Carbon Pollutant Emissions and Engine Performance Trade-Offs vs NO_x Emissions for Reciprocating Internal Combustion Engines Utilized in Gas Transmission Service

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ADVANCED ENGINE TECHNOLOGIES CORP.

Ushering the Reciprocating Engine Into the 21st Century

Carbon Pollutant Emissions and Engine Performance Trade-Offs vs NO_x Emissions for Reciprocating Internal Combustion Engines Fitted with Enhanced Mixing Combustion Technologies Utilized in Gas Transmission Service

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Executive Summary

Pending and/or proposed Federal and local regulations have generated increasing interest in trade-offs between emissions of NO_x versus CO, THC's and in particular HAPS. The Pipeline Research Council *I*nternational (PRC*I*) commissioned Advanced Engine Technologies Corporation (AETC) to compile a database of engine emission and performance data for typical two and four stroke cycle lean burn reciprocating engines in gas transmission service and then characterize the trade-offs between NO_x and other engine pollutant emissions in addition to engine performance (Reference 7).

The results confirmed the existence of decaying exponential trade-off's between NO_x emissions and other carbon pollutant emissions (THC, CO and HAPS) and engine performance (Brake Specific Fuel Consumption and combustion instability). The method of ignition system dictated the location of the trade-off knee while the mixing effectiveness seemed to determine the "base-line" emissions level.

Since completion of the original "trade-off" study, three companies serving the natural gas industry have developed technologies for enhancing performance of typical pipeline engines via enhanced mixing and flame propagation. These Enhanced Mixing Combustion Technologies (EMCT) are very cost-competitive and offer a number of benefits in BSFC and component loading. Using the same methodology as the prior PRC*I* study, this report assesses the trade-off characteristics of these technologies and compares them with more conventional emissions remediation methods.

The results indicate EMCT beneficially shifts the NO_x trade-off knee and/or eliminates the trade-off altogether, allowing operation at substantially reduced NO_x levels without the normal penalty in other emissions or engine performance. For example, EMCT favorably shifts the trade-off knee by about 3 g/BHP-HR NO_x for both H_2CO and THC while CO and Break Specific Fuel Consumption becomes invariant.

In addition, EMCT improves baseline combustion stability by almost a factor if 2, extending operation down to ~3 g/BHP-HR NO_x without any significant penalty. Open combustion chamber engines fitted with EMCT can initiate and propagate a flame under much leaner conditions than the same engine fitted with conventional fuel valves. This reduces sensitivity to lean cylinder unbalance and improves combustion stability substantially reducing the minimum achievable NO_x emissions for a given engine while extending the operable range. The addition of automatic balancing, often included with EMCT retrofits should further extend and sharpen the trade-off knee. In summary, EMCT offers a significant improvement in trade-off performance over other emission remediation technologies.

1.0 Objective

Compile a database of emissions and engine performance data for typical two stroke cycle lean burn reciprocating engines in gas transmission service fitted with Enhanced Mixing Combustion Technologies (EMCT) and then:

- Quantitatively define typical trade-off compromises between NO_x and carbon pollutant emissions (i.e. CO, THC & HAPS).
- Quantitatively define typical trade-off compromises between NO_x and engine performance (i.e. Brake Specific Fuel Consumption, combustion instability and operable range).
- Establish typical emission and performance levels for engines fitted with EMCT.

2.0 Background

A brief review of relevant background information follows.

2.1 Lexicon of Acronyms

Before proceeding, a lexicon of relevant acronyms follows.

2SC – Two Stroke Cycle
4SC – Four Stroke Cycle
AETC – Advanced Engine Technology Corporation
AMP - Air Manifold Pressure
AMT - Air Manifold Temperature
BMEP – Brake Mean effective Pressure
BSFC – Brake Specific Fuel Consumption
$BSNO_x$ – Brake Specific NO_x
CSU - Colorado State University
EMCT – Enhanced Mixing Control Technologies
HAPS - Hazardous Air PollutantS[1]
HPFi™ – High Pressure Fuel Injection
HPFV – HyperFuel Valve™ (not an official acronym, used to simplify graphs for this paper only)
LBET - Large Bore Engine Testbed
IT – Ignition Timing
LOPP - Location of Peak Pressure
OEM – Original Equipment Manufacturer
OCC – Open Combustion Chamber
PCC – Pre-Combustion Chamber
PP – Peak Pressure
PP_{cov} – Covariance of Peak pressure
PLGAV -Pipe Line Gas Admissions Valve
SdPP – Standard Deviation of Peak Pressure
SSEFI™ – Super Sonic Electronic Fuel Injection
SSMFI™ – Super Sonic Mechanical Fuel Injection

2.2 Prior Work

A review of relevant prior work follows.

[1] Prior work (Reference 6) in addition to that performed in conjunction with the PRC*I* PEMS Mapping Project (Reference 1) have demonstrated Formaldehyde is the only HAPS of interest emitted by the subject engines. Therefore, the subsequent analysis will focus on this HAPS compound alone.

2.2.1 *Emissions Trade-offs*

In anticipation of increasingly more stringent emissions regulations, in the late 1990's the natural gas pipeline industry identified the need to establish accurate emissions inventories for reciprocating engine-compressors to assess their contribution to overall emissions generation. The increasing interest in trade-offs between emissions of NO_x versus CO, THC's and in particular HAPS, contributed to heightened interest in "real world" engine emissions, and the associated trade-offs in lean burn engine performance. This created a strong incentive to collect, collate and characterize a reliable data base which owner/operators can utilize to make informed, cost competitive emissions related decisions.

Therefore the Pipeline Research Council *I*nternational (PRC*I*) commissioned Advanced Engine Technologies Corporation (AETC) to compile a database of engine emission and performance data for typical two and four stroke cycle lean burn reciprocating engines in gas transmission service and then characterize the trade-offs between NO_x and other engine pollutant emissions in addition to engine performance (see Reference 2 for the publicly available summary and Reference 7 for the confidential report).

AETC accumulated engine performance and emissions data from eight industry and client funded projects encompassing 24 engines of 18 different models typifying two (2SC) and four stroke cycle (4SC) open (OCC) and pre-combustion chamber (PCC) engines in gas transmission service.

AETC's analysis of the data base indicated the trade-off between NO_x emissions and other carbon pollutant emissions (THC, CO and HAPS) and engine performance (Brake Specific Fuel Consumption and combustion instability) were best characterized by plotting NO_x as the independent variable and the trade-off parameter of interest as the dependent variable. Plotting the data in this fashion normalizes the effects of trapped equivalence ratio, speed, torque, ignition timing and air manifold temperature.

When trended in this manner, the trade-off between carbon pollutant emissions, engine performance and NO_x exhibit a decaying exponential characteristic. AETC determined the method of ignition system dictated the location of the trade-off knee while the mixing effectiveness seemed to determine the "base-line" emissions level.

For a given ignition system and quality of mixing, due to this decaying exponential characteristic of the trade-off, carbon pollutant emissions and engine performance remained invariant over a relatively wide range of NO_x emissions levels. Only at minimum NO_x levels did significant trade-offs arise. In particular, a trade-off "knee" occurred at NO_x emissions levels of 6-7 g/BHP-HR for Open Combustion Chamber (OCC) engines and 1.5 g/BHP-HR for Pre-Combustion Chamber (PCC) fitted engines.

2.2.2 *Enhanced Mixing Technologies*

Since completion of the original "trade-off" study, three companies serving the natural gas industry have developed technologies for enhancing performance of typical pipeline engines. While the approach taken by each of these companies, Enginuity LLC, Hoerbiger and DigiCon, differs in details they all share the fundamental strategy of improving combustion via enhanced mixing and flame propagation. These methods are very cost-competitive when compared with more traditional pre-chambered based methods for NO_x emissions reduction (Reference 1). More recent investigation (Reference 8) has also confirmed these technologies offer a number of benefits in BSFC and component loading.

2.3 The Fundamental Mechanism of Performance Improvement

Typical 2SC pipeline engines exhibit varying degrees of air/fuel mixture stratification, particularly in comparison to more modern 4SC engines. The stratification basically results from design trade-offs made by the original designer to satisfy competing requirements of:

- efficiency
- reliability
- cost effectiveness

Some engine designers in the 1940's and 1950's apparently intentionally stratified the charge to obtain relatively rich mixtures near the spark plug to ensure the limited ignition systems of the time could reliably light the mixture.

When originally designed, emissions were not a consideration. Many of the more modern 2SC engines shipped in the 80's were specified to satisfy certain emissions limitations. However, those engines were not "Clean Sheet of Paper Designs." Rather, the OEM's married modern turbochargers, ignition systems and enhanced cooling to 1950's and 1960's designs.

OEM's made little attempt to review or address the original mixing design trade-offs. Because NO_x formation is exponential in combustion temperature, the hotter "rich" portions of the stratified mixture create disproportionate NO_x levels. This requires leaner overall mixtures that in turn require large, efficient and expensive turbochargers. Also, charge stratification reduces the lean limit.

New enhanced mixing technologies can provide new opportunities to better optimize and strike new and better compromises that the original designers never envisioned. Improved mixing compliments (and often supplements) PCC technologies by using the available air efficiently thereby reducing the level of overall leanness required to achieve a NO_x target (Figure 1)[2]. This in turn:

- Reduces the ignition energy required to ignite the less lean mixture and/or
- Reduces the amount of pressure boosting required to achieve that mixture ratio.

As reflected in Figure 1, "before" and "after" data available for two of the technologies applied to the same engine type virtually coincide. This indicates the performance improvements offered by these technologies are related primarily to fundamental improvements in mixing and combustion rather than to any unique aspect of either set of hardware.

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[2] Care should be taken when reviewing the extremely low NO_x numbers obtained with EMCT such as displayed in Figures 1 and 6. These low NO_x condition were achieved under special test conditions and narrow ranges of operation. They do not generally represent continuously achievable emissions levels.

2.4 The Need and Current Project Goal

As reflected in the previous sections, the emissions and non-emissions benefits afforded by EMCT are well documented and reasonably well understood. However, the trade-off characteristics are less well established. EMCT should have two impacts on trade-off performance. First, the better mixing afforded by the technology should reduce the baseline emissions levels. Second, the ability of these technologies to consistently propagate a flame in a lean mixture should shift the knee significantly to the left.

In this current study AETC applied the technical approach taken in the previous trade-off study (Reference 2, 7) to achieve similar goals for engines fitted with EMCT, i.e.:

- Quantitatively define typical trade-off compromises between NO_x and carbon pollutant emissions (i.e. CO, THC & HAPS).
- Quantitatively define typical trade-off compromises between NO_x and engine performance (i.e. Brake Specific Fuel Consumption, combustion instability and operable range).
- Establish typical emission and engine performance levels for engines fitted with EMCT.

3.0 Technical Approach

The technical approach mirrored that used for the Trade-off study (Reference 2 & 7). A summary of that approach follows.

3.1 Database Development

A summary of the database development follows.

3.1.1 Data Contained in the Database

AETC identified and collected all available engine emissions and performance data of suitable quality obtained during various PRC*I*-GRI programs including:

- CSU LBET test of Woodward Governor Company's (WGC) PLGAV[3] in September 1997
- CSU LBET test of Hoerbiger Company of America's (HCA[4]) HyperFuel Valve^{TM} in July 2001
- CSU LBET test of HCA's modified HyperFuel Valve^{TM} in February 2002
- CSU LBET test with HCA standard HyperFuel Valve^{TM} in August 2003 (Ion Sensor Test)
- CSU LBET test with HCA standard HyperFuel Valve^{TM} in October 2003 (PCC Test)
- Field test of the HyperFuel Valve^{TM} installed on a OCC GMW-10C
- Field test of the HyperFuel Valve^{TM} installed on a OCC TLA-6

In addition, AETC negotiated on behalf of INGAA for use rights for third party data of suitable quality including:

- Field test of the HyperFuel Valve^{TM} installed on a OCC TCV-10
- Field test of HPF*I*^{TM} installed on a OCC TCVD-16

AETC then:

- Entered each data set into the database[5]
- Calculated all relevant emission and engine performance parameters
- Collated, trended and reviewed the resultant data.

Based on the results of the review, AETC qualified all data suitable for inclusion in the final database.

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[3] The predecessor of HPF*I*^{TM}.
[4] PRC*I* funded the testing of HCA technology. HCA funded all valve development.
[5] Under the original PRC*I* project, AETC compiled all the data in an ACCESS database. Due to the inherent limitations of ACCESS, this proved too cumbersome to regularly use. AETC has since transferred that data, along with considerable client data, at its own cost to a Microsoft SQL Server database and translated all calculations into SQL commands. AETC makes this database available to industry users for a nominal fee.

The final database and resultant calculations include for each engine data set the following information (at a minimum):

- Engine Specifics (bore, stroke, compression ratio, etc.)
- Ambient Test Conditions (ambient temperature, relative humidity, etc.)
- Engine Control Parameters[6] (speed, torque, timing, air manifold pressure, air manifold Temperature)
- Engine Performance Parameters (fuel flow, cylinder temperatures, peak combustion pressures, etc.)
- Calculated Performance Parameters (BMEP, BSFC, Fuel/Air Equivalence Ratio, etc.)
- Emissions Data (NO_x, CO, CO_2, THC, Emissions Mass Flows, Brake Specific Emissions, Formaldehyde when available)

Table I summarizes the engine particulars and Table II the range of parameter and emissions variation for each data set.

3.1.2 Additional Information on the Test Programs

Relevant information on the test programs form which the data was obtained follow.

<u>CSU September 1997 Test of PLGAV</u>

PLGAV was the initial name for the preproduction version of HPF*I*™ first tested on the LBET in 1997. This comprehensive test program encompassed the normal range of engine operating conditions including air/fuel ratio, load and ignition timing. In addition it fully tested fuel injection parameters including:

- Injection Pressure
- Start of Admission
- Valve Lift/injection duration

From this data set, AETC selected data at 500 psi injection pressure rated speed and varying load as most representative of field conditions. Of the various available SOA's AETC selected 82° BTDC. While late compared to current field installations, the widest range of varying engine parameters occurred at this timing. As will be seen below, the late SOA had little impact on the trade-off performance. This dataset will henceforth be referred to as the "CSU Pre-Production HPFI™".

<u>CSU Tests of the HyperFuelValve™</u>

CSU tested the pre-production HyperFuel Valve™ in July 2001 including IT and air/fuel ratio maps at rated load and speed. Only the air/fuel ratio map included data over the NO_x range of interest, so AETC included this data in the database. This valve design did suffer from re-opening due to the low lift required for the LBET. This resulted in late admission of fuel increasing carbon pollutants. While this may have impacted baseline emissions levels, it did not appear to impact trade-off performance. AETC therefore included the data for comparative purposes, referred to as "CSU Pre Production HPFV™"

[6] The results of the PRC*I*-GRI PEMS project confirm these five parameters dominate emissions formation in engines. All remaining parameters have secondary or tertiary effects on a properly operating engine.

CSU later tested a modified production HyperFuel Valve^{TM} in February 2002 including multi-point load, IT and air/fuel ratio maps. Only the air/fuel ratio map (at rated load and speed) included data over the NO_x range of interest, so AETC included this data in the database, referred to as "CSU Production HPFV^{TM}"

CSU performed baseline air/fuel ratio mapping of the LBET in a OCC configuration with the final production HyperFuel Valve^{TM} in August 2003 as part of the industry funded timed PCC project. Since this represents the final production configuration AETC included the data in the database. Two spark plug hole heads had been fitted to the LBET prior to this test reducing the compression ratio. Consequently some data values, in particular BSFC, may not be comparable with previous data recorded at higher BSFC's. This does not impact overall trade-off performance, and the data is included referred to as "CSU PCC Test".

CSU performed air/fuel ratio mapping of the LBET in a OCC configuration with the final production HyperFuel Valve^{TM} in October 2003 as part of the industry funded Ion Sense project. AETC also included the data in the database for comparative purposes. The engine was still fitted with the lower compression ratio two spark plug hole heads. Also, the test team only collected emissions data on the left bank side of the engine to obtain more representative emissions values for comparison with the ion sense data collected on cylinder 1LB only. Consequently while baseline values may not match those of previous CSU tests the trade-off performance should remain unchanged. The data is refereed to as "CSU Ion Test".

Field Test of HyperFuelValve^{TM}

The pipeline industry funded field testing of production HyperFuelValve^{TM} systems on two typical pipeline engines, a TLA-6 and a GMWC-10. With the exception of ignition system upgrades, both engines were tested in "stock" configurations. The test data included load, air/fuel ratio and IT maps. Neither engine was fitted with a balancing system at the time of the test. The data is referred to by engine model.

Field tests of the HyperFuel Valve^{TM} installed on a OCC TCV-10 and HPF*I*^{TM} installed on a OCC TCVD-16

A third party owner/operator provided mapping performance test data, including formaldehyde emissions, for two engines fitted with EMCT. The engines were fitted with combustion monitoring and balancing systems but the systems may not have been enabled at the time of the test. This data compliments the industry funded data. The data is referred to my engine model.

3.2 Definition of Engine Categories

In support of the original trade-off analysis, AETC defined the following hierarchy of engine categories for the engines contained in the database:

Type of ignition system consisting of three sub-groupings:

- Single Strike Open Combustion Chamber (SSOCC)
- Multi-strike spark Open Combustion Chamber (MSOCC).
- Pre-Combustion Chamber (PCC).

Type of aspiration/scavenging consisting of four sub-groupings:

- 2 SC pump/blower loop scavenged
- 2 SC “pure” turbocharged loop scavenged
- 2 SC “pure” turbocharged uni-flow scavenged
- 4SC turbocharged.

Engine make/model including the following sub groupings:

- medium bore (14") 2 SC Cooper engines (all GMV types).
- large bore (18-20") 2 SC Cooper engines (the V, W and Z series).
- large bore (≈17") 2 SC Clark engines (the TLA/TCV series)
- intake port fuel injected 4 SC engines (Cooper LSV, Delaval HV)
- in cylinder fuel injected 4 SC engines (KVR, KVS)

Since EMCT is intended as a lower cost alternative to PCC’s, the study focused only on OCC and MSOCC engines retrofitted with EMCT. The current study included one 2SC blower scavenged engine (GMW-10C) with the balance being pure turbocharged 2SC engines. At the time of writing, no data was available for 2SC uniflow scavenged or any 4SC engines. The current study does include medium bore (CSU GMV) and large bore (GMW-10C) Cooper engines and large bore Clark engines (TLA-6, TCV-10 and TCVD-16).

3.3 Definition of Knee Location

To simplify and quantify the determination of the knee location and facilitate comparisons between data for conventionally fueled engines with that for EMCT fitted engines, AETC developed a new methodology for quantifying the knee location. AETC first curve fit each data set to a conventional decaying exponential curve fit of the form:

$$Parameter = a + be^{-cNOx}$$

Where:

Parameter = The trade-off parameter of choice
a, b ,c = Engine specific curve fit coefficients

AETC then used the curve fit parameters to locate the knee, which was defined as the first measurable departure from “baseline” performance. Baseline was taken as the performance at 9 g/BHP-HR NO_x, a typical operating point for conventionally fueled OCC fitted engines. For example, THC readings are generally repeatable to ~+/-20%. Therefore, the point where THC increases more 20% from the baseline level most likely represents the real beginning of the trade-off. This location was therefore defined as the knee. The use of the curve fit to define the knee rather than actual data eliminated the effects of data scatter and removed the arbitrariness of visually picking the knee from graphed data.

AETC similarly defined the knee locations for CO and H_2CO as the point of 20% increase from baseline. AETC utilized an increase of 25% for Combustion Stability and 2.5% for BSFC in a similar manner.

4.0 CSU Results

A summary of the CSU test results follows.

4.1 Representativeness

During the prior study, the CSU data emerged as the defining data sets for characterizing emissions and engine performance trade-offs. This reflects the benefits of precisely variable control available in the laboratory environment and the excellent mechanical condition of the engine. A discussion of the represetnativeness of this data follows.

4.1.1 Carbon Pollutant Data

When benchmaked against the field test data (see section 4.1 of reference 7) during the previous study, AETC determined the LBET CO and THC emissions data appear very representative of field test conditions, both in absolute value and relative sensitivity to NO_x trade-offs. Similar comparisons between laboratory and field H_2CO emissions were not possible. Nonetheless, the general similarity in relative emissions levels and performance trade-offs for CO and THC vs. H_2CO suggest the LBET H_2CO data should likewise be representative.

4.1.2 BSFC

However the LBET, an early vintage GMV-4TF model, operates over a BMEP range of only 57-75 psi. In contrast, the much later GMVH-C model of the engine operates at nearly twice the BMEP (107-128 psi), resulting in a substantial increase in thermal efficiency. The addition of a motor driven blower permits the LBET to operate at trapped equivalence ratios similar to later, more highly rated engines, resulting in similar emissions performance. The higher BMEP and associated increase in efficiency of later vintage units however can not be replicated.

In addition, extracting meaningful BSFC trade-off information from field test data proved quite difficult. Often, the non-repeatability and uncertainty (≈±1-3%) in the field test BSFC calculations are on the same order as the sensitivity to NO_x trade-offs making it quite difficult to discern trade-off trends. Therefore while not representative in numerical value, the CSU LBET BSFC measurements, based on accurate measurements of BHP with a dynamometer, still offer the best insight into *relative* trade-offs between BSFC and NO_x.

4.1.3 Engine-Health and Robustness

As described in section 6, the CSU engine is in excellent health. This in addition to the low cylinder count and low operating hours can result in atypically good performance. The engine regularly achieves NO_x emissions levels unattainable under field conditions. Consequently, while the engine exhibits typical trade-off performance the location of the trade-off knee and the knee's sensitivity to various technologies which improve engine robustness may not be representative.

4.2 Range of Parameter Variation

Table IIa summarizes the range of parameter variation for the various CSU tests. The CSU data sets encompassed variation of three of the five control parameters; speed, torque and trapped equivalence ratio. Like the results of the previous study, variations in torque and trapped equivalence ratio had little impact on overall trade-off characteristics (see Figure 1a which includes both variable torque and air/fuel ratio data). In general, parameter changes which decreased NO_x a fixed amount increased CO, THC and H_2CO and reduced combustion stability by fixed amounts. Whether the NO_x reduction was induced by leaning the trapped equivalence ratio at fixed torque or reducing torque at fixed air delivery, did not significantly alter the trade-offs.

As with the previous study the one exception, BSFC, did exhibit some sensitivity to torque (see the BSFC curve on Figure 1a). The lowest BSFC's always occurring at rated torque when operating to the right of the trade-off knee. At the same NO_x levels, the BSFC at ~80% torque was typically 3-4% greater. However, this comprises only a third of the overall range of variation in BSFC emissions. The effects of varying torque (or BMEP[7]) on BSFC remain secondary when assessed as a NO_x trade-off.

4.3 THC, CO,& H_2CO Trade-offs

Figures 1a-e display individual trends of THC, CO,& H_2CO as a function of NO_x for each LBET engine dataset included in the database. Figures 3a-c display comparative trends of THC, CO,& H_2CO as a function of NO_x. An evaluation of the trade-off characteristics for carbon pollutant emissions (i.e. THC, CO, & H_2CO) follows.

4.3.1 General Characteristics

All carbon pollutant emissions trends exhibited typical trade-off performance. Specifically, carbon pollutant emissions remained effectively invariant over a wide range of relatively high NO_x values, forming a sort of asymptotic baseline. Then as NO_x emissions reduced, carbon pollutant emissions began to increase dramatically, ultimately approaching a vertical asymptote, forming a kind of "fishhook". For each dataset the inflection point or "knee" for the three carbon pollutant emissions approximately coincided.

4.3.2 Range of Emissions Variation

For a given range of NO_x variation, the carbon pollutant emissions exhibited a significantly less variation (see Table IIa). For example, for the widest ranging dataset, the Pre Production HPFI™, NO_x varied over a range of ≈27:1 while THC varied ≈12:1, CO ≈4:1 and H_2CO ≈3:1. These ranges are about 2.5 times the ranges for the baseline variable boost data of the previous study (see Table 4.3.2a of reference 7).

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[7] For fixed speed operation, torque and BMEP are directly proportional.

This difference in parameter range reflects the difference in reaction kinetics and species source. Main chamber chemical kinetics, in particular the gas temperature, governs NO_x formation exclusively. NO_x emissions increase exponentially vs equivalence ratio, approaching a near vertical asymptote at the onset of auto-ignition.

In contrast, the carbon pollutant species of interest are products of incomplete combustion and or boundary effects. Relatively wide variations in equivalence ratio have very limited effect on formation of these species. Only at the lean extreme does the resultant combustion instability result in rapid increase in the formation of these species. This same instability however limits unit operable range under this condition.

Consequently, under normal operating conditions engines can exhibit wide variations in NO_x emissions while carbon species exhibit far less variation.

4.3.3 Knee Location

Table IIIa shows the calculated knee location for each CSU data set for each trade-off parameter of interest. The table also includes average values and the standard deviation[8] of the calculated knee location as a measure of uncertainty in that knee value. All three carbon pollutant show significant variation in knee locations when comparing different datasets. This presumably is an artifact of the range and number of data points included in each dataset. The largest and most varying dataset, Pre Production HPFI™, generally has the knee at 0.5-1.5 g/BHP-HR NO_x lower than the other datasets[9]. In general, an average knee location of ~2.5 g/BHP-HR NO_x can be taken as "typical" EMCT performance when applied to the CSU engine

When compared with the conventionally fueled base-line variable boost data for the CSU engine (Table IV) the average knee location for the engine fitted with EMCT shifted at lest somewhat to the left for all carbon pollutants. In particular the THC knee shifted by 0.2 g/BHP-NO_x, the CO knee by 1 g/BHP-HR and the H_2CO knee by 0.4 g/BHP-HR. The magnitude of the CO shift falls outside the uncertainty in the test data and appears real. The magnitudes of the shifts for THC and H_2CO fall within the uncertainty of the knee calculations and may not represent real improvements.

4.4 Cyclic Combustion Pressure Instability Trade-offs

Figures 1a-e displays trends of cyclic combustion pressure instability (cyclic instability) as a function of NO_x for each LBET engine dataset included in the database. Figure 3d displays comparative trends for all the engines.

An evaluation of the trade-off characteristics for cyclic combustion pressure instability follows.

[8] Admittedly, the population is too small to establish real measures of uncertainty or valid estimates of the standard deviations. The information is included only for comparative purposes.
[9] This could also be a result of the relatively late SOA of this data set, though that seems less clear.

4.4.1 General Characteristics

Trends of cyclic instability data for the current study are quite similar to those of the previous study. Specifically, like the carbon species pollutant data, the cyclic instability increased with decreasing NO_x emissions. However unlike the carbon pollutant emissions, the cyclic instability data does not exhibit the pronounced transition from an asymptotic baseline at high NO_x levels through a knee to a near vertical asymptote at reduced NO_x levels.

4.4.2 Range of Variation

The cyclic instability data for the LBET datasets consistently exhibited a range of ≈1:9-2 (Table IIa). This matches the range for the baseline variable boost data of the previous study (see Table 4.3.2a of reference 7).

4.4.3 Knee Location

The knee location for combustion stability (Table IIIa) varied from 3-5 g/BHP-HR NO_x with an average of 4. As reflected in Table IV, this coincides with the knee location for the baseline conventional fuel vari-boost data. EMCT does not appear to offer any benefit in combustion stability trade-off performance when applied to he CSU engine.

4.5 BSFC Trade-offs

Figures 1a-e displays trends of BSFC as a function of NO_x for each LBET dataset included in the database. Figure 3e displays comparative trends for those same engines. As previously noted, numeric BSFC values for the CSU LBET in the simulated turbocharged configuration are quite high due to the unit's low BMEP. In addition, BSFC's for the PCC and Ion tests are higher due to the reduced compression ratio. Nonetheless the relative trends for a given configuration appear representative.

4.5.1 General Characteristics

While exhibiting greater scatter[10] and far less range of variation than carbon species pollutant data, the BSFC data exhibited very similar decaying exponential trends with a pronounced inflection point at reduced NO_x levels approximately matching that of the carbon pollutants. This matches the results of the previous study.

4.5.2 Range of Emissions Variation

The BSFC data exhibited a range of variation of ≈1.0:1-1.4:1 similar to the baseline variable boost data of the previous study (see Table 4.3.2a of reference 7).

[10] In part due to the strong second order effects of torque/BMEP.

4.5.3 Knee Location

The knee location for BSFC (Table IIIa) varied from 0.8-2.6 g/BHP-HR NO_x with an average of 1.9 As reflected in Table IV the average knee location for the LBET fitted with EMCT offers a slight improvement (~0.5 g/BHP-HR) when compared with the conventionally fueled baseline vari-boost data. However the magnitude falls within the uncertainty of the knee estimate and may not be significant.

5.0 Field Test Results

Concurrent with the review of the CSU LBET data, AETC completed, compiled, reviewed and analyzed the field test database. This analysis included:

- Trending of trade-offs between NO_x and carbon pollutant emissions, efficiency, combustion stability and engine operable range.
- Quantitative characterization of typical emissions and trade offs.
- Comparisons with similar engines from the trade-off study fitted with conventional fuel valves.

The field test data largely mirrors the CSU LBET results, with EMCT shifting the trade-off knee significantly to the left. In general, the shift was much more pronounced than experienced with the CSU data.

A topical discussion of these findings follows.

5.1 Sensitivities to Changes in Control Parameters

As reflected in Table IIb, the field test data sets included variation of up to all five control parameters (speed, torque, trapped equivalence ratio, AMT and IT). Similar to conventionally fueled engines, variations in speed, torque, trapped equivalence ratio or AMT had little impact on overall trade-off characteristics. In general, parameter changes which decreased NO_x a fixed amount increased carbon pollutant emissions and BSFC and reduced combustion stability by fixed amounts. Whether the NO_x reduction was induced by leaning the trapped equivalence ratio or reducing torque at fixed AMP did not appear to significantly alter the trade-offs.

As previously noted, changes in torque do have a secondary impact on the BSFC trade-off. In addition, changes in IT significantly impacted both CO and BSFC trade-off performance for some of the field engines fitted with EMCT (see Figures 2a and 2b). As reflected in the data for the TLA-6 and GMW-10C, operation at more advanced IT for the same NO_x level (requiring a leaner air/fuel ratio) decreased CO and BSFC. This sensitivity to IT was not noted in the previous trade-off study for conventionally fueled engines and may be a unique characteristic of EMCT. Further analysis is warranted.

5.2 THC, CO,& H_2CO Trade-offs

Figures 2a-d display trends of THC, CO,& H_2CO as a function of NO_x for each field test dataset included in the database. Figures 3a-c show that same data plotted with the CSU data for each pollutant. When reviewing these plots, it is important to recall that conventionally fueled Clark T series engines generally exhibit elevated baseline THC, CO and H_2CO levels in comparison to Cooper engines included the CSU engine.

An evaluation of the trade-off characteristics for carbon pollutant emissions (i.e. THC, CO, & H_2CO) follows.

5.2.1 General Characteristics

While the carbon pollutant emissions trade-off trends generally exhibited typical trade-off performance similar to the CSU data, the knees were much less pronounced. The field data sets did not include the lower range of NO_x data (sub 1.5 g/BHP-HR) where the trade-off becomes particularly evident. The field test data also tended to exhibit significantly greater scatter than the CSU data due presumably to imbalance and other field factors (see section 6.1 below).

The field THC data fell in with the CSU data, both in magnitude and trade-off characteristics. The field data exhibited slightly higher H_2CO baseline levels, though the trade-off characteristics were quite similar to the CSU data. None of the field datasets exhibited significant CO trade-offs with all three Clark engines exhibiting higher baseline CO levels than the CSU engine. Two of the Clark engines (TCV-10, TLA-6 fitted with Hyper FuelValve^{TM}) may actually show counter trade-off performance, albeit with significant scatter. The one Cooper engine (also fitted with Hyper FuelValve^{TM}) did not exhibit the scatter or counter trend. Rather CO for this engine and the TCVD remained virtually invariant, even at sub 2 g/BHP-HR NO_x levels. Stated differently, these engines *exhibited no CO penalty as* NO_x *reduced!*

5.2.2 Range of Emissions Variation

In general, the field data exhibited much narrower ranges of parameter variation. This presumably reflects the challenges of running controlled tests in the field, and the effects of multi-cylinder operation (see section 6.1 below).

Like the CSU results, for a given range of NO_x variation, the carbon pollutant emissions exhibited a significantly lower range of variation (see Table IIb). For example, for the widest ranging dataset, the GMW-10C, NO_x varied over a range of ≈13:1 while THC varied ≈2:1, CO ≈1.8:1 and H_2CO ≈1.5:1.

5.2.3 Knee Location

Table IIIb shows the calculated knee location for each field data set for each trade-off parameter of interest. The table also includes average values and the standard deviation of the calculated knee location as a measure of uncertainty in that value.

THC consistently exhibited a knee location of ~4.7 g/BHP-HR for all four datasets. As already noted CO did not exhibit clear trade-off performances and/or exhibited counter trade-off performance. The location off the H_2CO knee varied from 0.6 to 3.2 with an average of 2.1 g/BHP-HR NO_x.

When compared with the conventionally fueled base-line variable boost data for the field engines (Table IV) the average knee location for the engine fitted with EMCT shifted substantially to the left for both THC (from 7.3 to 4.7 g/BHP-HR NO_x) and H_2CO (from 5.3 g/BHP-HR to 2.1 g/BHP-HR). As noted, the field test engines fitted with EMCT did not exhibit a CO knee, and the value when fitted with conventional fueling is already quite low (~2.8 g/BHP-HR).

The magnitude of both the THC and H_2CO knee shifts significantly exceed the estimation uncertainty. EMCT offers clear trade-off benefits for these two pollutants when applied to field engines.

While outside the scope of this study, it is interesting to note that EMCT cut the baseline THC emissions (i.e. the THC emissions at 9 g/BHP-HR NO_x) for Clark T series engines in half, bringing them down to levels typical for Cooper engines. There was little to no improvement in baseline CO or H_2CO levels.

5.3 Cyclic Combustion Pressure Instability Trade-offs

Figures 2a-d display trends of cyclic combustion pressure instability (cyclic instability) as a function of NO_x for each engine dataset included in the database. Figure 3d displays comparative trends for those same engines.

An evaluation of the trade-off characteristics for cyclic combustion pressure instability follows.

5.3.1 General Characteristics

Similar to the CSU results, trends of cyclic instability for field engines fitted with EMCT are quite similar to those fitted with conventional fueling. The cyclic instability data does not exhibit a pronounced transition from an asymptotic baseline at high NO_x levels through a knee to a near vertical asymptote at reduced NO_x levels. Rather the combustion stability gradually increases with decreasing NO_x.

5.3.2 Range of Variation

The cyclic instability data for the field data exhibited a range of ≈1.6-1:9 (Table IIb). This is similar to the range for the CSU data and field test data for conventionally fueled engines.

5.3.3 Knee Location

The knee location for combustion stability (Table IIIb) for the field engines fitted with EMCT averaged ~4 g/BHP-HR NO_x. This is identical to the CSU results (both EMCT and conventionally fueled) and a reduction of ~1.5 g/BHP-HR NO_x on the knee location for conventionally fueled field test engines (Table IV).

More importantly, the baseline combustion stability values (i.e. the values at 9 g/BHP-HR) for the field engines fitted with EMCT are approximately half those for conventionally fueled field engines (i.e. ~7.5% vs ~13%). Consequently, the EMCT fitted engines approach the baseline Combustion Stability values of conventionally fueled engines at ~2.5-3 g/BHP-HR NO_x. Stated differently, EMCT cuts the baseline combustion stability performance at 9 g/BHP-HR NO_x in almost half, allowing engine operation at down to ~3 g/BHP-HR NO_x without significant penalty in other pollutants or BSFC.

5.4 BSFC Trade-offs

Figures 2a-d display trends of BSFC as a function of NO_x for each dataset included in the database. Figure 3e displays comparative trends for the same engines.

5.4.1 General Characteristics

Unlike the CSU EMCT data, the BSFC data for the field engines fitted with EMCT exhibited almost little to no trade-off performance remaining virtually invariant (Figure 3e).

5.4.2 Range of Emissions Variation

The BSFC data exhibited a range of variation of ≈1.05:1 to 1:09:1 (Table IIb). In view of the inherent uncertainty in the measurement (~2.5%) this is virtually invariant.

5.4.3 Knee Location

The knee location for BSFC (Table IIIb) varied from 1.4-3.4 g/BHP-HR NO_x with an average of 2.6. As reflected in Table IV the average knee location for the field engines fitted with EMCT shifted to the left by ~3.5 g/BHP-HR NO_x (from ~6.2 g/BHP-HR to 2.6 g/BHP-HR) when compared with conventionally fueled field engines.

6.0 Discussion

The field test data exhibited pronounced shifts of the trade-off curves for THC, H_2CO and combustion stability in the beneficial direction (i.e. to the left) when applying EMCT. EMCT virtually eliminated the CO and BSFC trade-off, an even more beneficial condition! In contrast, the CSU data showed far less if any benefit in trade-off performance when applying EMCT. Both results are valid. They reflect some of the key differences between field and laboratory testing and the importance of system "robustness" in real world applications.

6.1 The Role of Imbalance and Cylinder Health

A discussion of the effects of imbalance and cylinder health on trade-off performance follows.

6.1.1 Imbalance and the Knee Location

As noted above the leanest cylinder of an unbalanced engine limits the minimum NO_x that engine can achieve. As that cylinder approaches flame-out it effectively establishes the knee *for the whole engine*. This is particularly true for conventionally fueled OCC engines. This also creates significant data scatter as individual cylinders approach the knee independently depending on the relative state of balance (i.e. a lean cylinder will seem to approach the knee sooner than a rich cylinder). Consequently, a well balanced engine in excellent operating condition will tend to exhibit a sharper knee at lower NO_x levels than a more poorly balanced, poorly running unit.

6.1.2 The Impact of Good Balance and Combustion Stability on Emissions Limits

The low cylinder count of the CSU engine permits careful manual balancing after each change in operating condition. This along with the low spark plug hours and overall excellent mechanical condition of the engine ensures optimum flame initiation and propagation at all operating conditions. Consequently all cylinders approach the lean limit in concert. This results in a sharp distinct knee at low NO_x levels not normally achieved by OCC engines in the field fitted with conventional fuel admission systems.

Data from the conventionally fueled OCC V-250 fitted with AutoBalance exhibited somewhat similar response to the CSU engine. In particular the data exhibits substantially less scatter than that of the TLA-6 and achieves significantly lower minimum NO_x, though not as low as the CSU engine. The V-250 data still does not exhibit the sharp distinct knee of the CSU data, probably reflected the effects of ignition system component health.

Rather interestingly, the minimum NO_x level for the V-250, like the TLA-6 and even the CSU unit appear to be defined by combustion instability. All thee units are limited to virtually identical instability values (~17%) even though the NO_x levels at that limit are significantly different for the three engines (Figure 4d).

6.1.3 Robustness of Flame Initiation and Propagation

The conventionally fueled PCC fitted engines in the original trade-off study consistently exhibited sharp knees with little scatter and low NO_x levels similar to the CSU engine fitted with conventional fueling (compare Figures 3.2a-b with 3.2 c-d in Reference 7). This reflects the better ability of PCC's to propagate a flame under lean environments in the field. This not only results in lower minimum achievable NO_x, but also reduces the limiting effect of the leanest cylinder on overall engine operation reducing data scatter as noted.

Like conventionally fueled PCC engines, OCC engines fitted with EMCT exhibited improved combustion stability at baseline conditions and can initiate and propagate a flame under much leaner conditions than the same OCC engine fitted with conventional fuel valves. This reduces sensitivity to lean cylinder unbalance in turn reducing data scatter and increasing the minimum achievable NO_x emissions. The addition of automatic balancing, often included with EMCT retrofits should further extend and sharpen the knee.

When tested at CSU, neither AutoBalancing nor EMCT have exhibited the same benefit as experienced in the field. For that matter, the benefits of PCC's are also not as pronounced on the LBET as in the field. All three technologies extend an engine's ability to operate under less than optimal conditions thereby maintaining best possible emissions and engine performance under real world conditions. The LBET by its nature already operates under optimal conditions resulting in best possible performance under virtually all conditions. Therefore test results from this engine tend to understate the benefits of these types of technologies which fundamentally improve the robustness of flame initiation and propagation maintaining good performance under less than optimal conditions.

6.2 The Primary Benefit of EMCT

While outside the scope of this project, the results of the trade-off analysis offer some further insights into exactly how EMCT reduces NO_x emissions. As reflected in the results, EMCT shifts the NO_x trade-off knee significantly to the left, or in the case of CO, often eliminates the trade-off altogether. This allows operation at substantially reduced NO_x levels without penalty in other carbon pollutant emissions or performance.

More fundamentally, on a cycle by cycle basis conventional fueling systems yield inconsistent and/or inhomogeneous mixtures at the spark plug and its vicinity. Combustion cycles with richer than average mixtures near the plug easily light off with high rates of pressure rise and high peak temperatures. Cycles with leaner than average mixtures near the plug result in late fires or even misfires. This manifests itself as cyclic instability. In addition, due to the exponential relationship between NO_x and peak combustion temperature, the richer combustion cycles create disproportionate mass of NO_x.

In contrast EMCT appears to yield a more uniform air/fuel mixture at the spark plug and its vicinity truly representative of the average air/fuel ratio. When coupled with a modern high energy ignition system this results in consistent flame initiation and propagation. This significantly improves combustion stability at baseline conditions by eliminating the no-fires and most late fires typical of conventional fueling systems due to cyclic variations in local air/fuel ratio. This also results in consistent peak temperatures, eliminating the cyclic high temperature excursions thereby reducing NO_x emissions at the same apparent or bulk air/fuel ratio. This creates the shift to the right (rich) in the NO_x vs trapped equivalence ratio curve often noted when applying EMCT (Reference 8). Finally at the engine level, EMCT reduces sensitivity to lean unbalance, further extending an engine's overall operating range.

This drastic improvement in baseline combustion stability and tolerance to lean unbalance allows significant leaning of the engine resulting in NO_x levels well below those achievable by a conventionally fueling system. By the point an EMCT fitted engine is at the baseline combustion stability of a conventionally fueled engine, the EMCT fitted unit is operating significantly leaner resulting in substantially lower minimum achievable NO_x emissions without incurring penalties in other emissions or performance.

The forgoing is largely speculative based on the limited available data and the author's first hand observations of EMCT systems in operation. While the industry has begun applying this technology for emissions reductions, it is still not clear exactly how the technology works or if the full potential has been yet exploited. The industry should consider funding a simple low cost theoretical study of EMCT to better understand the fundamental mechanisms underlying its performance benefits.

7.0 Conclusions and Recommendations

- EMCT beneficially shifts the NO_x trade-off knee and/or eliminates the trade-off altogether, allowing operation at substantially reduced NO_x levels without penalty in other emissions or performance.

- The application of EMCT to field engines shifts the trade-off knee location to the left (i.e. favorably) by about 3 g/BHP-HR NO_x for both H_2CO and THC. CO becomes invariant, an even greater benefit.

- Likewise, with the application of EMCT, BSFC becomes nearly invariant, shifting the knee (where it occurs) to the left by ~2.5 g/BHP-HR NO_x.

- The trade-off for some engines fitted with EMCT appear to exhibit a sensitivity to IT, with more advanced IT's at the same NO_x levels resulting in significantly lower CO emissions and BSFC. This deserves further investigation.

- The application of EMCT to field engines shifts the combustion stability knee from ~5.5 g/BHP-HR NO_x to ~4.0. More importantly, EMCT improves baseline combustion stability by almost a factor if 2, extending operation down to ~3 g/BHP-HR NO_x without significant penalty in carbon pollutants or BSFC.

- Field OCC engines fitted with EMCT can initiate and propagate a flame under much leaner conditions than the same OCC engine fitted with conventional fuel valves. This reduces sensitivity to lean cylinder unbalance and improves combustion stability substantially reducing the minimum achievable NO_x emissions for a given engine.

- EMCT did not appear to offer the same benefits when applied to the CSU engine as compared to performance with conventional fuel valves. However when fitted with conventional fuel valves, the CSU engine already exhibits extremely low NO_x emissions and extremely favorable trade-off performance. This same level of performance is not achievable in the field or representative of typical field performance.

- Due to its low cylinder count and excellent mechanical condition, the CSU LBET always operates optimally. As a consequence, test results for technologies which enhance an engine's robustness (such as EMCT, PCC's or AutoBalance) allowing that engine to obtain optimal performance under less than optimal operating conditions tend to understate their benefit when tested in the lab. When tested in the field these same technologies far better show their true potential.

- The addition of automatic balancing, often included with EMCT retrofits should further extend and sharpen the knee.

- The fundamental mechanism underlying the benefits of EMCT remains unclear. The full potential of the technology may be unrealized. The industry should consider funding a simple low cost theoretical study of EMCT to better understand the fundamental mechanisms underlying its performance benefits.

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Table I
Engine Particulars

Engine Make	Engine Model	Cylinder Count	Rated Speed (rpm)	Rated Output (BHP)	Bore (in)	Stroke (in)	Cycle
Clark	TCV-10	10	300	3,400	17	19	2
Clark	TCVD-16	16	330	7,800	17.75	19	2
Clark	TLA-6	6	300	2,000	17	19	2
Cooper	GMV-4 CSU	4	300	440	14	14	2
Cooper	GMW-10C	10	250	2,700	18	20	2

Table IIa
Range of Parameter Variation - CSU Data

Parameter		Pre Production HPF*I*™		Pre Production HPFV™		Production HPFV™		Ion Sense Test		PCC Test	
Speed	*Max*	300	1.0	300	1.0	300	1.0	300	1.0	300	1.0
	Min	300		300		300		300		300	
BHP	*Max*	440	1.7	440	1.0	440	1.0	440	1.0	440	1.0
	Min	265		440		440		440		440	
IT	*Max*	10.0	1.0	N/A	N/A	N/A	N/A	10.5	N/A	10.0	N/A
	Min	10.0		N/A		N/A		9.4		10.0	
$BSNO_x$	*Max*	10.8	27	10.8	7.9	18.4	10	18.2	7	14.1	9
	Min	0.4		1.4		1.8		2.8		1.5	
BSCO	*Max*	2.8	4.1	1.8	2.5	0.8	1.6	0.8	1.1	0.8	1.4
	Min	0.7		0.7		0.5		0.7		0.6	
BSH_2O	*Max*	0.27	2.7	0.27	2.0	0.17	1.3	0.26	1.4	0.21	1.3
	Min	0.10		0.14		0.13		0.18		0.16	
BSTHC	*Max*	32.8	12	11.3	3.3	7.9	2.0	6.7	1.4	7.0	1.8
	Min	2.7		3.4		3.9		4.9		3.9	
BSFC	*Max*	10,936	1.4	9,576	1.1	8,592	1.1	9,646	1.0	9,216	1.1
	Min	8,052		8,861		7,976		9,419		8,697	
Comb Stab	*Max*	15%	1.9	17%	1.9	21%	1.9	15%	1.7	19%	2.0
	Min	8%		9%		11%		9%		9%	

Table IIb
Range of Parameter Variation - Field Test Data

Parameter		TLA-6		TCV-10		TCVD-16		GMW-10C	
Speed	*Max*	300	1.0	300	1.1	330	1.2	250	1.3
	Min	300		270		270		200	
BHP	*Max*	2059	1.0	3447	1.4	7862	1.4	2749	1.7
	Min	1961		2398		5490		1652	
IT	*Max*	7.0	2.3	9.0	1.1	8.7	1.6	10.0	5.0
	Min	3.0		8.5		5.4		2.0	
$BSNO_x$	*Max*	10.1	4.0	5.8	2.2	13.1	8.2	21.1	13
	Min	2.5		2.7		1.6		1.6	
BSCO	*Max*	1.7	1.5	1.5	1.4	1.0	1.1	1.0	1.8
	Min	1.1		1.1		0.9		0.5	
BSH_2O	*Max*	0.28	1.2	0.27	1.3	0.19	1.4	0.20	1.5
	Min	0.23		0.21		0.13		0.13	
BSTHC	*Max*	4.4	2	6.0	1.5	4.9	1.9	4.4	2.0
	Min	2.9		4.0		2.6		2.2	
BSFC	*Max*	7,738	1.1	7,551	1.1	6,843	1.0	7,892	1.1
	Min	7,295		6,953		6,534		7,296	
Comb Stab	*Max*	11%	1.6	N/A	N/A	14%	1.9	N/A	N/A
	Min	7%		N/A		7%		N/A	

Table IIIa
Knee Location for CSU Data
Fittd with EMCT

Constituent	Threshold	Pre Production HPFI™	Pre Production HPFV™	Production HPFV™	Ion Sense Test	PCC Test	Average	Standard Deviaiotn
THC	20%	1.0	2.5	2.4	3.5	2.4	2.3	0.8
CO	20%	1.8	2.7	3.3	N/A	2.5	2.6	0.5
H2CO	20%	1.6	2.2	2.6	3.9	2.4	2.5	0.7
CS	25%	3.4	3.2	4.5	4.0	5.0	4.0	0.7
BFSC	2.5%	0.8	1.7	2.4	2.6	1.9	1.9	0.6
Average		1.7	2.5	3.0	3.5	2.8	2.7	0.7

Table IIIb
Knee Location for Field Data
Fitted with EMCT

Constituent	Threshold	TCVD-16	GMW-10C	TLA-16	TCV-10	Average	Standard Deviaiotn
THC	20%	4.8	4.7	4.7	4.4	4.7	0.2
CO	20%	N/A	N/A	N/A	N/A	N/A	N/A
H2CO	20%	3.2	1.6	0.6	2.9	2.1	1.0
CS	25%	4.4	N/A	4.1	N/A	4.2	0.1
BFSC	2.5%	N/A	1.4	3.4	2.9	2.6	0.9
Average		4.1	2.6	3.2	3.4	3.4	0.6

Table IV

Average Knee Location for CSU and Field Data

EMCT and Conventional Fueling

		CSU-Avg	**Field Avg**	**CSU**	**Field Avg**
Constituent	**Threshold**	**EMCT**		**Conventional**	
THC	20%	2.3	4.7	2.5	7.3
CO	20%	2.6	N/A	3.6	2.8
H2CO	20%	2.5	2.1	2.9	5.3
CS	25%	4.0	4.2	4.1	5.5
BFSC	2.5%	1.9	2.6	2.4	6.2
Average		2.7	3.4	3.1	5.4

Figure 1a

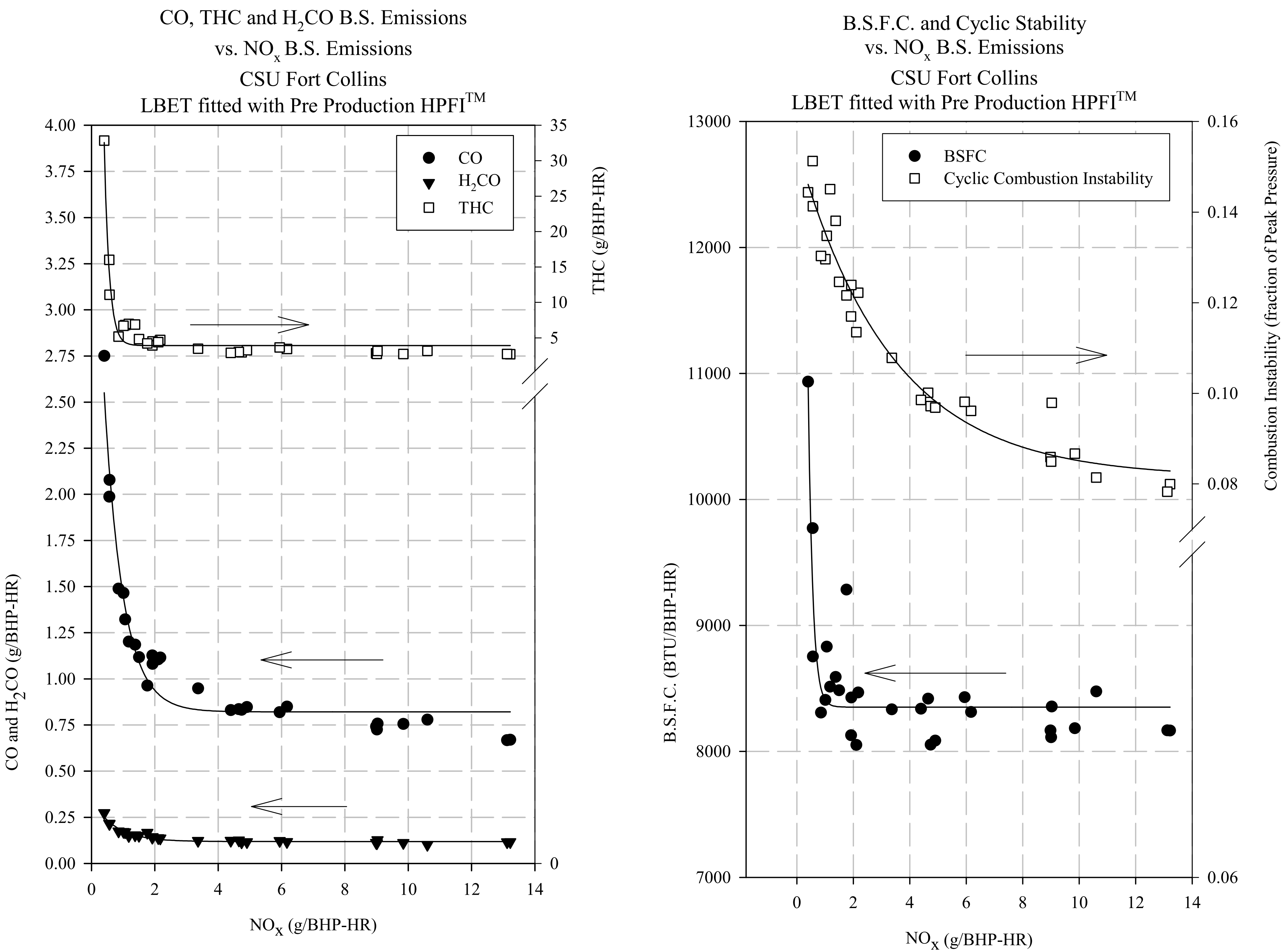
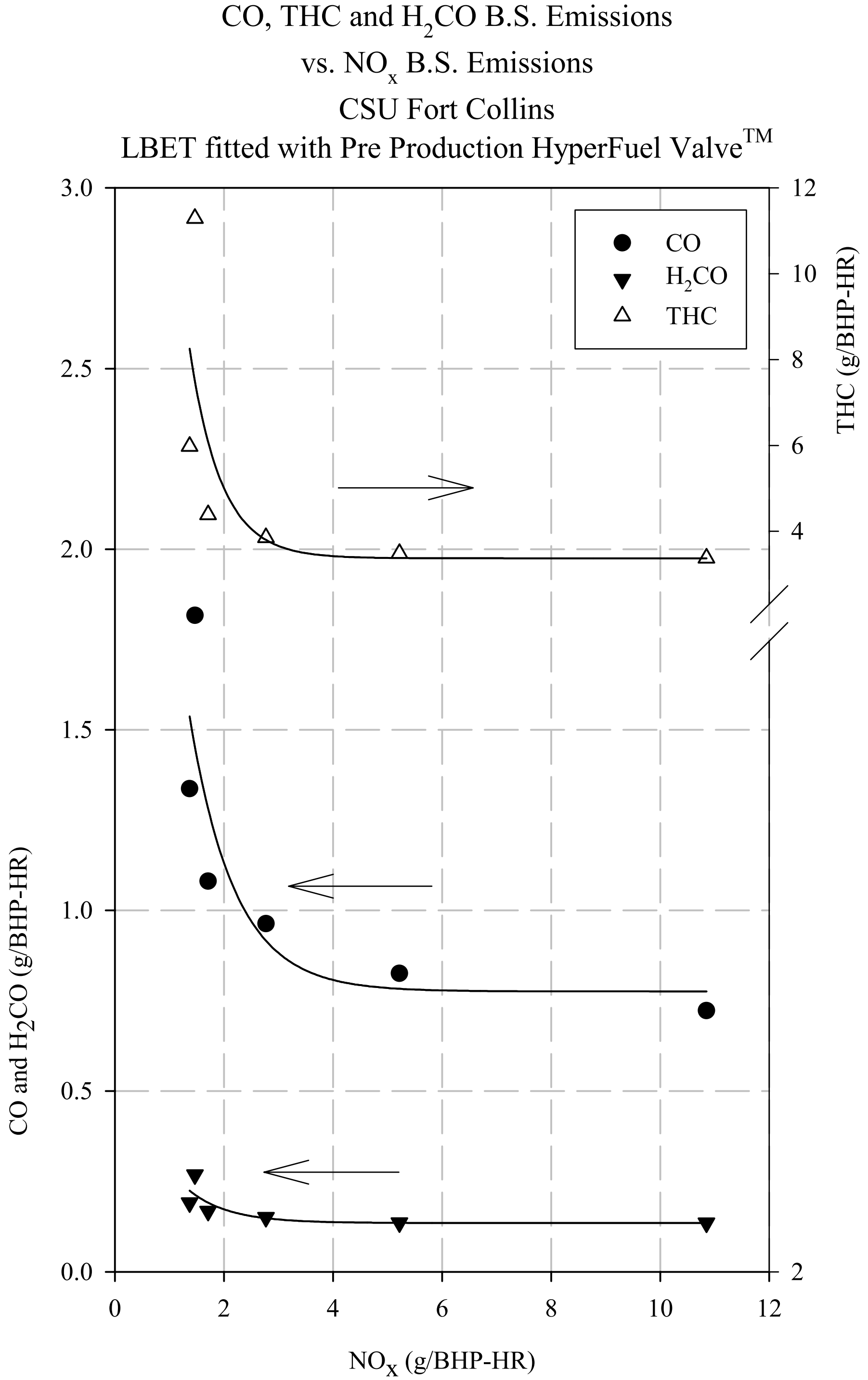
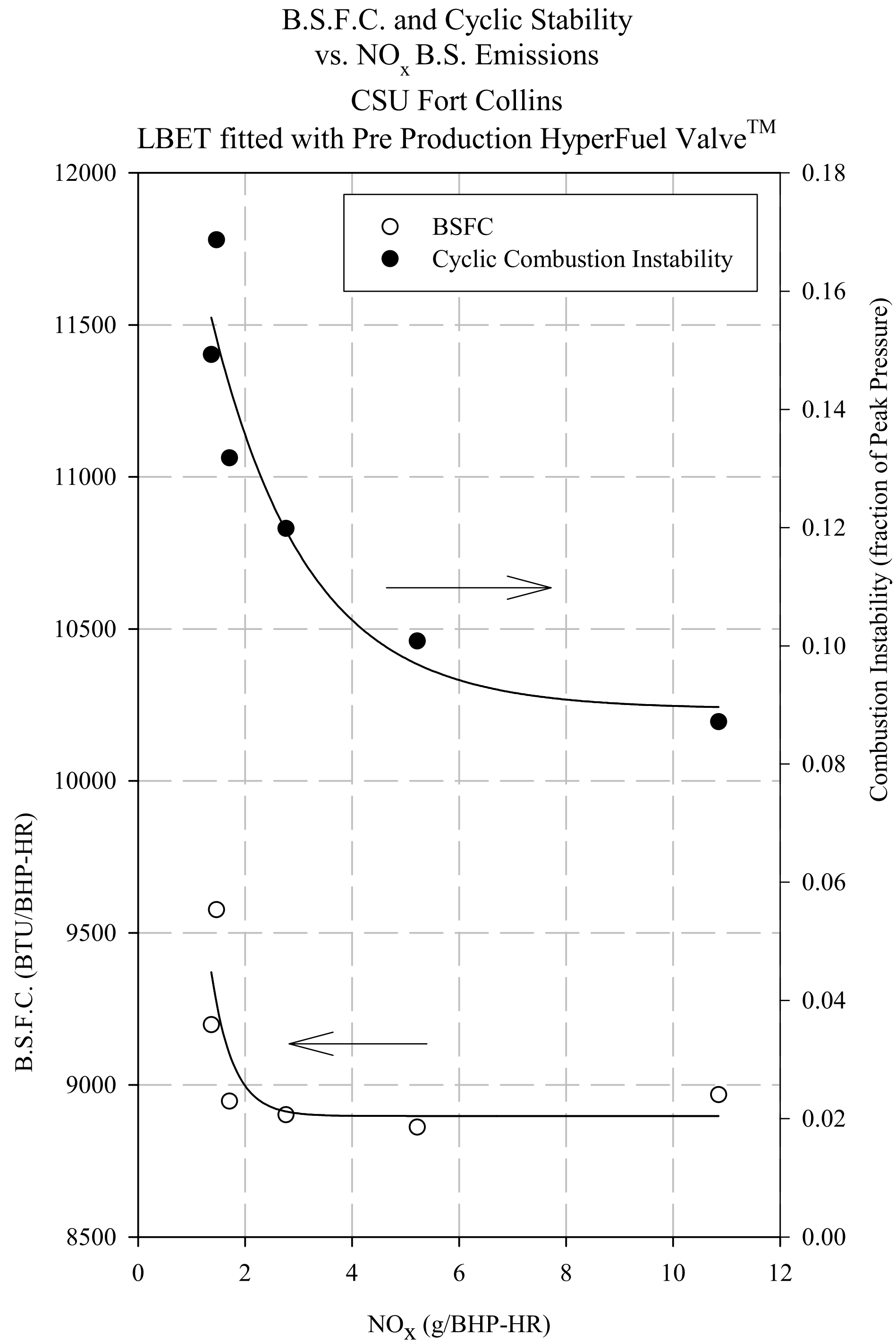

CO, THC and H2CO B.S. Emissions
vs. NOx B.S. Emissions
CSU Fort Collins
LBET fitted with Pre Production HPFI™
CO
H2CO
THC
CO and H2CO (g/BHP-HR)
THC (g/BHP-HR)
NOx (g/BHP-HR)
B.S.F.C. and Cyclic Stability
vs. NOx B.S. Emissions
CSU Fort Collins
LBET fitted with Pre Production HPFI™
BSFC
Cyclic Combustion Instability
B.S.F.C. (BTU/BHP-HR)
Combustion Instability (fraction of Peak Pressure)
NOx (g/BHP-HR)

Figure 1b

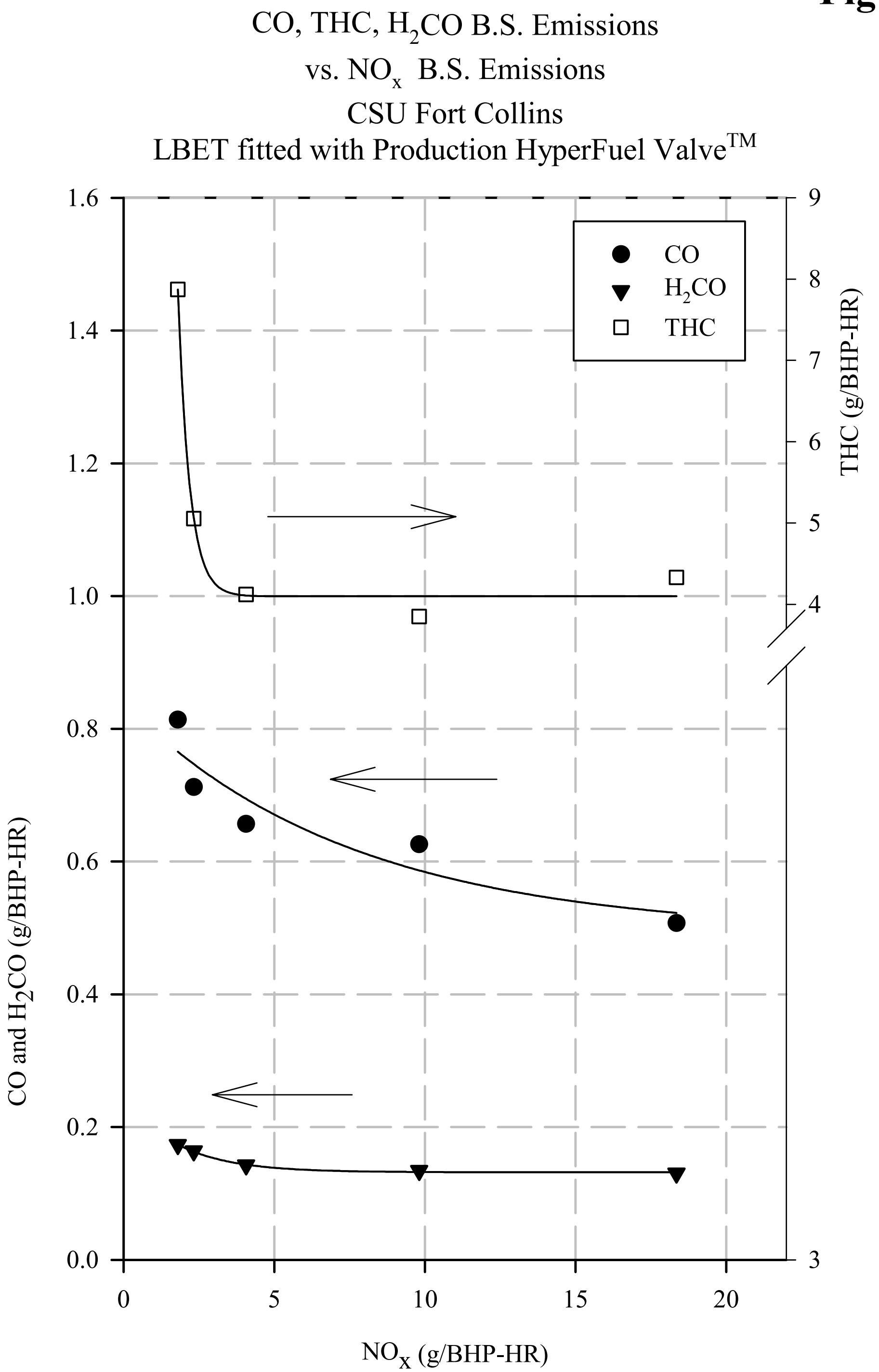


CO, THC and H_2CO B.S. Emissions
vs. NO_x B.S. Emissions
CSU Fort Collins
LBET fitted with Pre Production HyperFuel Valve™
CO
H_2CO
THC
CO and H_2CO (g/BHP-HR)
THC (g/BHP-HR)
NO_x (g/BHP-HR)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
2
4
6
8
10
12
0
2
4
6
8
10
12

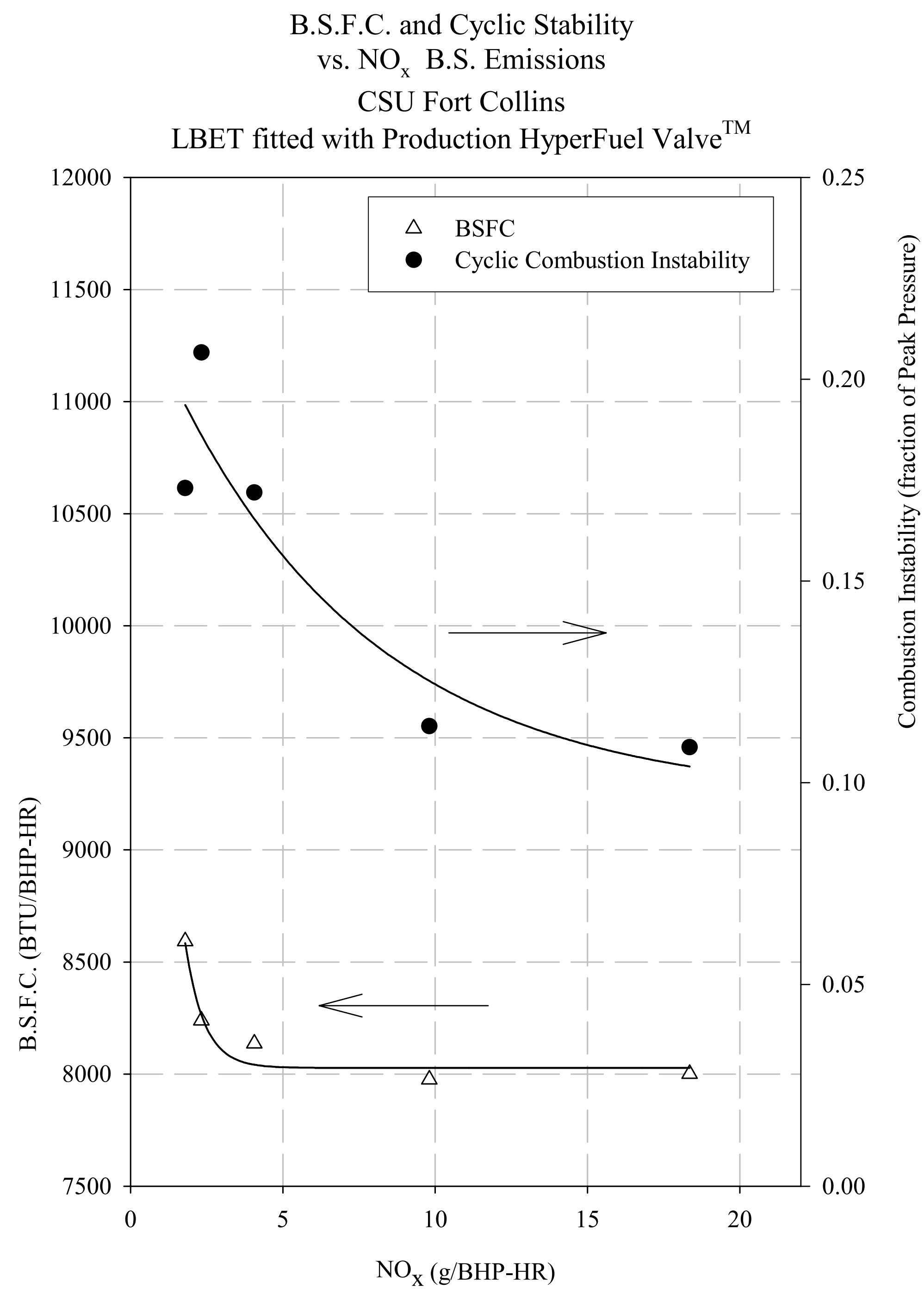


B.S.F.C. and Cyclic Stability
vs. NO_x B.S. Emissions
CSU Fort Collins
LBET fitted with Pre Production HyperFuel Valve™
BSFC
Cyclic Combustion Instability
B.S.F.C. (BTU/BHP-HR)
Combustion Instability (fraction of Peak Pressure)
NO_x (g/BHP-HR)
8500
9000
9500
10000
10500
11000
11500
12000
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.18
0
2
4
6
8
10
12

Figure 1c

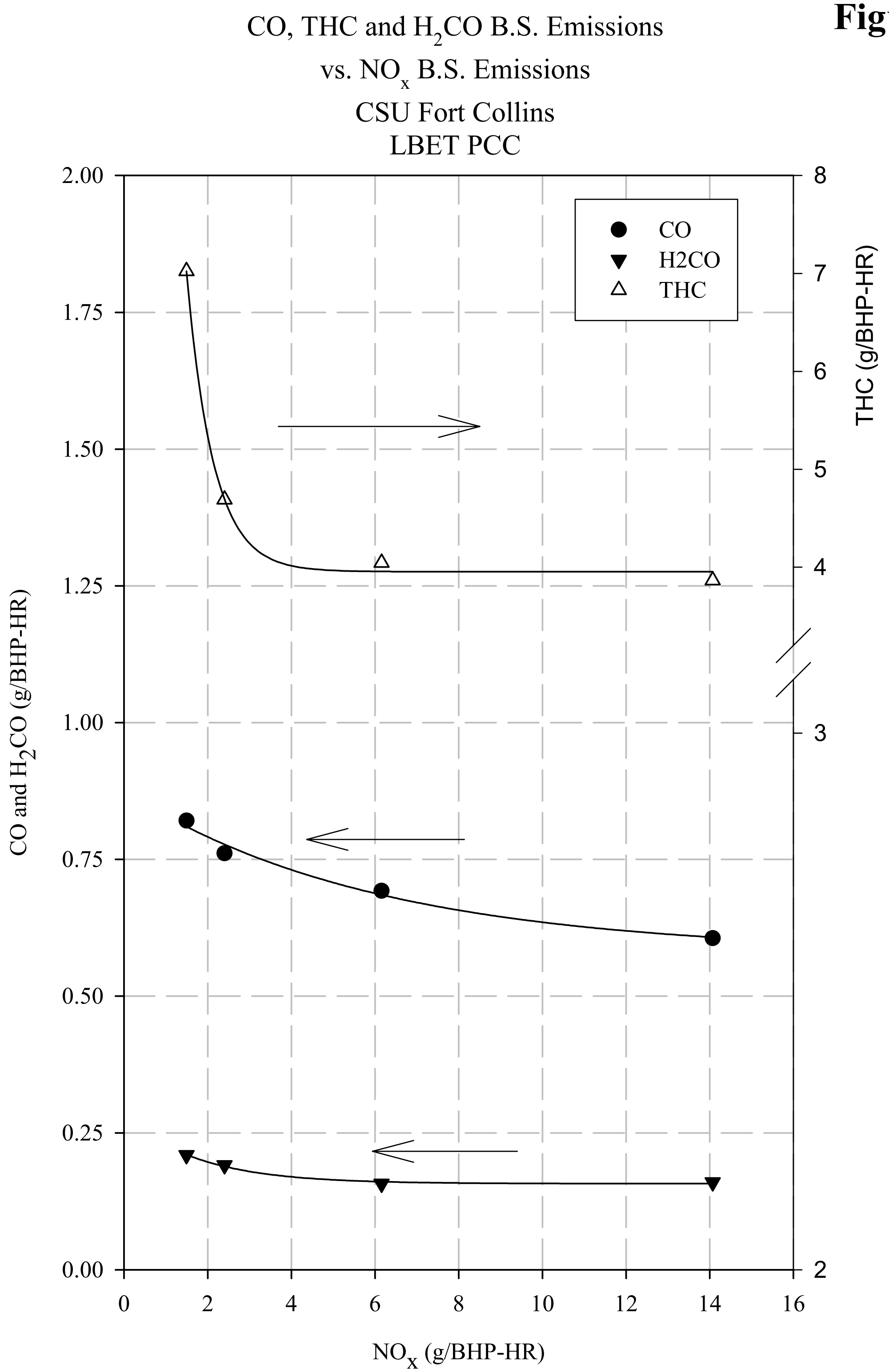


CO, THC, H_2CO B.S. Emissions
vs. NO_x B.S. Emissions
CSU Fort Collins
LBET fitted with Production HyperFuel Valve™
CO
H_2CO
THC
THC (g/BHP-HR)
CO and H_2CO (g/BHP-HR)
NO_x (g/BHP-HR)



B.S.F.C. and Cyclic Stability
vs. NO_x B.S. Emissions
CSU Fort Collins
LBET fitted with Production HyperFuel Valve™
BSFC
Cyclic Combustion Instability
Combustion Instability (fraction of Peak Pressure)
B.S.F.C. (BTU/BHP-HR)
NO_x (g/BHP-HR)

Figure 1d


CO, THC and H_2CO B.S. Emissions
vs. NO_x B.S. Emissions
CSU Fort Collins
LBET PCC
CO
H2CO
THC
CO and H_2CO (g/BHP-HR)
THC (g/BHP-HR)
NO_x (g/BHP-HR)
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2
3
4
5
6
7
8
0
2
4
6
8
10
12
14
16

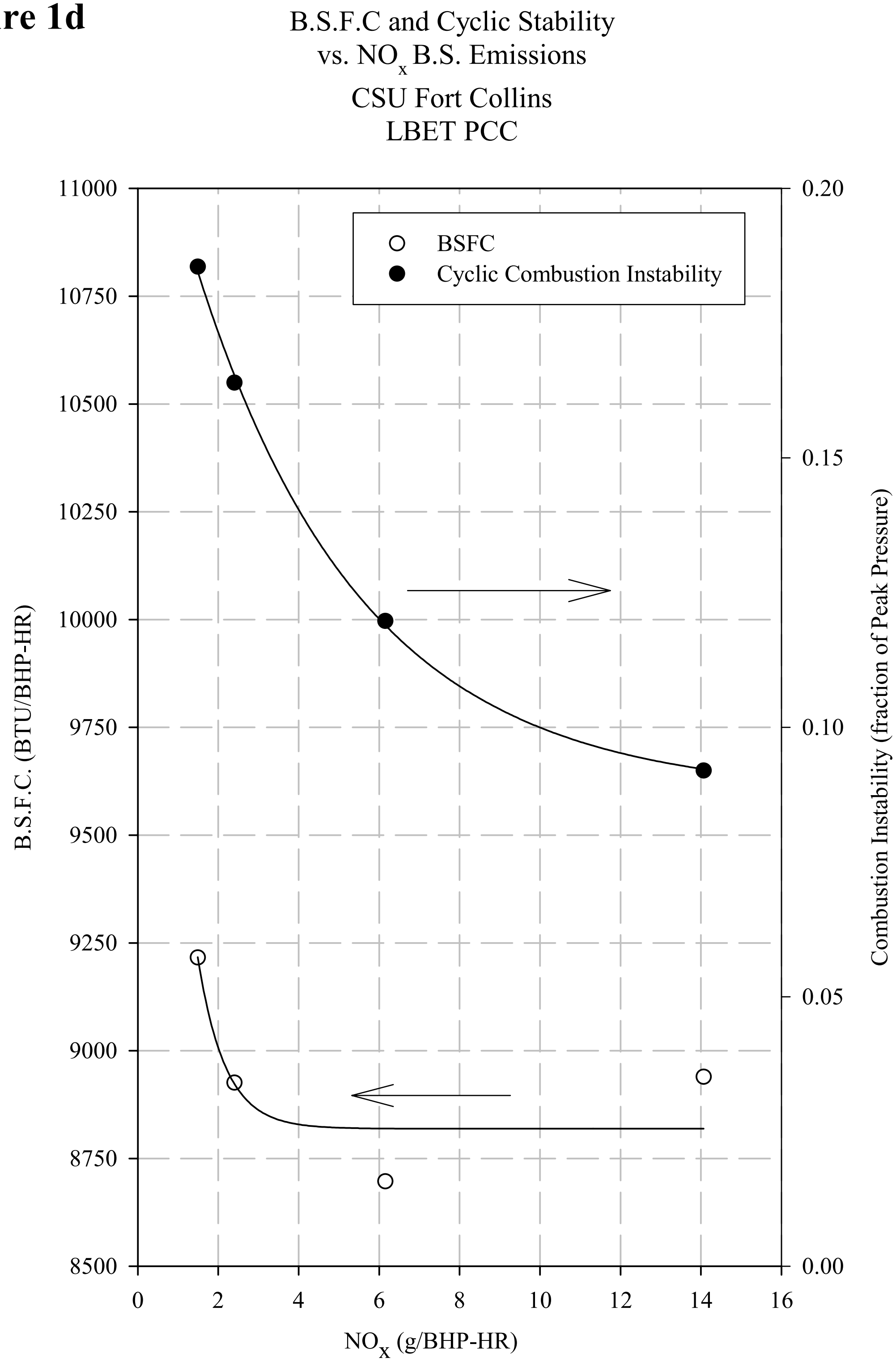
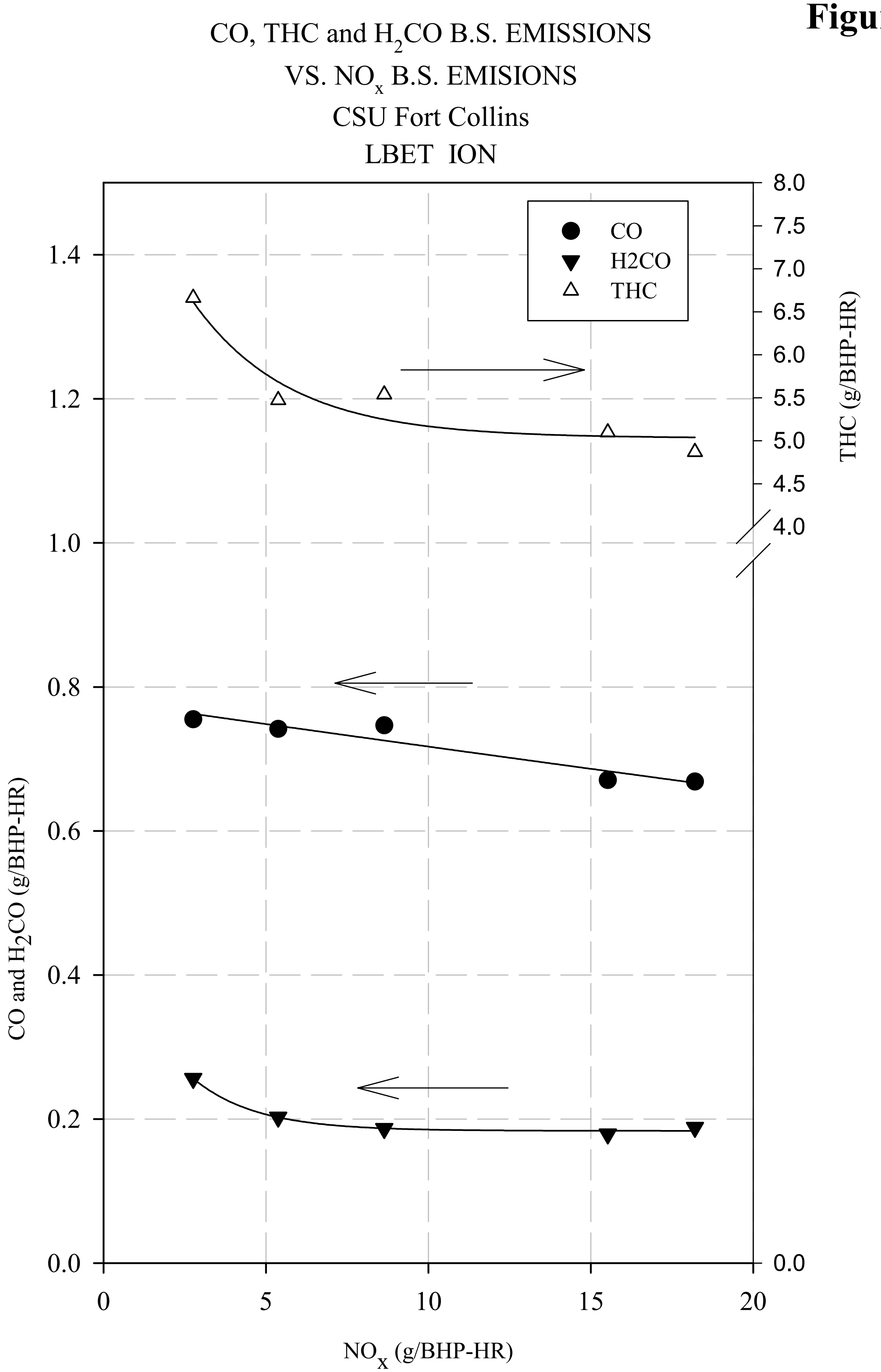

B.S.F.C and Cyclic Stability
vs. NO_x B.S. Emissions
CSU Fort Collins
LBET PCC
BSFC
Cyclic Combustion Instability
B.S.F.C. (BTU/BHP-HR)
Combustion Instability (fraction of Peak Pressure)
NO_x (g/BHP-HR)
8500
8750
9000
9250
9500
9750
10000
10250
10500
10750
11000
0.00
0.05
0.10
0.15
0.20
0
2
4
6
8
10
12
14
16

Figure 1e


CO, THC and H_2CO B.S. EMISSIONS
VS. NO_x B.S. EMISIONS
CSU Fort Collins
LBET ION
CO
H2CO
THC
CO and H_2CO (g/BHP-HR)
THC (g/BHP-HR)
NO_X (g/BHP-HR)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
0.0
4.0
4.5
5.0
5.5
6.0
6.5
7.0
7.5
8.0
0
5
10
15
20

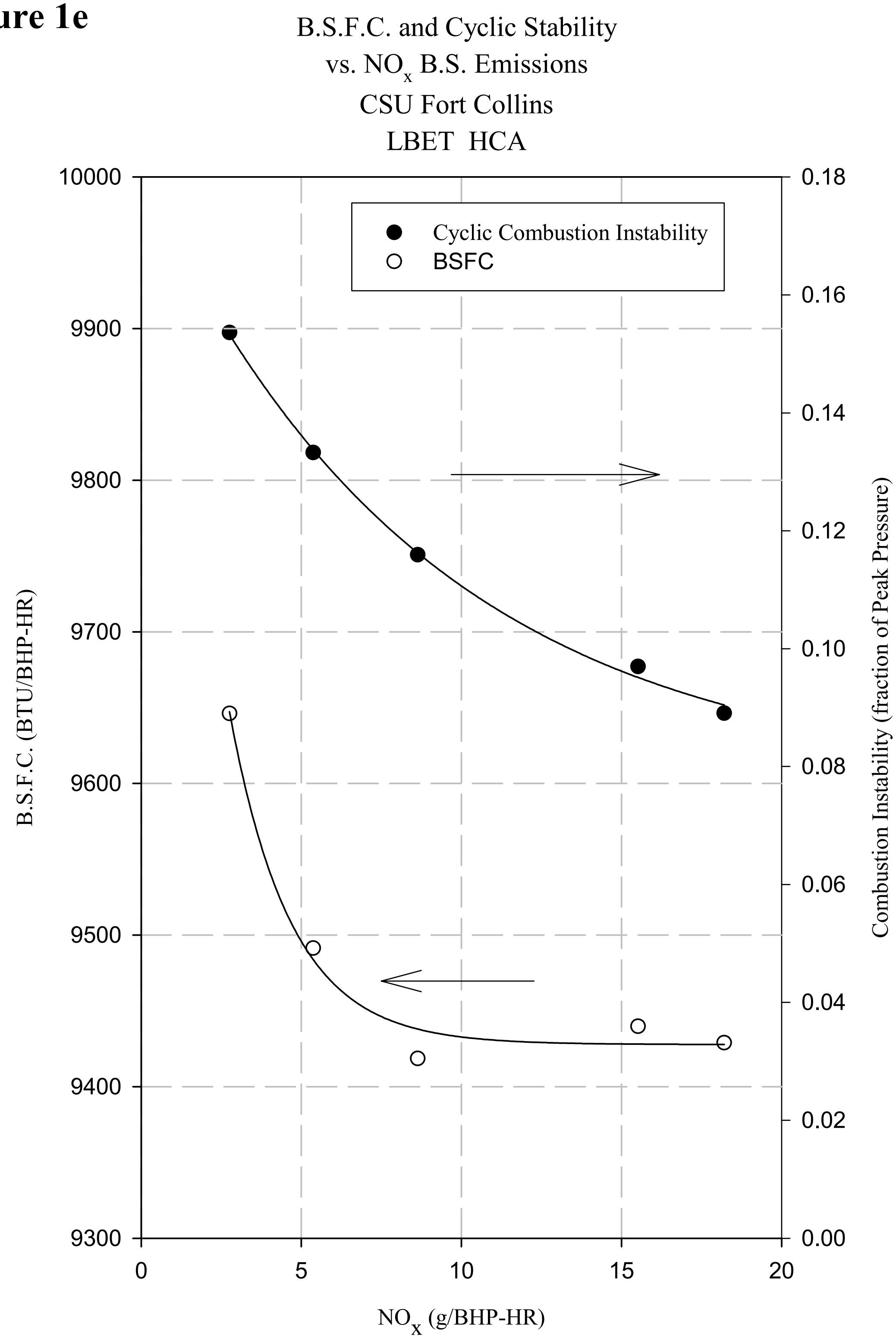
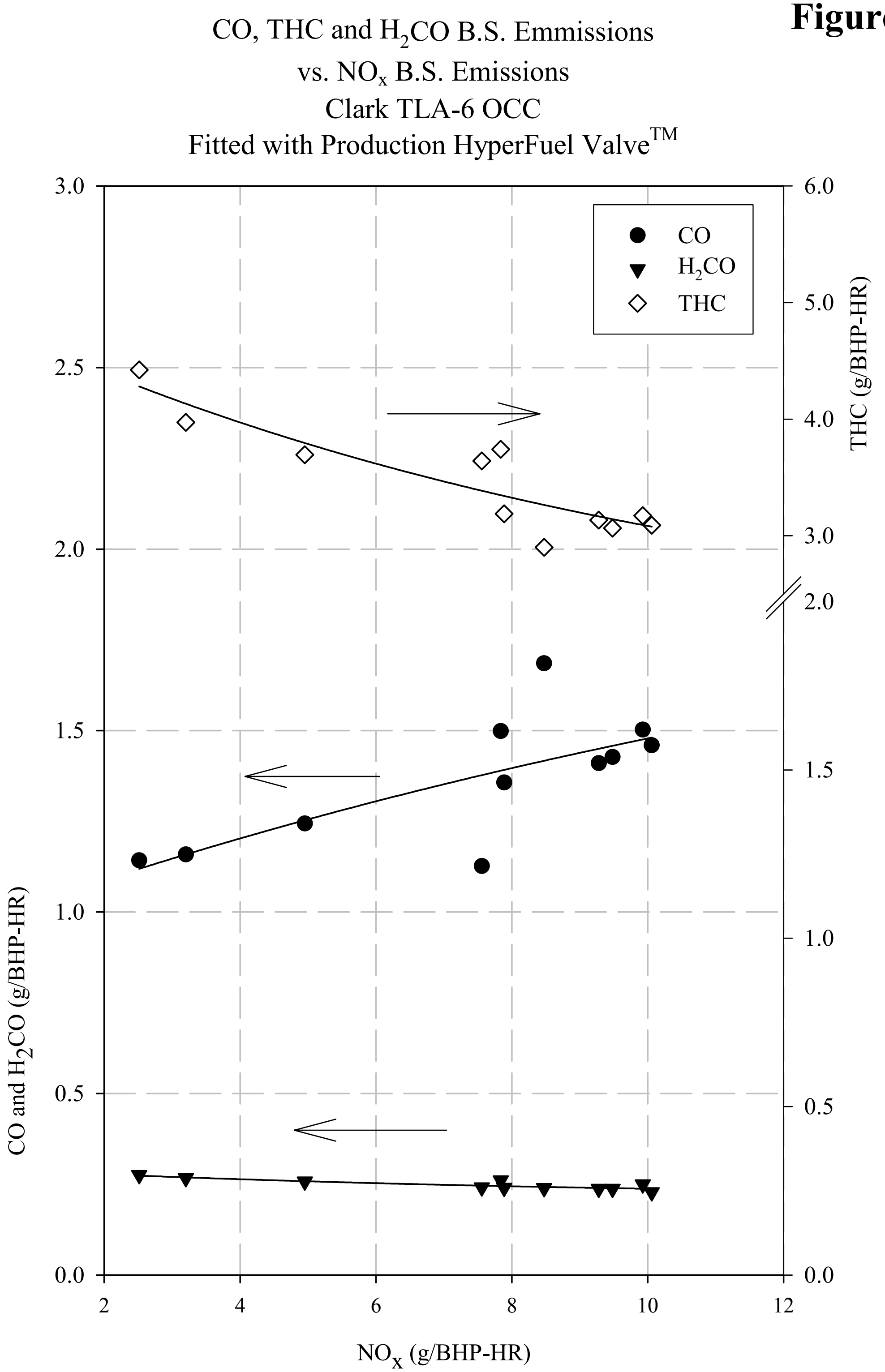

B.S.F.C. and Cyclic Stability
vs. NO_x B.S. Emissions
CSU Fort Collins
LBET HCA
Cyclic Combustion Instability
BSFC
B.S.F.C. (BTU/BHP-HR)
Combustion Instability (fraction of Peak Pressure)
NO_X (g/BHP-HR)
9300
9400
9500
9600
9700
9800
9900
10000
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.18
0
5
10
15
20

Figure 2a


CO, THC and H_2CO B.S. Emmissions
vs. NO_x B.S. Emissions
Clark TLA-6 OCC
Fitted with Production HyperFuel Valve™
CO
H_2CO
THC
CO and H_2CO (g/BHP-HR)
THC (g/BHP-HR)
NO_x (g/BHP-HR)

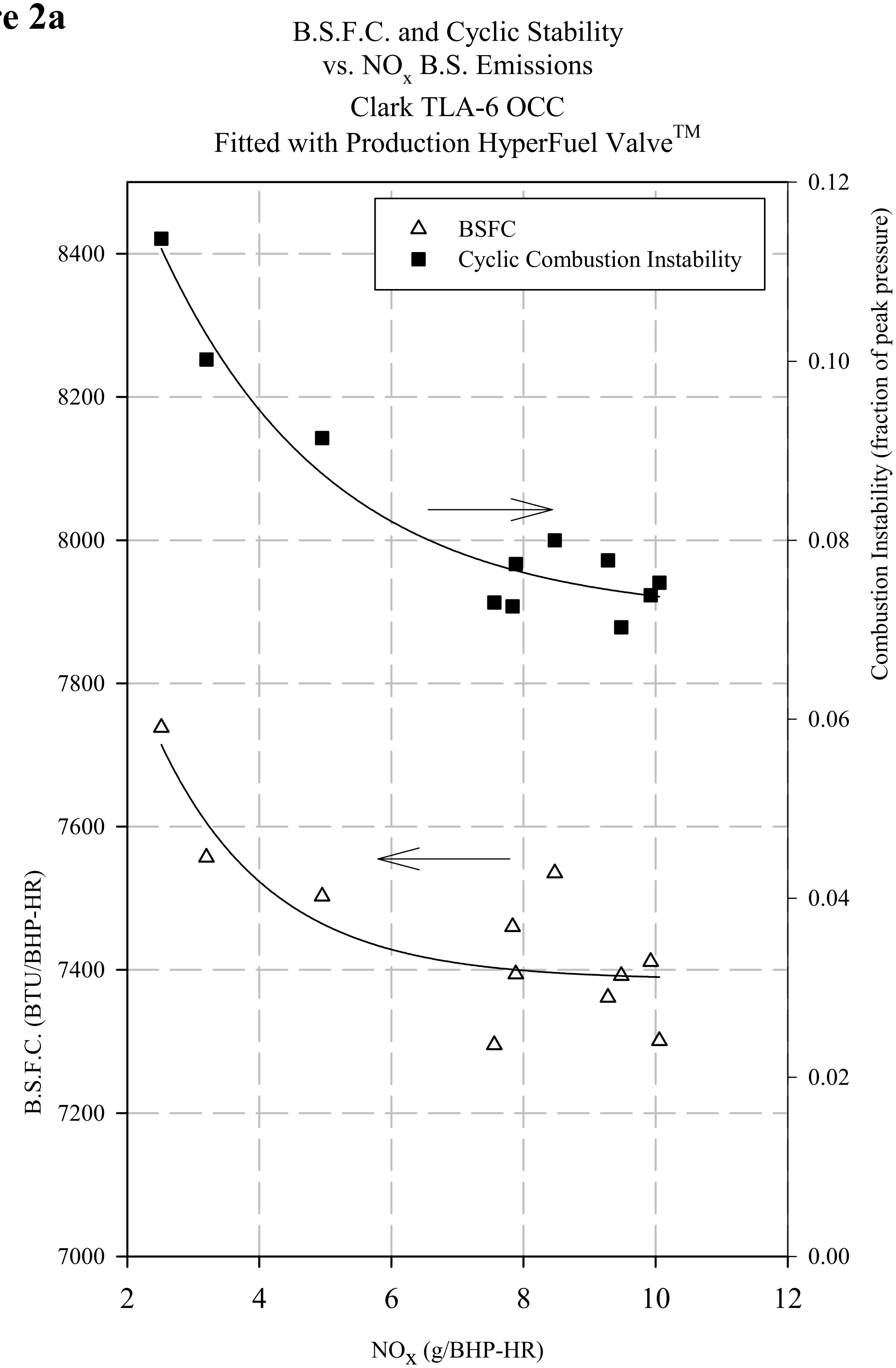
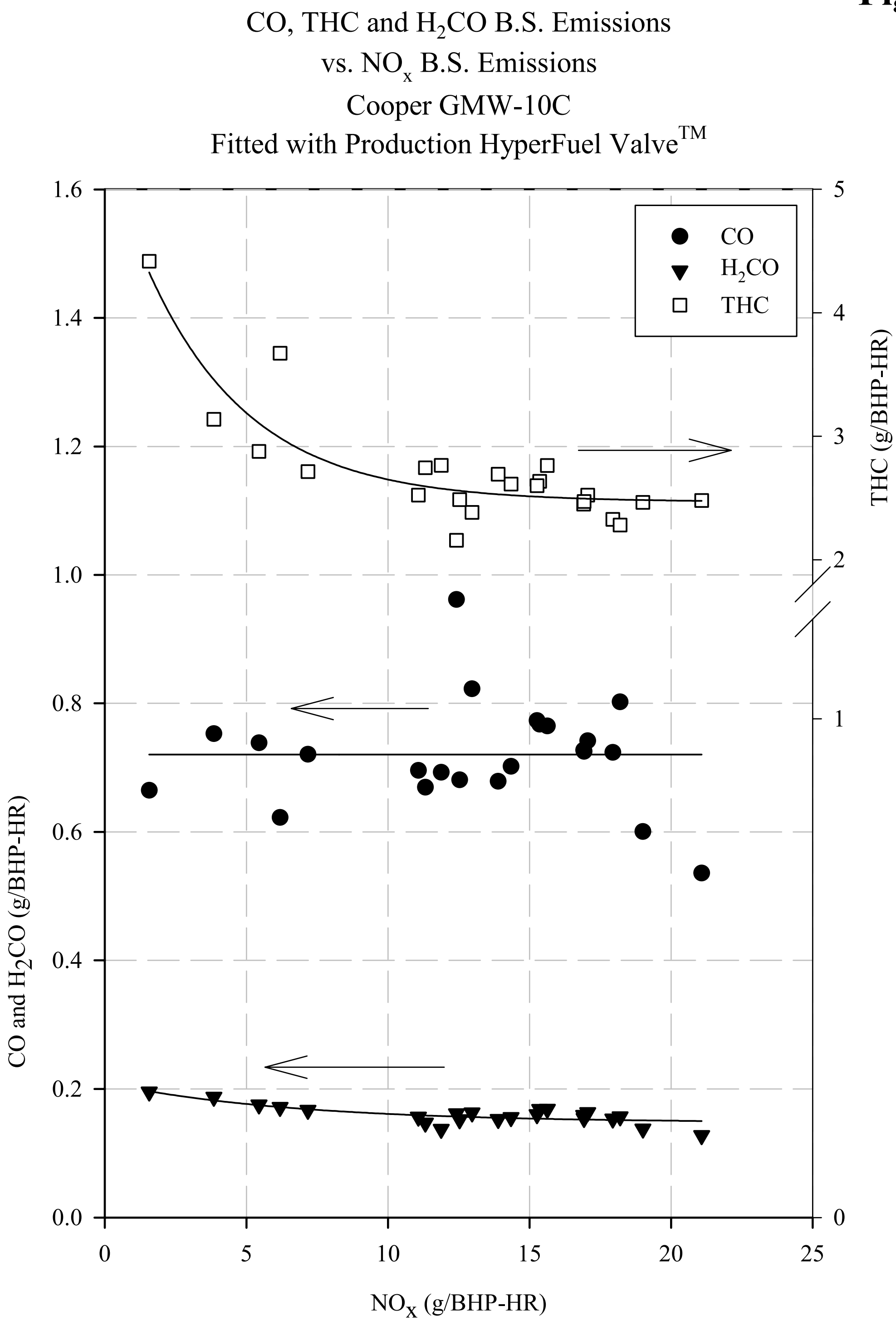

B.S.F.C. and Cyclic Stability
vs. NO_x B.S. Emissions
Clark TLA-6 OCC
Fitted with Production HyperFuel Valve™
BSFC
Cyclic Combustion Instability
B.S.F.C. (BTU/BHP-HR)
Combustion Instability (fraction of peak pressure)
NO_x (g/BHP-HR)

Figure 2b


CO, THC and H_2CO B.S. Emissions
vs. NO_x B.S. Emissions
Cooper GMW-10C
Fitted with Production HyperFuel Valve™
CO
H_2CO
THC
CO and H_2CO (g/BHP-HR)
THC (g/BHP-HR)
NO_x (g/BHP-HR)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
0
1
2
3
4
5
0
5
10
15
20
25

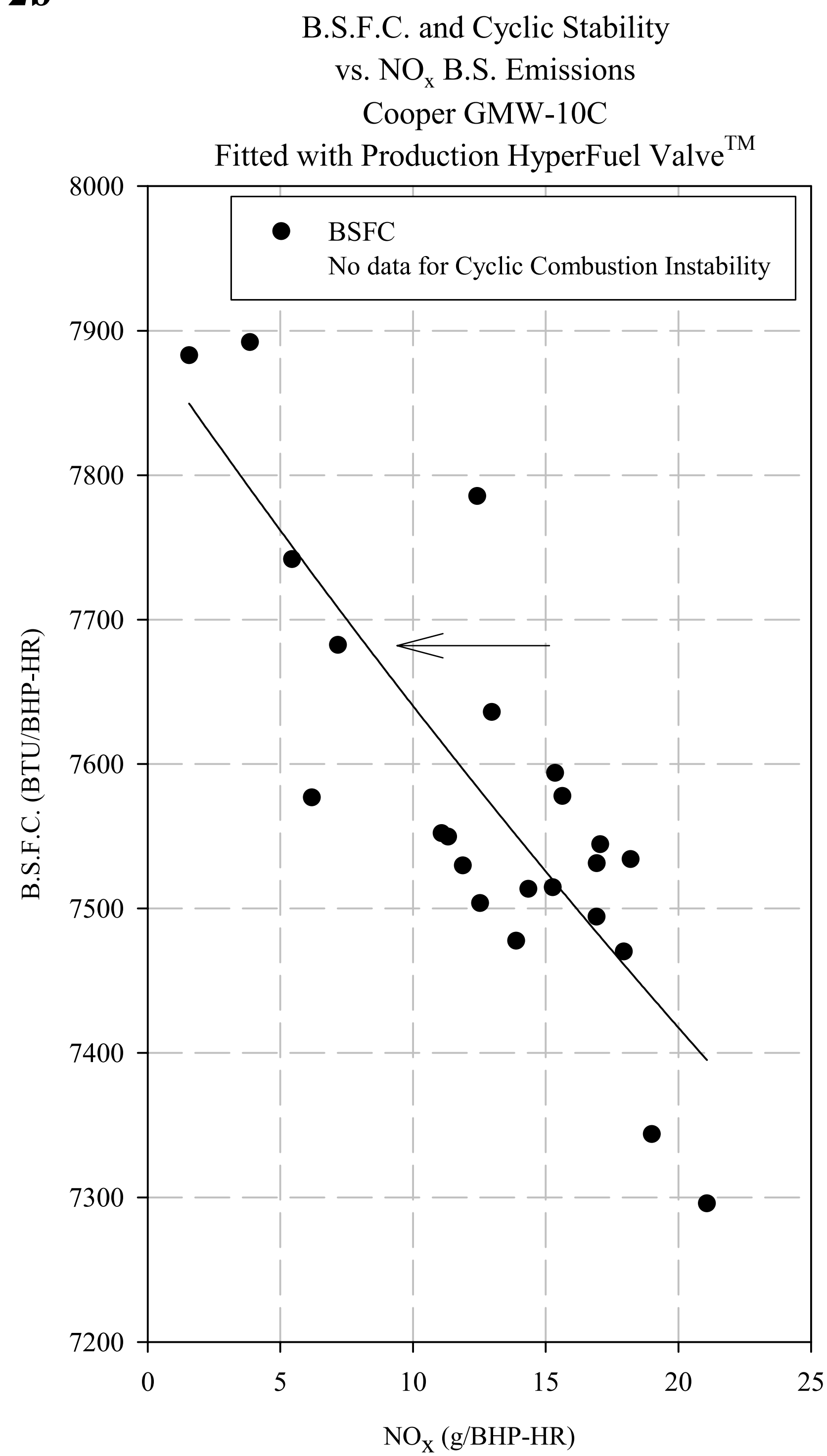
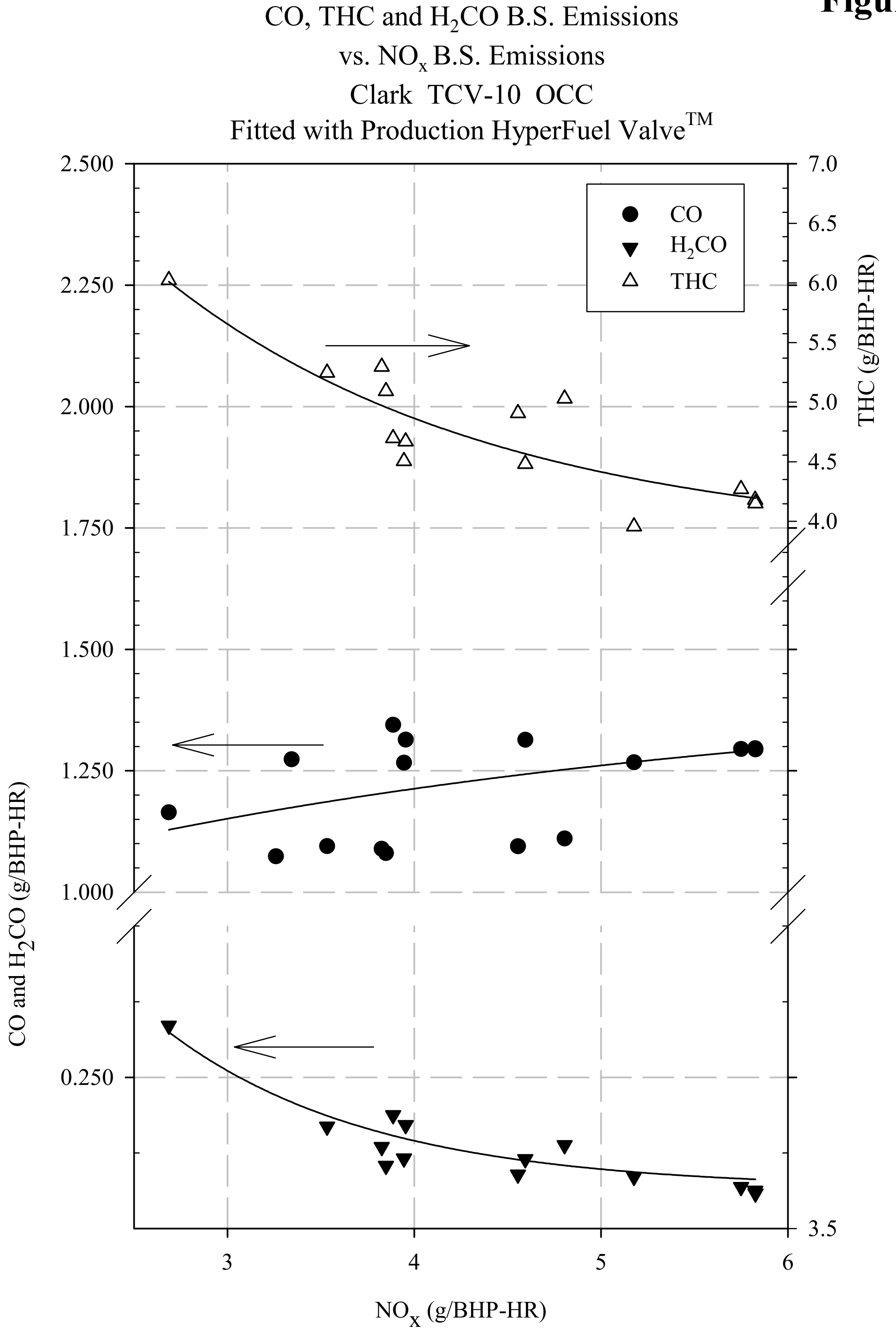

B.S.F.C. and Cyclic Stability
vs. NO_x B.S. Emissions
Cooper GMW-10C
Fitted with Production HyperFuel Valve™
BSFC
No data for Cyclic Combustion Instability
B.S.F.C. (BTU/BHP-HR)
NO_x (g/BHP-HR)
7200
7300
7400
7500
7600
7700
7800
7900
8000
0
5
10
15
20
25

Figure 2c


CO, THC and H_2CO B.S. Emissions
vs. NO_x B.S. Emissions
Clark TCV-10 OCC
Fitted with Production HyperFuel Valve™
CO
H_2CO
THC
CO and H_2CO (g/BHP-HR)
THC (g/BHP-HR)
NO_x (g/BHP-HR)
2.500
2.250
2.000
1.750
1.500
1.250
1.000
0.250
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3
4
5
6

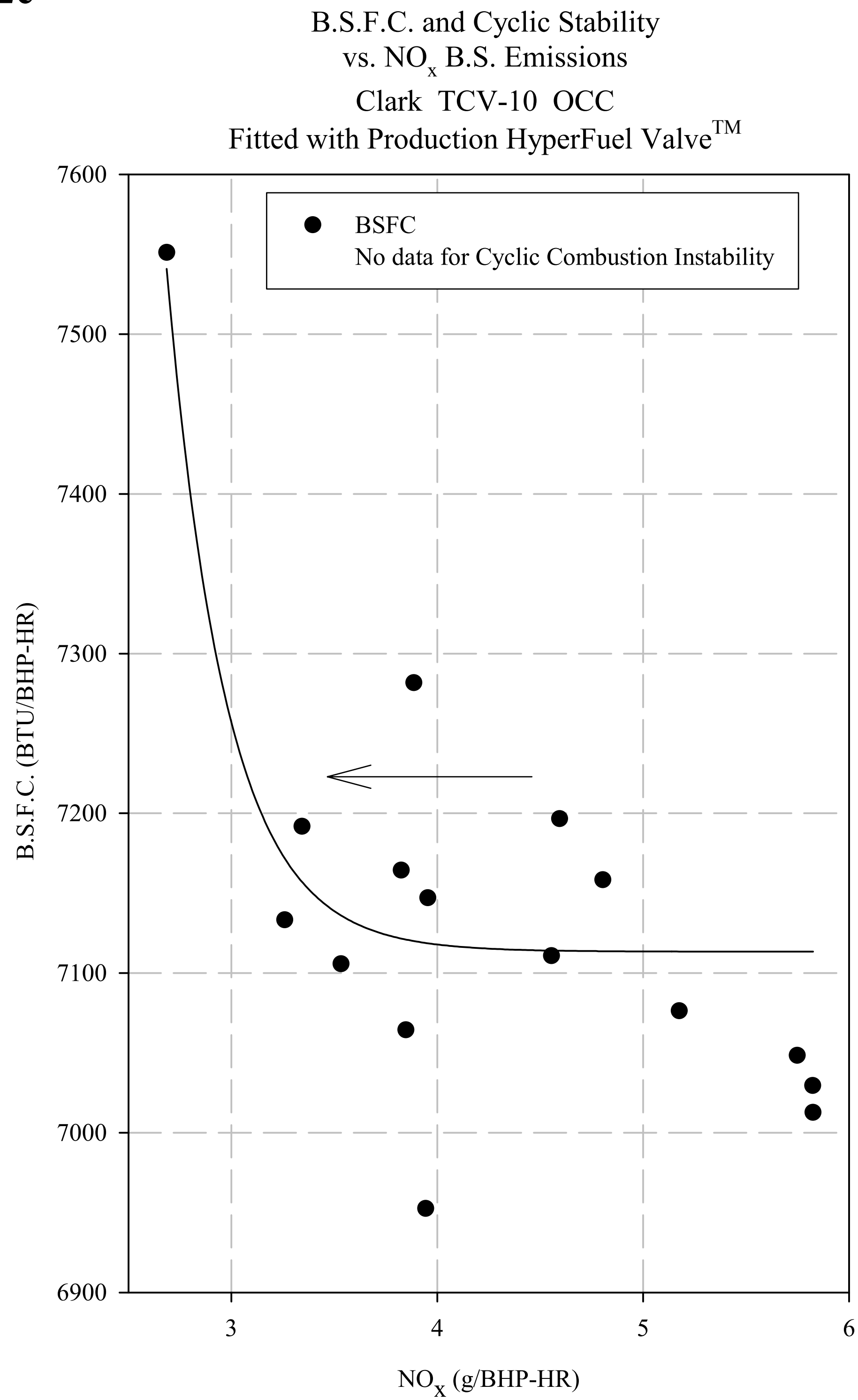

B.S.F.C. and Cyclic Stability
vs. NO_x B.S. Emissions
Clark TCV-10 OCC
Fitted with Production HyperFuel Valve™
BSFC
No data for Cyclic Combustion Instability
B.S.F.C. (BTU/BHP-HR)
NO_x (g/BHP-HR)
7600
7500
7400
7300
7200
7100
7000
6900
3
4
5
6

Figure 2d

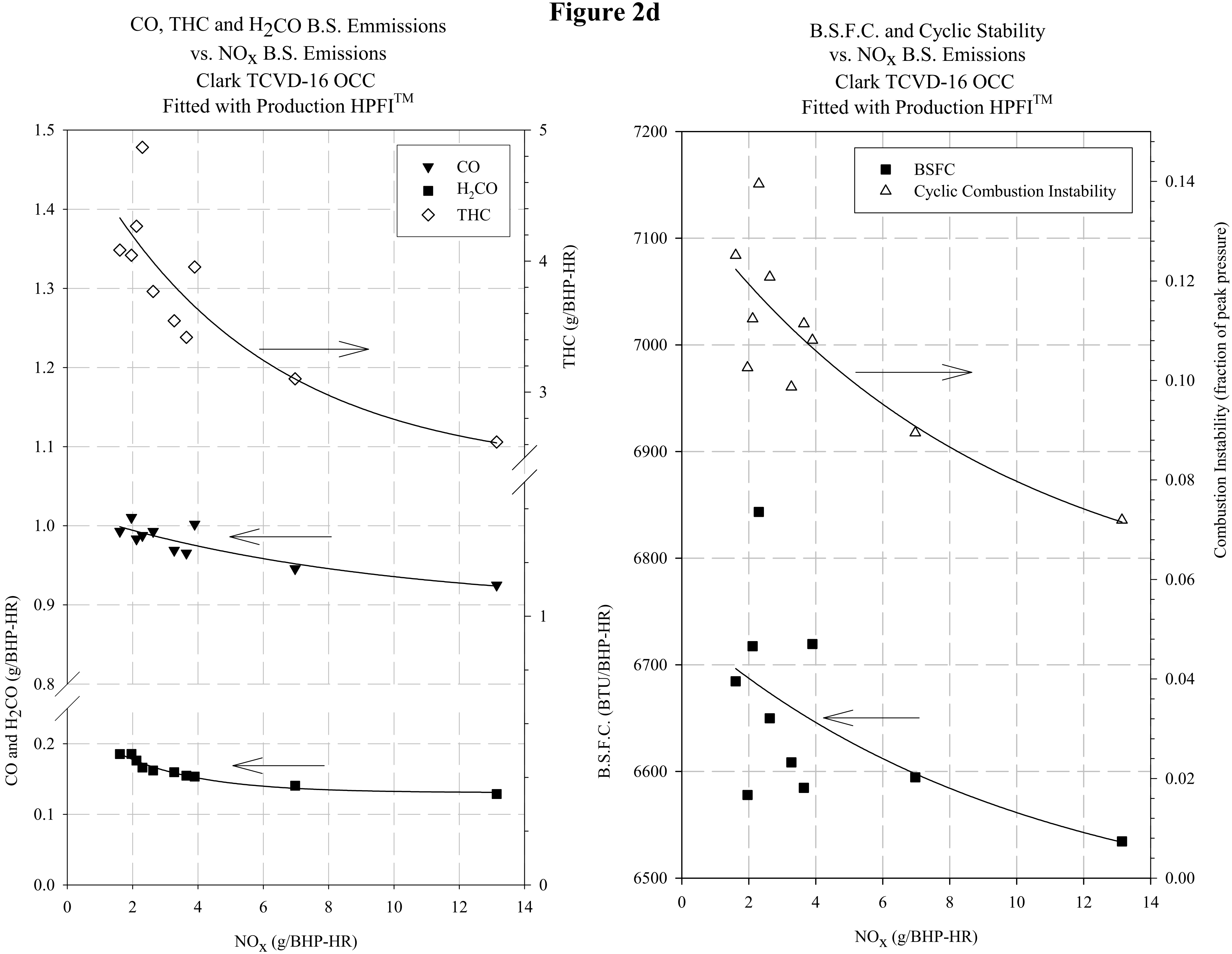

CO, THC and H_2CO B.S. Emmissions
vs. NO_x B.S. Emissions
Clark TCVD-16 OCC
Fitted with Production HPFI™
CO
H_2CO
THC
CO and H_2CO (g/BHP-HR)
THC (g/BHP-HR)
NO_x (g/BHP-HR)
B.S.F.C. and Cyclic Stability
vs. NO_x B.S. Emissions
Clark TCVD-16 OCC
Fitted with Production HPFI™
BSFC
Cyclic Combustion Instability
B.S.F.C. (BTU/BHP-HR)
Combustion Instability (fraction of peak pressure)
NO_x (g/BHP-HR)

Figure 3a

Brake Specific THC vs Brake Specific NO_x

All Engines

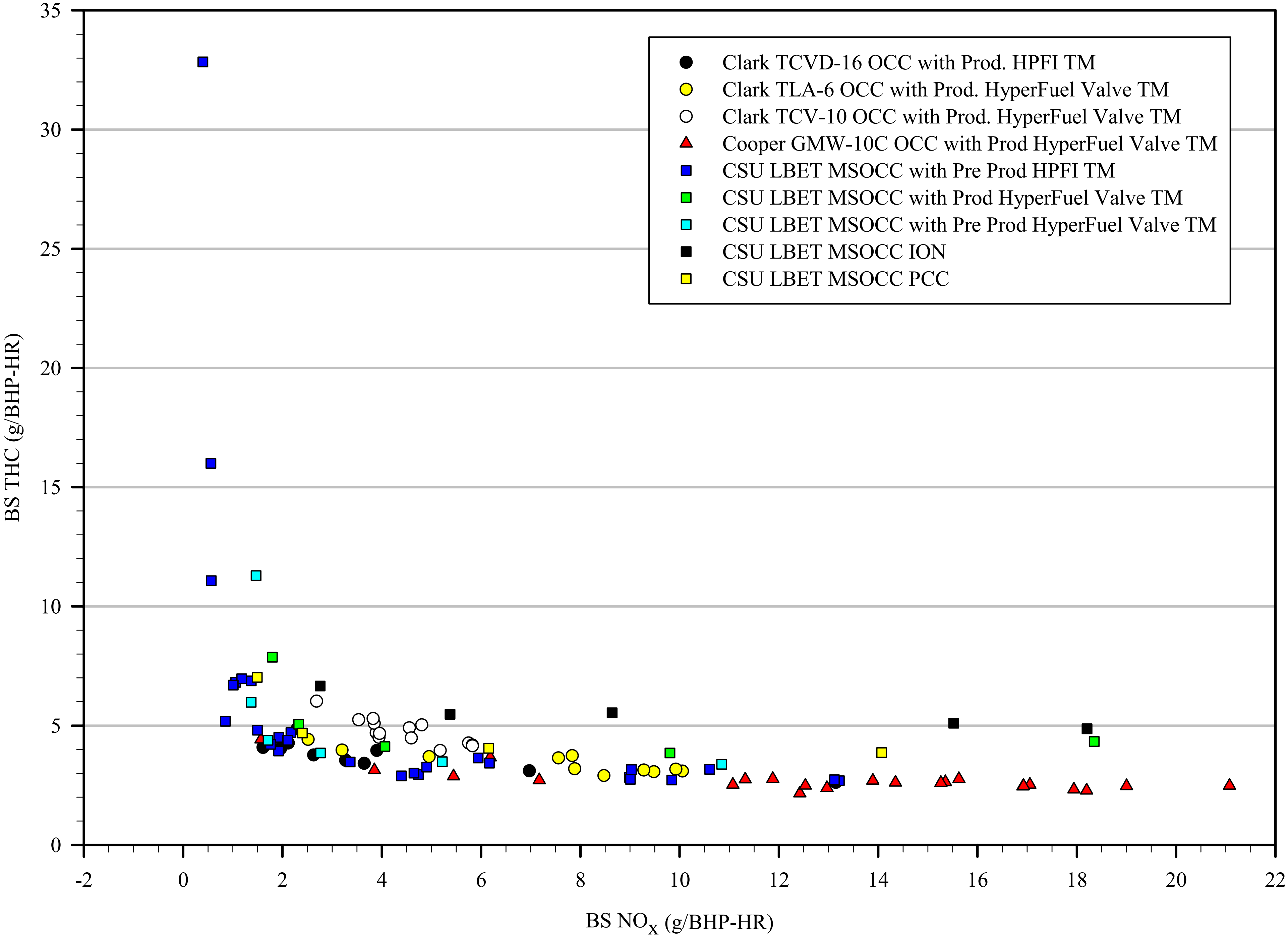


Figure 3b

Brake Specific CO vs Brake Specific NO_x

All Engines

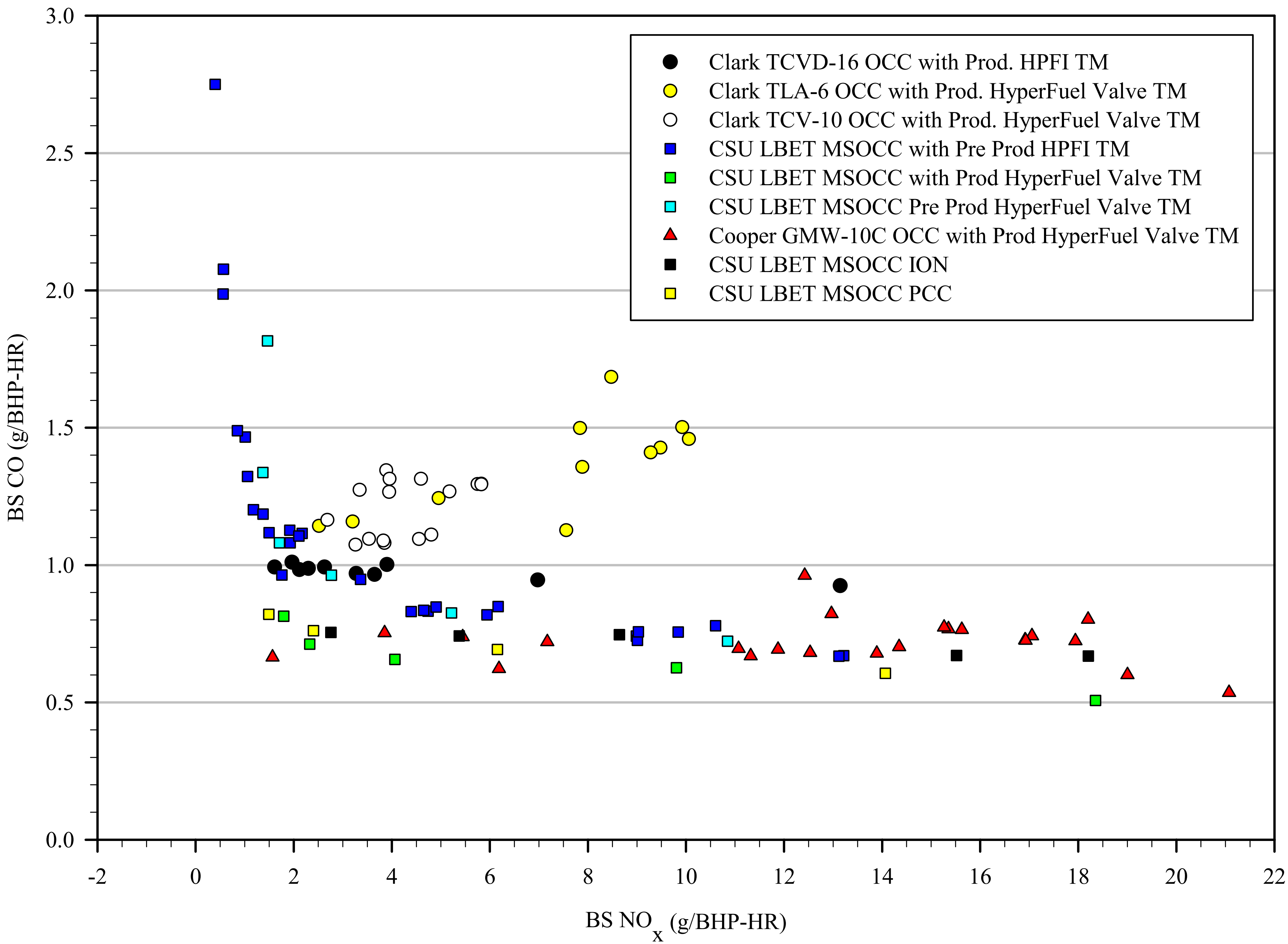


Figure 3c

Brake Specific H_2CO vs Brake Specific NO_x

All Engines

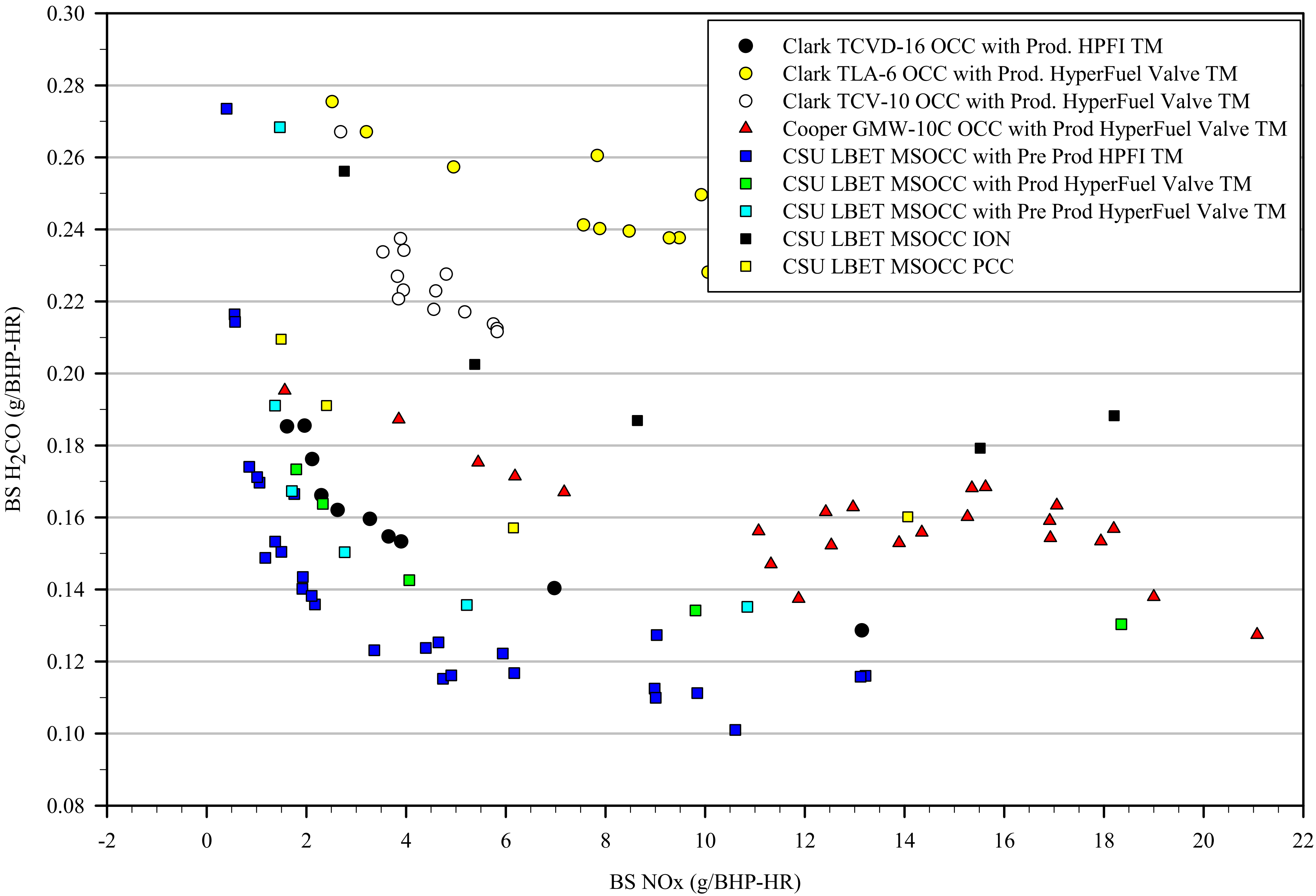


Figure 3d

Cyclic Stability vs Brake Specific NO_x

All Engines

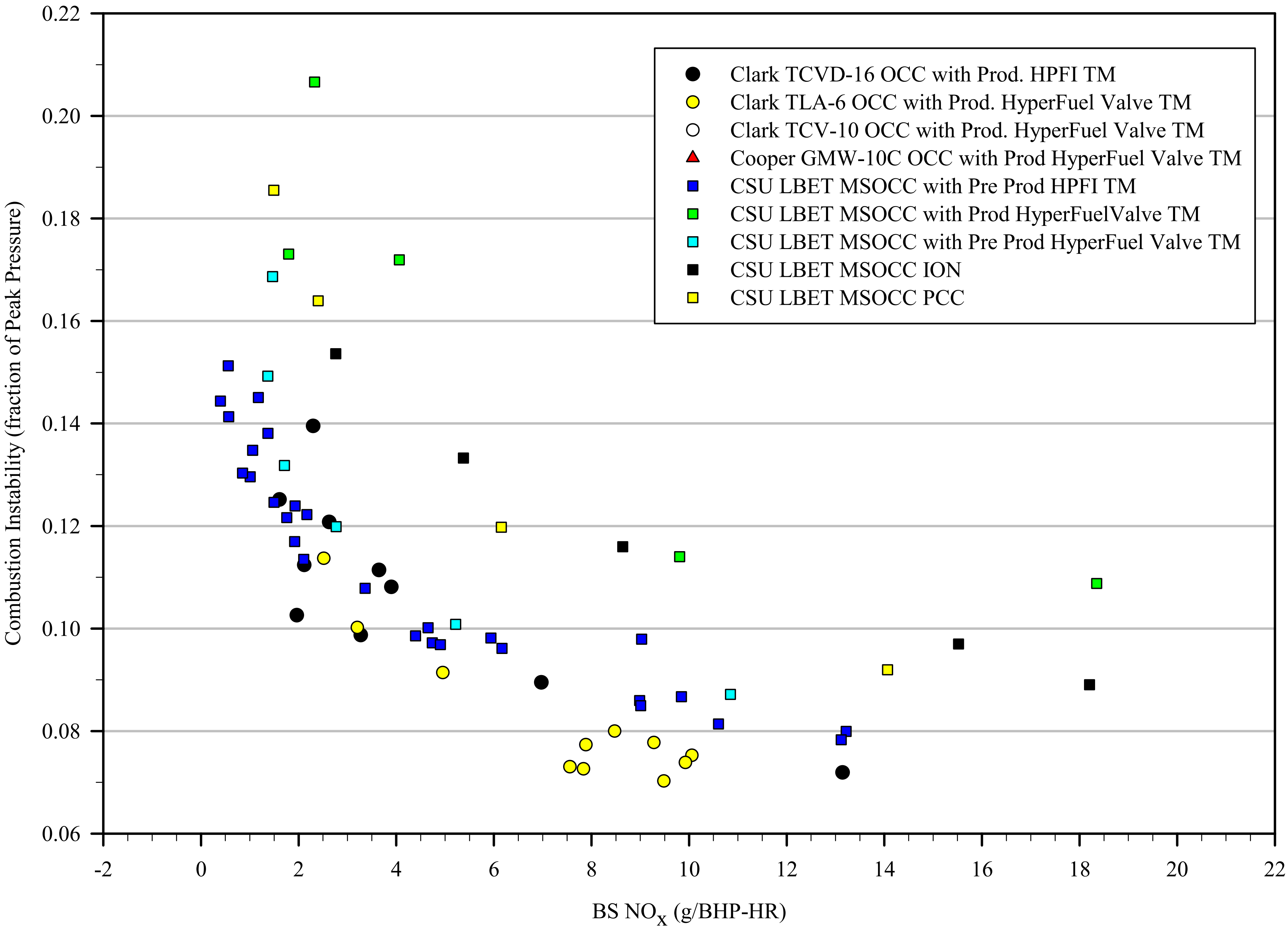


Figure 3e

B.S.F.C. vs Brake Specific NO_x

All Engines

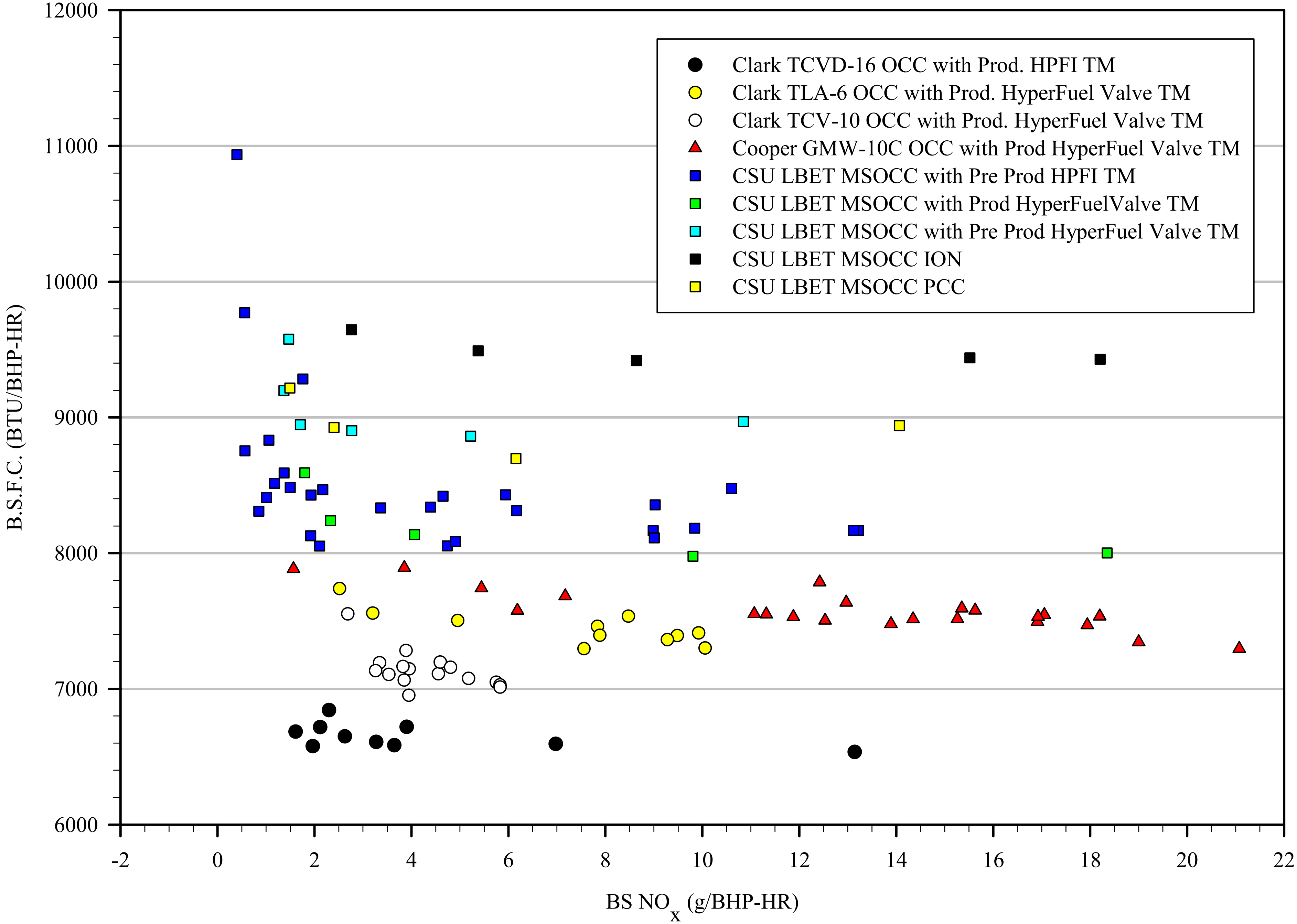


Figure 4.a
Brake Specific THC vs Brake Specific NO_X
Selected 2SC OCC Engines

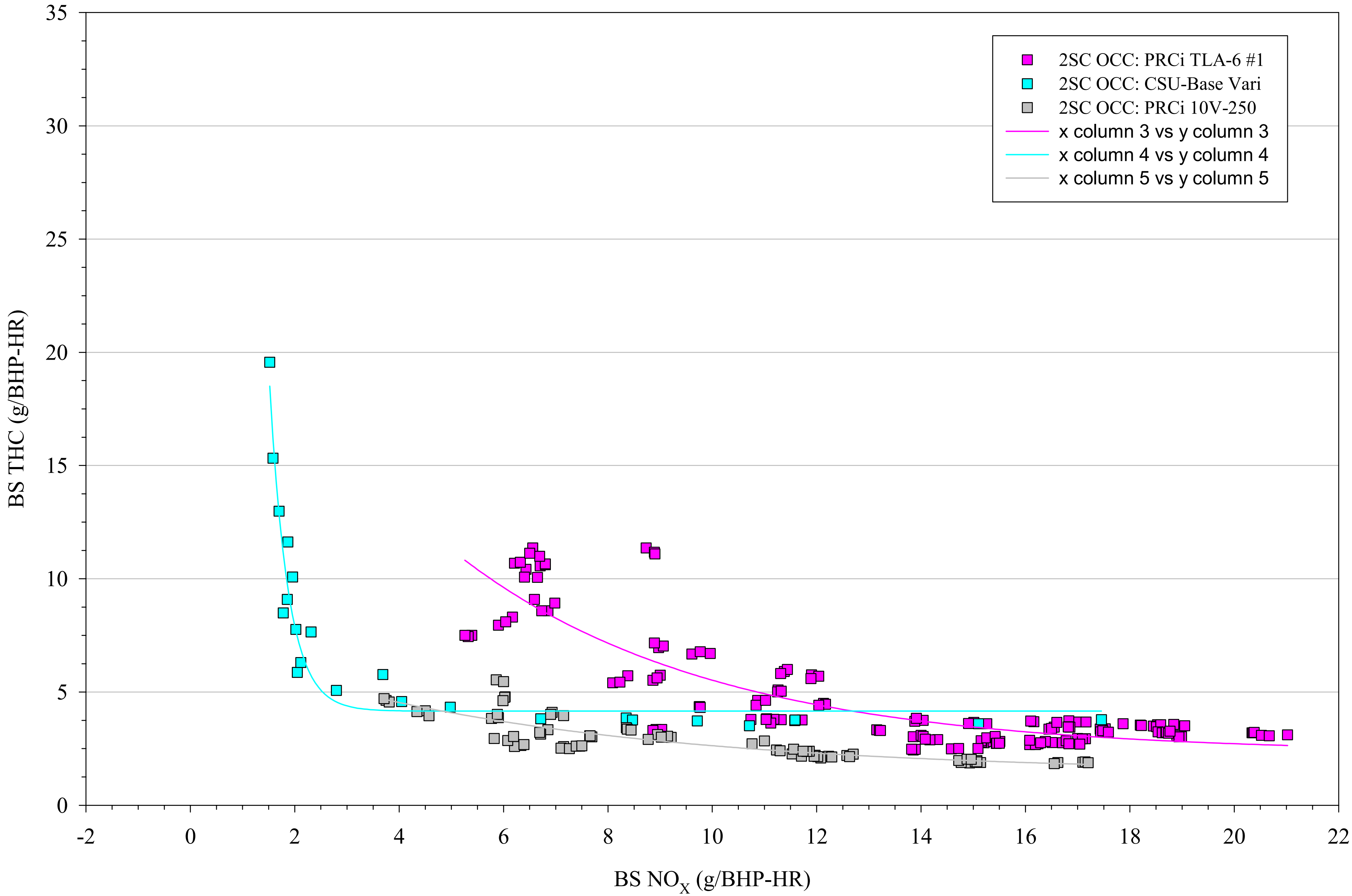


Figure 4b

Brake Specific CO vs Brake Specific NO_X

Selected 2SC & 4SC OCC & PCC Engines

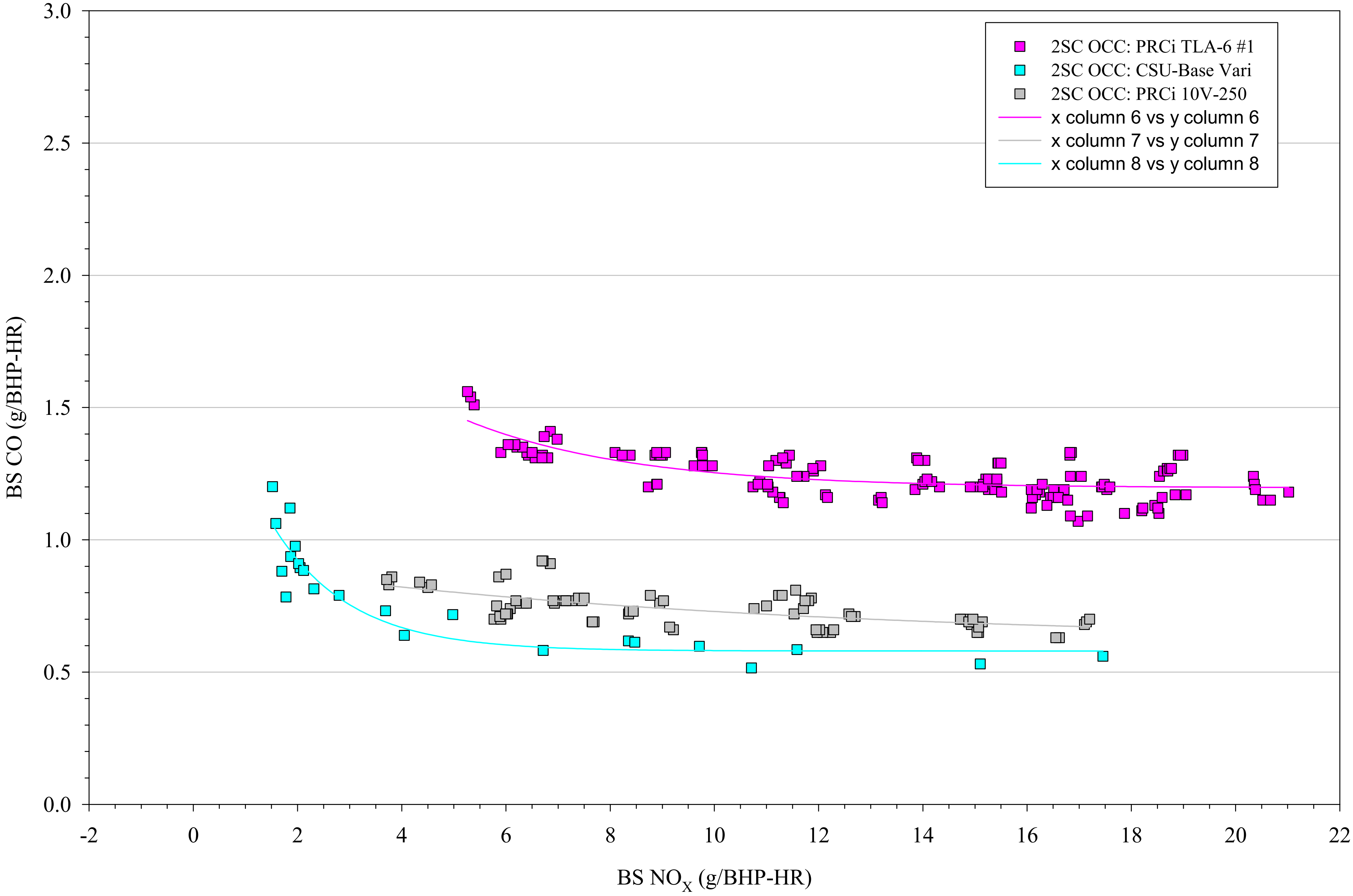


Figure 4c

Brake Specific H_2CO vs Brake Specific NO_X

Selected 2SC OCC Engines

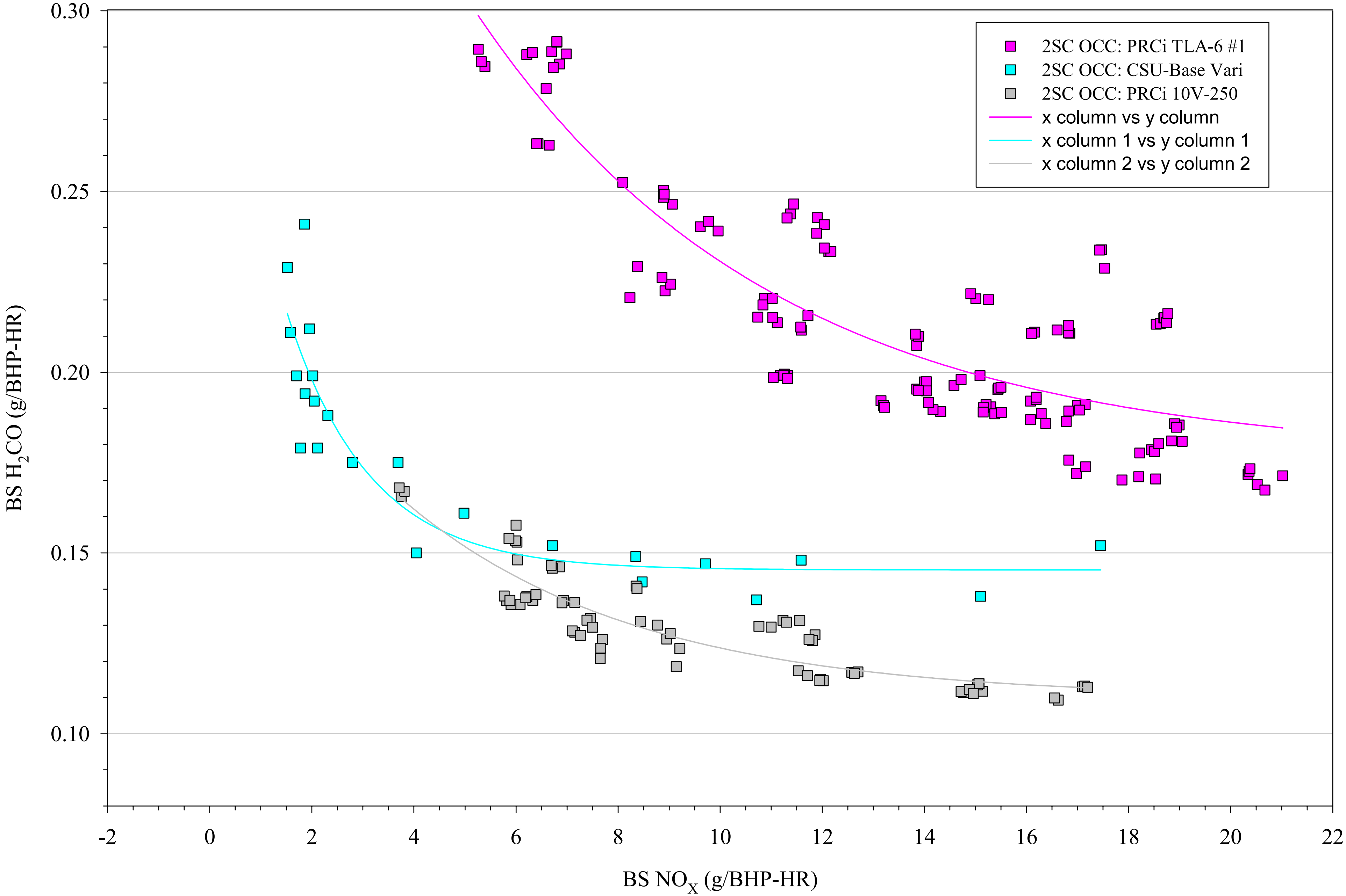


Figure 4d

Cyclic Stability vs Brake Specific NO_X

Selected 2SC OCC Engines

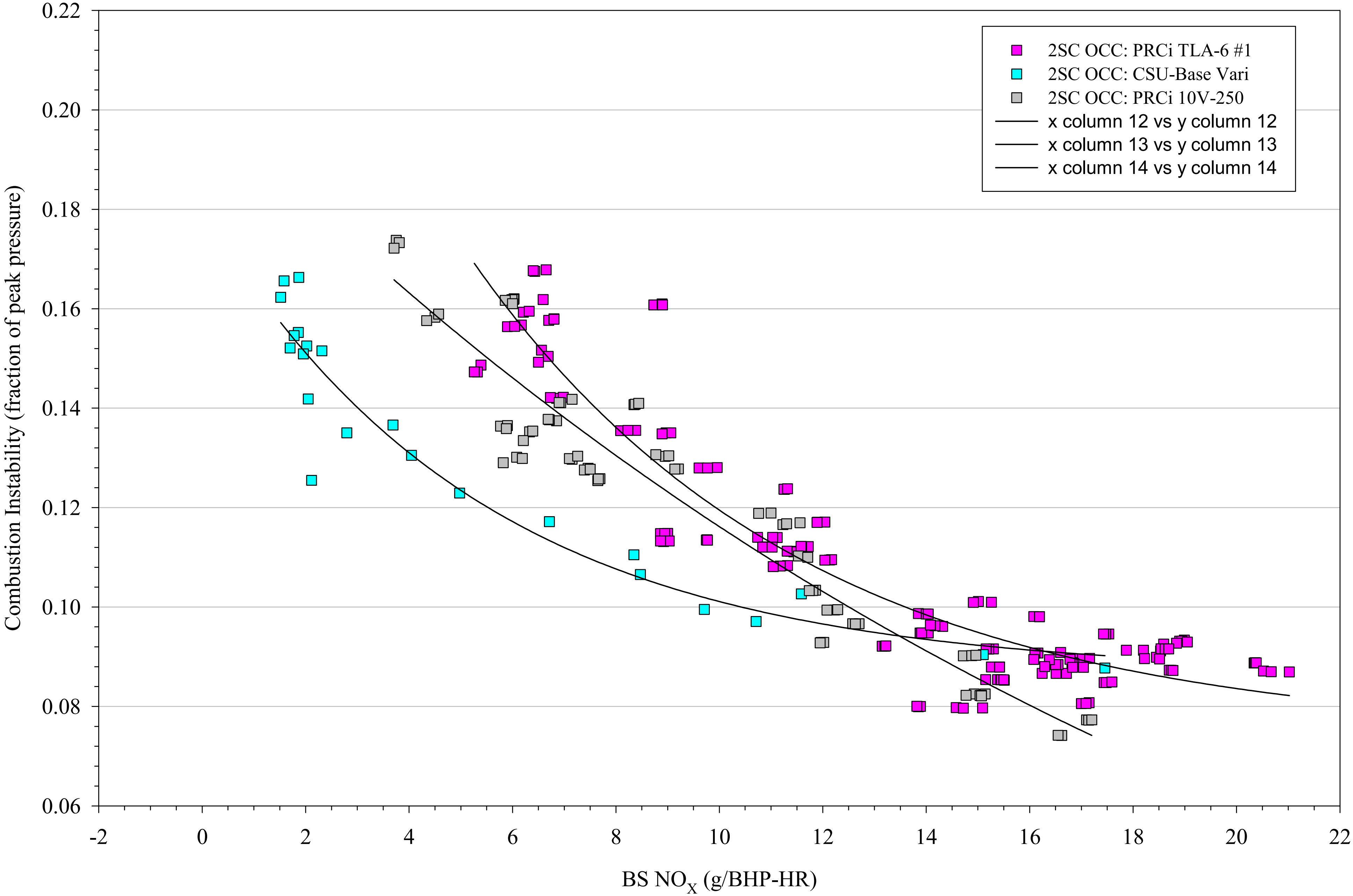


Figure 4e

B.S.F.C. vs Brake Specific NO_X

Selected 2SC OCC Engines