A RETROFIT SYSTEM TO CONVERT
A LOCOMOTIVE TO NATURAL GAS OPERATION

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ABSTRACT

This paper describes the equipment and the operation of a system used to convert an EMD diesel locomotive engine to operate using natural gas as a major energy source. The retrofit system developed uses electronic controls, sensors and actuators to monitor system variables and perform the required control functions of the dual fuel locomotive engine. Among the required controls are gas injection timing and rate, the control of the diesel pilot level, turbocharger waste gate and a device that causes the engine to operate alternately on half of its cylinders during times of low specific power output. Along with the addition of controls, changes were made to the design of the pistons, cylinder heads and engine air cooling.

Keywords: dual fuel engines, natural gas conversion, diesel engine, alternative fuel, low-pressure gas injection.

NOMENCLATURE

BN	Burlington Northern
BSFC	brake specific fuel consumption
GIV	gas inlet valve
NMHC	non–methane hydrocarbons

BACKGROUND

The developments outlined in this paper were inspired largely by the success of Burlington Northern Railroad's (BN's) first gas locomotive, BN No. 1961. That unit used existing engine technology newly applied to a locomotive, along with a compressed natural gas tender car. The project was undertaken as part of an R&D program established to examine the use of alternative fuels in railroad applications. Natural gas was selected because it provided more economic, environmental, and safety benefits than the other fuels, such as methanol and propane, that were being considered (Olson, 1993; Ditmeyer, 1993). The tests BN conducted between 1982 and 1987 proved that running locomotives on natural gas was a workable concept. BN's efforts also brought into focus several issues that needed to be addressed before natural gas locomotion would be truly practical. For the development discussed in this work, BN stipulated the following requirements:

1. Natural gas capability must be provided by a means of conversion or adaptation of existing high-power locomotives;
2. The converted engine must be capable of operating on 100% diesel fuel;
3. The converted engine must be able to withstand locomotive duty cycles;
4. The converted engine must produce not less than 90% diesel-rated power;
5. The engine must not lose any thermal efficiency; or, if it can produce 100% diesel-rated power, then it must not lose more than 10% thermal efficiency.

Using these guidelines, ECI developed a conversion system for a General Motors EMD 645E3 locomotive engine. This engine is a 45°–V, two-stroke, turbocharged, medium speed diesel, with cylinder configurations of 8, 12, 16, and 20 (see Table 1 for specifications).

SYSTEM OVERVIEW

The converted engine is equipped with new electronic engine controls, sensors and actuators. Newly designed pistons, cylinder heads and charge air coolers replace the originals.

With the conversion installed, the engine starts and idles on diesel. It retains the ability to operate on full diesel, with critical components such as the engine governor and fuel injectors remaining virtually unchanged. Under normal circumstances, when the engine throttle handle is placed in notch 3, dual fuel operation automatically takes place. Engine speed is controlled by varying the gas flow to a pressure-timed fuel delivery

TABLE 1. LOCOMOTIVE ENGINE SPECIFICATIONS

Engine type	45º–V two-cycle
Number of cylinders	16
Displacement per cylinder	645 cu. in. (10.6 l)
Compression ratio	12.5:1
Power rating	3300 HP (2460 kW) @ 900RPM
Diesel injector	unit type needle valve
Gas injector	electronically controlled poppet valve

system. Gas fuel is delivered directly to the combustion chamber early in the compression stroke. Combustion is initiated by injecting a small amount of diesel near top dead center of the compression stroke.

SYSTEM COMPONENTS

Gas Inlet Valves

The gas fuel cannot be introduced and mixed with the engine’s air inlet because a significant amount of this air escapes from the engine during exhaust scavenging. Gas must be injected directly into the combustion chamber after exhaust valves have closed. One of the issues that surfaced with the testing of Locomotive No. 1961 related to cam-actuated gas valves. If the engine isn’t running on gas most of the time, the mechanical valves will cause problems. For example, the mechanical valves are operating constantly, even when the engine is running under 100% diesel. The design of the mechanical valve allows lube oil to pass along the valve stem past the valve guide into the gas admission chamber. When the engine is off gas, the backpressure that normally inhibits the passage of oil is not present. The valve lube oil that gets past the guides is then blown into the gas headers by the aspiration of the engine. These and other difficulties promoted the design effort on the gas inlet valve.

The gas inlet valve (Figure 1) fits into the cylinder head much like a diesel injector. Its purpose is to control the timing of gas delivery to the combustion chamber and to hold back the pressure of combustion. Its basic design involves a spring return poppet valve with appropriate valve guides and housing so gas can be channeled to the combustion chamber when the valve is opened. The gas inlet valve uses an electric solenoid valve to control compressed air. When energized the solenoid valve allows air pressure to act on a small piston that is attached to the stem of the poppet valve. The air pressure on the surface of the piston compresses the valve spring and the valve opens. The gas inlet valve is therefore electronically controlled, pneumatically actuated. Electronic control allows the valves to be left closed during non-gas operating modes. Timing and duration of valve opening is controlled by the electronic control unit. The gas pressure required for the system is 5.9–8.6 bar (85–125 psig) The required injection pressure (gas pressure down stream of the flow control valve) is both speed- and load-dependent.

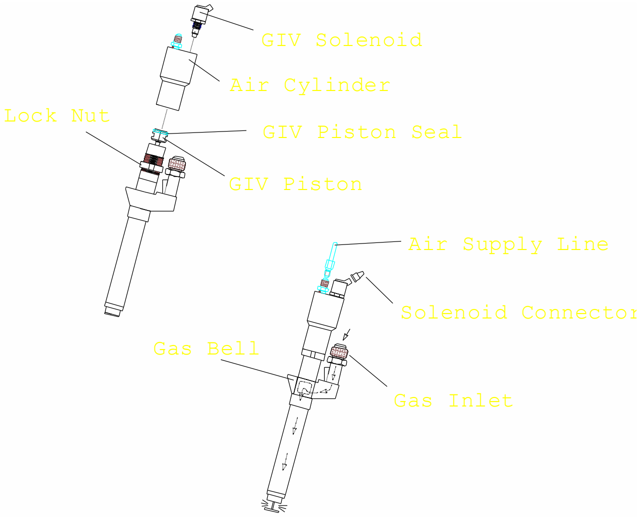

FIGURE 1. GAS INLET VALVE.

Cylinder Head

To inject gas to the combustion chamber, the cylinder head has been manufactured with an additional port that accepts the gas inlet valve. Apart from the gas inlet valve port and a cutout for gas inlet valve clearance, the cylinder head is unchanged, retaining standard exhaust valves and other components.

Piston

The piston design is modified to reduce the compression ratio and promote turbulence. During development, piston designs were tested with the use of a two piece test piston, allowing a number of crown designs to be evaluated. A reentrant type of design provided increased power capacity due to the better mixing of air and fuel.

Electronic controls

Electronic controls are employed to provide the flexibility, performance, and automation required by a locomotive engine application. The electronic control unit is an enclosure that contains two microprocessor-based control boards, signal conditioning, isolation and interconnecting hardware. External to the electronic control unit is a power supply assembly, power supply transient filter and additional signal conditioning modules.

The “valve sequencer” is one of these control boards. This board has been designed specifically for timing control of the gas inlet valves. Two sensors generate electrical pulse information from targets located on the flywheel. The signal timing provides information the valve sequencer needs to determine when and for how long the gas inlet valves should be energized. These signals are evaluated to insure that they occur when expected and that control functions are not being carried

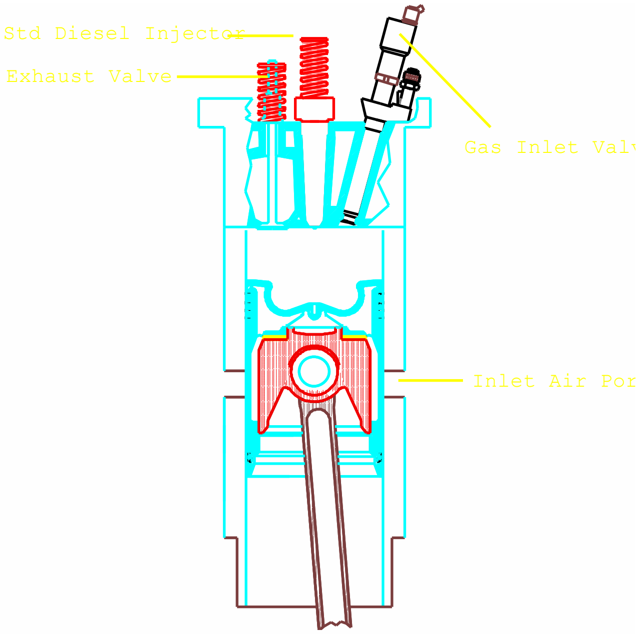

FIGURE 2. DUAL FUEL POWER ASSEMBLY CROSS–SECTION.

out using faulty information. The valve sequence receives a discrete signal from the main control board telling it to operate. The valve sequencer in turn responds by returning a status signal indicating that it is operational. The timing resolution of this board is 64 µs, which represents 0.34° of flywheel rotation at 900 RPM. The control signals from the valve sequencer are sent to a solenoid driver board. This board contains fuel injection driver chips that hit the solenoid valves with full voltage until the current reaches a 4 A peak and then reduces the current to a holding level of 1 A. This creates a high response valve without excessive heat buildup in the valve coil.

The main control processor is a 16-bit board running at 10 MHz with 12-bit analog-to-digital conversion. This board processes analog signals representing engine speed, load, temperatures and pressures. It also processes digital input signals representing the position of the throttle handle, load control contactors, valve sequencer status, power supply status and operator input. Once the controller has determined that all of the necessary prerequisites have been met, gas operation commences. The controller uses two analog outputs to control the speed of the engine, and the load placed on the generator, when on gas. Digital outputs control the diesel's governor, pilot fuel level and waste gate. Speed control accomplished by a modified PID algorithm that ramps to the new values for speed set point and integral when the throttle position is changed. The engine load control signal is generated by another PID loop based on predetermined set points and the rate of gas fuel flow. The load control signal turns on a simple transistor circuit that shunts some of the power from the existing load control to ground**.**

TABLE 2. PREREQUISITES FOR GAS OPERATION

Engine speed	500-950 RPM
Minimum load	18%
Jacket water temperature	150ºF (65.6ºC)
Gas supply pressure	85–125 psig (5.9–8.6 bar)

TABLE 3. ELECTRONIC CONTROLLER SPECIFICATIONS

Operating temperature	–40 to 185°F (–40 to 85ºC)
Operating voltage	50–140 VDC
Analog inputs/outputs	32/2
Digital inputs/outputs	16/24
Frequency inputs	1
Frequency outputs	2

Wastegate

The level of excess air required for combustion of the natural gas along with the reduced efficiency of the combustion event created the need for a turbocharger wastegate. The flow paths of the EMD turbocharger, like other medium speed V–configured diesel engines, has two air paths and only one exhaust path. For this reason we chose to install the controlling valve on the exhaust side of the system. The waste gate allows exhaust gas to bypass the turbine. The dual fuel engine is very tolerant to varying air/fuel ratios, but wastegating some of the exhaust energy not only reduces the turbine speed but increases the fuel efficiency of the engine as well. The wastegate is a very simple gate-type valve whose operation is either fully open or fully closed. In the open position the flow of the exhaust bypassing the turbine is controlled by an orifice plate. The wastegate is opened when the boost pressure from the turbo exceeds a predetermined level.

Pilot Fuel

Due to the changes in engine speed and load, the pilot fuel control is not as simple as providing a single stop position for the diesel fuel racks. The rack position must be adjusted as the engine speed increases to maintain minimum pilot fuel. To perform this task, three air cylinders are mounted together such that they provide a linear motion that increases with the number of cylinders having air applied to them. As speed increases, the air pressure is relieved from the cylinders in sequence and the pilot setting decreases accordingly. The diesel injectors are altered only in the way that they are calibrated. Calibration of the injectors is done at the pilot fuel rack setting 1.880" instead of the normal 0.780" rack setting. Using standard recalibrated injectors a pilot fuel level of 8% fuel charge energy is achieved. If injector modifications were desired and accepted, a reduced pilot fuel level could easily be achieved.

Bank Idling

The operating duty cycle of a locomotive changes with the train and route that they are assigned to; however, typical operation shows that a locomotive spends more than 40% of the time in idle. Idle speed ranges from 250–300 RPM to 500 RPM in low ambient temperatures. Low load, low speed operation along with the reduced compression ratio of the dual fuel piston results in less than optimum diesel combustion. To curb smoke and reduce fuel consumption at idle and low load conditions, bank idling is employed. Bank idling reduces the number of cylinders that are producing power by reducing the fuel rack of one bank of cylinders to a no-fuel position. This increases the work that the remaining cylinders must do. The increased work causes combustion to be cleaner and more efficient.

To implement bank idling we designed linkages that are spring loaded to the normal fuel position. When the controller determines that low load condition exists, air pressure is applied to one of the two linkages. The air compresses the spring and the linkage floats to the no-fuel position. After a period of time the air pressure is switched to the opposite linkage and the engine then operates on the opposite bank of cylinders. The cycling is maintained during idle, keeping both banks warm and relatively clean.

Charge Air Cooling

On nearly all turbocharged diesels, some sort of heat exchanger is used to control the temperature of the air exiting the turbocharger. At high loads the temperature is reduced, which in turn enhances the engine's efficiency. EMD turbocharged engines use engine jacket water in their charge air aftercoolers. On locomotives this jacket water serves two purposes. At low speed and load these heat exchangers work to increase the air temperature, enhancing the diesel combustion quality. At high speeds and loads, the heat exchangers reduce the air temperature, allowing more air to enter the combustion chamber. On the dual fuel engine air temperatures play a strong role in the level of power that can be produced before knock occurs. To achieve diesel-rated power, enhanced aftercooling of charge air is required. The converted locomotive is equipped with additional radiators. Water is circulated and cooled from these radiators and directed to the aftercoolers. Thus the air from the turbocharger is cooled to a greater extent than with the standard cooling configuration and higher power is achieved. In the case of low engine speed and load, the water flow is no longer taken from these radiators, but instead from the outlet of the engine. The engine water is then directed into the aftercoolers and thus heating the air for good combustion. For more discussion on the cooling strategy, see Stolz (1992).

PERFORMANCE

Efficiency

Figure 3 indicates typical converted engine performance in the locomotive. The eight speeds represent the so-called throttle notches, or preset speed/load settings, at which the locomotive operates. Power in the two lower notches is provided by diesel fuel only, since the power generated and the fuel used is below that which is desirable for gas operation.

Continued testing has shown that pilot levels of <5% and advanced injection timing provide 1.5% better efficiency and a increased fuel replacement. Injectors capable of properly supplying this level of pilot fuel however limit the amount of power produced on diesel. In the future we look forward to testing designs that will potentially enhance the overall operation of the engine in locomotive service. These designs include increased air fuel ratio control, optimized air fuel mixing in the combustion chamber, reduced pilot fuel without reduced diesel power and spark ignition eliminating diesel altogether.

Fig. 3 Thermal efficiency of ECI converted EMD

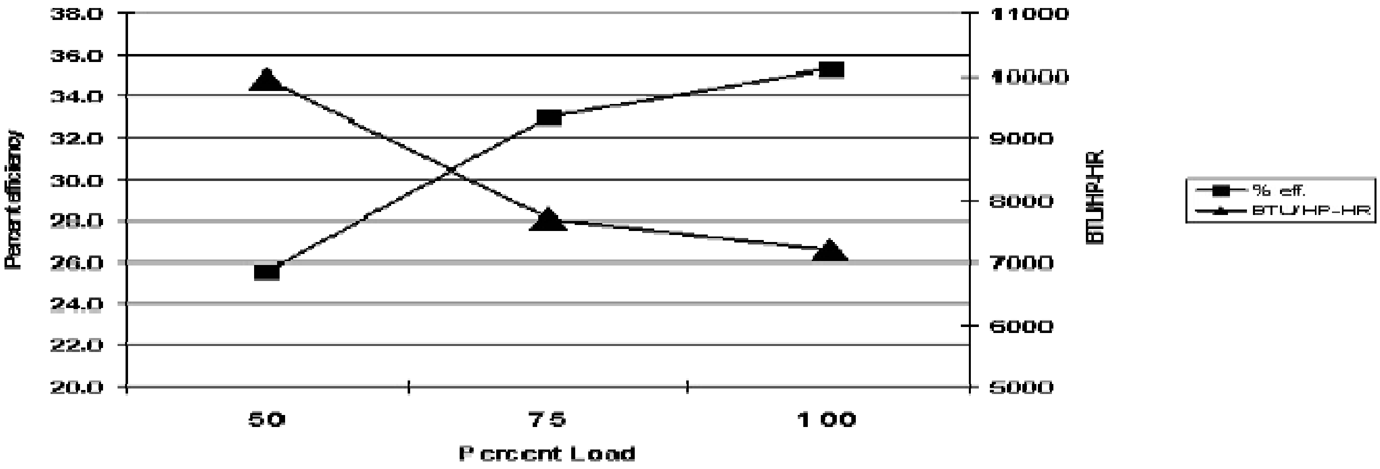

TABLE 4. DUAL FUEL ENGINE EMISSIONS AT FULL LOAD

Component	g/hp–hr (g/kW–hr)
NMHC	0.31 (0.42)
NO_X	3.6 (4.8)
CO	8.5 (0.7)
Particulate	0.195 (0.261)
Component	Mol % Exhaust Gas
CO_2	4.73%
O_2	13.03%

Emissions

Emissions reductions played no part in the initial development, but as time passes it becomes a stronger issue. The emissions of locomotive 7890 were measured by Southwest Research Institute in October of 1991. This test was commissioned by Burlington Northern Railroad and Air Products and Chemicals. The emissions results have never been published in a final report. However, ECI has been granted the right to use the numbers recorded at full speed and load for the use of marketing literature to stationary power generation customers. Several significant changes have taken place since the time of the testing. Draft report (Fritz, 1992) values for full speed and load emissions are given in Table 4.

SUMMARY

At this time two of these systems are operating on locomotives running in revenue service. They have been operating on the rails for approximately two years. The concepts and hardware in the product have proven to be functional and operational. New developments continue to be investigated in the areas of emissions, efficiency and control technology.

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