Operation a Diesel Locomotive with Liquid Methane Fuel

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ABSTRACT

Shortages of motor fuels several years ago prompted many efforts toward alternative fuels. One such exploratory effort, by Burlington Northern Railroad, was to operate a locomotive with compressed natural gas (CNG) as a dual fuel, diesel—gas, engine.Ll] Recognizing the large storage volume and other limitations to the use of CNG for this application, a program was initiated to fuel a locomotive with liquified natural gas. (See Figure 1.) Since natural gas composition can vary with its source or with Its processing it would also be desirable to control its composition to essentially pure liquid methane as the engine fuel. This paper will describe the efforts taken to provide the fuel supply system on board the train and to convert the diesel engine to burn gas in a dual fuel mode.

Initial testing results show the locomotive system has achieved full diesel rated power when operating on gas and with equivalent fuel efficiency (BSFC). Extended testing, including an American Association of Railroad (AAR) 500 hour durability test, was undertaken to produce information on engine life, wear rates, lube oil life, etc. Gaseous and particulate exhaust emissions monitoring can lead to further engine modifications for minimizing of emissions. Preliminary testing, however, shows smoke free full load operation.

INTRODUCTION

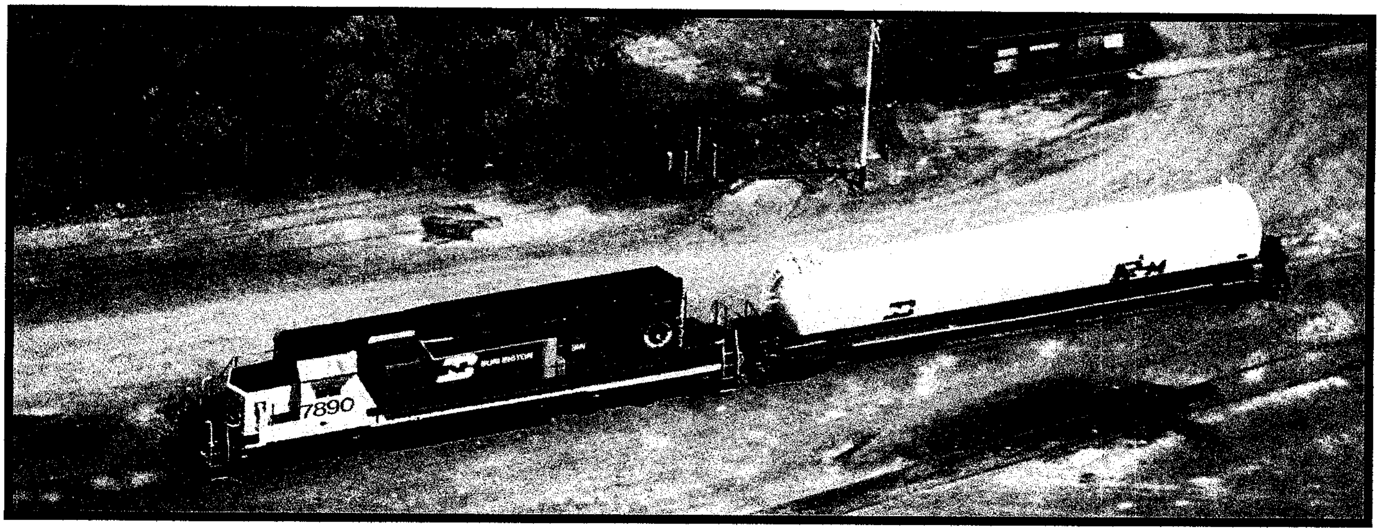
The fueling of railroad locomotives plays an important part in the economics of the railroad by virtue of the availability of fuel, the cost of fuel and the environmental effects of the fuel. During the days of the coal fired steam locomotives there were the drawbacks of smoke and dirty operation using coal plus the limited range of travel between water and fueling stops. The diesel engine locomotive solved these problems but recent clean air studies [and legislation are now threatening diesel emissions, plus periodic oil shortages threaten the cost and availability of diesel fuel. These factors have led to the search for alternative fuels.

Natural gas has become a popular choice of many people as an alternative fuel, either as compressed natural gas (CNG) or as liquid natural gas (LNG). For trains it is important to carry enough fuel for long runs and thus liquefied gas was the fuel of choice for this program. One can store approximately five times the amount of fuel on board a vehicle as a liquid compared with CNG at 2,000 psi, with equivalent space requirements. Nhen compared with diesel fuel however, LNG does require approximately twice the volume for the equivalent fuel value, thus necessitating the use of a tender car. Using LNG as the locomotive fuel posed quite a few challenges which will be reviewed in this paper.

ECONOMIC DRIVING FORCES

As with any business, economics is of key concern and thus it is gratifying that this program of gas fueling locomotives promises: 1) Clean burning fuel, 2) domestic supply, and 3) lower cost. Studies by Durbln and Midkiff, Bell, Hong & Ramseyt demonstrate the possibilities with clean engine emissions using gas. Domestic supply of natural gas eliminates the dependence upon foreign crude oil and the cost of natural gas is expected to remain lower than diesel fuel.

1 Some of the significant current and future users of CNG and LNG are the Roadway Trucking Fleet, Houston, TX METRO busses, and United Parcel Trucks.



Fuel costs are typically In excess of ten percent of a U.S. railroad's operating costs which forms a strong driving force to convert to gaseous fuel. The liquefied gas fuel supply to the locomotives Is expected to cost 10—157. less than No. 2 diesel fuel at current price levels. It is anticipated that reformulated, cleaner burning, diesel fuel will also increase In price by 5—157..

LNG COMPOSITIONS

Natural gas, as received from the well head, can have varying compositions depending upon the well and Its location in the world. The gas will be mostly methane but can contain nitrogen, ethane, propane, butane, pentane, water vapor and lesser quantities of other heavies plus sulfur. As an engine fuel, one must consider the pros and cons of all these constituents.

Methane, the main constituent In natural gas, has the highest octane rating (130) value compared with ethane, propane and the heavier hydrocarbons. (See tables I and 2 for gas properties). Depending upon the engine design and combustion cycle used, the fuel composition could play a pivotal role. As with gasoline engines, the octane rating of the fuel gas influences the engine design and dictates the allowable compression ratio and power produced without knock and engine damage. Variations in fuel composition, such as occurs with LNG, could damage an engine when the fuel contains excess heavier hydrocarbons. For this program we decided that essentially pure methane was the fuel of choice. Methane as a gaseous fuel can be considered as a "Ui—Test' fuel compared to the other hydrocarbon gases. This has led to the development by Air Products and Chemicals, Inc., of refrigerated liquid methane, RLMTM fuel.

RLMTM is a trademark of Air Products and Chemicals, Inc.

Liquid methane as a locomotive fuel compares to diesel fuel, which it replaces as shown in Table 1. As you can see it takes twice as much liquid methane by volume to fuel the locomotive but about the same weight.

ENGINE CONVERSION

The locomotive chosen for conversion was an EMO SD 40—
2 manufactured by the Electro—Motive Division of General Motors. It was chosen for the program due to its wide usage with BN and other railroads and thus the opportunity to apply the technology to numerous units. This locomotive uses a 16 cylinder, 2 stroke cycle 645 cubic Inch (10.68 it) per cylinder diesel engine model 645 E3B rated at 3300 bhp (2462 KU) and 3000 hp (2238 KU) into the generator. The engine Is turbocharged with the cylinders having side port air supply admission for combustion air and scavenging air and with four exhaust valves In the cylinder hedd. The engine was converted to a dual fuel system using diesel fuel as a pilot ignition source while burning gas as the main fuel. The gas Is burned In the Otto cycle having been Injected into the cylinder at the beginning of the compression stroke, after the exhaust valves have closed and the air intake ports are covered by the rising piston. The fuel—air charge is then compressed and Ignited by the pilot diesel Injection.

2 3300 bhp at 900 rpm, 733 mm—Hg, (28.86 in—Hg)
pressure & aS.56 (6OF), AIR standard conditions.

Table 1

	Liquid Methane HHV	Liquid Methane LHV	# 2 Diesel HHV	# 2 Diesel LHV	Ratio
Heating Valve (KJ / 1 t)	55, 456	49, 920	45, 608	42, 788	1. 08
Heating Valve (Btu / 1b)	23, 893	21, 500	19, 650	18, 435	1.08
Heating Value (KJ / 1 t)	21, 710+	19, 544+	38, 353	35, 984	0.50
Heating Value (Btu / gal)	77, 890*	70,116*	137,600	129,100	0.50

* at 100psig & -210 deg F
\+ at 690 kPa & -134.5 deg C

The substitution rate of gas varies with load such that at full load the engine burns from 90 to 957. gas and at idle the engine is on diesel fuel alone. Full power has been obtained by providing colder combustion charge air. This offsets the power loss necessitated when operating in the Otto cycle with a reduced compression ratio. The engine conversion entails new cylinder heads, new pistons, new gas injection valves together with the gas feed control system and new electronic engine controls.

The engine fueling is controlled by a computer system which supplies the proper amount of diesel fuel for ignition and the proper amount of gas to satisfy the power range selected by the train engineer. The control system is designed to revert to full diesel operation in the event that the gas supply system malfunctions or is shut down for some reason. The diesel injectors were maintained as original equipment.

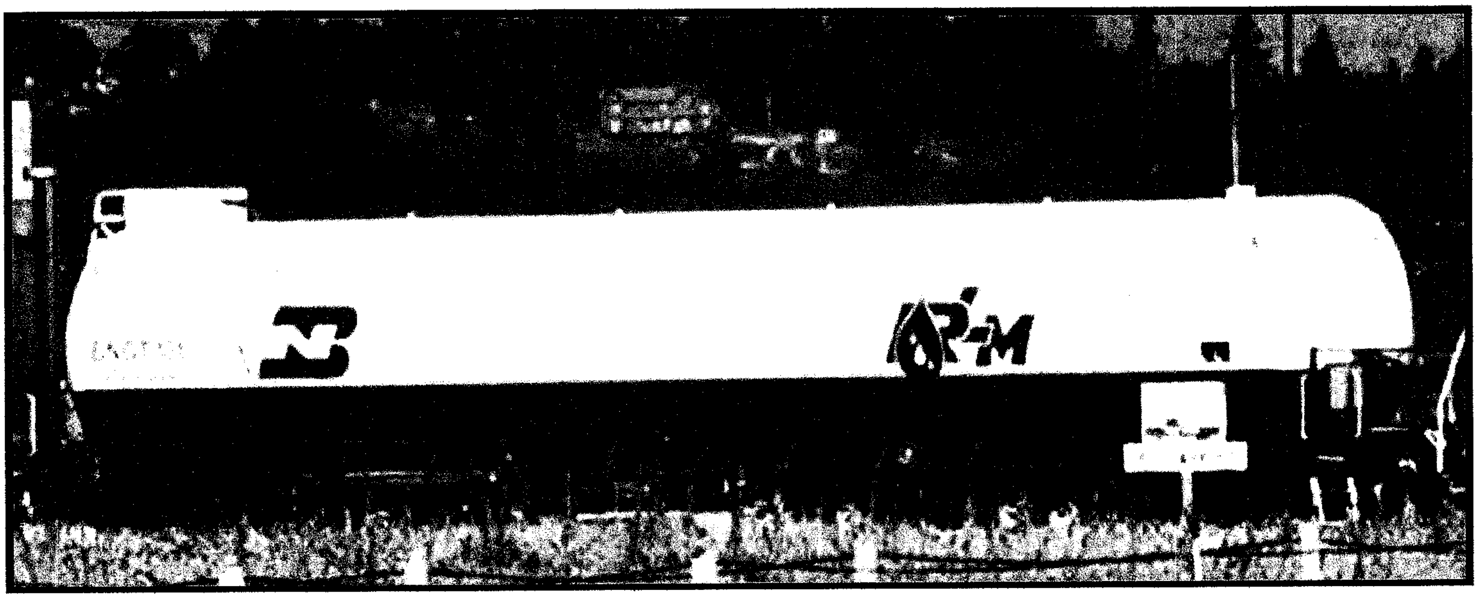
The engine conversion was performed by Energy Conversions, Inc. and incorporates proprietary features in the hardware designs and the control systems for the engine and locomotive.

Table 2

PROPERITIES OF HYDROCARBON FUELS (See Note)

	Formula	Mo / Wt	Auto Ign. Temp Deg C	Auto Ign. Temp Deg F	Lower Heating-Value KJ / kg	Lower Heating-Value Btu / 1b	Octaine Number
Methane	CH4	16.04	538	1000	49,920	21,500	120 - 130
Ethane	C2H6	30.07	521	970	47.490	20,420	100 -115
Propane	C3H8	44.10	470	878	46,350	19, 930	95-110
n - Butane	C4H10	58.12	410	770	45, 630	19, 620	88-94
#2 Diesel			260	500	42, 788	18, 435	

Note: The properties stated in this table are the properties used for this project and may or may not agree with published data. These values were sourced from Air Products and Chemicals, Inc. data books plus various published criteria which do not always agree. Where data did not agree, we have averaged or used our best judgment. References [3], [4], [5].



FUELING SYSTEM

The liquid methane fuel supply for the locomotive is carried In a separate tender car. (See Figure 2.) The tender car is a double walled cylindrical storage container mounted on a conventional center sill railroad frame and truck assembly. The tender car is vacuum insulated to store the cryogenic liquid methane for normal runs without any vapor loss by venting. The tender car is designed to fuel two locomotives, one from either end. It carries 20,000 gallons of RLM fuel which can fuel the two locomotives for the same distance as when using diesel fuel. The SD 40-2 locomotive diesel fuel tank holds 4,000 gallons. The tender car carries the liquid methane at approximately 100 psig and —2I0 although the pressure and temperature can be varied up or down depending upon pressure requirements and the base refueling station storage supply temperature. The base station will normally store RLM fuel at about 5 pslg and —250 Refueling time Is planned to be approximately 45 minutes. (See Figure 3.)

The tender car incorporates two vaporizers, one for each locomotive being fueled, plus the valving and controls needed for safe fuel supply and rapid refueling at the base station. The tender car design has been reviewed with the U.S. Federal Railroad Administration (FRA) Office of Safety and the Office of Hazardous Material Transport, both within the Department of Transportation. Design calculations were based on the most conservative results of either the Association of American Railroads (AAR) or American Society of Mechanical Engineers (ASME) codes. The insulation system, perlite—filled vacuum jacket, was tested for flame/thermal resistance at the AAR Transportation Test Center (TTC) located in Pueblo, Col. with excellent results.

The vaporized liquid gas supply is transferred to the locomotive by a flexible hose connection similar to normal air brake hose connections except that hose breakage or car coupling pull away will automatically activate a control valve to stop the fuel flow. The heat exchanger fluid from the locomotive to the tender car is also by flexible hoses similar to the gas supply hose. Initial operation has with with 50/50 ethylene glycol / water heat transfer. (See Figure 4.)

Engine Cooling 1System

The temperature and pressure of the combustion charge air supplied to the cylinder determines the amount of air mass available to combust the fuel and thus it was necessary to provide additional charge air cooling in order to reach full power. Most turbocharged engines provide cooling to the charge air with an aftercooling using engine jacket water as the cooling fluid. Alternatively an air to air cooler using ambient air exchange to the charge air could be used. We chose to add additional radiators to the locomotive with a separate cooling water system providing colder water to the turbocharger aftercooler. This lowers the charge air to a temperature of about 28 deg C (50 deg F) above ambient. (A typical locomotive aftercooler uses engine jacket water at 82 deg C (180 deg F) and cools the charge air to approximately 100 deg C (212 deg F)
at full load.)
Additional cooling is then provided by the refrigeration available in the liquid methane. A separate cooling system cooling system uses the heat extracted from the charge air to vaporize the liquid methane as it is used for fuel and this heat exchange is then capable of reducing the charge air temperature another 22 deg C (40 deg F). (See Figure 5.)

Summary

At the time of this writing, the locomotive and tender car system are undergoing extensive testing at various loads and operating conditions. We have observed good operation which promises a successful program; however, we believe it is too early to publish factual data in a technical paper. Engine performance, locomotive system and tender car operation are being monitored. Several modifications have been made to the original development design and we anticipate more changes before we are finished.
The sequence selected for this test program is set forth below:

- 500 hour durability test
- Inspect engine for wear and reassemble
- Operate for gaseous and particulate emissions testing
- Maintenance, repairs, or modifications
- Locomotive-tender car system field trials
- (short haul revenue service).

This project has shown that dual fuel locomotives are viable and we expect a broad usage in the next few years.