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ADVANCED LNG ONBOARD STORAGE SYSTEM (ALOSS)

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EXECUTIVE SUMMARY

Cummins Westport Incorporated (CWI) has designed and developed a liquefied natural gas (LNG) vehicle fuel system that includes a reciprocating pump with the cold end submerged in LNG contained in a vacuum-jacketed tank. This system was tested and analyzed under the U.S. Department of Energy (DOE) Advanced LNG Onboard Storage System (ALOSS) program. The pumped LNG fuel system developed by CWI and tested under the ALOSS program is a high-pressure system designed for application on Class 8 trucks powered by CWI's ISX G engine, which employs high-pressure direct injection (HPDI) technology.

A general ALOSS program objective was to demonstrate the feasibility and advantages of a pumped LNG fuel system relative to on-vehicle fuel systems that require the LNG to be "conditioned" to saturation pressures that exceeds the engine fuel pressure requirements. These advantages include the capability to store more fuel mass in given-size vehicle and station tanks, and simpler lower-cost LNG refueling stations that do not require conditioning equipment. Pumped LNG vehicle fuel systems are an alternative to conditioned LNG systems for spark-ignition natural gas and port-injection dual-fuel engines (which typically require about 100 psi), and they are required for HPDI engines (which require over 3,000 psi).

The figure below illustrates the LNG tank and fuel system configuration and components tested under the ALOSS program. This design evolved from a first-generation pumped system designed by Westport Innovations Inc. that mounted the pump in a vacuum-jacketed housing that was separate from but connected to the LNG fuel tank. The first-generation system has accumulated over 2.3 million miles of service on ISX G powered refuse transfer trucks operated by Norcal in South San Francisco, California. In the current system shown in the figure, the pump penetrates into the tank so that the cold end is submerged in LNG and the hydraulic drive is housed in the shroud. This provides immediate start-up capability with no vapor generation.

The Overall CWI LNG Tank, Pump, and Fuel System Components

The pump itself is a two-chamber reciprocating design based on the successful first-generation LNG pump. The two chambers and other design features provide the near-zero net positive suction head (NPSH) capability needed for this application. The pump housing and tank interface enables convenient pump removal for maintenance and minimizes heat transfer to the LNG. Other unique design features include an integrated vaporizer that is concentric around the pump drive shaft and an ullage drain connected to a fill-tube venturi, which ensures that the tank cannot be overfilled with liquid. The liquid level is measured with a capacitance sensor. The LNG tank is manufactured by Taylor-Wharton (which is part of Harsco Corporation) who contributed to the manufacturability, reliability and code compliance of the design. The baseline LNG tank capacity is 110 gallons, but initial tanks to be field tested by Norcal are 68 gallons in order to accommodate their requirements.

Many thousands of hours of pump tests using LNG tanks mounted on instrumented test carts at CWI have validated pump performance and durability. Net evaporation rate (NER) and hold-time tests have been carried out on multiple LNG tanks, and the results are consistent with respect to heat leak. Liquid level sensor tests show a near-linear relation between output signal and the weight of LNG in the tank. The LNG tanks have been drop tested consistent with the SAE J2343 Recommended Practice, and they passed both the 10-foot and 30-foot drop tests. Accelerated vibration tests have also been performed to confirm the LNG tank structural design adequacy when subjected to severe truck road loads.

LNG tanks fitted with pumps and other fuel system components are also being road tested on CWI's Kenworth T800 engineering truck (see figure below). The variety of tests carried out under the ALOSS program have demonstrated the general advantages of a pumped fuel system and the specific performance of the CWI design.

LNG Tanks Manufactured by Taylor-Wharton Have Been Tested on CWI's
ISX G Powered Kenworth T800 Engineering Truck

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Section 1 INTRODUCTION

1.1 Background

Natural gas use as a transportation fuel provides well-recognized benefits including reduced exhaust emissions and energy resource conservation. Natural gas is particularly beneficial when it replaces diesel fuel in trucks and buses, because diesel engine emissions are more problematic than gasoline engine emissions, and the high fuel consumption of heavy-duty vehicles enhances the economics. Because natural gas has a very low density at ambient conditions, it is stored on vehicles in a highly compressed state or as a cryogenic liquid. Liquefied natural gas (LNG) is preferred by most heavy truck fleets and many transit bus agencies because its higher density enables smaller and lighter-weight tanks, and other reasons involving refueling station advantages, fuel supply contracting, and fuel costs.

Most all LNG vehicle fuel tanks are cylindrical vacuum-jacketed (VJ) dewars with multi-layer insulation (MLI) between the inner vessel and outer shell. The purpose of this construction is to minimize the rate of heat transfer to the LNG, which reduces the pressure rise rate and therefore extends the hold time (defined as the time until the pressure reaches the pressure relief valve setting). There are different design approaches for suspending the inner vessel within the outer shell and for routing the liquid and vapor tubing. These options and many other factors affect the thermal insulation and hold time.

While all LNG fuel tanks have certain common features, they differ in the way that pressure is controlled and how the tank is refilled. Options include: pressure-transfer or pumped fuel delivery, one-line or two-line refueling, top-fill or bottom-fill, pressure-building and/or pressure-reducing capability, and saturation strategy. These options and the associated tradeoffs have been reviewed in various other publications (e.g., References 1, 2, and 3).

The LNG fuel system requirements and acceptable design options depend on the type of natural gas engine they support, primarily its fuel supply pressure. The basic types of heavy-duty natural gas engines and their approximate fuel supply pressure requirements are:

- Spark ignition natural gas (SING): typically between 60 and 100 psig
- Port-injected dual-fuel: typically slightly more than 100 psig
- High-pressure direct injection (HPDI): at least 3,000 psig

LNG is typically delivered to LNG refueling stations at a saturation pressure of less than about 30 psig. Even though this saturation pressure is increased somewhat by the various transfer operations (from tank truck to station storage tank to vehicle fuel tank), it is still less than the fuel supply pressure required by any of the commonly used natural gas engine types. For SING and port-injected dual-fuel engines, it has become common practice to add heat to the LNG at the refueling station in order to increase its saturation pressure so that, when it is transferred to the LNG vehicle fuel tanks, this pressure exceeds the engine fuel supply pressure requirements.

The process of purposely adding heat to the LNG at the refueling station to increase its saturation pressure is referred to as “conditioning.” The most common conditioning approach is

“bulk” conditioning, where the LNG is processed in a heat exchanger to increase its saturation pressure in the station storage tank. “On the fly” conditioning, where electric heaters near the dispensers increase the LNG saturation pressure as it flows to the vehicles, is also used at a few stations.

This conditioned LNG approach enables fuel to be supplied to the engine by pressure transfer, and this results in a relatively simple on-vehicle LNG tank and fuel system. However, this approach also has acknowledged disadvantages (which are discussed in more detail in References 1, 2, and 3):

- Less fuel can be stored on the vehicle in a given-volume tank (because LNG density decreases as saturation pressure increases).
- Additional refueling station equipment is needed to effect the LNG conditioning.
- Less LNG can be stored in a given-volume station tank if bulk conditioning is used.
- More expensive LNG storage tanks with a higher maximum allowable working pressure (MAWP) are needed at the station if bulk conditioning is used and the same hold-time is to be maintained.
- Significant electrical power is consumed by the station if on-the-fly conditioning is used.
- The potential for fuel enrichment problems is introduced (because most of these systems use an economizer valve circuit to draw vapor when needed to reduce the vehicle tank saturation pressure, and this increases the concentration of heavy hydrocarbons in the liquid).
- The LNG vehicle tank hold-time is decreased for a given heat leak and fill-to-vent pressure increment (because the ratio of pressure-rise-rate to heat leak increases as saturation pressure increases).

An alternative is an on-vehicle LNG fuel system with a means, such as a pump, to increase the fuel pressure from the LNG saturation pressure in the vehicle tank to the engine fuel supply pressure requirement. Such a system avoids all of the above-listed disadvantages. In particular, more fuel mass can be stored in a given-size vehicle tank, and the refueling station design is significantly simplified. The basic tradeoff is these advantages versus the additional complexity of a pump. A pumped system is required for HPDI engines, and it is an option to the previously discussed conditioned-LNG system for SING and port-injected dual-fuel engines.

Prior related work on pumped on-vehicle LNG fuel systems includes the Houston Metro buses, research carried out by Detroit Diesel and Caterpillar, and prior Cummins Westport Inc. (CWI) design and testing. In the mid-1990s, Houston Metro (the transportation authority in Harris County, Texas) operated approximately 280 LNG-fueled buses with Detroit Diesel 6V-92TA two-stroke cycle engines that utilized a pilot-injection natural gas (PING) technology, which required a fuel supply pressure of approximately 300 psig. These buses had LNG fuel systems manufactured by CVI (which was subsequently acquired by Chart Industries), which utilized a hydraulic-driven reciprocating pump (Reference 4). The single-stage pump was a modified version of the CVI cylinder-filling pump commercial product. The pump penetrated the fuel tank so that the cold end was submerged in LNG and the drive was external to the tank. This

CVI pump LNG fuel system was used on a few other vehicles including four LNG-fueled Maryland Mass Transit buses (Reference 5). CVI also fabricated a higher-pressure pumped LNG fuel system for Detroit Diesel to support their direct injection natural gas (DING) engine testing, but this R&D program was subsequently discontinued. Caterpillar also initiated a DING engine technology study, which included a review of pumped LNG fuel system technology (Reference 6), but this program was also discontinued.

Most of the work on high-pressure pumped LNG fuel systems has been carried out by CWI and Westport Innovations, one of its two parent companies,. This included analyses and experiments to assess pump and pump-tank design options (Reference 7), testing of a prototype system on the CWI engineering truck, and fleet field testing on fourteen LNG-fueled refuse transfer trucks operated by Norcal in South San Francisco, California.

Initial Westport pumped-LNG fuel system work focused on the pump design features required to provide the near-zero net positive suction head (NPSH) performance needed for on-vehicle applications. Part of this work was supported by DOE through a subcontract under a Small Business Innovation Research (SBIR) program issued to The Research Partnership. This work included extensive testing that demonstrated the feasibility of a multi-stage pump that processed liquid-vapor mixtures (i.e., a pump that could suck ullage vapor to provide the same capability as the previously discussed economizer valve used on low-pressure systems) as well as development of a simpler first-generation pump that was used in initial HPDI LNG truck field testing (Figure 1). Technical details pertaining to both efforts are documented in Reference 7.

Figure 1. First-Generation LNG Vehicle Fuel Tank and High-Pressure Pump

This first-generation pump was mounted external to the LNG fuel tank in a separate vacuum-jacked housing (which communicated with the LNG tank vacuum jacket), because it was anticipated that this approach would minimize heat leaks to the tank, make it easier to remove and service the pump, and enable the use of current LNG tank designs with minimal modifications. While this configuration has provided acceptable performance, our more recent experience shows that an internal pump (i.e., pump installed in the LNG tank) provides more advantages, which are discussed in Section 2. The reciprocating pump used with the first-generation system is a hydraulically actuated, low-speed, two-chamber design with single-acting suction and double-acting (i.e., continuous) discharge. The uni-flow design places the suction at the cold end and the discharge near the warm end so that much of the heat from the pump drive and mounting is carried away with the discharged high-pressure LNG. This pump will not be discussed in more detail here, because it was thoroughly documented in Reference 7 and many of its features are similar to the pump described in detail in Section 2.

The LNG fuel tanks used with this first-generation system were manufactured by Chart Industries based on the basic design developed by MVE (which was acquired by Chart), modified to accommodate the pump housing. Following testing on the CWI engineering truck, these tanks, pumps, and fuel systems were used with ISX G HPDI engines installed in Class 8 trucks operated by Norcal, Raley's, and Bobell. Figure 2 shows one of the fourteen Norcal Peterbilt 378 tractors equipped with this system. These refuse-transfer trucks, which have only one 75-gallon LNG tank due to their modest range requirements, have accumulated over 2.3 million miles of relatively problem-free service.

Figure 2. The Fourteen ISX G Powered Norcal Refuse Transfer Trucks Have Accumulated Over 2.3 Million Miles Using the First-Generation Pumped LNG Fuel System.

This first-generation LNG pump and fuel system development and fleet testing provided the basis for design improvements that were incorporated into the second-generation system. The second-generation LNG pump, tank, and overall fuel system was designed and developed by CWI, and certain testing and analysis work was carried out under this DOE Advanced LNG Onboard Storage System (ALOSS) Phase I program. This work is described in detail in Sections 2 through 4.

1.2 Objective

The overall objective of CWI's second-generation LNG fuel system development work and the ALOSS Phase I program was to carry out initial design, fabrication, testing, and evaluation of an advanced on-vehicle LNG fuel system that utilizes a pump to supply fuel for natural gas engines that require either high or low pressures. A specific objective was to avoid the liabilities (e.g., less fuel mass stored and more complicated refueling station requirements) of on-vehicle fuel systems that must be refueled with higher saturation pressure LNG. Another objective was to demonstrate performance improvements and design simplifications (i.e., potential cost reductions) relative to the first-generation CWI LNG fuel system, which utilized a pump mounted external to the tank in a separate but integrated vacuum-jacketed housing.

1.3 Report Organization

The overall LNG tank and fuel system design is described in Section 2. The fabrication and test program including LNG tanks, pumps, other system components, and test facilities is discussed in Section 3. The ALOSS test program and example results are presented in Section 4. Conclusions are summarized in Section 5.

Section 2

LNG TANK AND FUEL SYSTEM DESIGN

2.1 Application Requirements

The LNG fuel tank, pump, and overall system designs are driven by the application requirements. The main application targeted by the work reported here is the CWI HPDI ISX G engine installed in a Class 8 truck. The primary LNG fuel system requirements dictated by this engine application are the fuel supply pressure and maximum fuel flow rate, which are listed in Table 1.

Quantity	Approximate Requirement
Fuel pressure	4,800 psig
Maximum fuel mass flow rate	66 kg/hr (2.4 Lbm/min)

Table 1. LNG Fuel System Requirements Affected by ISX G Engine Requirements.

The actual ISX G engine fuel supply pressure requirement is somewhat less than the 4,800 psig value indicated in Table 1. This figure includes an increment to increase the mass of fuel resident in the vaporizer and fuel lines so that no separate accumulator vessel is needed (the previously discussed first-generation LNG fuel system included a 30-liter CNG vessel, which functioned as a reservoir or accumulator to ensure an adequate fuel supply for all operating conditions including startup). The 66 kg/hr fuel flow rate requirement shown in Table 1 is also somewhat greater than the maximum ISX G engine fuel flow requirement because it includes an appropriate margin to accommodate any unusual operating conditions.

Other less-quantitative application requirements include the capability for low-pressure fuel storage and various improvements based on the first-generation system fleet test experience. The low-pressure fuel storage capability benefits include increased on-vehicle fuel mass and simpler refueling station design, relative to systems that require higher-pressure saturated LNG, as discussed in Section 1.1. The primary design change indicated by the Norcal and other fleet testing experience is associated with the advantages of locating the LNG pump cold end inside of the fuel tank. The pump cold end is submerged in LNG while the pump drive is external to the tank (more details regarding the specific configuration are provided in Section 2.2). This eliminates the pump cool-down period, provides faster high-pressure fuel delivery during start up, and much less vapor is generated. Also, because the tank has no external appendage and the pump drive is compactly packaged in the shroud, safety is enhanced and the system more easily meets the drop tests specified by the SAE J2343 Recommended Practice.

A final application requirement pertains to the LNG fuel tank capacity. A variety of fuel storage capacities, which are affected primarily by driving range between refueling events, are required for different Class 8 truck applications. Also, different manufacturers' chasses have different specifications affecting the number, diameter, and length of fuel tanks that can be accommodated. CWI has extensively investigated these requirements and restrictions. Discussions with operators of truck fleets that are candidates for ISX G and LNG fuel system road trials indicate that many of their trucks have fuel tank length and diameter limitations of 78

inches and 26 inches, respectively. This translates to a 110-gallon LNG tank capacity, which was selected as the baseline.

However, it is planned to carry out initial LNG fuel system field trials at Norcal, in South San Francisco, using their refuse transfer trucks. Maximum payload weight is important to Norcal for this application, long range is not required, and their Peterbilt 378 tractors have specific chassis requirements. These factors are best accommodated with a 68-gallon LNG tank, and so this size has been used for initial LNG tank and fuel system development, fabrication, and testing.

2.2 Overall LNG Tank and Fuel System Design

The overall LNG tank and fuel system design is summarized here. Design details specific to the pump are discussed in Section 2.3, and the designs of other key fuel system components are reviewed in Section 2.4.

Figure 3 is a cutaway side view of the LNG tank, pump, and other components. The key features and components are labeled in Figure 3, and they are discussed below.

Figure 3. The LNG Fuel Tank, Pump, and Key Components.

The LNG fuel tank design is consistent with current code-compliant cryogenic vessel practice. The inner and outer tanks are both stainless steel. The annular space between the tanks is evacuated and it contains multi-layer insulation (MLI). The LNG tank maximum allowable working pressure (MAWP) has been established as 210 psig, and the inner tank is designed and fabricated to be ASME pressure vessel code compliant at this MAWP (see also Section 3.1). The outer tank is designed to withstand atmospheric pressure loading on the outside and a vacuum on the inside without distortion. It is fitted with a device to vent if the inside pressure exceeds atmospheric pressure (e.g., in case of an inner tank leak), so that it does not become a pressure vessel.

The inner tank is suspended within the outer tank by pins on each end of the inner tank that fit in holes in support straps welded to the inside of the outer tank. These supports are designed to provide the structural strength needed for heavy-duty truck service, the SAE J2343 drop tests, and the NFPA 8-g acceleration requirement, while minimizing heat conduction from the environment to the LNG. A third-generation support system with less thermal conductivity is currently being designed. A proprietary “getter” material combination is installed in the vacuum jacket to ensure that a long-term hard vacuum is maintained.

A key feature of the LNG fuel system design is the high-pressure pump, which is mounted in the LNG tank as shown in Figure 3. The pump is mounted so that the suction tube opening is very near to the bottom of the tank, and the pump itself remains submerged in liquid until the tank is nearly drained of fuel. The pump is installed in a vacuum-jacketed housing within the LNG tank. The housing inner-tube is joined to the outer tank, and the housing outer-tube is joined to the inner tank, as illustrated in Figure 3. This “telescoped” configuration results in a long heat-transfer path, which minimizes the additional heat leak associated with the pump installation. When the pump is installed, the face of the pump drive shaft tube seals against the flange that joins and closes the ends of the pump housing inner and outer tubes. This enables the pump to be easily removed for servicing without disrupting the tank vacuum. The pump-tank interface is referred to as a socket or hub or nozzle.

The bulkhead toward the right side of the inside of the LNG tank in Figure 3 forms the ullage space. The ratio of the volume of this space to the overall gross tank volume is 11%. With a first pressure relief valve (PRV) opening pressure equal to the 210-psig MAWP, this enables the tank to be filled with LNG having a relatively low saturation pressure without any risk of the tank becoming liquid full before venting.* Liquid slowly flows from the main tank into the ullage tank through a small hole in the ullage bulkhead, so that the main tank does not become liquid full as heat transfer to the liquid increases its saturation pressure and decreases its density. During refueling of a partially full tank, liquid is withdrawn from the ullage space through the tube that penetrates the ullage bulkhead through the ullage drain hole as illustrated in Figure 3. The suction to accomplish the ullage liquid withdrawal is provided because the ullage drain line is connected to a venturi section of the fill line, which creates a low pressure during filling. This ullage space drain function ensures that an adequate ullage volume results during refueling regardless of the liquid level in the main tank and ullage volume when refueling is initiated.

* Note that the current editions of NFPA 57 and SAE J2343 do not disallow a liquid full condition before venting for LNG vehicle tanks.

Refueling is terminated (i.e., fill stop) when the main tank becomes liquid full. The resulting abruptly reduced fuel flow rate or increased fill line pressure is sensed by the refueling station controls, and this triggers refueling flow termination. The LNG tanks fabricated and tested to date have been configured for one-line “vapor collapse” top filling. However, CWI is exploring other tank refueling strategies. The fill line, vent line, secondary relief line, and liquid drain line are indicated in Figure 3.

The LNG tank is equipped with a full-diameter shroud, which is a cylindrical extension on the end of the tank with a hinged and latched closure panel. The pump hydraulic drive, liquid and vapor shut-off valves, LNG liquid and vapor lines, engine coolant lines, hydraulic fluid lines, high-pressure gas filter, liquid level signal conditioner, and various other components are compactly housed within the shroud. The shroud itself absorbs energy when deformed, which protects the housed components and reduces loads transmitted to the tank during drop testing or a potential vehicle collision.

Various connections penetrate the shroud at two panels. The outward-facing panel contains the LNG fill receptacle (Carter or Parker), vent connection, and a tank pressure gage. The inward-facing panel contains a wiring harness feed through, mounting for the higher pressure gas filter, and connections for the high-pressure gas supply to the engine, RV vent line, hydraulic fluid supply and return, and engine coolant supply and return.

2.3 Pump Design

The LNG pump shown in Figure 4 incorporates the design features that have proven to be successful in the first-generation LNG high-pressure fuel system. This hydraulic-driven reciprocating pump has two chambers, which provide double-acting discharge and single-acting suction operation. As shown in Figure 4, the first chamber is the circular cylinder formed between the suction end and the forward end of the piston, and the second chamber is the annulus-shaped volume formed around the pump drive shaft. The piston has a check-valve that permits fluid to pass from the first chamber to the second chamber.

The LNG pump operates in the following manner. When the piston retracts (right to left movement in Figure 4), fluid is drawn through the suction tube into the first chamber through a one-way suction valve. When the piston extends from left to right, fluid is pushed through the check valve located in the piston and into the second chamber. The diameter of drive shaft is sized so the volume of the second chamber is about half the volume of the first chamber. Therefore, half the volume of the liquid in the first chamber will flow to the second chamber and the remainder will be pushed out to the left through the discharge line and a one-way discharge valve. When the piston retracts to the left again, more LNG will be drawn through the suction tube and into the first chamber while at the same time the previously transferred LNG in the second chamber will be discharged out through the discharge line. In other words, on each piston stroke, in either direction, about an equal amount of LNG is discharged. This is an advantage for smooth pump operation.

This configuration provides the near-zero NPSH performance needed for this application. Because the suction valve and discharge valve are located at opposite ends of the pump, this leaves more room for a large suction valve that causes a very low pressure drop and minimal flashing of the sucked fluid. Also, with this configuration, the fact that the pumped fluid is

slightly warmer than the sucked fluid (which would increase flashing if the valves were

Figure 4. Details of the Reciprocating High-Pressure LNG Pump Design.

co-located) has minimal effect on the LNG sucked fluid state. This layout is sometimes referred to as a uni-flow configuration.

This pump can accommodate some fluid flashing or cavitation without passing vapor or heat back to the LNG in the fuel tank. Any vapor in the first chamber following the suction (retract) stroke is condensed (liquefied) as it is compressed during the subsequent extend stroke. When operating in this fashion, the pump may be regarded as a two-stage pump, and the pump volumetric efficiency decreases as flashing or the quantity of sucked vapor increases. The relative volumes of the two chambers are selected to provide optimum performance in this regard for typical on-vehicle operating conditions. Additional details and test results pertaining to the vapor-processing capabilities and NPSH performance of this basic pump configuration were documented in Reference 7. Proprietary-design piston and shaft seals provide the needed durability and fluid isolation functions for this application.

This LNG pump is designed specifically for in-tank installation and operation. The long drive shaft and housing, as well as the tank penetration discussed in Section 2.2, minimize the rate of heat transfer from the environment to the stored LNG. The pump hydraulic drive unit is very compact (so that it fits completely within the tank shroud), and it is designed to self-regulate

the stroke length. Directional control valves in the hydraulic drive avoid potentially troublesome limit switches.

2.4 Other System Components

The LNG fuel system vaporizer transfers heat from the engine coolant to the pumped LNG so that the gas delivered to the engine is near room temperature. While its basic function is similar to vaporizers used with lower-pressure saturated LNG systems, the thermodynamic states of the LNG and the vaporizers' design features are quite different.

Figures 5 and 6 compare the paths of the LNG from the tank to the engine for this system and a low-pressure saturated LNG fuel system. Figure 5 compares the paths in terms of pressure versus density, and Figure 6 compares the paths in terms of temperature versus density. The LNG saturation line is shown for reference in both diagrams. For simplicity, the LNG is assumed to be pure methane, the pumping process is assumed to be isentropic, and pressure drops associated with flows through the vaporizers are neglected in these diagrams. A key observation from Figures 5 and 6 is that the high-pressure fluid flowing through the vaporizer is supercritical. While no fluid is literally vaporized in this process, the term "vaporizer" is used here because that is conventional practice. Figures 5 and 6 also illustrate the previously discussed advantage of this LNG fuel system in terms of the mass of LNG stored in the fuel tank. For a typical pumped system tank filling saturation pressure of 20 psig and a typical conventional system tank filling pressure of 100 psig, the density difference and pumped system tank mass capacity advantage is about 10%.

The vaporizer is basically a single-pass shell-and-tube heat exchanger. The high-pressure LNG flows through the coiled tube, and coolant from the engine flows through the shell. The vaporizer is shaped as an annulus that surrounds the pump drive shaft near the pump flange and LNG tank socket as illustrated in Figure 4. This provides a very compact package because the ALOSS vaporizer is integrated with the pump and tank instead of being a separate unit that must also be mounted on the truck with additional fuel and coolant connections.

The liquid level in the LNG tank is sensed by a capacitance gage (the vertical tube in Figure 3). The capacitance gage signal is processed by an electronic signal-conditioning unit located inside the shroud. The sensed capacitance is converted to a 0.5- to 4.5-volt signal to the level gage in the truck cab. The signal-conditioning unit effects various corrections to account for calibration shifts and other effects such as EMI.

The high-pressure LNG flows from the pump vaporizer through a 0.3-micron filter located within the tank shroud region (see Figure 3). This filter ensures that no potentially abrasive particles in the LNG reach the HPDI fuel injectors. Other LNG fuel system components include the liquid fill-line check-valve, the liquid and vapor valves located within the shroud, the pressure relief valves, and the secondary inlet on the high-pressure gas filter for two-tank installations.

Figure 5. High-Pressure Pumped and Low-Pressure Saturated LNG System Fuel Path Comparison: Pressure versus Density.

Figure 6. High-Pressure Pumped and Low-Pressure Saturated LNG System Fuel Path Comparison: Temperature versus Density.

Section 3 FABRICATION AND TEST PROGRAM

3.1 LNG Tanks and Components Fabrication

The LNG fuel tanks were fabricated by Taylor-Wharton, which is part of the Gas & Fluid Control Group of Harsco Corporation. CWI and Taylor-Wharton engineering personnel collaborated regarding the design of the LNG tanks discussed in Section 2.2. The design was influenced by reliability, manufacturability, and code-compliance considerations. The 68-gallon capacity of initial tanks (as compared to the 110-gallon baseline tank capacity) was selected to facilitate initial fleet testing on Norcal trucks as discussed in Section 2.1. The LNG tanks were fabricated at Taylor-Wharton's plant in Theodore, Alabama.

Figure 7 is a photograph of 68-gallon Taylor-Wharton-manufactured LNG tanks delivered to CWI for testing. The inner LNG tanks are designed, fabricated, tested, and labeled in accordance with the ASME Boiler and Pressure Vessel Code. Figure 8 shows the nameplate on the LNG tanks, which indicates compliance with the ASME code. Other LNG fuel system components such as the pump were fabricated to CWI specifications by selected vendors.

3.2 Test Facilities

CWI facilities in Vancouver, Canada, include a LNG fueling station, a test area devoted to LNG tank and fuel system testing, test carts for testing LNG tanks and pumps, and high-speed digital data acquisition systems. These facilities were used to test the LNG tanks and pumps discussed in Section 2. Example tests and results are discussed in Section 4.

Figure 9 shows an LNG tank mounted on a test cart. This particular tank is a 150-gallon LNG tank fabricated by a supplier that was being evaluated by CWI prior to initiation of the ALOSS program. These relatively large tanks were sometimes used for pump durability testing because they maximize the cycles and hours of pump operation between tank refillings. Figure 10 shows the shroud end of a 68-gallon LNG tank and pump on a cart being tested at CWI. LNG tanks with pumps, vaporizers, and other fuel system components are mounted on these carts for functionality, performance, and durability testing. The carts are equipped with all interfaces needed to simulate operation on a truck. This includes connections for the high-pressure gas as well as the engine coolant and hydraulic fluid (which are supplied from separate fixtures). The carts have a control panel and transducers to measure flow rates, pressures, and temperatures. LNG is supplied from CWI's LNG fueling station.

3.3 Engineering Truck

CWI owns and operates an "engineering truck" which serves as a test bed for ISX G engines and LNG tanks and fuel systems. Figure 11 shows the CWI engineering truck with a preliminary-build Taylor-Wharton LNG tank. The CWI engineering truck (which is properly referred to as a tractor) is a Kenworth T800 with a prototype CWI ISX G engine. Because the ISX G employs HPDI technology with diesel fuel pilot injection, a small capacity diesel fuel tank is needed. The diesel fuel tank is shown mounted forward of the LNG tank in Figure 11. This configuration is appropriate when two LNG tanks are mounted on the truck. If only one LNG tank is mounted on the truck, the diesel fuel tank can be mounted on the opposite side.

Figure 7. 68-Gallon LNG Tanks Fabricated by Taylor-Wharton and Delivered to CWI for Testing.

Figure 8. The LNG Tanks Manufactured by Taylor-Wharton Comply with the ASME Boiler and Pressure Vessel Code.

Figure 9. CWI High-Pressure LNG Fuel System Test Cart with a Large-Capacity Tank Used for Pump Durability Testing.

Figure 10. Shroud and Pump-Drive End of Taylor-Wharton-Manufactured LNG Tank Mounted on a CWI Test Cart.

The CWI engineering truck was used to test the on-vehicle on-road performance of the previously discussed LNG tanks, pumps, and other components. The truck can refuel at the CWI LNG station and at the LNG station operated by Bobell Trucking in Aldergrove, British Columbia. Depending on the test objective, engineering truck tests can be carried out for various speed and load conditions with or without a loaded trailer to provide a GVW of up to 80,000 pounds. Specific LNG fuel system engineering truck tests are discussed in Section 4.

Figure 11. The CWI Engineering Truck is a Kenworth T800 Tractor Used for On-Road Testing of ISX G Engines and LNG Fuel Systems.

Section 4 TEST AND VALIDATION PROGRAM RESULTS

4.1 Testing Overview

Extensive testing of the LNG tank, pump, and integrated system described in Section 2 was carried out as part of the ALOSS program and CWI in-house programs. These tests utilized the CWI facilities discussed in Section 3 as well as subcontractors' facilities in some cases. A substantial quantity of test data was generated and analyzed, and refinements to the test procedures as well as the LNG fuel system component designs were implemented in an iterative fashion based on these analyses. Highlights of these tests and example data are summarized in the following subsections.

4.2 Pump Performance and Durability

A key LNG fuel system component is the LNG pump described in Section 2.3 and illustrated in Figure 4. This pump, with some minor design refinements, was extensively tested using the LNG test carts described in Section 3.2. Figure 12 is a photograph of an LNG test pump removed from a cart-mounted LNG fuel tank. These tests addressed multiple pump-related objectives including performance and durability as well as the functionality of the pump hydraulic drive and vaporizer.

Figure 12. A Test Pump Removed from a Cart-Mounted LNG Fuel Tank.

Figure 13 shows a durability test data example. This graph indicates the pump discharge mass flow rate and LNG fuel tank pressure recorded over approximately 40,000 pump stroke

cycles, which required 14 LNG fuel tank refillings. The pump discharge pressure (of the gas downstream of the vaporizer) was regulated to approximately 4,800 psi for the test shown in Figure 13. Note that the average pump mass flow rate was approximately 85 kg/hr (approximately 3.1 Lbm/min or 0.93 gpm), which significantly exceeds the maximum ISX G fuel flow requirement.

Figure 13. Example LNG Pump Durability Test Data: Discharge Mass Flow Rate and LNG Tank Pressure While Pumping Approximately 1,000 Gallons of LNG.

Energy is removed from the fuel tank slightly faster than heat leaks into the tank at this high-flow pumping condition, and so this slowly decreases the saturation pressure of the liquid and vapor in the tank as shown by the tank pressure data in Figure 13. The pump discharge mass flow rate is a function of the suction fluid density, the stroke rate (which was nearly constant at about 45.8 cycles/min for these tests), and the volumetric efficiency (which decreases as the liquid level in the tank decreases). The net effect, as shown in Figure 13, is a slight decrease in the pump mass flow rate as the tank is pumped from full to empty.

Figure 14 shows some key quantities recorded during a brief period (10 seconds) of pump testing. The small variation in pump discharge pressure (from 4,640 psi to 4,130 psi) is slightly different from what would be seen by a HPDI engine fuel rail. This is because, when applied to the engine, the pumping is modulated by the engine fuel flow requirements, but a back-pressure regulator is used on the test cart rig to ensure constant full-flow pump operation. The LNG fuel tank pressure was approximately 44 psig during this test period. The pump discharge mass flow rate is measured by a MicroMotion (Coriolis type) mass flow meter in the line downstream of the vaporizer. The mass flow profiles shown in Figure 14 reflect a significant damping relative to the

Figure 14. Example LNG Pump Performance Test Data: Discharge Mass Flow Rate and Pressure, Tank Pressure, Hydraulic Pressure, and Stroke Rate Recorded Over Eight Stoking Cycles.

flow at the pump discharge port due to the volume and compressibility of fluid between the pump and meter as well as the response of the meter itself. In actuality, the pump has negligible discharge during that part of the extend stroke during which the vapor in the first chamber is being condensed, but it generally discharges from the second chamber during all of the retract stroke (which is also the suction stroke). The remaining curve in Figure 14 indicates that the pump was stroking at a nearly constant 46 cycles/min over the 7.7 cycles shown in this graph.

Minor LNG pump design refinements were implemented based on the performance and durability test results. For example, the pump drive shaft guide bearing and seal design, as well as the pump assembly procedure, were modified to reduce the maximum tolerance stack-up and ensure that the drive shaft is guided so as to provide more precise concentricity. The diameters of the pump tie rods and drive shaft were increased to enhance the overall pump assembly strength. Piston and seal design refinements to further extend pump durability are ongoing.

4.3 Heat Leak, NER, and Hold Time

Extensive LNG tank normal evaporation rate (NER) and hold-time tests were conducted to measure the heat leak characteristics of different generations of LNG tank designs. Comprehensive finite element method (FEM) thermal and structural modeling was also carried

out to characterize the heat transfer performance of design variations and compare with the test data. This is an ongoing process. The example test results reported here are for an interim design, and fabrication and testing of an LNG tank with a modified suspension system and pump socket designed to further reduce heat transfer is continuing as part of a CWI internal program.

Figure 15 shows the LNG tank weight versus time data from an example NER test. The NER test procedure, which is standard for cryogenic vessels, consists of filling the tank with LNG, venting the vapor at atmospheric pressure, and weighing the tank and recording the LNG and ambient temperature, and the tank pressure, as the LNG evaporates. The NER can then be calculated as pounds per hour or percent per day from the slope of the weight versus time data recording, e.g., Figure 15. Because LNG tanks are typically refueled with LNG saturated at pressures greater than one atmosphere, the initial mass loss rate is quite high as the liquid flashes to lower its saturation pressure to one atmosphere (e.g., for approximately three hours for the test shown in Figure 15), and then the mass loss rate is relatively constant. The heat leak rate can be calculated from the NER, and this calculation is simplified if the LNG is assumed to be pure methane and if the liquid and vapor in the tank are assumed to remain saturated at one atmosphere. Subject to these assumptions, the ratio of the heat leak to the mass loss rate is approximately equal to methane's heat of vaporization at one atmosphere (220 Btu/Lbm). The heat leak calculated in this fashion from the example NER test data shown in Figure 15 is 20.9 Watts.

Hold-time tests were conducted consistent with the SAE J2343 Recommended Practice and the NFPA 57 Standard. Following the SAE J2343 procedure, the tank is filled 75% full, the saturation pressure is allowed to build to 105 psig (one-half of the 210-psig MAWP), and the time to reach the MAWP (which is also the first PRV pressure) is measured. The CWI procedure is to record the tank pressure, tank temperature, and ambient temperature from when the tank is fueled to when the PRV pressure is reached.

Figure 16 shows the LNG tank pressure recorded as a function of time for an example hold-time test (the same tank used for the NER test shown in Figure 15). The PRV opening at approximately 210 psig is apparent in Figure 16.

Hold-time test data such as shown in Figure 16 were compared with analytical predictions based on mass and energy balance considerations and the thermodynamic properties of methane (using National Institute of Standards and Technology property models). These analyses, for example, precisely predict the upward curvature of the pressure versus time data graph such as Figure 16. Subject to the assumptions of pure methane saturated liquid and vapor (i.e., no stratification), the heat leak rates that exactly agree with the hold-time test data were determined. The heat leak indicated by the example data shown in Figure 16 is 20.3 Watts. More precise analyses, which accounted for the fact that the heat leak decreases slightly with time as the saturation temperature of the liquid and vapor in the tank increases, were also carried out. These analyses resulted in initial heat transfer rates that were somewhat less than, and average heat transfer rates that were very slightly more than, the heat transfer rates calculated based on the constant heat transfer assumption.

Figure 15. Example NER Test Data for a 68-Gallon LNG Tank.

Figure 16. Example Hold-Time Test Data for a 68-Gallon LNG Tank (these data and the data shown in Figure 16 are for the same tank).

Figure 17 shows the heat transfer rates calculated from the NER and hold-time test data for three LNG tanks that are directly comparable. The fact that the heat transfer rates calculated for the hold-time tests were generally in good agreement with the heat transfer rates calculated from the NER tests suggests that stratification effects (i.e., non-saturation and non-isothermal effects) were either negligible or similar for both types of tests.

Figure 17. Heat Leak Rates Computed from NER and Hold-Time Test Data for Three Comparable 68-Gallon LNG Tanks.

As previously discussed, it is important to note that the NER, hold time, and heat leak results presented here are for an interim LNG tank design, and CWI is currently developing a lower heat leak design.

4.4 Liquid Level Sensor

The overall liquid level sensor system includes the capacitance sensor element in the tank, the signal-conditioning box, cables and connectors, and the gage itself (which will be located in the truck cab). The objective of these tests was to determine the accuracy of the liquid level sensor over the anticipated range of LNG quantities in the fuel tank. These tests were carried out using a 68-gallon LNG tank. The tank was mounted on a scale, the capacitance sensor cable was connected to the signal-conditioning box, and the voltage from the signal-conditioning box and the tank weight were recorded as LNG was drained from the tank.

Figure 18 shows the results of an example liquid-level sensor test. The linear relation between the mean of the output voltage and the LNG weight indicates that the system can accurately measure the liquid level with a simple calibration factor. Figure 18 also shows an example linear fit to the sensor data. Multiple tests of this type confirmed the near-linear relation

between the sensor signal and the quantity of LNG in the tank. CWI is continuing to refine the signal conditioning electronics to include automatic liquid level recalibration features and reduce the noise in the conditioning-box signal sent to the gage.

Figure 18. Example Liquid Level Sensor Test Data.

4.5 Drop Tests and Vibration Tests

Drop tests of Taylor-Wharton-manufactured 68-gallon LNG fuel tanks were conducted by Wyle Laboratories in Huntsville, Alabama, under subcontract from CWI. The drop tests were carried out in strict accordance with the procedures specified in the SAE J2343 Recommended Practice for LNG Powered Heavy Duty Trucks. Tanks (fitted with LNG pumps and other components) containing an equivalent full weight of liquid nitrogen saturated per the SAE specification were dropped from a 10-foot height on the piping end (i.e., the shroud end) and from a 30-foot height on the opposite end.

The 68-gallon LNG fuel tanks passed the 10-foot and 30-foot drop tests. Figure 19 shows an LNG tank being hoisted in preparation for a 10-foot drop test, and Figure 20 shows the damaged shroud end of the tank after the test.

Integrated accelerated vibration tests of LNG fuel tanks were also carried out to validate the structural design adequacy when subjected to the truck vibrations associated with severe road loads. These tests were conducted by B83 Testing in Milwaukee, Wisconsin, using accelerated

Figure 19. LNG Fuel Tank Being Hoisted in Preparation for a Drop Test at Wyle Laboratories.

Figure 20. Shroud End of LNG Tank After 10-Foot Drop Test.

severe road load simulation vibration test profiles provided by PACCAR Corporation. These tests are continuing as part of the CWI internal program to develop the lower heat leak tank suspension system.

4.6 Engineering Truck Tests

LNG tanks equipped with pumps and other components were road-tested on CWI's engineering truck throughout the program, and this testing is continuing as part of a CWI internal program. The CWI engineering truck is a Kenworth T800 with an ISX G engine. It was described in Section 3.3 and Figure 11 is a photograph of the truck fitted with an LNG fuel tank. Figure 21 shows a more recently manufactured 68-gallon LNG tank mounted on the engineering truck. This is a rear-view photograph of the tank with the shroud closure open. The square-shaped component is the pump hydraulic drive. The blue hoses supply and return engine coolant to and from the integrated vaporizer. The fill receptacle and pressure gage are on the left (outboard) side of the tank. Other components visible in Figure 21 are the liquid and vapor shut-off valves, the hydraulic fluid lines, and the high-pressure gas filter.

Preliminary LNG fuel system road tests on the CWI engineering truck address multiple objectives pertaining to system operation in actual truck application. These involve functionality, performance, and durability. For example, the engineering truck tests demonstrated that the LNG tank and fuel system met CWI-defined first-tier durability and reliability objectives of 500 hours of on-road operation with no mission-disabling failures.

Figure 21. Rear View of LNG Tank and Fuel System Mounted on CWI Engineering Truck.

Section 5 CONCLUSIONS

The ALOSS program demonstrated the feasibility of a pumped LNG vehicle fuel system and the advantages of this design relative to systems that require conditioning the LNG to a saturation pressure exceeding the engine fuel pressure requirement. LNG tanks mounted on test carts and the CWI engineering truck were repeatedly filled with LNG saturated at 20 to 30 psig. More fuel mass was stored in the vehicle tanks as well as the station tank, and no conditioning equipment was required at the fueling station.

The ALOSS program also demonstrated the general viability and specific performance of the CWI pumped LNG fuel system design. The system tested as part of this program is designed to be used on Class 8 trucks with CWI ISX G HPDI engines. Extensive test cart and engineering truck tests of the pump demonstrated good durability and the high-pressure performance needed for HPDI application. The LNG tanks manufactured by Taylor-Wharton passed SAE J2343 Recommended Practice drop tests and accelerated road-load vibration tests. NER and hold-time tests produced highly consistent results. Additional tests confirmed the design adequacy of the liquid level sensor, vaporizer, ullage volume, and other fuel system components.

While the testing work performed under this program focused on a high-pressure pumped LNG fuel system design, the results also validate the feasibility of a low-pressure pumped fuel system. A low-pressure pumped fuel system could incorporate various design refinements including a simpler and lighter-weight pump, which would decrease costs somewhat relative to a high-pressure system.

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