

ADVANCED INTERNAL COMBUSTION ENGINE RESEARCH

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Abstract

In this manuscript, research on hydrogen internal combustion engines is discussed. The objective of this project is to provide a means of renewable hydrogen based fuel utilization. The development of a high efficiency, low emissions electrical generator will lead to establishing a path for renewable hydrogen based fuel utilization. A full-scale prototype will be produced in collaboration with commercial manufacturers.

The electrical generator is based on developed internal combustion engine technology. It is able to operate on many hydrogen-containing fuels. The efficiency and emissions are comparable to fuel cells (50% fuel to electricity, ~ 0 NO_x). This electrical generator is applicable to both stationary power and hybrid vehicles. It also allows specific markets to utilize hydrogen economically and painlessly.

Introduction

Two motivators for the use of hydrogen as an energy carrier today are: 1) to provide a transition strategy from hydrocarbon fuels to a carbonless society and 2) to enable renewable energy sources. The first motivation requires a little discussion while the second one is self-evident. The most common and cost effective way to produce hydrogen today is the reformation of hydrocarbon fuels, specifically natural gas. Robert Williams discusses the cost and viability of natural gas reformation with CO₂ sequestration as a cost-effective way to reduce our annual CO₂ emission levels. He argues that if a hydrogen economy was in place then the additional cost of natural gas reformation and subsequent CO₂ sequestration is minimal (Williams 1996).

Decarbonization of fossil fuels with subsequent CO₂ sequestration to reduce or eliminate our CO₂ atmospheric emissions provides a transition strategy to a renewable, sustainable, carbonless society. However, this requires hydrogen as an energy carrier.

The objectives of this program for the year 2000 are to continue to design, build, and test the advanced electrical generator components, research hydrogen based renewable fuels, and develop industrial partnerships. The rationale behind the continuation of designing, building, and testing generator components is to produce a research prototype for demonstration in two years. Similarly, researching hydrogen based renewable fuels will provide utilization components for the largest possible application. Finally, developing industrial partnerships can lead to the transfer of technology to the commercial sector as rapidly as possible.

This year work is being done on the linear alternator, two-stroke cycle scavenging system, electromagnetic/combustion/dynamic modeling, and fuel research. The Sandia alternator design and prototype will be finished, and the Sandia and Magnequench designs will be tested. Work on the scavenging system consists of learning to use KIVA-3V, and designing the scavenging experiment. Ron Moses of Los Alamos National Laboratories is conducting the modeling; modeling of the alternator is being performed. Hydrogen based renewables, such as biogas and ammonia, are the fuels being researched. Outside of modeling and research, an industrial collaboration has been made with Caterpillar and Magnequench International, a major supplier of rare earth permanent magnet materials. A collaborative research and development agreement (CRADA) has been arranged with Caterpillar, and Magnequench is designing and supplying a linear alternator. In addition, the prestigious Harry Lee Van Horning Award presented by the Society of Automotive Engineers (SAE) was awarded in October 1999 for a paper concerning homogeneous charge compression ignition (HCCI) with a free piston (SAE 982484).

Background

Electrical generators capable of high conversion efficiencies and extremely low exhaust emissions will no doubt power advanced hybrid vehicles and stationary power systems. Fuel cells are generally considered to be ideal devices for these applications where hydrogen or methane are used as fuel. However, the extensive development of the IC engine, and the existence of repair and maintenance industries associated with piston engines provide strong incentives to remain with this technology until fuel cells are proven reliable and cost competitive. In addition, while the fuel cell enjoys high public relations appeal, it seems possible that it may not offer significant efficiency advantages relative to an optimized combustion system. In light of these factors, the capabilities of internal combustion engines have been reviewed.

In regards to thermodynamic efficiency, the Otto cycle theoretically represents the best option for an IC engine cycle. This is due to the fact that the fuel energy is converted to heat at constant volume when the working fluid is at maximum compression. This combustion condition leads to the highest possible peak temperatures, and thus the highest possible thermal efficiencies.

Edson (1964) analytically investigated the efficiency potential of the ideal Otto cycle using compression ratios (CR) up to 300:1, where the effects of chemical dissociation, working fluid

thermodynamic properties, and chemical species concentration were included. He found that even as the compression ratio is increased to 300:1, the thermal efficiency still increases for all of the fuels investigated. At this extreme operating for instance, the cycle efficiency for isoctane fuel at stoichiometric ratio is over 80%.

Indeed it appears that no fundamental limit exists to achieving high efficiency from an internal combustion engine cycle. However, many engineering challenges are involved in approaching ideal Otto cycle performance in real systems, especially where high compression ratios are utilized.

Caris and Nelson (1959) investigated the use of high compression ratios for improving the thermal efficiency of a production V8 spark ignition engine. They found that operation at compression ratios above about 17:1 did not continue to improve the thermal efficiency in their configuration. They concluded that this was due to the problem of non-constant volume combustion, as time is required to propagate the spark-ignited flame.

In addition to the problem of burn duration, other barriers exist. These include the transfer of heat energy from the combustion gases to the cylinder walls, as well as the operating difficulties associated with increased pressure levels for engines configured to compression ratios above 25:1 (Overington and Thring 1981, Muranaka and Ishida 1987). Still, finite burn duration remains the fundamental challenge to using high compression ratios.

The goal of emissions compliance further restricts the design possibilities for an optimized IC engine. For example, in order to eliminate the production of nitrogen oxides (NO_x), the fuel/air mixture must be homogeneous and very lean at the time of combustion (Das 1990, Van Blarigan 1995). (It is subsequently possible to use oxidation catalyst technologies to sufficiently control other regulated emissions such as HC and CO.) Homogeneous operation precludes diesel- type combustion, and spark-ignition operation on premixed charges tends to limit the operating compression ratio due to uncontrolled autoignition, or knock. As well, very lean fuel/air mixtures are difficult, or impossible to spark ignite.

On the other hand, lean charges have more favorable specific heat ratios relative to stoichiometric mixtures, and this leads to improved cycle thermal efficiencies. Equivalence ratio is no longer required to be precisely controlled, as is required in conventional stoichiometric operation when utilizing tree way catalysts. Equivalence ratio is defined here as the ratio of the actual fuel/air ratio to the stoichiometric ratio.

Combustion Approach

Homogeneous charge compression ignition combustion could be used to solve the problems of burn duration and allow ideal Otto cycle operation to be more closely approached. In this combustion process a homogeneous charge of fuel and air is compression heated to the point of autoignition. Numerous ignition points throughout the mixture can ensure very rapid combustion (Onishi et al 1979). Very low equivalence ratios ($\phi \sim 0.3$) can be used since no flame propagation is required. Further, the useful compression ratio can be increased as higher temperatures are required to autoignite weak mixtures (Karim and Watson 1971).

HCCI operation is unconventional, but is not new. As early as 1957 Alperstein et al. (1958) experimented with premixed charges of hexane and air, and n-heptane and air in a Diesel engine. They found that under certain operating conditions their single cylinder engine would run quite well in a premixed mode with no fuel injection whatsoever.

In general, HCCI combustion has been shown to be faster than spark ignition or compression ignition combustion. And much leaner operation is possible than in SI engines, while lower NO_x emissions result.

Most of the HCCI studies to date however, have concentrated on achieving smooth releases of energy under conventional compression condition (CR ~ 9:1). Crankshaft driven pistons have been utilized in all of these previous investigations. Because of these operating parameters, successful HCCI operation has required extensive EGR and/or intake air preheating. Conventional pressure profiles have resulted (Thring 1989, Najt and Foster 1983).

In order to maximize the efficiency potential of HCCI operation much higher compression ratios must be used, and a very rapid combustion event must be achieved. Recent work with higher compression ratios (~21:1) has demonstrated the high efficiency potential of the HCCI process (Christensen et al 1998, Christensen et al 1997).

In Figure 1, the amount of work attained from a modern 4-stroke heavy duty diesel engine is shown at a 16.25 : 1 compression ratio. The results show that under ideal Otto cycle conditions (constant volume combustion), 56% more work is still available. This extreme case of non-ideal Otto cycle behavior serves to emphasize how much can be gained by approaching constant volume combustion.

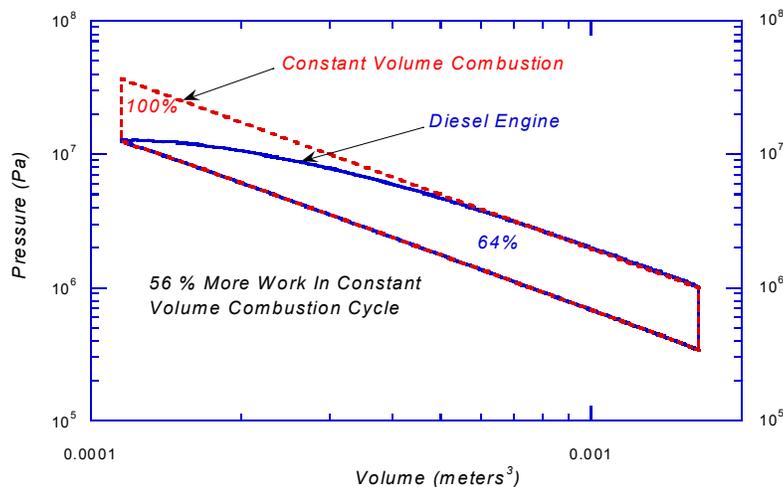


Figure 1 – Modern 4-Stroke Heavy Duty Diesel Engine

Engineering Configuration

The free piston linear alternator illustrated in Figure 2 has been designed in hopes of approaching ideal Otto cycle performance through HCCI operation. In this configuration, high compression ratios can be used and rapid combustion can be achieved.

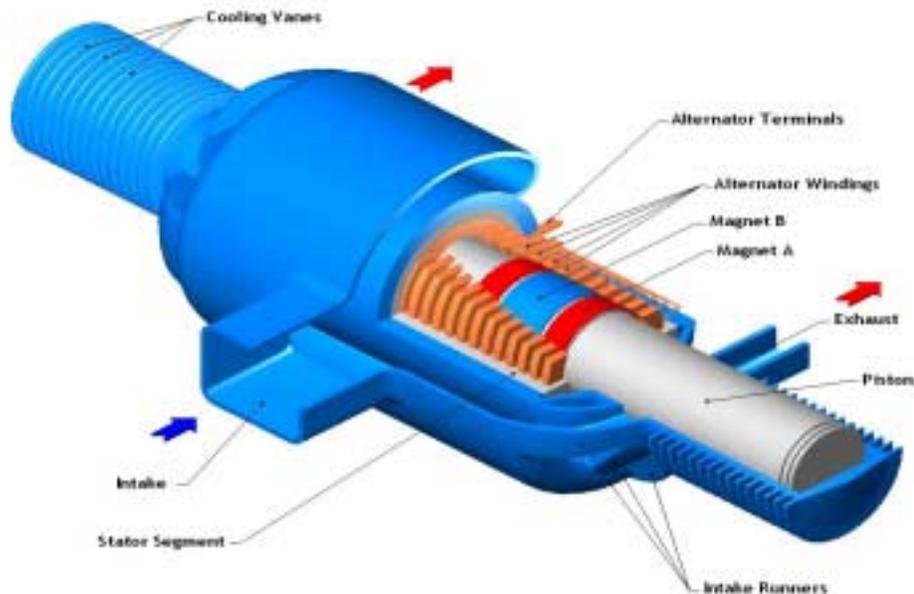


Figure 2 – Free piston linear alternator

The linear generator is designed such that electricity is generated directly from the piston's oscillating motion, as rare earth permanent magnets fixed to the piston are driven back and forth through the alternator's coils. Combustion occurs alternately at each end of the piston and a modern two-stroke cycle scavenging process is used. The alternator component controls the piston's motion, and thus the extent of cylinder gas compression, by efficiently managing the piston's kinetic energy through each stroke. Compression of the fuel/air mixture is achieved inertially and as a result, a mechanically simple, variable compression ratio design is possible with sophisticated electronic control.

The use of free pistons in internal combustion engines has been investigated for quite some time. In the 1950's, experiments were conducted with free piston engines in automotive applications. In these early designs, the engine was used as a gasifier for a single stage turbine (Underwood 1957, Klotsch 1959). More recent developments have integrated hydraulic pumps into the engine's design (Baruah 1988, Achten 1994).

Several advantages have been noted for free piston IC engines. First, the compression ratio of the engine is variable; this is dependent mainly on the engine's operating conditions (e.g., fuel type, equivalence ratio, temperature, etc.). As a result, the desired compression ratio can be achieved through modification of the operating parameters, as opposed to changes in the engine's hardware.

An additional benefit is that the mechanical friction can be reduced relative to crankshaft driven geometries since there is only one moving engine part and no piston side loads. Also, combustion seems to be faster than in conventional slider-crank configurations. Further, the unique piston dynamics (characteristically non-sinusoidal) seem to improve the engine's fuel economy and NO_x emissions by limiting the time that the combustion gases spend at top dead center (TDC) (thereby reducing engine heat transfer and limiting the NO_x kinetics). Finally, one researcher (Braun 1973) reports that the cylinder/piston/ring wear characteristics are superior to slider/crank configurations by a factor of 4.

The combination of the HCCI combustion process and the free piston geometry is expected to result in significant improvements in the engine's thermal efficiency and its exhaust emissions. The following advantages should be found:

1. For a given maximum piston velocity, the free piston arrangement is capable of achieving a desired compression ratio more quickly than a crankshaft driven piston configuration. This point is illustrated in Figure 3 where the piston position profiles of both configurations are plotted. The reduced compression time should result in higher compression of the premixed charge before the onset of autoignition.

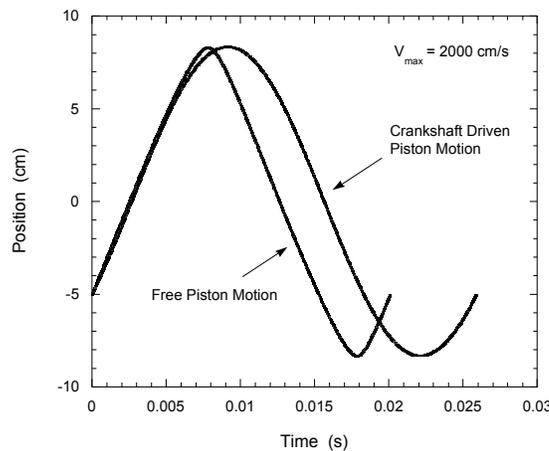


Figure 3 – Piston position vs. time

2. High compression ratio operation is better suited to the free piston engine since the piston develops compression inertially, and as such there are no bearings or kinematic constraints that must survive high cylinder pressures or the high rates of pressure increase (shock). The use of low equivalence ratios in the HCCI application should further reduce the possibility of combustion chamber surface destruction (Lee and Schaefer 1983, Maly et al 1990).
3. The free piston design is more capable of supporting the low IMEP levels inherent in low equivalence ratio operation due to the reduction in mechanical friction.

Integration of the linear alternator into the free piston geometry provides further benefits to the generator design. In this arrangement mechanical losses in the system are dramatically reduced since there is essentially one moving part, and this allows engine operation at a more or less constant piston speed. These points aid in the generator design, and further improve the fuel-to-electricity generation efficiency of the device.

The linear alternator itself is based on technology developed for brushless DC motors. This class of motors is characterized by high efficiency and high power density, typically 96% efficiency and 1 hp per pound density. Put simply, the rotary configuration is unrolled until flat, then rolled back up perpendicular to the first unrolling to arrive at the linear configuration. Relative to the rotary geometry the linear device is approximately 30% heavier due to not all of the coils being driven at the same time. Efficiency will be comparable.

2-Stroke Cycle

Inherent in the configuration selected is the need to scavenge the exhaust gases out of the cylinder and replace them with fresh fuel/air charge while the piston is down at the bottom of the cylinder. This requirement is due to the need to have trapped gases in the cylinder to act as a spring, as well as to provide the next combustion event.

Conventional 2-stroke cycle engines have developed a reputation for low fuel efficiency and high hydrocarbon emissions due to short-circuiting of the inlet fuel/air mixture directly to the exhaust port. The typical 2-stroke application stresses power density over efficiency and emissions – chain saws, weed whackers, marine outboard motors. These devices must operate over a wide speed and power range.

In this case the requirements are quite different. The speed of the free piston oscillation is essentially fixed. Power is varied by modification of the equivalence ratio, not the quantity of gas delivered. Power density is not a driving requirement. As a result, the design of this system can be optimized within tight constraints utilizing computational fluid dynamics and experimental gas dynamics techniques.

Experimental Results - FY 2000

Figure 4 shows the results of experimental combustion studies completed with hydrogen. In this investigation, a single-stroke rapid compression-expansion machine has been used to compression ignite hydrogen. Hydrogen is the fastest burning fuel out of all the fuels tested. The high rate of combustion does approach constant volume combustion. Figure 3 shows a typical logarithmic P/V diagram for hydrogen combustion at top dead center at 33:1 compression ratio. The piston has, for all practical purposes, not moved during the combustion event. In the free piston configuration high pressure-rise rates can be handled without difficulty since there are no load bearing linkages, as in crankshaft-driven engines. Additionally, operation at equivalence ratios less than 0.5 reduces the need to consider piston erosion, or other physical damage (Maly et al. 1990).

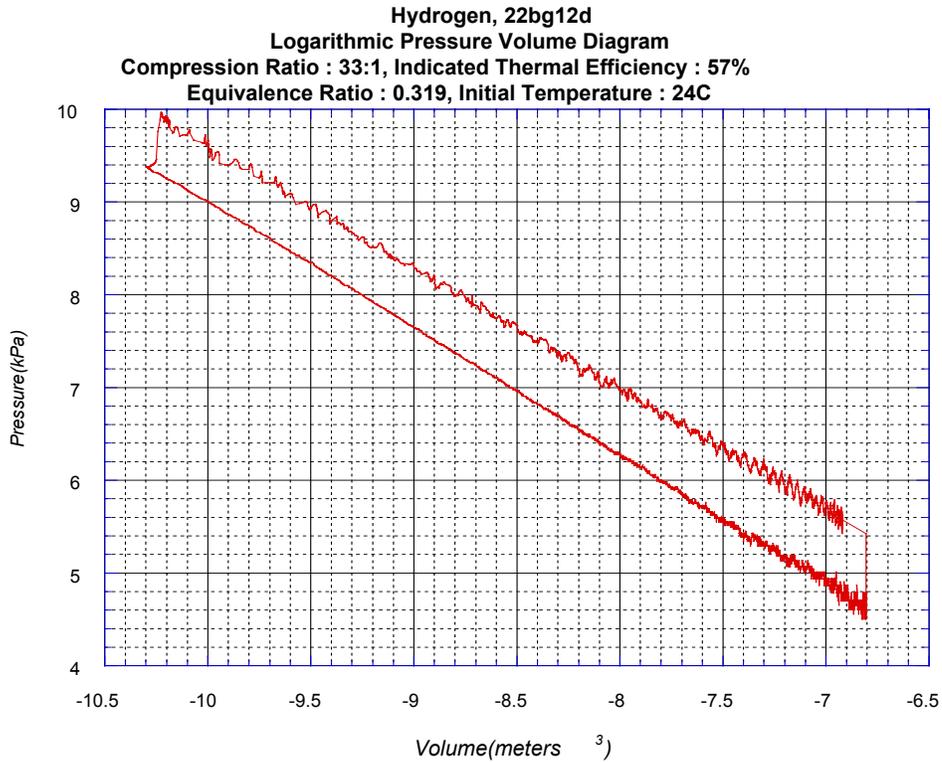


Figure 4 - Hydrogen Combustion

Figure 5 shows the free piston generator again. The overall length of the generator is 76 centimeters, its specific power is 800 watts per kilogram, and it has a power density of 800 watts per liter. Hydrogen based renewable fuels such as bio-gas (low BTU producer gas H_2-CH_4-CO), ammonia (NH_3), methanol (CH_4O), and/or hydrogen (H_2) can be used directly.

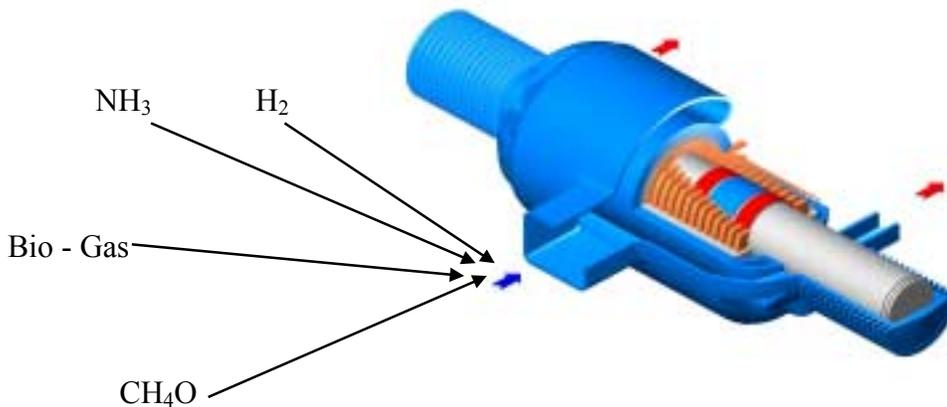


Figure 5 – Free Piston Generator

The alternator consists of moving rare earth permanent magnets and stationary output coils and stator laminations. The design is similar to a conventional rotary brushless DC generator.

Figure 6 shows the magnetic flux path for the linear alternator. It can be seen that the flux through the coils changes direction as the permanent magnet assembly moves down the alternator core. This changing flux induces current in the coils.

Two parallel paths are being pursued to develop the linear alternator. An alternator is being built and tested in house. As a design tool, we are utilizing a two dimensional finite element computer code to solve Maxwell's equations of electromagnetism. The code, called FLUX2D, is produced by MagSoft Corporation. We have investigated various design configurations, and have optimized a design with respect to maximizing efficiency and minimizing size. In parallel Magnequench, a commercial development partner, is also designing and fabricating an alternator. Both alternator designs are being fabricated and will be tested under full design output conditions on a Sandia designed Caterpillar engine based tester. The tester will measure both power output and mechanical to electrical conversion efficiency.

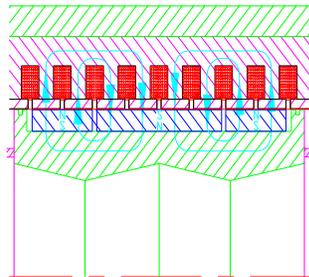
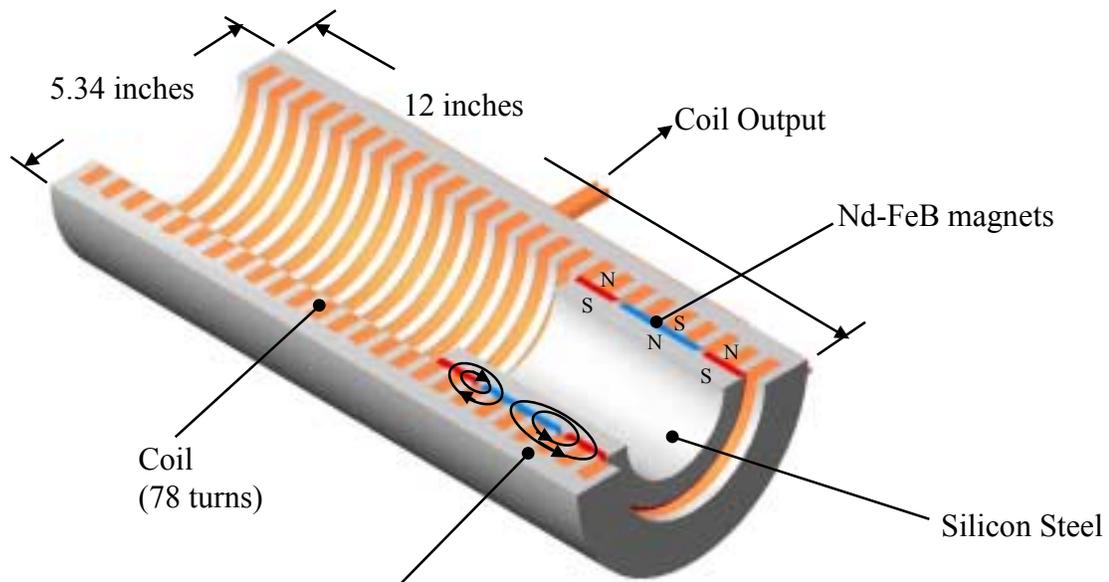


Figure 6 – Alternator Design



Figure 7 – Magnequench Linear Alternator Stator Assembly

Magnequench has delivered three stator assemblies to Sandia, one of which is shown in Figure 7. Also shown in Figure 7 are a short and a long magnet ring. These magnets are pressed from neodymium-iron-boron rare earth material and magnetized in the radial direction. Sandia will assemble the Magnequench supplied magnets to the moving part back iron and provide linear bearing supports. One assembly will then be returned to Magnequench for their own testing.



Power Output : 40kW
 Efficiency : 96%
 Weight 60 pounds

Oriented Grain Silicon steel Laminations
 (1600 each)

Figure 8 – Sandia Linear Alternator Design

Figure 8 shows a cut away of the Sandia alternator design. The power output of the linear alternator is 40 kW, and has an efficiency of 96%. The Magnequench design is very similar; the differences are primarily in the coil configuration, magnet fabrication and stator material. The Sandia magnet assembly is fabricated from 10 degree arc magnet segments, which are magnetized in a linear direction.

The Sandia stator is an assembly of 1600 laminations punched from anisotropic oriented grain silicon steel. Each lamination has a small angle ground so the assembly stacks into a cylinder. The Magnequench stator material is pressed iron powder in an adhesive matrix.

The Magnequench coils consist of a single row winding of flat wire. The Sandia coils contain 78 turns of square cross section wire. The Magnequench coils must be connected in moving groups of five as the magnet assembly moves in the stator. The Sandia design isolates each coil from the other coils with a Wheatstone bridge. This has the advantage of not requiring an active magnet assembly following switching network.

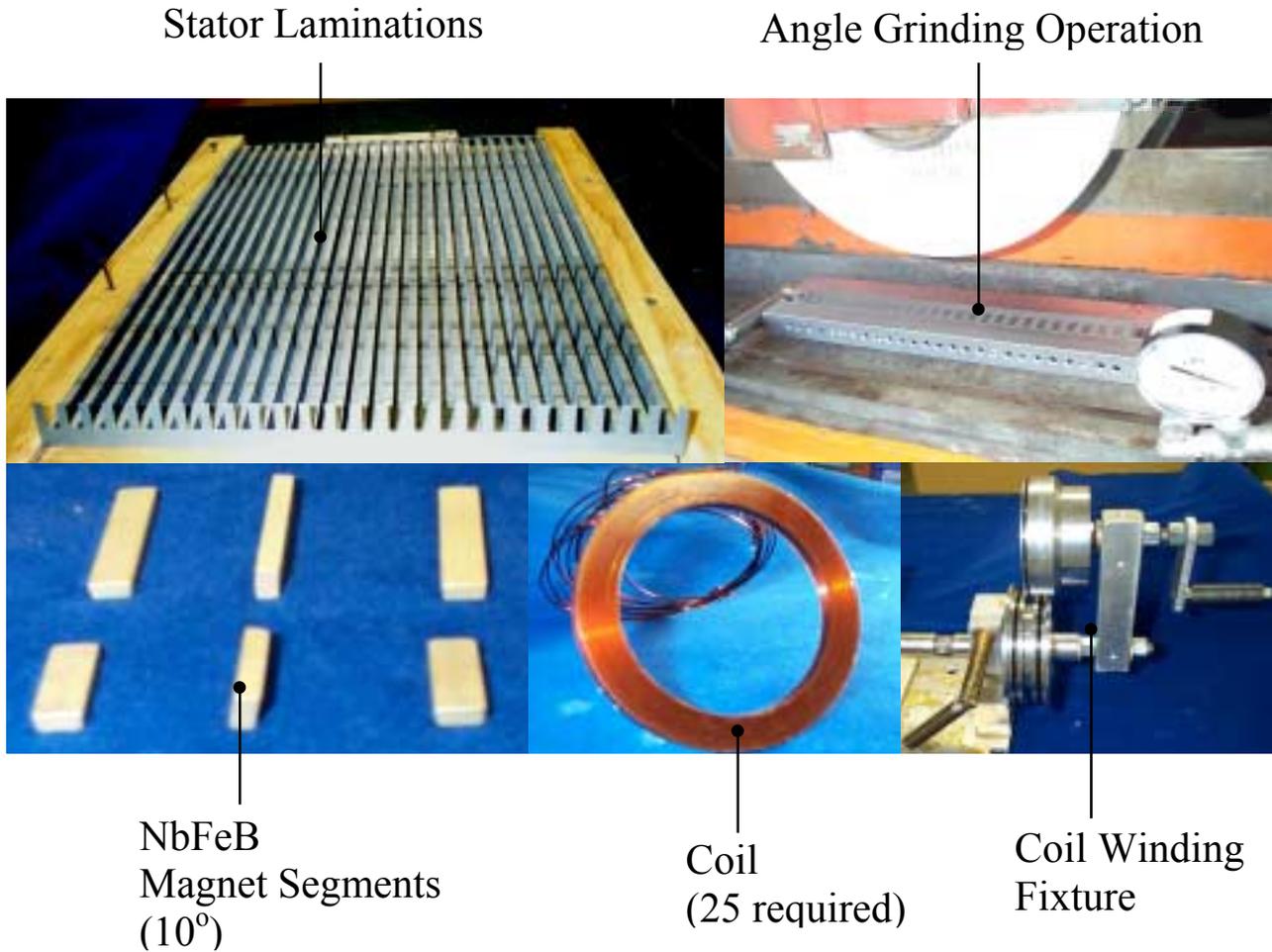


Figure 9 – Linear Alternator Design Components

Some of the components and fabrication tools for the Sandia linear alternator are shown in Figure 9.

Alternator Modeling

In preparation for designing the generator control algorithms a comprehensive mathematical model of the entire physical system is required. One of the challenging aspects of the system model is the electromagnetic performance of the linear alternator. The finite element model (FLUX2D) utilized in the design process is too cumbersome for use in a real time system model.

To circumvent this situation we have contracted with Ron Moses of Los Alamos National Laboratory to derive a simplified alternator model. Ron is an expert in electromagnetic systems and excited to be part of our project team. We intend to have Ron develop, with our input, a total system model capable of predicting control system response.

Two Stroke-Cycle Scavenging System Design

Conventional two-stroke cycle engines are designed to maximize power density at the expense of efficiency and emissions. They also must operate over a wide speed and power range.

Our design intent is to maximize efficiency while minimizing emissions at a narrow power output operating condition. As a result, the configuration of the scavenging ports and operating pressures is likely to be unique to this design.

Our approach is to utilize KIVA-3V to design the scavenging system and to validate the KIVA-3V predictions at selected conditions. Towards this goal we have designed an add-on scavenging experiment for our free piston combustion test facility. Figure 10 shows the scavenging experiment on the upper left side connected to the existing combustion experiment on the lower right side. The experiment will reproduce combustion cylinder pressure and temperature conditions immediately prior to scavenging port opening and replicate piston motion during one scavenging cycle. By measuring gases in the cylinder and in the exhaust collector we will be able to discern trapping efficiency and scavenging efficiency during realistic operating conditions.

Figures 11 and 12 show the KIVA-3V modeling results for one particular configuration being investigated. We are striving to design a loop scavenged flow system due to the simplicity it possesses. We are also designing a uniflow system with an exhaust valve in the cylinder head. This approach is thought to be a more confident solution from a fluid mechanics viewpoint.

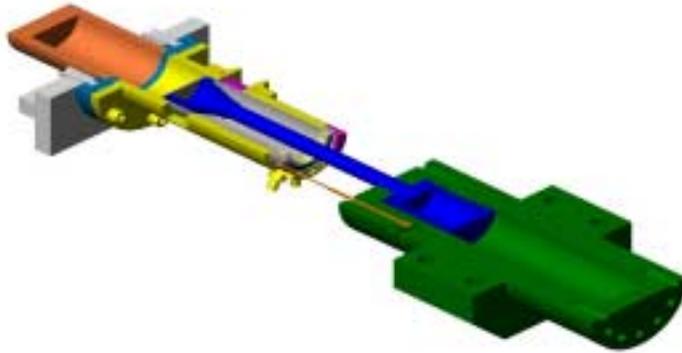


Figure 10 – Scavenging Experiment

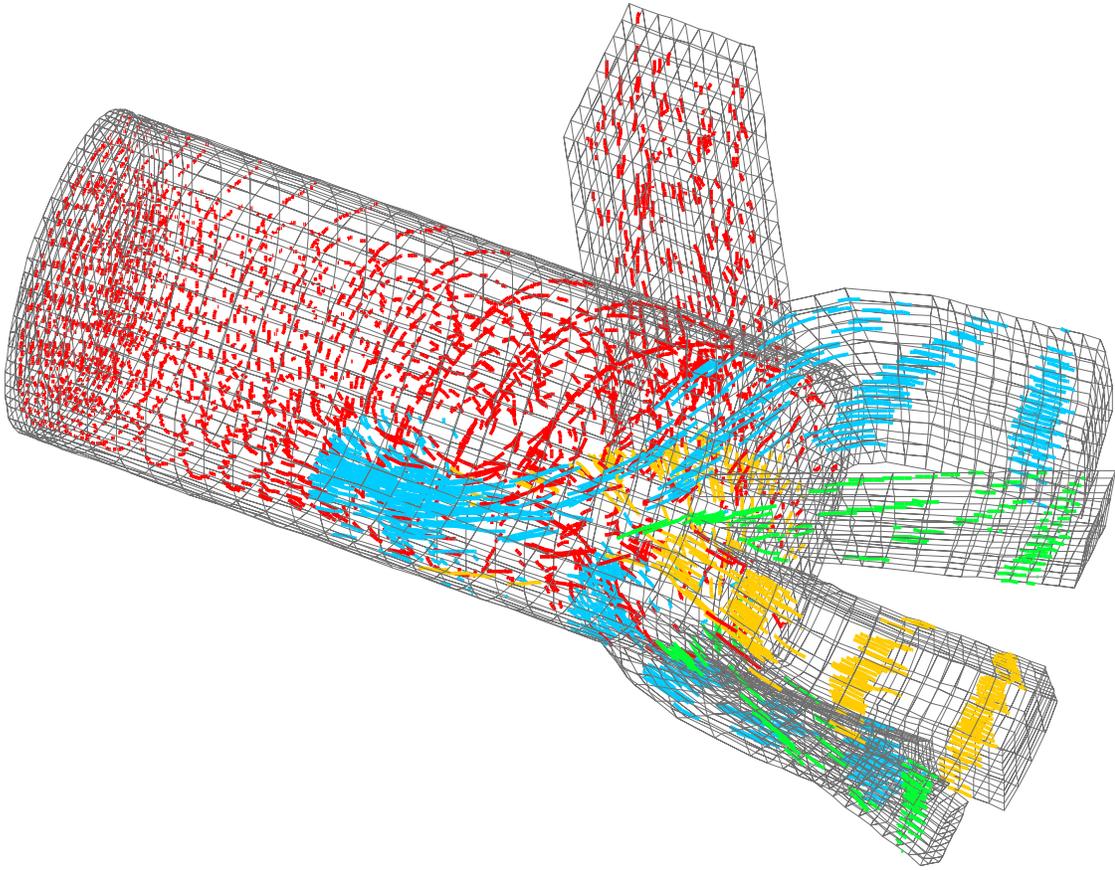


Figure 11 – KIVA-3V flow pictorial

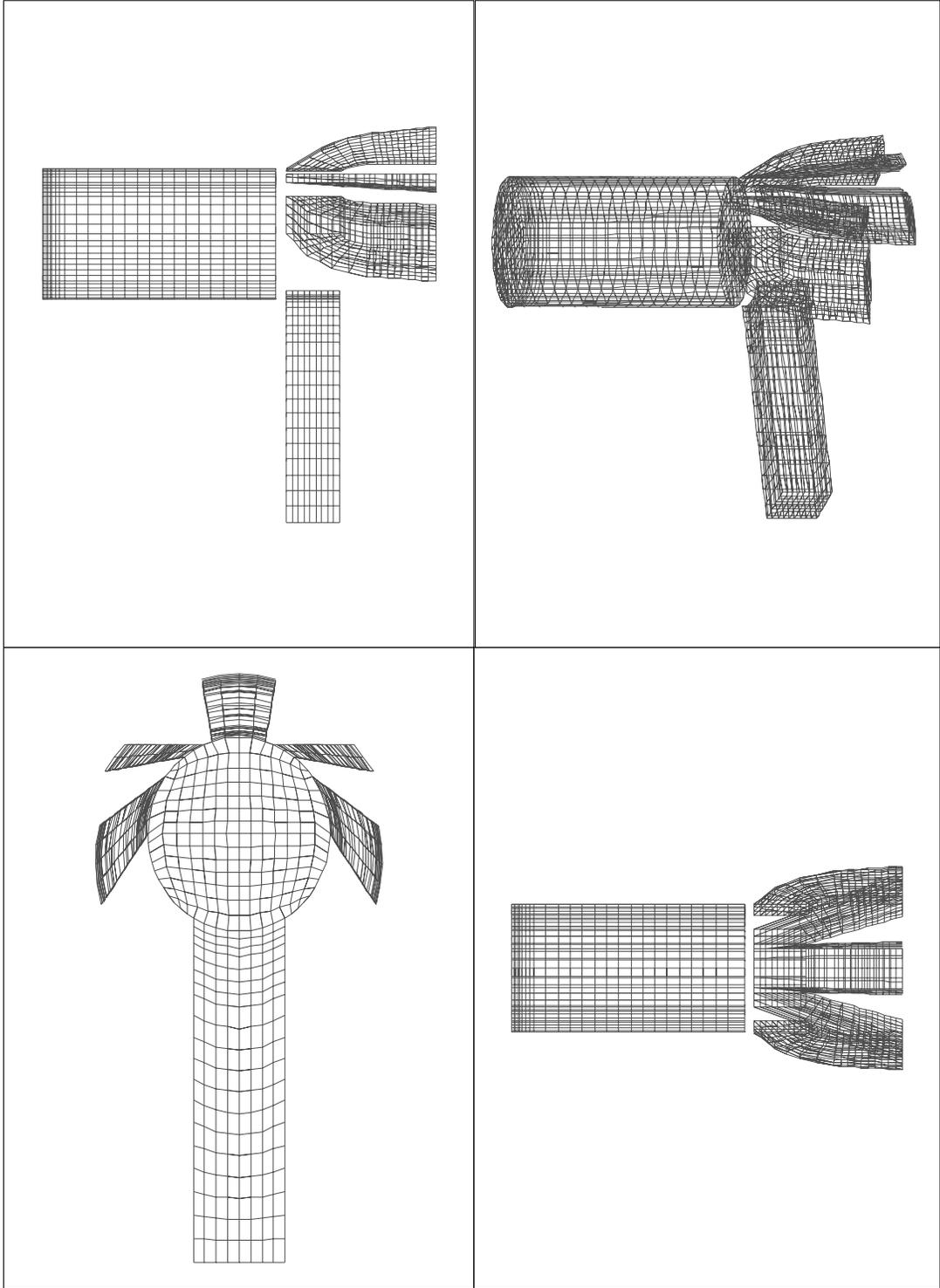


Figure 12 – KIVA-3V grid

Hydrogen Based Renewable Fuels

Bio-gas

One of the unique characteristics of HCCI combustion with a free piston is the ability to combust extremely lean mixtures. In the field of gasification of biomass the simplest approach is to combust the material in an oxygen-starved environment. The resultant gas is a mixture of hydrogen, carbon monoxide, carbon dioxide, methane, and nitrogen. The mixture is too lean for utilization in spark-ignition engines and requires a pilot diesel fuel injection when fumigated into a diesel engine.

Figure 13 shows the results of combustion of a typical low BTU producer gas as would be produced from a crude gasifier as would be found in a developing country. The formulation was kindly supplied by William Hauserman of Hauserman Associates. The results indicate excellent performance in the free piston experiment. In fact, this lean mixture is ideal for achieving the NO_x control our concept is based upon.

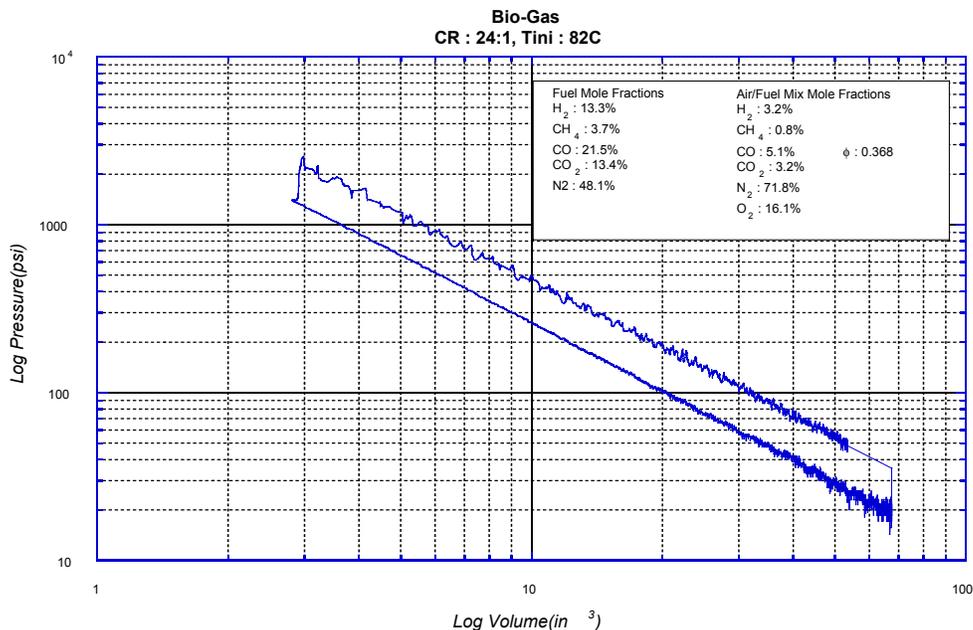


Figure 13 – Bio-gas Ideal Otto Cycle Performance

Ammonia

The two most challenging aspects of widespread hydrogen application are the storage of hydrogen for mobile applications and the distribution infrastructure. In the United States approximately 1,000,000 farms have access to anhydrous ammonia. The distribution infrastructure already exists to deliver approximately 8 billion pounds of anhydrous ammonia to

these farms for direct use as a nitrogen soil supplement. The farmers are already handling anhydrous ammonia and could easily use it as a fuel for their farm equipment if an efficient utilization device was available.

In Figure 14, the combustion of ammonia exhibits ideal Otto cycle performance in our free piston combustion experiment, and produces conversion efficiencies comparable to hydrogen (see Figure 15). Ammonia is an ideal hydrogen based renewable fuel to use in our free piston generator for several reasons. Ammonia is widely available. 35,000,000,000 pounds of anhydrous ammonia are produced in the United States per year. Ammonia contains no carbon, and can be easily made from hydrogen or natural gas.

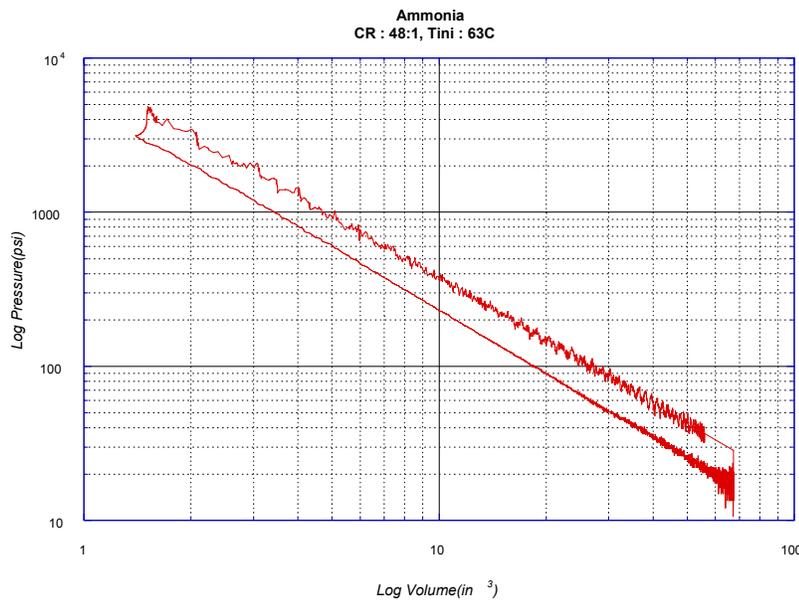


Figure 14 – Ammonia Ideal Otto Cycle Performance

Anhydrous ammonia is stored in the same manner as propane, as a liquid under approximately 100 pounds per square inch vapor pressure at room temperature. If released into the atmosphere, ammonia's density is lighter than that of air and thus dissipates rapidly. In addition, because of its characteristic smell the nose easily detects it in concentrations as low as 5 ppm. Finally, ammonia has such a narrow flammability range that it is generally considered non-flammable when transported.

Ammonia is comparable to gasoline as a fuel for combustion engines. Three gallons of ammonia is equivalent to one gallon of gasoline in energy content. In other terms, 2.35 pounds of ammonia is equivalent to one pound of gasoline in energy content. Cost wise in 1998, bulk ammonia was \$1.13 per gallon gasoline equivalent.

In using ammonia as a fuel, ammonia and air would enter the free piston generator through the intake port. After combustion, any generated NO_x emissions can be readily reduced by reaction with ammonia over a zeolite according to one of the following two reactions:

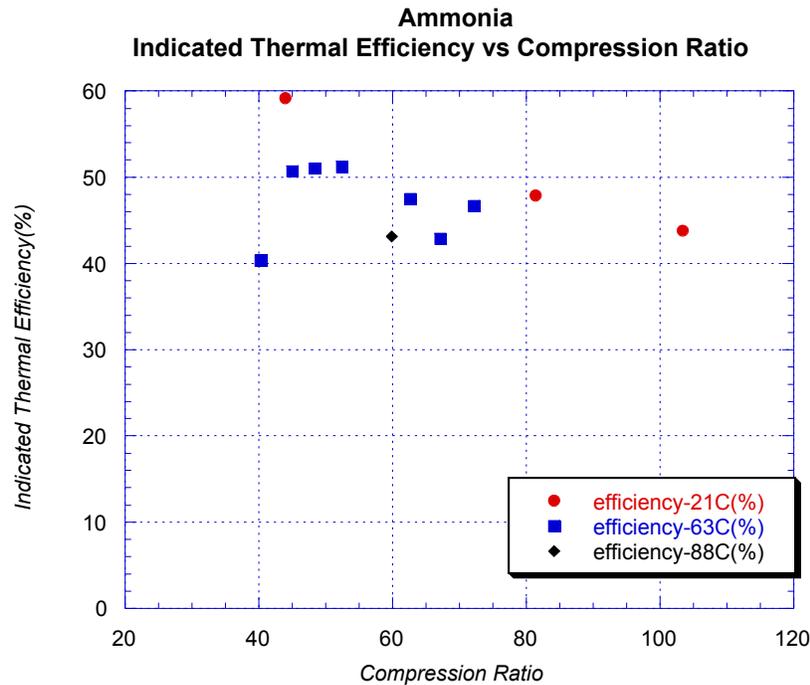
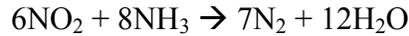
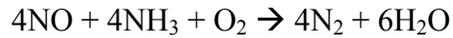


Figure 15 – Ammonia Combustion

Industrial Collaboration

As previously discussed Magnequench International, Incorporated is supplying a linear alternator at no cost in order to develop new applications for rare earth permanent magnets. In addition, Caterpillar Corporation is entering into a cooperative research and development agreement (CRADA) with our group. The purpose of the collaboration is for CAT to share their free piston lubrication and sealing technology with Sandia while in return applying our linear alternator technology to their free piston hydraulic pump program.

Both of these collaborations will ease the transfer of this exciting new technology to the industrial sector.

Future Work

Plans for the 2001 fiscal year include completing the two-stroke scavenging system design, developing a comprehensive system model, designing a prototype starting system, investigating alternative funding, and quantifying performance of both alternator designs. The principal

objectives are to select a prototype scavenging system, obtain a predictive model of electrical and mechanical components, select a starting system, and collaborate with industrial partners in pursuing other funding.

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