#1

questionable methods
look of calcs. + key point data.

FROM: Jon Ice

DIESEL & GAS ENGINEERING COMPANY
RTE. 414, R.D. #2
BEAVER DAMS, NY 14812

FAX #: 1-607-936-4288

IC Engine
Criteria Pollutant
exhaust, Inlet CH4
flow data.

DATE: 4/14/89

TO: Stan Drake
ET
124 Sills Rd.
Yaphank, NY

FAX #: 516-924-5627

PAGES TO FOLLOW: 21

COMMENTS:
Text Only
Bound Original Complete To Follow By FedEx

DGEC
DIESEL and GAS ENGINEERING Co.
Research • Development • Service

Technology and Comprehensive Consulting...
...for Engines, Energy and Emissions.

April 14, 1989

Stan Drake, President
Energy Tactics
124 Sills Road
Yaphank, NY 11980

Dear Stan:

Accompanying this letter is the test report on **ET-20** at Tripoli Landfill. The emissions data which was collected, and the supplementary information derived will prove to be very valuable to **DGEC** in our efforts to develop improvements in the performance of our systems on low quality fuels and on Cat 6.25" bore engines in general. Presumably, it will also help **ET** in its business development wherever air quality permits are required.

As a cautionary note when submitting the data to air quality agencies, the achievement of a level of 1.2 g/BHP-hr NO_x, as opposed to 2.0 g/BHP-hr, provides sufficient margin to allow for site differences in fuel and engine condition, as well as some room for ambient and load variations. The emissions control picture, as you may expect, is subject to the law of diminishing returns: as compliance levels become more restrictive, so do the practical operations restrictions on the equipment. Nonetheless, it is clear that we could potentially achieve <u>much lower</u> NO_x numbers, below 1 g/BHP-hr, in moderate ambients with rating in the range of 540 - 560kW. Due to fuel supply limitations and the resultant limits on our test during the Tripoli tests, it remains to be demonstrated if these lower 1 g/BHP-hr numbers can be attained at or near 600kW on a continuous basis.

Our further analysis shows that the mass flow of charge air is increased from a baseline of about 1.15 - 1.2 stochiometric to the range of 1.3 - 1.4 stochiometric for emissions compliance and with increased charge air pressure, the compressor discharge temperature increases. This will obviously affect the aftercooler circuit heat load. My "worst case" calculations (ignoring any increased allowable maximum charge air temperature) indicate a capacity factor of 2.5 fully accommodates the added heat rejection demands. I would like to have the opportunity to show you some equipment we have previously designed which may provide a quick, compact and inexpensive way to accommodate an A/C loop capacity increase and be incorporated with the module.

...cont'd.

Rte. 414, RD 2
Beaver Dams, NY 14812
(607) 936-4124

FAX #: 1-607-936-4288

From our perspective, we have reason to be very excited about the data since this has been our first opportunity to completely document a landfill gas application. I'm sure you understand what it is like trying to decipher and patch together data which you have not collected and know the source and reliability of firsthand. For one thing, we had long suspected from the results of our digester gas experience that the high concentrations of CO_2 in the fuel gas would contribute to higher CO emissions than those we measure on clean dry natural gas. We have done some kinetic modelling and find that during combustion, the $CO_2 = CO + .5O_2$ equilibrium shift occurs, and as the burned gas cools during expansion, some of this CO "freezes" out, leading to higher CO levels. It is interesting to us that this data shows about 50% more CO than we would expect on natural gas. Based on this, it would be advisable to request about 2.25 g/BHP-hr (308ppmv @ 15% O_2) as a CO limit in a permit application for operation on landfill or digester gas.

Stan, thanks very much for the opportunity to work with you and ET. I hope you will find the test report informative. We look forward to your further interest.

Sincerely,

Jon K. Tice

Jon K. Tice
President - DGEC

xc: F.D. Mills - DGEC w/attachment
Bob Wilkins - AEI w/attachment

TESTING OF ET-20 AT TRIPOLI LANDFILL

TEST REPORT

Prepared for

ENERGY TACTICS Inc.
124 Sills Road
Yaphank, NY 11980

by

Diesel and Gas Engineering Co.
Beaver Dams, NY

April 14, 1989

Written by

Nallan C. Suresh
Research Staff

Approved by

Jon K. Tice
President

REPORT ON TESTING OF UNIT ET-20 AT TRIPOLI LANDFILL SITE

EXECUTIVE SUMMARY

- o Unit ET-20 was installed with the PSC® emission control system and tested at various loads for detonation suppression and emissions compliance.
- o Detonation was suppressed for loads up to
  - a) 590 kW at air manifold temperatures (AMT) of 123.7/120.7 F (left/right)
  - b) 560 kW at AMT 131.5/125.1 F
  - c) 550 kW at AMT 137.9/130.1 F
  - d) At other loads, AMT reached 133.1/138.4 F without detonation.
- o Emissions levels of 1.2 g/BHP-hr NOx, 1.8 g/BHP-hr CO and below 2.0 g/BHP-hr total hydrocarbons, were attained at a load of 590 kW, the original specifications being 2.0 g/BHP-hr NOx, 2.0 g/BHP-hr CO and 2.0 g/BHP-hr non-methane hydrocarbons (NMHC).
- o Higher loads (600 kW) could not be attained for the above tests because fuel supply pressure at the test site was found to be insufficient.
- o The boost required and charge air flow requirements for both above-mentioned system set-ups were estimated and it was determined that these could be met if the fuel pressure were sufficient.
- o Air flow requirements for detonation suppression and emissions compliance at 600 kW have been calculated and are reported in the text.
- o The minimum required fuel pressure to supply sufficient fuel to the engine at a load of 600 kW, on both set-ups, was calculated to be 45 in. Hg. The available pressure on site was 33 in. Hg..
- o A chromatographic test of the fuel gas was made and its lower heating value was found to be 488 Btu/SCF. No non-methane hydrocarbons were found in the fuel.
- o The DTS III Digital Tracking System was shown to successfully maintain air-fuel ratios over the load range, and compensate for ambient temperature. However, testing should be repeated in summer to fine tune the compensation coefficient.

- Further summertime tests are recommended also to investigate extension of the air manifold temperature window to 140-145 F without detonation.
- PSC® air dilution can simultaneously meet the detonation and emission criteria with sufficient margin, if sufficient fuel pressure is available on the site.

Table of Contents

Table of Figures

Table of Tables

INTRODUCTION

The following report discusses the testing performed by DGEC (April 3-5, 1989) on site at Tripoli Landfill, Onondaga, NY, on Unit ET-20, installed with the PSC® emission control system. The emission control system was retrofitted on the engine by DGEC personnel, and the air dilution control system incorporating the digital DTS III controller was also mounted. The primary objective of the project was to prove that the excess dilution air supplied by the PSC® system could lower combustion temperatures and prevent detonation from occurring in the cylinders for loads up to 600 kW, at charge air temperatures up to 130 F. It was also sought to prove that PSC® air dilution could bring emissions below certain specified limits, and to show that the turbocharger wastegating could be controlled so as to supply the boost and air flow requirements for the above two set-ups. The objectives and results are discussed in detail below.

OBJECTIVES

PSC® air dilution was to be supplied to meet the following objectives:

a) **Maintain 600 kW output without detonation at charge air temperatures up to 130 F.**
b) **Maintain 600 kW output with maximum emissions of 2.0 g/BHP-hr NOx, 2.0 g/BHP-hr CO and 2.0 g/BHP-hr non-methane hydrocarbons (NMHC).**
c) **Provide boost pressure and charge air flow requirements on both system set-ups.**

The DTS III digital tracking system was set-up on the site and programmed to supply the correct amount of PSC® air dilution at various loads and also compensate for ambient temperature variations.

TESTING EQUIPMENT

The DGEC Mobile Emissions Laboratory was stationed on site at Tripoli Landfill from April 3-5, 1989. The DGEC Mobile Emissions Laboratory is equipped with Beckman continuous sampling analyzers for NOx, CO, CO2, O2 and THC emissions. A Hewlett Packard computer system performs on-line data acquisition and reduction. A custom-built gas chromatograph (GC) (Analytical Instruments Corporation) uses a Flame Ionization Detector

(FID) for analysis of NMHC emissions and a Thermal Conductivity Detector (TCD) for fuel gas analysis, in separate sample loops and column systems. The chromatograms are analyzed by a Spectra Physics computing integrator. However, the GC was not taken to the test site for this project, and samples were brought back to DGEC for analysis.

The exhaust sample is taken from the stack to an ice bath and condenser to remove moisture; a diaphragm pump then pushes the sample through two canisters of inert 'Drierite' to complete drying, and transports it to the mobile lab. A vented back pressure regulator maintains fresh sample at a constant pressure in a sample header in the lab, for distribution to the analyzers at constant flow. The fuel sample was taken in a purged sample bomb and connected to the fuel sample loop of the GC.

The continuous monitoring analyzers were calibrated several times during each test day using certified grade calibration gases from Scott Specialty Gases. During the second day of testing, 4/4/89, a leak in a gas line caused the emptying of fuel to the hydrocarbon analyzer, and we could not perform hydrocarbon measurements any further. However, the total hydrocarbons measured in the exhaust on previous tests were all well below 2.0 g/BHP-hr. Moreover, it is observed in practice that the NMHC/THC fraction in the exhaust is characteristically consistent with the NMHC/THC fraction in the fuel gas. Since the fuel analysis showed non-methane content to be negligible, the same is expected to be true of the exhaust.

TESTING PROCEDURE

The following test procedure was adopted to achieve the stated objectives. To bring the engine into emissions compliance, the amount of air intake into the engine, as indicated by the exhaust O2 content, was increased in steps, with the engine running at load. Data runs were made at several points, with the wastegating adjusted at each position, until sufficient air flow was achieved for the required emissions.

For the second phase of the testing, in order to control detonation at high charge air temperatures, elevated ambient conditions were artificially simulated by restricting the aftercooler water discharge. This raised the charge air temperature to above 130 F. The above exercise was performed at various loads, and at each load point a base run was made, followed by a run with sufficient PSC® dilution air to get the exhaust O2 level to 4%, the load being maintained constant for each pair of data points. The results of the testing are discussed below.

RESULTS AND DISCUSSION

The results of the tests and their discussion are presented in various sections, as follows:

a) Detonation suppression of ET-20
b) Emissions compliance
c) Boost pressure and charge air flow requirements
d) Projected fuel supply pressure requirement
e) Gas chromatographic test of the fuel
f) Load tracking by the DTS III

A synopsis of the relevant data is presented in Table 1.

A. DETONATION SUPPRESSION OF ET-20

Runs 5 (4/4/89),10 and 12 (4/5/89) (See Table 1), were performed at various charge air temperatures and the following results were obtained. Detonation was suppressed for loads up to

a) 590 kW at air manifold temperatures (AMT) of 123.7/120.7 F (left/right)
b) 560 kW at AMT 131.5/125.1 F
c) 550 kW at AMT 137.9/130.1 F
d) At other loads, AMT reached 133.1/138.4 F without detonation.

While loads up to 560 kW were achieved with charge air temperatures over 130 F, the targeted load of 600 kW was not achieved, due to insufficient fuel supply pressure. 32.5 to 33.5 inches of Hg was available, whereas a minimum of 40 inches Hg is determined to be necessary for this purpose(See calculations in Section D). In Section D is also a more detailed discussion of the minimum fuel pressure requirement for optimum NOx control. To corroborate this observation, it was found that Unit # 19, the engine operating without PSC® air dilution, was supplying only 590 kW due to insufficient supply fuel pressure at the same time that ET-20 was running at 590 kW. At this condition, some load fluctuations occurred because the boost pressure was "deadheading" the fuel pressure downstream of the regulator, causing a fluctuation in the fuel flow rate.

B. EMISSIONS COMPLIANCE

The target of 2.0 g/BHP-hr on NOx, CO and NMHC was met with sufficient margin at 590 kW. The actual emissions recorded were (See Table 1, Run #12) 1.2 g/BHP-hr NOx and 1.8 g/BHP-hr CO. As explained in a previous section hydrocarbon runs were discontinued due to a leakage. However, the trend of previous runs (See Run #1, 4/4/89, and Runs of 4/3/89, Also See Table 1) showed a total hydrocarbon content of 324 ppm corrected to 15% O2, at a load of 545 kW, which works out to 1.4 g/BHP-hr, and decreasing with increasing load. The fuel analysis (See Section E) showed that the fuel contained negligible amounts of NMHC, and this hence ensures that the exhaust also contained negligible amounts of NMHC and definitely below 2.0 g/BHP-hr.

Once again the fuel supply pressure limited the maximum load attainable.

Using a nominal engine conversion efficiency of 30% and the gas BTU values measured, the conversion factors from ppm corrected to 15% O2, to g/BHP-hr, were determined to be 83 ppmc/g/BHP-hr for NOx. Corresponding values for CO and HC were 137 and 238, respectively.

C. BOOST PRESSURE AND CHARGE AIR FLOW REQUIREMENTS

For detonation suppression set-up at 600 kW

BOOST PRESSURE (in. Hg.)	AIR FLOW (lb/min)	GAS PRESS. REQD.(in. Hg.)
24.0	126	40

For emission compliance at 600 kW and concurrent detonation suppression

BOOST PRESSURE (in. Hg.)	AIR FLOW (lb/min)	GAS PRESS. REQD. (in. Hg.)
29.1	138	45

The boost pressures and charge air flow requirements were calculated from the measured data for the detonation test at 560 kW, and the emission test at 590 kW, and scaled accordingly. These requirements have been calculated at the available fuel pressure of 33 in. Hg., and while they can be met, it is clearly indicated that 600 kW and greater, can be achieved at lower boost pressures if the fuel supply pressure were to be raised to 45 in. Hg..

D. PROJECTED FUEL SUPPLY PRESSURE REQUIREMENT

The attached graph (Fig. 2) explains the fuel supply pressure requirement of the engine for loads up to 600 kW. As we can see in the graph, the boost in inches of Hg. increases from around 17 to 20.2 from 490 to 540 kW. After this point it increases sharply at higher loads. The carbureted mixture which was 2.7% exhaust O2, dry, at 500 kW leans out to 3.85 % exhaust O2 at 590 kW. With proper fuel bias, the regulators are supposed to maintain a constant air-fuel ratio over these loads. The leaning-out occurs because there is insufficient fuel pressure to the engine, and we essentially "run out of fuel". Table 3 gives the measured differential pressure, in inches of water, between the gas after the regulator, and the charge air, basically the pressure difference available to feed gas into the carburetor. This measured value is 2.6 in. of water. The IMPCO handbook recommends that this pressure be, at least, 4-7 in. of water for natural gas containing over

90% methane. For landfill gas, with 50% methane, this number is expected to be higher, at least 8-10 inches of water. The fact that the pressure is only 2.6 in. of water gives the reason for the insufficient fuel supply, and hence the leaning out of the carbureted mixture.

The dotted line gives the projected boost for loads from 550 kW to 600 kW assuming a constant fuel bias (which will occur if sufficient fuel pressure is available, and regulators track as designed). From this graph, and from obtained data (Table 3), we can calculate the minimum required fuel supply pressure. From the data we see that fuel pressure available before the regulator is, nominally, 33 in. Hg.. At 500 kW, the boost is 21.2 in. Hg.. This gives a bias of about 12 in. Hg.. We need at least this much bias (or 16 in. Hg. with sufficient margin) at loads of 600 kW, where the boost is around 29 in. Hg.. This puts the required fuel supply pressure at 45 in. Hg..

E. GAS CHROMATOGRAPHIC TEST OF THE FUEL

A gas chromatographic analysis of the fuel (See Table 2 and Data in Appendix), showed the lower heating value of the fuel to be 488 BTU/SCF (Average of two runs). No (or undetectable amounts of) non-methanes were present in the fuel. The fuel was comprised of approximately 53% methane and 47% non-combustibles (N_2 and CO_2).

F. LOAD TRACKING BY THE DTS III

The DTS III digital tracking system was used to control the amount of air dilution, and to maintain a total (carbureted + diluted) air-fuel ratio with variation in ambient temperature. The oxygen content vs load swing graph (Fig. 3) shows that O_2 levels of around 4% were maintained over a 350-560 kW load range at charge air temperatures of 130 F. The final runs on 4/5/89 (Runs # 13 and 14, see Table 1) showed that O_2 was kept at 4.2% with charge air temperatures reduced to around 90 F. This showed that the DTS III system had successfully compensated for temperature variations and load variations. A repeat of this test should be done in the hot summer months to fine tune the temperature compensation coefficient. (See Fig. 4 for curve programmed in the DTS III. See Appendix for Installer's Data Sheet.)

CONCLUSIONS

The PSC® system as installed and set up at Tripoli landfill will meet all of the stated objectives if a slight increase in gas supply pressure is provided. It must be noted that all of the stated objectives will be met with sufficient margin, as evidenced by the tests. It can be shown that detonation can be suppressed for charge air temperatures up to and above 130 F, and NOx, CO and NMHC emissions levels can be maintained for all loads, up to and including 600 kW, well below 2.0 g/BHP-hr. A gas pressure of at least 45 in. Hg. (16 in. Hg. above boost pressure), is required to maintain the steady fuel flow rate needed at 600 kW. It was thought during the planning stages of the project, that the available gas pressure (estimated at 37 in. Hg. or 18 psig), would just meet the increased requirement. The actual site pressure measured by the mercury manometer was, unfortunately, somewhat less, at 33 in. Hg. or 16.2 psig. Even so, the engines did attain 93.3% to 98.3% of full power. This is consistent with the fact that the fuel gas density at site pressure is 94% of the value that was expected.

Barometric pressure = 29.5 in. Hg.
Fuel gas pressure expected = 37 + 29.5 = 66.5 in. Hg. (absolute)
Fuel gas pressure measured = 33 + 29.5 = 62.5 in. Hg. (absolute)

Therefore
Fuel gas density measured = (62.5/66.5) of Fuel gas density expected
= 94% of Fuel gas density expected.

RECOMMENDATIONS

From the testing it was determined that detonation could be suppressed at loads up to 600 kW at charge air temperatures of 130 F, providing sufficient fuel pressure was available. It is recommended that the engine be retested in the summer months to investigate control of detonation for charge air temperatures of up to 145 F, and in order to fine tune the ambient compensation coefficient in the controller, to accommodate for these temperatures. To perform these tests, it is necessary that fuel pressure at this site and possible future sites be at least 45 in. Hg.

TABLE 1. TABLE OF RELEVANT DATA

DATE	RUN	O2(%)	NOXc	HCc	COc	LOAD (kW)	TEMP (L)	TEMP (R)	BST (L)	BST (R)
4/3/89	1	5.365	105	412	218	490	-	-	-	-
4/3/89	2	4.8	155	336	240	542.6	-	-	-	-
4/4/89	1	4.58	191	324	246	545	93.5 F	93.4 F	19.8"Hg	20.7"Hg
4/4/89	2	4.9	146	355	241	532	95.3 F	95.5 F	20.1"Hg	20.5"Hg
4/4/89	3	4.94	142	362	240	503	105.3 F	107.8 F	19"Hg	19.7"Hg
4/4/89	4	4.79	166	-	246	560	106.1 F	107.3 F	23"Hg	24.1"Hg
4/4/89	5	5.34	100	-	249	590	123.1 F	120.7 F	28.4"Hg	28.8"Hg
4/4/89	6	4.72	167	-	247	570	101.3 F	100.5 F	23.3"Hg	23.9"Hg
4/5/89	10	3.97	419	-	257	550	130.9 F	137.9 F	20.7"Hg	21.7"Hg
4/5/89	12	4.04	378	-	260	560	125.1 F	131.5 F	21"Hg	21.5"Hg
4/5/89	13	4.29	281	-	287	595	90.1 F	88.1 F	23.0"Hg	23.7"Hg
4/5/89	14	4.29	270	-	289	594				

TABLE 2. DATA FROM GC RUNS (SYNOPSIS)

LOWER HEATING VALUE OF FUEL	488 BTU/SCF
MOLE % METHANE	53%
MOLE % NON-COMBUSTIBLES (CO_2 & N_2)	47%

TABLE 3. GAS PRESSURE DATA (at 590 kW)

	GAS PRESSURE BEFORE REGULATOR, P1 (in. Hg.)	GAS PRESSURE DIFFERENTIAL AVAILABLE TO FEED FUEL INTO CARBURETOR (P2 - P3) (inches of water)
AVERAGE	33	2.6

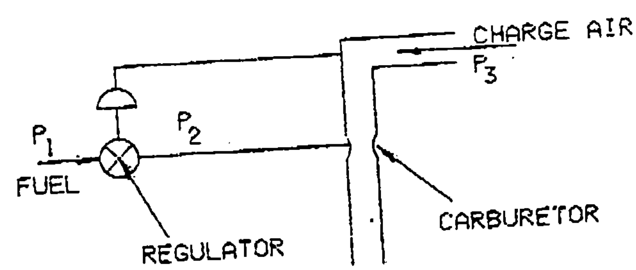


FIG. 1 OXYGEN CONTENT VS LOAD SWING

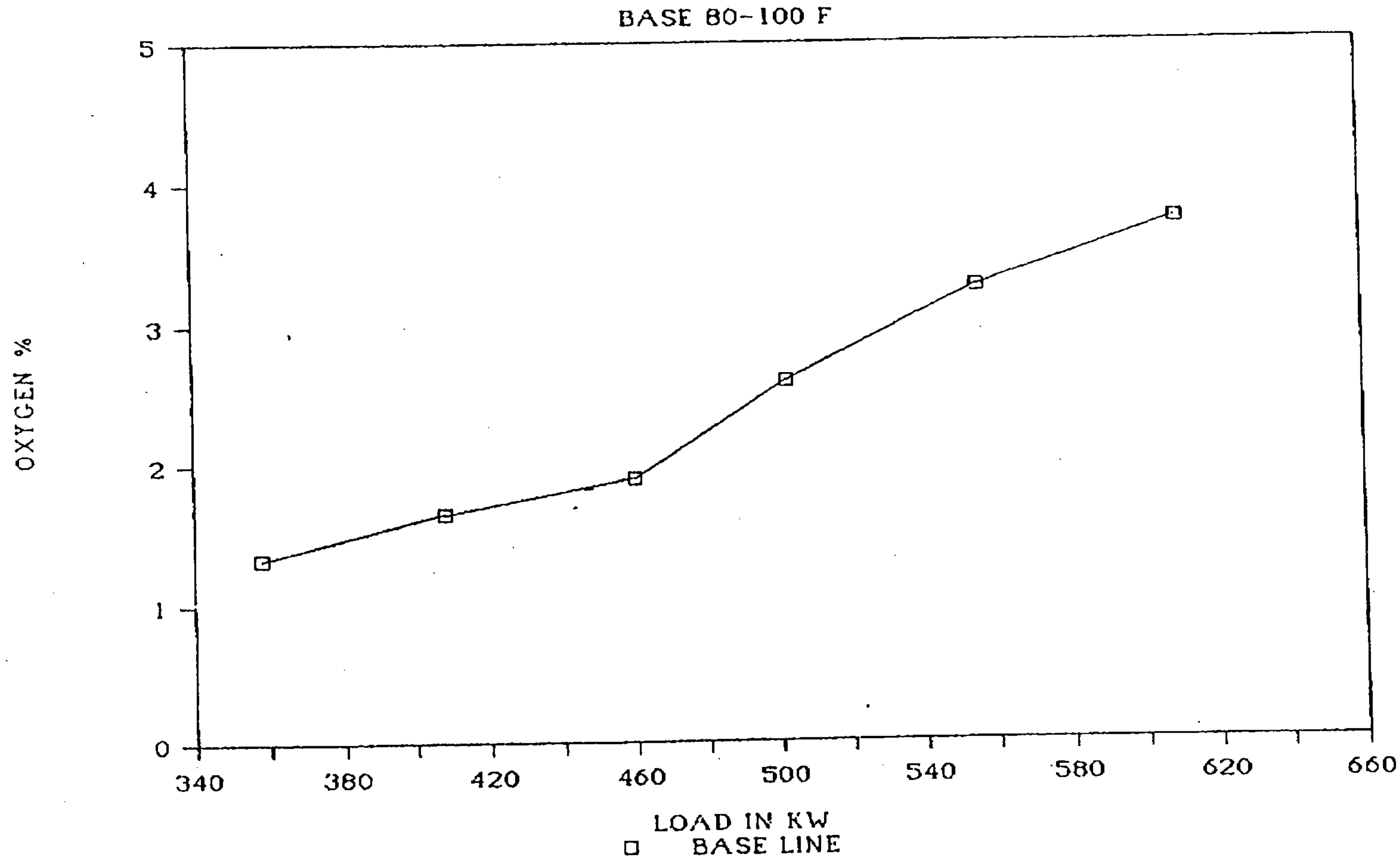


FIG. 2 BOOST VS LOAD

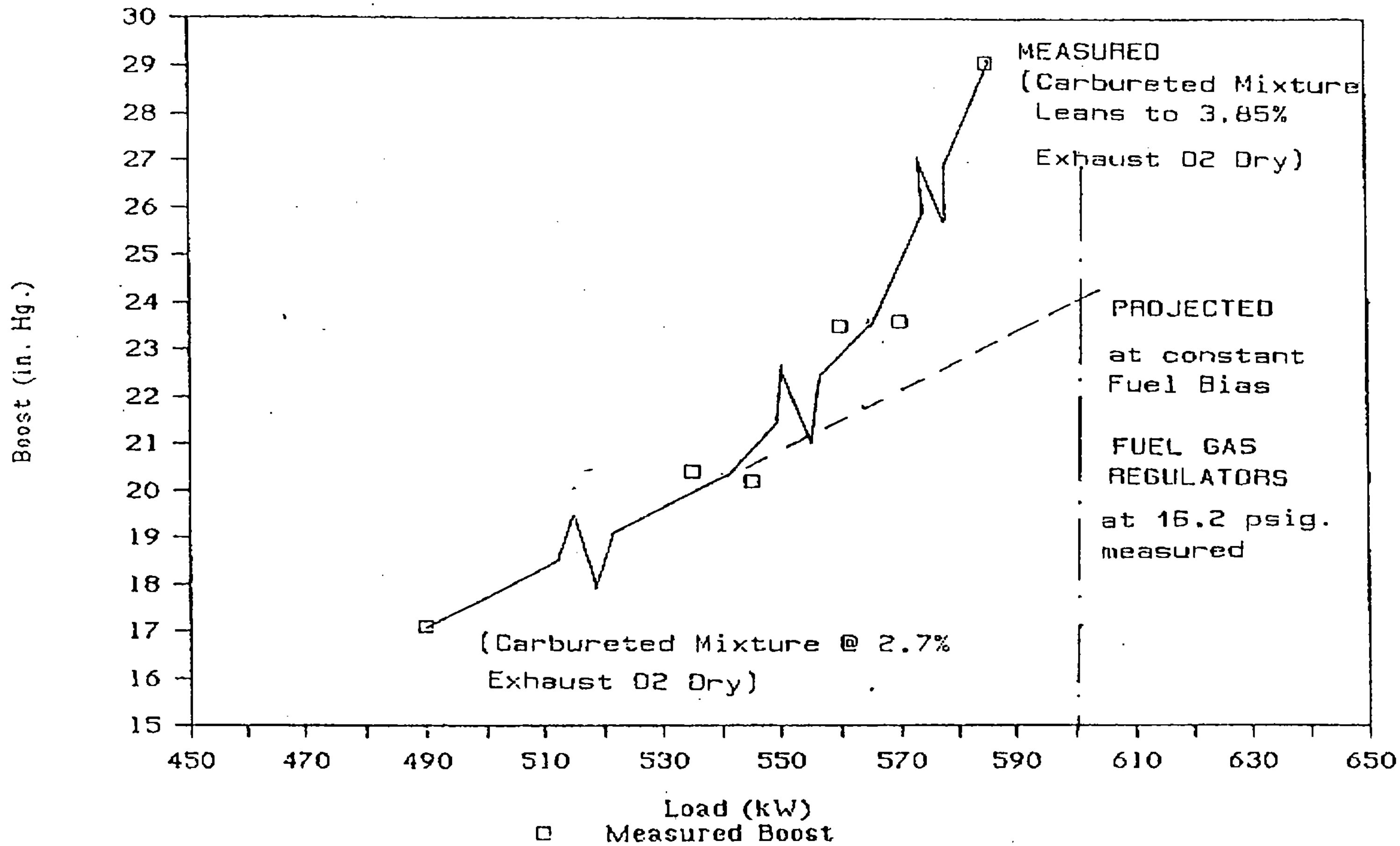


FIG.3 OXYGEN CONTENT VS LOAD SWING

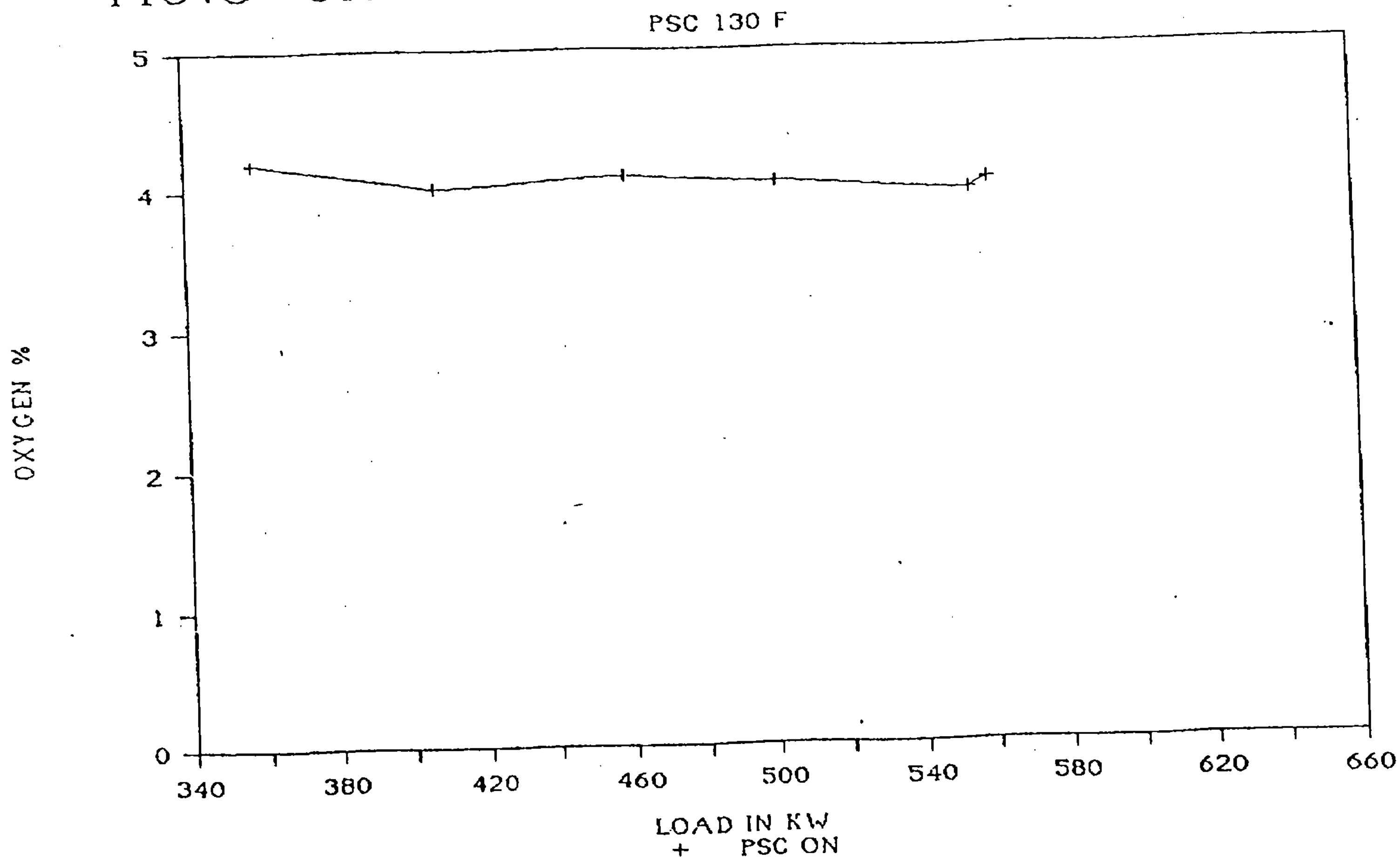
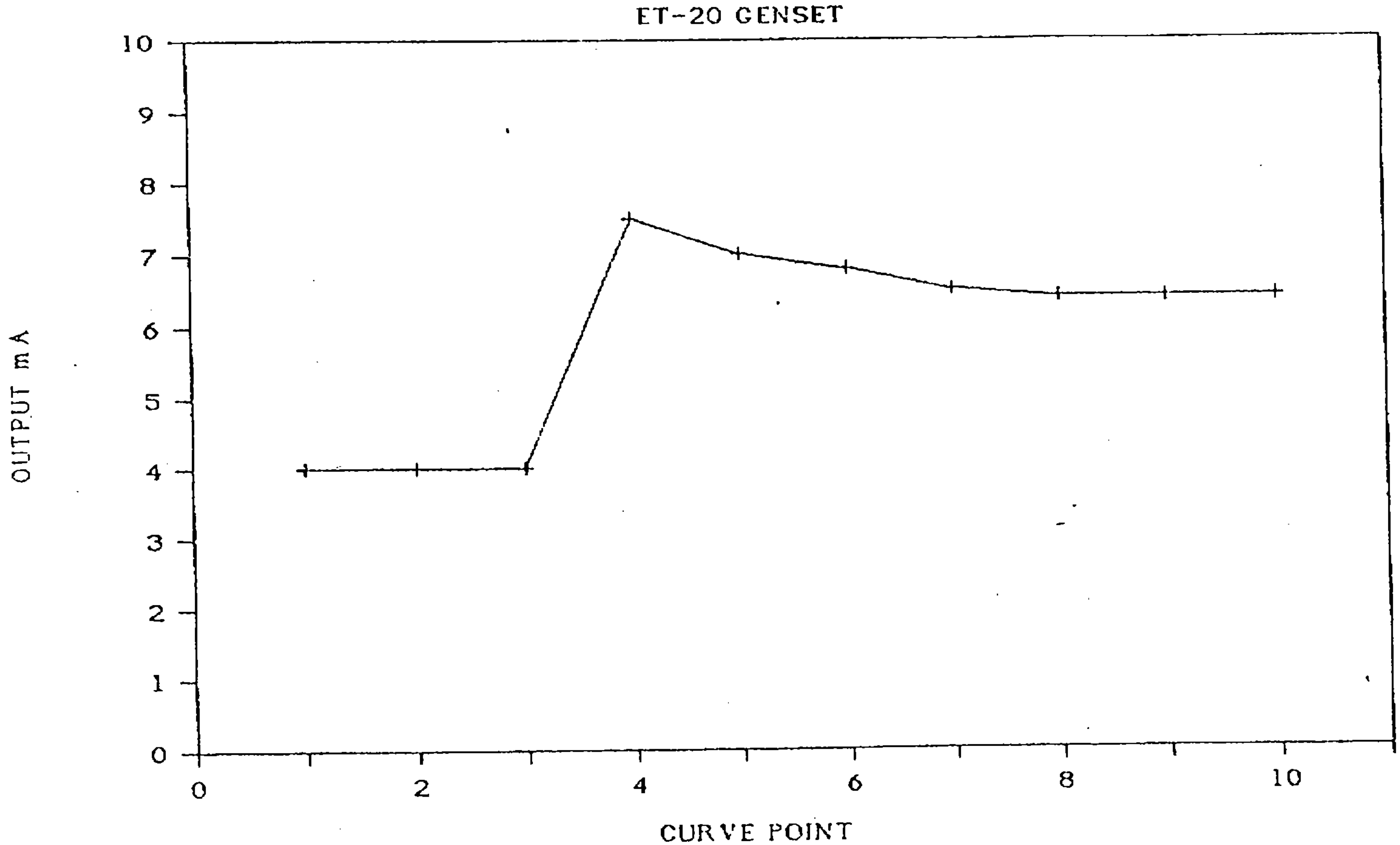


FIG. 4 PROGRAMMED CURVE FOR DTS-III



ET energy tactics, inc.

Phone: (516) 924-5300
FAX: (516) 924-5627

May 3, 1994

USEPA
Global Warming Branch
Mail Drop 63
Triangle Park, NC 27711

Attention: Susan Thornloe

Dear Susan:

I hope you have the available manpower to pore over these things. I've broken them into three packages and I will have to ask you to return it all.

1. The first package concerns our Oceanside facility. Included are some promotional literature concerning a prestratified charge (PSC) system, a report on a preliminary evaluation performed at our Onondaga site and a full blown compliance report done on one of our engines at Oceanside. We employed the PSC on all our Oceanside engines. We don't exactly love it because it is temperamental. Jon Tice has given up his involvement in the system turning his rights over to someone who has given us very little support. The technology appears to be dormant at this time.

2. The second package is a test report on our Fairbanks Morse, 6 cylinder, opposed piston, two stroke engine in Manchester, NH.

3. The third package is some information on the Stirling engine. Most of it concerns an automobile conversion program that was remarkably successful. There is a wealth of useful data and software in the hands of MTI that could be used to spark the development of a highly efficient, low emission stationary engine. It kills me to see it unexploited.

If I were to ask for funding in this area, I would pursue a cooperative effort by which MTI would provide the thermal analysis for off-the-shelf hardware that we would modify as a Stirling engine generator system to operate directly from landfill gas combustion or via heat recovery from our existing engines.

P.O. Box 7, 124 Sills Rd. (RT. 101), Yaphank, N.Y. 11980

ET **energy tactics,** inc.

May 3, 1994
Page Two.

USEPA
Global Warming Branch

Attention: Susan Thornloe

I expect that the former configuration (direct gas combustion) would make gas production tax credits available. The latter approach would yield higher revenues from existing sites. Either way there is a financial incentive that could augment the development cost.

Give me your thoughts.

Very truly yours,

ENERGY TACTICS, INC.

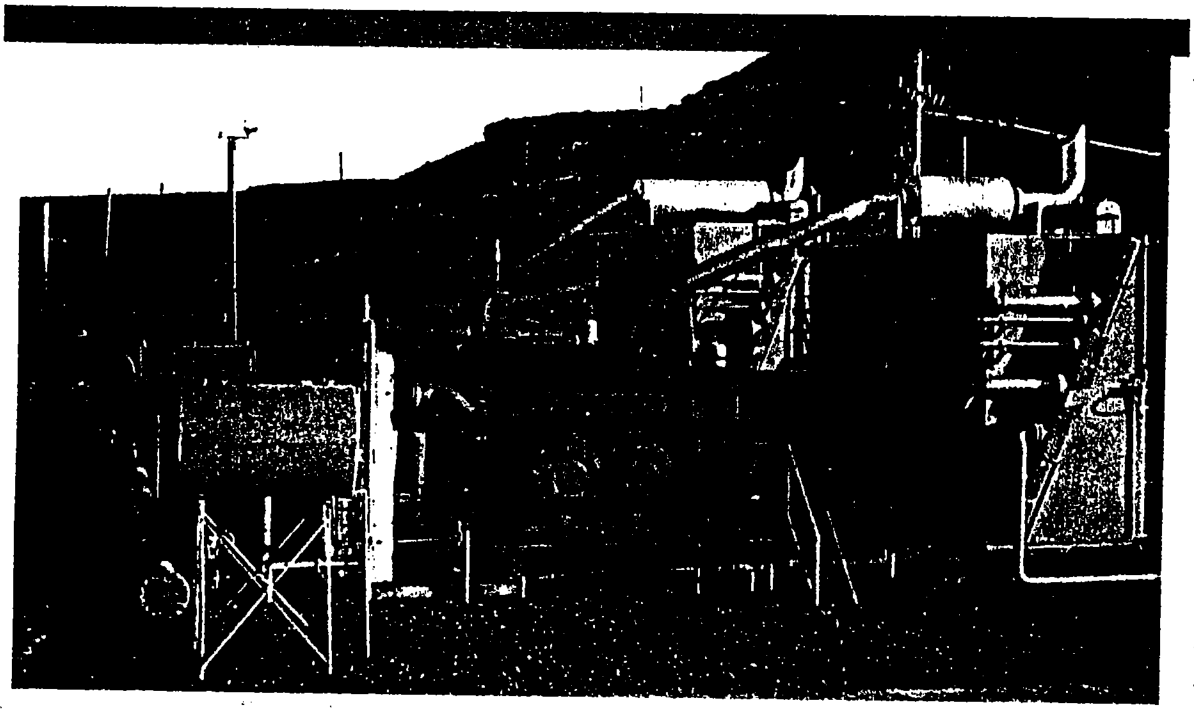
Stan Drake

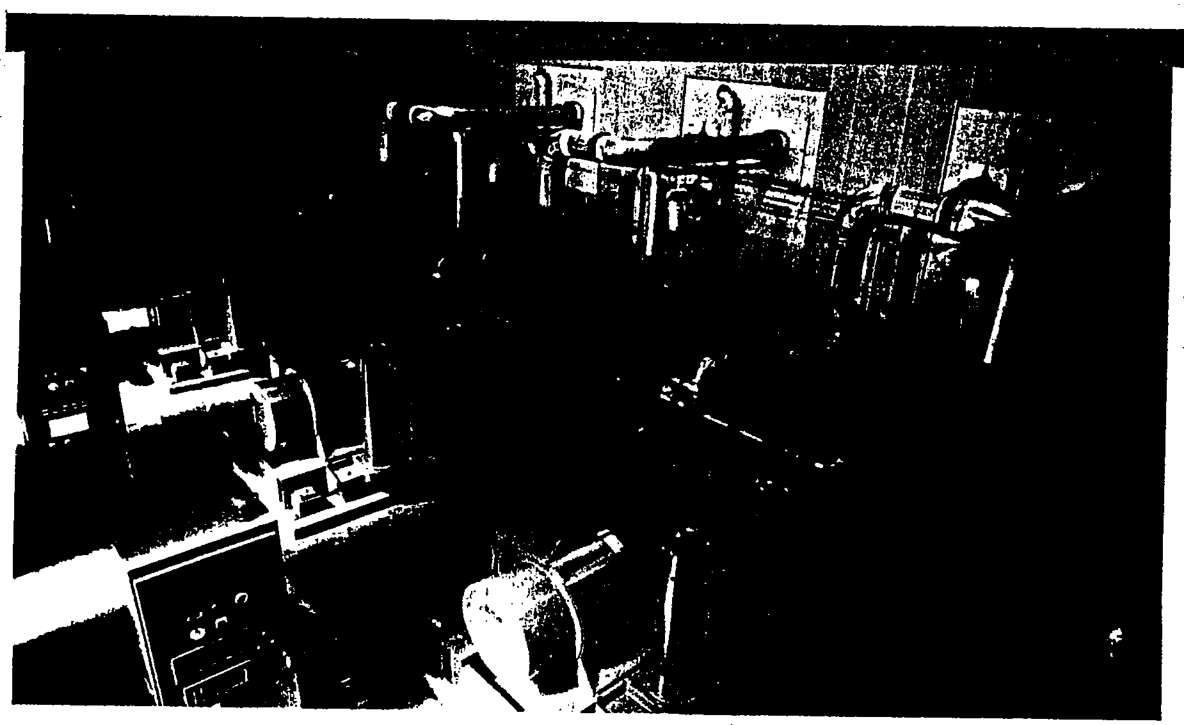
STAN DRAKE
President

/af

This Paper is Recycled.

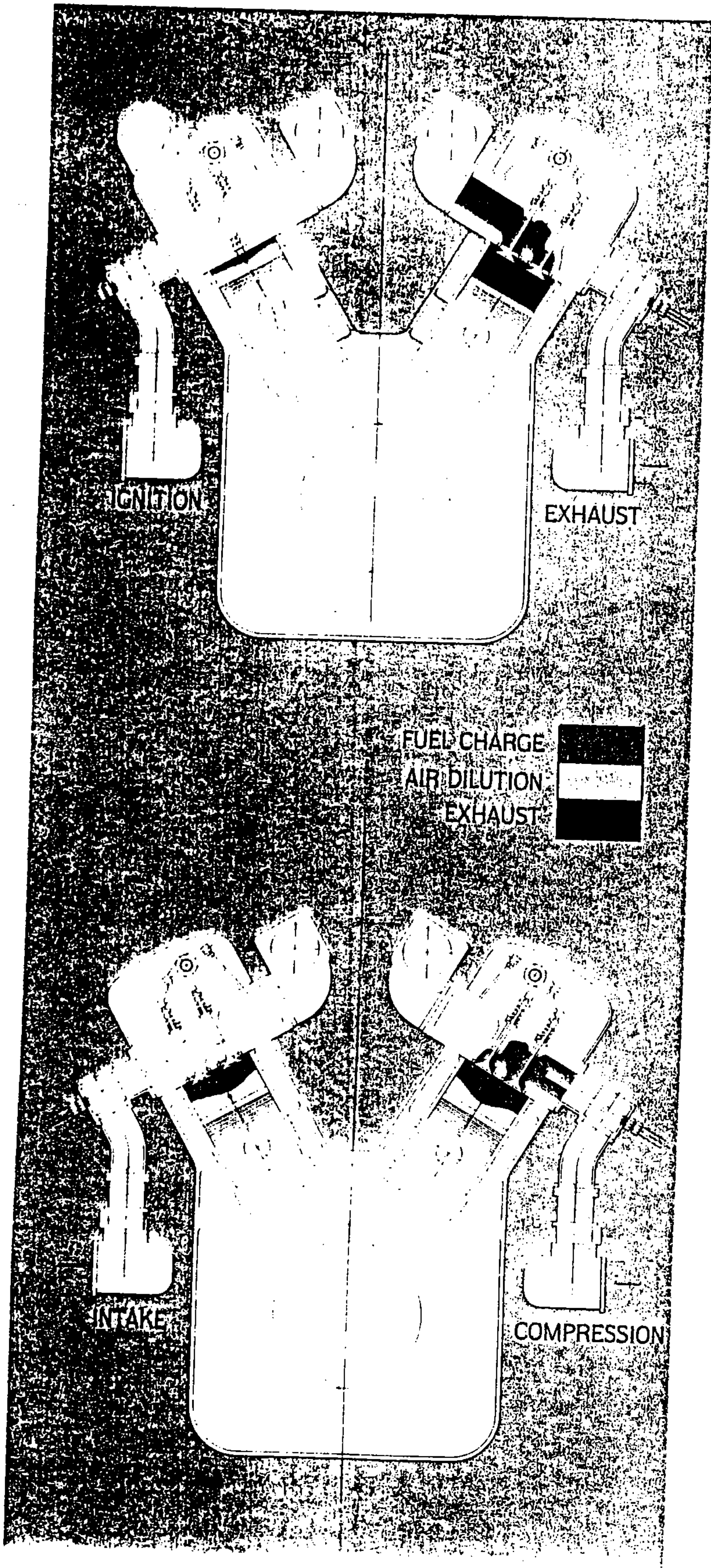
EMISSION SYSTEMS FOR GAS ENGINES





-PRE-STRATIFIED CHARGE

PRE-STRATIFIED CHARGE SYSTEM OPERATION AND DESIGN PRINCIPLES



1—With the intake valve to a cylinder closed, the air flow in the port and manifold runner comes to rest for about three quarters of the four stroke cycle while the remaining cylinders are filling with fresh charge.

2—During that time, the next air charge to this cylinder is prestratified, or "pre-arranged" in the port and runner by the dilution straws. This arrangement yields a mixture of fresh charge which is separated from the dilution air. As a result, the engine retains the simplicity of rich burn while obtaining the relevant advantages of overall lean burn operation.

3—When the intake valve opens, the prestratified air enters the cylinder first, followed by fresh charge from the carburetor or mixing valve.

4—The compression stroke occurs rapidly, so very little time is available to mix the charge and destroy the stratified layers. Therefore, an easily ignitable fresh charge mixture ends up near the spark plug, with highly diluted mixtures near the piston crown.

5—Upon combustion, the high dilutions "cool" the burning gases. And much less NOx forms with the PSC® system than would otherwise occur. The cooling effect provided by the PSC system substantially reduces the risk of detonation. The operator then gains freedom to optimize the spark timing for substantial improvements in fuel economy, within the constraints imposed by his NOx reduction requirements.

Cover photos courtesy of City of Oxnard WWTP, Oxnard CA, and Production Operators Inc., Houston, TX.

THE PSC® SYSTEM OFFERS THESE IMPORTANT FEATURES TO EFFECTIVELY CONTROL NOx EMISSIONS FROM STATIONARY INTERNAL COMBUSTION ENGINES

SIMPLICITY

The process is self-activated by the basic principle upon which the four stroke engine operates. The simplicity of an entirely mechanical system means that there are no catalysts to maintain or replace.

RELIABILITY

PSC provides more stable operation without degradation that occurs with catalyst installations. Precise air-fuel ratio controls are not required to maintain combustion efficiency and system performance. Instead, a simple pneumatically controlled modulation valve maintains dilution at desired levels.

SERVICEABILITY

Routine maintenance involves only the normal replacement of engine air filters. Total system service, if needed, can be accomplished by general maintenance personnel with ordinary hand tools.

COST EFFECTIVENESS

PSC requires no internal engine modifications or use of pre-combustion chambers. Downstream replacement costs are eliminated and in most instances, fuel savings are realized. Complete with controls and installation, PSC costs range from $20-$200 per ton/yr. NOx, depending on unit size. For comparison, BACT requirements for cost-effective NOx control vary from $2,000 to over $20,000 per ton/yr. NOx in various regulatory districts nationwide.

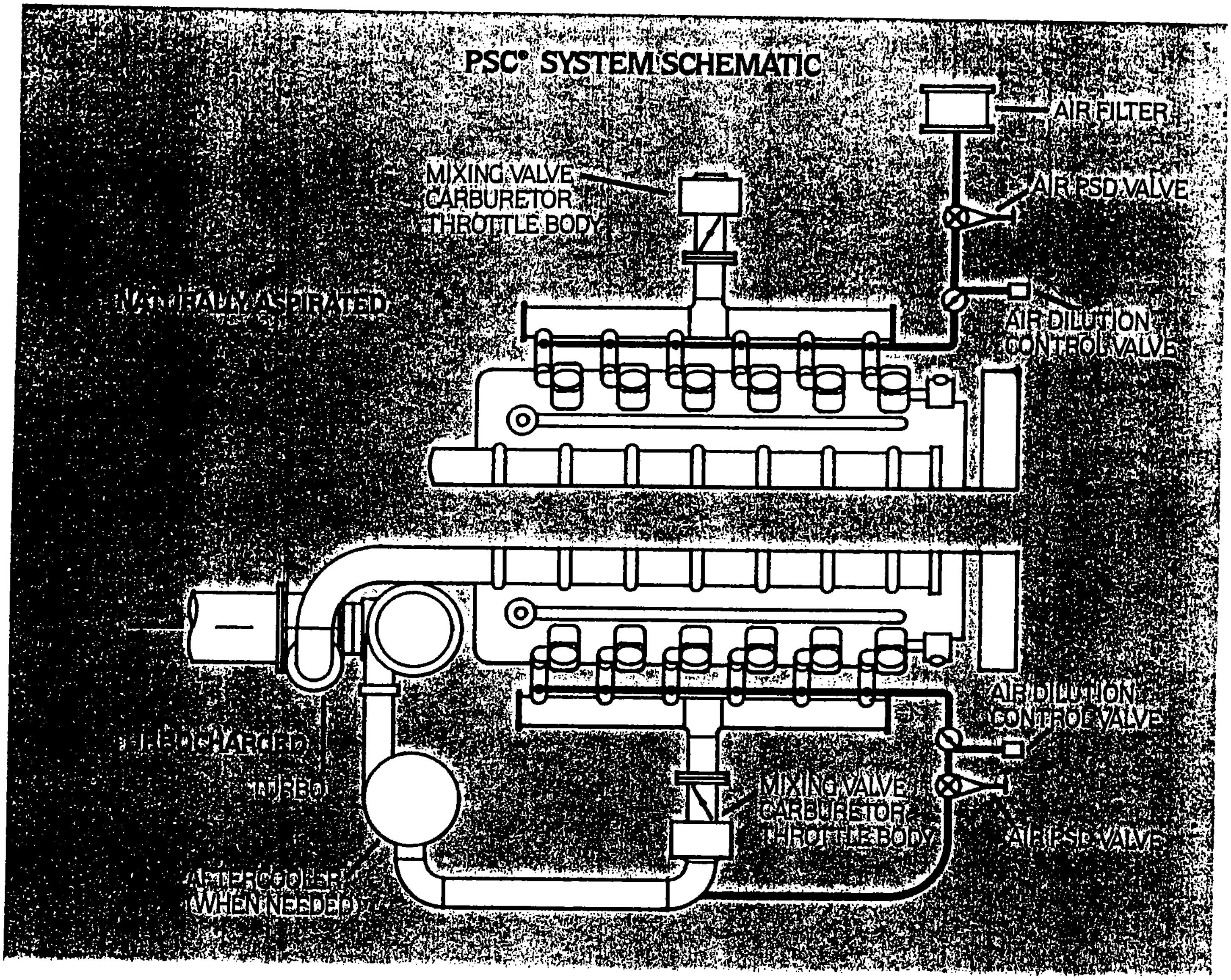
VERSATILITY

Since the system is activated by the engine cycle alone, it is not sensitive to cyclic load operation or adverse fuel composition, such as H_2S, digester, sewage, and landfill gases. PSC may be applied to any gas engine using carburetors, whether naturally aspirated or turbocharged, even those engines no longer in production by the manufacturers.

OTHER ADVANTAGES

Even if NOx control is not a primary concern, PSC can save costly downtime as a proven deterrent to detonation and the engine damage it can cause.

NEW OR RETROFIT INSTALLATION



Installation of the PSC Emissions System enables the conversion of rich burn engines to lean burn operation by simple retrofit of the intake manifolding. There are no expensive precombustion chambers, special fuel injection equipment or changeout of cylinder heads and cams required.

The principal PSC System components, constructed of durable materials are prefabricated for ease of field installation. Normally, the field conversion may be accomplished within one or two days, depending upon the size of the engine and installation requirements.

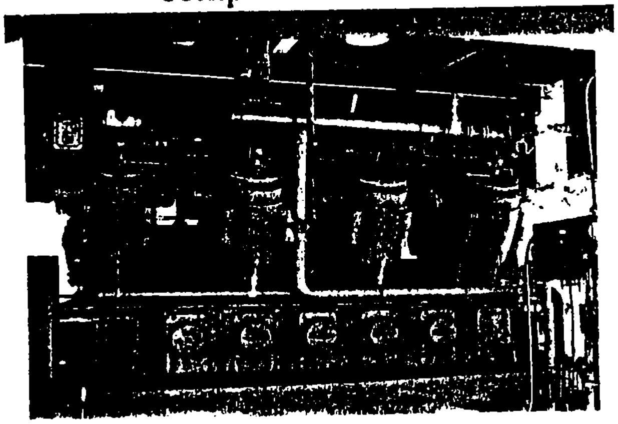
DGEC & its distributors provide "turnkey" installation, including startup and performance check-out of the PSC System. Experienced technical services personnel are also available to assist in any testing for verification and compliance when requested, and are backed by our engineering R & D staff, recognized as leading experts in the field of engines, combustion, and emissions.

COMPARATIVE FEATURES OF THE PSC® SYSTEM WITH NSCR CATALYSTS

PSC SYSTEM	NSCR CATALYSTS
Requires no precision air/fuel ratio controls. Simple operation with use of a totally mechanical system and throttle body dilution control valve.	Requires expensive and complex precision air/fuel ratio controls to maintain system integrity and combustion efficiency.
The entire system consists of materials which are commonly available and standard throughout the industry.	Constructed of exotic metallurgy and ceramic components for withstanding chemical reactions and high temperatures in the exhaust stream.
Good life expectancy of continual operation over five years and beyond in service.	Life expectancy of the catalyst element is 8,000 hours or less. System degradation takes place rapidly if air/fuel ratios are not precisely maintained.
Fuel savings have been observed ranging from 4%-8%, particularly at near peak-load operation.	Expected penalties in fuel consumption averaging 8-12%.
System is versatile and not sensitive to cyclic load operation or fuel composition. Furthermore, with the -L/C & T/C versions of PSC *no deration* of engine output occurs.	Landfill and sewage digester and "sour" gases cannot be burned in engines without poisoning the catalyst. Engines which operate on varied or unsteady load conditions may fail the catalyst due to rapid changes in air/fuel settings and control tracking problems.
Regular maintenance involves only the normal replacement of engine air filters. Total service, if required, may be accomplished by general maintenance personnel using ordinary hand tools.	In addition to anticipated periodic replacement of the catalyst element, malfunction of the controller requires service by highly skilled technicians familiar with microprocessor and electronic sub-systems.
Competitively priced with NSCR catalysts on an installed basis, with an achieved merit factor in maintenance and fuel savings.	Not overall cost effective when considering installation and downstream costs that are realized. Cost prohibitive for the smaller units.

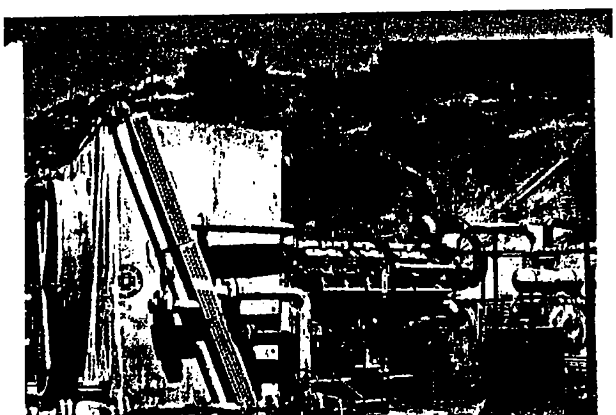
PSC® APPLICATIONS

Compressor Service



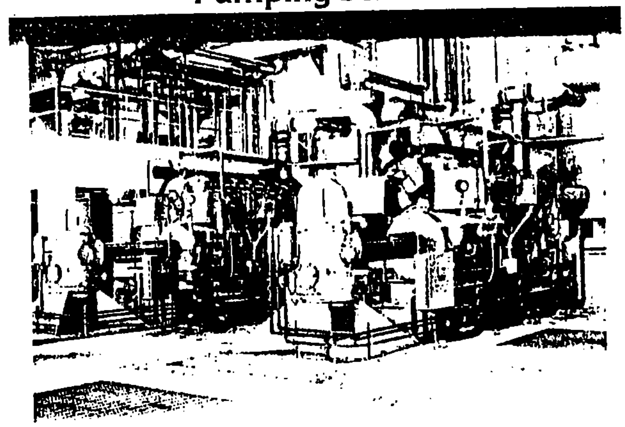
Ingersoll-Rand XVG8 Gas Storage

Waukesha L7042 GSI—Field Gas



Caterpillar G-398 with Load Compensating Turbocharger Upgrade

Pumping Service



Waukesha L5108GU—Digester Gas

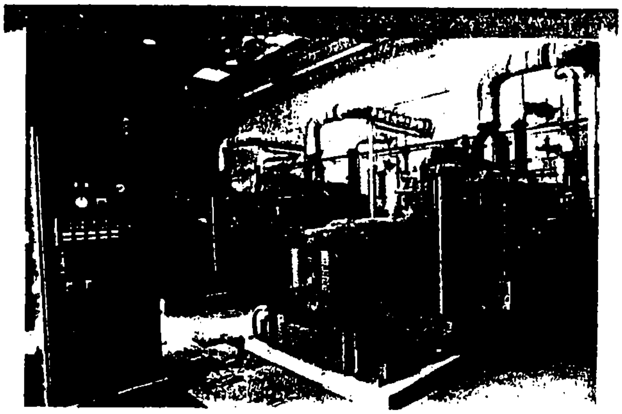
Superior 8G-825—Field Gas

Waukesha 140 GZU—Field Gas

The PSC emissions system provides a simple, yet effective means of pollution control for stationary internal combustion engines. System integrity is maintained over the entire operating range of the engine, and is not affected by variable load conditions. Even at maximum continuous load ratings, the PSC system can routinely achieve 80% NOx reduction as compared to the uncontrolled engine, and in most cases, reductions exceeding 90% are attainable. Actual field performance tests have demonstrated emissions reductions within the compliance levels currently specified by stringent air quality regulations in the South Coast Air Quality Management District of Southern California under Rule 1110.1, as well as the even more strict rules imposed by Ventura County APCD Rule 74.9. With the introduction of Load Compensation Kits (-L/C) and kits for turbocharged carbureted engines, there is *no deration* of engine capacity.

Introduction of the PSC system allows for operation of the existing rich burn engine with leaner fuel mixtures. Measured exhaust O_2 readings of greater than 10% have been observed in many natural gas fueled engines with

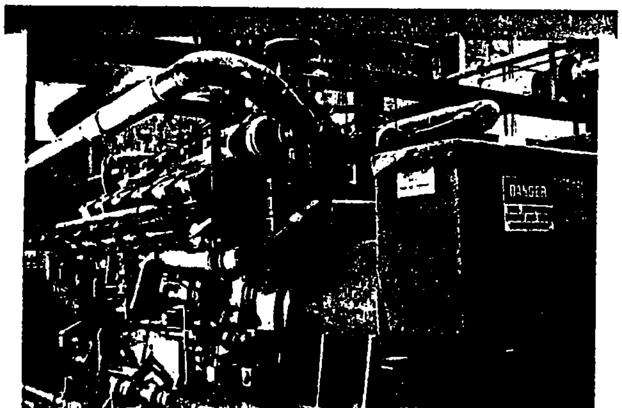
Generator Service



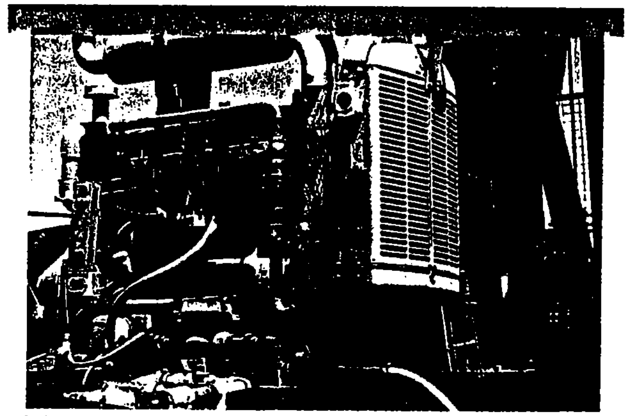
Waukesha P9390GU—Digester Gas

Oil Well Pumping

Waukesha F554G—Field Gas



Waukesha L7042 with Load Compensating Turbo Upgrade



Minneapolis-Moline HD-800 Well Head Gas

DGEC Emissions Control work is supported by commitment to modern technology.

DGEC Cadam System

DGEC Mobile Emissions Lab

PSC® application. The lean burn mode of operation permits greater latitude in optimizing spark advance for improved fuel efficiencies, yet provides reliable combustion stability even with the use of lower BTU rated fuels. Higher knock limit margins are achieved without the risk of detonation.

An additional advantage of the Pre-Stratified Charge process, is that engine cycle temperatures are greatly reduced, resulting in better oil retention and lower thermal stress and wear on critical engine components.

Applications

PSC kits are available for the following engine models

Caterpillar	Ingersoll-Rand	Minneapolis-Moline	Superior	Waukesha		
342	JVG	425	6G-825	554	2476	5108
379	XVG	605	8G-825	817	2895	5790
398	SVG	800	12G-825	1197	3521	7042
399	KVG		16G-825	1905	3711	9390
	KVGR			Roline 884	Climax V-125	

For engine models not listed, please consult factory.

Application of Pre-Stratified Charge emissions technology to gas fueled four stroke engines, represents over 10 years of research and development efforts which began at Cornell University in the mid-1970's.

Diesel and Gas Engineering Company's corporate staff were principally involved in this effort. Together with our combined years of experience in the gas engine industry, we have become widely recognized as leaders in the field of engines, combustion, energy, and emissions.

Our expanded capabilities include the following engineering and technical support services which are backed by the commitment to provide the best quality and professional services available to our customers. When your requirements demand this expertise, you can rely upon DGEC.

- Emissions technology for the lean burn family of gas fueled engines.
- Computerized balance control systems to monitor overall engine performance and fuel distribution, for maintaining optimum combustion efficiencies.
- Research in combustion, aerodynamics and thermal sciences.
- Cogeneration systems and waste heat recovery.
- Conversion of diesel fueled engines to clean natural gas operation.
- Advanced Technology for turbocharging of gas and diesel stationary, locomotive and marine engines, to enhance fuel economies.
- Consulting services and feasibility studies.

LOCAL DISTRIBUTOR

New Products & Services

- Mobile Test Lab: On site emissions testing & performance evaluation.
- DGEC 3500 low NOx gas engine: Ratings to 100BHP for compression, pumping, and power generation.
- DGEC Micro-PCC™: economical low-NOx conversion of older gas engines.
- DGEC 4080 Econogen™ cogeneration unit: rated 40KW electrical/80KW thermal at 2 gr/BHP-hr NOx.

DGEC ®
·DIESEL and GAS ENGINEERING Co·

Research • Development • Service

Technology and Comprehensive Consulting...
...for Engines, Energy and Emissions.

CORPORATE OFFICE
Route 414, RD#2
Beaver Dams, New York 14812
~~(607) 936-4124~~ FAX #(607) 936-4288

Applications photos courtesy of: Southern California Gas Company, Orange County Sanitation Districts, CA, City of Oxnard, CA, Long Beach Oil Development, CA, Henry Leasing Company, CA.

Design by Tom Ripley 217-359-1081 TILE 7224 FALL 1988

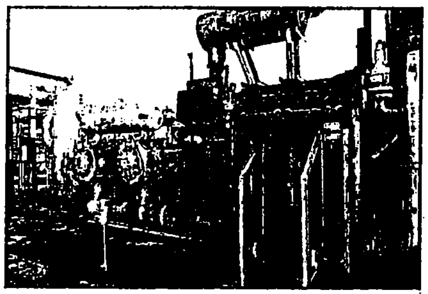
Pre-Stratified Charge System For Natural Gas Engines

Operators of natural gas engines, suddenly forced to comply with local or national emission regulations, have generally looked to catalytic convertors and air-fuel ratio controls as an emission control option. The other choices were to rebuild the engine to a pre-combustion chamber design or, to consider shutting the operation down.

About four years ago, a new system began to be installed on older, rich-burn, four-stroke cycle engines. This system involved modifying existing engines to take advantage of modern stratified charge technology. The patented system is known commercially as PSC—pre-stratified

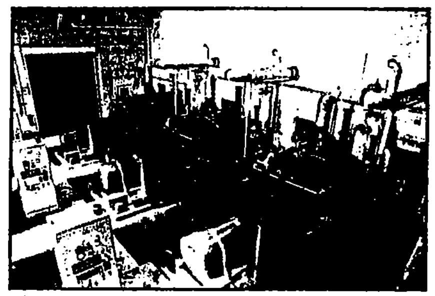
The PSC or pre-stratified charge systems have been installed on 19 Waukesha 7042 GSIU engine/four-throw compressor units rated 750 kW at 1000 r/min. The engine compressor packages are meeting emission compliance levels in Kern County, California, U.S.A.

charge. The technology and system components were developed by Cornell University in the U.S. The design uses reworked manifolds, air "straws," a controller and, sometimes, turbocharger modifications to cause a very lean fuel-air mixture to occur directly over the piston, while permitting the spark-ignitable rich mixture to remain in the area of the spark plug. The result is a substantially leaner mixture, on the average, which can significantly reduce NO_x emissions; fuel consumption can also be improved. In addition, only minimal changes are required to be made on the engine.

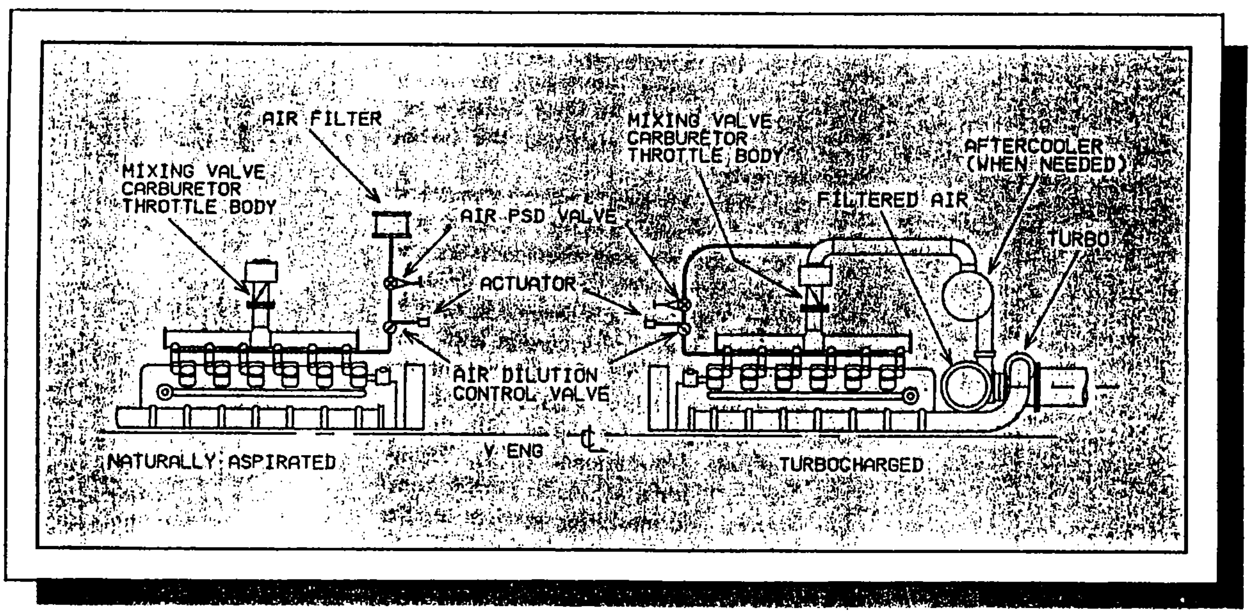


A system that can be retrofitted on existing, rich-burn, four-stroke cycle natural gas engines has been developed by Diesel and Gas Engineering Co. and marketed by Engine Controls International. The PSC — pre-stratified charge technology develops a lean fuel-air mixture over the piston, while the rich air-fuel mixture remains near the spark plug, all leading to reductions in NO_x emissions.

The patents developed at Cornell University have been licensed to Diesel and Gas Engineering Co. (DGEC), Beaver Dams, New York, U.S.A. DGEC has developed and tested the technology needed to modify specific engine models. To date, kits have been manufactured for Waukesha, Ingersoll-Rand, Cooper-Superior, Caterpillar, Roiline and Minneapolis-



A wastewater treatment plant in Oxnard, California, U.S.A., operates on sewage digester gas. These Waukesha P9390 engine generator sets provide plant power and utilize waste heat to heat digesters. The engines were fitted with the PSC system and are achieving less than 50 ppmv at 15% O_2 NO_x levels. The systems operate in Ventura County, California, U.S.A., which has some of the most stringent emission requirements for internal combustion engines in the U.S.



Typical PSC system schematic.

PRODUCT BULLETIN

Programmable Air Dilution Control System for use with PSC® emission controls

DTS III - DIGITAL TRACKING SYSTEM

The DTS III is a versatile digital controller, which is programmed for use with the pre-stratified charge emission control system. It accepts inputs of 0-10VDC and outputs 4-20mA DC. The transfer function is programmable, by simply punching in the points on the required curve through a user-friendly touch pad programmer.

The I/O curve will consist of a total of ten (10) curve points. The curve can be linear or non-linear, and have up to 9 different slopes.

The DTS III can control up to three engines. It accepts three 0-10VDC, (CT or throttle postion sensor) load signals from the engines and one 0-10VDC signal from a temperature sensor for ambient compensation. It outputs three 4-20mA outputs for engine control. The outputs are corrected for the ambient temperature by an amount determined by a programmable coefficient. A 10VDC output is also supplied to provide potential drops across throttle position type load sensing potentiometers connected in parallel (min. combined resistance 500 ohms).*

The controller has 12 software controlled relays, rated at 2A, which can be set to switch contacts at programmable mA output setpoints. The DTS III can also be reconfigured for other purposes, using the same hardware configurations, by simply changing the software. More than three engines can be controlled, by adding additional I/O cards.

SPECS	
SIZE:	10.08" x 6.1" x 3.7"
POWER:	24 VDC, 2A
INPUT:	Four 0-10 V inputs
OUTPUT:	Three (3) programmable 4-20 mA outputs. One (1) constant 10 VDC output to potentiometers.
RELAY:	2 A (12 computer controlled relays)
AMBIENT:	32 - 104 F

* NOTE : Distance from engine can affect voltage signals to and from throttle sensor due to electric noise. Hence, good shielded wire is recommended, Belden 9608, or equal.

PSC® Emission Control Kits Are Available For:

CATERPILLAR

G-342
G-379
G-398
G-399

INGERSOLL-RAND

JVG-6
JVG-8
SVG-6
SVG-8
XVG-6
XVG-8
PKVG-10
KVG/KVGR-8
KVG/KVGR-10
KVG/KVGR-12

COOPER-SUPERIOR

6G-825
8G-825
12G-825
16G-825

WAUKESHA

554
817
1197
1905
2475
2895
3521
3711
5108
5790
7042
9390

CLIMAX

V-125

ROILINE

884

MINNEAPOLIS-MOLINE

425
605
800

PSC® V.S. NSCR Catalysts

PSC®
Reduced NOx
Reduced Fuel Consumption
Reduced Maintenance
Reduced Overall Cost

NSCR CATALYSTS
Reduced NOx
Increased Fuel Consumption
Increased Maintenance
Increased Overall Cost

OVERVIEW
A Pre-Stratified Charge System is simple to operate. It requires no precision air-fuel ratio controls and operates as a totally mechanical system that incorporates a throttle-body dilution control valve. The entire system consists of standard common materials, available throughout the industry.

Good Life Expectancy: Over five years of continuous service with little or no deterioration beyond normal maintenance indicates a relatively long and useful operating life cycle.

Fuel savings are commonly 4 to 8%. Good results are seen near peak load operation.

The PSC® system is versatile and not sensitive to cyclic load operation or fuel composition. Further, with the Load-Compensating and Turbocharged versions of the system, no deration of engine output occurs.

The PSC® system is competitively priced. Payback is relatively fast, and maintenance, which consists mainly of periodically changing engine air filters, is almost negligible when compared to the cost of operating a catalytic converter.

ASSOCIATES COMMITTEE REPORT

ON

STATUS OF AIR EMISSION

CONTROL TECHNOLOGIES FOR

INTERNAL COMBUSTION ENGINES USING

DIGESTER GAS

Report Issued In May, 1987

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FOREWARD

This representation by the Associates Committee of the California Association of Sanitation Agencies (CASA) is a voluntary effort and is made possible through the private resources of all CASA Associates. Additional copies are available for the cost of printing and postage. Send requests to:

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Sacramento, California 95814

May 5, 1987

STATUS OF AIR EMISSION CONTROL TECHNOLOGIES FOR INTERNAL COMBUSTION ENGINES USING DIGESTER GAS

TABLE OF CONTENTS

STATUS OF AIR EMISSION CONTROL TECHNOLOGIES FOR INTERNAL COMBUSTION ENGINES USING DIGESTER GAS

ABBREVIATIONS USED IN THIS REPORT

APCD	Air Pollution Control District
AQMD	Air Quality Management District
BAAQMD	Bay Area Air Quality Management District
BTDC	Before Top Dead Center
BTU	British Thermal Unit
CASA	California Association of Sanitation Agencies
CO	Carbon Monoxide
DGEC	Diesel and Gas Engineering Company
HC	Hydrocarbon
LACSD	Los Angeles County Sanitation Districts
NMHC	Non-Methane Hydrocarbon
NOx	Nitrogen Oxides
NSCR	Non-Selective Catalytic Reduction
PPM	Parts Per Million (By Volume)
PSC	Pre-Stratified Charge
SCAQMD	South Coast Air Quality Management District
SCR	Selective Catalytic Reduction
THC	Total Hydrocarbon
VCAPCD	Ventura County Air Pollution Control District

May 4, 1987

CHAPTER 1

BACKGROUND AND PURPOSE

Background

Many California Association of Sanitation Agencies (CASA) member agencies produce digester gas as a byproduct of the anaerobic stabilization of sludge. Although digester gas is often disposed of by flaring it in a waste gas burner, it is a valuable medium BTU (British Thermal Unit) fuel that can be used to produce energy. The technology that is normally used for producing power from digester gas is an internal combustion reciprocating engine, although turbines and other technologies exist. This report deals only with control of air emissions from engines.

Burning digester gas in engines results in the emission of air pollutants in amounts which often exceed the requirements. Several different technologies exist for controlling the emissions from internal combustion engines and some of these have been tried on digester gas fueled engines. Many of these trials have, however, ended in failure.

Purpose

The purpose of this report is to summarize the past efforts and experiences of various wastewater treatment agencies in their attempts to to meet air emission requirements. It is also the purpose of this report to identify those technologies that are the most promising to pursue in the attainment of air quality standards and to eliminate from future consideration those technologies that have proved to be unsuccessful.

Because the report is intended to be of use to CASA agencies, many of whom are finding it difficult to comply with air pollution control requirements, the emphasis of this report is on retrofit technologies that can be applied to existing installations.

Approach

The Associates' Digester Gas Utilization subcommittee of CASA undertook the task of gathering information on air emission technologies. Various CASA agencies who were involved with the problem were requested to submit information on their activities. This information was summarized and presented at the CASA meeting in Palm Springs in January, 1987 and a preliminary report was circulated.

Many comments on the preliminary report and much additional useful information were received. In some cases, additional information was solicited by telephone. As a result of the information and comments received, the earlier report has been completely rewritten.

Drafts of parts of this report were circulated to the persons and agencies who had supplied information for further comment. This final report represents a "best effort" at summarizing the information that was received.

It should be noted, however, that in many cases differences of opinion exist and/or there have been differing results when a technology was applied in different installations. More information is becoming available in this rapidly developing field as time passes and this study was by no means exhaustive in searching out the information that currently exists. The information presented herein should therefore be considered only as a status report of currently available information, and thus as only a starting point for further investigation.

Terminology

As is often the case in new and/or rapidly evolving fields, the terminology of air emissions control from digester gas fueled engines has not yet become standardized. Often the same phrase is used by different people to mean different things. Discussed below is the terminology that is being used in this report.

Prestratified Charge (PSC)

In this report, this term will be used for the air dilution system that is manufactured by Diesel and Gas Engineering Company (DGEC). The term is, however, sometimes used to refer to "lean combustion" engines (see below).

Lean Combustion

This term is used in this report to mean a turbo-charged engine with a precombustion chamber in which a small amount of a standard fuel mixture is burned to produce a torch that ignites a very lean mixture in the main combustion chamber. This is the system used in the Honda CVCC car engines.

The South Coast Air Quality Managment District (SCAQMD) defines a lean combustion engine as one that has more than four percent oxygen in the exhaust. Some naturally aspirated engines can be run at sufficiently lean mixtures to achieve four percent oxygen in their exhausts, but in this report, such an arrangement is not considered to be a "lean combustion" engine.

Air Dilution

This term is used broadly in this report for any method of burning a very lean mixture. In some engines, the mixture can be leaned out enough just by adjusting the carburetor to achieve significant reduction in emissions. The DGEC PSC system is one type of air dilution system.

May 6, 1987

CHAPTER 2

SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

None of the air emission control technologies for internal combustion engines using digester gas can be considered fully proven, i.e., to be so widely applied and so well understood that they can be designed from readily available data with a high degree of confidence that they will perform as intended and meet the regulatory requirements.

A considerable amount of information is available about emission control technologies for digester gas fueled engines but it is badly fragmented among various manufacturers, air pollution control agencies, and wastewater treatment agencies. There is an obvious need for a gathering and exchange of information.

Air Dilution/Prestratified Charge

The air dilution technology is "near-proven". The Orange County Sanitation Districts and the Los Angeles County Sanitation Districts (LACSD) have each submitted a Plan of Compliance to the South Coast Air Quality Management District (SCAQMD) which includes the use of air dilution technology on multiple engines. Four "Prestratified Charge" (PSC) air dilution systems by Diesel and Gas Engineering Company (DGEC) have been installed and tested on digester gas fueled engines in Ventura County and all have met the requirements of the Ventura County Air Pollution Control District (VCAPCD). Approximately 100 of the DGEC systems are in operation, mostly using natural gas as a fuel. The VCAPCD has stated in a letter (see Appendix A) that they consider this technology to be proven and will continue to issue Authorities to Construct for facilities proposing to use this technology.

A group of eight wastewater agencies in the Bay Area have demonstrated that their digester gas fueled engines emit only 4 to 7 grams/brakehorsepower-hour of NOx when operated with a lean air/fuel mixture. This level of emissions may be adequate to meet the requirements in their area.

On the other hand, there have been some difficulties. A DGEC PSC system on a natural gas fueled engine in an oil field application in Ventura County has come close, but not yet met, the requirements of the VCAPCD, possibly because of the type of governor that is installed on the engine. The VCAPCD hedged its letter by noting that their data are "fairly limited". Extensive experimentation has been necessary at the LACSD plant to develop an air dilution system which will meet their emission requirements. An attempt to test air dilution at the Santa Rosa wastewater treatment plant was thwarted by an inability to reduce the load on the existing equipment.

This is Sun Oils' Cat 398: Now equipped w/ lf kit it has compliance tested at 0.6gr/BHP-hr. Governor problem . . !

Base Metal Catlaytic Converter With Ammonia Injection (SCR)

Three of these systems, each by a different manufacturer, have been installed, operated and tested for about one year at wastewater treatment plants in California. Two are still in the startup phase. The current phase of testing of the third system has been completed and the system has successfully met the mission control requirements. SCR systems appear to be capable of meeting very low emission levels and apparently are not poisoned by digester gas. The are, however, large and have high capital and operating costs. The spent catalyst may be classified as a toxic waste, depending upon the catalyst used. Because of the size and cost, it appears that this technology is unlikely to be economically feasible for any but the very largest digester gas facilities.

Noble Metal Catalytic Converter (NSCR)

Several of these systems have been installed on digester gas fueled engines in California and all have failed in a short period, apparently due to poisoning of the catalyst by constituents of the digester gas. It appears extremely unlikely that this technology will be pursued further for digester gas fueled engines.

Lean Combustion Engines (Combustion Prechamber)

Several manufacturers are now beginning to offer retrofit kits which would convert standard rich burn engines into lean combustion engines, however, no such conversions have been done to date. The cost of such a retrofit can approach the cost of a new engine, requires the installation of compressors to boost the fuel pressure (two compressors if both natural gas and digester gas are used as fuel), may change the heat balance in an unacceptable way and may require considerable modification of the piping systems. Since a retrofit involves extensive rebuilding of the engine, there is a significant potential for unforeseen startup and mechanical problems.

For new installations, however, there seems to be a consensus of opinion that lean combustion engines represent a proven technology for meeting air emission requirements.

Thermal Reactor

The thermal reactor is used only for reducing CO emissions and does not reduce NOx emissions. Its applicability to emission control is therefore limited.

Air/Fuel Ratio Controller and Timing Adjustment

Air/fuel ratio controllers are available from several manufacturers and allow the air/fuel mixture to be closely controlled. NOx emissions usually can be reduced by running the engine either rich or lean of stoichiometric. In some cases, for example as proposed by the group of eight wastewater agencies in the Bay Area, the reduction in emissions which can be achieved by controlling the air/fuel ratio alone may be sufficient to meet emission requirements.

Air/fuel ratio controllers may improve the performance of other control technologies by allowing better control of engine operation.

Air emissions often can be somewhat reduced by retarding the engine timing. New devices which automatically change the engine timing as load and/or speed change are also being put in service. As with air/fuel ratio controllers, the main use of automatic timing adjustment mechanisms may be to improve the performance of other control technologies.

Removable Pelletized Catalyst

A removable pelletized catalyst does not affect emission levels, but it can facilitate maintenance of a catalytic converter by allowing particulate blinding to be easily corrected.

RECOMMENDATIONS

Because it is "near-proven", simple to install and to operate, and relatively inexpensive, it is strongly recommended that development of air dilution technology be encouraged to the maximum practical extent. Perhaps the best approach would be to install air dilution technology on some additional digester gas fueled engines and to carefully document the performance of these systems to provide a larger information base on the conditions under which this technology does, and does not, work.

It is also recommended that mechanisms such as the CASA Digeter Gas Utilization Subcommittee be set up and/or strengthened for exchanging information on emission control technologies.

CHAPTER 3

REGULATORY REQUIREMENTS FOR AIR EMISSIONS CONTROL

In California, air pollution control regulations and enforcement are handled by county or regional agencies. The county agencies are called Air Pollution Control Districts (APCD), for example the Ventura County Air Pollution Control District (VCAPCD). Although the air pollution control districts are units of the county government, they have jurisdiction over incorporated areas as well. There are regional agencies, called Air Quality Management Districts, for the San Francisco Bay and Los Angeles areas. These are named the Bay Area Air Quality Management District (BAAQMD) and the South Coast Air Quality Management District (SCAQMD). In this report, all of these agencies will be referred to as "Districts".

The Districts are rather independent and each writes its own regulations. While this has the advantage of allowing the air pollution control programs to be specifically tailored to the needs of the local area, it also results in differing standards and interpretations which make it difficult to compare results or discuss control measures between the Districts.

In addition, each District proceeds more or less on its own and technical information that is developed in one District often does not come to the attention of other Districts. There is no central clearing house for technical information among the air pollution control districts, nor among wastewater treatment agencies.

The lack of information transfer can be very costly. For example, although a noble metal catalytic converter failed on digester gas at the San Jose wastewater treatment plant as early as 1981, many similar systems were still being installed as late as 1984. All of the later units failed in the same manner that the San Jose unit failed.

Most Districts have a minimum size, below which stationary engines are exempt from the air pollution control regulations. These minimum sizes vary, for example, from 50 horsepower in Ventura County to 500 horsepower in the SCAQMD area. Some jurisdictions add up the capacities of all the engines on a given site to see if the minimum is exceeded while others consider each engine alone.

Above the minimum size, engines must be equipped with Best Available Control Technology (BACT). In the BAAQMD area, the technology selected as BACT for new installations must reduce the emissions of NOx to not more than 2 grams/brakehorsepower-hour.

In the SCAQMD area, for existing engines BACT consists of reducing nitrogen oxide (NOx) emissions by 90 percent initially (and 80 percent thereafter), or to 90 parts per million (PPM) for rich burn engines. For lean burn engines, NOx must be reduced by 80 percent initially (70 percent thereafter) or to 150 PPM. A lean burn engine is defined as one that has more than four percent oxygen in the exhaust. Carbon Monoxide (CO) is limited to 2000 PPM for both existing and new installations.

The San Diego APCD requires as BACT that NOx be reduced to 1.4 grams/brakehorsepower-hour and that selective catalytic reduction (SCR) be installed if cost effective. It is understood that the measure of cost effectiveness is that the total cost (capital and operating, annualized) not exceed $7,000 per ton of NOx removed. In practice, SCR has rarely been cost effective.

In air basins where the ambient air standards are not being attained and for very large emissions, the discharger may also be required to obtain "offsets". Offsets can be obtained by shutting down other equipment that emits air pollutants, but it usually is necessary to provide offsets on more than a one for one basis, e.g., if one is applying to emit 100 units of air pollutants, the requirements may be that 120 units of offsets be obtained.

Some difficulties arise in comparing the standards of one District to another. The use of PPM versus grams/brakehorsepower-hour requires that somewhat different parameters be measured. As an approximation, 75 PPM equals 1.0 grams/brakehorsepower-hour.

In attempting to comply with the regulations by obtaining a percent reduction, there is a question of what should be used as a baseline. The general expectation is that the reduction should be from the emission levels under "normal" engine operation, but how is "normal" to be defined? To maximize the probability of passing the test, an emitter would want to adjust the engine to produce the maximum emissions and to use this value as the baseline so that the percent reduction is maximized.

Another question is whether the engine is to be tested at full load, which is usually near the point of lowest emissions, or at partial loads as well. Full load might represent normal operation for an engine driving a base-loaded generator, but an engine driving a pump or blower probably operates near full load only a small percentage of the time.

In the SCAQMD area, the definition of a lean combustion engine as one with more than four percent oxygen in the exhaust has also led to disagreements. It has been reported that this definition was originally developed to apply to catalysts. It was known at the time that noble metal catalysts required a rich fuel mixture while base metal catalysts required a lean mixture which resulted in more than four percent oxygen in the exhaust. The definition was intended to separate these two types of catalysts.

When applied to air dilution techniques, the rule results in ambiguity because some standard rich burn engines can be leaned out enough to have four percent oxygen in the exhaust. In this case, the definition seems to connote a mode of operation rather than a type of hardware. As noted in Chapters 1 and 8, this report overcomes this difficulty by defining a lean combustion engine to be a turbocharged engine with a precombustion chamber.

May 4, 1987

CHAPTER 4

HOW AIR POLLUTANTS ARE FORMED

Whenever a fuel is burned, air pollutants are generated. The type and amounts of pollutants that are generated depend upon the fuel and the combustion conditions, and can include nitrogen oxides (NOx), sulfur compounds, carbon monoxide (CO), unburned hydrocarbons, and particulates. In general, the air pollutant of most concern from digester gas fueled engines is NOx and it is the pollutant which is the most difficult to prevent or remove. Carbon monoxide emissions often exceed the local standards but these can be reduced with relative ease by providing more oxygen so that combustion is completed to carbon dioxide. In some areas, sulfur oxide emissions also are of concern.

The air emissions control technologies discussed in this report fall into three categories:

Those that change the combustion conditions
Those that treat the pollutants after they are formed
Miscellaneous facilitating equipment improvements.

The first two of these categories are somewhat analogous to pretreatment of wastewater, i.e., preventing the pollutants from reaching the wastewater treatment plant, versus treating water pollution after it occurs.

Prevention

The fuel mixture that is fed to an engine is usually approximately the stoichiometric mixture, i.e., the mixture at which there is just enough oxygen present to combine with all of the fuel. Under ideal stoichiometric conditions, the exhaust from the engine would contain neither any oxygen nor any unburned fuel. For best fuel economy, an engine might be run on a slightly lean mixture. For maximum power, the mixture usually would be set a little rich of stoichiometric. A rich mixture may be required where maximum power is required or where the engine has to react quickly to rapid changes in speed and/or load.

The relative emission levels of various pollutants from a typical internal combustion engine versus the fuel mixture are shown graphically in Figure 1. The exact position of the various lines in Figure 1 varies with the type of fuel, the engine model, and other factors including engine condition but the shapes of the curves is usually more or less as shown for internal combustion engines burning gaseous fuels.

It can be noted in Figure 1 that (as one would expect from Murphy's Law) the NOx emissions are at a peak in the range of fuel mixtures that one would like to use, i.e., operation under normal conditions tends to produce the maximum amount of NOx. Operation either at very rich or at very lean mixtures results in much lower NOx levels.

In complete combustion, oxygen in the air combines with carbon in the fuel to form carbon dioxide, which is not a pollutant. If insufficient oxygen is present, the combustion process only goes to partial completion leaving carbon monoxide which is a pollutant. In Figure 1, the CO curve is high at the left side of the graph where the fuel mixture is very rich. As more oxygen is added and the mixture moves to the right toward stoichiometric, the amount of CO declines and it remains low in the lean mixture area to the right of stoichiometric because there is excess oxygen present.

The unburned hydrocarbon (HC) curve also is high at the left of the chart where there is not enough oxygen in the mixture to combine with all of the fuel and declines as the mixture moves toward stoichiometric.

The amounts of sulfur compounds that are emitted from an engine depends upon the amount of sulfur in the fuel and is not affected by the fuel mixture. In digester gas, the sulfur is mostly in the form of hydrogen sulfide. Where sulfur emissions must be controlled, the control measures usually involve adding chemicals (such as ferrous chloride) to the wastewater or sludge which will precipitate the sulfides so that they do not appear as gaseous hydrogen sulfide in the digester gas, and/or scrubbing the digester gas to remove the gaseous hydrogen sulfide. Control of sulfur emissions is required in relatively few areas and is only briefly mentioned in this report.

As shown in Figure 2, the formation of NOx is highly dependent upon termperature. At temperatures below about 1500 degrees F, very little NOx is formed. Since typical waste gas burners and hot water boilers operate at temperatures of about 1000 degrees F, no NOx problem is created when excess digester gas is flared or used in a boiler. In typical naturally aspirated rich burn engines, however, the combustion temperatures are in the range of 3000 to 4500 degrees and much NOx can be produced.

The information presented in Figures 1 and 2 suggest several strategies for controlling NOx emissions by altering the conditions of combustion. These strategies are discussed below and form the basis upon which some of the technologies that are presented in subsequent chapters of this report work.

One of the earliest strategies that was used was to adjust the engine carburetor to a rich mixture corresponding to the intersection of the NOx and CO lines. This was called the "equal NOx and CO" setting. As can be seen from Figure 1, this strategy might reduce the NOx emissions to perhaps one third to one half of the peak NOx emission levels, albeit at an increase in the amount of CO produced. In some cases (e.g., Santa Rosa), this reduction may be sufficient to meet the air pollution control requirements, but in many heavily developed areas, the requirements are for 80 or 90 percent reduction of NOx which cannot be met by this approach.

Another strategy that is suggested by Figure 1 is to run the engine at very lean mixtures. With lean mixtures, there is a relatively larger mass of mixture available and combustion temperatures do not rise as high. The lower temperature of combustion results in less NOx being produced.

There are practical difficulties which limit the extent to which lean mixtures can be used. As the mixture is leaned out further and further from stoichiometric, the tendency of the engine to misfire increases. It is very difficult to obtain stable and reliable operation of standard engines if the amount of air in the fuel mixture is as much as 25 percent more than stoichiometric. The ability of engines to use lean mixtures varies among the various manufacturers and it has been observed that some engines (e.g., those manufactured by Ingersoll-Rand) seem to have an inherent ability to operate on very lean mixtures.

Recent technological advances have improved engine performance on lean mixtures and have expanded the range of fuel mixtures which can be used. One such improvement is a high powered or "flame thrower" ignition system which uses high intensity coils and long duration spark plugs. These systems may use multiple spark plugs or spark plugs with multiple electrodes. High powered ignition systems are available from Altronics, Fairbanks-Morse, and probably other manufacturers and have been used in conjunction with several of the technologies discussed in this report.

Another innovation is the use of a precombustion chamber that burns a small amount of a standard rich mixture. The flame from this precombustion chamber throws a torch of flame through an orifice into the main combustion chamber which is hot enough to ignite a very lean mixture. This arrangement is the "lean combustion" technology which is discussed in Chapter 8.

Treatment

In addition to the strategies discussed above which alter the combustion conditions, air pollution control strategies which remove the pollutants after they are formed are also available. These include the catalytic converters and the thermal reactor.

Typical Emission Levels

Discussed below are the typical emission levels that might be expected from an internal combustion engine without any control devices. The emission levels depend on many factors, including at least: make and model of the engine; physical condition of the engine; engine tuning; and operational setting. Since so many factors affect the emissions level, the information presented below can be taken only as a rough guide.

Natural gas fueled engines might normally emit 15 to 18 grams/brakehorsepower-hour of NOx. This level could approach 25 grams/brakehorsepower-hour if the engine were to be seriously out of adjustment.

Digester gas fueled engines usually have uncontrolled NOx emission levels of just under 10 grams/brakehorsepower-hour. These levels are lower than for natural gas because the digester gas contains a significant proportion of inert carbon dioxide which reduces the heat of combustion. (See Chapter 5). As a worst case scenario, a digester gas fueled engine might emit 18 grams/brakehorsepower-hour if the tuning was far out of adjustment.

Diesel engines and dual fuel engines typically emit approximately 8 to 10 and 4.5 to 6 grams/brakehorsepower-hour of NOx respectively.

Carbon monoxide emissions vary significantly depending upon the fuel mixture. Where the mixture is set somewhere near the stoichiometric level, the CO levels usually are below 1000 PPM.

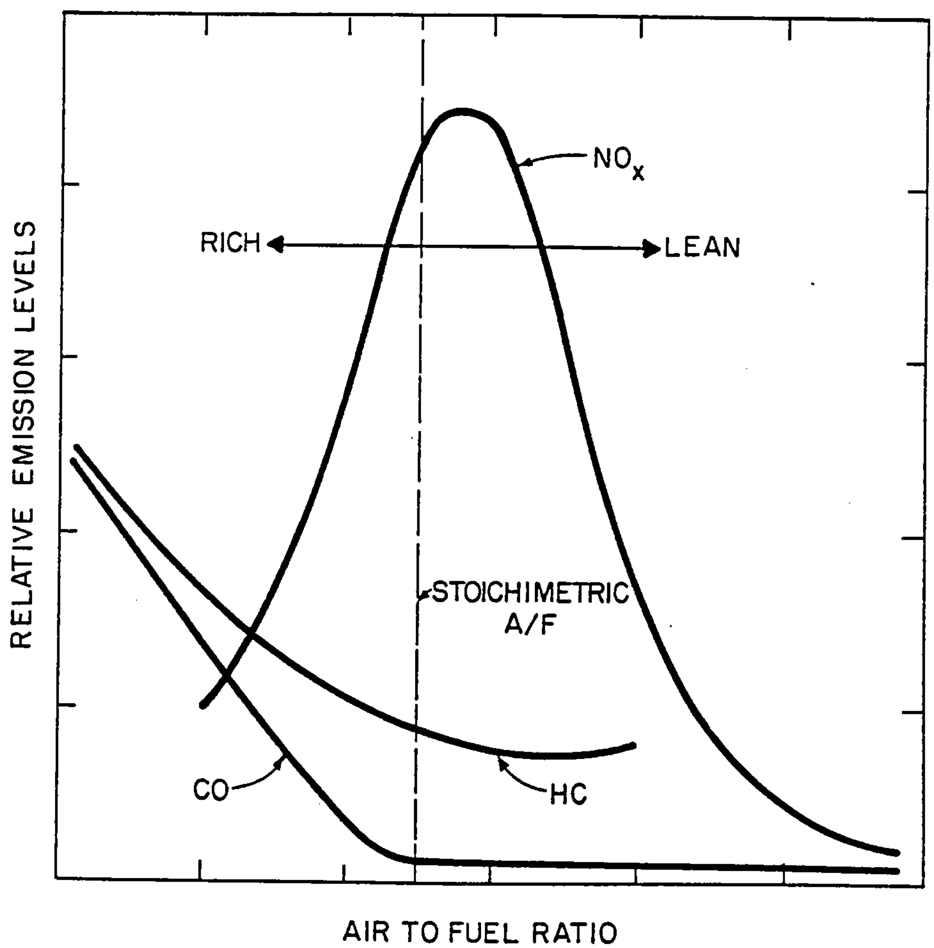
Hydrocarbon emissions from gas fueled engines are rarely exceed the regulatory requirements. Normally, total hydrocarbon (THC) levels are less than 2 grams/brakehorsepower-hour and non-methane hydrocarbon (NMHC) levels are less than 0.5 grams/brakehorsepower-hour.

Particulate emissions from gas fueled engines almost never exceed the regulatory requirements.

Fuel Value

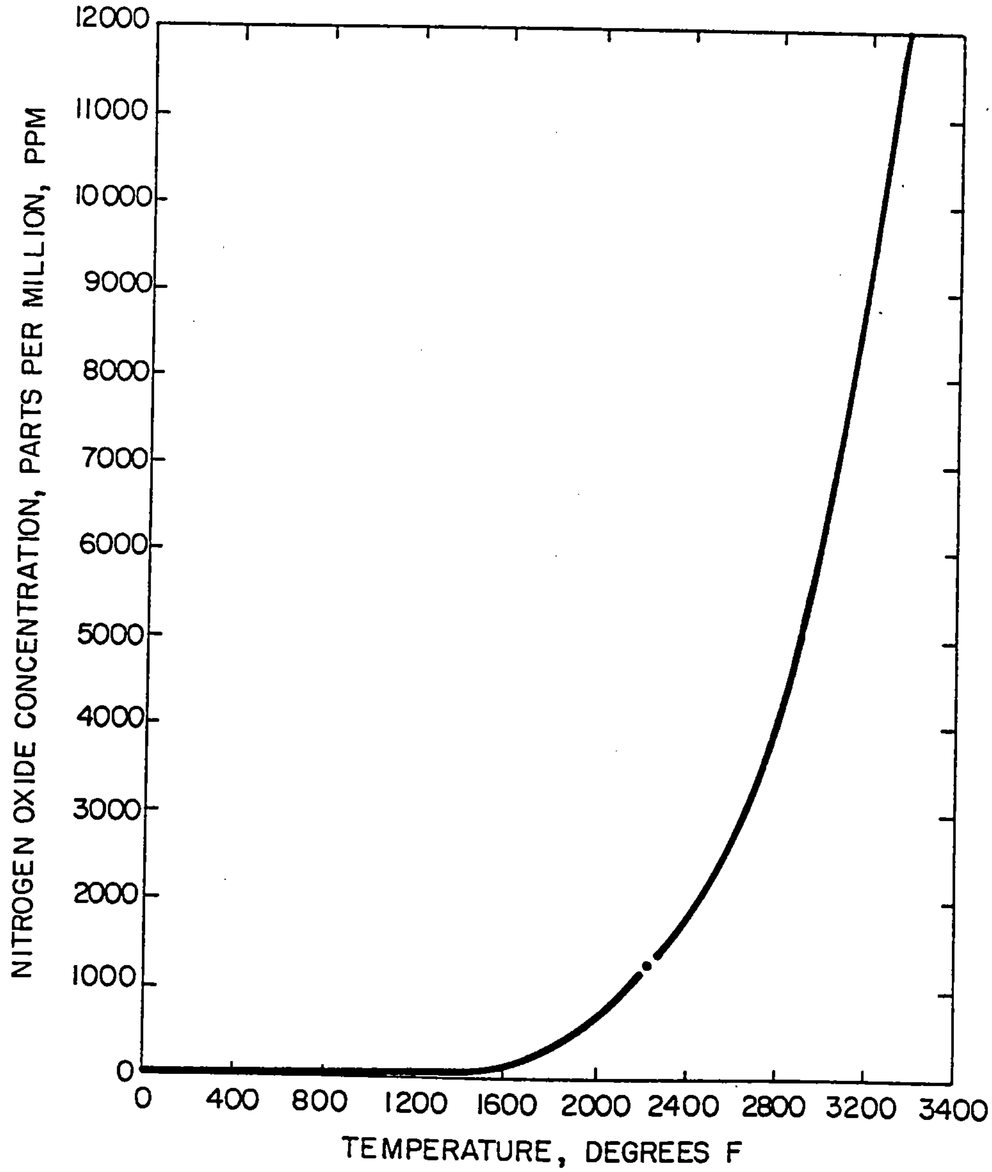
Digester gas typically contains 60 to 65 percent methane. The remainder of the gas is carbon dioxide, except for perhaps one percent of other gases. Included in the remaining one percent is hydrogen sulfide which typically ranges from 1000 to 2000 PPM. In areas that have a high sulfate level in the drinking water or get infiltration of seawater, hydrogen sulfide levels may rise as high as 5000 PPM.

The lower heat value of digester gas typically is about 550 BTU/Cubic Foot. By contrast, natural gas usually has a lower heat value of 913 BTU/Cubic Foot. Landfill gas often has a lower heat value of 450 BTU/Cubic Foot but this can vary considerably depending upon the nature of the material in the landfill. Landfill gas usually also many trace gases. such as chlorinated hydrocarbons, which may adversely engine performance.



EXHAUST EMISSIONS CHARACTERISTICS AS AFFECTED BY AIR-FUEL RATIO

FIGURE I



NITROGEN OXIDE FORMATION AS A FUNCTION OF TEMPERATURE

FIGURE 2

May 6, 1987

CHAPTER 5

AIR DILUTION/PRESTRATIFIED CHARGE

As discussed in Chapter 4, the amount of NOx that will be formed during combustion is reduced if the combustion temperature is lowered, and to a lesser extent if extra oxygen is available during combustion. One way of lowering the combustion temperature, is to dilute the charge in the combustion chamber with extra air or recirculated exhaust gas. Dilution spreads the heat of combustion over a larger mass of gas which results in a smaller temperature rise than when a near-stoichiometric mixture is burned. The large amount of excess air also reduces NOx formation and results in much more complete combustion and thus relatively low levels of CO and unburned hydrocarbons in the exhaust.

Digester gas is inherently diluted since it usually contains 35 to 40 percent CO_2. This natural dilution probably is the reason that digester gas fueled engines usually have significantly lower levels of NOx emissions than engines fueled with natural gas.

Many different installations have experimented with running engines on very lean mixtures and have achieved varying degrees of NOx reduction.

A practical difficulty in controlling NOx emissions to very low levels by dilution is that engines typically begin to misfire as the air content of the charge rises above the stoichiometric ratio by 25 percent or more. Some engine designs permit successful firing of much leaner mixtures than other designs. Two-stroke engines and turbocharged engines typically operate at very lean mixtures.

Technological developments which have allowed very lean mixtures to be successfully ignited include the use of a precombustion chamber to provide an ignition torch and improved and high powered ignition systems. The precombustion chamber approach, which is called "lean combustion" in this report, is discussed in Chapter 7. The improved ignition systems (sometimes called "flame-thrower" ignition systems in the vernacular) can include high intensity and long duration coils and special and/or multiple electrode spark plugs. On installations with variable load and/or speed, the ignition system may be programmed to change the spark advance with changes in the load or speed. Most installations seem to be using the Altronic III system but Fairbanks Morse offers its Model 9000 which is claimed to be comparable.

One form of air dilution system is the "Prestratified Charge" (PSC) system offered by Diesel and Gas Engineering Company (DGEC), Route 414, RD 2, Beaver Dams, NY 14812 (Tel. (607) 936 4124). This system inducts air, and in some applications exhaust gas, into the intake manifold runner close to the intake valve. The air is inducted next to the valve and the exhaust gas, when used, a bit farther away. The normal mixture is in the intake manifold beyond the dilution layer(s). When the intake valve opens, the prestratified layers of gas are drawn into the combustion chamber in order so that the normal (rich) mixture is at the top near the spark plug, the exhaust gas is in the middle, and the dilution air is at the bottom next to the piston. DGEC notes that in fact there is some mixing of the layers but claims to have laboratory data to show that to a considerable extent the charge remains stratified in the combustion chamber. DGEC believes that their system must result in a relatively rich mixture near the spark plug since they manage to obtain smooth ignition at mixtures that would cause misfiring if the charge were completely mixed. With their system, DGEC can successfully increase the air in the mixture to 40 percent above stoichiometric and beyond.

In this report, the term "air dilution system" refers both to the DGEC PSC system and to other air dilution systems, unless otherwise noted.

DGEC has more than 95 systems in operation, about 30 percent of which have been in operation for more than one year. Most of the systems are on natural gas fueled engines but several are on digester gas or landfill gas fueled engines.

The PSC system has been installed both on naturally aspirated and turbocharged engines, but no idgester gas fueled turbocharged engines are known to be in operation at present. DGEC usually supplies remachined intake manifolds which have been machined with the necessary ports, and the miscellaneous other hardware for the system, and arranges for turnkey installation and testing of the system. The intake manifolds from the customer's engine are returned to DGEC. Field installation thus involves only the exchange of external parts. No field cutting or tapping is generally required.

Where a slightly (say 50 to 75 PPM) higher level of NOx emissions can be tolerated, the PSC system can use air dilution only and the exhaust gas recirculation can be omitted. The PSC system must be made of stainless steel if exhaust gas is recirculated because of the corrosive nature of this gas. The air-only system does not require stainless steel and thus is less expensive. DGEC recommends the air-only system where naturally aspirated engines are loaded at less than 70 percent of full load and the required NOx reduction is less than 80 percent, and on all turbocharged engines.

The PSC system may require some auxiliary equipment. The engine may require an electronic (high energy, i.e., "flamethrower") ignition system if it does not already have one if a very low NOx level is to be guaranteed. If the engine does not operate with at least 7" Hg of vacuum, then the engine and dilution air must be pressurized (turbocharged) and only air is used for dilution. An Air Dilution Control Valve (ADCV) system is offered where engines operate at varying load to adjust the dilution rate to the changes in load. Air/Fuel ratio controllers are not required.

DGEC claims that their PSC system on naturally aspirated engines has consistently obtained results of 84 to 90 percent reduction in NOx on natural gas fueled engines, and absolute NOx emissions of less than 150 PPM @ 15 percent oxygen for digester gas and landfill gas fueled engines. Average NOx emissions of approximately 1.5 grams/brakehorsepower-hour are considered to be achievable. CO emissions in all cases are said to average less than 250 PPM on a corrected basis.

A group of medium size wastewater treatment agencies in the San Francisco Bay Area have been experimenting with air dilution as a retrofit technology for their digester gas fueled engines. Testing has demonstrated that their engines emit only 4 to 7 grams/brakehorsepower-hour of NOx if tuned to a lean air/fuel mixture. Because the NOx requirements in the Bay Area are less stringent than in the Los Angeles area, this level of emissions may meet the requirements. The eight agencies are requesting variances which allow them to operate using this air dilution technology. Because the air pollution control authorities may be reluctant to accept a technology that depends upon correct tuning of the engine, it has been proposed that oxygen sensors be installed in the exhausts to demonstrate that the engine is being operated at a lean air/fuel mixture.

Advantages of Air Dilution/Prestratified Charge Systems

- Mechanically simple.
- Relatively low capital costs.
- Low operating and maintenance (O&M) costs.
- Improved fuel economy.
- Retrofit or new.
- Fairly widely tested.
- Often provides very low levels of emissions.

Air dilution systems, including the PSC system, tend to be quite simple. In some cases, all that is required is a change in the air/fuel ratio plus perhaps an improved ignition system. The O&M costs were reported by the Los Angeles County Sanitation Districts (LACSD) and the Orange County Sanitation Districts (OCSD) to be "negligible".

The cost of the DGEC system is higher than the cost of some of the other air dilution technologies and varies with the number of cylinders. The installed cost is reported by the manufacturer to approximate $1,500 per cylinder for the air only system and $2,500 for the air and exhaust gas (stainless steel) system. Thus the cost for retrofitting a six cylinder engine which might be driving a generator with a rating of a few hundred KW would be in the range of $10,000 to $15,000. Source testing and other services and any other system modifications would, of course, not be included in this cost, and might double the costs above.

Another advantage of air dilution systems is that they usually improve the fuel economy by perhaps five percent. DGEC has observed a range of 2 to 14 percent improvement in fuel economy.

The PSC systems have only been installed as retrofit units to date. There seems to be no reason, however, that they could not be installed as original equipment. The availability of this technology in an easy retrofit package would be especially advantageous to existing installation which are not currently able to meet air pollution control regulations.

A significant number of PSC systems are in operation and numerous installations are experimenting with this or other air dilution systems. Considerable amounts of technical data are therefore becoming available on the air dilution technology.

The PSC system has achieved very low levels of emissions which have met the requirements of several air pollution control districts in California. In addition, LACSD has submitted a plan of compliance to the South Coast Air Quality Management District which includes the use of air dilution technology to meet the emissions control requirements. These are discussed later in this chapter.

Disadvantages of Air Dilution/Prestratified Charge Systems

Misfiring.
Derating of the engine.
Uncertain results in some installations.

The problem of misfiring when engines use very lean mixtures was discussed above. Ways of assuring reliable ignition of lean mixtures, such as the PSC system and flamethrower ignition systems, have been devised to overcome this problem. Nevertheless, beyond some amount of dilution misfiring may become a problem.

All of the air dilution systems result in the derating of a naturally aspirated engine. These engines typically are rated at a Brake Mean Effective Pressure (BMEP) of 115 PSI. Best results seem to be achieved when the BMEP under operation is 90 PSI or lower, thus to get the lowest emissions, the engine output is derated by perhaps 25 percent.

The need for derating may not be a serious problem at some wastewater treatment plants. If the engine is generating power, then the plant can simply settle for generating less power. (If the generator is connected to dedicated loads, some of these may have to be shifted to other circuits). In addition, there may be 25 percent extra capacity in the engine since engines come only in discrete sizes and during design the usual practice is to round up to the next larger size. For example, with Waukesha engines, each model tends to have a capacity that is 20 to 45 percent greater than the next smaller size.

Furthermore, it may be possible to recover full-load carrying capacity by installing a low ratio turbocharger, at some additional cost.

Derating may be unacceptable, however, where the full capacity of the engine is needed for the application, for example where the full capacity of the pump that the engine is driving is needed during peak flow conditions. It may also be impractical to practice air dilution where the engine is driving a positive displacement blower and the load cannot be reduced. Derating will also mean a loss of income from power generation, which may be a significant economic factor. In addition, derating may result in an inadequate supply of heat from the system. This lack of heat may be especially important in smaller installations where all of the heat available from the system is needed to keep the digesters warm.

While air dilution has often been successful in meeting emission control requirements, there are some installations where this has not been the case. Some of these are discussed in the case histories below. It should also be noted that considerable experimentation has been required at some of the installations where they have been successful. The number of personnel and the types of skills that are available at smaller wastewater treatment plants may not be adequate to provide such experimentation.

Case Histories

Ventura County

DGEC PSC systems have been installed on a Waukesha 817 NA engine driving a generator at the Santa Paula wastewater treatment plant, on two Caterpillar G-379 NA engines driving influent pumps at the Oxnard wastewater treatment plant, and on a Waukesha 9390 engine driving a generator at the Oxnard plant. All four of these engines were tested for emissions and passed. Some of these tests were witnessed by staff members of the Ventura County Air Pollution Control District.

PSC systems have also been installed on natural gas fueled engines at two oil company installations. These are a Waukesha 817 in a constant speed and load application at a Chevron installation in the Montalvo area and a Caterpillar 398 on a variable load compressor application at a Sun Oil installation in Santa Paula. Emissions at both installations have been tested. The constant speed and load Chevron installation has passed.

The DGEC system on the Sun Oil installation has achieved NOx reductions of 88 to 94 percent, but is required to achieve a 90 percent reduction at all times. According to DGEC, the hydraulic/mechanical governor on this engine does not respond adequately to the occasional perturbations ("burps") on the suction side of the compressor. The engine loses speed and does not recover properly.

Unit has passed @ 0.6gr/BHP-hr see below ¶

The system can be made to obtain 90 percent NOx reduction but requires manual attention to recover from the perturbations. This is the engine which is referred to in the next to the last paragraph of the Ventura County Air Pollution Control District letter of February 27, 1987 which is discussed at the end of this chapter. DGEC is continuing to work on the Sun Oil installation. They propose to install an automatic dilution control valve on this installation which they believe will allow the system to successfully meet the emission requirements. They are also proposing that the engine be turbo-boosted to bring it up to full rated capacity.

Los Angeles County Sanitation Districts (LACSD)

In 1986, a PSC system was tested at LACSD on an Ingersoll-Rand Model PKVG-10 engine rated at 1,180 BHP. This engine operates at speeds from 198 to 300 RPM and loads varying between 220 and 1,000 BHP pumping primary effluent. There are large diurnal variations depending on flows and tidal conditions and during storm flows, the full capacity of the engine is needed. The engines are equipped with mixing valves rather than carburetors.

The PSC system did <u>not</u> meet the expectations of the LACSD in this application. The LACSD installation is somewhat unusual in: the type of engine; the very low engine speed; the mixing valves; the large variation in speed and load; and the need to avoid derating the engine during periods of storm flows. Some combination of these factors may have prevented the PSC system from meeting the District's expectations.

After the DGEC tests were finished, an Altronic III ignition system was installed on the test engine. The District found that the DGEC air ejectors coupled with an automatic spark advance system synchronized with engine speed and calibration of the mixing valves was capable of reducing NOx to less than the required 90 PPM @ 15 percent oxygen. By a more or less trial and error approach, the District has been able to find a combination of mixing valve calibration and spark angle setting that works over the entire dry weather flow speed range without the operator having to make manual adjustments to any equipment. The settings are, however, unique for each engine.

On December 31, 1986, LACSD submitted a Plan of Compliance to the South Coast Air Quality Management District (SCAQMD) which included the proposal to install the air injection and automatic spark advnace system on the other four identical primary effluent pumps.

The LACSD Plan of Compliance also involves use of a lean air/fuel ratio to bring two of its three secondary influent pumps into compliance. The secondary influent pumps are driven by Ingersoll-Rand engines similar to the primary effluent pumps, but these three engines are subjected to much smaller diurnal variation in speed and load and are less heavily loaded. In addition, some derating of these engines from full capacity is acceptable.

Extensive testing by LACSD has demonstrated that NOx emissions from two of these engines can be reduced to less than 90 PPM @ 15 percent oxygen simply by setting the air/fuel ratio controllers to a very lean mixture and optimizing the spark angle (timing).

<u>Orange County Sanitation Districts (OCSD)</u>

During July 1986, OCSD conducted extensive tests on a Waukesha 7042 engine equipped with a DGEC PSC system. It was found that NOx emissions of approximately 125 PPM @ 15 percent oxygen could be consistently achieved. Since there was more than 4 percent oxygen in the exhaust when operating with the PSC air dilution system, OCSD claimed that this engine was now a lean burn engine and that the SCAQMD 150 PPM requirement for lean combustion engines was met. PSC equipment was ordered for and installed on an additional Waukesha 7042 (Rothrock 1) and two White Superior 16-G825 V-16 engines (Foster 9 and 10). All four engines drive pumps.

Late in 1986, SCAQMD notified OCSD that they did not consider these engines to be lean combustion engines even though they have more than 4 percent oxygen in the exhaust. Several meetings and hearings have been held and the discussion of this issue is continuing.

Early in 1987, the three engines which were newly fitted with the PSC devices were tested. In general, it was found that in the testing that the NOx emissions could be held below 150 PPM if the oxygen content in the exhaust was kept high, i.e., if very lean mixtures were used.

OCSD has 17 units equipped, tested & passed @ < 90ppm NOx

It is understood that the SCAQMD and the OCSD are discussing a compromise in which the PSC systems will be accepted and permit conditions will be set at some level which can be reasonably achieved with this equipment.

<u>Waukesha Experimentation at the Santa Rosa Wastewater Treatment Plant</u>

The City of Santa Rosa has three Waukesha engines direct coupled to lobe type positive displacement blowers, which supply air for the activated sludge process. At present, the air permit allows them to run only one engine at a time since the engine emissions are uncontrolled. The plant will be somewhat short of aeration capacity, especially during warmer months, until some planned improvements to the aeration system can be made. They would therefore like to operate more than one engine at a time.

Waukesha Engine Division of Dresser Industries assisted the City of Santa Rosa in conducting some experiments to achieve lower NOx emissions by operating at leaner air/fuel mixtures. Tests run by Waukesha at its facility in Waukesha, Wisconsin indicate that NOx values in the range of 2 to 3 grams/brakehorsepower-hour may be achieved at about 7 percent exhaust oxygen carburetor setting. In order to run at this lean mixture, the load on the engine must be reduced to about 70 percent of its rated capacity. To assure reliable ignition of the lean mixture, an Altronic III high energy (flamethrower) ignition system was installed on the engine.

Testing was conducted in February, 1987. It was not possible to operate the engine with exhaust oxygen concentrations above 6.3 percent because the positive displacement blower is direct coupled to the engine and exerts virtually full load on the engine at all speeds and thus prevents the engine from being partially unloaded. At 6.3 percent exhaust oxygen concentration, the NOx emission rate was 9.1 grams/brakehorsepower-hour at a timing of 26 degrees before top dead center (BTDC). The NOx level declined to about 6 grams/brakehorsepower-hour at a setting of 20 degrees BTDC. This latter NOx emission rate corresponds to 8.6 pounds per hour which was in excess of the 7 lb/hour limit that had been set.

Further testing revealed, however, that NOx emissions could be reduced to 4.5 grams/brakehorsepower-hour by running the engine rich and at a timing of 10 to 12 degrees BTDC, albeit at a considerable increase in CO emissions. A point was found which appears to allow simultaneous operation of two engines to meet the requirements for both NOx and CO total emissions and the City of Santa Rosa is applying for a temporary variance to operate in this manner until improvements can be made to the aeration diffusion system which will eliminate the need to operate more than one engine driven blower.

Conclusions and Recommendations

Air dilution systems are a promising emission control technology. Different air dilution systems have been demonstrated to have met the regulatory requirements in several digester gas installations. The capital costs can be relatively low, O&M costs are extremely small, and the systems are simple.

But are the air dilution systems "proven" technology?

Since the digester gas installations of the PSC system are in Ventura County, a letter was sent to the Ventura County Air Pollution Control District (VCAPCD) asking them if they consider the DGEC PSC system to be a "proven" technology, i.e., would they issue an Authority to Construct to a project that proposes to use this technology. The letter to the District and their reply are presented in Appendix A. Item 4 of the VCAPCD states that they consider the PSC system to be a proven technology and that they will issue Authorities to Construct for installations proposing to use this system, provided that they incorporate the exhaust gas recirculation model. (The air-only configuration apparently is not yet considered proven or is considered inadequate). The VCAPCD letter goes on, however, to note that their data are "fairly limited" and that the PSC system installed on a Caterpillar G398 NA engine (the Sun Oil installation) has not yet managed to meet the requirement of a 90 percent NOx reduction. The Sun Oil installation is discussed above.

Orange County has successfully tested the PSC system and on the basis of these tests has installed it on three additional engines as its means of compliance with the emission control requirements.

The Waukesha engine company believes that it can achieve emission levels as low as 2 grams/brakehorsepower-hour with air dilution techniques. Although they were was unsuccessful in demonstrating this at Santa Rosa, Waukesha is continuing to experiment with the concept of air dilution.

DGEC has stated that it will offer to guarantee on new installations that its PSC system will reduce NOx emissions to not more than 2 grams/brakehorsepower-hour if certain provisions are incorporated into the design of the facility. The most significant of these provisions is that the engine be sized so that it operates at no more than about 70 percent of capacity or is fitted with a low ratio turbocharger to bring the engine back up to full capacity.

While the number of successes with air dilution systems is impressive, there have been some disappointments. The PSC system did not meet the expectations at LACSD and has not yet worked at the Sun Oil installation. Waukesha, a very experienced engine manufacturer, was unable to conduct a successful air dilution test of their proposed air dilution system at Santa Rosa. The LACSD installation is somewhat unusual (low speed Ingersoll-Rand engines, mixing valves rather than carburetors, varying load and speed) and the way in which the regulations should be applied at LACSD and OCSD is still under discussion, i.e., the conditions at these plants may be unique and the solutions developed there may not be entirely applicable elsewhere. Successful employment of these technologies may require extensive experimentation, which may be beyond the capabilities of the staff of a smaller wastewater treatment plant.

Based on the available information, it is our opinion that the <u>air dilution technologies cannot be considered fully proven at this time</u>. It would therefore seem to be imprudent to prescribe an air dilution technology as a blanket solution to emission control for all digester gas fueled engines

It is clear however that some air dilution technologies are "<u>near-proven</u>" and because of their simplicity and relatively low cost, they are very attractive. It is therefore <u>strongly</u> recommended that development of various air dilution technologies be encouraged to the maximum practical extent.

Perhaps the best approach will be to install air dilution technologies on some additional digester gas fueled engines and to carefully document the performance of these systems to provide a larger information base on the conditions under which these technologies do, or do not, work. This appears to be occurring, i.e., Los Angeles and Orange Counties are proceding with DGEC systems and the eight Bay Area agencies are proposing to use lean air/fuel mixtures with oxygen sensors in the exhausts for monitoring performance.

May 6, 1987

CHAPTER 6

BASE METAL CATALYTIC CONVERTERS WITH AMMONIA INJECTION (SCR)

Catalytic converters are devices attached to the exhaust pipes of engines which chemically convert the NOx in the exhaust stream to other compounds. The chemical reaction is facilitated by the use of a catalyst which is coated on either a ceramic honeycomb matrix or pellets (see Chapter 11) through which the gas passes.

There are two general categories of catalytic converters--base metal and noble metal. Noble metal catalytic converters are discussed in the next chapter. The two different types of systems of catalytic converters have approximately the same physical configuration; the differences are in the catalysts used and the injection of ammonia in base metal converters.

The base metal catalytic converter normally uses a vanadium and/or titanium catalyst. The optimum operating conditions are a temperature range of 600 to 850 degrees F and a lean fuel mixture. By contrast, noble metal catalytic converters require a rich mixture.

The chemical reaction by which the SCR system works can be characterized as follows:

$$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O$$

As can be seen from the equation, it is necessary to have oxygen available (i.e., to have a lean mixture) and to inject ammonia. The ammonia reacts selectively with NOx, therefore this process is called Selective Catalytic Reduction (SCR). The amount of NOx reduction is theoretically proportional to the amount of ammonia fed. In practice at LACCO, the NOx:Ammonia molar ratio ranged from 1:1.1 at lean fuel mixtures to 1:1.3 at very rich mixtures.

The noble metal catalytic converters cause reaction of a broader spectrum of constituents of the digester gas and thus the noble metal process is called Non-Selective Catalytic Reduction (NSCR).

Advantages of the SCR System

- Not poisoned by digester gas.
- Can achieve very low NOx levels.
- Lower cost catalyst than noble metal catalytic converters.

The major advantage of the SCR system is usually considered to be that it overcomes the cause of the failure of noble metal catalytic converters--poisoning of the catalyst. (See Chapter 7).

Another advantage of the SCR system is that it can achieve very low levels of NOx emissions. To do so, however, requires that increasing levels of ammonia be injected to drive the chemical reaction to nearly complete removal of the NOx. As 100 percent NOx reduction is approached, depending on mixing efficiencies, there may be some ammonia measured in the exiting exhaust. NOx reduction is dependent on the availability of ammonia with which to react. In short, mixing of the exhaust gas and ammonia is very important.

There are no known air pollution control agencies rules or regulations which set standards for ammonia emissions. However, some District staffs have adopted an operating criteria of 50 PPM of ammonia in the exhaust stream. This number is the same as the OSHA standard for the work place.

Disadvantages of the SCR System

- Plugging of the honeycomb type catalyst.
- High capital cost.
- High O&M cost
- Small derating of the engine
- Used catalyst may be a toxic waste, depending on the metal used.

In order to bring the exhaust gas into intimate contact with the catalyst, the catalyst is placed on some sort of inert matrix with small openings or impregnated on pellets. This results in the gas passing close to a large surface area containing the active catalyst. The exhaust gas contains, however, some particulate matter which could plug ("blind") the small openings in the media and thus to restrict the flow of exhaust gas and increase the backpressure on the engine. Since there is a limit to the amount of backpressure that the engine can operate against, the catalyst must be cleaned or replaced when it becomes plugged. Considerable experimentation has been done with guardbeds to protect the catalyst from plugging.

The capital cost of base metal catalytic converters is relatively high, perhaps approaching $75,000. The O&M costs are also relatively high both for the ammonia gas that must be fed and for periodic replacement of the catalyst. Catalysts are typically expected to last three to five years. The cost of replacing the catalyst may be about 70 percent of the original cost of the system.

Because the engine must be run lean for the SCR system to work, there may be a slight loss of capacity (derating) on naturally aspirated engines. The amount of derating is less than with the air dilution systems discussed in the previous chapter because the mixtures used with the SCR system are not nearly as lean as those used in air dilution systems. Two-stroke engines or turbocharged engines which already operate with a lean air/fuel ratio would not be subject to this derating.

A significant unknown in the use of base metal catalytic converters is whether the spent catalyst constitutes a hazardous waste. If it does, then it must be disposed of in a toxic waste landfill and the agency that used the catalyst becomes liable for lawsuits that might arise concerning the landfill. The vanadium that is used in units is known to be extremely hazardous in the powder form that is used in the manufacturing process. It is thought that the vanadium is safely tied up in the ceramic matrix of the catalyst so that the catalyst itself is not hazardous but this apparently is not entirely accepted as a fact. Other catalyst materials which will not be considered to be toxic wastes may be available from some manufacturers.

Case Histories

There are only three known California installations of noble metal SCR catalytic converter systems on digester gas fueled engines, although the technology has been used on natural gas fueled engines:

- Los Angeles County Sanitation Districts--Nitrogen Nergas
- San Jose--Engelhard
- San Diego Point Loma--Kawasaki.

In addition, a base metal catalytic converter installation without ammonia injection was installed at Daly City.

Information received about these installations is discussed below.

Los Angeles County Sanitation Districts (LACSD)

LACSD tested a base metal catalytic converter supplied by Nitrogen Nergas (West Coast representative: Reino Corbeil, P.O. Box 1291, Lomita, CA 90717, Tel. (213) 539 5541) on an Ingersoll-Rand Model PKVG-10 engine driving a secondary influent pump. This engine is a 10 cylinder, slow speed (300-310 rpm), 1150 hp model, and is subject to variations both in load and speed.

The reactor consists of stainless steel inner baskets and a 3/8" carbon steel outer shell. The total reactor is 5' in diameter by 8' tall. The reactor is mounted on a structural steel frame. designed to meet earthquake loadings. A pelletized catalyst is used and the reactor contains a proprietary guardbed for filtering the exhaust gas before it enters the catalyst. The normal temperature operating range is between 525 and 900 degrees F. Temperatures somewhat outside this range can be accommodated by inclusion of special features in the design. The LACSD installation is presently the only Nitrogen Nergas system on a digester gas fueled engine. Nitrogen Nergas does have several SCR systems in operation on natural gas fueled engines.

The total cost of the equipment was about $50.000. Adding the cost of installation by District personnel at an estimated $15.000. the total installation cost was approximately $65.000. Nitrogen Nergas offers a turn-key installation and reports the highest installation cost to date was less than $20.000.

The regulatory requirement for NOx at LACSD is 90 PPM @ 15 percent oxygen for rich burn engines. which corresponds to 1.5 grams/brakehorsepower-hour. At the lean mixtures recommended by Nitrogen Nergas (0.5 percent oxygen or higher). the SCR system met the NOx emission requirement by reducing the 7. grams/brakehorsepower-hour uncontrolled NOx level at 310 RPM to a level of only 1.1 grams/brakehorsepower-hour. This latter figure corresponds to 20 PPM. A 90 percent NOx reduction was possible at exhaust oxygen concentrations of approximately 3 percent or higher.

There was a slight decrease in the overload capacity of the engine at the lean fuel mixtures used.

The ammonia flow rate required for achieving the NOx reduction to 90 PPM at 15 percent oxygen was 3 SCFM (a mass flow rate of 8 pounds of ammonia per hour). Ammonia costs ranged from $5 to $12 per day.

An ashless synthetic crankcase oil was used in order to avoid any possible fouling of the catalyst by oxidized oil additives. The use of this ashless oil was possible because of the relatively low levels (100 PPM) of hydrogen sulfide in the digester gas. Levels of 500 PPM or more would rapidly deteriorate such oil. The effect of regular petroleum-based crankcase oil on catalyst longevity is at this time unknown in digester gas applications. In conventionally fueled applications, oils containing ash create no problems when exhaust temperatures are maintained at 650 degrees or higher. At lower exhaust temperatures, the ash is collected on the guardbed and this low cost material is handled as necessary. The system was operated for about 9000 hours without any noticeable indication of plugging of the catalyst or guardbed and no reduction in catalyst efficiency.

If the hydrogen sulfide in the digester gas proves to be a problem. Nitrogen Nergas offers a low cost guardbed material that removes sulfur to 2 PPM. This catalyst is slightly more expensive than the guardbed material normally used by Nitrogen Nergas but is equally effective in protecting the SCR catalyst.

LACSD felt that the Nitrogen Nergas system proved itself to be effective in reducing NOx to the required levels. The optimum conditions were: 650 to 750 degree F exhaust temperature leaving the reactor: excess oxygen in the exhaust of 0.6 percent and higher: and use of a synthetic crankcase oil (which requires a low hydrogen sulfide level in the digester gas). There was a slight reduction in engine overload capacity.

Nitrogen Nergas has indicated that they will guarantee that their system will meet the air pollution rules and regulations. as well as all OSHA regulations and all local codes. In. addition they will guarantee the catalyst life.

The Plan of Compliance which LACSD submitted to the South Coast Air Quality Management District proposed. however. the use of an in-house developed air dilution technology which was considered to be more suitable to their operation than SCR technology.

<u>San Jose</u>

The base metal catalytic converters at the San Jose wastewater treatment plant was supplied by Engelhard Corporation. Specialty Chemicals Division. 2655 U.S. Route 22. Union. NJ 07083 (Tel. (201) 964 2763). It is the only Engelhard base metal unit that has been installed on digester gas.

The system serves two turbocharged V-16. 3900 horsepower DeLaval Enterprise engines that drive 2800 KW generators. One converter is installed on each side of each engine so that there are a total of four catalytic converters.

The total cost of the system including the ammonia feed system. controls. etc. was about $600,000 for the four units. The converters represented about thw-thirds of this cost. A change of catalyst is estimated to cost about $225,000.

The regulatory requirement at San Jose is a NOx emission of not more than 1.5 grams/brakehorsepower-hour (a reduction of [illegible]0 percent). There is no ammonia requirement in the San Jose permit. at present. The permit indicates that the ammonia injection rate and slippage rate will be determined at a later time.

Although Engelhard guaranteed the system at San Jose, they noted that guarantee offers on systems elsewhere will depend on fuel quality, i.e., on the preconditioning of the fuel.

San Diego

Kawasaki base metal catalytic converters have been installed on two 600 RPM HVA 12G (12 cylinder) DeLaval Enterprise engines at the Point Loma wastewater treatment plant in San Diego. The engines drive constant speed and load generators. The catalytic converters are very large, measuring approximately 30' high x 4' wide by 7' long.

A titanium catalyst on a ceramic honeycomb is used in the Kawasaki units. It is thought that this will be considered a toxic waste when the catalysts are disposed of. The total cost of the two catalytic converters was approximately $1.3 million. The cost of the catalyst bed for each unit is $500,000. The lead time for obtaining a replacement charge is six months, and a crane is required to install the bed.

The regulatory requirements are 1.4 grams/brakehorsepower-hour and SCR for lean burn engines.

The catalysts are said to work well but there have been numerous problems with other parts of the system. The automatic ammonia feed system which was supposed to pace the supply of ammonia to the NOx level has not worked well and the system is now run manually. The air/fuel ratio controller has not proven capable of following the hourly variations in the system, possibly because the air density changes significantly as the sea breezes change.

The total allowable pressure drop through the catalyst is 4". This has been approached several times. The plant staff has implemented a program of cleaning the catalyst by a combination of vacuuming it and hosing it. The cleaning procedure requires disassembly of parts of the system and takes four days. There has been a gradual increase in the permanent pressure drop after cleaning, however, which has now reached 3". The system has been in service 16 months and it appears that it will require replacement after approximately two years of operation at the previously mentioned cost of $500,000 per unit.

Some of the blinding problems are thought to have resulted from magnesium in the sea air reacting with the sulfated ash in the oil. This resulted in an extremely hard deposit on the cylinder walls, clogging of the heat exchangers, and perhaps the blinding of the catalyst. The plant shifted to a calcium barium ash oil. The particulate matter that occurs when this oil is used is powdery and easy to remove.

Daly City

A Maxim base metal catalytic converter was installed at Daly City (formerly North San Mateo County Sanitation District). The original design and installation of the system did not include a thermocouple heat sensor upstream of the converter. During a misfire, raw fuel passed to the converter, started a serious internal fire and destroyed the unit. It was replaced by the supplier at his cost because the sensor was omitted from the system even though it was specified by Maxim.

The replacement unit lasted for only one month in regular use.

The next unit was a Maxim pelletized catalyst but the pellets are not removable from this model. It appeared to be functioning for a while but downstream tests proved that it was not giving satisfactory NOx removals when running on digester gas. The media has been removed from the housing and the engine is being run without a catalytic converter pending further developments with the Bay Area Air Quality Management District.

Conclusions

The base metal catalytic converter with ammonia injection (SCR) technology must be considered as unproven at this time on digester gas applications. Each of the three known manufacturers has only a single installation in California. Although the Nitrogen Nergas facility at LACSD performed satisfactorily during a year of testing, the other two systems are still in the startup and testing phase. The capital and operating costs of these systems are sufficiently high that the technology appears to be applicable only to the largest digester gas facilities. The catalyst materials used by some manufacturers may be deemed to be toxic material.

May 6, 1987

CHAPTER 7

NOBLE METAL CATALYTIC CONVERTERS (NSCR)

Noble (precious) metal catalytic converters have been widely and successfully used to control emissions of NOx from natural gas fueled engines. These devices consist of a chamber in the exhaust pipe of the engine where the exhaust gases are forced against some sort of medium that is coated with a catalyst. The catalyst facilitates a chemical reaction which converts the pollutants in the exhaust gas stream into non-polluting compounds.

As discussed in Chapter 6, noble metal catalytic converters have about the same physical configuration as base metal catalytic converters. The major differences are: a precious metal, often platinum, rather than a base metal is used; rich rather than lean fuel mixtures are required; and the optimum operating temperatures are high, 1200 to 1400 degrees F compared to the 500 to 850 optimum range for base metal catalytic converters. Because of the fairly narrow range of optimum conditions, air/fuel ratio controllers are often used with noble metal catalytic converters.

The catalysts used in noble metal catalytic converters cause reactions of a broad spectrum of compounds, including oxygen (thus the need for rich fuel mixtures which leave little oxygen in the exhaust) and are not specific for NOx. This technology is therefore called Non-Selective Catalytic Reduction (NSCR).

In the early 1980's, noble metal catalytic converters were installed at several wastewater treatment plants in California, including at least: Orange County, Los Angeles County, Encina, Aliso, Fairfield-Suisun, Oro Loma, West Contra Costa, South Bayside, Hayward, Delta Diablo, Dublin-San Ramon, Central Marin Sanitation Agency, and Union Sanitary District. At all of these facilities it was found that within a short period of time, the efficiency of the catalyst declined to very low levels and that virtually no control of NOx emissions was being achieved. Similar results were experienced with landfill gas fueled engines in many locations including the West Monterey County Marina Landfill and at Menlo Park.

Extensive investigations of these failures have concluded that the major cause was some sort of "poisoning" of the catalyst. The source of the poisoning has been attributed to the fuel, the engine oil, and other factors but since the poisoning phenomenon does not seem to have seriously affected engines fueled with natural gas it appears that the digester gas is at least one source of the poisoning agent.

Despite considerable experimentation, to date no solution has been found to the problem of poisoning of noble metal catalysts and this technology is considered to have failed completely on digester gas fueled engines.

There have been some problems with fires and/or explosions in catalytic converters. If the engine misfires, unburned fuel can be discharged to the exhaust system. This fuel can create a fire or an explosion when it hits the hot catalyst. Such problems may also occur in base metal catalytic convertors

Another problem that has been reported is cracking of rigid catalyst media. If the media cracks, the exhaust gas can escape through the cracks without properly contacting the pollutants with the catalyst. The cracking apparently can be caused by excessive temperatures or explosions in the system.

May 6, 1987

CHAPTER 8

LEAN COMBUSTION ENGINES (COMBUSTION PRECHAMBER)

As discussed in Chapter 4, NOx emissions can be reduced by operating engines on very lean fuel mixtures but there are practical difficulties in obtaining stable operation on lean mixtures. One solution to the problem of getting lean mixtures to ignite reliably is the "lean combustion" engine. In this report, a lean combustion engine is defined as one with a combustion prechamber.

Approximately 5 percent of the fuel is fed as a rich mixture into a small prechamber which is located near the main combustion cylinder and connected to it by a small port. This rich mixture is ignited in the conventional manner with a sparkplug and shoots a torch of flame through the port into the main combustion chamber. The torch is able to reliably ignite lean mixtures that cannot be ignited by sparkplugs. This system is used by Honda in its CVCC model automobiles. Cooper-Superior has copyrighted the name "Clean Burn" for their engines of this type. At least five major engine manufacturers now offer lean combustion engines, including Alco, Caterpillar, Cooper-Bessemer, Cooper-Superior, and Waukesha.

A considerable amount of experience has been obtained with lean combustion engines fueled with natural gas, and a few digester gas fueled engines are in operation. The preliminary results indicate that the performance of lean combustion engines on digester gas is comparable to their performance on natural gas. Lean combustion engines are capable of reducing NOx emissions to below 2 grams/brakehorsepower-hour and many air pollution control districts will accept it as BACT.

Several manufacturers are now offering retrofit kits which will convert their rich burn naturally aspirated engines into lean combustion engines, however, such conversions are <u>not simple</u>. First, all currently available lean combustion engines are turbocharged. This requires that a gas compressor be provided to boost the digester gas pressure. If natural gas will also be used as a fuel, then two compressors are required. The cost of a typical compressor package ranges from $50,000 to $75,000 and the compressors are relatively high maintenance items. The turbocharged engine can produce approximately 25 percent more power than the naturally aspirated engine, but to use this larger capacity will require that the driven equipment be changed out. The heat balance of a turbocharged engine is different than for a naturally aspirated engine and it may be necessary to change out some of the heat exchangers and other components of the heat

transfer systems as well. Less heat may be recovered from the turbocharged engine.
A turbocharged lean combustion engine is usually found to have a fuel efficiency that is five to 10 percent higher than that of a comparable naturally aspirated engine, but this increase in fuel efficiency is almost exactly offset by the parasitic load of the gas compressor(s).

For mid-sized Waukesha engines, the cost of a lean combustion conversion might be approximately $100,000, not counting the cost of the gas compressors. A major overhaul of the naturally aspirated engine costs approximately $50,000 and involves much of the same work required in a conversion, so the incremental cost of a conversion might be reduced to approximately $50,000 if it was done at the same time as a major overhaul. The total $100,000 cost of the conversion approaches the cost of a new engine which is perhaps $150,000. The conversion cost noted does not include the cost of any required gas compressors.

The cost of lean combustion heads for a DeLaval engine are estimated to be approximately $18,000 per cylinder. For a 12 cylinder engine, the cost of the heads alone would therefore be $216,000.

To date, no cases are known in which engines have been converted to lean combustion models. Since the conversion involves replacement of many or most of the internal parts of the engine, there is a significant potential for startup and unforeseen mechanical problems.

April 30, 1987

CHAPTER 9

THERMAL REACTOR

During the data collection for the initial report which was issued in January, 1987, information was received that Genstar had developed a thermal reactor at their landfill gas facility in Menlo Park which reduced NOx emissions.

A followup telephone call revealed that the thermal reactor that Genstar developed in fact is used to reduce CO emissions, not NOx emissions. There is a limitation on the total amount of NOx that the Menlo Park site is allowed to discharge. To stay within this limitation, the four engines are run at a rich mixture. This more or less corresponds to the "equal CO and NOx" strategy described in Chapter 4.

It was noted that this strategy would have been very costly if one had to pay for the extra fuel but at the Menlo Park landfill there is more gas available than can be used and thus the extra gas is virtually free.

The rich fuel mixture setting resulted in CO emissions of 20,000 ppm which greatly exceeded the allowable limits. An attempt was made to inject air into the cylinders, i.e., in effect to turbo-charge the engines, but the 100 psi air that was required was expensive to compress and was found to have little effect on the CO emissions.

An initial attempt at mixing exhaust gas with air by passing it through a series of nozzles was found to reduce the CO emissions by about 80 percent.

The thermal reactor that was finally developed injects air at the engine exhaust flange and agitates the exhaust gas/air mixture. CO reductions of 95 percent and up have been achieved.

The exhaust gas temperatures from the Cooper-Superior engines at this site are very hot, ranging from 1500 to 1600 degrees F. It is thought that this high temperature is necessary to make the thermal reactor work. While high temperatures are often found in heavily loaded landfill gas engines, they may not be available on the more conservatively loaded engines found at wastewater treatment plants.

May 4, 1987

CHAPTER 10

AIR/FUEL RATIO CONTROLLER AND TIMING ADJUSTMENT

Air/Fuel Ratio Controller

An air/fuel ratio controller is a system which maintains the ratio of fuel to engine combustion air at a constant ratio as the ambient air temperature, air pressure, and humidity vary. Since it controls the fuel mixture, it in effect can be used to control the conditions of combustion. Its major use, however, probably is as an auxiliary device to provide stable engine operation for other emission control technologies, especially catalytic converters.

One type of air/fuel ratio controller has an oxygen sensor in the exhaust and adjusts the flow of air, or fuel, or both to maintain the oxygen content at a given setpoint. The sensors are like those used in catalytic converters on automobiles and in some cases these standard automotive sensors are themselves used as original or replacement units. The type of system with a sensor will also compensate for variations in the composition of the fuel since it is a closed loop control system. Misfiring of the engine can damage the sensor and there can also be problems of poisoning of the sensor, although Waukesha claims that their sensor is suitable for use on digester gas.

Another type of air/fuel ratio controller measures the flow rate of fuel, air temperature, and perhaps other parameters, and calculates the amount of air to be fed to the engine. Since this type of system does not sense the result, it cannot compensate for errors in the measurements or for variations in the assumed fuel composition.

An air/fuel ratio controller can be set to maintain a fuel-rich, fuel-lean, or stoichiometric air/fuel ratio, i.e., this device allows the engine to be set to operate anywhere on the curve presented in Figure 1 in Chapter 4. The device was first put into widespread use in the early 1980s to maintain engine operation within the relatively narrow range that was required by catalytic converters that were being installed. It has also been used on rich burn engines to maximize fuel economy and, as discussed in Chapter 4, it can be used to adjust the fuel mixture to the "equal CO and NOx" point as an emission control measure.

Air/fuel ratio controllers are well proven on rich burn engines but are relatively new to turbocharged engines.

Manufacturers include Engelhard, Johnson Matthey, Waukesha, and

Cooper-Superior, and probably others. Engelhard and Johnson Matthey may not guarantee their devices on digester gas and Waukesha and Cooper-Superior only make them for their own engines. The technology is rapidly evolving several manufacturers are said to be coming on the market with second generation devices.

Timing Adjustment

NOx emissions can be reduced somewhat by retarding the ignition timing. Firing the charge later in the cycle shortens the time during which the high temperatures persist in the cylinder which reduces the amount of NOx which is formed. There may, however, be a concurrent loss of engine power and/or fuel economy.

For optimum engine performance, the timing ought to be adjusted for changes in load and/or speed. This is impractical with manually adjusted timing systems but new devices are now coming on the market which allow the timing to be adjusted from remote a location. Control of these timing adjustment mechanisms can be instrumented so that the timing varies with load or speed.

While a limited control of air emissions might be achieved by use of a variable timing system alone, the major use of these devices to date seems to have been to improve the performance of other control technologies.

April 30, 1987

CHAPTER 11

REMOVABLE PELLETIZED CATALYST MEDIA

A secondary problem that has been experienced both with noble and with base metal catalytic converters is blinding of the catalyst by particulates. The blinding of the catalyst causes the backpressure on the engine to build up to the limit allowed by the engine manufacturer, at which point the engine must be shut down and the catalyst must be cleaned. It usually has been found that most of the particulates can be removed by vacuuming or hosing the media, but that with rigid media there is a progressive, permanent plugging, i.e., it has not proven possible to restore the media completely to new condition. At some point as the permanent plugging continues, it becomes necessary to remove and discard the media and to replace it with new media.

Another approach to overcoming the blinding problem is to put the catalyst on a replaceable pelletized media. The compartment that holds the pellets is arranged so that pellets can be drawn out of the bottom and poured back in on top. As the bed settles into the space left by the withdrawn pellets, the movement of the pellets breaks up the layer of particulates and allows the exhaust gas to once again pass through the bed without excessive pressure loss. It has been found that the pellets which are removed can be restored to nearly new condition merely by washing with water.

A distinction should be made between removable and non-removable pelletized media. Some catalysts are offered in a pelletized form but the pellets are mounted in cages such that they cannot be readily removed and replaced. This chapter specifically addresses only the concept of arranging the pelletized catalyst so that the pellets can be easily removed to facilitate breaking up particulate blankets that are blinding them.

Removable pelletized media is not a separate air emission control technology but is merely an innovation which overcomes one problem that has threatened to limit the use of catalysts. The problems of poisoning that were discussed in Chapter 7 would be expected to continue even if the noble metal catalyst were to mounted on removable pelletized media.

In many cases, the pellets have been blown out of the system by backfires of the engine or by explosions in the exhaust system caused by misfiring of the engine. This may be considered a disadvantage of pelletized media over rigid media, but on the other hand, backfires and explosions in the exhaust system have also fractured and ruined rigid media. It thus appears that both pelletized and rigid media are subject to destruction by backfires and explosions in the exhaust system and neither media may be superior in resisting such events.