BECK ENGINEERING, INC.

Optimization and Testing of the

Beck Engineering Free-Piston Cryogenic Pump for LNG Systems on Heavy Vehicles

Contract Number: DE-AC02-99CH10979

Final Technical Report

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Figure 1: Test Results for Prototype LNG System.

Summary. This Final Report describes our accomplishments under Contract Number DE-AC02-99CH10979 for the DOE. We tested our Free Piston Cryogenic Pump (FPCP) in a prototype LNG system. Figure 1 is a plot of the key results. Figure 2 shows the prototype LNG system. The prototype LNG system can maintain a set-point delivery pressure of vapor, independent of flow demand, up to a maximum flow capacity. The type of performance of the prototype LNG system is consistent with requirements of fuel systems for heavy vehicles. However, the maximum flow capacity of our prototype LNG system (liquid flow of 16 ml/s) is significantly less than the total flow requirement (maximum liquid flow of 45 ml/s) for a typical 400 hp natural-gas engine¹. The flow capacity of our prototype LNG system is determined by a cavitation limit for our FPCP. The cavitation limit can be extended to higher flows by making components of the pump larger. Further development will: (1) increase sizes of components in our FPCP to increase its flow capacity; (2) reduce heat losses in a prototype storage tank we built; and (3) make all components of our prototype LNG system suitable for fielding on heavy vehicles. In the following, we describe our accomplishments under the contract in more detail.

¹ A complete LNG system for a heavy vehicle might include two pumps (one associated with each of two tanks), but it would be prudent to operate each pump at only half of its maximum flow capacity.

Figure 2a: Prototype LNG System (Shows Vaporizer/Accumulator).

Figure 2b: Prototype LNG System (Shows Pump in Emptied Liquid Reservoir).

1. Complete LNG System.

A complete LNG system for heavy vehicles consists of the following components:

- (1) **LNG Supply Tank.** The supply tank stores the LNG at a low pressure (and a cold temperature and high density) and uses a pump to raise the pressure of the LNG.
- (2) **Free Piston Cryogenic Pump (FPCP).** The pump raises the pressure of the LNG to a pressure suitable for the engine.
- (3) **Vaporizer/Accumulator.** The vaporizer/accumulator converts LNG from the pump into a constant-pressure supply of natural gas at near room temperature.

A system that is currently used on heavy vehicles consists of an insulated supply tank and a vaporizer, which uses engine coolant as a source of heat to convert the LNG to natural gas at near room temperature. Our system has potential advantages over the current system:

- (1) **High-Pressure Capability.** Initial systems would be designed to deliver natural gas at pressures up to about 150 psig. Soon, manufacturers of heavy vehicles might require higher pressures (up to 3,000 psig or more) for high-pressure direct injection to increase engine efficiency. A system that is currently used cannot deliver these high pressures. On the other hand, our system would require only a simple swapping of pump designs to achieve the high pressures.
- (2) **Minimal Lost Natural Gas at Refueling.** A current system stores LNG at about 150 psig, so high-pressure natural gas must be vented before the supply tank is refueled. On the other hand, our system stores LNG at lower pressures, so less natural gas would be lost at refueling.
- (3) **Larger Stored Fuel Mass in Same Space.** LNG stored in a saturated state at low pressures (and, therefore, cold temperatures) is denser than LNG stored at higher pressures (and, therefore, higher temperatures). Because our system stores LNG at low pressures, our system can hold about 10% more fuel mass than the current system, in the same tank space claim.

2. Prototype LNG System.

We tested our FPCP in the prototype LNG system shown in Figure 2. We designed and built a storage tank for our prototype LNG system but, for simplicity, we used a liquid reservoir instead of the storage tank to test our pump (Figure 2 shows the liquid reservoir). This difference between our prototype LNG system (without a tank) and a complete system (including a tank) does not affect the ability of our FPCP to operate in an LNG system for heavy vehicles.

In the following, we first describe results from our tests of the prototype LNG system. Then, we describe the three components (listed above) of our prototype LNG system.

2.1 Test Results.

Figure 1 shows our test results, and Figure 2 shows pictures of the prototype LNG system we used in the tests. For each set of tests, we adjusted the regulator to provide a set-point delivery pressure. Figure 1 shows two sets of data for two different set-point pressures: (1) 190 psig set-point pressure; and (2) 160 psig set-point pressure. We then adjusted a valve immediately upstream of the rotameters (see Figure 2a) and recorded the rotameter readings. The valve provided a variable flow resistance, so we could achieve different flows through the rotameters (associated with different engine demands for natural gas) with a constant upstream pressure (controlled by the regulator). We adjusted the valve and recorded data for rotameter readings vs. delivery pressures until the system reached a maximum flow capacity. When we opened the valve in an attempt to achieve flows beyond the maximum flow capacity of the prototype LNG system, the delivery pressure fell to very low values (about 10 psig). After the delivery pressure fell to very low values, we had to recharge the Vaporizer/Accumulator (by closing the valve) before we could record more data.

Cavitation Limit of FPCP. The maximum flow capacity of our prototype LNG system is determined by a cavitation limit for our FPCP. When the delivery flow is greater than the cavitation limit, the inlet liquid flashes to vapor, the pumping rod of our FPCP moves back-and-forth through its full stroke, and the pumping rod compresses and expands vapor instead of pumping liquid. The cavitation limit can be extended to higher flows by making components of the pump larger. In particular, increasing the flow areas of the inlet check valves extends the cavitation limit to higher flows.

Constant Set-Point Pressure. The data plotted in Figure 1 indicate that our prototype LNG system can maintain a nearly constant set-point delivery pressure of vapor, independent of flow demand, up to a maximum flow capacity. The delivery pressure varied by only a maximum of 6 psi during the tests. Therefore, the delivery pressure should be sufficiently constant for fuel metering systems on heavy vehicles.

Pressure Losses. The maximum flow capacity of our prototype LNG system is 16 ml/s of liquid. The maximum flow capacity corresponds with a 300 psig delivery pressure for our FPCP operating separately (see Table 1). This means there might be pressure losses in the prototype LNG system that are accounting for about 100 psi of pressure losses. We measured a pressure drop across our Vaporizer/Accumulator of 13 psi. Therefore, it is likely the pressure losses are in the plumbing of our LNG system.

Maximum Flow Capacity. The maximum flow capacity is significantly less than the total flow requirement for a typical 400 hp natural-gas engine. A typical 400 hp SI natural-gas engine requires a maximum liquid flow of 45 ml/s. A complete LNG system for a heavy vehicle might include two pumps (one associated with each of two tanks). An LNG system with a pump in each tank would allow the tanks to operate separately and eliminate the need to transfer LNG from one tank to the other. An FPCP with a maximum flow capacity of 22.5 ml/s would provide enough flow capacity for an LNG system with two pumps. However, because the LNG system needs to recharge after it has gone beyond its maximum flow capacity, it would be prudent to

operate the system far away from its maximum flow capacity. For example, it would be prudent to operate the LNG system at only one half of its maximum flow capacity.

2.2 Prototype LNG Supply Tank.

We built and tested a sub-scale unit of an LNG supply tank. Key features of our tank are:

- (1) **Low Heat Leakage.** From a conservative analysis, we project a 119 gal version of our tank will have less than 8 Btu/hr of heat leakage. This low heat leakage will produce a hold time (without atmospheric venting of natural gas) much longer than five days. The projected heat leakage is less than commercially available tanks (typically about 40 Btu/hr). However, avoidable design features of our prototype supply tank led to an excessively high heat leakage.
- (2) **119 gal Capacity.** Our (full-scale) tank is designed to be a replacement for currently used systems. Current systems have two 119 gal tanks and two vaporizers. Our complete LNG system would use two 119 gal tanks (with a pump associated with each tank) and one vaporizer/accumulator.
- (3) **Pump.** Our tank holds LNG at a low pressure, and a pump raises the pressure of the LNG to a pressure suitable for the engine.

The most important feature of our tank is its potential for low heat leakage, which will yield a long hold time. In the following, we show why our tank design has this potential for low heat leakage.

Low Heat Leakage. LNG will be stored in our tank at temperatures of 121 K (which is the temperature of saturated methane at 15 psig). The outside of the tank will be at near atmospheric temperature (about 300 K). Therefore, there will be a large temperature difference of about 180 K between the outside of the tank and the stored LNG, so we will need to insulate the stored LNG very well to minimize heat leakage to the LNG to yield a long hold time.

Superinsulation. A common technique for insulating stored cryogenics and cryogenic equipment is to use superinsulation (see Weisend²). Superinsulation is a low-pressure (typically about 10^{-5} torr) volume that contains layers of multilayer insulation (MLI). The low pressure precludes convection heat transfer, and the MLI limits radiation heat transfer. As with any superinsulated cryogenic tank, the dominant mode of heat leakage in our tank is heat conduction along tank supports. There is also heat leakage along tank penetrations (the fill line, for example), but these heat leaks are negligible compared to conduction through the supports. We have an innovative design for tank supports that minimizes heat conduction.

² Weisend, J.G., Handbook of Cryogenic Engineering, Taylor and Francis, Philadelphia, PA, 1998.

Characterization Results. We characterized our prototype LNG supply tank by measuring the heat leakage into the tank while the tank held liquid nitrogen. We measured heat leakages that were significantly greater than our projection of less than 8 Btu/hr. We identified sources of large heat leaks that we could eliminate through further tank design work. The focus of this project was pump development, so further tank design work was beyond the scope of this project.

For our characterization tests, we filled tank with liquid nitrogen, sealed all feedthroughs to the tank except for a boil-off line, and measured the boil-off with a rotameter. Two key results are: (1) large heat leakage; and (2) the heat leakage decreases with time. In the following, we describe these results.

Large Heat Leakage. The heat leakage through the wall of the supply tank is excessive. We have identified two sources of large heat leaks:

- (1) **Conductive Superinsulation.** Avoidable features of the design of our prototype tank led to conduction paths through the superinsulation.
- (2) **Conductive Feedthroughs.** For ease of assembly, we used short and, therefore, highly conductive feedthroughs. Further design work and development of assembly procedures would lead to low-conduction feedthroughs.

Heat Leakage Decreases with Time. Heat leakage through the wall of the prototype supply tank decreases with time. Initially, the tank is full, so all inside surfaces of the tank are at approximately the saturation temperature of the contained liquid. Therefore, the temperature differences between the inside of the tank and the outside of the tank are large, and heat leakage is large. As the liquid boils-off, the top of the tank empties and the top inside surfaces become warmer than the saturation temperature of the contained liquid. This reduces the heat leakage as time progresses.

Figure 3: Free Piston Cryogenic Pump (FPCP) Design.

Figure 4: Voltage Input and Current Response of Coils.

Table 1: Data for FPCP Performance with Liquid Nitrogen.

Delivery Pressure, psig	Flow, ml/s
270	>19
285	18
300	16
330	14

2.3 Free Piston Cryogenic Pump (FPCP).

Beck Engineering, Inc. paid for work to optimize the design of our Free Piston Cryogenic Pump (FPCP) to maximize its efficiency and minimize its costs for volume production. Figure 3 is a picture of our pump design, and Table 1 lists performance data for operation with liquid nitrogen. In the following, we describe components of our FPCP.

Electrical Drive System. Figure 4 is a schematic that shows the voltages supplied by the electrical drive system to each coil (Coil A and Coil B) of our FPCP. Figure 3 also shows the resulting current that flows through each coil. The drive system ensures that the current that flows through each coil is always either positive or zero. When the applied voltage is positive, the drive system supplies power to the coils. When the applied voltage is negative, the drive system absorbs power from the coils. Our Phase I drive system dissipated the power absorbed from the coils. This accounted for a significant loss in our Phase I system. In Phase II, we used a Regenerative Drive System (a subcontractor assembled the electronics) which stores the electrical energy absorbed from the coils and supplies this stored energy to the coils later in the cycle (when the applied voltage is positive).

Valve Flow-Pressure and Leakage Losses. Our FPCP uses 2 inlet and 2 outlet check valves. In Phase I, we produced check valves that had acceptable performance and were easy and inexpensive to produce. Good check-valve performance means a low resistance to flow in the forward-flow direction and a high resistance to backflow. In other words, when the check valve is open (when the poppet is lifted), only a small driving pressure difference should be required to force the flow through the check valve. When the check valve is closed (when the poppet is seated), there should be little leakage through the seal between the poppet and its seat.

In Phase II, we optimized the flow path through the check valves to minimize flow-pressure losses. The Phase II check valves are larger (larger flow areas) than the Phase I check valves. In addition to optimizing the flow path through our check valves, we also improved the seals in Phase II. We have proprietary techniques that enable us to produce excellent seals at a low cost.

Table 2: Properties of Nitrogen and Methane at 150 psig.

Symbol:	Description:	Nitrogen:	Methane:
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Δh , J/ml	Enthalpy change from saturation to 50 F, per ml of saturated liquid.	228	240
T_{sat} , K	Saturation temperature.	105.8	151.9
T_{ave} , K	$(T_{sat} + 50 \text{ F})/2$.	194.5	217.5
ρ_{VAP} , kg/m ³	Density of vapor, evaluated at T_{ave} .	20.2	10.7
ρ_{LIQ} , kg/m ³	Density of saturated liquid.	651	355
μ_{VAP} , kg/m-s	Viscosity of vapor, evaluated at T_{ave} .	12.3E-6	8.69E-6

2.4 Prototype Vaporizer/Accumulator.

Figure 5 is a picture of the prototype Vaporizer/Accumulator we built and the apparatus we used to test it. In our LNG system, our Vaporizer/Accumulator performs two functions with one unit: (1) vaporize LNG by adding heat from warm engine coolant to convert the LNG to warm natural gas; and (2) accumulate natural gas to smooth pressure fluctuations caused by our Free Piston Cryogenic Pump (FPCP).

In the following, we describe tests we performed that indicate our Vaporizer/Accumulator can vaporize LNG with only a small drop in flow pressure.

Vaporizer/Accumulator Has a Small Pressure Drop. For a liquid flow associated with nearly full load of a 400 hp diesel engine, we measured a 13 psi pressure drop across our Vaporizer/Accumulator. This pressure drop is small. For a delivery pressure of 200 psig, our Free Piston Cryogenic Pump (FPCP) would require only a 7% increase in input power to compensate for a 13 psi pressure drop. For higher pressures, the pressure drop would be even less, because vapor densities would be larger. For simplicity and low cost, we measured the pressure drop across our Vaporizer/Accumulator using nitrogen instead of natural gas. Simple analysis indicates using nitrogen instead of natural gas is conservative, because using natural gas will result in even smaller pressure drops.

Most of the pressure drop across our Vaporizer/Accumulator occurs as the vapor is superheated. Table 2 compares properties of nitrogen with properties of methane (natural gas is typically over 90% methane). To simulate operation of our prototype LNG system and its components using nitrogen instead of natural gas, we use the same volumetric flow rates for the saturated liquids, because the operation of our FPCP is most dependent on this quantity. For a given volumetric flow rate of the saturated liquids, the resulting volumetric flow rates of superheated nitrogen and superheated methane are nearly equal. However, methane vapor is less dense than nitrogen vapor, so the pressure drop across our Vaporizer/Accumulator will be less when natural gas is used instead of nitrogen.

Figure 5: Vaporizer/Accumulator.