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Laboratory and Demonstrations

The Liquid Nitrogen Fueled Engine: A Cool Demonstration of Pressure-Volume Work

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A chemical demonstration illustrating pressure volume work is presented. Details are given for the construction of a small but powerful mechanical engine that is fueled with liquid nitrogen. Students are able to disassemble the engine to inspect the engine components and study the operating mechanism.

Interest and curiosity of undergraduate students can be sparked by…the liquid nitrogen fueled (LNF) engine.

Pressure–volume (*PV*) work associated with the expansion of gases is discussed in most introductory general chemistry texts (e.g., [1]) and courses, and an automotive internal combustion engine is typically used as a practical application of this concept. Interest and curiosity of undergraduate students can be sparked by an alternative and creative illustration of pressure volume work— the liquid nitrogen fueled (LNF) engine. This

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engine operates under the same principle as the combustion engine— gas(es) are expanded in cylinders to move pistons, and this movement is translated into the motion of wheels. The expanded gas is released through a valve, and a flywheel returns the piston to its original position. Both the LNF and combustion engines convert thermal energy into work through the thermal expansion of gases. The LNF engine utilizes the *heat of vaporization* of liquid nitrogen; whereas, automobile engines utilize the *heat of combustion* of gasoline.

The assembled LNF engine and views of individual engine components are shown in Figures 1–6. It is composed of a brass engine frame (Figure 3), two brass valve cylinders (Figure 4, only one is illustrated), two steel pistons and two brass fly wheels (Figure 5), and a steel retaining clip (Figure 6). The pistons, which should be made from a different metal than the cylinders, also serve as connecting rods to the fly wheel. The opening and closing action of the valves on the engine frame are actuated by the reciprocating action of the fly wheels. Copper tubing (1/4 inch in diameter) connects the engine inlet to a 500 mL steel container full of liquid nitrogen (see Figure 1, approximate dimensions of the steel container are 9 in. length by 2.25 in. diameter). A Dewar flask, or any glass flask for that matter, should not be used for engine components, because it will not withstand the significant pressures generated (typically over 100 psi). The engine assembly is mounted to a large (#12) rubber stopper, and the stopper is secured into place over the container of liquid nitrogen with a threaded brass fitting (see Figure 1). A needle valve (see Figures 1 and 2) is installed between the steel container and engine inlet, and another valve on the steel holding container in order to regulate the speed of the fly wheels and pressure within the container. It is important for safety considerations that liquid nitrogen is never allowed to boil off in a completely sealed container. The engine will run for about a minute, depending on the size of the liquid nitrogen reservoir and the speed of the fly wheels. Engine components were made from scrap parts typically found around a machine shop (e.g., the cylinders were constructed from a slide-bolt lock). The complete engine illustrated in Figure 1 was fabricated by a skilled machinist in approximately 8 hours. This assembled engine is less than three inches high, and it can be passed around the lecture hall for student inspection. After the demonstration, students are allowed to disassemble and visually examine the various components to determine how gases flow through the engine. Such a visual inspection cannot be easily accomplished with a conventional combustion engine.

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FIGURE 1. VIEW OF THE ASSEMBLED LIQUID NITROGEN FUELED ENGINE, INCLUDING LIQUID NITROGEN RESERVOIR.

While the students are examining the moving parts of the engine, the following theoretical aspects, which are discussed in many general chemistry texts [1], are pointed out.

Work is defined as a force times a distance.

$$W = F \times d \tag{1}$$

Pressure is defined as a force per area.

$$P = F / A \tag{2}$$

Rearrangement of (2) and substitution into (1) yields.

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FIGURE 2. CLOSE-UP VIEW OF ASSEMBLED LIQUID NITROGEN FUELED ENGINE.

$$W = (P \times A) \times d \qquad (3a)$$

or

$$W = P \times (A \times d) \qquad (3b)$$

Recognizing $A \times d = V$, and substitution into (3b) yields.

$$W = P \times V \qquad (3c)$$

Thus, it is algebraically illustrated that work results from the expansion of gas at constant pressure. Although the work produced by a single stroke of the LNF engine may be calculated during lecture using appropriate experimental values, this

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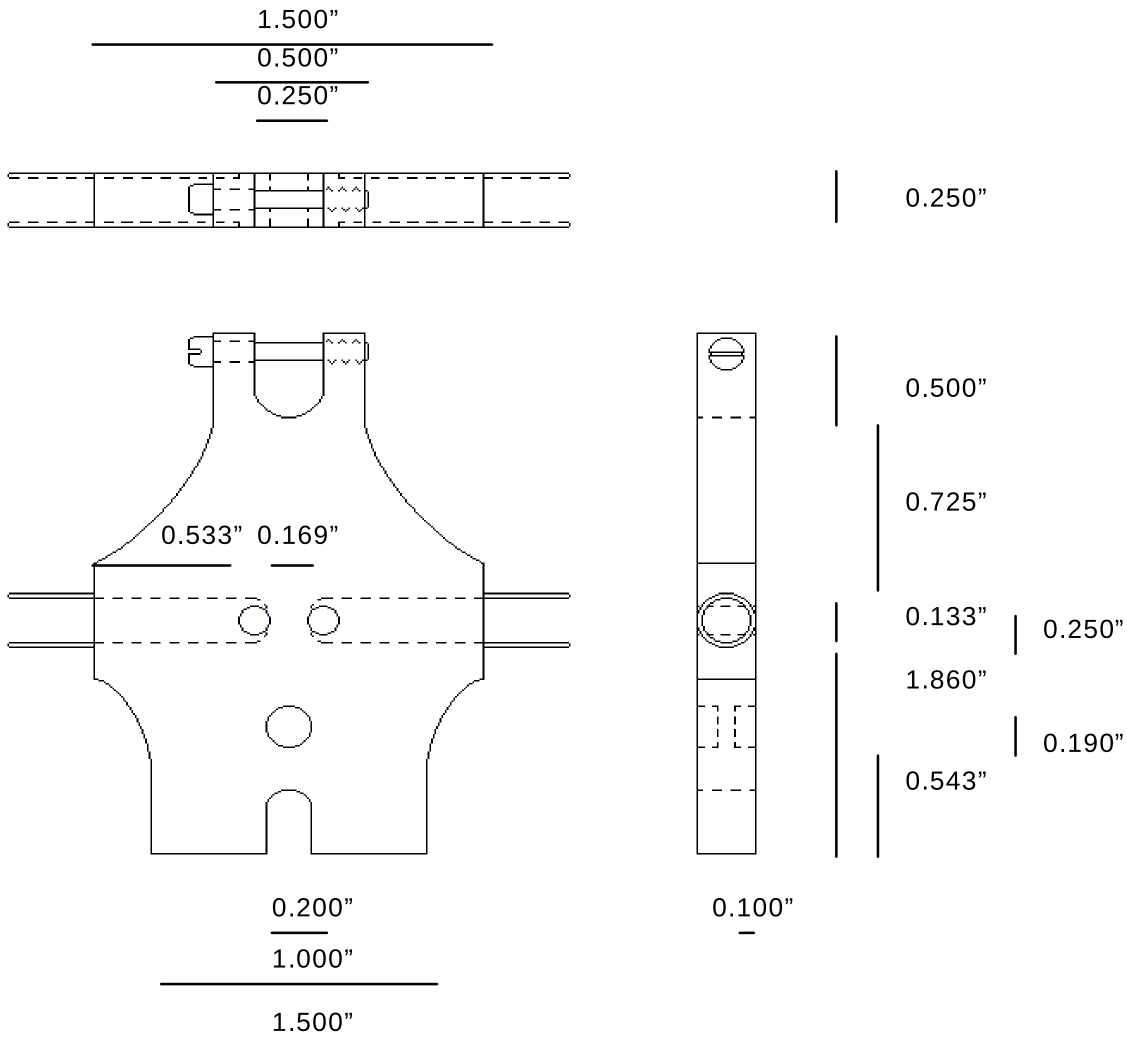

FIGURE 3. TOP, SIDE AND CROSS SECTION VIEW (CLOCKWISE FROM TOP) OF THE ENGINE FRAME FOR A LIQUID NITROGEN FUELED ENGINE. ACTUAL DIMENSIONS ARE SHOWN IN INCHES.

demonstration is typically used only to provide a dramatic and innovative illustration of pressure–volume work.

This demonstration provides an interesting and curious illustration of pressure–volume work for undergraduate general chemistry students. It however, may also be readily used to illustrate basic thermodynamic principles in physical or environmental chemistry courses, which discuss energy conversion processes [2, 3]. Indeed, the development of thermodynamics during the nineteenth century was closely linked to industrial engineering problems associated with steam engines, and the second law of thermodynamics was derived from these studies. In conventional mechanical engines, a

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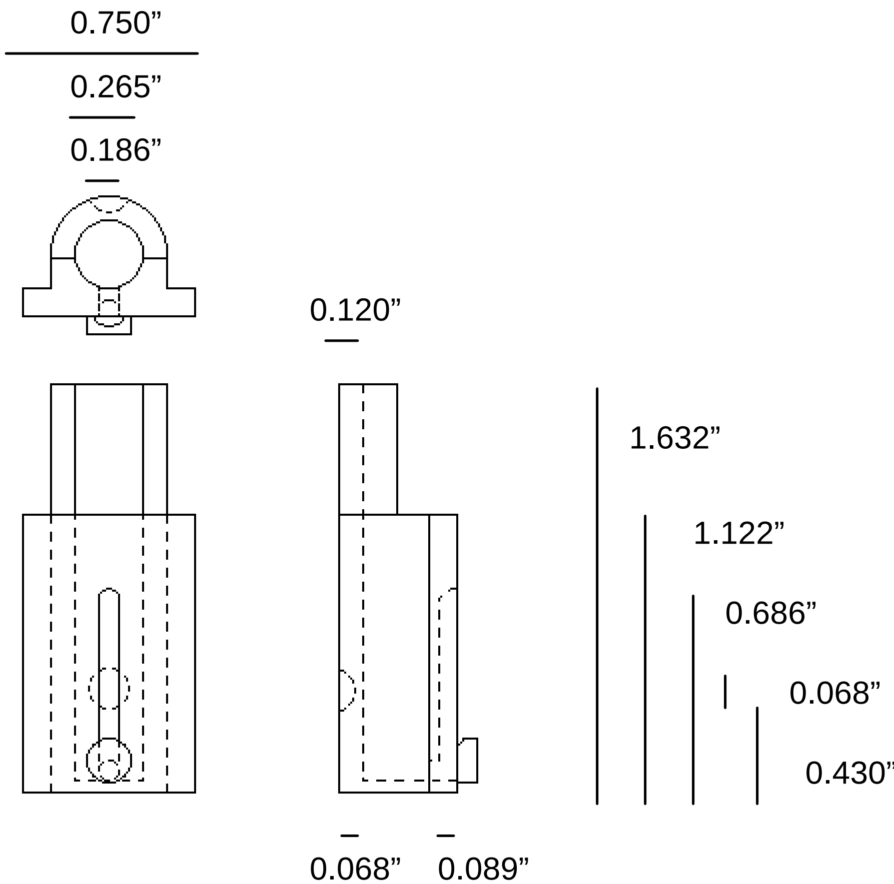

FIGURE 4. TOP, SIDE AND CROSS SECTION VIEW (CLOCKWISE FORM TOP) OF THE VALVE CYLINDERS (ONE IS SHOWN, TWO ARE REQUIRED) FOR A LIQUID NITROGEN FUELED ENGINE. ACTUAL DIMENSIONS ARE SHOWN IN INCHES.

cooled engine withdraws heat from a reservoir at a higher temperature, converts some heat to work, and discards remaining heat to a sink at lower temperature. Carnot first realized that work could only be obtained when heat was removed from a hot source to a cold sink.

According to the second law of thermodynamics, all the heat absorbed by the expansion of a gas cannot be completely converted to mechanical work, and the maximum efficiency of an engine is determined by the Carnot Theorem: $(T_{high} - T_{low}) / T_{high}$ [2, 3]. This thermodynamic principle applies to the LNF engine as well, yielding a maximum theoretical efficiency of $(298 - 77) / 298 = 0.74$. In contrast, steam turbines can achieve a maximum 0.85 efficiency by converting heat to electrical work [2]. Steam turbines can operate at very high temperatures thereby creating a larger difference between the heat reservoir and heat sink. Typical generating stations and combustion engines have

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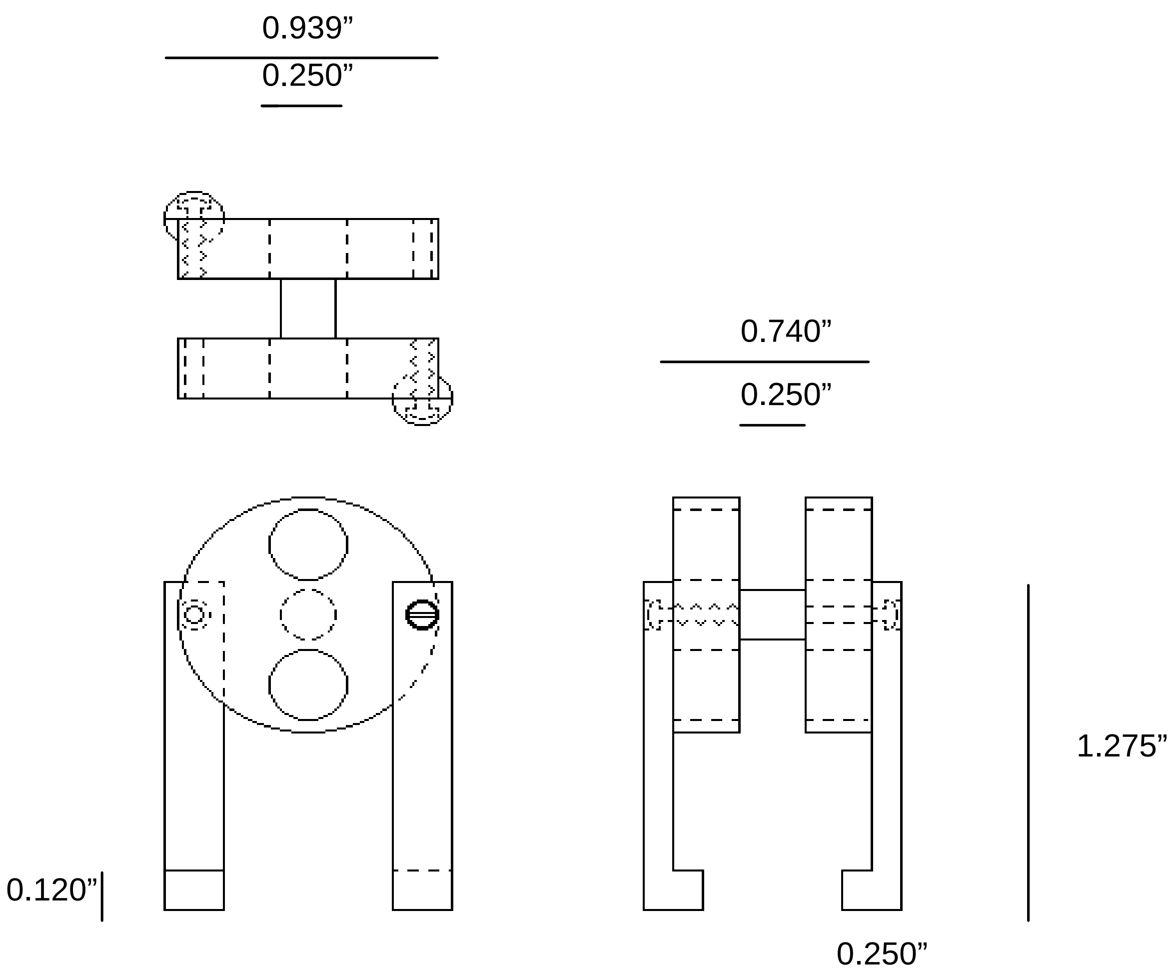

FIGURE 5. TOP, SIDE AND CROSS SECTION VIEW (CLOCKWISE FROM TOP) OF THE PISTON AND FLY WHEELS FOR A LIQUID NITROGEN FUELED ENGINE. ACTUAL DIMENSIONS ARE SHOWN IN INCHES.

thermodynamic efficiencies of 0.55 and 0.56, respectively [3]. The low efficiency (0.32) of nuclear fission power plants is attributed to the small difference in temperature between the heat reservoir and heat sink [2]. Thus, the efficiency of the LNF engine is quite good compared to other conventional systems. In fact, the LNF engine would be more efficient than a steam engine operated over a similar temperature differential between the heat reservoir and heat sink $(\text{i.e.}, (519 - 298) / 519 = 0.43)$.

In conclusion, this demonstration was primarily developed for undergraduate chemistry students to creatively illustrate a fundamental thermodynamic concept— pressure–volume work. Students are able to investigate the mechanism of a simple mechanical

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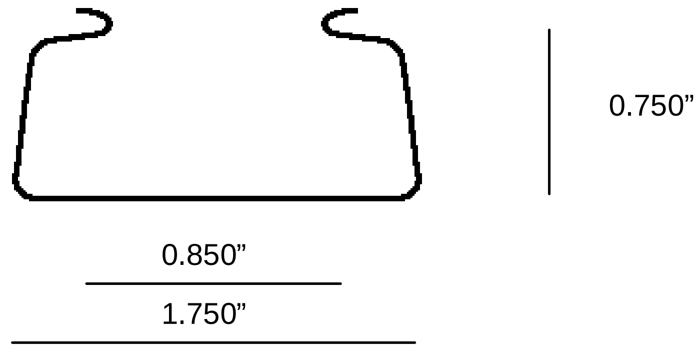

FIGURE 6. SIDE VIEW OF RETAINING CLIP FOR VALVE CYLINDER FOR A LIQUID NITROGEN FUELED ENGINE. ACTUAL DIMENSIONS ARE SHOWN IN INCHES.

engine. In addition, this demonstration may also be used in more advanced physical science courses to illustrate basic thermodynamic concepts related to energy transfer processes.

Handling and Disposal Problems: Do not allow liquid nitrogen to evaporate in a sealed container. Do not use any glass components.

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