Operating characteristics of a hydrogen-oxygen-fueled roller engine

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Operating characteristics of a hydrogen-oxygen-fueled roller engine

by

James E. Ettaro

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The use of carbon based fuels for energy production is resulting in severe global environmental damage. Hydrogen has been identified as the ultimate, universal fuel that could eliminate this problem. In order to implement a hydrogen infrastructure advances in hydrogen technology must continue to occur (Padro 1996).

Engines fueled by hydrogen gas combusted in a combustion chamber with air produce oxides of nitrogen. These oxides of nitrogen are responsible for photochemical smog, health and environmental problems. On the other hand, hydrogen combusted in pure oxygen would eliminate the formation the oxides of nitrogen (de Boer & Hulet, 1980). Modern engine designs, however, cannot effectively convert the energy of stoichiometric hydrogen-oxygen combustion into useable power.

In this research, a roller engine design powered by stoichiometric hydrogen-oxygen combustion was investigated to determine the operating characteristics of torque output and hydrogen peroxide exhaust emissions. These operating characteristics were investigated at different mixture injection pressures, mixture injection durations and engine speeds. It was observed that, as mixture injection pressures are increased, torque output increased. Also the greatest torque output occurred between 180° and 240°, close to 210° of mixture injection duration of mainshaft rotation. Higher engine torque output was also observed at lower engine speeds.

Low concentrations of hydrogen peroxide emissions were detected in the exhaust with the greatest amount being produced at 110/300/120 psi mixture injection pressure. Also, as mixture injection duration increased hydrogen peroxide exhaust concentration increased.
Increases in engine speeds caused decreases in hydrogen peroxide concentration (parts per million).

Based on the findings of this research it is recommended that investigation continue on the hydrogen-oxygen-fueled roller engine to advance its development. A hydrogen-oxygen-fueled roller engine may prove effective at utilizing hydrogen-oxygen combustion for a useable power output producing steam and water as exhaust. Further development of this engine may lead to significant research toward saving our environment.
CHAPTER 1. INTRODUCTION

The engine of technological advancement is fueled by energy production and utilization, and the need for energy is increasing. Figure 1.1 shows the increase in energy demands over a 22-year period for developed and developing countries. Energy production is considered the largest business in the modern world (Aubrecht, 1995).

![Figure 1.1. Energy consumption by developed and developing countries (Department of Energy, 1994)](image)

On the other hand, "The production and use of energy cause more environmental damage than any other activity, and the problem is only going to grow over the next decade or two" (Ervin, 1996, p2). These environmental problems range in broad scope and include: (a) pollution of the air (Figure 1.2 shows that over 70% of air pollution is directly created by energy production and use); (b) depletion of the ozone layer; (c) global warming from carbon dioxide emissions (Figure 1.3 shows the increasing amounts of carbon dioxide emissions for developed and developing countries over a 22 year period); (d) strip mining runoff; (e)
Figure 1.2. Air pollution distribution by source in the United States (*Statistical abstract of the United States*, 1995, Washington, DC: Government Printing Office, Table 1107)

Figure 1.3. Carbon dioxide produced by developed and developing countries (Department of Energy, 1994)
radioactive fallout from nuclear power plant accidents, such as Three Mile Island and Chernobyl; and (f) depletion of natural resources and the degradation of land and water.

Furthermore, because some researchers believe that continued use of hydrocarbon fuels will lead to a complete worldwide social and environmental catastrophe, they are demanding immediate change (Zweig, 1992). Many of these problems could be reduced or eliminated by the use of hydrogen as an alternative fuel and energy carrier being produced by environmentally benign production methods such as wind and solar (McAlister, 1997).


This need to move toward a hydrogen economy is so great that governments and industries are promoting hydrogen’s research and development. For example, overall funding in 1996 through the United States Department of Energy totaled $122.3 million toward the development of hydrogen as an alternative fuel and energy carrier (Padro, 1996). Furthermore, most governmental agencies throughout the world are funding the development of hydrogen fuels, with the greatest financial resources being provided by Germany, Japan, China, and Russia (Deyou, 1994).
Many industries are also gearing up to embrace the opportunity to develop hydrogen-based technologies that will provide potential economic rewards along with a clean environment. Some of these companies include Daimler-Benz, BMW, Mazda, General Motors (GM), Ballard Power Systems, and Ford Motor Company. Much of the ongoing research is focused on the development of hydrogen fueled transportation systems.

The aforementioned research tends to focus on fuel storage and power production. Currently there are two main methods being seriously investigated to produce power from hydrogen fuels: fuel cells and internal combustion engines. Fuel cells generate electricity by combining hydrogen and oxygen in an electrochemical process. While fuel cells offer high efficiency (60% to 65%), low noise, and zero emissions, their power densities are not yet acceptable for passenger transportation.

Internal combustion engines, however, offer excellent power densities but with noise and pollution. Even with hydrogen as a fuel, internal combustion engines that have been optimized for efficiency still produce oxides of nitrogen in their exhaust. Oxides of nitrogen are mostly responsible for photochemical smog, acid rain, and health problems. When hydrogen fueled internal combustion engines are optimized to produced low nitrous oxide emissions, their efficiency and thus power deteriorates. Internal combustion engines using hydrogen as a fuel combined with pure oxygen could offer a pollution free solution.

Past investigations into hydrogen-oxygen fueled engines were centered around submarine/torpedo propulsion, the space program and low emissions vehicles (de Boer & Hulet, 1980). Many investigators reported problems relating to the use of a stoichiometric
hydrogen-oxygen mixtures in current internal combustion engine designs. These problems include very high peak pressures, pre-ignition, degradation of lubrication, and lack of useable power output. The hydrogen-oxygen-fueled roller engine design may reduce these tendencies offering a practical solution to utilizing stoichiometric hydrogen-oxygen fuel mixtures.

**Problem of the Study**

The problem of this study was to determine the operating characteristics of an experimental hydrogen-oxygen fueled roller engine. More specifically, it was to determine the engine operating characteristics of torque output and hydrogen peroxide exhaust concentrations at different mixture injection pressures, mixture injection durations in degrees of mainshaft rotation, and engine speeds.

**Purpose of the Study**

The purpose of this study was to:

1. offer new information on engine design modification, engine torque output, and hydrogen peroxide exhaust emissions which will impact positively the development of the hydrogen-oxygen fueled roller engine;

2. move toward a practical hydrogen-oxygen fueled engine design; and

3. contribute knowledge which can lead to environmental protection.

**Need for the Study**

The acceptance of hydrogen as a fuel is limited by the effectiveness of manufacture, storage, distribution, and utilization (United States Department of Energy, 1996). The development of an efficient hydrogen fueled heat engine will help advance the process of
hydrogen utilization. Utilizing hydrogen may help save our world environment by reducing the toxins released due to the exploration, extraction, refining manufacture, distribution, dependency, protection, and utilization of carbon based fuels.

Hypotheses of the Study

The hypotheses of the study center on the need to determine if changing mixture injection pressures and mixture injection durations for different engine speed have a significant effect on engine torque output and hydrogen peroxide exhaust concentration.

1. **Ho**: There is no difference in engine torque output when mixture injection pressures are changed to 80/200/80, 110/300/120, and 140/400/160 psi (hydrogen/oxygen/water).

   **Ha**: Mixture injection pressures effect engine torque output.

2. **Ho**: There is no difference in engine torque output when mixture injection durations are changed to 180°, 210°, and 240° of mainshaft rotation.

   **Ha**: Mixture injection durations effect engine torque output.

3. **Ho**: There is no difference in engine torque output for engine speeds of 500 and 1000 rpm.

   **Ha**: Engine speed effects engine torque output.

4. **Ho**: No interaction occurs between mixture injection pressures and mixture injection durations for engine torque output.

   **Ha**: Interaction occurs between mixture injection pressures and mixture injection durations for engine torque output.

5. **Ho**: No interaction occurs between mixture injection pressures and engine speeds for engine torque output.

   **Ha**: Interaction occurs between mixture injection pressures and engine speeds for engine torque output.
6. \( H_0 \): No interaction occurs between mixture injection durations and engine speeds for engine torque output.

\( H_a \): Interaction occurs between mixture injection durations and engine speeds for engine torque output.

7. \( H_0 \): No interaction occurs between mixture injection pressures, mixture injection durations and engine speeds for engine torque output.

\( H_a \): Interaction occurs between mixture injection pressures, mixture injection durations, and engine speeds for engine torque output.

8. \( H_0 \): There is no difference in hydrogen peroxide exhaust concentration when mixture injection pressures are changed to 80/200/80, 110/300/120, and 140/400/160 psi (hydrogen/oxygen/water).

\( H_a \): Mixture injection pressures effect hydrogen peroxide exhaust concentration.

9. \( H_0 \): There is no difference in hydrogen peroxide exhaust concentration when mixture injection durations are changed to 180\(^\circ\), 210\(^\circ\), and 240\(^\circ\) of mainshaft rotation.

\( H_a \): Mixture injection durations effect hydrogen peroxide exhaust concentration.

10. \( H_0 \): There is no difference in hydrogen peroxide exhaust concentration for engine speeds of 500 and 1000 rpm.

\( H_a \): Engine speed effect hydrogen peroxide exhaust concentration.

11. \( H_0 \): No interaction occurs between mixture injection pressures and mixture injection durations for hydrogen peroxide exhaust concentration.

\( H_a \): Interaction occurs between mixture injection pressures and mixture injection durations for hydrogen peroxide exhaust concentration.

12. \( H_0 \): No interaction occurs between mixture injection pressures and engine speeds for hydrogen peroxide exhaust concentration.

\( H_a \): Interaction occurs between mixture injection pressures and engine speeds for hydrogen peroxide exhaust concentration.

13. \( H_0 \): No interaction occurs between mixture injection durations and engine speeds for hydrogen peroxide exhaust concentration.
Interaction occurs between mixture injection durations and engine speeds hydrogen peroxide exhaust concentration.

14. $H_0$: No interaction occurs between mixture injection pressures, mixture injection durations, and engine speeds for hydrogen peroxide exhaust concentrations.

$H_a$: Interaction occurs between mixture injection pressures, mixture injection durations and engine speeds for hydrogen peroxide exhaust concentrations.

Assumptions of the Study

It is assumed that:

1. The independent variables have variance.
2. The variance is random.
3. The testing instrumentation provides valid and reliable data.

Limitations of the Study

The limitations of the study are:

1. Testing was performed on the only existing hydrogen-oxygen-fueled roller engine prototype.
2. Equipment was available at the university for testing engine torque output and hydrogen peroxide exhaust concentration.
3. Design, modification, and testing were planned to not exceed one year.
4. Engine run times were limited to prevent excessive heating and resulting destruction of the prototype.
Definitions of Terms

After Top Dead Center (ATDC): The progression of the mainshaft or crankshaft in its normal running direction after Top Dead Center, usually expressed in degrees of crankshaft or mainshaft rotation.

Aphodid burner: A combustion device that typically combines oxygen and hydrogen or another fuel to produce high temperature and pressure steam.

Carnot cycle efficiency: A theoretical efficiency calculation based on thermal performance of a fuel which is determined by the combustion temperature minus the exit temperature after the work is performed divided by the combustion temperature.

Diluent: Generally an inert medium such as nitrogen, helium, argon, steam, or atomized water. A diluent is used to slow combustion rates, decrease combustion temperatures, and to act as a working fluid. Occasionally it is referred to by some researchers as an “expander”.

Dynamometer: A device used to measure and absorb engine torque and speed.

Equivalency ratio: A numerical representation of air or oxidizer to fuel mixtures, with 1.0 representing a stoichiometric mixture or complete combustion. Values less than one represent a lean fuel mixture and values over one a rich fuel mixture.

Hydrogen economy: A economic basis derived from the production and use of hydrogen and an energy carrier instead of petroleum and electricity.

Jolly Roller Engine: An rotary engine design patented in 1983 by Dr. Frank Jolly. This engine used two rollers orbiting in a curricular case. The first roller was responsible for intake and compression and the second for power and exhaust. The engine operated in 1985-1986 and produced 30 horsepower at 6000 rotations per minute.
**Mainshaft:** The power output shaft on a rotary engine—comparable to the crankshaft in a reciprocating engine.

**Mainshaft duration:** The total amount of mainshaft rotation expressed in degrees of rotation.

**Oxides of nitrogen (NOx):** A compound that is formed by fuels burning in air at a high temperature.

**Peak pressures:** Pressures produced in the combustion chamber of an internal combustion engine that are unusually high and timed incorrectly, resulting in rough running and potential engine damage.

**Phase:** The term used to describe the parts of a rotary engine power cycle, i.e., what is usually described as the intake stroke in a reciprocating engine would be referred to as the intake phase in a rotary engine. (In other words, rotary engines have *phases* whereas reciprocating engines have *strokes*.)

**Power density:** A term used to describe the amount of power that can be produced per volume.

**Pre-ignition:** Ignition of a fuel-oxidizer mixture before it is intended. Usually caused by a hot spot in the combustion chamber, a lean mixture, and/or too high of compression ratio. Causes rough running and could cause potential engine damage. Also referred to as knock or ping.

**Roller engine:** A type of experimental rotary internal combustion engine (not a Wankel) that uses a round rotor orbiting in a circular housing with working chambers being divided by a rocker or vane.

**Rotor:** The prime mover or rotary piston in a rotary engine.
Stoichiometric mixture: A mixture of hydrogen and oxygen that when burned leaves no residual hydrogen or oxygen—a complete reaction.

Top Dead Center (TDC): The farthest point of the pistons travel away from the crankshaft in a reciprocating engine. In a rotary engine (Wankel), it is usually the point of greatest compression or least volume. For a roller engine it is the point at which the rocker is fully displaced into its cavity.

Wankel rotary engine: A rotary engine design, invented by Felix Wankel and developed in the 1950s, is currently in production in the Mazda RX7 automobile.
CHAPTER 2. REVIEW OF LITERATURE AND RESEARCH

Hydrogen has been researched as a fuel for more than 150 years. This chapter traces the development of hydrogen as a fuel as reviewed in the literature and research. The organization of this chapter is divided into seven major sections: (a) Hydrogen as a Fuel, (b) Hydrogen-oxygen Fuel Combustion; (c) Hydrogen-oxygen Fueled Internal Combustion Engines; (d) Roller Engine Development; (e) Hydrogen-oxygen-Fueled Roller Engine Development; (f) Further Research to Modify the Hydrogen-oxygen Fueled Roller Engine; (g) Statistical Designs and Procedures

Hydrogen as a Fuel

The concept of using hydrogen as a fuel is not new. In the novel The Mysterious Island written by Jules Verne in the 1800s, many of the issues concerning the future of humankind were discussed. One of the major areas was that of energy production and use. In the book, Verne states that hydrogen contained in water would power man’s energy needs better than coal (Das, 1990). Hydrogen has long been investigated as a potential fuel. What was considered to be the first internal combustion engine was operated on hydrogen fuel (North, 1992). This engine was invented by Reverend W. Cecil in 1820 and operated on the vacuum principle (Cecil, 1822).

Otto developed the spark-ignited, four-stroke-cycle internal combustion engine in 1860s and 1870s, and used synthetic producer gas for most of his research (Cox, 1979). This synthetic producers' gas most likely contained over 50% hydrogen (Das, 1990). The Otto cycle engine is the most common power plant in use today. In the 1920s and 30s hydrogen
was extensively proposed by engine researchers Erren and Hastings-Campbell in Germany and England as a potential clean burning fuel for automotive use. Hydrogen was promoted as a fuel to protect the environment and reduce dependency on foreign oil exports (Cox & Williamson, 1979). It is estimated that Erren converted as many as 1000 vehicles to operate on hydrogen fuel (Hoffmann, 1981).

During World War II hydrogen was investigated as a potential replacement for petroleum fuels. It was also investigated for application in submarine and torpedo propulsion. Shortly after the war, the interest in hydrogen fuel declined due to the availability of low cost petroleum, but it continued to be investigated as an alternative to gasoline by Roger Billings in 1966. At the age of 16, Billings converted a Model-T Ford truck to operate on hydrogen fuel in Provo, Utah (Hoffmann, 1981).

The reduced interest in hydrogen as a fuel did not last long. The early 1970s brought about renewed interest and U.S. government funded research. Concern was heightened to reduce U.S. dependency on foreign oil due to an energy crisis that created much interest in hydrogen as an alternative fuel for vehicle propulsion. This interest continued, and during the 1980s hydrogen was investigated as an alternative fuel and promoted around concerns of depleting petroleum reserves and protecting the environment.

**Recent thrusts in hydrogen fuel research**

Currently the need to develop hydrogen as a fuel is being hailed as the only real solution to curb the depletion of natural resources, the preservation of the environment, and the strengthening of the national economy (McAlister 1997; U.S. Department of Energy, 1996). The Persian Gulf War was an obvious indicator of the world’s dependency on foreign
oil reserves. It is interesting to note that congressman Bill Alexander calculated the cost of gasoline to be $5.50 per gallon when taking into account the military expense of Desert Storm (Zweig, 1992). Research shows that hydrogen as a fuel, produced from environmentally benign sources, could be distributed and sold for an estimated $1.19 to $1.83 per gallon energy equivalent to gasoline (Dane, 1990; Hoffman, Bluestone, & Schreffler, 1988; McAlister, 1996).

Over the past several years substantial research funding has become available via governmental agencies throughout the world. In the United States the implementation of the Hydrogen Research, Development, and Demonstration (HRDD or Matsunaga) Act of 1990 was enacted. This legislation provided funding for a five-year program to focus on the development of environmentally benign methods for hydrogen production. This act also created a plan for technology assessment and transfer among various agencies.

In addition, the Matsunaga Act provided funding for the creation of the Hydrogen Technical Advisory Panel (HTAP) in 1990. This panel is comprised of representatives from industry, universities, professional societies, and government laboratories, along with input from financial, environmental, and other appropriate organizations (Padro, 1996). The Energy Policy Act of 1992 extended the Matsunaga Act to include research into fuel storage technology for vehicular applications, the conversion of natural gas pipelines to distribute hydrogen, and gave power to the U.S. Department of Energy to investigate and support other hydrogen fuel related research.

The majority of these funds are directed toward applied research—directly developing and implementing a hydrogen infrastructure. This infrastructure centers around hydrogen
production, storage, distribution, and utilization and thus the development of a hydrogen economy. Hydrogen has been referred to as the ultimate, universal fuel (Colucci & Gallopoulos, 1977; Oney, Vezireoglu, & Dulger 1994; Vezireoglu & Barbir, 1992; Zweig, 1992). This reference not only refers to hydrogen's environmentally friendly aspects of clean burning and non-toxic, but its ease of generation, storage, distribution, and utilization.

Hydrogen fuel's versatility

Hydrogen can be effectively produced by many different methods as shown by Figure 2.1. The most promising includes cracking of petroleum, biological decomposition, thermo-chemical splitting, and electrolysis of water. The cracking of petroleum, mainly methane (CH₄), is currently used to produce most all commercial hydrogen (Fulcheri & Schwob, 1995; Muradov, 1993; Rothstein, 1996). While this method of producing hydrogen is well developed, the current processes allow the production of large amounts of carbon dioxide (a known green house gas) to be released into the environment. Many researchers feel that this process could be effectively altered to produce solid carbon material (carbon black) instead of carbon dioxide (Fulcheri & Schwob, 1995; Muradov, 1993). Carbon black is predominately used in the rubber industry for reinforcing and filler materials. Furthermore, it is suggested that the solid carbon by-product, being of high purity, could be used as a resource for the production of carbon fiber products (McAlister, 1997).

Another method that is being strongly investigated by German and Saudi Arabian researchers uses genetically altered bacteria that consume algae in the presence of sunlight to release hydrogen and carbon dioxide gasses (McAlister, 1996, Steeb, Seeger, and Oud 1994).
The hydrogen is extracted while the carbon dioxide is used by the algae during the photosynthesis process to produce food.

The next method of hydrogen production currently being investigated is the thermo-chemical splitting of water with high temperatures in the presence of a catalyst (Norman, 1991). In this process water is exposed to temperatures around 1600°F in the presence of various catalysts and breaks apart into its elemental forms. This process is expensive but could potentially be achieved by using mirrors to concentrate solar energy.

The last and potentially most promising method of generating hydrogen is via the electrolysis of water. In this process an electrical current is passed through water, disassociating the hydrogen from the oxygen. The process is currently used to produce high purity research-grade hydrogen. This process is highly desirable for it offers the greatest flexibility for the use of hydrogen as an energy carrier from environmentally benign electrical
generation methods such as solar and wind. Both large and small scale solar-hydrogen demonstration facilities have been built and tested around the world (Galli & Stefanoni, 1997; Lehman & Chamberlin, 1991; Steeb et al., 1994; Szyszka, 1992, 1994). These facilities generate electricity through photo-voltaic cells during the day which is used by an electrolizer to produce hydrogen and oxygen gasses. The gasses are compressed or liquefied for storage and used later in fuel combustors (boilers) or fuel cells generating heat and electricity (Hoelzner & Szyszka, 1994).

The storage of hydrogen fuel, unlike petroleum, can take many forms. Hydrogen can be stored as a compressed gas, a cryogenic liquid, or in solid form as metal hydrides (Braum, 1991). Compressed gas cylinders are commonly used in industry for hydrogen storage and have provided an excellent safety record. Recent developments in helically wound titanium composite cylinders developed for compressed natural gas (CNG) fueled vehicles offer greater strength, capacity, weight savings and safety than other types of compressed gas storage devices (McAlister, 1994). These cylinders could be extended for use with hydrogen fuels with little or no modifications.

The next method of storing hydrogen is as a cryogenic liquid contained within a vacuum dewar. This method for storing hydrogen fuel is commonly used in aerospace and medical research industries. Another method of storing hydrogen is as a solid metal hydride. Some metal hydrides such as lanthanum-nickel (LaNi5), iron-titanium (FeTi), and cesium-chrome (CeCo5) offer low pressure storage densities two to three times that of liquid hydrogen (Ming & Goudy, 1997). Metal hydrides operate by allowing the hydrogen gas to permeate the crystalline metal matrix becoming a hydride. To release the hydrogen from the
metal hydride small quantities of heat are applied. While metal hydrides offer a safe, low pressure, ambient temperature storage method they are heavy and expensive. The flexibility of storage methods could offer greater versatility for the distribution, application and utilization of hydrogen fuels and products.

The distribution of hydrogen fuel could safely and effectively occur through existing natural gas pipelines (McAlister, 1997). While hydrogen does require more energy to transmit than natural gas at equivalent pressures, higher pressure transmission yields greater efficiencies. When compared to the losses produced in electrical transmission over the same distance, the losses in hydrogen energy transmission are negligible (Oney et al., 1994). Earlier concerns over hydrogen embrittlement of steel natural gas pipelines are unfounded (McAlister, 1994). Hydrogen embrittlement of steel occurs only at high temperatures and pressures—not the normal operating conditions for natural gas pipelines (Borruto & Marani, 1996). Furthermore, distribution of hydrogen through existing natural gas pipelines will aid in effective utilization through greater availability.

Hydrogen is perhaps the most versatile fuel (Veziroglu & Barbir, 1992). It can be utilized in many ways including flame and catalytic combustion, direct steam production, and electro-chemical reaction. Hydrogen can be combusted through open flame or in the presence of a catalyst to produce heat for cooking and warmth. It can be used in all types of internal and external combustion engines, including the Otto, Diesel, Brayton, and Stirling cycles, and it can be combined in a fuel cell to efficiently produce electricity and water. The electricity used to power the space shuttle and the drinking water for the astronauts is provided by hydrogen and oxygen combined in a fuel cell.
Safety aspects of hydrogen as a fuel

For many individuals, the mention of hydrogen brings visions of the Hindenburg zeppelin dramatically bursting into flames over the Lakehurst, New Jersey countryside in 1937 (Dane, 1990). The Hindenburg zeppelin disaster claimed the lives of 36 passengers and 22 crewmen, mainly as a result of jumping from the airship and from the diesel fuel fires on-board (Dickson, 1977; Williamson & Edeskuty, 1986). Less known about the Hindenburg disaster was that there were 65 survivors.

In 1986, the Challenger space shuttle’s liquid oxygen and hydrogen tanks exploded resulting in the death of all seven astronauts on board. However, the astronauts lost their lives when the remains of their craft impacted the ocean, not because the explosion killed them. This disaster was caused when a leak in an O-ring seal of the solid fuel booster rocket burned through the liquid oxygen tank causing it to burst. This, in turn, ruptured the liquid hydrogen and oxygen tanks, and ignited their contents.

These disasters have left a substantial emotional impact and have served to perpetuate the belief that hydrogen is unsafe (North, 1992). The unjustified reaction to these accidents or suspected act of terrorism is commonly referred to in hydrogen fuel research circles as the “Hindenburg syndrome” (McAlister, 1995).

The utilization of hydrogen fuels can also be done safely. Hydrogen is considered by many as one of the safest fuels (Cruver, 1989; Veziroglu & Barbir, 1992). The National Aeronautics and Space Administration (NASA), the industrial-gas industry, and various commercial, industrial, and laboratory applications have demonstrated that liquid and gaseous hydrogen can be safely produced, stored, and handled (Williamson & Edeskuty, 1986).
Hydrogen fuel, by its very nature, is a safe fuel. This is supported by the lower luminosity value which radiates less heat, the high dispersion rate if spilled, and the fact that hydrogen fires burn upwards. In contrast to hydrogen related accidents, gasoline fires claim 2,000 to 3,500 American lives every year according to an estimate by the U.S. Department of Transportation (Williamson & Edeskuty, 1986). This figure does not reflect the number of lives lost due to wars over petroleum or the loss of life due to the environmental hazards created by the production, transportation, and use of petroleum. Hydrogen burns cleanly and can be produced without dependence on foreign resources or politics (McAlister, 1997).

By examining the characteristics of hydrogen we find that hydrogen is inherently safer than might be first thought. Table 2.1 shows the characteristics generally accepted of common fuels such as gasoline, methane, compared to hydrogen. Furthermore, by ranking the characteristics of fuels from best (1) to worst (3) from a safety standpoint, it is obvious that hydrogen provides the greatest margin of safety than the other fuels (Table 2.2).

Finally, it is concluded that hydrogen is the ultimate universal fuel due to its compatibility with the environment, versatility of use and production, and inherent safety. Veziroglu and Barbir (1992) also add that hydrogen is the best transportation fuel and most efficient fuel with the lowest effective cost to society when compared to other fuels such as syn-gas, SNG, gasoline, natural gas, methanol, ethanol, and LPG. By using hydrogen as a fuel combined with air, the exhaust products would not contain unburned hydrocarbons, carbon monoxide, and carbon dioxide except from the pyrosis (burning) of lubricating oils, but would contain oxides of nitrogen. Methods of reducing the oxides of nitrogen such as lowering combustion temperatures or running rich mixtures substantially reduce engine
Table 2.1. Fire hazard characteristics of potential automotive fuels (Veziroglu & Barbir, 1992)

<table>
<thead>
<tr>
<th>Property</th>
<th>Gasoline</th>
<th>Methane</th>
<th>Hydrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density* (kg m⁻³)</td>
<td>4.4</td>
<td>0.65</td>
<td>0.084</td>
</tr>
<tr>
<td>Diffusion coefficient in air* (cm² s⁻¹)</td>
<td>0.05</td>
<td>0.16</td>
<td>0.61</td>
</tr>
<tr>
<td>Specific heat at constant pressure (J g⁻¹K⁻¹)</td>
<td>1.2</td>
<td>2.22</td>
<td>14.89</td>
</tr>
<tr>
<td>Ignition limits in air (vol.%)</td>
<td>1.0-7.6</td>
<td>5.3-15</td>
<td>4.0-75.0</td>
</tr>
<tr>
<td>Ignition energy in air (mJ)</td>
<td>0.24</td>
<td>0.29</td>
<td>0.02</td>
</tr>
<tr>
<td>Ignition temperature (°C)</td>
<td>228-471</td>
<td>540</td>
<td>585</td>
</tr>
<tr>
<td>Flame temperature in air (°C)</td>
<td>2197</td>
<td>1875</td>
<td>2045</td>
</tr>
<tr>
<td>Explosion energy** (g TNT kJ⁻¹)</td>
<td>0.25</td>
<td>0.19</td>
<td>0.17</td>
</tr>
<tr>
<td>Flame emissivity (%)</td>
<td>34-42</td>
<td>25-33</td>
<td>17-25</td>
</tr>
</tbody>
</table>

*At normal temperature and pressure
** Theoretical maximum: actual 10% of theoretical

Table 2.2. Safety ranking of fuels (Veziroglu & Barbir, 1992)

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Fuel ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gasoline</td>
</tr>
<tr>
<td>Toxidity of fuel</td>
<td>3</td>
</tr>
<tr>
<td>Toxicity of combustion products (CO, SOx, Nox, HC, PM)</td>
<td>3</td>
</tr>
<tr>
<td>Density</td>
<td>3</td>
</tr>
<tr>
<td>Diffusion coefficient</td>
<td>3</td>
</tr>
<tr>
<td>Specific heat</td>
<td>3</td>
</tr>
<tr>
<td>Ignition limits</td>
<td>1</td>
</tr>
<tr>
<td>Ignition energy</td>
<td>2</td>
</tr>
<tr>
<td>Ignition temperature</td>
<td>3</td>
</tr>
<tr>
<td>Flame temperature</td>
<td>3</td>
</tr>
<tr>
<td>Explosion energy</td>
<td>3</td>
</tr>
<tr>
<td>Flame emissivity</td>
<td>3</td>
</tr>
<tr>
<td>Totals</td>
<td>30</td>
</tr>
<tr>
<td>Safety factor</td>
<td>0.53</td>
</tr>
</tbody>
</table>
efficiency. Furthermore, the burning of hydrogen with pure oxygen would eliminate oxides of nitrogen from the exhaust.

**Hydrogen-Oxygen Fuel Combustion**

Hydrogen-oxygen combustion is the most studied reaction due to its simplicity and its foundations in other reactions (Karim & Taylor, 1973). Stoichiometric hydrogen-oxygen combustion liberates significantly more heat per mole than the combustion of other conventional fuels (Cai & Fang, 1991). The equation for stoichiometric hydrogen-oxygen combustion combines one mole of hydrogen with one half mole oxygen yielding one mole gaseous water and a large heat release as follows.

\[
H_2 + \frac{1}{2}O_2 \rightarrow H_2O(gas) \quad \Delta H^\circ_{298} = -241 \text{ kJ/mol}
\]

The theoretical temperature of hydrogen-oxygen combustion is approximately 2807°C. Combustion limits range from 5% to 95% hydrogen in pure oxygen by volume. The approximate speed of stoichiometric hydrogen-oxygen combustion is 2800 meters per second. Hydrogen also has a minimum ignition energy of 0.02 MJ. Due to its characteristics, some of the advantages of hydrogen-oxygen combustion include the absence of pollution, complete combustion, high thermal efficiencies, a wide range of potential mixture strengths, and reduced ignition power requirements and the elimination of ignition advance.

Some of the disadvantages for these combustion characteristics are that combustion temperatures are not metallurgically acceptable, burn rates are so fast creating rapid pressure increases potentially resulting in rough running or engine damage, and wide flammability limits and low ignition energy resulting in auto ignition and flashback (Das, 1996). On the other
hand, the positive characteristics of this fuel-oxidizer—if utilized correctly—offer a real advantage.

A device that uses a stoichiometric hydrogen-oxygen fuel combustion to produce high temperature and pressure steam is referred to as an Aphodid burner or direct steam generator. Aphodid steam generators claim extremely high efficiencies (up to 99%) are significantly smaller and lighter than conventional steam generators (Mathis 1976; Veziroglu & Barbir, 1992). Furthermore, Aphodid burners offer instantaneous steam production while, on the other hand, conventional steam boilers may take many hours before they are up to temperature, eventually operating at efficiencies of only 75% to 80%. Aphodid burners have been studied and recommended for a multitude of items such as micro-biological sterilizers and electrical power generation (Sternfeld & Heinrich, 1989; Sternfeld & Paulus, 1993).

Water is usually added in the combustion chamber of an Aphodid burner to reduce combustion temperatures since stoichiometric hydrogen-oxygen combustion occurs at about 2807°C (3080°K) which would not be suitably contained in metallic vessels. While this addition of water decreases temperature and increases steam output, there is a slight drop in efficiency as explained through the Carnot cycle efficiency equation which is determined by the formula (Mathis, 1976):

\[
\eta_{\text{Carnot}} = \frac{T_{\text{max}} - T_{\text{min}}}{T_{\text{max}}}
\]

Where \( \eta \) is the Carnot efficiency, \( T_{\text{max}} \) is the theoretical combustion temperature, and \( T_{\text{min}} \) is the exit temperature. For example, if the theoretical combustion temperature of hydrogen in oxygen is 3080°K and the exit temperature is 2800°K:
then the Carnot cycle $\eta = 9\%$, a drop of 9\% efficiency due to the heating of the water to reduce combustion temperatures in this example.

As seen with the Aphodid burner, there is a need to control the rate and temperature of hydrogen combustion in pure oxygen through the addition of water. This water is usually referred to as a diluent or working fluid in internal combustion engine research. Common diluents include argon, nitrogen, helium, hydrogen, and steam or atomized water. Atomized water is preferred by this researcher because it could be readily obtainable in most predicted engine applications by condensing the exhaust gasses. The importance of a diluent in the operation of internal combustion engine can be explained in the following statement. It is a common belief that the “explosion” of the fuel-air mixture in the combustion chamber of an engine is what provides all the energy to push the piston down. When in fact, it is the heat from the rapid combustion of fuel-air mixture that acts upon the nitrogen in the air creating a pressure increase in the cylinder which pushes the piston down (Jolly, 1986). Nitrogen is the natural diluent or working fluid in air.

**Hydrogen-Oxygen Fueled Internal Combustion Engines**

There are two main categories of hydrogen-oxygen fueled internal combustion engines. These categories can be differentiated mainly by the engine’s mode of operation. The first engine category operates by compression of the working fluid (hydrogen, oxygen, and diluent) prior to combustion, much like conventional Otto and Diesel cycles and will be referred to (for lack of a better descriptor) as Type 1. The second mode of operation is one in
which the engine does not compress the working fluid (hydrogen, oxygen, and diluent) but are injected directly into the combustion chamber under high pressures either in a continuous or pulsed operation and will be referred to as Type 2.

Type 1 hydrogen-oxygen fueled internal combustion engines

Hydrogen combined with pure oxygen for use in internal combustion engines has been researched in the past for two main reasons (de Boer & Hulet, 1980; Dini, 1990). The first is to provide an engine that can operate in the absence of air, such as underwater or in space. The other main reason is to provide an internal combustion engine that is free from harmful emissions.

The first type 1 engine concept was presented to the British Navy, in the 1930s, by Erren. His hydrogen-oxygen fueled engine design was to be used for submarine and torpedos. Engines using this fuel mixture would leave no telltale exhaust bubbles due to a totally condensable exhaust, and they would reduce pumping losses associated with other types of fuel engines exhausted underwater. In Erren’s submarine power concept, the engine would operate on diesel fuel during surface running generating electricity to produce and store hydrogen and oxygen. For underwater running, these gasses would be combined and burned in the same engine with the exhaust products being totally condensable—eliminating the need for large and heavy batteries and electric motors normally used. This feature was stated to provide extra range and a greater margin of safety.

It is interesting to note that the British Navy rejected Erren’s proposals of a hydrogen-oxygen fueled sub, but in 1942, a German submarine that used Erren’s concept and claimed it benefited from these principles was captured much to the surprise of the Allied forces
(Hoffmann, 1981). Erren discussed using direct injection, exhaust gas re-circulation and water injection to make hydrogen-oxygen combustion suitable for internal combustion engines. Unfortunately, Erren's research was destroyed in the war from the Allied bombings (Cox & Williamson, 1979).

Underwood and Dieges (1971) investigated the concept of using hydrogen and oxygen specifically for automotive use and created the Perris Smogless Automobile Association. During their investigation they design, built, and tested three vehicles to operate on a hydrogen-oxygen fuel mixture. The first vehicle was a 1950 Studebaker, in which hydrogen and oxygen mixture was force fed into the intake manifold through a plate mounted on the carburetor mounting flange. Initial attempts at operation with stoichiometric fuel-oxygen mixtures resulted in slight engine damage without successful running.

A later attempt using a very rich hydrogen mixture yielded engine operation but consumed incredible amounts of hydrogen (Hoffman, 1981). It is apparent that the researchers were not initially knowledgeable of the need for a diluent or working fluid. In this case hydrogen was the diluent, and using hydrogen as a diluent without recovery would create a very inefficient engine. Observations of the engine’s characteristics included reliable starting, and a smooth and quiet operation. However, the engine was destroyed accidentally when the oxygen supply was inadvertently increased instead of decreased (Underwood & Dieges, 1971).

The second vehicle, a 1930 Model A Ford, was converted and incorporated complete exhaust gas re-circulation back into the intake manifold in an attempt to reduce the amount of hydrogen being consumed (Underwood & Dieges, 1971). The exhaust gasses first passed
through a condenser to remove the steam from the diluent (hydrogen) before being reintroduced into the combustion chamber. The vehicle operated and was found to start reliably and operate quietly and smoothly. However, the vehicle produced less power and was quite bulky, and it required great attention for maintenance and operation. A factor which should be expected from a research vehicle.

The third vehicle was a 1960 Ford truck, converted to use much of the same type exhaust gas re-circulation system while incorporating improvements learned from earlier work. The systems in the vehicle were more compact and better organized. It was reported that this vehicle started with ease and ran quite well. Fuel consumption was stated to be greater or at least comparable to gasoline (Underwood & Dieges, 1971).

In 1972, W. Escher produced a report discussing the feasibility of a hydrogen-oxygen fuel mixture for powering automotive applications. In this report he extensively reviewed the work of other research efforts in the area and promoted hydrogen-oxygen fueled systems as a cure-all to depleting resources, environmental accountability, and economic decline. Furthermore, Escher made many references to the works of Underwood and Dieges, Reese and Carmichael, and Engdahl and Tillman which are also covered in this review of literature.

Also in the early 1970s, Karim and Taylor (1973) produced a feasibility study to investigate the potential of a hydrogen-oxygen fueled engine in an attempt to decrease the need of petroleum resources and protect the environment. The focus of this research was specifically to develop a computer program to model the characteristics of a hydrogen-oxygen fueled reciprocating, spark-ignited, internal combustion engine. The design of this engine incorporated a constant volume model in that the exhaust system was hooked up to the intake
manifold much like the work of Underwood and Dieges (1971). Their research yielded two main modes of operation. The first mode considered a recycled portion of the exhaust gasses into the intake manifold with a stoichiometric hydrogen-oxygen mixture being added to fuel the engine. In this case the exhaust steam acted as the diluent. In the second model a stoichiometric hydrogen-oxygen mixture would be added at the inlet to a hydrogen gas diluent. The exhaust steam was condensed to water and removed from the system (Karim & Taylor, 1973). The results of their research showed that an indicated thermal efficiency of about 35% could be obtained.

Other research that investigated type 1 hydrogen-oxygen fueled engines in an attempt to determine efficiencies included work by de Boer and Hulet (1980). In this research he used an American Society for Testing Materials—Cooperative Fuel Research (ASTM—CFR) single cylinder engine fueled with hydrogen and oxygen with an argon diluent. The gasses were mixed through external formation and exhaust gasses were not recycled into the intake manifold. However, re-circulating exhaust gasses was proposed for practical application, so as to not waste the argon diluent.

In this research de Boer and Hulet (1980) used stoichiometric hydrogen-oxygen mixtures diluted to various levels with argon. These hydrogen-oxygen/argon mixtures were tested at different compression levels and ignition timings. Observations made during this research included difficulty in maintaining satisfactory operation especially at high compression ratios due to pre-ignition (knock). When satisfactory operation was obtained the engine produced thermal efficiencies of up to 50%. This figure is much better than thermal efficiencies of hydrogen-air fueled engines. This high level of thermal efficiency is largely due
to the higher specific heat value for argon verses nitrogen (de Boer & Hulet). Since the early 1980s there has not been much published applied research done in the area of type 1 internal combustion engines which is probably due to the complexities involved with recirculative exhaust gasses with condensers etc..

**Type 2 hydrogen-oxygen fueled internal combustion engines**

Perhaps the most significant research in relationship to the hydrogen-oxygen-fueled roller engine is the type 2 mode of operation. Aphodid burners and rocket engines function in the type 2 mode of operation but, do not produce a shaft power output on their own. In 1964 the National Aeronautics and Space Administration (NASA) in cooperation with Vickers Inc. produced a report concerning the development of an internal combustion engine for space applications using gaseous hydrogen-oxygen fuel. This internal combustion engine was designed to provide auxiliary electric power or as a prime mover for other applications with fuels that are normally on board space vehicles. This engine was capable of producing 3-Kilowats (4.0 HP) and was quite unique in design. This uniqueness in design was due to the fact that this engine does not internally compress the working fluid prior to combustion, unlike conventional Otto or Diesel cycles. Instead the gasses are individually injected at high pressure near top dead center of the pistons stroke. This method of operation is compatible with the conditions of low volume fuel storage found in space vehicle applications (Cameron & Morgan, 1964).

The engine that was developed displaced 44.6 cubic centimeters (2.72 cu. in.) with a stroke of 3.91 centimeters (1.54 in.) and a bore of 3.81 centimeters (1.5 in.) with hydrogen and oxygen injectors being mechanically driven from the camshaft. The camshaft was
designed so that cam timing could be altered to provide flexibility in testing. A catalytic plug in the cylinder head was used to provide an ignition source. While this engine somewhat resembles a two-stroke-cycle engine in that the exhaust occurs through ports in the cylinder wall uncovered by the piston, the fuel-oxidizer induction is delivered through injection valves located in the cylinder head. Furthermore, the engine used a vacuum exhaust to simulate operation in space.

The research of Engdahl and Tillman (1971) yielded information on the theoretical performance of a hydrogen-oxygen fueled steam generator hooked to a positive-displacement sliding vane expander providing a shaft power output. Their calculations showed that actual efficiency for this system would range from 24% to 39% depending on method of operation. This level of efficiency is much higher that that of the gasoline fueled reciprocating internal combustion engine of this era which ranged from about 17% to 26%.

In the early 1990s the idea of using hydrogen and oxygen as an internal combustion engine fuel in a type 2 configuration resurfaced. It was believed that a high efficiency rotary engine could be developed that utilized the characteristics of high pressure hydrogen and oxygen gasses for operation (Etteraro, 1994). A proof-of-concept hydrogen-oxygen-fueled roller engine was designed, built, and tested. This engine was capable of exceeding 2000 rpm with quiet operation, producing steam and water as the exhaust (Etteraro).

**Roller Engine Development**

The roller engine concept was invented by Dr. Frank Jolly in the early 1980s at Humboldt State University, Arcata, California, in the Department of Industrial Technology. A
prototype was constructed and tested in 1985-86. Figure 2.2 shows a cross-sectional view of the engine and will be used to explain the principle of operation.

The Jolly Roller engine is comprised of two separate roller chambers connected via a combustion chamber. The first roller mechanism (C) is responsible for intake (X through N)
and compression (Y) phases of the fuel air mixture while the second roller (C₁) provides the power (Z) and exhaust (W out N₁) phases. The rockers play an important role in separating the working chambers—intake and compression (D), and power and exhaust(D₁). The roller mechanisms, or rotary pistons, roll in their case, are either fitted to a common mainshaft or with separate mainshafts (A, A₁) synchronized through the use of a timing belt or chain. Thus the power roller drives the compression roller with the correct timing interval for efficient operation.

The combustion chamber is comprised of a check (G) valve, ceramic housing (J) and spark plug (not shown). The compression roller forces the fuel air mixture through the check valve into the combustion chamber which has been sealed by the power rocker(D₁). The mixture is then ignited by the spark plug. The high pressure combustion gasses then exit the combustion chamber through the port uncovered by the rocker. These high pressure gasses act upon the roller surface (C₁) providing a torque output. Furthermore, the combustion gasses impinge on the shoe of the rocker when exiting the combustion chamber creating additional sealing pressure between the rocker and the roller reducing the need for a heavy following spring. The combustion chamber was constructed of ceramic material to maintain a high temperature potentially providing for multiple-fuel capabilities. A water injection port (P) was added in the power roller chamber to reduce combustion temperature and speed if necessary.

In 1985 the engine was tested on a variety of fuels including gasoline, ethanol and methanol alcohol. The engine’s operation was smooth and quiet when generally compared to today’s reciprocating engines. Maximum output for this engine yielded 30 hp at 6000 rpm.
(Jolly, 1986). The throttle response was rapid and, on occasion, the engine speed exceeded 10,000 rpm (Jolly). Testing of the prototype ceased when the ceramic combustion chamber cracked, sending chips into the power roller chamber, destroying the prototype for further testing. Some of the predicted advantages of the Jolly roller engine were high efficiency due to rotary motion, multiple fuel capability from the ceramic combustion chamber, smooth torque output as a result of the changing effective area of the roller, and capacity for high or low speed operation.

**Hydrogen-oxygen Fueled Roller Engine**

In the early 1990s a proof-of-concept hydrogen-oxygen-fueled roller engine was designed, fabricated, and tested at the Multi-Fuels Research Laboratory at California State University, Fresno, in the Department of Industrial Technology (Ettaro, 1994). This engine could be best described as a rotary, positive-displacement, single, roller-rocker motor with a hydrogen-oxygen combustor. Figure 2.3 shows a cross sectional view of the engine and identifies its main components. Many hours were spent in the design phase of the hydrogen-oxygen-fueled roller engine in the specifications of materials for engine components. Engine components were designed to survive high temperature oxidizing environments that would be present in this type of engine. See Ettaro (1994) for a detailed descriptions of the designs, materials, and manufacturing techniques used.

This roller-rocker motor is somewhat similar in design to the roller-sliding-vane pumps found in some large commercial refrigeration compressors (Jolly, 1985). However, the roller-rocker design is capable of operating at far greater pressures due to the rocker design that allows combustion forces to be absorbed by a rotating bearing. In the roller-sliding-vane, the
Figure 2.3. Hydrogen-oxygen-fueled roller engine components

combustion forces create bending moments on the vane which will most likely cause the vane to stick.

The theory of operation of the hydrogen-oxygen-fueled roller engine is quite straightforward but quite different than conventional Otto or Diesel cycles. It is different in that it does not compress the working fluid (fuel, oxidizer, and diluent) prior to combustion. Instead it injects the gasses directly into the combustion chamber for ignition near top dead center. Figure 2.4 shows the engine position at the initiation of the injection/ignition phase.

As seen in the figure, the combustion chamber has been filled with hydrogen-oxygen fuel mixture and ignition has occurred. Water is also being injected to act as a diluent filling
Figure 2.4. Engine position at initiation of injection/ignition phase

the combustion chamber with high temperature and pressure steam. Forward progression of the mainshaft in a counterclockwise direction allows the high temperature and pressure steam to travel through the transfer tube to the rocker shoe. The expanding steam from the combustion chamber impinges on the rocker shoe, helping to create a sealing pressures between the rocker and roller surfaces reducing the need for heavy rocker-roller following springs. The high pressure steam then acts on the roller surface, providing the power phase and torque output through the mainshaft.

Figure 2.5 shows the power phase. As the high pressure steam continues to expand the effective area of the rotary piston increases as forward progression of the mainshaft occurs.
Figure 2.5. Engine power phase

to provide a smooth power output. With continued progression of the roller, the exhaust port is uncovered and the expanded steam is released through the rocker ports and the rocker cavity into the atmosphere, providing the exhaust phase. During the next engine cycle the roller cavity is completely swept clear of the exhaust steam gasses. Figure 2.6 shows the exhaust phase.

The induction system provides the injection of the hydrogen, oxygen and water is shown in Figure 2.7. This system was designed to deliver the hydrogen fuel, oxygen oxidizer and water diluent from their storage containers directly into the engine's combustion chamber. The system is comprised of gas storage bottles, pressure regulators, anti-flashback/check
Figure 2.6. Engine exhaust phase

valves, connecting lines solenoid controlled valves, check valves, and injectors. This system proved to be effective for the needs of the proof of concept research.

After much time determining operating parameters of the engine, successful operation was obtained. Many of the parameters included hydrogen, oxygen, and water injection pressures, injection timings, and injection durations along with ignition timings. After testing various combinations, optimum conditions were determined which resulted in an engine speed of over 2000 rpm. Observations of the engine operation yielded a quiet operation with steam and water as the exhaust (Ettaro, 1994).
Recommendations by Ettaro (1994) suggested further testing of the hydrogen-oxygen-fueled roller engine. The main areas to be investigated included conducting further specific tests to determine engine power output and investigating better materials for thermal management, improving injection and ignition controls and reliability and determining possible emissions in the exhaust.
Further Research to Modify the Hydrogen-oxygen Fueled Roller Engine

Following preliminary concept research and investigation to design, build, and run the proof-of-concept model, further research was performed on the hydrogen-oxygen fueled roller engine. Unpublished research was conducted by the researcher after 1994 to improve the understanding of the engine’s operating characteristics. During a one-year period, numerous intermittent run times of 30 - 90 seconds were logged which totaled more than three hours.

During this research many additional discoveries were made that were not initially apparent during earlier testing. From the recommendations of Ettaro (1994) and unpublished research it was determined that there was a need for further investigation on data collection, thermal and mechanical engine modifications, and computer/electronic control systems. Data collection included a further investigation into power absorption dynamometers, hydrogen peroxide emissions, and hydrogen fueled engine testing safety.

Data collection

Prior to determining engine operating characteristics of torque output and hydrogen peroxide exhaust concentrations, a thorough literature review of existing methods of testing was necessary. In order to determine engine power output, there was a need to investigate different methods of engine loading. A secondary need was to determine if an appropriate style of dynamometer could be found to test the engine at a higher level beyond proof-of-concept. There was also a need to investigate methods of determining the hydrogen peroxide exhaust concentrations. Furthermore, safety issues concerning hydrogen fueled engine research needed to be investigated to insure adequate preparation.
Dynamometer design

It was determined that a dynamometer would have to be manufactured specifically to test the hydrogen-oxygen roller engine due to its unique operating characteristics, size, and cost of pre-manufactured dynamometers. An investigation of existing dynamometers yielded four main types: prony brake, electric, water brake, and hydraulic.

Prony brake dynamometers are simply a drum or disk brake with a scale to measure torque. While these dynamometers provide simplicity and ease of construction, they lack in precision and smoothness of power absorption over a wide range of engine speeds.

Electric dynamometers are comprised of an electric motor/generator and loading resistors. These types of dynamometers are known for their smooth power absorption, and ease and accuracy of control. However, they are usually large with complex control systems and high cost. Furthermore, the motor/generator’s stator usually has high inertial mass thus creating delayed throttle response. A unique advantage of these types of dynamometers is that they can be operated as motors. This advantage allows them to be used to start the engine or drive the engine to determine its frictional torque. The feature is handy in determining “indicated” power output which is the sum of the brake power output and the friction power.

Water brake dynamometers are quite commonly used due to their favorable characteristics. Some of these characteristics include: a low inertial mass, ease and accuracy of control, and affordability (Superflow, 1996). Water brake dynamometers, however, have a limitation of poor load control at low engine speeds (rpm). After specifically investigating
small engine research, hydraulic pump/motors were found to be most accommodating (Cameron & Morgan, 1964; Cullen, 1993, 1994; Jolly, 1986).

Hydraulic pump/motors offer relative low cost with ease of construction, ease and accuracy of control, a wide speed range, low inertial mass, smooth power absorption. They are also capable of providing a constant torque load regardless of engine speed. Another unique advantage of this type of dynamometer is that it can be operated as a motor like an electric dynamometers. This advantage allows them to be used to start the engine or drive the engine to determine its frictional torque. The feature is handy in determining “indicated” power output which is the sum of the brake power output and the friction power.

A disadvantage of this type of dynamometer is that pump efficiencies at different speeds and pressures can create difficulties in calculating true engine output due to unknown differences in actual pump efficiency versus manufacture provided efficiency charts. A hydraulic pump in combination with an inline shaft style load cell (strain gage) to measure torque and rotations per minute (rpm) may offer the best solution to this problem (Dautremont, 1996; Van Gerpen, 1997). One such load cell manufactured by Lebow Products, a division of Eaton Corporation, offers a wide range of engine speeds (0 to 15,000 rpm), torque measurement form 0 to 500 inch pounds, rapid frequency response and a tachometer output (Lebow Products, 1990). A strain gage signal conditioner manufactured by Daytronic is provided with the load cell to convert torque to a voltage output. This voltage output can be measured with an oscilloscope to accurately determine instantaneous torque to ½ degree engine rotation. Further more, this equipment may also be used to provide torque curve information per engine rotation and engine speed.
Hydrogen peroxide emissions

Hydrogen peroxide has been identified as a potential emission in the exhaust stream of hydrogen fueled engines (Griffith, 1974; Swain, Swain, Leisz, & Adt, 1990). It is an irritant and a source of hydroxyl radicals which, when exposed to sunlight, catalyze the production of photochemical smog (Das, 1990). Hydrogen peroxide occurs through a recombination of hydroperoxy radicals produced by the rapid cooling or quenching of hydrogen-oxygen combustion (Colucci & Gallopoulos, 1977). The formulas below show this two-step process, the first of which is the formation of hydroperoxy radical and the second is the formation of hydrogen peroxide.

\[
\begin{align*}
H + O_2 + M &\rightarrow HO_2 + M \quad \Delta H^{\circ}_{298} = -197 \text{kJ/mole} \\
HO_2 + HO_2 + M &\rightarrow H_2O_2 + O_2 + M \quad \Delta H^{\circ}_{298} = -178 \text{kJ/mole}
\end{align*}
\]

While much early research showed that hydrogen peroxide was detected in hydrogen fueled engine's exhaust (Colucci, 1977; Griffith, 1974), more current research shows that earlier hydrogen peroxide testing methods were faulty. A common test for the detection of hydrogen peroxide is a standard titration with (0.1N) potassium permanganate (KMnO4) solution (Koltoff, 1952). A literature review revealed that oxides of nitrogen could produce a false positive for this testing method (Swain et al., 1989).

A phenol-ferrous sulfate solution was used to test hydrogen fueled engines by Swain (1989). This solution produces no color change in the presence of oxides of nitrogen but creates a strong color change with hydrogen peroxide. A hydrogen fueled engine was tested at different loads and fuel air mixtures or equivalency ratios and yielded no production of hydrogen peroxide at normal operating conditions (Swain et al., 1989).
Hydrogen peroxide could be produced by operating the engine under no load at equivalency ratios less than 0.5. Swain et al. (1989) concluded that "... the operating conditions which produce hydrogen peroxide in the exhaust of hydrogen fueled engines would not occur in properly functioning engines because they correspond to a very inefficient use of hydrogen" (p. 266).

At the time of this writing no studies have been found that test hydrogen peroxide emissions in hydrogen-oxygen fueled engines. Since the use of diluents such as argon and steam are common in hydrogen-oxygen fueled engine research it is presumed that similar results to that above may be obtained (nitrogen is the natural diluent found in air). However, testing the exhaust from hydrogen-oxygen fueled engines for hydrogen peroxide emissions should be further investigated. In addition, the potential to create hydrogen peroxide through the use of water as a diluent may be greater due to the potential quenching effect provided by the latent heat of vaporization required to convert water from a liquid to a gaseous state. Other investigators, however, feel that hydrogen peroxide emissions, if present, could be effectively eliminated through a correctly designed exhaust system or with the use of a catalyst producing only water vapor and oxygen (Colucci & Gallopoulos, 1977).

Since no oxides of nitrogen exist in the exhaust stream of a hydrogen-oxygen-fueled engine, the potassium permanganate method for the identification of hydrogen peroxide could be used without concern of false reading. To detect hydrogen peroxide a sample of exhaust is taken from the exhaust manifold and is bubbled or scrubbed through a chilled 0.1N potassium permanganate solution. The color change is compared to a standard color chart or known sample concentration mixtures to determine the hydrogen peroxide concentration.
An alternative sampling method may be used since water is being used as a diluent in this research. Since water is being used as a diluent, the exhaust products from the hydrogen-oxygen-fueled roller engine are condensable. A sample of condensed exhaust gasses can be titrated into the potassium permanganate solution to determine the presence of hydrogen peroxide.

**Hydrogen fueled engine testing safety**

The testing of internal combustion engines that use gaseous fuels requires some different safety precautions than those using liquid fuels. Testing of engines usually involves determining the limitations of operation which are usually discovered when they are exceeded. Since more work is being done in the area of engine testing with gaseous fuels, the current literature recommends the adoption of specific safety precautions in order to protect research personnel and facilities. Most recommendations are directed to reducing the potential of fire or explosion from the unique conditions and characteristics presented by the use of gaseous fuels.

While hydrogen is a safe fuel it presents some greater challenges to an efficient safety design than other gaseous fuels such as methane and propane due mainly to the wide flammability limits (4% to 75%) and low ignition energy of hydrogen fuel. More stringent compliance to safety measures must be incorporated when using hydrogen in the presence of pure oxygen due to an increase in flammability limits (4% to 95%) and reduction in ignition energy.

To reduce or eliminate the hazards of the fire and explosion potential that could exist in the testing of hydrogen fueled engines, the following recommendations should be observed.
These recommendations come from the broad review of literature as well as personal experience (Aldrich, 1994; Cameron & Morgan, 1964; Cullen, 1995; Ettaro, 1994; Hansel, 1993; Hansen, 1984, 1994; Hooper, 1994; Jolly, 1987; Mahr, Essers, Briem, & Sterner, 1996; Superflow, 1992, 1996).

1. Use explosion-proof electrical switches, lights, motors, controllers, etc., along with grounding of equipment to eliminate the accumulation of static electricity.

2. Provide adequate and continuous ventilation of the test cell at all times through the use of extraction fan(s). Insure that concentrations of potential escaped hydrogen gas cannot exceed 4%.

3. Require that the design of the ceiling of the test cell eliminates pockets that could accumulate escaped hydrogen gas.

4. Provide for adequate ventilation of gaseous fuel storage areas and supply lines, and keep them separate from the engine testing cell.

5. Ensure that the control and distribution of gaseous fuels are in accordance with acceptable industrial guidelines and standards in reference to gaseous fuels: regulators, color codes, left-hand (fuel) and other fittings, leak checks, anti-flashback and check valves, pressure relief valves with external venting, etc.

6. Purge gaseous fuel lines with inert gasses (dry nitrogen, argon, etc.) prior to and after testing.

7. Make provisions to separate the research personnel from the test cell during operation and incorporate safety or kill switches and/or video monitoring along with gas tight seals of test cell.
8. Keep the load absorption dynamometer (mainly electric styles) separate from the engine test cell.

9. Keep designated engine intake and exhaust ventilation systems separate from the test cell’s ventilation system.

10. Shield high voltage wires such as in ignition systems.

11. Develop safety checklists (individually and/or integrated into data collection procedures), similar to those used in aeronautical or aerospace applications.

12. Identify and maintain no smoking areas and regulations.

13. Provide a pressure relief wall or ceiling structures to reduce or eliminate damage from explosion.

14. Use active and passive warning devices such as gas sensors, and automatic and manual fire extinguishing equipment.

15. Most importantly, provide the adequate training of research personnel in the procedures for normal and special hazards associated with engine testing and fuels handling, along with the identification of potential hazardous situations that may be encountered in this work environment.

In addition to the above safety requirements the use of high pressure oxygen presents other safety needs such as eliminating combustible materials in the immediate vicinity, and openly specify oxygen compatible lubricants and materials. As an example, some materials, such as steel, that are perceived safe, can actually burn readily in the presence of pure oxygen. It should be noted that the use of liquefied gaseous fuels would present additional hazards that are not discussed because they are beyond the scope of this research.
Thermal and mechanical engine modifications

After observing the operation of the hydrogen-oxygen fueled roller engine, it was apparent that modifications would have to be made to the proof-of-concept model before more rigorous testing could be performed. These modifications focused on thermal management and lubrication concerns. While selection of materials that could endure high temperature oxidizing environments was carefully investigated for engine construction, the hydrogen-oxygen-fueled roller engine proof-of-concept model was not designed with a continuous cooling or lubrication system. It was determined that a full fledged cooling and lubrication system were beyond the scope of the current research program (Ettaro, 1994).

Cooling of the proof-of-concept model was achieved simply by limiting run times and by pouring tepid water over the hot components. Lubrication was provided by packing bearings with non-flammable Teflon-based grease and lubricating rubbing components with a non-flammable Teflon-based oil. This oil was squirted on rubbing components prior to and during assembly before testing. While it was decided that a full-fledged cooling and lubrication system for the hydrogen-oxygen-fueled roller engine are still beyond the scope of this research, a few items could improve the engine’s durability for improved testing.

After discussing possible alternatives with Professors Clift Cullen and Les Aldrich at California State University at Fresno, recommendations were made to investigate ceramic and polymer coatings as a possible solution to some of the heating and lubrication problems. Jim Shipley of Advanced Racing Technologies of Kill Devil Hills, North Carolina, was also contacted. Mr. Shipley’s background is specifically in coating technologies used in aerospace applications. He worked for Rockwell International, Rocketdyne Division in this capacity for
many years. Currently Shipley uses advanced coating technologies to improve the efficiency of professionally owned racing engines. Shipley was very helpful and provided a great deal of information on different coatings, processes and costs involved.

The current investigation yielded many different types of coatings, application processes, and costs. A process and material that has been used for a number of years for coating the inside of aluminum aircraft and some Porsche engine cylinders is referred to as flame sprayed chrome. In this process a thin, hard, smooth chrome (or stainless steel) layer is applied to the inside of the aluminum cylinder. The process produces such a smooth surface that small dimples must be created by etching to provide small wells for lubrication. Without these wells the cylinder would fail because the lubricating oil could not stick to the smooth surface. The dimples are sometimes called Braille, thus the cylinders are also referred to as Braille. The process was investigated earnestly because the aluminum front and rear case covers along with the aluminum case center for it would provide a hard smooth surface for the roller and rocker to slide against. Unfortunately this special application process was cost prohibitive for the current data collection experience.

Another coating to be investigated for thermal management was a type of ceramic referred to as zirconia. This material is applied to components through a plasma sprayer. The material and process produce an excellent thermal barrier. While the process produces a hard surface it is somewhat rough, thus it could not be used in a sliding application. The material is also sensitive to thermal shock which could cause it to crack and flake off, especially if coefficients of expansion are different from the materials to which they are applied.
Furthermore, the costs of plasma spraying even a few square inches of non-contact surfaces such as the rocker face and combustion chamber was prohibitive.

After investigating Mr. Shipley’s recommendations and informing him of the need for reducing cost factors, he recommended a product called CBC2 which is manufactured by Tech Line Coatings & Lubricants of Waxahachie, Texas. CBC2 is a blend of ceramic-metallic materials designed to coat aluminum which is applied to a prepared surface and baked, resulting in a hard, smooth, and highly heat reflective and resistive “cermet” (i.e., ceramic metallic) coating at a reasonable price. It is interesting to note that the coating material actually reacts with the aluminum-base material much like anodizing to provide a permanent bond. CBC2 is advertised to withstand temperatures greater that the melting point of the aluminum base metal. Furthermore, arrangements were made to provide this author with proprietary application instructions to accomplish the coating process independently, thus saving money.

Investigation into dry film lubricants yielded many alternatives. Mr. Shipley was once again a primary resource. In discussion of low friction fluropolymer (Teflon) coatings which have been available for a number of friction-reducing lubrication applications in automobiles for many years, he mentioned several limitations. Teflon was not recommended for use directly in the combustion chamber since its serviceable temperature limit is around 500°F. Above this temperature the Teflon breaks down. Furthermore, the load-bearing strength of most fluoropolymers is limited to approximately 15,000 psi. Since many of the hydrogen-oxygen fueled roller engine components are most likely to be exposed to temperatures above
500°F and higher, load protection would be a benefit, thus fluoropolymer (Teflon) coatings were not further investigated.

Other lubricating coatings that could withstand higher temperatures and pressures were investigated. One such coating, also manufactured by Tech Line Coatings & Lubricants of Waxahachie, Texas, met requirements. This dry film lubricant coating is referred to as TLML. TLML is comprised of a mixture of high pressure, low friction lubricants including Molybdenum and Tungsten disulfides. These ultra high pressure lubricants are advertised to withstand pressures high as 350,000 psi and temperatures to 2800°F. This coating is applied in a similar method to CBC2. The proprietary coating process was granted for this data collection experience.

Another problem observed during initial testing of the proof-of-concept model was that the rocker would lose contact with the roller surface during engine speeds exceeding approximately 2000 rpm. This was determined by an disturbing audible metallic clanking noise and a popping noise from the exhaust port. This problem became more prominent when the engine was hot but also occurred at lower temperatures.

Research by Jolly (1985) also discussed trouble from the rocker loosing contact with the roller under high load (high temperature) but apparently no trouble from high speed operation (engine speeds exceeded 10,000 rpm). This problem was caused by rapid thermal expansion of the aluminum rocker causing it to lose contact with the roller surface (stick)(Jolly).

In investigating the hydrogen-oxygen-fueled roller engine the determination was made that the inertia of the rocker was high due to the fact that it was made of stainless steel to
accommodate the high temperature oxidizing environment. Mechanical modification that could reduce this problem included lightening the rocker and/or installing stronger tensioning springs along with increasing rocker-case clearancing.

Computer/electronic engine control systems

After observations of the hydrogen-oxygen-fueled roller engine, it was determined that improvements could be made in the control systems of the engine. The analog electronic controls for ignition and injection were adequate for proof-of-concept work but offered severe limitations in regards to adaptability to different testing methods considered in further research. Furthermore, while designed and constructed for high reliability, the old electronic controls had limitations in reliability. These reliability limitations were mainly due to false triggering from the optical sensors and voltage spikes created by counter electro-magnetic force. Consequently, it was determined that a small programmable computer could offer the flexibility in design necessary for further testing.

Initial work began with the Motorola 2066 microprocessor miniature controller. This system proved very time-consuming to program, too slow for multiple tasks at higher engine speeds, and sensitive to false triggering. In addition, it required much additional support circuitry and was somewhat cumbersome. These limitations prompted investigation into other microprocessors, or miniature controllers, including: Z-World Engineering, Micro Genius; Coactive Aesthetics Inc., GCB11; and Parallax Basic Stamp I and Basic Stamp II. A chart is provided in Table 2.3 which compares the specifications to the Motorola 2066.

While initially familiar with the Basic Stamp I in many small applications, the initial reason for trying the Motorola controller included the belief that machine code at 2 MHz
Table 2.3. Comparison of computer-controller specifications to the Motorola 2066

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>2066</th>
<th>Micro Genius</th>
<th>GCB11</th>
<th>Basic Stamp I</th>
<th>Basic Stamp II</th>
</tr>
</thead>
<tbody>
<tr>
<td>RS-232 Port</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>Language</td>
<td>Assembly</td>
<td>Dynamic C</td>
<td>C or Assembly</td>
<td>Parallax Basic</td>
<td>Parallax Basic</td>
</tr>
<tr>
<td>Processor Speed</td>
<td>2 MHz</td>
<td>6.14 MHz</td>
<td>up to 16 MHz</td>
<td>4 MHz</td>
<td>20 MHz</td>
</tr>
<tr>
<td>Input/Output Ports</td>
<td>8</td>
<td>12</td>
<td>20</td>
<td>8</td>
<td>16</td>
</tr>
<tr>
<td>Power Down Save</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>EEPROM</td>
<td>256 byte</td>
<td>512K</td>
<td>512 byte</td>
<td>256 byte</td>
<td>2K</td>
</tr>
<tr>
<td>Cost</td>
<td>$100</td>
<td>$79</td>
<td>$179</td>
<td>$29</td>
<td>$49</td>
</tr>
<tr>
<td>Development Kit</td>
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<td>$249</td>
<td>$139</td>
<td>$99</td>
<td>$99</td>
</tr>
<tr>
<td>Example Programs</td>
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<td>some</td>
<td>some</td>
<td>many</td>
<td>many</td>
</tr>
<tr>
<td>Familiarity</td>
<td>low</td>
<td>none</td>
<td>none</td>
<td>high</td>
<td>medium</td>
</tr>
</tbody>
</table>

would be much faster than an interpreted language at 4 MHz. This did not prove so in this application. In a timed test to perform the same functions, the Basic Stamp I was faster by about 25%. The Basic Stamp I was not earlier considered due to experiences in the Society of Automotive Engineers (S.A.E.) Supermilage 1994 and 1995 competitions in which processing speed limited reliable engine performance to a maximum of 4000 rpm for an electronic fuel injection system. In the hydrogen-oxygen-fueled roller engine the computer would have to control ignition and the injection of the fuel, oxidizer, and diluent. Therefore, other microprocessors were investigated. Fortunately, just before the purchase of another type of miniature controller, the Basic Stamp II became commercially available. The Basic Stamp II was chosen since it offered the greatest speed and required features at the lowest cost.
Fuel, oxidizer, and water injection systems

The fuel, oxidizer, and water injection system that was used for initial testing proved to be adequate for a proof-of-concept model. However, it was thought that improvements could be made to provide greater flexibility with the incorporation of computer controls, greater output through increased injection pressures, and longer run times via improved water injection atomization and location.

Greater testing flexibility through computer controls is highly desirable. The original system used an analog circuit that could only fire injectors simultaneously. This injection method proved functional but lacked true optimization. Therefore, it was determined that the system should be designed with the capability to fire injectors individually, together, and/or multiple times. This feature would allow a greater range of possible injection methods to be investigated.

Another aspect of the injection system during earlier testing was the limitation of injection pressures. Injection pressures for the original research were limited to the maximum pressure that was obtainable by the gas regulators. The maximum pressure was 100 psi for hydrogen, 200 psi for oxygen, and 100 psi for water. This limitation occurred mainly because of the costs involved for high delivery pressure regulators. Generally, high delivery pressure regulators are "two stage" or "three stage" meaning that they are comprised of two or three regulators in one. Furthermore, they are low demand, special order items. The factors of increased complexity, low demand, and special order drives the cost up substantially. Higher injection pressures are desired to potentially increase power output. In the research of
Cameron and Morgan (1964) who used direct injection into the combustion chamber hydrogen injection, the pressures were 300 psi while oxygen was injected at 800 psi.

High pressure regulators manufactured by Harris and Victor were also investigated. While it was initially desired to get regulators with similar pressures as used in the research of Cameron and Morgan (1964) so that a comparison of research could be accomplished, expense was a limiting factor. Pressures of over 500 psi would also require a complete redesign of the injection system to safely conduct tests. Furthermore, the injectors would have to be completely redesigned which was beyond the scope of the problem.

During initial testing of the proof-of-concept model, it was observed that the water injection system was effective at lowering combustion temperatures and cooling internal engine components (Ettaro, 1994). The data showed differences in engine speed for different water injection pressures (volumes). It was concluded that the amount of water injected had a significant effect on engine speed. The data also showed that increasing water to a certain point also increased engine speed. It is believed that this was due to the water being effectively vaporized through the heat generated by combustion, increasing engine efficiency.

On the other hand, too much water decreased engine speed. It is believed that too much water reduced combustion temperatures, thus inhibiting performance. Another observation was that the water could have been better atomized. Fine atomization of the water might improve performance. Furthermore, the water was not very effective at cooling the combustion chamber.

During initial testing the combustion chamber would form a red hot spot after 20 to 30 seconds of operation, but after 45 to 60 seconds the red hot spot would turn to yellow. Water
injection pressures had no observable effect on this hot spot and were the limiting factor in engine run times. It was felt that the water injection system could be altered to improve atomization, eliminate the hot spot, and increase engine performance. Since water is a liquid similar to liquid fuels in engine applications, the engine application of fuel atomization was investigated.

To achieve better fuel-air atomization of liquid fuels such as gasoline, the fuel in automotive applications is usually introduced where the air velocity has been increased. Examples of this phenomenon are found in both carburated and injected engines. For carburated engines the fuel is drawn in at the center of the venturi. According to Bernoulli’s law the velocity of the air is higher and the pressure is lower at this point in the system. This increase in velocity and decrease in pressure aids in the atomization of the fuel by imparting the energy and vapor pressure of the fuel. In high performance injected engines fuel is delivered at the intake valve during the intake stroke. In this system the intake valve in the manifold increases the air’s velocity and decreases the pressure resulting in greater atomization.

Hooper (1994) noted that improved atomization occurred when the fuel’s velocity was increased through the injector’s nozzle and across the pintel to exceed the speed of sound. Hooper believed that by breaking the sound barrier, the energy imparted to the liquid fuel through the “sonic boom” helped atomization. Another method discussed that is similar to that of Hooper is the use of an ultra-sonic wave generator to improve the atomization of fuel.

Still another method of atomizing liquid fuels includes changing injection pressures and nozzle design. Research performed by General Motors in the 1980s uses a timed high
pressure burst of air to force the fuel directly into the combustion chamber achieving excellent atomization. A chemical method for improving the atomization of fuel has been researched by Gunnerman of A-55 in Reno, Nevada. Gunnerman’s (1994) employed surfactants to lower the surface tension of the fuel which in theory would produce better (finer) atomization. While potentially promising, this method for improving the atomization of water was not considered because it would add chemicals to the combustion process that would create unknown effects, and it was also beyond the focus of the current research.

**Fuel-oxidizer ignition systems**

The fuel-oxidizer ignition system that was used for the initial testing of the proof-of-concept hydrogen-oxygen fueled roller engine model proved adequate but unreliable at times (Ettaro, 1994). It was decided that improvements could be made to increase reliability by different methods of ignition. Possible methods of hydrogen-oxygen ignition investigated include electrical discharge (spark), glow plug or hot wire, catalytic, and plasma jet.

**Electrical discharge (spark).** Electrical discharge (spark) ignition systems are used to ignite fuel-air mixtures in internal combustion engines, boilers, and furnaces. In gasoline fueled internal combustion engines the minimum ignition energy required to ignite a stoichiometric mixture is 0.2 MJ and 0.3 MJ for rich or lean mixtures. For stoichiometric hydrogen-oxygen mixtures the minimum energy requirement is 0.02MJ, one tenth that of gasoline.

There are five main types of electrical discharge or spark-ignition systems: conventional, electronic, multiple-discharge, capacitor-discharge, and magneto. Conventional
spark ignition systems basically consist of a battery, ignition switch, ballast resistor, coil, points, condenser, distributor and spark plug. These items work together to provide a timed spark to a specific engine cylinder. The points are mechanically operated and, when opened, cause the coil's field to collapse discharging the coil energy across the spark plug.

While the above system is simple and inexpensive there are limitations. The main limitations come from the points. They are mechanically operated, limiting computer control. They also suffer voltage discharges, reducing life spans; and do not break cleanly, reducing output efficiency. Due to these characteristics this system was not selected for the hydrogen-oxygen-fueled roller engine. Interestingly enough, many modern automobiles are still equipped with conventional spark ignition systems largely due to their low cost and availability parts.

An electronic ignition system is much like the conventional system, but the points have been replaced with a hall effect or optical sensor that triggers a transistor to collapse the coil's field. The hall effect, or optical sensors, do not wear and the transistors give a clean electrical break. These two aspects make the electronic ignition almost twice as efficient. For example, a conventional system delivers a 26,000 volt spark whereas an electronic one can provide around 50,000 volts. Furthermore, electronic ignition systems can be operated and adjusted by computer controls. The hydrogen-oxygen-fueled roller engine used an electronic ignition system during early testing.

Difficulties arise primarily from the optical sensor causing misfires due to incidental light and difficulties in adjustments. Furthermore, cold starts create condensation fouling of
the spark plug thus reducing engine reliability. Other forms of ignition, specifically a multiple discharge ignition system, were also investigated in order to alleviate the above problems.

A multiple discharge ignition system is similar to the electronic described previously but it fires numerous times during the power stroke or phase. This multiple discharge process claims benefits of more reliable and complete ignition and reduced spark plug fouling, which in gasoline fueled internal combustion engine means better mileage, lower emission, and longer spark plug life.

The next type of electrical discharge ignition investigated was capacitor-discharge (CDI). These systems are generally used in high speed, high output, multiple cylinder, internal combustion reciprocating and rotary engines found in high performance and racing vehicles (Unrich, 1988, 1993). They operate by the electrical energy being stored in a capacitor instead of a coil used in conventional and electronic types. As stated before, the main advantages include high speed and high output whereas the main disadvantage is that the spark duration is very short, typically 0.1 to 0.3 milliseconds. Furthermore, the performance of modern electronic ignition systems is comparable to capacitor discharge.

Due to the low speed, single roller, and low ignition energy requirements found in the operational characteristics of the hydrogen-oxygen fueled roller engine, it was decided that a capacitor discharge ignition was not required. Also, since the combustion burn in the hydrogen-oxygen-fueled roller engine occurs over an extended time it was felt that one spark at 0.1 to 0.3 milliseconds could lead to potential ignition reliability problems.

Magneto style ignition systems are commonly found on small engines and aircraft due to their simplicity, light weight, high reliability, and the absence of need for external electrical
power to operate. Magneto style ignition was investigated by Cameron and Morgan (1964) for use on hydrogen and oxygen fueled engines. These types of ignition systems basically operate by inductance created by a magnet (on the flywheel) moving past a stationary coil. Thus, the newer transistorized magneto ignition systems manufactured by Briggs and Stratton were thoroughly investigated for this research as a possible solution. These ignition systems offer a high voltage output, long spark durations, and high reliability with simplicity of use. Unfortunately, magneto systems require a minimum engine speed of about 300 rpm for reliable operation, and are not capable of multiple discharges or computer controls which eliminated them from use in this research.

During operation of the hydrogen-oxygen-fueled roller engine it was observed that the ignition system alone was unsuccessful at stopping engine operation when turned off after the hot spot formed on the combustion chamber (much to the surprise of the researcher). This characteristic of operation was thoroughly investigated to determine the cause. Finally it was concluded that the hot spot on the combustion chamber was at a high enough temperature to cause auto-ignition of the hydrogen-oxygen fuel mixture. Furthermore, if this "hot spot" method of operation were to be used in future, an ignition device would only be required to start the engine and bring it to temperature.

Auto-ignition engine operation from a hot spot was also observed by Cameron and Morgan (1964) in their hydrogen-oxygen fueled engine research. This observed operating characteristic of the hydrogen-oxygen fueled roller engine caused complete reevaluation of the importance of correct ignition timing verses injection timing relationships, since auto-ignition
will occur during injection when the mixture is within combustion limits (5% to 95% for hydrogen in oxygen by volume).

**Glow-plug or hot wire ignition.** Hot wire or glow-plug ignition systems are commonly used in diesel and gas turbine engines for starting purposes. They have also been found in the literature for direct injection two- and four-stroke cycle hydrogen fueled engines (Cox & Williamson, 1979; Welch & Wallace, 1990; Williamson & Edeskuty, 1986). In these engine designs hydrogen is injected at or near top dead center (Cox & Williamson). While some researchers have used conventional diesel engine glow plugs, others have used platinum or nickel-chromium wire with an electrical current creating temperatures approaching 1000° C (Williamson & Edeskuty, 1986).

The use of hot wire ignition has also been investigated for ignition of hydrogen-oxygen fuel mixtures (Buckel & Chandra, 1996; Kumar, 1989). This research was performed for two main reasons. The first reason was to better understand the characteristics of hot surface ignition of hydrogen to aid in the design of safe hydrogen systems. The second was to assist hydrogen fuel researchers by providing a better understanding of the factors that influence hot surface ignition of hydrogen.

The majority of past research in hot surface ignition of hydrogen-oxygen mixtures was performed with the mixture at or below atmospheric pressures. The researchers felt that these conditions were not representative of actual operating conditions that may occur in such applications such as internal combustion engines. Thus their research focused on determining the hot wire ignition temperature at different mixture strengths and pressures (Buckel & Chandra, 1996).
The research also showed that reliable ignition occurred between 1200 and 1300°K with the increasing concentration of hydrogen requiring higher temperatures to ignite. This observation was explained by the fact that hydrogen has extremely high thermal conductivity and thus as the concentration of hydrogen increased the ability to pull the heat away from the hot spot also increased. Furthermore, as pressures increased less heat was required for ignition.

Catalytic ignition. Catalytic plugs have been used in some research involving hydrogen-oxygen fueled internal combustion engines (Cameron & Morgan, 1964). This type of ignition system offers high reliability yet complexity in operation. For this ignition device heat must be applied for reliable operation. After the plug is up to temperature the catalyst causes the combustion of the hydrogen-oxygen mixture. Usually temperature of combustion is adequate to maintain the plug to operating temperature. However, a starting system must be employed to initiate the process.

Starting systems include spark discharge ignition and glow plugs. Cameron and Morgan (1964) used a platinum-palladium catalyst plug in their hydrogen-oxygen fueled engine research. This plug operated without regular preheating methods discussed above. Instead, the initiation of combustion occurred in the presence of the catalyst due to the fact that the injected hydrogen gas was preheated to 800°F (Cameron & Morgan). Investigation into catalytic plug manufactures yielded no information. Thus it was assumed that one would have to be manufactured specially. Further investigations yielded safety concerns due to the potential toxicity of palladium.
**Plasma jet ignition.** Plasma jet ignition systems have been researched over the years in an attempt to improve the ignition of lean mixtures in internal combustion engines. Lean fuel-air mixtures near the lean misfire limit produce the greatest efficiency and reduced emissions but are unreliably ignited. Plasma jet ignition has shown reliable ignition of lean mixtures with the benefits stated however, these types of ignition systems add complexity, are short lived, and use appreciably larger amounts of electrical energy than that of conventional automotive ignition systems.

Plasma jet ignition operates by the traveling of combustion gasses through an electric discharge (arc) which creates a jet of plasma. This plasma jet enters the combustion chamber and, being of high energy/temperature, ensures the ignition of both lean and rich mixtures and greater flame propagation. Lee and Weinburg (1984) extensively researched and developed a plasma jet ignition system that used a conventional ignition coil.

Early engine testing of un-optimized plasma plugs yielded appreciable decreases in burn times (5% to 10%) but were unreliable due to variations in engine operating conditions such as varying throttle positions, loads, and speeds. A testing device was constructed to measure flame propagation in a methane/air mixture to compare ignition with conventional plugs and plasma jet plugs. Furthermore, plasma jet plugs cavity size were tested for optimization. Test results showed an improvement in flame propagation of 64% to 80% for plasma jet plugs using methane/air mixtures introduced in the plug cavity and 162% to 351% for plugs with an methane/oxygen mixture within, compared to conventional spark plugs (Lee & Weinburg, 1989).
Statistical Design and Procedures

There were many factors that needed to be considered before a statistical design could be selected. These factors included the fact that there is only one engine to be tested, engine wear, limited run times, limited number of runs possible. Thus a statistical design was desired that would provide the most information about the operating characteristics of the engine with the least number of data points. A completely randomized block design or a three factor factorial appears to be the best statistical design in testing the hydrogen-oxygen-fueled roller engine due to the above factors (Cochran & Cox, 1992; Montgomery, 1997; Steel & Torrie, 1980).
CHAPTER 3. METHODOLOGY

Procedure of the Study

The procedure of this study is divided into six major sections (a) Data Collection Equipment Development; (b) Thermal and Mechanical Engine Modifications; (c) Computer/Electronic Engine Controlled System; (d) Range of Operational Settings Determination; and (e) Data Collection Methods.

Data Collection Equipment Development

Before the next phases of research on the hydrogen-oxygen-fueled roller engine could be accomplished testing devices and methods needed to be developed. These included dynamometer design, construction and calibration, hydrogen peroxide emissions collection and testing, and safety procedures development and implementation.

Dynamometer design and construction

Following a review of the literature and research in the area of dynamometers it was determined that a hydraulic pump style with a shaft load cell (strain gage) would be used to absorb the engine load and provide data on torque and engine speed. Hydraulic dynamometers are a relatively low cost manufactured item with low inertial mass, smooth power absorption, and they are capable of providing a relatively constant torque load to the engine regardless of its speed. Limitations on determining the true load due to differences in actual pump performance and pump manufactures specifications were eliminated through the use of a shaft style load cell.
The shaft style load cell (strain gage) used in the research was manufactured by Lebow Products, a division of Eaton Corporation, and offered load (torque) measurement from 0 to 500 inch-pounds through a range of engine speeds 0 to 15,000 rpm. This torque sensor also offered a tachometer output which was used to determine engine speed.

A strain gage conditioner manufactured by Daytronic was used to convert the strain gage output to a voltage measured by a volt meter and oscilloscope to determine engine load. The engine's load was created by driving the hydraulic pump's fluid output through a pressure relief valve in the hydraulic system. A D05 fixed displacement hydraulic gear pump and a SQ400-SM12 pressure relief valve manufactured by Parker Fluid Power were also used in the research. Figure 3.1 shows the hydraulic load control system schematic and Figure 3.2 shows the completed unit. Figure 3.3 shows the load cell strain gage.

Figure 3.1. Engine torque measurement and hydraulic load control system
Figure 3.2. Hydraulic power absorption dynamometer

Figure 3.3. Load cell (strain gage) used for measuring torque and rpm
The dynamometer was calibrated for torque load by hanging known weights off the end of a measured torque arm hooked to the input shaft of the load cell with voltage output measured by a volt meter (Micronta 22-182) and oscilloscope (Elenco #MO-1252). Engine speed calibration was checked by measuring the frequency output of the load cell with a digital frequency counter (Tektronix #CFC250), and comparing readings to oscilloscope and digital tachometer during operation to insure consistency. The calibration processes was done at the beginning and end of testing along with once repeated at random during testing procedures. This repeated calibration was performed to insure reliability of the torque and speed test data. Appendix A shows the dynamometer calibration data.

The procedural method of dynamometer engine load testing used in the research is described as follows. The engine was started and warmed up with the flow valve open and the pressure relief valve (system pressure) preset to provide the desired torque load. While the engine was brought up to speed the flow valve was closed creating a differential torque that could be measured through the shaft-style load cell and strain gage conditioner by the volt meter and oscilloscope. Engine speed was measured from the digital frequency counter.

**Hydrogen peroxide emissions**

Hydrogen peroxide emissions have been detected in the exhaust of hydrogen fueled engines operating at low efficiency. Hydrogen peroxide has been identified as an irritant, a catalyst for photochemical smog, and is responsible for health and environmental problems. Thus it was deemed important that the hydrogen-oxygen-fueled roller engine be tested for hydrogen peroxide emissions.
Tests were performed on the engine exhaust emissions to determine the presence of hydrogen peroxide. Hydrogen-peroxide can be detected with the use of a standard (0.1N) potassium permanganate (KMnO₄) titration solution (Koltoff, 1952). Samples of the hydrogen-oxygen-fueled roller engine’s exhaust were condensed, collected, and added to the potassium permanganate solution. A color change of this solution would indicate the presence and quantity of hydrogen-peroxide in the exhaust sample. The data were then compared to the engine operating characteristics of torque and speed.

**Hydrogen-oxygen-fueled roller engine testing safety**

Safety procedures concerning the use of gaseous fuels in engine testing are somewhat different than that of liquid fueled engines. Chapter 2 provided a list of the safety requirements that should be maintained while testing hydrogen as a fuel. Since a gaseous fuels engine dynamometer test cell was not available and building one was beyond the scope of the investigation, the engine testing was performed outdoors. This eliminated much of the need to provide adequate ventilation (but prevented testing during bad weather).

In addition, a safety check list (see Appendix B) was incorporated into the data collection sheets. Besides other things, this check list ensured that gas lines were purged prior to and after testing. In addition, the procedures ensured that at the end of testing, gases and electrical were shut off and other condition met. A carbon dioxide fire extinguisher was also available in the event of a fire. Other safety features incorporated in the design of systems such as the hydrogen-oxygen control system are discussed in those sections where safety needs are indicated. Furthermore, special attention to safety was applied in the selection of oxygen compatible lubricants and materials for use in the engine and during testing.
Thermal and Mechanical Engine Modifications

Conclusions and observation of the hydrogen-oxygen-fueled roller engine in past studies showed a need to modify or improve certain components to provide greater durability for more rigorous testing (Ettaro, 1994). The main engine modifications included applying thermal management and dry film lubrication coatings, relocating the water injector, lightening the rocker, and other minor improvements to enable systems to operate.

Thermal and dry film lubricant coatings

Selected engine components were modified with thermal management and/or dry film lubricant coatings to increase reliability and survivability of the prototype engine. The thermal management coatings are a patented metallic ceramic type that are provided by Tech Line Coatings & Lubricants. The dry film lubricant coatings are a patented molybdenum disulfide and tungsten disulfide based also provided by Tech Line Coatings & Lubricants. The coatings are applied to a prepared surface, baked on, and burnished in. In addition dry film lubricant coatings can be applied over the thermal management coating. The researcher applied the coatings per the instructions provided by Tech Line Coatings & Lubricants.

Detailed information on the coating processes is the proprietary information of Tech Line Coatings & Lubricants Inc., permission to disclose this procedure was withheld. These coating have proven to be effective in aerospace and automotive racing applications. They were a promising option to the re-manufacturing of roller engine components from ceramics and other high temperature self-lubricating materials. Figure 3.4 depicts the roller following application of thermal management and dry film lubricant coatings, and Figure 3.5 depicts the
Figure 3.4. Thermal management/dry-film lubricant coatings applied to roller

Figure 3.5. Dry-film lubricant coatings applied to mainshaft
mainshaft following application of the dry film lubricant coatings. Other components that were coated include the rocker, front and rear case covers and case center.

**Combustion chamber modification**

Observations made during past engine testing showed that the combustion chamber developed a red hot spot on its side opposite the oxygen injector after approximately 20 to 30 seconds of operation. This hot spot turned bright yellow after about 50 to 60 seconds of engine operation largely dependent on injection pressures. At this point the engine was immediately shut off and allowed to cool. More rapid cooling was achieved by squirting cool water on the combustion chamber. The development of this hot spot prevented more rigorous testing of the engine prototype.

The original water injector location (see Figure 3.6) was ineffective in preventing the development of this hot spot. Recommendations were made to devise a cooling jacket around the combustion chamber to eliminate this hot spot. It was reasoned that a cooling jacket would work effectively at eliminating the hot spot but would reduce engine efficiency. The heat energy of combustion should be used to develop engine power and not be dragged away by the cooling system. Thus, relocating the water injector to inject water directly into the combustion chamber may be shown to be a more effective alternative than a cooling jacket. Furthermore, combining water in the oxygen injection stream may further help control combustion temperature and speed through increased atomization.

A new design was produced and the combustion chamber cap was modified to incorporate a water injector (see Figure 3.7). This design allowed for the introduction of
Figure 3.6 Original water injector location

Figure 3.7 Combustion chamber with water injector
atomized water into the oxygen injection stream. The design worked very well at providing an atomized water spray in bench testing.

**Rocker and other mechanical modifications**

During past testing of the hydrogen-oxygen-roller engine speeds above about 2000 rpm were difficult to achieve with light rocker springs. The cause of this limitation was determined to be from the high inertia of the stainless steel rocker. The roller engine by Jolly (1985) used an aluminum rocker which provided low inertia and high speed with light rocker springs. However, Jolly's rocker had a tendency to stick due to rapid thermal expansion of aluminum. Furthermore, an aluminum rocker would have a difficult time taking the heat load applied by hydrogen-oxygen combustion.

In the current research, the rocker's weight was reduced by removing material and drilling lightening holes. Additionally, rocker clearancing was also modified to allow for the reduction of potential rocker sticking due to thermal expansion that could occur in the greater heat load environment of load testing. Other engine component modification included fitting the flywheel with a magnet to activate hall effect sensors utilized by the electronic engine control system and making new brackets to hold the sensors.

**Computer/Electronic Engine Control System**

The new engine control system was designed to use a small microprocessor to allow for greater flexibility and accuracy of fuel-oxidizer-water injection and ignition. The Basic Stamp II module appeared to be ideal for this application for reasons listed in Chapter 2. The
module was readily programmable and offered flexibility in engine control. Example programs are listed in Appendix C.

Inputs to the Basic Stamp II module to detect engine position and speed incorporated two hall effect sensors triggered by a magnet located on the rotating flywheel. This method of engine position sensing showed greater reliability in bench testing than optical sensors used in previous work due to the elimination of false triggering due to incidental light sources. The location of the sensors was also changed to make them readily accessible and easy to adjust.

Initially the circuit incorporated an engine throttle feature which was controlled by the operator. This throttle was provided to increase power output by regulating the fuel-oxidized-water injector's pulse width duration (time on). This method of operation, while good for starting and bringing the engine up to speed, did not produce repeatable data when the engine was loaded. It was determined that a change in injection pulse width changed engine speed. In turn, this influenced the duration of injection in degrees of engine rotation thus having a pronounced effect on engine speed stability and torque output.

Therefore, in this research the method of injection timing was changed to inject the fuel-oxidizer for a duration based on degrees of mainshaft rotation. This change appeared to eliminate the problems mentioned above and produced repeatable data in preliminary testing. Flexibility in the programming of the Basic Stamp II module allowed the change to occur without redesigning the electronic circuit.

The ignition system in this research was also totally redesigned from the earlier proof-of-concept model (Ettaro, 1994), and it was also controlled with the Basic Stamp II module. It was determined that the incorporation of a multiple discharge ignition circuit may offer
some important advantages. Multiple ignition firings include greater probability for igniting the hydrogen-oxygen mixture, re-ignition of mixture if combustion stops, continued ignition over long injection durations, and improved de-fouling of the spark plug.

In order to accomplish multiple firings, two ignition control methods were investigated. The first was to use programming steps within the Basic Stamp II module to fire the ignition circuit at multiple times through either a loop counter or through multiple pulse-pause statements located throughout the program’s injection phase (see Appendix C). After designing the circuit and creating many different programs, bench testing determined that both programming methods required too much processing time and would limit the maximum reliable engine control speed to 800 to 1200 rpm.

The second method investigated was to modify the circuit to incorporate a 555 timer which operated in a monostable configuration, with the R-C constant made adjustable to provide a range of 150 to 500 firings per second as desired. This method of operation was bench tested and shown to give reliable injection and ignition up to and above 3000 rpm.

This ignition system was tested on the engine with varying degrees of success but it proved unreliable during cold starts due to condensation fouling of the spark plug. Condensation fouling of the spark plug during cold start has created much difficulty since the beginning of the hydrogen-oxygen-fueled roller engine research and was discussed by Ettaro (1994).

Another observation made during preliminary tests of this research showed the new water injector location created increased condensation fouling of the spark plug. Other methods to remedy the cold start problem in the past included switching to a hotter plug,
modifying the spark plug, changing the reach and preheating. The highest heat range plug, a C9E was special ordered from NGK Spark Plug Co. Ltd. This, however, as earlier hypothesized would not solve a cold start problem. A high heat range plug works only after it is hot.

The next attempt to eliminate the cold start problem was to modify the spark plug in various manners in an attempt to eliminate the loci of condensation fouling. These modifications included removing much of the spark plug's skirt, exposing the insulator cone. While this helped considerably, reliable cold start ignition was still not obtained. Figure 3.8 show a regular and modified spark plug. Other modifications included altering the ground electrode shape and discharge position but yielded similar results. The next thing that was investigated was to change reach of the plug. Changing the reach means to alter the plugs position in reference to the combustion chamber in or out. This also showed little improvement. The last method which proved most reliable but inconvenient was to pre-heat the spark plug with a blow torch external to the combustion chamber and install and start the engine while hot. While this method proved most reliable for cold starts it was difficult to carry out in an expedient manner.

A review of the literature yielded information on an electrically heated spark plug being investigated by Honda Motor Co. of Japan in an attempt to reduce cold start emissions in gasoline fueled internal combustion engines. After much time spent in pursuit of more information on this or a similar heated plug, consideration to manufacture one came to mind.
Difficulties in manufacturing such a plug led to an investigation into other ignition methods discussed in Chapter 2. Catalytic and plasma style plugs were investigated at some length but difficulties in obtaining materials and the complexity of designs limited their appeal. Since fuel-oxidizer injection occurs directly into the combustion chamber of the hydrogen-oxygen fueled roller engine, combustion can be initiated through correct injection timing, much like a diesel engine. Diesel engines commonly use glow plugs for cold starting.

A glow plug was manufactured for this research by completely removing the skirt of a NGK C7E spark plug and wrapping a coil of 0.05" nickel-chromium wire around the insulator cone. The ends of this wire coil were mechanically attached to the center electrode and grounding shell and silver soldered. Then an electrical current was passed through a limiting
resistor to the wire coil. The coil glowed yellow-orange hot and demonstrated reliable
ignition of the hydrogen-oxygen fuel mixture during bench testing.

Difficulties arose however, in the operation of the glow plug. While it proved quite
reliable in igniting the hydrogen-oxygen mixture when on the test bench without the addition
of the water when the water was added through the oxygen stream the glow plug failed at
igniting the mixture consistently. Many different water injection pressures were tried but with
little positive result. It was determined that the injection of the water in the combustion
chamber through the oxygen stream cause droplets to collect on the glow plug effectively
cooling it preventing it from igniting the mixture. Thus, since reliable ignition with both
multiple discharge electronic ignition and the glow plug was not achieved with the water
injector in the combustion chamber it was determined to place it back in the original position.
The original position allowed water to be injected in the transfer tube. This position while not
effectively cooling the combustion chamber would allow for more reliable cold starts as seen
in past research.

The glow plug was then again tried as the ignition source for the hydrogen-oxygen
mixture. The glow plug worked effectively at cold starting the hydrogen-oxygen-fueled roller
engine but failed quickly in the high temperature-oxidizing environment found in the
combustion chamber. A switch was made back to the multiple discharge electronic ignition.
This system proved reliable at cold starts.

Description of the engine control circuit

The engine control circuit used a Basic Stamp II module (IC1) which is wired to
receive inputs and give outputs according to a downloaded engine control management
program (RS 232) (see Figure 3.9). Mainshaft position inputs to the Basic Stamp II were given by the hall effect sensors (IC4 and IC5). Throttle position was provided through a variable resistor (R8). Outputs from the Basic Stamp II module operated transistors (T1, T2, T3, and T5) controlling the hydrogen, oxygen, and water injectors (INJ1, INJ2, and INJ3, respectively). The output of the Basic Stamp II module also controlled the multiple discharge ignition circuit.

The multiple discharge ignition circuit is comprised of a 555 timer (IC3) operated in a monostable configuration controlled through the R-C constant, triggering the power Metal Oxide Field Effect Transistor (MOSFET)(T4). The MOSFET, when turned off, caused inductance in the coil (I1) firing the spark plug (SP1). Rectifiers were provided to assist in the protection of the power transistors and MOSFET from Counter Electro-Magnetic Forces (CEMF).

Electrical power was supplied to the system by a 12 volt automotive style battery (B1). A 5 volt regulator (IC2) was provided for operating the Basic Stamp II. Light Emitting Diodes (LED) were furnished throughout the circuit to provide a visual indication of power (LED1) and input (LED5 and LED6 [both not shown]) and output triggers (LED2, LED3, and LED4). Figure 3.10 shows the completed control system board.

Range of Operational Settings Determination

Before serious testing could begin and the bugs had been worked out of the new designs and modifications, tuning had to be accomplished to determine a range of operational settings. The main tuning areas include the stoichiometric hydrogen-oxygen mixture and the
Figure 3.9. Electronic injection and ignition circuit
hydrogen-oxygen-water mixture. Furthermore, it was determined that a conservative test regiment be designed to assist in the promotions of engine longevity.

**Hydrogen-oxygen mixture-tuning stoichiometric**

Tuning of the hydrogen-oxygen-fueled roller engine for correct mixture strength (stoichiometric) was performed in a similar manner to that of previous research. Basically, the oxygen gas pressure was set at a predetermined point and the hydrogen was then set a little lower based on prior observations. A blow torch flame was ignited and placed at the exhaust port of the engine. The engine was started and un-reacted hydrogen that came form the exhaust port was ignited which was shown by a “popping” noise or a small flame. The hydrogen pressure was then decreased until the flame or “popping” noise stopped. This method should be able to accurately tune the engine mixture to 5% hydrogen in oxygen. Due to the wide flammability limits of hydrogen in air (5% to 75%) any un-reacted hydrogen remaining in the exhaust, over 5%, would ignite with the assistance of the torch as soon as it mixed with the outside air showing a flame or a “pop”. Furthermore, a slightly hydrogen rich mixture is preferred. Oxygen rich mixtures could create a higher potential to produce hydrogen peroxide exhaust emissions.

This method of tuning is somewhat similar to how an oxy-acetylene torch is properly adjusted. Basically, the acetylene is turned on and ignited. Oxygen in the air combines with the acetylene allowing it to burn with an orange flame forming particulate carbon. When the oxygen is added and increased less and less particulate carbon forms until no particulate carbon forms, a blue or neutral flame results, and the mixture is stoichiometric. Mixture tuning was achieved by randomly selecting the three replication at one of three test points.
Table 3.1 shows the hydrogen to oxygen pressure relationship for stoichiometric operation in the hydrogen-oxygen-fueled roller engine.

Tuning of the fuel-oxidizer to water ratio was a little more difficult. After the correct pressures for stoichiometric combustion were determined for the hydrogen-oxygen mixture water pressures were determined for the range. To accomplish this the hydrogen and oxygen pressures were set at the points determined prior. Water injection pressures were initially set at three-quarters hydrogen pressures. The engine was started and allowed to come up to temperature. The water injection pressure was then increased until maximum engine speed was attained. As early research showed water injection pressures influenced engine speed. The blow torch was also used and hydrogen pressures changed to check that the mixture relationship did not fluctuate due the injection of water. Table 3.2 shows the relationship between hydrogen-oxygen and water pressures.

Table 3.1. Hydrogen to oxygen pressures for stoichiometric operation

<table>
<thead>
<tr>
<th>Setting</th>
<th>Hydrogen pressure</th>
<th>Oxygen pressures</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>80</td>
<td>200</td>
</tr>
<tr>
<td>2</td>
<td>110</td>
<td>300</td>
</tr>
<tr>
<td>3</td>
<td>140</td>
<td>400</td>
</tr>
</tbody>
</table>

Table 3.2. Hydrogen-oxygen-water relationship

<table>
<thead>
<tr>
<th>Setting</th>
<th>Hydrogen pressure</th>
<th>Oxygen pressures</th>
<th>Water pressures</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>80</td>
<td>200</td>
<td>80</td>
</tr>
<tr>
<td>2</td>
<td>110</td>
<td>300</td>
<td>120</td>
</tr>
<tr>
<td>3</td>
<td>140</td>
<td>400</td>
<td>160</td>
</tr>
</tbody>
</table>
Data Collection Methods

Data were collected by operating the engine at various selected injection pressures and durations and loading it to maintain one of two engine speeds. During the individual runs exhaust gasses were collected. It was determined that three different mixture injection pressures and three different mixture injection durations would be tested at two engine speeds for the engines torque output and hydrogen peroxide exhaust concentrations. The injection pressures for hydrogen, oxygen, and water were determined above. The mixture injection durations included 180°, 210°, and 240° of mainshaft rotation. The two engine speeds that were selected included 500 and 1000 rpm. Injection pressures were based on the availability of high pressure regulators and the safely limitation of the designed system. Mixture injection durations were determined from past experience in engine operation which required greater than 160° of injection duration for reliable operation. While higher engine speeds are attainable, the engine speeds that were selected would give reliable operation over the complete range of injection pressures and durations without stalling. Since the prototype hydrogen-oxygen-fueled roller engine is the only one in existence and reconstructing another is beyond the scope of the research, a conservative test program was implemented to promote the engine’s life expectancy to complete all testing and allowing for future testing and demonstration.
CHAPTER 4. RESULTS OF EXPERIMENTATION

The hydrogen-oxygen-fueled roller engine was tested at Iowa State University within the Department of Industrial Education and Technology. This chapter will discuss the results of the engine testing for torque output and hydrogen peroxide emissions at three different mixture injection pressures for three different mixture injection durations at two different engine speeds, with two replications, for a total of 36 points. The engine is unique to see in operation because of its smooth, quiet performance without a muffler and steam exhaust. Figure 4.1 shows the engine in operation with a steam cloud as the exhaust.

Figure 4.1. Engine during operation
Data Analysis

The analysis of data for comparing the influence of different mixture injection pressures, mixture injection durations, and engine speeds was conducted to determine the operating characteristics of the hydrogen-oxygen-fueled roller engine in reference to engine torque output and hydrogen peroxide exhaust concentration. Analysis of the data collected during experimentation are presented by hypothesis.

**Hypothesis 1:** There is no difference in engine torque output when mixture injection pressures are changed to 80/200/80, 110/300/120, and 140/400/160 psi. (hydrogen/oxygen/water).

Figure 4.2 shows that as mixture injection pressure were increased torque output increased. Higher mixture injection pressures translate to higher energy input, thus greater energy out. The standard error of mixture injection pressure means equals 0.11.

![Figure 4.2. Engine torque output for mixture injection pressures](image)
Based on the results of experimentation, Hypothesis 1 was rejected. There were differences in engine torque output for changes in mixture injection pressures.

_Hypothesis 2: There is no difference in engine torque output when mixture injection durations are changed to 180°, 210°, and 240° of main shaft rotation._

Figure 4.3 illustrates the mixture injection durations with engine torque output. This graph shows that the greatest torque output occurred for mixture injection duration between 180° and 240° close to that of 210° of main shaft rotation. It is believed that, due to the mechanical relationship of the main shaft position and the effective area of the roller, an optimum point of energy transfer exists. For shorter than optimum mixture injection durations, energy input limits the output. For longer mixture injection duration more, energy input yields no increase in energy output. The standard error of mixture injection duration means equals 0.11.

Figure 4.3. Engine torque output for mixture injection durations
Based on the results of experimentation, Hypothesis 2 was rejected. There were differences in engine torque output for changes in mixture injection durations.

_Hypothesis 3: There is no difference in engine torque output for engine speeds of 500 and 1000 rpm._

Figure 4.4 shows that torque output decreased as engine speed increased. This was expected as the energy input to the engine would convert to a power output which follows according to the horsepower equivalency formula—torque decreases as the speed increases. By calculating horsepower for the two torque averages, however, it showed that a slightly greater efficiency was produced at the lower (500 rpm) engine speed. This greater efficiency at low engine speeds many be attributed to frictional losses which increase as speed increases. The standard error of torque output means for engine speed equals 0.09.

Based on the results of experimentation, Hypothesis 3 was rejected. There were differences in engine torque output for changes in engine speed.

![Figure 4.4. Engine torque output for engine speeds](image-url)
Hypothesis 4: No interaction occurs between mixture injection pressures and mixture injection pressures for engine torque output.

The interaction between mixture injection pressures and mixture injection durations for engine torque output was shown to be significant in the analysis of data, with an F statistic probability of 0.009. After examining the data graphs the interaction between mixture injection pressures and mixture injection durations was determined to be insignificant from a practical standpoint. Thus, based on graphing the results of experimentation Hypothesis 4 was not rejected.

Hypothesis 5: No interaction occurs between mixture injection pressures and engine speeds for engine torque output.

Figure 4.5 shows the interaction between mixture injection pressures and engine speeds for torque output. This figure also shows that increasing mixture injection pressures

![Figure 4.5. Engine torque output interaction for mixture injection pressures and engine speeds](image-url)
had a greater effect on torque output for the engine speed of 500rpm than that of 1000 rpm.
The standard error of the interaction means of mixture injection pressures and engine speeds was 0.16.

Based on the results of experimentation, Hypothesis 5 was rejected. There was interaction between engine torque output for changes in mixture injection pressures and engine speeds.

Hypothesis 6: No interaction occurs between mixture injection durations and engine speeds for engine torque output.

The interaction between mixture injection durations and engine speeds for engine torque output was also shown to be significant in the analysis, with a F statistic probability of 0.001. After examining the data graphs, the interaction between mixture injection durations and engine speeds was determined to be insignificant from a practical standpoint. Thus, based on graphing the results of experimentation Hypothesis 6 was not rejected.

Hypothesis 7: No interaction occurs between mixture injection pressures, mixture injection durations and engine speeds for engine torque output.

The interaction between mixture injection pressures, mixture injection durations and engine speeds for engine torque output was also shown to be significant in the analysis, with a F statistic probability of 0.008. After examining the data graphs, the interaction between mixture injection pressures, mixture injection durations and engine speeds was determined to be insignificant from a practical standpoint. Thus, based on graphing the results of experimentation Hypothesis 7 was not rejected.

Hypothesis 8: There is no difference in hydrogen peroxide exhaust concentration when mixture injection pressures are changed to 80/200/80, 110/300/120, and 140/400/160 psi (hydrogen/oxygen/water).
Figure 4.6 compares the mixture injection pressures with hydrogen peroxide exhaust concentrations. This graph shows that the greatest hydrogen peroxide concentrations occurred for mixture injection pressures between 80/200/80 and 140/400/160 close to that of 110/300/120. It is believed that, due to the change in mixture injection pressures a change in combustion zone location may occur. The combustion zone location for the mixture injection pressure of 110/300/140 may be more susceptible to flame quenching from water injection than other locations. The standard error of mixture injection pressure means equals 7.0.

Based on the results of experimentation, Hypothesis 8 was rejected. There were differences in hydrogen peroxide exhaust concentrations for changes in mixture injection pressures.

![Figure 4.6. Hydrogen peroxide exhaust concentration for mixture injection pressures](image-url)
Hypothesis 9: There is no difference in hydrogen peroxide exhaust concentration when mixture injection durations are changed to 180°, 210°, and 240° of mainshaft rotation.

Figure 4.7 shows that as mixture injection duration increases hydrogen peroxide exhaust concentration increases. Greater mixture injection durations could cause an increase in hydrogen peroxide exhaust concentrations from the potential changing of the hydrogen-oxygen mixture relationship through the cycle. This potential change in mixture relationship could be caused by the differences of their individual injection pressures. Due to this factor it is theorized that the mixture may become more oxygen rich for longer injection durations promoting the production of hydrogen peroxide. The standard error of mixture injection duration means equals 7.0.

Based on the results of experimentation, Hypothesis 9 was rejected. There were differences in hydrogen peroxide concentrations for changes in mixture injection durations.

Figure 4.7. Hydrogen peroxide exhaust concentration for mixture injection durations
Hypothesis 10: There is no difference in engine hydrogen peroxide exhaust concentration for engine speed.

Figure 4.8 shows that as engine speed increases hydrogen peroxide concentration decreases. This observation could also be possibly explained by differences in individual injection pressures. For engine speeds of 500 rpm higher back pressures, due to higher load, occur in the combustion chamber and power chamber than that of engine speeds of 1000 rpm. This higher back pressures could cause an imbalance in hydrogen-oxygen mixture creating an oxygen rich environment promoting the production of hydrogen peroxide. The standard error of hydrogen peroxide concentration means for engine speed was 5.72.

Based on the results of experimentation, Hypothesis 10 was rejected. There were differences in hydrogen peroxide concentrations for changes in engine speeds.

![Figure 4.8. Hydrogen peroxide exhaust concentration for engine speeds](image)
Hypothesis 11: No interaction occurs between mixture injection pressures and mixture injection durations for hydrogen peroxide exhaust concentration.

The interaction between mixture injection pressures and mixtures injection durations was shown to be insignificant in the data analysis, with an F statistic probability of 0.07.

Based on the results of experimentation Hypothesis 11 was not rejected.

Hypothesis 12: No interaction occurs between mixture injection pressures and engine speeds for hydrogen peroxide exhaust concentration.

Figure 4.9 shows the interaction between mixture injection pressures and engine speeds for hydrogen peroxide concentration. This figure also shows that hydrogen peroxide concentrations were greatest toward the 100/300/120 mixture injection pressure for both

![Figure 4.9. Hydrogen peroxide exhaust concentration interaction for mixture injection pressures and engine speeds](image)
engine speeds. This could possibly be explained by the combustion zone location as discussed previously which could have a more pronounced effect at higher engine speeds. The standard error of the interaction means of mixture injection pressures and engine speed was 9.90. Based on the results of experimentation, Hypothesis 12 was rejected. There was interaction between hydrogen peroxide concentrations for changes in mixture injection pressures and engine speeds.

*Hypothesis 13: No interaction occurs between mixture injection durations and engine speed for hydrogen peroxide exhaust concentration.*

The interaction between mixture injection durations and engine speeds was shown to be insignificant in the analysis, with an F statistic probability of 0.11. Based on the results of experimentation Hypothesis 13 was not rejected.

*Hypothesis 14: No interaction occurs between mixture injection pressures, mixture injection durations, and engine speed for hydrogen peroxide exhaust concentrations.*

The interaction between mixture injection pressures, mixture injection durations and engine speeds was also to be insignificant in the analysis, with an F statistic probability of 0.84. Based on results of experimentation Hypothesis 14 was not rejected.

Complete ANOVA tables for engine torque output and hydrogen peroxide concentration exhaust emissions are given in Appendix D. Tables for graphed information are given in Appendix E, and the raw data is provided in Appendix F.
CHAPTER 5. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

This chapter presents a discussion of the need to change from carbon-based fuels through an enhancement of hydrogen energy, research performed in this area, and recommendations for continued research to protect the environment through the promotion and development of hydrogen as a fuel. The chapter contains the following sections: (a) Summary; (b) Conclusions; and (c) Recommendations.

Summary

The global need for energy is constantly increasing. The use of carbon-based fuels to feed this need is resulting in severe damages to the environment. Continued use could result in catastrophic global consequences (Zweig, 1992). Many researchers are demanding changes to protect the environment.

Hydrogen has been identified as the ultimate, universal fuel for its many positive traits. These traits include potential pollution free combustion, ease of flexibility in storage and transmission versatility in use with a high degree of safety (Erren, 1933; United States Department of Energy, 1996; Veziroglu & Barbir, 1992; Zweig, 1992). Hydrogen has been identified as an energy carrier that makes environmentally benign production methods more practically and economically feasible (McAlister, 1997; Padro, 1996). Furthermore, hydrogen could be produced without reliance on foreign governments (McAlister, 1997).

Many governments and industries are supporting the growth of hydrogen as a fuel and are directing their efforts towards applied research and development. The areas of interest are in developing more effective production, storage, transmission, and utilization methods and
thus the rise of a hydrogen infrastructure. By developing this infrastructure and a hydrogen
based economy would result with many benefits as discussed in the literature.

Even though hydrogen has been investigated as a fuel for many years for internal
combustion engines, the potential to produce pollutants in the form of oxides of nitrogen still
exists if air is used for combustion. Hydrogen combined with pure oxygen would eliminate
oxides of nitrogen in the exhaust, but current engine designs cannot effectively convert the
energy of hydrogen-oxygen combustion into useable power (Cox & Williamson, 1979;
Mathis, 1976; Underwood & Dieges 1971). Thus the need exists to develop new types of
internal combustion engines to utilize hydrogen and oxygen combustion effectively. The
hydrogen-oxygen-fueled roller engine may be a step in the direction of this development.

The hydrogen-oxygen-fueled roller engine was designed, constructed, and tested for
operation in earlier research (Ettaro, 1994). Modifications to the proof-of-concept model
were performed in an attempt to improve performance and increase durability and reliability
for more rigorous testing. Some of the modifications performed and tested included:
development of engine testing equipment, thermal and mechanical engine modifications, and a
computer/electronic engine control system governing electronic injection and multiple
discharge ignition.

In this research study, the engine was tested at different mixture injection pressures,
mixture injection durations and engine speeds for torque output and exhaust emission.
Analyses of the data were performed yielding information on the operating characteristics of
the hydrogen-oxygen-fueled roller engine.
Conclusions

Conclusions for this research are broken down into two main categories. The first category presents information about the performance of the data collection equipment and attempted improvements made to enhance engine operation. The second category deals with the actual testing of the engine for torque and emission at different mixture injection pressures and mixture injection durations at two engine speeds.

In this research the data collection equipment were proven effective. The hydraulic dynamometer was effective at loading the engine through a full range of operating conditions. The load cell was also efficient at providing engine speed and torque data. Hydrogen peroxide emissions, sampling, and the testing method proved effective but were somewhat limited in concentration level discrimination due to color comparison difficulties. The safety precautions effectively eliminated the hazards associated with this type of research and ensured that the potential for accidents was reduced to a minimum.

Thermal management and dry film lubricant coatings appeared effective in some applications at increasing engine durability but failed in the rocker shoe-face application due to ultra-high heat loads. Modifications to the combustion chamber to improve cooling and power production were observed to be effective at reducing combustion chamber temperatures. However, they produced severe condensation that fouled the ignition devices and resulted in unreliable operation, and were thus discontinued. Lightening and clearancing of the rocker improved speed performance and reduced the potential of sticking.

Ignition devices that were used included a multiple discharge electronic ignition and a glow plug. The glow plug, while reliable at igniting the hydrogen-oxygen mixture on bench
tests, failed in operation after only a short time due to the high temperature oxidizing environment found in the combustion chamber. Modifications to the spark plug, along with the multiple discharge electronic ignition, were very effective at totally eliminating cold start problems that plagued earlier research and testing.

The use of a computer-controlled injection and ignition system offered greater flexibility in testing designs and reliability in operation through the use of programming and better sensors. In addition, alterations in the fuel, oxidizer, and water injection systems allowed for greater injection pressures and control.

Conclusions for engine testing based on hypotheses yielded the following findings for engine torque output and emissions.

1. Engine torque output changed as mixture injection pressures changed. Engine torque output increased as mixture injection pressures increased.

2. Engine torque output changed as mixture injection durations changed. The greatest engine torque output was achieved between 180° and 240° closest to 210° of mixture injection duration.

3. Engine torque output changed as engine speed changed. Greater engine torque output occurred at lower engine speeds.

4. Interaction occurred between mixture injection pressures and engine speed for engine torque output. The greatest engine torque output was achieved at high mixture injection pressures and low engine speeds.
5. Hydrogen peroxide exhaust concentration changed as mixture injection pressures changed. The greatest hydrogen peroxide exhaust concentration was achieved between 80/200/80 psi and 140/400/160 psi closest to 110/300/120 psi mixture injection pressure.

6. Hydrogen peroxide exhaust concentration changed as mixture injection durations changed. Hydrogen peroxide exhaust concentration increased as mixture injection durations increased.

7. Hydrogen peroxide exhaust concentration changed as engine speeds changed. Hydrogen peroxide exhaust concentration decreased as engine speed increased.

8. Interaction occurred between mixture injection pressures and engine speeds for hydrogen peroxide exhaust concentration. The greatest hydrogen peroxide exhaust concentration was achieved between 80/200/80 psi and 140/400/160 psi closest to 110/300/120 psi mixture injection pressures for both engine speeds of 500 and 1000 rpm.

Based on the these conclusions, other observation during data collection, and subsequent reviews of related literature and research, recommendations could be made.

**Recommendations**

Based on this research, a few recommendations are suggested to assist future experimentation efforts. The development of the hydrogen-oxygen-fueled roller engine is in its very early stages and much more research is needed to advance this engine concept to a usable level. Generally, investigations should continue to further the development of the hydrogen-oxygen-fueled roller engine.

Further testing should be conducted to determine efficiency characteristics of engine output versus fuel consumption. Efficiency studies should be investigated only after
Improvements are made in the areas of materials, sealing, cooling and lubrication along with improved combustion chamber design. Improvements in materials would include designing and constructing the engine with materials that are more suitable for high temperature oxidizing environments.

While the coatings provided by Tech Line offered improved longevity of engine operation at relatively low cost, they are only a partial solution to the manufacture of a prototype engine suitable for rigorous testing. Improved sealing and separation of engine working chambers would result in better performance and efficiency through reducing pressure losses. Development of cooling and lubrication systems would provide greater run times and increased engine longevity.

An investigation should be conducted to optimize combustion chamber design to yield effective reduction in heat loading while producing low hydrogen peroxide emissions and maintaining hydrogen-oxygen mixture ignition reliability. Improvements should be made in hydrogen, oxygen, and water injectors that would allow greater flow rates and sized such that equal delivery pressures can be used to attain stoichiometric mixture combustion regardless of operating conditions.

Improvements are also suggested for the electronic controls with the incorporation of more sensors to provide the real-time measurement of engine temperature, combustion chamber pressures and exhaust gasses for free hydrogen and oxygen and hydrogen peroxide. These additional sensors and controls would allow for tuning of the engine's mixture as needed for efficient operation.
The final and most important recommendation of this research is to move forward to seek alternative methods of energy production to protect the environment, especially through continued promotion and development of hydrogen as a fuel.
APPENDIX A: DYNAMOMETER CALIBRATION SHEET

Dynamometer Calibration Sheet

Performed by: Jim Ettaro
Date: 5/26/95

Order | Weight g | Weight lb. | Torque in-lb. | Volts |
--- | --- | --- | --- | --- |
1 | 85.8 | 0.189 | 2.270 | 0.07 |
2 | 362.7 | 0.800 | 9.595 | 0.30 |
3 | 641.5 | 1.414 | 16.971 | 0.52 |
4 | 935.7 | 2.053 | 24.754 | 0.76 |
5 | 1210.4 | 2.688 | 32.022 | 0.99 |
6 | 1496.3 | 3.299 | 39.585 | 1.23 |
7 | 1776.3 | 3.916 | 46.993 | 1.46 |
8 | 2069.1 | 4.562 | 54.739 | 1.69 |
9 | 2363.4 | 5.210 | 62.525 | 1.94 |
10 | 2664.7 | 5.875 | 70.496 | 2.18 |
11 | 2936.4 | 6.474 | 77.684 | 2.40 |

Calibration #1

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<tr>
<th>Torque in-lb.</th>
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<th>1.00</th>
<th>1.50</th>
<th>2.00</th>
<th>2.50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
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<td>0.50</td>
<td>1.00</td>
<td>1.50</td>
<td>2.00</td>
</tr>
</tbody>
</table>

Speed

Frequency counter | 60 | 60
| 120 | 120
| 500 | 501
APPENDIX B: DATA COLLECTION SHEET AND SAFETY CHECKLIST

Hydrogen-Oxygen-Fueled Roller Engine Test Sheet

Instructions: Complete form before, during, and after testing
Note any inconsistencies and other observation in the area provided

<table>
<thead>
<tr>
<th>Performed by:</th>
<th>Date:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test No.</td>
<td>Order No.</td>
</tr>
</tbody>
</table>

Hydrogen lines purged

Hydrogen Pressure
Oxygen Pressure
Water Pressure

Torque Load
Volts: Inch-pounds:

Engine Speed
Frequency: RPM:

Density Pressure psi

Hydrogen gas off
Hydrogen line purged
Oxygen gas off
Inert gas off
Electrical off
Battery disconnected
Engine cool

Notes and Observations:
APPENDIX C: MIXTURE INJECTION AND IGNITION PROGRAMS

Hydrogen-Oxygen Fueled Roller Engine Research
Fuel-Oxidizer-Water Injection and Ignition Program
By Jim Ettaro M.S.I.T
Iowa State University/Psycho Research & Development Labs
7/10/96
Revision 5.0
Fires hydrogen injector first then oxygen and water injectors simultaneously
Incorporates a multiple discharge ignition feature
For Use With The Basic Stamp II

thr var word
x var word
y var word
z var word

START:
  high 2 'Discharge throttle position capacitor
  pause 1 'Delay to allow capacitor to discharge
  rctime 2,1,thr 'Measure throttle position

INJ:
  pulsin 0,0,x 'Start injection phase
  if x = 0 then inj 'Wait for timing mark
  high 15 'Hydrogen injector on

IGN:
  pulsin 1,0,y 'Start ignition phase
  if y = 0 then ign 'Wait for timing mark
  high 11 'Fire Ignition Coil! Multiple discharge ignition
  low 15 'Hydrogen- injector off'
  high 14 'Oxygen injector on'
  high 13 'Water injector on'
  pause thr 'Hold injectors on for pulse width
  low 14 'Oxygen injector off'
  low 13 'Water injector off'
  low 11 'Multiple discharge ignition off'

goto start 'return to start of program
'Hydrogen-Oxygen Fueled Roller Engine Research
Fuel-Oxidizer-Water Injection and Ignition Program
'By Jim Ettaro M.S.I.T
'Iowa State University/Psycho Research and Development Labs
'11/20/96
'Revision 6.0
'Fires hydrogen injector first then oxygen and water injectors and ignition simultaneously
'Incorporates a multiple discharge ignition feature
'For Use With The Basic Stamp II

thr var word
x var word
y var word
z var word

START: high 2 'Discharge throttle position capacitor
pause 1 'Delay to allow capacitor to discharge
rctime 2,1,thr 'Measure throttle position

INJ: pulsin 0,0,x 'Start injection phase
if x = 0 then inj 'Wait for timing mark
high 15 'Hydrogen injector on

IGN: pulsin 1,0,y 'Start ignition phase
if y = 0 then ign 'Wait for timing mark
high 11 'Fire Ignition Coil! Multiple discharge ignition

high 14 'Oxygen injector on
high 13 'Water injector on

pause thr 'Hold injectors on for pulse width

low 15 'Hydrogen- injector off
low 14 'Oxygen injector off
low 13 'Water injector off

low 11 'Multiple discharge ignition off

goto start 'return to start of program
'Hydrogen-Oxygen-Fueled Roller Engine Research
'Fuel-Oxidiser-Water Injection and Ignition Program
'By: Jim Ettaro M.S.I.T.
'Iowa State University/Psycho Research and Development Labs
'3/16/97
'Revision 7.0 H2O2P7.BS2
'Fires Hydrogen, oxygen, and water injectors and ignition simultaneously
'Incorporates a multiple discharge ignition feature
'For use with the Basic Stamp II module

x var word
y var word

FIRE: pulsin 0,0,x 'Start injection and ignition
  if x = 0 then FIRE 'wait for timing mark
  high 15 'Hydrogen injector on
  high 14 'Oxygen injector on
  high 13 'Water injector on
  high 11 'Ignition on

DOWN: pulsin 1,0,y 'Stop injection and ignition
  if y = 0 then down 'wait for timing mark
  low 15 'Hydrogen injector off'
  low 14 'Oxygen injector off'
  low 13 'Water injector off'
  low 11 'Ignition off'

goto FIRE
APPENDIX D: ANOVA TABLES FOR ENGINE TEST DATA

### ENGINE TORQUE OUTPUT ANOVA TABLE

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<tr>
<th>Source</th>
<th>D.F.</th>
<th>S.S.</th>
<th>M.S.</th>
<th>F.V.</th>
<th>Pr &gt; F</th>
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</table>

R-Square C.V. Root MSE
0.997 3.78 0.384

### HYDROGEN PEROXIDE EXHAUST EMISSIONS ANOVA TABLE

<table>
<thead>
<tr>
<th>Source</th>
<th>D.F.</th>
<th>S.S.</th>
<th>M.S.</th>
<th>F.V.</th>
<th>Pr &gt; F</th>
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R-Square C.V. Root MSE
0.969 4.98 24.25
### Engine torque output and mixture injection pressures

<table>
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<tr>
<th>Mixture injection pressures</th>
<th>80/200/80</th>
<th>110/300/120</th>
<th>140/400/160</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque (in.lb)</td>
<td>5.8</td>
<td>10.0475</td>
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### Engine torque output and mixture injection durations

<table>
<thead>
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<th>Mixture injection durations</th>
<th>180°</th>
<th>210°</th>
<th>240°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque (in.lb)</td>
<td>9.724</td>
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<td>9.121</td>
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### Engine torque output and engine speeds

<table>
<thead>
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<th>Engine speed (rpm)</th>
<th>500</th>
<th>1000</th>
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</thead>
<tbody>
<tr>
<td>Torque (in.lb)</td>
<td>13.661</td>
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### Torque for mixture injection pressures and engine speeds

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<th>110/300/120</th>
<th>140/400/160</th>
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</thead>
<tbody>
<tr>
<td>500 rpm</td>
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<td>7.217</td>
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### Hydrogen peroxide concentration and mixture injection pressures

<table>
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<th>Mixture injection pressures</th>
<th>80/200/80</th>
<th>110/300/120</th>
<th>140/400/160</th>
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</thead>
<tbody>
<tr>
<td>$\text{H}_2\text{O}_2$ (ppm)</td>
<td>437.5</td>
<td>575</td>
<td>445.8</td>
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</table>

### Hydrogen peroxide concentration and mixture injection durations

<table>
<thead>
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<th>Mixture injection durations</th>
<th>180°</th>
<th>210°</th>
<th>240°</th>
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</thead>
<tbody>
<tr>
<td>$\text{H}_2\text{O}_2$ (ppm)</td>
<td>445.8</td>
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### Hydrogen peroxide concentrations and engine speeds

<table>
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<th>Engine speed (rpm)</th>
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<tr>
<td>$\text{H}_2\text{O}_2$ (ppm)</td>
<td>536.1</td>
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### Hydrogen peroxide concentration interaction for mixture injection pressures and engine speeds

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<td></td>
<td>80/200/80</td>
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<tr>
<td>500 rpm</td>
<td>516.7</td>
</tr>
<tr>
<td>1000 rpm</td>
<td>358.3</td>
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Raw data for hydrogen-oxygen-fueled roller engine

<table>
<thead>
<tr>
<th>Rep</th>
<th>RPM obs</th>
<th>RPM</th>
<th>Pressure</th>
<th>Duration</th>
<th>Torque(volts)</th>
<th>Torque (in. lb.)</th>
<th>H2O2 (ppm)</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>511</td>
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