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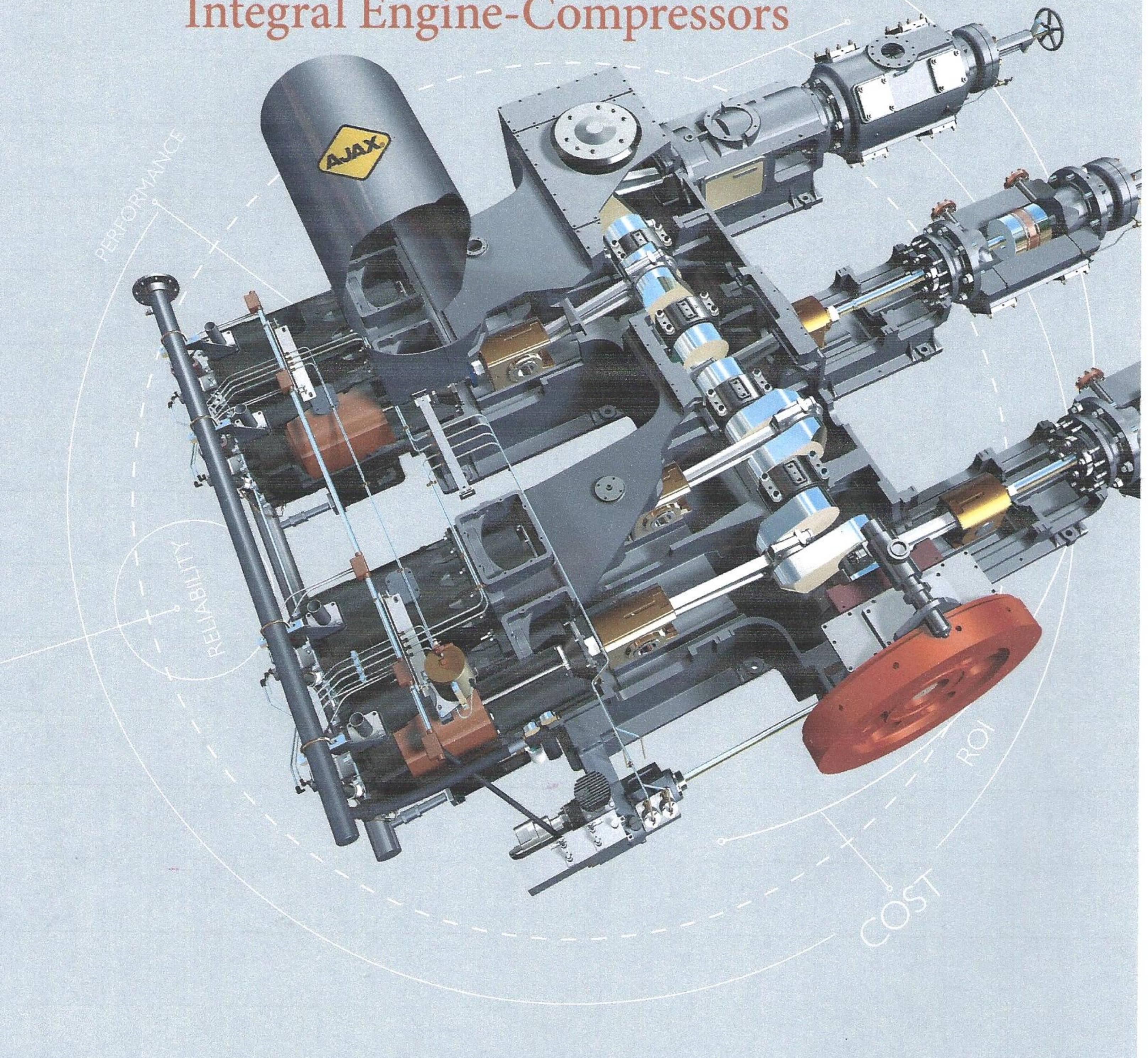
A GUIDE TO
Integral Engine-Compressors



A GUIDE TO AJAX INTEGRAL ENGINE-COMPRESSORS

FIELD DATA AND COMPARATIVE ANALYSES BETWEEN AJAX INTEGRAL ENGINE-COMPRESSORS AND HIGH-SPEED SEPARABLE PACKAGES

BY BRUCE CHRISMAN

ABOUT THE AUTHOR

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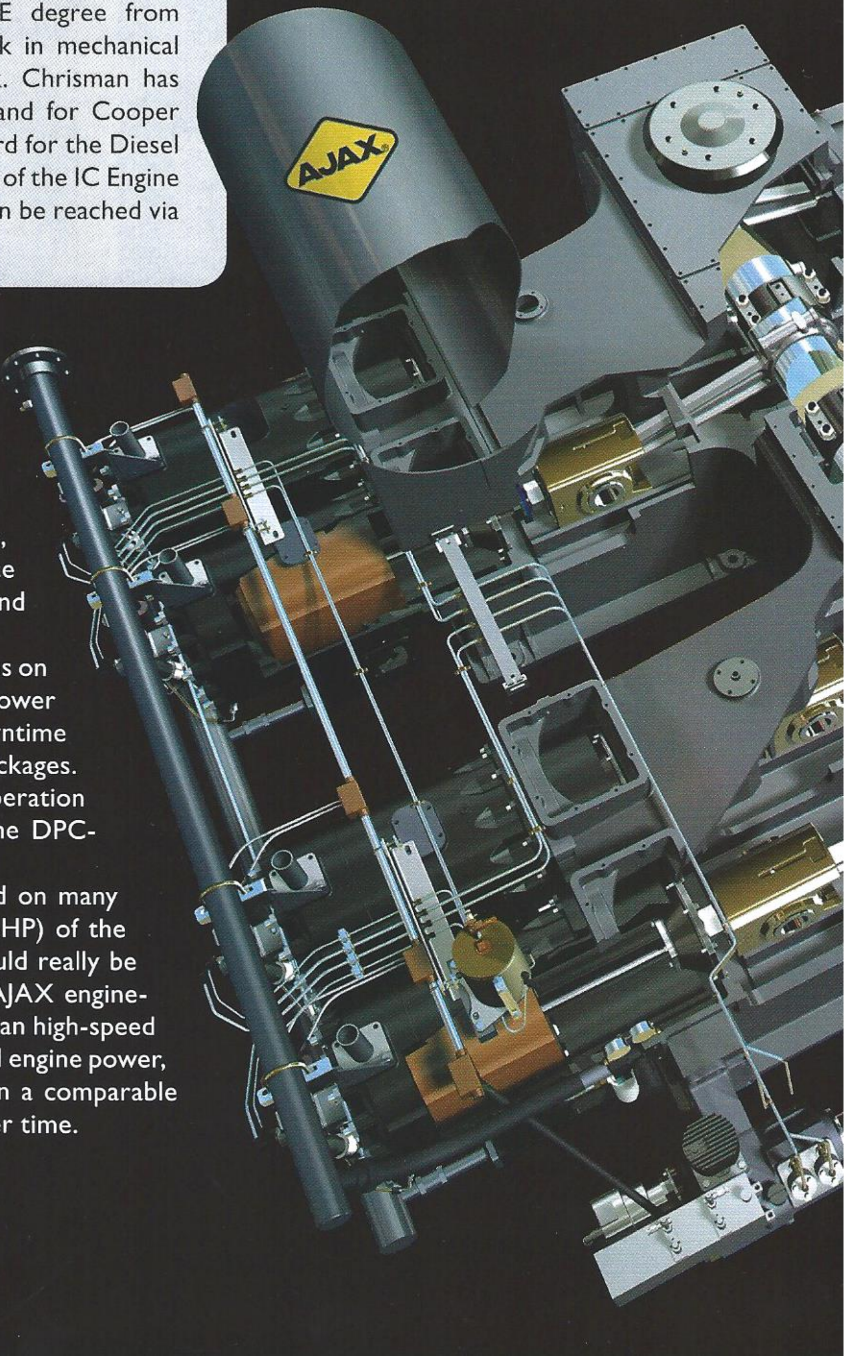

Selection of optimum equipment for gas compression applications requires a thorough comparison of both engines and compressors. Important factors to consider include first cost, operating and maintenance costs, expected service life of the equipment, compression efficiency, and regulatory compliance issues.

Engineers designed the AJAX integrals with a focus on strength and simplicity. These qualities resulted in lower operating and maintenance costs and lower downtime than is characteristic of high-speed separable packages. AJAX integrals are especially well suited for operation in remote sites with harsh conditions, such as the DPC-2803LE installations shown in Figures 1 and 2.

Selection of a gas compression package is based on many factors, one of which is the brake horsepower (BHP) of the engine. However, the main factor to consider should really be the gas compression throughput of the package. AJAX engine-compressor packages offer lower BHP/MMSCFD than high-speed separable packages, meaning that for the same rated engine power, more gas is compressed by an AJAX package than a comparable high-speed package, resulting in higher revenue over time.

AJAX DESIGN

AJAX packages feature an integral engine and compressor with an overall mechanical efficiency of 95%. However, separable packages consist of an engine and a compressor with two frames, two crankshafts, and their associated bearings. Considering a 95% mechanical efficiency for the engine and for the compressor, the horsepower available for compression for a separable package is 0.95 x 0.95 x engine BHP = 0.902 x engine BHP.

The single frame and crankshaft design for AJAX integral engine-compressors results in substantially fewer wearing parts than a high-speed separable package. The AJAX two-stroke engine design is illustrated in Figure 3. Unlike high-speed engines, the AJAX engine does not have intake and exhaust valves and therefore does not need a valve train, which eliminates maintenance issues with the valves and valve train. Instead, the intake air and exhaust are controlled with ports in the cylinder.

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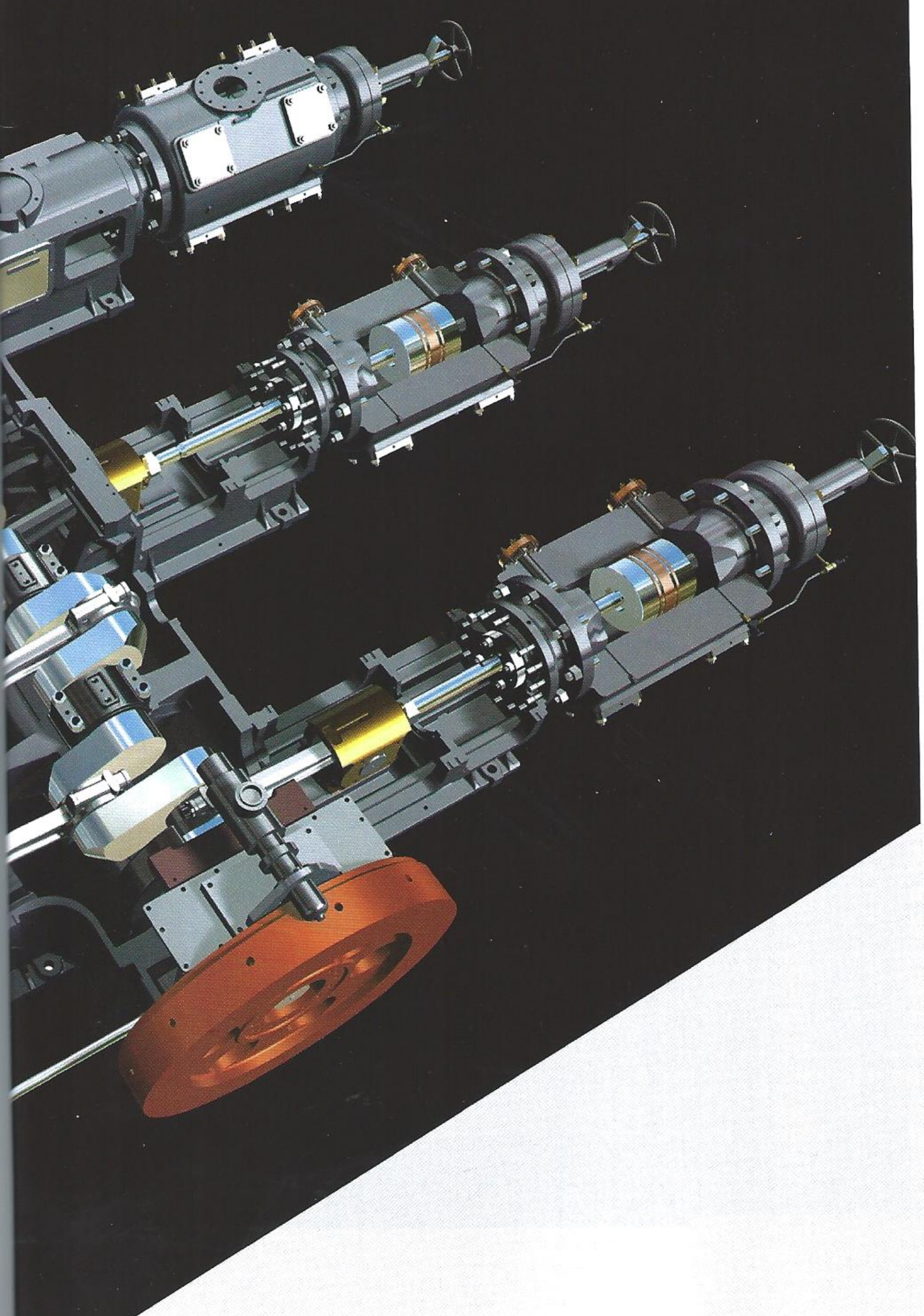


Figure 1: AJAX DPC-2803LE Package In Southwestern USA

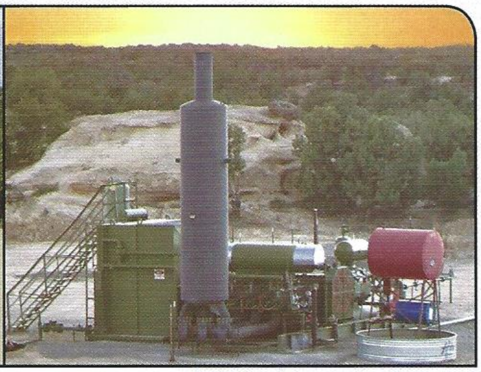


Figure 2: AJAX DPC-2803LE Package In Southwestern USA

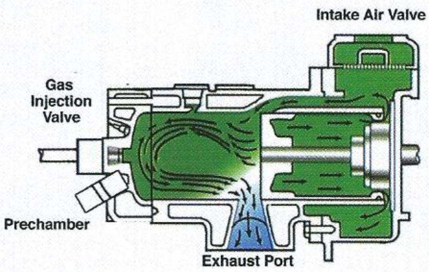


Figure 3: Power Cylinder Of AJAX Engine

The two-stroke piston-scavenged design eliminates the need for several parts, including turbocharger and aftercooler, intake and exhaust valves, rocker arms and pushrods, valve seats, camshaft and cam bearings for the intake and exhaust valves, and timing chain/gears.

The engine cycle begins with the intake air flowing through a check valve into the scavenging box of the AJAX engine. As the piston moves toward the head end of the cylinder, the intake air is pulled into the volume at the crank end of the piston. After the piston compresses the air and fuel mixture in the power cylinder, combustion occurs, which pushes the piston back toward the crank end of the cylinder. As the piston moves toward the crank end of the cylinder, it compresses the fresh air in the scavenging box. By the time that the piston timing edge uncovers the intake ports, the fresh air charge has been pressurized to about 10 psig (0.68 bar). This pressurized air then flows through the ten intake ports into the power cylinder. This process provides a boost pressure to the power cylinder without the need for the turbocharger and aftercooler, which are used with the high-speed engines.

The method for controlling the air/fuel ratio throughout the operating range of an AJAX engine is described in Figure 4. The air flow is controlled by the swept volume of the piston in that the volume of air that is compressed on the back side of the piston is directly proportional to the engine speed. This results in a linear relationship between the air entering the power cylinder and the engine rpm, as shown in the top curve of Figure 4. The lower curve details the results produced by the AJAX electronic governor, showing that the fuel flow controlled by the governor is a linear relationship with the engine BHP. Combining the air flow and fuel flow curves results in control of the air/fuel ratio throughout the operating range of the engine. This system for controlling the air/fuel ratio is simpler and needs much less maintenance than the control systems used with high-speed engines.

AJAX engines tolerate a wide range of fuel gases without requiring modifications to the engine. They perform well with fuels, ranging from large inert gas content to large amounts of heavier hydrocarbons. They can operate continuously at the full-rated BHP with fuels having a normal butane number up to 10, which corresponds with a mixture of 90% propane and 10% methane. With fuels richer than pure propane, a BHP derate curve is used to define the site-rated BHP.

Because of the unique design of the AJAX engine, the power cylinder and scavenging box are isolated from the crankcase. Therefore, combustion blowby cannot enter the crankcase and cause an acidic attack to the bearings and other components. Further, the AJAX engine has no intake or exhaust valves to be damaged by acidic attack. Because of its design, the AJAX engine can operate continuously with fuels having a hydrogen sulfide (H_2S) content of at least 3% by volume. An H_2S content greater than 3% needs to be approved by the engineering department of Baker Hughes, a GE company (BHGE).

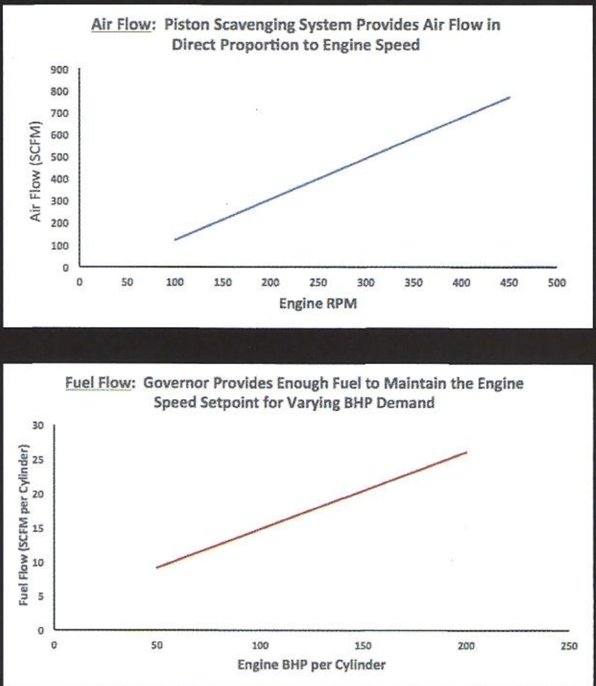
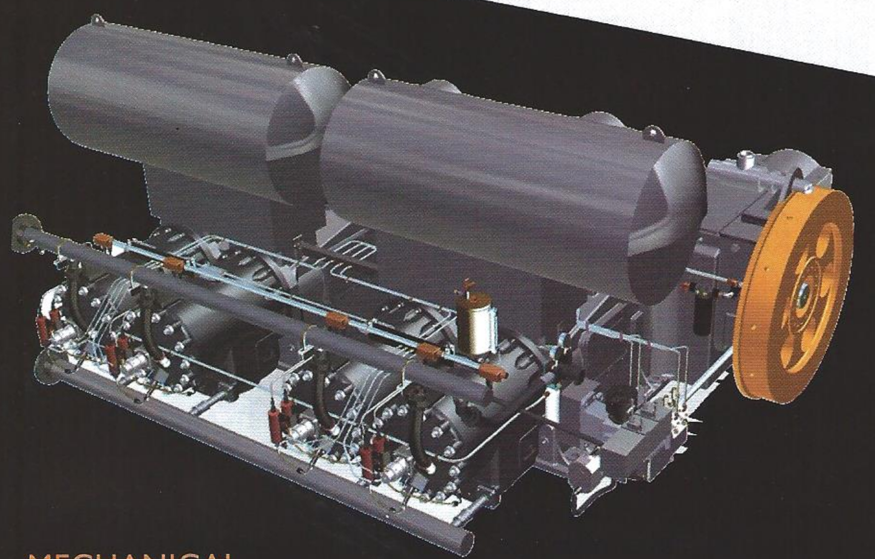


Figure 4: Air/Fuel Control Curves For AJAX Engines



MECHANICAL EFFICIENCIES

The mechanical efficiency for an AJAX integral engine-compressor is 95%, while the mechanical efficiency for a separable package is 90.2%, due to the two frames and two crankshafts used with high-speed separable packages. In addition, AJAX compressors feature generous valve flow areas, which equates to low pressure drops across the suction and discharge valves. Combining the higher mechanical efficiency with minimal pressure losses through the compressor valves means that AJAX packages exhibit better compression efficiencies than high-speed separable packages.

Another consideration in selecting a package is the fuel consumption. Fuel consumption is usually expressed in BTU/BHP-hr for the engine. However, it is more meaningful to consider the fuel used by the engine compared to the gas compression capacity for the package.

The typical online availability for an AJAX integral engine-compressor is 98% or higher, as compared to a typical 96% availability for a high-speed separable package. The availability advantage for the AJAX integral package is based on low brake mean effective pressure (BMEP) operation with substantially fewer moving parts at lower operating speeds than the high-speed separable packages.

The splash lubrication system for an AJAX engine-compressor means that there is no oil pump and no oil filter to maintain. The power cylinder of an AJAX engine is isolated from the crankcase so that combustion blowby products cannot enter the crankcase, meaning that oil changes are needed only once per year, as opposed to several each year for high-speed separable packages. The oil change interval for the AJAX integral can be extended beyond one year with an oil analysis program.

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COMPARISON OF COSTS

Selection of a gas compression package should be based on more than the initial capital cost of the package. It is critical to also consider factors such as gas compression efficiency, online availability, and operating and maintenance expenses over the long term.

As an example of the overall expenses for a compression package, Figure 5 compares an AJAX integral with a high-speed separable package. The packages compared are rated at 400 BHP, and the expenses associated with these packages are based on operating continuously through the year at a production rate of 1.0 MMSCFD with a gas price of US$3.00 per mcf.

In the range of 400 to 600 BHP, the first costs for an AJAX integral engine-compressor and a high-speed separable package are essentially the same. Outside this BHP range, the first costs for the high-speed separable packages are generally somewhat lower than those for the AJAX integrals. However, when the total costs for purchasing and operating these packages are considered, the AJAX integrals have a substantial advantage.

As shown in Figure 5, the total costs that need to be considered include the first cost, the operational and maintenance (O&M) costs, and the online availability for the units. The O&M costs consist of fuel usage plus maintenance, including parts and service hours. The lost production costs are based on the typical online availabilities, which amount to 7.3 days of downtime per year for the AJAX integral and 14.6 days of downtime per year for the high-speed unit.

The resulting total costs for five years show a US$210,000 savings for the AJAX integral. This chart is based on a five-year service period for the packages, but the typical service life for an AJAX engine-compressor package is in the range of about 40 years, so the large advantage shown for the AJAX integral becomes even more critical over the expected life of the package.

The curves in Figure 6 compare the same 400-BHP packages that are summarized in Figure 5. These curves are also based on packages operating through the year with a production rate of 1.0 MMSCFD with a gas price of US$3.00 per mcf. These curves originate with the first costs of the packages and plot the O&M costs over a period of five years. After five years, the AJAX integral has a cost advantage of US$110,000. This advantage does not include the higher online availability for the AJAX integral.

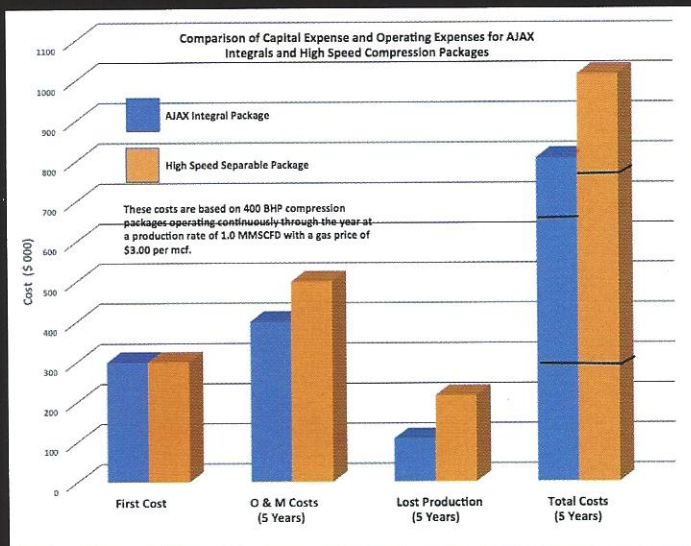

Figure 5: Comparison Of First Cost And O&M Expenses

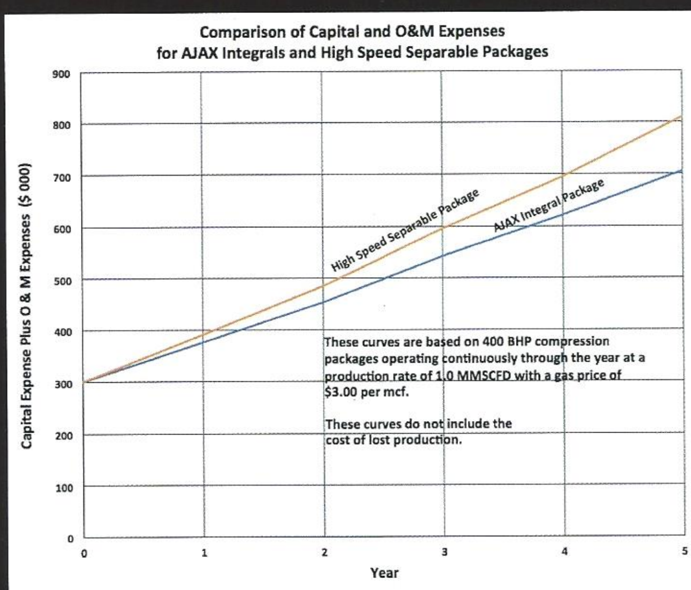

Figure 6: Comparison Of Capital And O&M Expenses

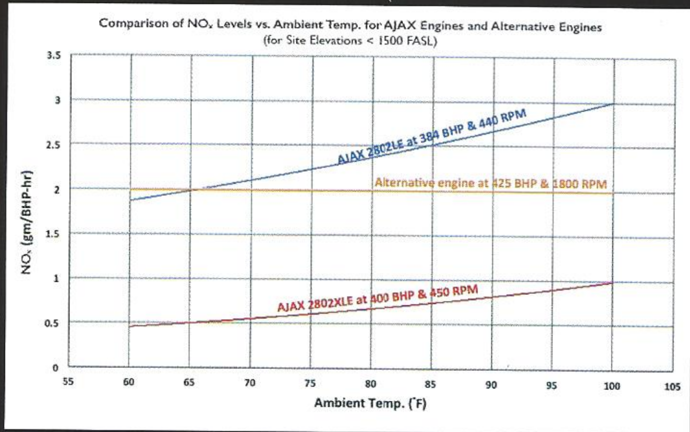

Figure 7: NO_x Vs. T_{AMB} For AJAX Engines And An Alternative Engine

BHP RATINGS AND EXHAUST EMISSIONS COMPARISON

AJAX engines operate with lean air/fuel ratios, resulting in low carbon monoxide (CO) and volatile organic compound (VOC) emissions. The emission that is most difficult to reduce is NO_x. Typically, the engine improvements aimed at increased BHP ratings and lower fuel consumption will increase the NO_x levels. Therefore, Baker Hughes has focused much attention on reducing NO_x while maintaining competitive BHP ratings and fuel economy.

During the last 30 years, there have been many developments for AJAX engines that were focused on reducing exhaust emissions. Introduced in 1991, the AJAX LE engine features a pre-chamber which allows the engine to operate at very lean air/fuel ratios while exhibiting excellent combustion stability. With this pre-chambered design, the NO_x at the rated BHP is less than 2.0 gm/BHP-hr at the rated BHP for all 2200LE and 2800LE series engines. Because of the lean and stable combustion, the published CO level is 1.2 gm/BHP-hr and the VOC level is 0.5 gm/BHP-hr at the rated BHPs for the 2800LE engines. These emissions levels are referenced to a standard average ambient temperature of 65°F (18.3°C). The VOC level is based on operating with pipeline quality natural gas. VOC is defined as non-methane, non-ethane hydrocarbons.

Between 2003 and 2004, patented designs were introduced for the AJAX exhaust expansion chamber and the AJAX oxidizing converter. The expansion chamber reduces the NO_x level at the rated BHP by as much as 60%. This reduction occurs because the expansion chamber traps more air in the power cylinder by controlling the pressure pulses at the exhaust ports. The oxidizing converter reduces the CO level by > 80% and the VOC level by up to 70%.

Recent BHGE development work focused on the 2800XLE design configuration. This design includes poppet intake valves with increased flow area, a new multi-orifice pre-chamber design, and a new gas injection valve design. With the XLE configuration, NO_x levels have been reduced to < 1.0 gm/BHP-hr at the rated BHP with the emissions referenced to an ambient temperature of 100°F (37.7°C).

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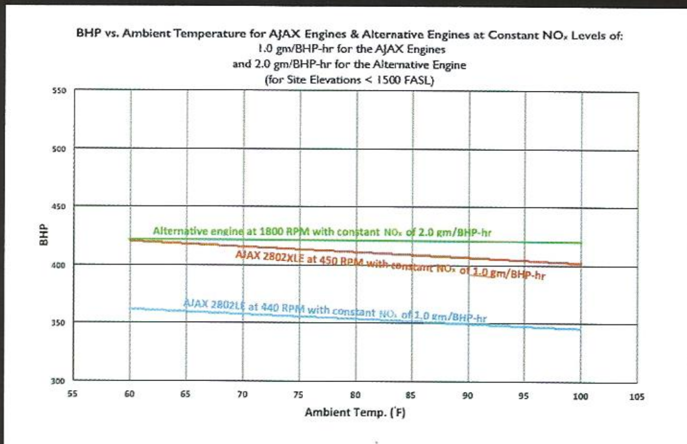

Figure 8: BHP Vs. T_{AMB} For Ajax Engines And An Alternative Engine At NO_x Levels Of 1.0 gm/BHP-hr For The Ajax Engines And 2.0 gm/BHP-hr For The Alternative Engine

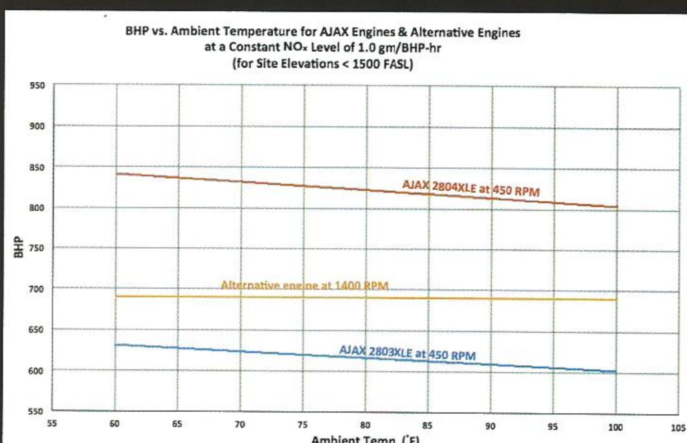

Figure 9: BHP Vs. T_{AMB} For AJAX Engines And An Alternative Engine At NO_x = 1.0 gm/BHP-hr

NO_x emissions curves for AJAX engines and an engine supplied by another manufacturer are compared in Figure 7. These curves are plots of NO_x levels vs. ambient temperature for the AJAX 2802LE engine, the AJAX 2802XLE engine, and another low emissions engine.

The alternative low emissions engine maintains a NO_x level of 2.0 gm/BHP-hr at 425 BHP throughout the ambient temperature range. This curve is level because this engine is turbocharged and aftercooled. An intake manifold temperature of 130°F (54.4°C) is held regardless of the ambient temperature.

The current production AJAX 2802LE engine is quoted at a NO_x level of 2.0 gm/BHP-hr at its rating of 384 BHP at 65°F. As the ambient temperature increases above 65°F, the NO_x level will increase as shown in the curve in Figure 7.

The design changes already incorporated into the 2802XLE engine result in large NO_x reductions throughout the ambient temperature range. With the 2802XLE, a NO_x of 1.0 gm/BHP-hr can be quoted at a rating of 400 BHP at 100°F.

Figure 8 demonstrates the BHP available from AJAX engines and an alternative engine for constant NO_x levels of 1.0 gm/BHP-hr for the AJAX engines and 2.0 gm/BHP-hr for the alternative engine. These curves plot the available BHP vs. the ambient temperature.

In Figure 8, the curve for the alternative engine is flat because this engine is turbocharged and aftercooled.

The curves for the AJAX 2802LE and 2802XLE engines in Figure 8 express the BHP derate that is needed to maintain a NO_x level of 1.0 gm/BHP-hr as the ambient temperature increases. The curves in Figure 8 for the AJAX engines emphasize the large increase in BHP available with the XLE configuration.

Figure 9 expresses the BHP available for larger AJAX engines and an alternative engine for a constant NO_x level of 1.0 gm/BHP-hr. As before, these curves plot the available BHP vs. ambient temperature for the AJAX 2803XLE engine, AJAX 2804XLE engine, and the alternative engine through the ambient temperature range.

The 2803XLE is rated at 600 BHP with a NO_x of 1.0 gm/BHP-hr at an ambient temperature of 100°F, and the 2804XLE is rated at 800 BHP with a NO_x of 1.0 at 100°F.

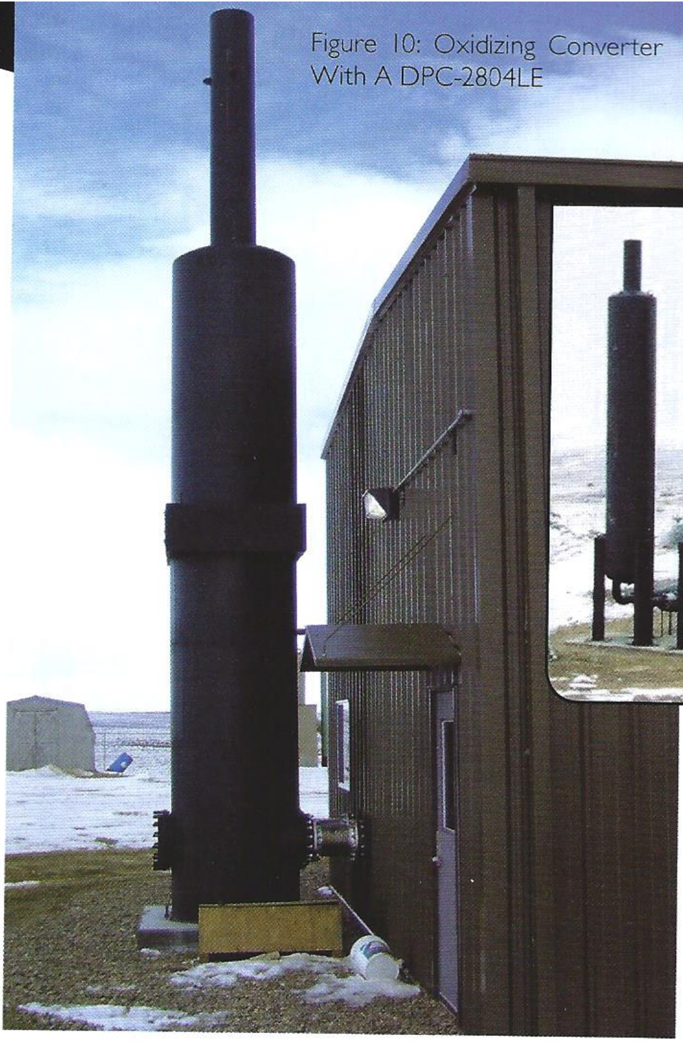

Figure 10: Oxidizing Converter With A DPC-2804LE

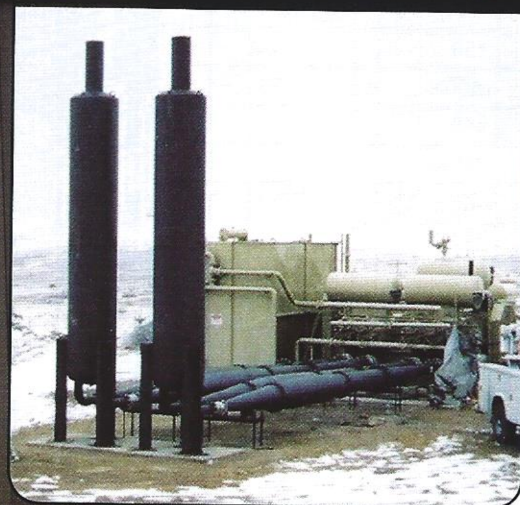

Figure 11: Expansion Pipes With A DPC-2804LE

- Mechanical Condition of the Engine – Initial emissions quotations are based on a well-maintained engine. Factors such as leaking gas injection valves, worn rod packings, dirty air filters, worn piston rings, bad spark plugs, bad coils, and bad secondary wiring will all affect the emissions levels.

During the last 10 years, field emissions test results for AJAX engines have been collected into a database. For the purpose of this paper, results from many of these field tests were analyzed and put into the same format, and are recorded in Appendix A.

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ANALYSES OF FIELD EMISSIONS TESTS

There are many factors at field sites that will cause the measured emissions to be different from the standard published emissions for AJAX engines. These factors include:

- Engine Load – Most field emissions tests are conducted with less than the site-rated BHP. BMEP's below the rated load will decrease NO_x and will increase CO and VOCs.
- Ambient Temperature – High temperatures can increase NO_x, while low temperatures can increase CO and VOC levels.
- Cylinder Pressure Balance – It is important to have each cylinder carrying its fair share of the engine load, meaning that average peak cylinder pressures should be balanced to within ± 15 psi (1.03 bar). If the average peak firing pressure is high for one or more cylinders, then the engine NO_x level will increase substantially.
- Fuel Composition – Exhaust emissions for AJAX engines are quoted based on the fuel composition at the site. Fuel composition has a strong effect on VOC levels in the exhaust. The ratio of non-methane, non-ethane (NMNE) hydrocarbons to total hydrocarbons (THC) in the exhaust is directly proportional to the ratio of NMNE hydrocarbons to THC in the fuel.

ENGINE	RATED BHP*	RATED SPEED (RPM)	NO_x @ RATING (gm/BHP-hr)*
AJAX 2802XLE	400	450	1.0
Alternative	425	1800	2.0
AJAX 2893XLE	600	450	1.0
Alternative	637	1800	2.0
Alternative	690	1400	1.0
AJAX 2804XLE	800	450	1.0
Alternative	1035	1400	1.0

Figure 12: BHP Ratings And NO_x Levels For AJAX Engines And Alternative Engines
*For Site Elevations ≤ 1500 FASL & Ambient Temps. ≤ 100°F

Figure 13: Narrow DPC-2802LE Package For Shipment On One Truck

These field test results verify that AJAX engines have emissions levels that are lower than the quoted emissions levels, thereby eliminating non-compliance issues.

All the emissions are expressed as gm/BHP-hr in this spreadsheet.

For eight of these field tests, the actual engine BHP was not recorded. However, sufficient data, such as compressed gas suction and discharge temperatures, allowed for the estimation of the BHP.

Oxidizing converters were in use for 17 of the tests in the spreadsheet. Exhaust expansion chambers were in use for five of these tests. Figure 10 is a photo of an oxidizing converter installed with a 2804LE application. Figure 11 shows exhaust expansion chambers installed on a 2804LE package.

VOC emissions were measured for six of these tests, and the formaldehyde levels were measured for two of the tests.

Four columns near the center of the spreadsheet record the measured NO_x and CO levels and compare them to the NO_x and CO levels, which would be predicted= at the test conditions. For these tests, the actual NO_x is less than the predicted NO_x for the site conditions.

For 20 of these tests, the actual CO is the same as or below the predicted CO level for the site conditions. In the three instances in which the actual CO was higher than predicted, the actual and predicted levels were very close to each other.

Large NO_x reductions for AJAX engines were recently achieved by improving the air flow to the power cylinder and modifying the gas injection valve and pre-chamber. The resulting engine configuration has been designated as the DPC-2800XLE series.

A comparison of the performance of the 2800XLE engines with alternative engines is provided in Figure 12.

CO and VOC levels for AJAX engines are low because of the lean operation of these engines. For sites requiring even lower levels of CO and VOCs, BHGE provides oxidizing converters that remove 90% of the CO and up to 70% of the VOCs.

SUMMARY

Research into improving the design for AJAX engine-compressors is ongoing, and customer feedback is critical to this process, including initiatives to reduce the package footprint and to improve transportability. The package design team created narrow skid 2802LE packages that are 8.5 x 38 ft (2.5 x 11.5 m) with the entire package, including the cooler, now able to ship on one truck (see Figure 13). Additionally, the team looked at site preparation and determined that the skids could be pre-filled with concrete at the BHGE plant and would therefore be ready for service without having a concrete pad at the compression site.

AJAX integral engine-compressors have a long track record of reliability, ease of maintenance, lower operating and maintenance expenses, higher efficiencies, and overall greater online availability when compared to high-speed separable packages. With minimal maintenance required, AJAX integrals are well suited for operation in remote areas. These packages are typically monitored from a central office, and there is seldom a need to send a service technician to the remote site. The selection of an AJAX integral package for a gas compression application provides many long-term benefits and unique advantages.

Appendix A: Spreadsheet Of Results From AJAX Engine Field Emissions Testing (6/27/17 BC)

			Elevation	Test Date	Actual	Actual	Rated	Site	Act. BMEP as a % of Rated	Meas. NO_x	Pred. NO_x (2)	Meas. CO	Pred. CO (2)	VOC	HCHO	Amb. Temp	Exh. O_2	Special
	Engine Model	State	(FASL)	Mo-Yr	BHP	RPM	RPM	Rated BHP	BMEP at Act. RPM (3)	gm/ BHP-hr	gm/ BHP-hr	gm/ BHP-hr	gm/ BHP-hr	gm/ BHP-hr	gm/ BHP-hr	(OF)	(%)	Equipment
1	DPC-115	WY	4500	Mar-10	60 (1)	225	360	100	96	1.26	3.2	0.99	1.3	n/a	n/a	45	18.2	n/a
2	DPC-180LE	WY	6000	Mar-16	120 (1)	400	400	150	80	0.27	1.1	1.39	1.8	n/a	n/a	70	13.6	n/a
3	DPC-360	WY	5500	Mar-16	300 (1)	400	400	305	98	4.25	6.4	1.53	1.45	n/a	n/a	74	14.6	n/a
4	DPC-2201LE	WY	6500	May-17	90 (1)	392	440	125	81	0.34	1.2	0.034	0.2	0.29	n/a	56	13	Oxid. Conv.
5	DPC-2801LE	WY	6700	May-17	105 (1)	354	440	162	81	0.25	1.1	0.11	0.21	0.34	n/a	58	13.4	Oxid. Conv.
6	DPC-2202LE	PA	1380	Sep-14	259	420	440	296	92	0.09	1.5	0.08	0.18	0.04	n/a	72	15.45	Oxid. Conv.
7	DPC-2802LE	MT	2800	Feb-16	210	392	440	369	64	0.11	0.9	0.19	0.18	n/a	n/a	35	16.1	Oxid. Conv.
8	DPC-2802LE	CO	6400	Oct-10	230	380	440	327	81	0.38	1.2	0.07	0.2	0.4	n/a	72	15.4	Oxid. Conv.
9	DPC-600LE	MT	2200	Apr-16	399	336	400	563	84	0.21	1.25	0.82	1.35	n/a	n/a	50	15.7	n/a
10	DPC-600LE	MT	2200	Apr-16	414	352	400	563	84	0.21	1.1	1.13	1.4	n/a	n/a	50	15.6	n/a
11	DPC-800	OK	1675	Jan-17	650 (1)	375	400	764	90	4.12	10	1.43	1.6	n/a	n/a	70	15.6	n/a
12	DPC-2803LE	ND	2300	Jun-09	520 (1)	440	440	586	88	0.32	1	0.04	0.14	n/a	n/a	70	14.8	Oxid. Conv.
13	DPC-2803LE	ND	2300	Jun-09	490 (1)	438	440	586	84	0.07	0.7	0.08	0.13	n/a	n/a	70	14.7	Oxid. Conv.
14	DPC-2804LE	WY	7200	Feb-07	598	440	440	663	90	0.4	0.7	0.02	0.13	n/a	0	35	15.4	Oxid. Conv.
15	DPC-2804LE	WY	7200	Mar-10	540	409	440	663	87	0.09	0.7	0.01	0.18	n/a	n/a	31	15.8	Oxid. Conv.
16	DPC-2804LE	ND	2370	Aug-11	785	435	440	800	99	0.37	0.8	0.19	0.19	n/a	n/a	80	14.1	Oxid. Conv. & Exp. Cham.
17	DPC-2804LE	ND	2370	Dec-11	752	435	440	800	95	0.18	0.7	0.02	0.19	0.37	n/a	35	14.1	Oxid. Conv. & Exp. Cham.
18	DPC-2804LE	WY	7200	Mar-12	636	440	440	663	96	0.25	0.8	0.02	0.13	n/a	n/a	45	15.2	Oxid. Conv.
19	DPC-2804LE	WY	7200	Apr-13	636	440	440	663	96	0.27	0.8	0.27	0.13	n/a	n/a	50	17.5	Oxid. Conv.
20	DPC-2804LE	CO	5275	May-12	551	391	440	710	87	n/a	1.2	0.03	0.16	n/a	n/a	84	16	Oxid. Conv.
21	DPC-2804LE	PA	1380	Sep-14	695	417	440	728	100	0.14	0.5	0.02	0.14	0.006	0.003	72	13.91	Oxid. Conv. & Exp. Cham.
22	DPC-2804LE	PA	1380	Sep-16	676	403	440	728	100	0.09	0.4	0.06	0.14	n/a	n/a	47	14.74	Oxid. Conv. & Exp. Cham.
23	DPC-2804LE	PA	1380	Sep-16	657	410	440	728	96	0.21	0.5	0.07	0.14	n/a	n/a	66	14.47	Oxid. Conv. & Exp. Cham.

Notes:

(1) Estimated BHP for test based on site elevation and other test parameters.

(2) NO_x and CO predicted at the field test conditions.

(3) This column is the % of the site-rated load at the test RPM & site elevation.