Chapter 6

NOx Formation and Reduction in Reciprocating Internal Combustion Engines (RICE)

Editor's Note:

Chapter 6 – NOx Formation and Reduction in Reciprocating Internal Combustion Engines (RICE) – includes some of Chapter 9 from the 2000 version of APTI 418 written by Jack Wasser. Additional sections covering improvements in combustion chamber design and the development of lean burning engines with much lower NOx emissions were written by Brian Doyle and Chuck Solt.

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Table of Contents

Chapter 6 i

NOx Formation and Reduction in Reciprocating Internal Combustion Engines (RICE) .. i

Table of Contents iii

- Reciprocating Internal Combustion Engines 1
- Controls Common to SI and Diesel Engines 1
- Spark Ignition Engine Concepts 3
- Diesel Engine Controls 3
- Emerging RICE NOx Control Technologies 4
  - Hydrogen Injection for Ultra-Lean Burn 4
  - Homogeneous Charge Compression Ignition (HCCI) 6
  - Attainment Technologies 7
- Review Exercises 9

Reciprocating Internal Combustion Engines

In engineering terms both gas turbines and reciprocating engines are internal combustion (IC) engines. In keeping with US EPA terminology this manual uses the terms *reciprocating internal combustion engine* (RICE) and *combustion turbine* (CT) to distinguish between the two types of IC engine.

While this course focuses on relatively large stationary engines, much of the engine and NOx control technology is applicable to any size engine. Large spark ignition engines use natural gas instead of gasoline - used in small and mobile engines. While marine diesels frequently use residual #6 oil, both stationary and mobile compression ignition engines in this country are pretty much restricted to distillate fuels: #2 oil, diesel fuel or kerosene. Mobile diesel engines increasingly use ultra-low sulfur (15 ppm maximum) fuel, while stationary diesels may, depending on permit conditions, use #2 oil with up to 0.5% sulfur.

NOx is the major pollutant from any RICE. CO, hydrocarbons and particulate matter can be emitted in relatively small amounts that may, or may not, be significant. Since some of the organic components of diesel exhaust are carcinogenic, diesel engine permits frequently limit multiple pollutants in addition to NOx.

Controls Common to SI and Diesel Engines

Spark ignition and diesel engines have fundamentally different combustion (premixed versus diffusion. The most recent methods for limiting NOx formation are quite different for the two types of engines. Some earlier approaches, while still applicable, are common to both types of engine. In most cases the basic approach is to reduce the peak flame temperature – none of the fuels in common use contain much organic nitrogen, so virtually all the NOx is thermal in origin.

Ignition Timing

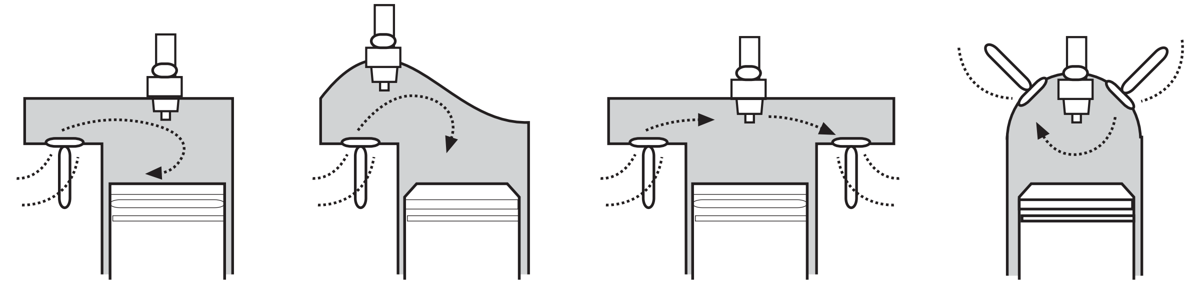
Adjusting the ignition timing adjustment can provide a nominal NO_X reduction. The best engine performance is obtained by timing the spark up to 20° (of crankshaft rotation) prior to top dead center. Retarding the ignition will reduce residence time, lower peak temperature and delay peak pressure during the engine cycle. Of course this reduces efficiency or power. For comparable reductions in NO_X emissions, engine performance is affected less by spark timing retardation than by reduced compression ratios. A NO_X reduction of up to 50% can be obtained by firing the spark at TDC for mobile spark ignition IC engines.[1] Somewhat less NOx reduction can be expected for slower turning stationary engines.

Exhaust Gas Recirculation

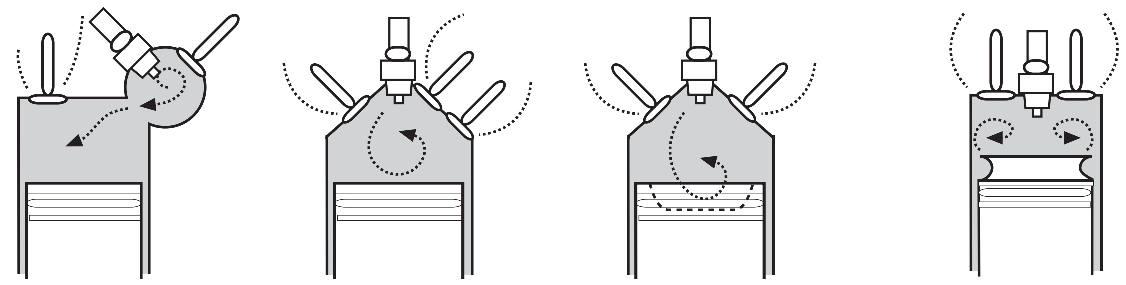
EGR (same as flue gas recirculation) can reduce NO_X emissions by 10% to 20% in any RICE. EGR systems recirculate as much as 15% to 20% of the exhaust flow. The amount of exhaust mixed with the combustion air is controlled with a valve or damper. The addition of inert exhaust gases to the air dilutes and cools the combustion. The penalty for EGR includes the possibility of slight reduction of engine efficiency, significant loss of power, engine misfiring and increased carbon monoxide and hydrocarbon emissions. EGR has seen fairly limited application to date. It is a key element in *virtual lean burn combustion* discussed later in this chapter.

Combustion Chamber Design

Combustion chamber design can have a major effect on NOx formation, particularly when combined with other technologies. Until the 1990's, chamber design was more art than science. The only way to develop a concept was to build it and run the engine. Figure 6-1 illustrates several designs developed this way. The wedge chamber is designed to control detonation, the hemispherical chamber is designed to provide greater power, and the stratified charge chamber is designed to lower emissions with a combination of rich and lean combustion. The stratified design ignites a fuel-rich (low NOx) mixture in a separate chamber. The resulting flame has sufficient energy to ignite lean fuel mixture in the main chamber. This approach can reduce NOx by 90% with minimal penalty on engine performance or on CO emissions.



Nonturbulent L Turbulent (wedge) L Nonturbulent T Hemispherical



Honda stratified charge MCA jet valve Scooped bowl piston Sonic pulse burn

Figure 6-1. Various Combustion Chamber Designs

With advent of powerful fluid modeling programs, combustion chamber design moved from the machine shop to the computer. This has greatly accelerated the development of novel NOx reduction concepts in both gas fired and diesel engines.

Spark Ignition Engine Concepts

Air-to-Fuel Equivalence Ratio

In Chapter 3 we showed that all emissions are highly dependent on air-fuel ratio. Rich burning reduces NOx formation at the expense of greatly increased CO, smoke and hydrocarbons. Lean burning can reduce all pollutants, but traditional engine designs will not operate very far from an air-fuel equivalence ratio of 1. Substantial progress has been made since about 1990 in the development of engines that operate lean or very lean. The pre-chamber design shown in Figure 6-1 is one of the earliest examples of lean burn engines. A more recent concept is based on the use of a high energy spark that can ignite a relatively lean mixture. Two more concepts are discussed under the heading of **Emerging Technologies** at the end of this Chapter

Diesel Engine Controls

NOx reduction on diesel engines is more challenging than in SI engines because diffusion combustion of liquid fuel generates higher temperatures and the air-fuel ratio cannot easily be controlled.

Water Injection/Emulsified Fuel

Water injection/emulsified fuel techniques can be effective for reducing NOx from diesel engines. Adding a heat sink in the form of water reduces combustion temperature. However, the enthalpy required to heat the water reduces engine efficiency. Water injection is usually done by emulsifying the fuel with water and increasing the size of the injection system enough to handle the mixture. The water needs to be clean to avoid deposits and corrosion in the engine. Although CO is not substantially affected by the addition of water, increased hydrocarbon emissions are possible.

Pre-Chamber Designs/Indirect Injection

Pre-chamber designs, indirect injection, improved nozzle design, and higher injection rates are often used in combination for controlling emissions. These design features increase the mixing of air and fuel by increasing turbulence and producing finer fuel droplets. Improved nozzle designs and increased injection pressure produce finer fuel droplets that vaporize quickly. Similarly, hot surfaces are also used to evaporate injected fuel. While these approaches improve combustion and may reduce NOx, none of them constitutes premixing that could support lean low temperature combustion.

Table 6-1 displays the fuel consumption necessary to maintain a rated power output, which serves as a direct indication of engine efficiency change. The associated changes in NOX emissions are also shown.

Table 6-1
Compression Ignition NOx Control Methods

NO_X Control Technique	Fuel Consumption (Change)	NO_X Emissions (Reduction)
Prechamber Designs	8% to 15%	50%
Indirect Injection	3%	40% to 50%
Exhaust Gas Recirculation	4%	45% to 55%
Injection Retardation	2% to 5%	15% to 35%
Water Injection	-2% to 0%	35%
Inlet Air Temperature Reduction	-2%	12%

Emerging RICE NOx Control Technologies

There are a number of new exhaust cleanup technologies being demonstrated for Reciprocating Internal Combustion Engines that will be discussed in Chapter 8, but a few combustion control technologies specific to RICE warrant comment:

- Hydrogen Injection for ultra-lean burn
- Homogeneous Charge Compression Ignition
- Exhaust Gas Recirculation with NSCR

Hydrogen Injection for Ultra-Lean Burn

This section contains a discussion of Lean-Burn technology which allows operation of SI engines at higher pressure ratios. The lean combustion results in a lower peak flame temperature and accordingly, substantially lower NOx emissions. The higher pressure ratio results in substantially better efficiency.

Several companies have been doing lab tests, pilot projects and demonstration projects on a technology where hydrogen is added to the fuel. This allows operating the engine at a leaner level and the NOx emissions and efficiency both benefit.

The typical arrangement is to pass a portion of the fuel gas through a reformer to produce hydrogen. The reformate is then blended back into the primary fuel gas stream so that the hydrogen content of the resulting fuel is between 5 and 10% hydrogen. Since the hydrogen can be ignited more easily than the methane, the air (or exhaust gas recirculation) and be increased to the equivalent of 10% oxygen in the exhaust (typical lean-burn is 7% O_2 or 50% excess air). Tests have shown a NOx reduction of 75 to 80% more than typical of a lean-burn engine may be achievable.

It appears that the technology can be retrofitted to most standard engines without major modifications.

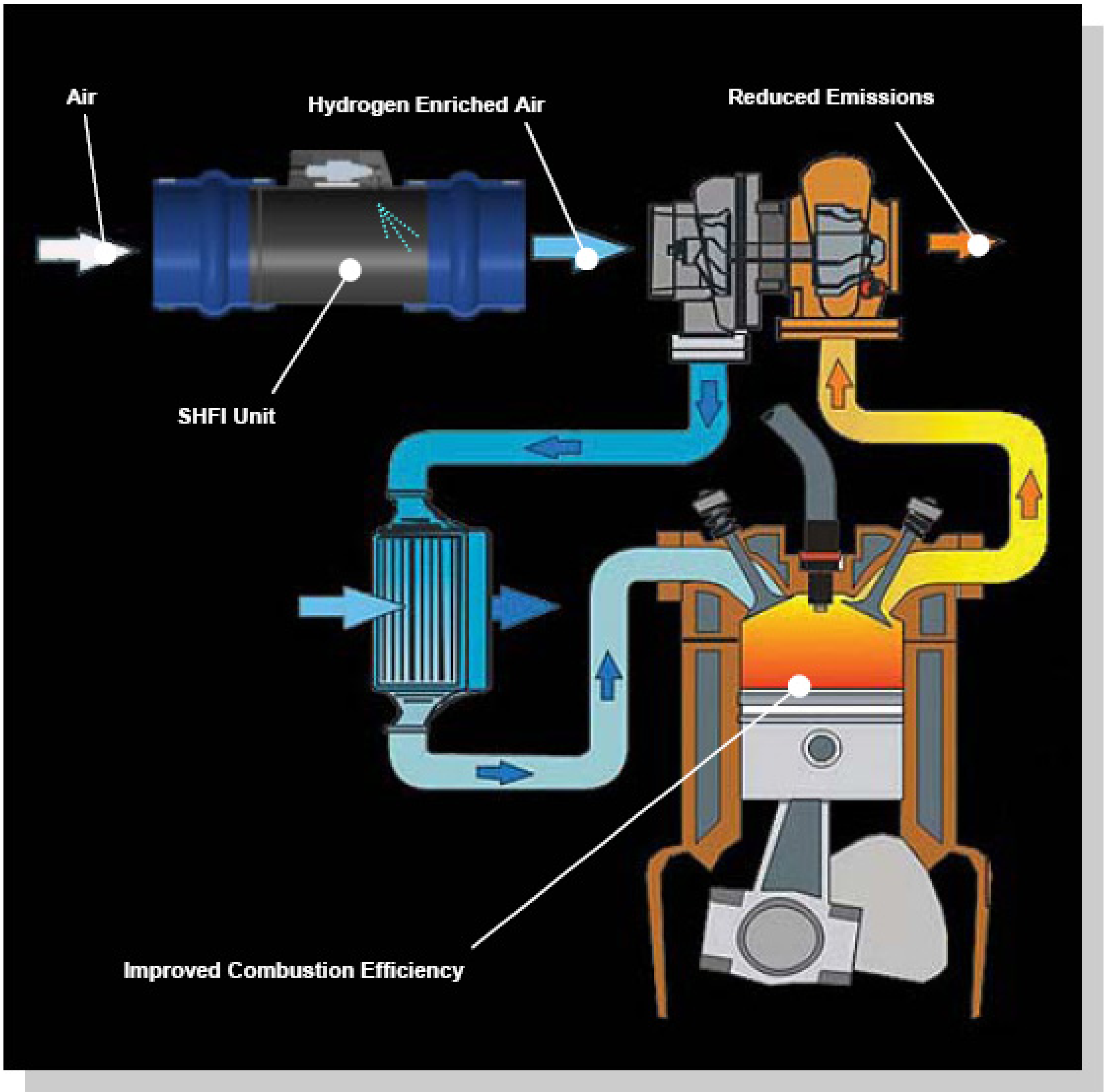


Figure 6-2. Ultra-Lean Hydrogen Enriched Engine.

The major addition to a generation system will be the reformer. There are a number of reformer technologies available, and some can be quite expensive. Steam reformers are the most common, but if steam is not available, the reformer system will need an electric boiler. This not only is a significant capital cost, but it will impose a substantial parasitic electric load. The boiler will require a supply of highly deionized water which will also be an operating cost burden. Many of the steam and plasma reformers use a catalyst. If the system is applied to a bio-gas project, the fuel will have a substantial amount of H_2S which will have to be scrubbed before entering the reformer.

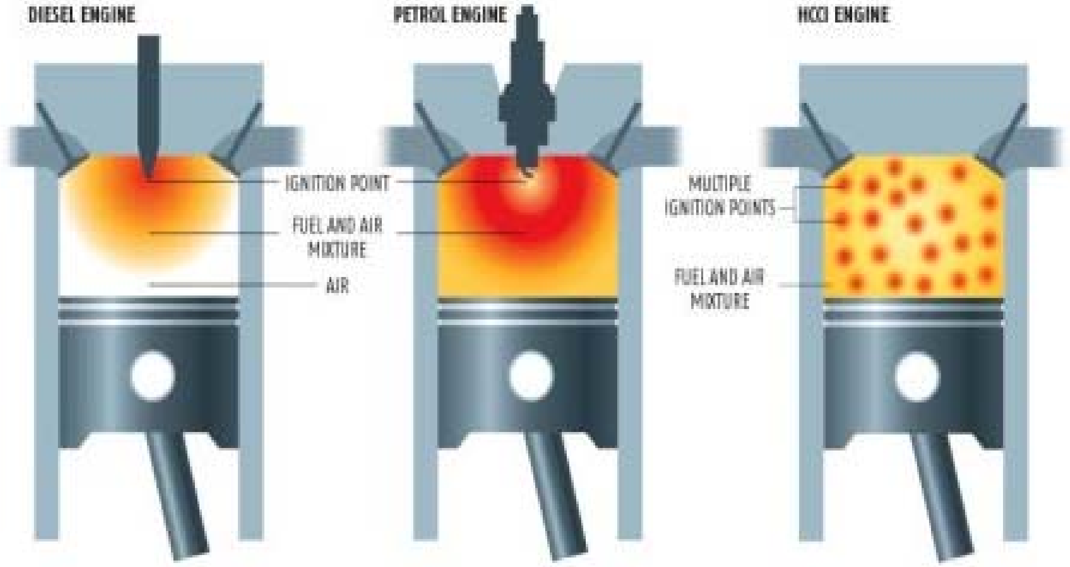
The other new reformer system is a plasma reformer. The technology is much newer and the cost can vary dramatically.

Most of the work to date has been done on diesel vehicular engines. They have been able to meet the Tier 3 standard with hydrogen only and Tier 4 with hydrogen and a three-way catalyst. Work is presently being done on a demonstration project for a bio-gas generator set which should be operating before the end of 2009.

Homogeneous Charge Compression Ignition (HCCI)

Operationally, this technology has many of the same characteristics as the Ultra-Lean Hydrogen Enriched system discussed above. It has lower emissions, higher efficiency, and development thus far has been primarily for the automotive industry. It operates much leaner than the conventional lean-burn engine and at a higher pressure ratio. But, the technology is very different.

It is a compression ignition engine like a diesel, but it is used for methane based fuels like natural gas or bio-gas. Unlike a diesel, the fuel is not injected, it is carbonated into the inlet air and goes into the combustion cylinder as a homogeneous mixture (premixed). Ignition results when the temperature resulting from the compression reaches the auto-ignition temperature of the air/gas mixture. The temperature rise form compression in a 20 to 1 diesel engine is not sufficient to reach the required temperature, but this is resolved by heating the air/fuel mixture before it enters the cylinder. The heating typically is achieved with an inlet/exhaust heat exchanger.



Comparison of Compression Ignition, Spark Ignition and HCCI

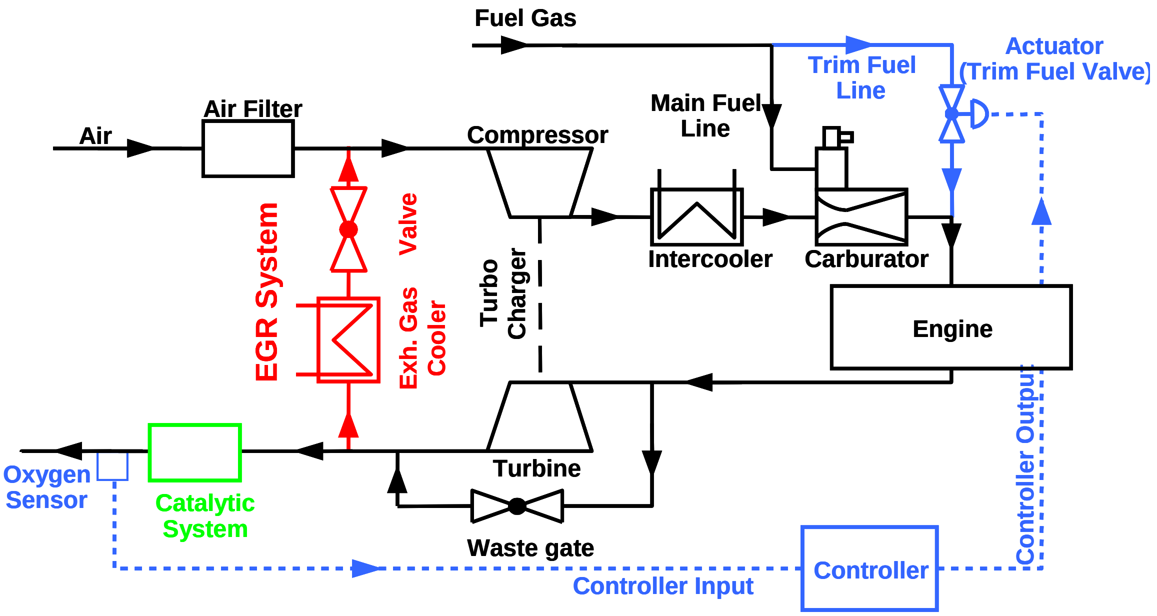
The engine has no spark plug and no fuel injector, so one would ask “How do they control the ignition timing?” This is done primarily by temperature control – the concept is that the autoignition temperature is reached shortly before the piston hits top dead center. Depending on the temperature control method, there might not be a very fast response to a quick load change. A slow temperature response would make the engine more suitable to operation in a true hybrid car or a generator unit with a utility inter-tie where load changes are infrequent and can probably be gradual.

Work has been progressing on the HCCI for over 30 years and there is a bio-gas project due for startup in mid 2010.

Attainment Technologies

There are 2 features to this technology.

- First the engine operates as a virtual lean-burn engine. The combustion process is completed with no excess oxygen. A portion of the exhaust stream is cooled and a precisely controlled portion is mixed with the inlet air such that after combustion of the fuel, the oxygen content of the exhaust stream is zero. The oxygen content of the exhaust is monitored and the signal is used to control of the exhaust mixing. This allows operation at a high compression ratio, similar to conventional lean-burn engines. The result is low NOx without exhaust gas clean-up. For all process purposes, the engine is operating as a lean-burn engine except that the exhaust has no oxygen.



Attainment Technologies ERU 1001

- Since there is no oxygen in the exhaust, a non-selective catalytic reduction (NSCR) system can be used to further substantially reduce the NOx emissions. NSCR will be discussed further in Chapter 8, but at this point it is significant to mention that it is a well proven, very effective, low maintenance, and inexpensive NOx control technology.

This technology allows the engine to operate with the higher efficiency associated with lean-burn engines, but with no oxygen in the exhaust which allows the system to use the NSCR exhaust gas NOx control catalytic system. The NSCR system is very effective in reducing NOx and does not require a reagent such as Ammonia or Urea.

Compliance testing on AT systems have demonstrated NOx emissions below 0.1 g/BHP-Hr.

As of mid 2009, AT has about 25 systems in operation. Six of these systems are in continuous operation and have accumulated over 15,000 hours of operation each without emission permit violations. The technology is available on a wide variety of engines for operation on either natural gas or bio-gas.

Review Exercises

1. Why do CI engines typically emit higher NO_X emissions than spark ignition engines?
   - a. CI fuels (diesel) have higher N content than SI fuels (gasoline).
   - b. CI engines cool more rapidly than SI engines.
   - c. CI engines generally run at a lower speed than SI engines.
   - d. CI engines operate at higher pressures than SI engines.
   - e. All of the above

2. Diesel engines generally operate at which of the following conditions?
   - a. $\phi < 1$
   - b. $\phi > 1$
   - c. $\phi = 1$
   - d. None of the above

3. When the air-fuel ratio for an SI engine is increased beyond ideal stoichiometric conditions, which of the following is likely to occur?
   (Select all that apply.)
   - a. NO_X emissions will increase
   - b. CO emissions will increase
   - c. Hydrocarbons will increase
   - d. Catalytic control efficiency will increase
   - e. None of the above

4. Why is NO_X formation in CI engines greater than in SI engines?
   (Select all that apply.)
   - a. CI fuels contain less nitrogen
   - b. CI engines run slightly fuel-lean
   - c. CI engines operate at higher pressures
   - d. CI engine speeds are higher
   - e. None of the above

5. Damage to catalysts can occur from which of the following?
   (Select all that apply.)
   - a. Lead in the fuel
   - b. Flue gas temperatures of 400°F to 500°F
   - c. SO_2 emissions
   - d. Lubricating impurities
   - e. None of the above