Sensitivity Measurements

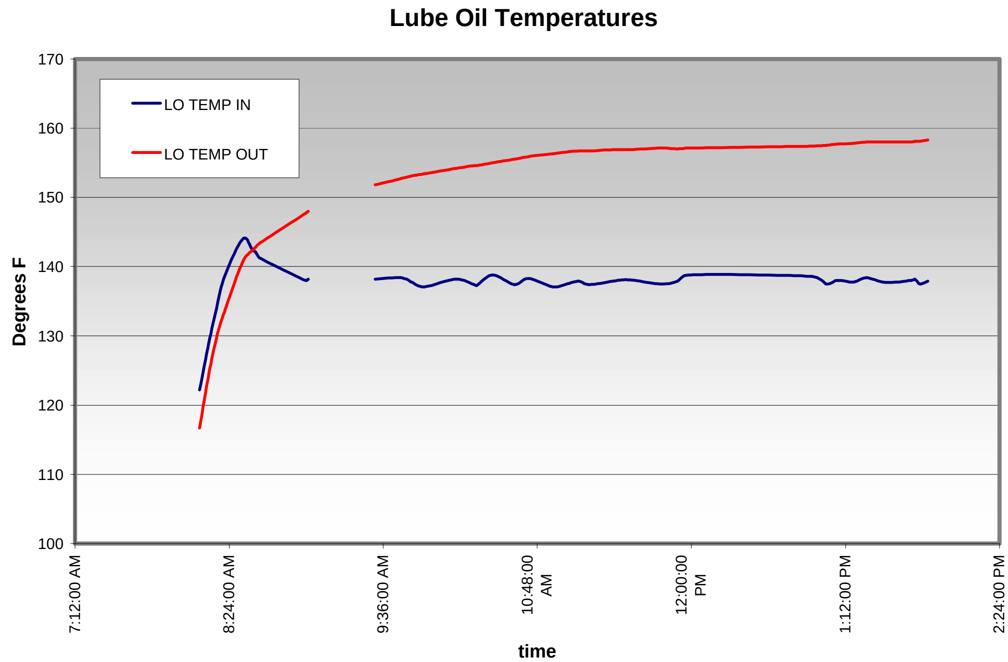

Figure 5-7. Variation of Oil Inlet and Outlet Temperatures

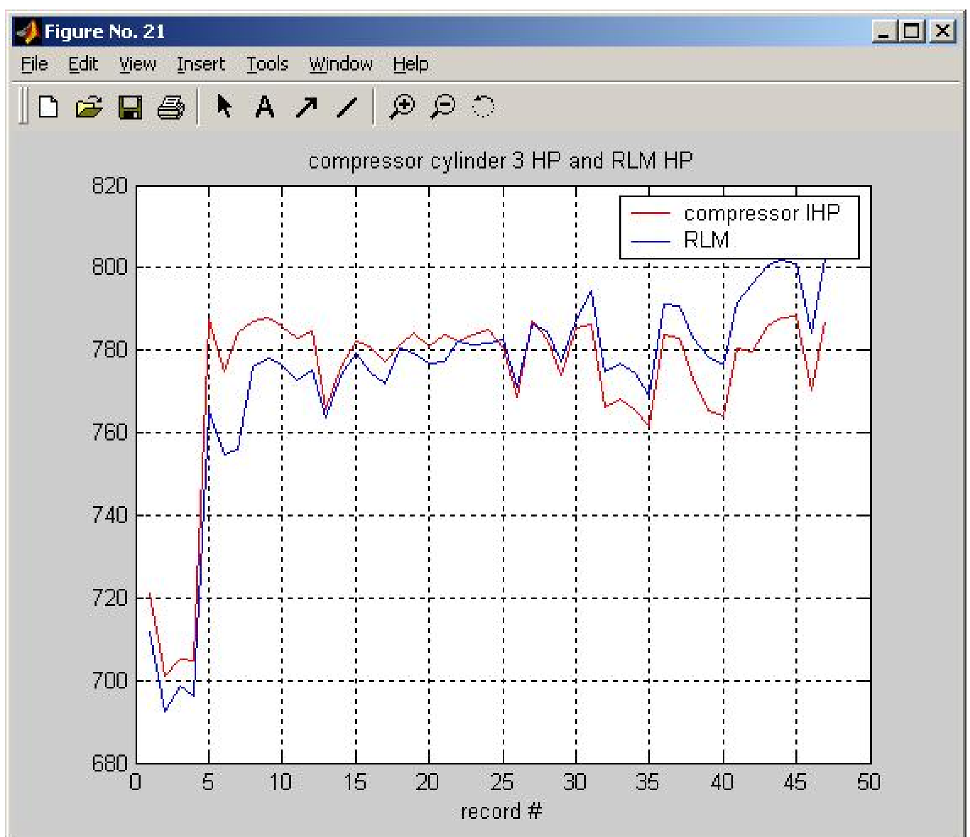

Figure 5-8. Compressor IHP and RLM HP

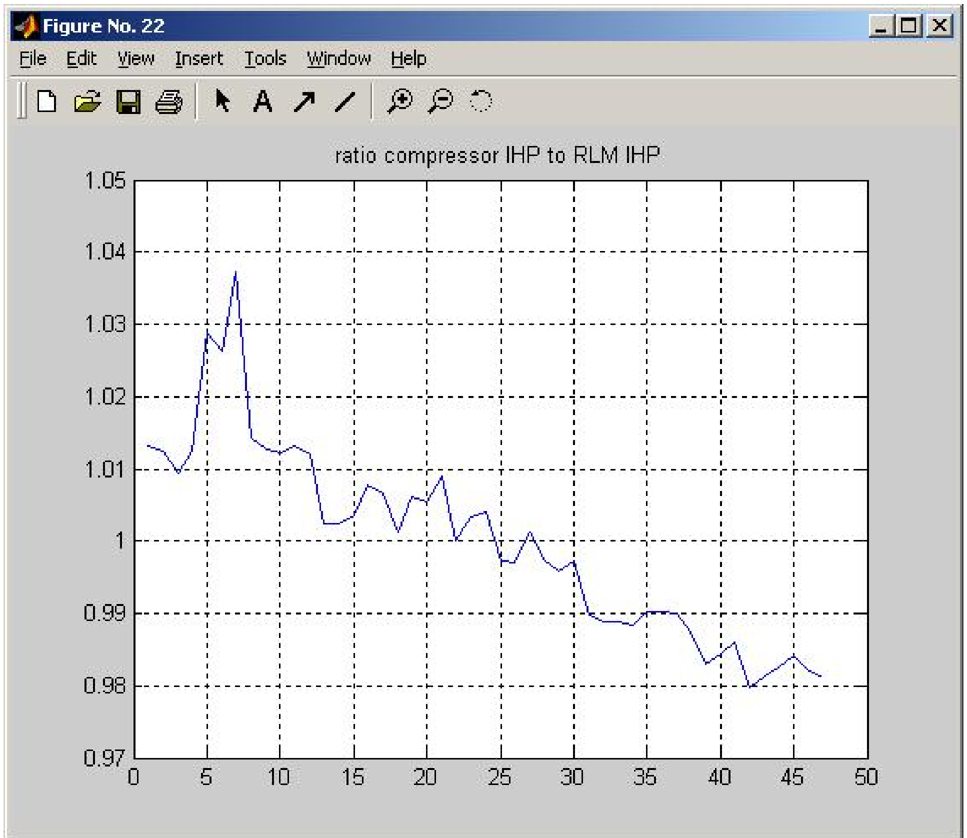

Figure 5-9. Residual Ratio Compressor IHP to RLM HP

5.3 INFLUENCE OF LOAD AND LOAD STEP

During a second day's testing, the influence of load step was investigated. The first objective was to investigate how load step might influence brake thermal efficiency or heat rate when the unit was otherwise operating at the same horsepower. Some test results on a preceding GMRC/PRCI project had suggested that the way the compressor cylinder load is distributed along the shaft might influence the power cylinder behavior to a small extent under part load. A second objective was to investigate how load on the engine might influence compression pressure and rod load data.

These objectives encountered mixed success. By combining a change in load step with pinching the suction line to increase ratio, it should in principle be possible to achieve the same horsepower with a different load step. However, the efforts to readjust the horsepower back to the value before the load step change were not successful – a series of operational problems and unit trips showed that this was not readily attainable – at least under the prevailing pipeline conditions. Thus, the first objective could not be met during these tests.

The change in load step prior to efforts to change suction pressure did however accomplish a change in horsepower, as would be expected, and data was obtained on how compressor load influences compression pressure in the power cylinder and the relationship of rod load monitor to indicated horsepower. Figure 5-10 shows the variation of horsepower during the tests. Approximately 20% increase in compressor power was obtained over the test range. Figure 5-11 shows the corresponding variation in compression pressure in the ten power cylinders. They all track each other and appear to maintain a similar separation. Figure 5-12 confirms this by plotting the difference from cylinder #1 compression pressure for all the other cylinders. In spite of substantial absolute variation in compression pressure (over 30 PSI) the difference of all cylinders from cylinder #1 shows at most a 5 to 6 PSI variation. This is further indication of a consistent cylinder-to-cylinder variation in the trapped mass of air, which is a basis for a separately proposed air balance investigation.

Figure 5-13 shows the change in indicated cylinder #3 horsepower and the corresponding ratio of indicated horsepower to RLM horsepower (this time without temperature correction). The need for temperature correction is re-emphasized by this data. The uncorrected data in Figure 5-13 shows much wider variation of the horsepower ratio than the corrected data for the previous day in Figure 5-9.

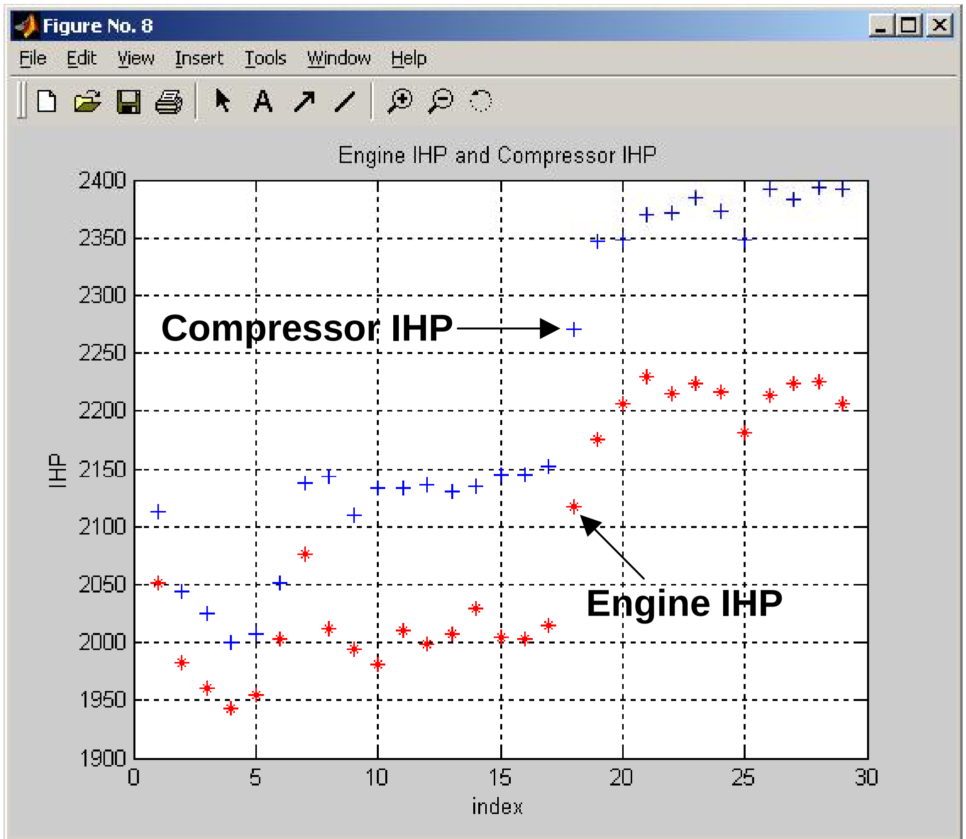

Figure 5-10. Variation in Power during Second Day's Testing

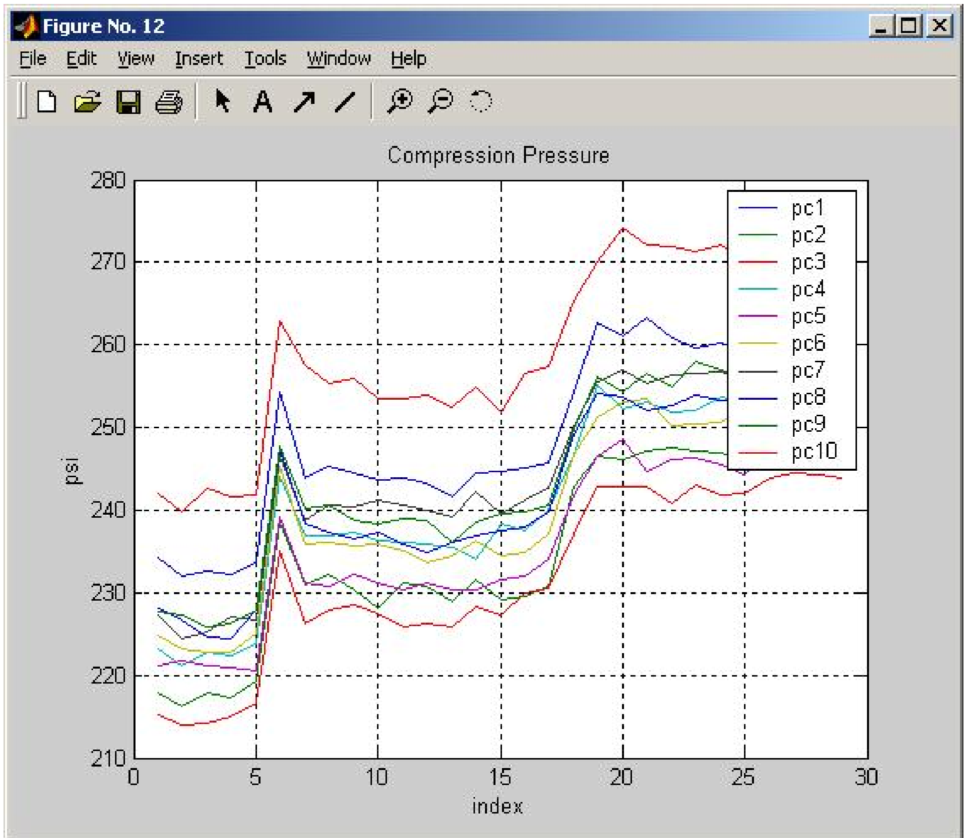

Figure 5-11. Compression Pressure for Ten Power Cylinders during Second Day's Testing

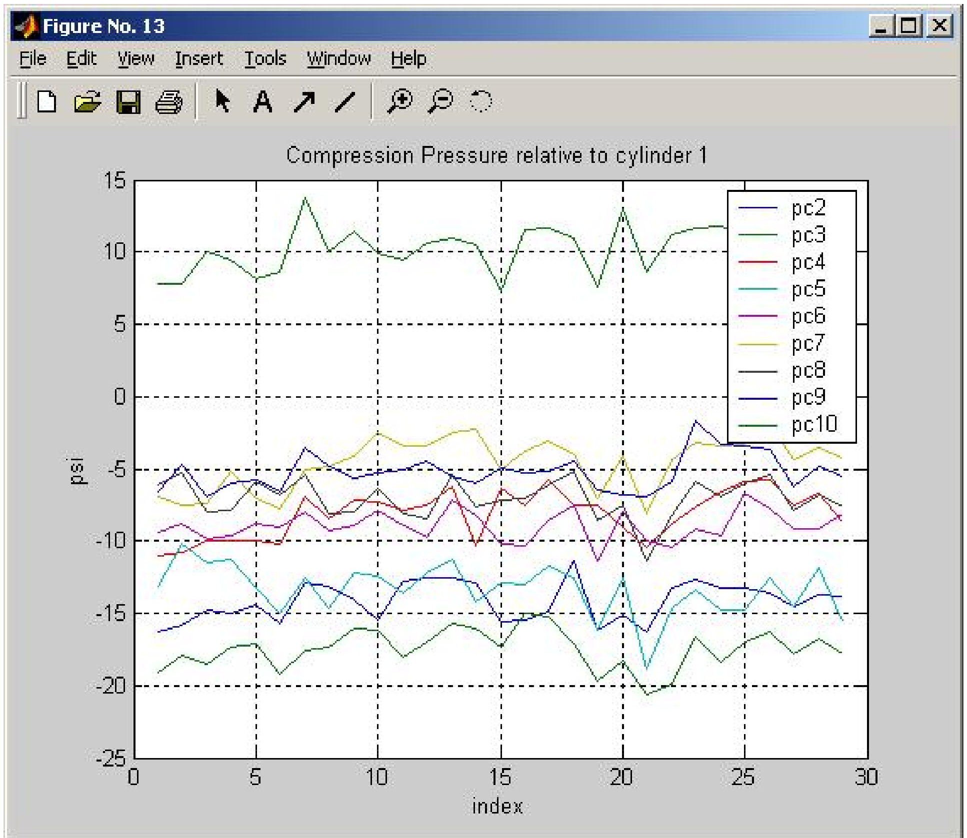

Figure 5-12. Compression Pressure Relative to Cylinder #1 for Second Day's Testing

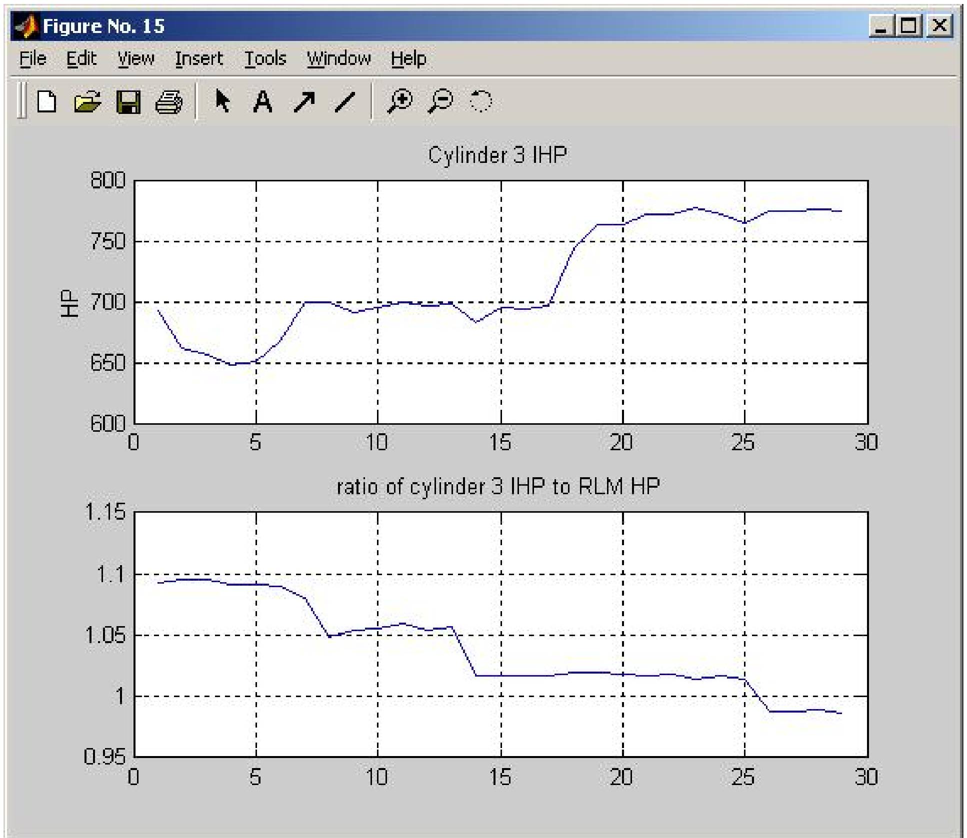

Figure 5-13. Cylinder Indicated HP and Ratio of IHP to Rod Load HP (without Temperature Correction)

6. OPERATIONAL OPTIMIZATION

Based on the preceding analysis of data from the first and second test sites, the following potential methods for optimizing operation have been identified:

- Combustion Balancing to Equalize Combustion Pressure Ratio (CPR Balancing)
- Advancing Timing Subject to Knock Detection and Avoidance
- Closed-Loop Control of Global Equivalence Ratio
- Starting the Engine with Preheated Oil
- Running with Hotter Oil
- Manifold Redesign and Retrofit to Reduce Air Imbalance
- High-Pressure Fuel Injection on Turbocharged Engines
- Maintaining Unit Load by Monitoring Compressor Rod Load

Plans for follow-up tests to further evaluate these have been prepared and transmitted to the IAC for review. These plans are attached as appendices to this report.

7. CONCLUSIONS

7.1 Based on initial GMW10 tests, high-pressure fuel injection is a promising technology for enhancing operation of two-stroke reciprocating compressors.

7.2 A "before and "after test on a unit to be retrofitted with high-pressure fuel injection would provide more conclusive quantitative evidence of the value of this retrofit technology.

7.3 Additional tests of CPR balancing; timing advance subject to knock detection and avoidance; equivalence ratio control; running with hotter oil will provide evaluation of other technologies to enhance operation (planned for the El Paso Kinder station test site).

7.4 The heat rate-NOx trade-off line for the Sour Lake tests clarifies benefits and penalties associated with timing and air manifold pressure changes.

7.5 The rod load monitor (RLM) requires temperature-stabilized components. The stabilized RLM should be tested on the return visit to El Paso's Kinder station.

8. REFERENCES

8.1 Harris, R.E., Bourn, G.D., and Smalley, A.J., "Enhancing Operation of the Existing Natural Gas Compression Infrastructure," GMRC Gas Machinery Conference (GMC), October 6-8, 2003, Salt Lake City, Utah.

9. LIST OF ACRONYMS AND ABBREVIATIONS

AGA	American Gas Association
AMP	Air Manifold Pressure
BEI	Manufacturer's Trade Name
BTDC	Before Top Dead Center
BTU	British Thermal Unit
CO	Carbon Monoxide
CPR	Compression Pressure Ratio
DAS	Data Acquisition System
DOE	U.S. Department of Energy
ECOM A+	An Emissions Analyzer Model
EQ	Equivalence Ratio
FY	Fiscal Year
GMC	Gas Machinery Conference
GMRC	Gas Machinery Research Council
GMW10	Pipeline Engine Model
HBA-6	Clark Engine Model
HBA-6T	Clark Engine Model
Hg	Mercury
HP	Horsepower
HPFI™	Enginuity's High Pressure Fuel Injection System
IAC	Industry Advisory Committee
IHP	Indicated Horsepower
IP	Intellectual Property
IRV	Instantaneous Rotational Velocity
KVG	Dresser-Rand (Originally Ingersoll-Rand) Model
MW	Megawatts
NGK	Manufacturer's Trade Name
NETL	National Energy Technology Laboratory
NO	Nitric Oxide
NO_2	Nitrous Oxide
NOx	Oxides of Nitrogen
O_2	Oxygen Molecule
OEM	Original Equipment Manufacturer
PRCI	Pipeline Research Council International
PFP	Peak-Firing Pressure
PID	Proportional-Integral-Differential
PPM	Parts Per Million
PSI	Pounds Per Square Inch
RLM	Rod Load Monitor
RPM	Revolutions Per Minute
SDCM	Strain Data Capture Module
SwRI®	Southwest Research Institute®
TGP	Tennessee Gas Pipeline

10. APPENDIX A: TECHNOLOGIES TO ENHANCE OPERATION OF THE EXISTING NATURAL GAS INFRASTRUCTURE (PLAN FOR SECOND TEST SERIES AT EL PASO STATION 823 – KINDER, LOUISIANA)

TECHNOLOGIES TO ENHANCE OPERATION OF THE EXISTING NATURAL GAS INFRASTRUCTURE

DOE Contract No. DE-FC26-02NT41646
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Plan for Second Test Series at El Paso Station 823
Kinder, Louisiana

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4. **TEST PLAN SUMMARY** 6

1. INTRODUCTION

Test data acquired at the Kinder facility indicates that compressor performance based on efficiency was on the high end of the installed pipeline units (>90%). For this reason, our follow-up test effort is focused on addressing some of the key engine issues associated with the HBA6T tested. The HBA6T unit is operated at a retarded timing condition over factory recommendations for this engine. In addition, the air manifold pressure is manually adjusted, without the benefits of any closed-loop control. The engine operates with large variations in cylinder peak-firing levels, and is difficult to balance. Part of the balancing problem arises from the variation in engine compression pressure. Addressing this issue is proceeding on two fronts. First, TGP is co-funding an effort to optimize the design of the intake and exhaust manifolds to airflow balance the cylinders. An alternative approach, developed by SwRI on this project, is to implement compression pressure ratio balancing (CPR). CPR balancing attempts to use the ratio of peak-firing pressure to compression pressure as a surrogate for cylinder air fuel ratio. Simulations completed by SwRI indicate that, for engines exhibiting cylinder-to-cylinder air imbalance, this ratio is an excellent surrogate for in-cylinder air fuel ratio. The predicted benefits of achieving equal CPR values between cylinders are a further reduction in NO_x emission over that achieved with traditional balancing, as well as minor improvements in performance. As part of the follow-up test effort at the Kinder station, we will attempt to CPR balance and document the impacts on measured engine performance parameters.

Our goals at this time, with respect to the operation of the HBA6T at Kinder, are to implement a simplified control strategy which will allow safe operation of the unit at advanced ignition timing (over current set point levels), while checking for detonation with currently available sensors. Operator desire to retard timing is driven by the need to reduce the tendency to detonate over a wide range of operating and ambient conditions. This effectively enhances engine mechanical integrity at the expense of engine performance. In addition, we propose to control air manifold pressure (AMP) using global EQ ratio measured continuously using the NGK-Locke NO_x/O_2 sensor already evaluated in this project. Global control of EQ ratio will compensate for changes in ambient air conditions, as well as turbocharger efficiency and output with respect to engine speed.

Over a number of hours of testing on the first test series, the ratio of compressor HP to engine increased. It is hypothesized that the cause is increasing sump oil temperature. Further testing of this hypothesis and the opportunity to further increase the ratio is planned.

2. BACKGROUND

During the initial test at Station 823 in Kinder, LA, the Clark HBA-6T was found to be operating with high standard deviation of peak cylinder pressure. This unit had no automatic control of air/fuel ratio or air manifold pressure (AMP). The AMP level was set manually by adjusting a regulator in the panel that controls air pressure to the pneumatic actuator on the wastegate. The original setting of AMP was relatively high, creating a lean operating condition and poor combustion stability. When the operators were asked why this high AMP setting was set, the response was that the unit experienced detonation (knock) during hot days. When ambient temperature becomes high, the turbocharger inlet air becomes less dense and the resulting AMP for a given wastegate setting will reduce. This reduction in AMP will cause the air/fuel ratio to richen and potentially lead to knock. Therefore, it appeared that a wastegate setting was found by the operators to allow the unit to operate under most ambient conditions with minimal adjustment. The problem with this approach is that the engine will experience swings in air/fuel ratio, corresponding to swings in AMP, with the mostly fixed wastegate position over varied ambient conditions. Swings in air/fuel ratio lead to poor efficiency when excessively lean and relatively high NO_x emissions under rich conditions. A simple means of automatically controlling air/fuel ratio should provide significant improvements in efficiency and emissions on this unit as compared to the original configuration.

In addition to a less than optimal control of air/fuel ratio, the spark timing was found to be retarded from OEM specifications. The response to a question on this setting was in-line with the AMP setting, and was related to engine knock. A retarded spark timing will lead to reduced efficiency if retarded from optimal setting, of which the OEM recommended timing is assumed to be. Spark timing advance typically leads to higher peak-firing pressures and NO_x emissions for a given air/fuel ratio. Advanced spark timing will also reduce the energy in the exhaust, due to phasing combustion earlier in the cycle, which can lead to a boost-limited condition during extreme highs in ambient temperature that will create a rich air/fuel ratio. Therefore, the spark timing should be advanced to the OEM recommended setting with an appropriate setting of air/fuel ratio with the above control for best efficiency-NO_x trade-off condition, and a knock detection system implemented to retard spark timing only during extreme ambient temperature (or boost-limited) conditions when knock begins to occur.

3. PLANS FOR SPARK TIMING AND AIR FUEL RATIO CONTROL

3.1 AMP AUTOMATIC CONTROL SYSTEM OPTIONS

There are a few options for demonstrating a simple AMP or air/fuel ratio control system. The most common approach is to control AMP as a linear function of fuel header pressure (FHP). With this approach, there may be several functions that relate to each engine speed that the engine is operated at. A more advanced version of this technique is to implement an algorithm to correct the AMP setting, such that only one function exists at all operating conditions, and requires a few additional measurements and empirical data-based look-up table for speed related coefficients. A more advanced system would involve additional measurements and a model-based algorithm that estimates the trapped fuel/air equivalence ratio for which control is based. This system, however, is complex and expensive, and would require different programming for different engine models and configurations.

Since the purpose of this effort is to demonstrate a low-cost, simple control system, a single variable approach would be desirable. The original technique for setting AMP involves a manual adjustment with no automatic feedback. Therefore, the simplest approach is to install a single input PID controller that would modulate the wastegate to control to a user input setting of either AMP or exhaust equivalence ratio. The NGK-Locke NO_x/O_2 sensor, being used for data acquisition, has a 0-5v signal that has been calibrated to exhaust equivalence ratio. This signal could be connected to the PID controller to allow automatic closed-loop control of fuel-air equivalence ratio. Although very simple, this approach should offer significant improvement over a manual setting and compensate for varying ambient conditions until the extreme case where the engine may become boost-limited.

Two options exist for the approach for this demonstration. The first is an offer from Woodward Governor to provide, on loan and no cost, a 723 control module. The 723 control module would be programmed with standard HBA fuel curves (AMP *versus* fuel header pressure) and recently developed algorithms for trimming the fuel curve based on O_2 sensor input. The controller would also have standard programming for start-up, shutdown, and safeties, which would not be utilized unless El Paso decides to permanently install this system for long-term evaluation. The delivery time and effort to install this system, even temporarily, is still being determined.

The second option is to utilize a simple PID controller coupled to an I/P, with only the O2 sensor (or AMP) feedback. A Honeywell UDC 2300 Universal Digital Controller has been used in the labs at SwRI for similar closed-loop controls. This controller would be the simplest approach to provide an automatic air/fuel ratio control system. A linear calibration can be programmed into this unit to turn the voltage signal from the O_2 sensor into exhaust equivalence ratio engineering units. The controller has both manual and automatic modes. In manual mode, the unit will work almost exactly as turning the regulator knob on the control panel in the current setup. Therefore, the operators should have some comfort in its use. In automatic mode, a standard PID loop will adjust the 4-20 mAmp output to an I/P to move the wastegate until the user entered equivalence ratio is achieved. SwRI will bring the Honeywell controller, O_2 sensor, and I/P for this demonstration.

3.2 Spark Timing Control and Knock Detection

If the simple PID controller for AMP or exhaust equivalence ratio is employed, a system to detect knock and compensate with timing retard should be implemented. This system would allow spark timing to be advanced to OEM specifications and prevent knock in the extreme condition where insufficient boost pressure can be delivered to maintain the air/fuel ratio. The unit is currently configured with an Altronic II-CPU, which has a feature for automatic timing retard through a 4-20 mAmp signal. Several companies make knock detection systems that feature accelerometers tuned for the particular knock frequency of a given engine.

Modern knock detection systems utilize accelerometers strategically located on the engine and tuned to the specific knock frequency of a given engine. This signal is routed to a control module that is programmed to look at this signal only during the combustion duration of each cylinder, called windowing, to prevent false triggering from vibrations caused by other engine events. Once the signal exceeds a programmed threshold, the control system commands the ignition timing to be retarded. The timing retard is usually done in steps, with the knock sensor signal rechecked to determine if knock has subsided. The controller will keep retarding ignition timing if a knock trigger is continually detected. If timing retard has continued to a significant level and knock is still being triggered, the control system will send a signal to either shut down the engine or reduce load or some other corrective action that is programmed.

The approach for this demonstration was to obtain a demonstration unit from either Woodward or Altronics for field testing. Both companies have knock detection systems available. The Altronics system would have been more ideal, as it would interface directly with the II-CPU ignition system on the HBA. However, Altronics is unable to provide a demonstration system. The current approach is to acquire the accelerometer(s) and install on at least one cylinder of the engine. It is anticipated that a Metrix sensor, used by Altronics, will be obtained for demonstration. A Bosch broadband sensor will also be obtained and installed on the engine for acquisition of frequency spectrum data for analysis of the knock frequency on the particular engine. The broadband sensor is typically used in this manner on development engines at SwRI, and a resonant sensor with a particular frequency level is obtained after determining the knock frequency with the broadband sensor. The resonant sensor with the correct frequency is then implemented in the knock detection system. The signals from the Metrix and Bosch sensors will be routed to the SwRI data acquisition system to display the knock signals. A manually adjusted trim pot will be used to interface with the II-CPU ignition module to manually reduce timing when knock is intentionally induced on one cylinder and the sensor signals clearly demonstrate detection. While not an automatic system, this setup will allow demonstration of the technology and show the potential for its use on these two-stroke integral engines.

4. TEST PLAN SUMMARY

Day 1: Install Transducers and Controllers/Detectors

- Fuel Flow Transducer
- Self-Powered Rod Load Monitor
- Sump Temperature Measurement
- Power and Compressor Cylinder Pressure Transducers
- Air Manifold Pressure (AMP) Transducer
- Global Equivalence (EQ) Ratio Controller
- Knock Detector for Timing Control/Protection

Day 2: Check-out and Shake down Installation

Day 3 / 4: Testing

1. Baseline Data Acquisition; Acquire Data; Compute Performance: Compressor and Engine Powers from Cylinder Pressure, Efficiencies, Power from Instrumented Rod, CPR, Measures of Variance, PPM; Acquire Station Data Records
2. Vary Speed without EQ Controls and Engine as is; Monitor AMP and Global EQ and Anticipated Variation in Global EQ with Changing Conditions; Acquire Data; Compute Performance
3. Activate Global EQ Controller and Repeat Preceding Test Item; Monitor for "Hoped For" Near Constant EQ as AMP Changes
4. Activate Knock Detector; Advance Timing up to or Near to Manufacturers Spec; Acquire Data and Compute Performance
5. Force Knock and Evaluate Effectiveness of Knock Detector for use in Protective Control

6. Evaluate How Number of Samples affects Balancing Parameters and their Consistency; Select Number of Samples for Further Balancing Tests
7. Perform Conventional Peak-Firing Pressure Balancing; Acquire Data; Compute Performance
8. Perform CPR Balancing; Acquire Data; Compute Performance; Evaluate Effectiveness of Programmed Fuel Adjustment Guidance
9. Based on test results from start-up of unit, confirm variation of compressor to engine HP ratio with sump oil temperature under normal oil cooler controls.
10. Investigate benefits on compressor to engine HP ratio of increasing oil temperature control set points.

11. APPENDIX B: TECHNOLOGIES TO ENHANCE OPERATION OF THE EXISTING NATURAL GAS INFRASTRUCTURE (PLAN FOR FOLLOW-UP TESTING ON AN ENGINE WITH HIGH-PRESSURE FUEL INJECTION)

TECHNOLOGIES TO ENHANCE OPERATION OF THE EXISTING NATURAL GAS INFRASTRUCTURE

DOE Contract No. DE-FC26-02NT41646
SwRI Project No. 18.06223

Plan for Follow-up Testing on an Engine with High-Pressure Fuel Injection

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PLAN FOR FOLLOW-UP TESTING ON AN ENGINE WITH HIGH-PRESSURE FUEL INJECTION

1. SUMMARY

In this document, we provide to the Industry Advisory Committee (IAC) for review some refinement of plans for FY 2004, which address the second test series, hosted by Transco.

The IAC has already received plans for the first series follow-up testing on a conventionally fueled HBA-6T.

Specifically, the refinement discussed in this document will enable a "before and after" test on high-pressure fuel injection, and also some demonstration tests of CPR balancing on two different commercial balancing platforms at Williams Station 60 in St. Francisville, Louisiana (overview plans presented here); the opportunity to do this is made available by Williams Transco, and is recommended by their representative to the IAC. Our plans and hopes are to help the deployment of CPR balancing on commercial platforms, as discussed subsequently in more detail.

This refined plan will require an extra site test relative to previous plans for the return visit to Site 2. We have prepared a budget for FY 2004, and believe we can accomplish this "before and after" test and all other originally planned (but not yet accomplished) work through FY 2004 (including two testing visits to hosted Site 3 and one testing visit to hosted Site 4) within the budget for FY 2004. Cost control at Station 60 will be achieved as a result of assistance offered by Transco.

At the same time, the project provides a natural contingency - should we incur costs beyond those budgeted. As a contingency, we would keep the same number of tests as originally planned, but postpone either the second visit to Site 3 or the first visit to Site 4 into FY 2005, and keep the extra test on high-pressure fuel injection in FY 2004. Thus, the contingency, should it be required, will involve no reduction in scope as measured by the number of testing site visits in FY 2004.

We seek the IAC review and concurrence with this refined plan. We believe the "before and after" test will document clearly for the industry the benefits of high-pressure fuel injection in reliable lean operation, in reduced fuel consumption, and in reduced emissions with improved crankshaft integrity.

Thus, this accomplishment would be consistent with the project's title: "Technologies to Enhance Operation of the Existing Natural Gas Compression Infrastructure".

Recognizing widening emissions regulation and increasing cost of natural gas to the consumer, this accomplishment is also very consistent with the goals of DOE's Natural Gas Infrastructure Program: to increase reliability of natural gas deliverability, to reduce the fuel burnt in transportation, to reduce operating costs, and to enhance capacity of the installed infrastructure. Thus, there is distinct public good to be achieved by the plan.

2. DETAILED DISCUSSION

In August of 2003, with the assistance of the site host company, Williams Transco, SwRI performed tests on a GMW10 at the Transco Sour Lake Station (Station 40). This unit has high-pressure fuel injection installed (Enginuity's HPFI™ System); the retrofit equipment on the engine also includes a new turbocharger system and pressure transducers on the power cylinders, which are currently used within software installed with the HPFI™ System to guide cylinder fueling adjustments to achieve peak-firing pressure balancing. This was the second site at which tests were performed under the subject project.

As documented in SwRI's fourth quarterly report for the period July 1, 2003 through September 30, 2003, the engine demonstrated lean operation, low heat rate, and low emissions. The global equivalence ratio was typically 0.187 during the tests, and the heat rate was 7200 to 7300 BTU/HP-hour over most of the test. Data analysis also shows a system thermal efficiency of 29.7% (compressor and engine combined efficiency of conversion of fuel energy to useful work on the transported gas), which could be increased to almost 31% by advancing timing (with some reduction in emissions margins). The corresponding system thermal efficiency number for the first test site of the program was between 25.8 and 26.8%, in spite of a high thermal efficiency (~91%) for that compressor (compared to about 85.5% compressor thermal efficiency at the site with high-pressure fuel injection).

The data from Transco Station 40 suggests that high-pressure fuel injection, combined with a new turbo-charger system, offers an attractive technology to enhance operation of the existing compression infrastructure. It combines reduced emissions with low fuel consumption. Even for engines not yet forced by regulation to reduce emissions, it offers a means to reduce the fuel used for a given amount of compression work, and in the process to pre-emptively reduce emissions. This may have value for "cap and trade" scenarios.

Thus, tests have shown that, after modification to high-pressure fuel, this engine performed well compared to the fleet, but to make this case most convincing, a "before and after" comparison is needed.

Station 40 is one of a series of stations at which Transco is installing high-pressure fuel injection. The next station to have similar modifications installed is St. Francisville, Transco Station 60. A series of engines at this station will have the modification performed over the first few months of calendar year 2004. The elapsed time between start and completion of the modification for a particular engine at Station 60 is projected by Transco to be 4 to 5 weeks.

Given these plans for adding high-pressure fuel injection to these GMW units, the IAC committee member from Transco and Transco management have recommended that the Compression Infrastructure project take advantage of the upcoming opportunity to directly measure the incremental benefits of installing high-pressure fuel injection. If the nominally planned return visit to Sour Lake is replaced with two matching tests, one before and one after the installation of the high-pressure fuel injection technology on a GMW10 at St. Francisville, then the DOE Compression Infrastructure project will be able to provide this data. This can be arranged in the February-March 2004 time frame. As previously noted, the Coerr database shows the GMW to be the most widely deployed engine in gas transmission, based on the number of units (336 GMWs *versus* 296 KVGs - the next most common model).

Transco has further recommended that the engines at St. Francisville represent an opportunity to test and demonstrate, in several ways, the CPR balancing method invented on the DOE compression Infrastructure project:

1. As a means to achieve improved combustion balancing on engines, which tend to detonate when fuel balanced to achieve equal peak-firing pressure, as a result of air imbalance.
2. As an additional algorithm in a manual, computer assisted, balancing system.
3. As an additional algorithm in a fully automated balancing system.

Item 3 above should be straightforward and mainly involves code changes. Item 2 may present more challenges. Item 1 will be implemented with the SwRI data acquisition system as a back-up demonstration.

Transco has made significant offers of assistance with the testing, data acquisition, and installation of instrumentation, so that SwRI's costs can be minimized in this two-visit test. Cost reduction will be achieved by limiting SwRI staff's presence at the tests to one man (Ralph Harris). The specific help and manpower skills to be made available by Transco throughout the tests will make this possible.

Almost all the instrumentation involved in the test at Williams Station 60 will be installed for the "before and after" test, with the exception of frame vibration and the rod load monitor. We will include all cylinder pressure monitoring and crankshaft integrity measurements. (We will concentrate on demonstrating the self-powered rod load monitor in the revisit to the first site.)

In analyzing this opportunity relative to the proposed program, a review of all work proposed, but not yet accomplished, and the associated costs has been undertaken. The planned work, <u>as originally proposed</u>, is as follows:

1. Return visits to first and second tests sites to demonstrate and evaluate hypotheses developed on the basis of data obtained (in FY 2003) on the first visits to each of these sites.
2. Preparation of topical report based on results and analysis of initial and return visits to first two sites. This completes the planned Phase I work.
3. Review of topical report and decision point for further work, based on results so far. The decision point leads to Phase II.
4. Selection, arrangement, and performance of tests at two additional sites – Sites 3 and 4; analysis of data; development additional hypotheses based on results, and a return visit to one of these sites. This is FY 2004 Phase II work.
5. Preparation of a paper for GMC 2004.

Thus, we are adding an additional visit to the work to be performed prior to the topical report, in order to do a "before and after" test at a high-pressure fuel injection site. To complete the originally proposed future plans and to include the "before and after" test at Transco Station 60, the total number of testing visits would now be six (6) instead of the five (5) originally proposed through the end of FY 2004.

We have prepared a budget for 2004, including this recommended approach to the second site "revisit," and the relatively ambitious plans for the Site 1 revisit. The budgeted costs presently show that all tests and analysis planned for FY 2004 can be completed within the $200,000 budgeted ($150,000 from DOE and $50,000 from GMRC and PRCI). However, this will require continued vigilance in cost management throughout the 2004 fiscal year. With such a requirement, some risk remains that costs for this slightly more ambitious plan will exceed the budget at some point. The planned contingency for managing this risk is to be prepared to bring the number of test visits back to the originally proposed five (5), by postponing either the return visit to Site 3 or the first visit to Site 4 into FY 2005. This is not the present plan, but remains a risk management option (contingency), which will allow the recommended "before and after" test on high-pressure fuel injection to be performed and, as a minimum, accomplish the same number of tests in FY 2004 as originally proposed.

If CPR balancing demonstrates value in these tests, its prototyped implementation in commercially available manual and automated balancing systems, in use at a company with expressed interest in the technology, points the way to a natural commercialization path. While some protection for the invention has been obtained by filing of a provisional patent, it will be necessary to execute non-disclosure agreements with the system developers. This will give these developers a head start on commercialization, but it would probably be GMRC's intent to make the method available to any provider of automated or computer-assisted balancing systems.

It was agreed with DOE, in project negotiations, that intellectual property resulting from this project, such as the CPR balancing invention, become property of the contractor (SwRI) as a not for profit institution (with option for royalty-free license for the government's own use). SwRI is pursuing a patent for the CPR balancing invention (application for a utility patent already filed). At initiation of the project, SwRI also agreed to give GMRC royalty-free license of any IP coming out of the project, and GMRC further agreed to sublicense this IP to achieve wide distribution and application to the benefit of the industry.

3. STEPS TO BE PERFORMED PRIOR TO THE PLANNED "BEFORE AND AFTER" TESTS AT TRANSCO'S STATION 60

1. Obtain review and comments from IAC on this document.
2. Obtain concurrence with this plan from the DOE project manager.
3. Prepare non-disclosure agreements for CPR balancing technology to be signed by Transco, Enginuity, and any suppliers of balancing platforms involved in the CPR demonstrations planned for Station 60.
4. Prepare memorandum of understanding for execution between GMRC and suppliers of balancing platforms involved in CPR tests.
5. Complete logistical arrangements with host company and station personnel.