

# **Exploration of a Fuel Cell/Internal Combustion Engine Combined Cycle for High Efficiency Power Generation (A GCEP Exploratory Project)**

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## **Abstract**

This research explored the objective of demonstrating how engines of a size suitable for transportation and/or distributed generation can be made at efficiencies exceeding 70% (LHV). The approach stemmed from the realization, developed via detailed system modeling, that even the most advanced internal combustion engine (ICE) configurations—configurations that include use of thermal barrier coatings, optimal expansion, and even bottoming or regenerative cycles—cannot achieve efficiencies higher than the mid 60% range. Similarly, although it is possible for very lightly loaded fuel cell systems to achieve 70% efficiency, they have challenges associated with their fuel requirements, and are not capable of achieving high efficiency at high load. As load increases fuel cell efficiency declines significantly, often dropping below 40% at peak load.

The approach we followed was to seek a combination of ICE and fuel cell technologies, taking advantage of the complementary, and even synergistic, nature of these two approaches. Piston-based ICE technology is inexpensive and can produce high efficiencies if properly configured. It also has the intrinsic characteristic that efficiency improves as load is increased—providing a natural complement to the fuel cell. In addition, we have demonstrated that if a rich combustion system is chosen for at least part of the ICE, it can be used as a quick-start syngas generator (coupled with a shift reactor) to provide hydrogen for a fuel cell. At the same time, the overall system architecture provides both the balance of plant needed to efficiently support the electrochemical conversion in the fuel cell and to provide near-optimal exergy extraction from the overall system. In effect, we are adding electrochemical conversion to the suite of technologies available from which an ultra-high efficiency engine system can be synthesized.

In the exploratory phase of this research, we used systems-level modeling to understand how to span the space and determine what is possible in configuring a fuel cell/ICE combined cycle. We were able to determine how well each technology can be adapted for our purpose and the complications that might arise from interfacing these devices. We have experimentally explored rich combustion of methanol, ethanol, and gasoline and measured the resulting syngas levels up to the point of combustion stability or noticeable soot emissions. A high-temperature (iron-chrome based catalyst) water-gas-shift reactor has been designed and built to reduce exhaust gas CO and allow for fuel cell testing of actual shifted engine exhaust gas. A high temperature PEM (HTPEM) fuel cell of the type produced by BASF has been designed and is being implemented for testing with our shifted rich engine exhaust gas and to demonstrate a completely coupled system – engine through shift reactor to fuel cell.

## Introduction

Achieving efficient engine operation is one of the clearest, most economical paths to mitigation of greenhouse gas (GHG) emissions. Consumption of significantly less fuel per unit of work provides a method of GHG mitigation that is immediately attractive to consumers, and therefore requires no incentives other than individuals acting in self-interest.

When it comes to engines used for transportation and distributed generation (< 500 kW output), piston engines dominate since gas turbines of such a small size are significantly less efficient than their larger counterparts. Similarly, use of fuel cells has been and is continuing to be investigated for this size range, but cost has been shown to be a challenge given current levels of efficiency (~50% to electricity for the Bloom box). The goal of this research is to determine if an efficient, transportation-scale engine could be developed by combining an internal combustion engine with a fuel cell.

Figure 1a shows the results of an exergy analysis of two modern transportation engines operating at their most efficient conditions [1]. The engine to the left is a spark-ignited engine using gasoline as fuel and achieving 36% for its peak exergy efficiency (38% LHV). The engine to the right is a turbo-charged Diesel of comparable output, achieving a peak exergy efficiency of 41% (43% LHV).

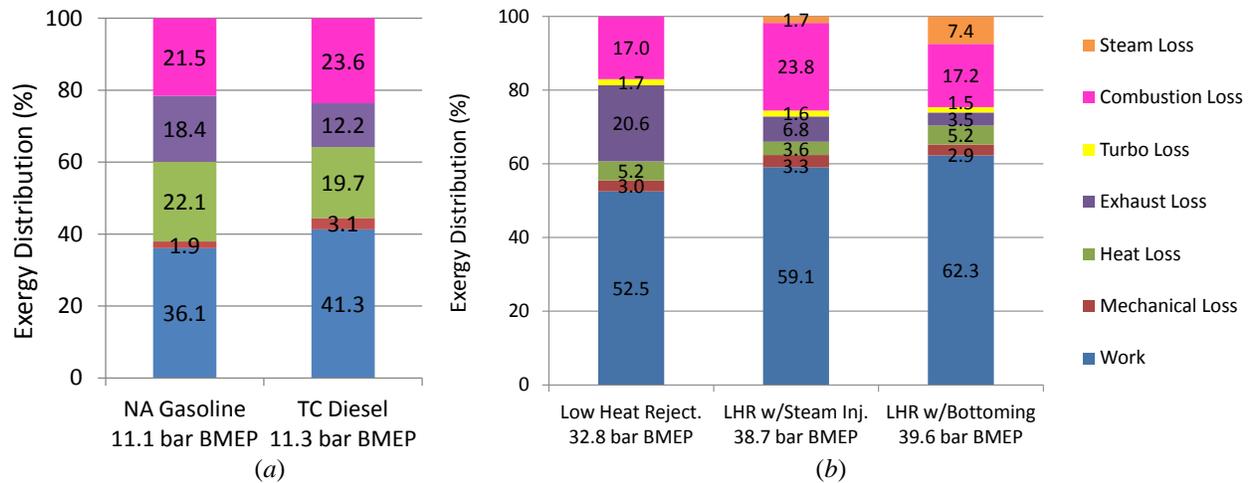


Figure 1: Exergy distribution comparison between today's state-of-the-art engines (a) and three advanced configurations (b). While significant improvements can be realized, under no conditions can an efficiency >70% be achieved due to the irreversibility inherent in the use of combustion (~17% exergy loss in the best case).

Contrast these engines with the three hypothetical engines whose exergy distributions are depicted on the right. These engines use a combination of low-heat rejection (thermal barrier coating) technology (LHR), advanced combustion strategies, turbo-charging and/or turbo-compounding, and even a Rankine bottoming cycle. All are modeled with state-of-the-art performance metrics for existing devices and technologies (e.g., turbocharger efficiency, temperature limits of thermal-barrier coatings, etc.), and realistic-but-optimistic capabilities in areas where actual performance is unknown. These three examples show that exergy efficiencies in the mid-60% range can be achieved if we are aggressive about eliminating passive heat rejection (the green boxes), and at the same time, deploying suitable-but-conventional technologies to convert the exhaust energy to work.

Here is the point of the comparison: Even if all of the promising approaches currently under discussion are deployed successfully, the efficiency of transportation (and distributed generation) engines will remain below 70%. Note that this is not for lack of trying: In addition to employing multiple efficiency (and even combined-cycle) measures—most probably to the point of being uneconomical—the exergy distribution indicates that the losses are now so dispersed that there is only one place to look to for further improvement—the loss due to combustion (the pink boxes).

This is no surprise to our group based on previous work—we have long regarded the ~20% loss of exergy due to combustion to be unacceptable. We have analyzed this loss and shown that the only way it can be reduced is by moving to states of extreme energy density when conducting the combustion process—the so-called *extreme states* principle that emerged from our prior GCEP research [2]. It was this concept that was used to demonstrate 60% indicated efficiency for a free-piston engine in our laboratory, and that provided the basis for a start-up company developing a commercial engine that uses extreme compression to achieve >50% efficiency (LHV to electricity).

Setting the use of extreme states aside, is there another way to cut into the loss of exergy that prevents us from achieving efficiencies over 70%? The answer is, yes, but it cannot be based solely on combustion for energy conversion. It must be based, at least in part, on use of a restrained chemical reaction, the only practical examples of which come from fuel cells [3].

## **Background**

The best known example of a mixed restrained/unrestrained reaction engine is the solid-oxide fuel cell/gas-turbine (SOFC/GT) combined-cycle engine system. This idea first surfaced decades ago when it was recognized that some of the limitations/deficiencies of each type of chemical energy conversion technology were mitigated by the complementary method of reaction. We have watched developments in this area closely and have seen data from companies working on this approach (Mitsubishi Heavy Industries, as reported in [4]) that indicate efficiencies in the range of 70-74% (LHV) using a triple-cycle configuration (SOFC/GT/ST) are now expected, and that lifetimes in excess of current heavy-frame gas turbine maintenance intervals (~20,000 hours) have already been demonstrated for the SOFC elements. This technology appears to be viable; the question is now one of economics.

From a fundamental perspective we have analyzed and understand why the SOFC/GT/ST combination is capable of achieving such high efficiency [5]. It is due to the complementary nature of the three types of work extraction: electrical in the SOFC, flowing expansion in the GT, and a heat engine (the Rankine cycle of the ST). Each of these provides a near-independent method of extracting work, each has low exergy destruction in itself, and each has the capability of utilizing the form of exergy transferred to it by the upstream components as its primary resource

The question we ask here is whether something similar is possible at small scale? By small we mean a scale suitable for distributed generation at the largest, and light-duty transportation at its smallest. Speaking practically, this is also a scale at which we can demonstrate the principles and performance using piston engines in our laboratory.

## Results

Much of our effort to date has been focused on understanding the potential for this approach and the possible ways in which that potential can be realized. The most important thing we have learned is that essentially all configurations can be explored based around just two combustion systems and two fuel cell systems. The two combustion systems correspond to low-temperature combustion (like HCCI) and high-temperature combustion (like LHR direct-injection combustion [6]). These in turn provide an excellent match to the two candidate fuel cell technologies—low temperature (like HTPEM or phosphoric acid) and high-temperature (like SOFC). Similarly, the coupling between these elements suggests two fuel processing opportunities—water-gas shift conversion for the low-temperature system, and direct fuel reforming for the high-temperature system. So while the complexity of the research space remains high, we believe that we understand how to span the space so as to determine just what is possible in configuring such systems.

With these systems-level realizations as background, we have begun to investigate how well each of these technologies can be adapted, and what the complications might be that arise from the new combinations (and interfaces) required. For example, with respect to using a high-temperature combustion process for syngas generation, a key question is how much CO and H<sub>2</sub> can be generated, and how rich can the combustion process be pushed before we are limited by soot.

Figure 3a shows the results of an exploratory experiment using isooctane as fuel in a conventional, spark-ignited engine. In order to obtain these data, systems were developed for direct measurement of the hydrogen and carbon monoxide concentrations present under these conditions. Along with the data are shown the results of an engine model using detailed chemical kinetics for prediction of the exhaust composition under rich conditions [7]. The results show reasonably good agreement between the CO and H<sub>2</sub> emissions measured and predicted up to the measured soot limit, but with somewhat higher CO concentrations in the measured data. This difference might well be explained by the characteristics of the research engine used for the measurements; it is an engine with a large crevice volume such that significant, late conversion of unburned hydrocarbons to CO is likely. These crevices are not represented in the engine model used for comparison. Total hydrocarbon emissions were measured and found to represent only 2% of the chemical energy exiting the engine (the rest being CO and H<sub>2</sub>). The plot in Fig. 3a also shows the expected composition if water-gas shifting is applied downstream of the engine at 250°C and with sufficient water added to reduce the carbon monoxide to HTPEM-compatible levels.

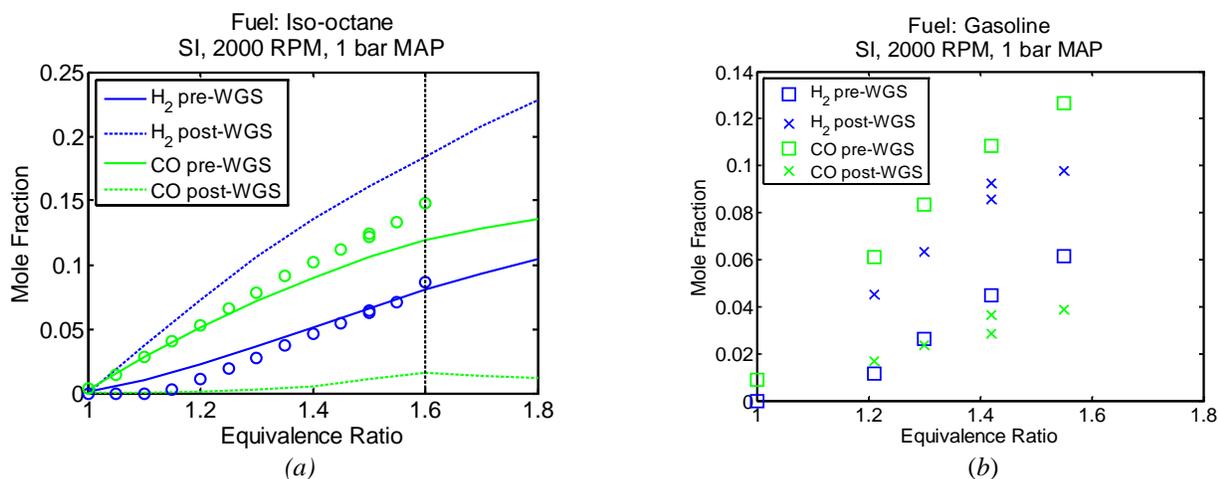


Figure 3: (a) Measured (symbols) and predicted (lines) syngas composition for rich spark-ignited (SI) combustion of isooctane up to the measured soot limit at 1.6 equivalence ratio (dashed vertical line). (b) Measured composition for gasoline combustion in the same engine, both before and after a high-temperature water-gas-shift reactor.

Figure 3b shows the results of our first attempt to shift the syngas output from rich gasoline combustion using a high-temperature water-gas shift (WGS) catalyst ( $\sim 400^{\circ}\text{C}$ ). Although we will ultimately want to shift the composition toward equilibrium at lower temperatures ( $\sim 250^{\circ}\text{C}$ ) using an additional (copper-based) catalyst, we are now in a position to perform systematic investigations of how the engine-generated syngas might be processed before it is fed to the downstream HTPEM cell.

Gasoline (with isooctane as a surrogate) is not the only fuel that should be considered for this application. The alcohols, methanol and ethanol, and natural gas are also candidate fuels. Figure 4 shows exploratory measurements made with methanol and ethanol, again under spark-ignition engine conditions. A particularly important aspect of using the alcohols is that they can be burned under very rich conditions without sooting. Understanding how rich these fuels can go, and therefore how much chemical energy can be transferred to the fuel cell without the need for additional reforming, will be an important question for determining the range of performance for these systems.

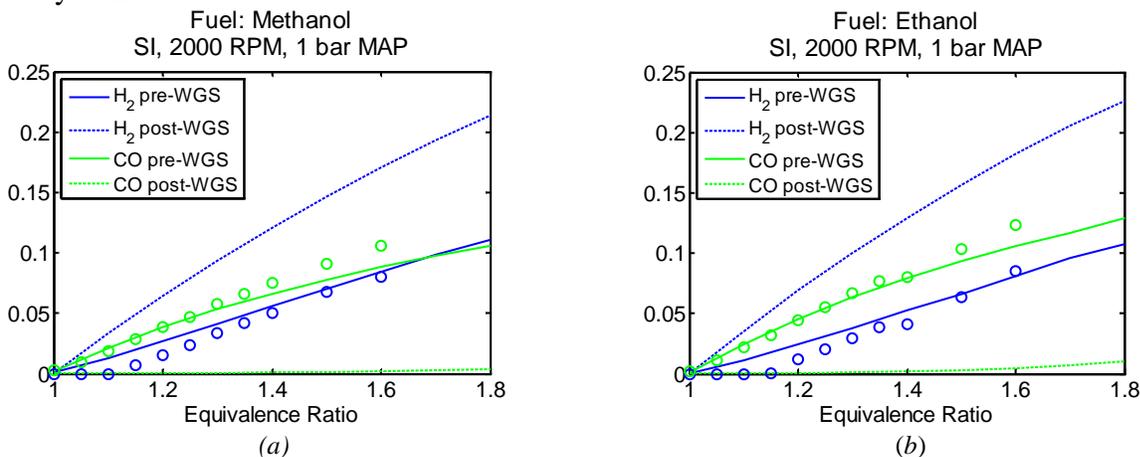


Figure 4: Measured (symbols) and predicted (lines) syngas composition (mole fraction) using rich spark-ignited (SI) combustion of (a) methanol and (b) ethanol. Total hydrocarbon emissions were also measured and found to represent  $\sim 5\%$  of the chemical energy passed from the engine to the downstream fuel cell system for both fuels.

Another area in which we have begun investigation is in relatively low-temperature fuel cells for matching with a low-temperature combustion process. By low-temperature fuel cells we mean cells operating near 200°C such that only a shift reactor is required to reduce the CO concentration to the requisite level. One candidate technology is the HTPEM cell of the type produced by BASF. These cells operate at up to 180°C and have the ability to tolerate a few percent CO in their fuel gas. Since one of the critical questions is how such a cell will respond to the exhaust gas composition produced by internal combustion (plus shift), we have built a prototype setup—both shift reactor and HTPEM—that will allow us to test this type of cell with actual engine exhaust gas.

Figure 5 shows a photograph of the two setups developed in the lab under the exploratory grant, along with the nominal  $V-I$  curves for the BASF membrane electrode assemblies (MEAs) currently under study. Using the combined setup we will soon be in a position to demonstrate a completely coupled system—from engine through shift to fuel cell—and to verify operation using actual engine generated syngas.

One of the reasons for focusing initial exploration on the low-temperature option for this approach is that it has higher uncertainty than for the high-temperature approach. By this we mean that more is known about the ability of SOFCs to handle internal reforming, anode recycling, etc., such that we are fairly confident good high-temperature results can be obtained. What we are less confident of is that the various compatibility issues (thermal, species) can be handled at low-temperature, hence making this the focus of our exploration. But having done this, we note that we have also developed models for SOFCs, vitiated fuel reforming, etc.—we have just not begun experimental efforts along those lines.

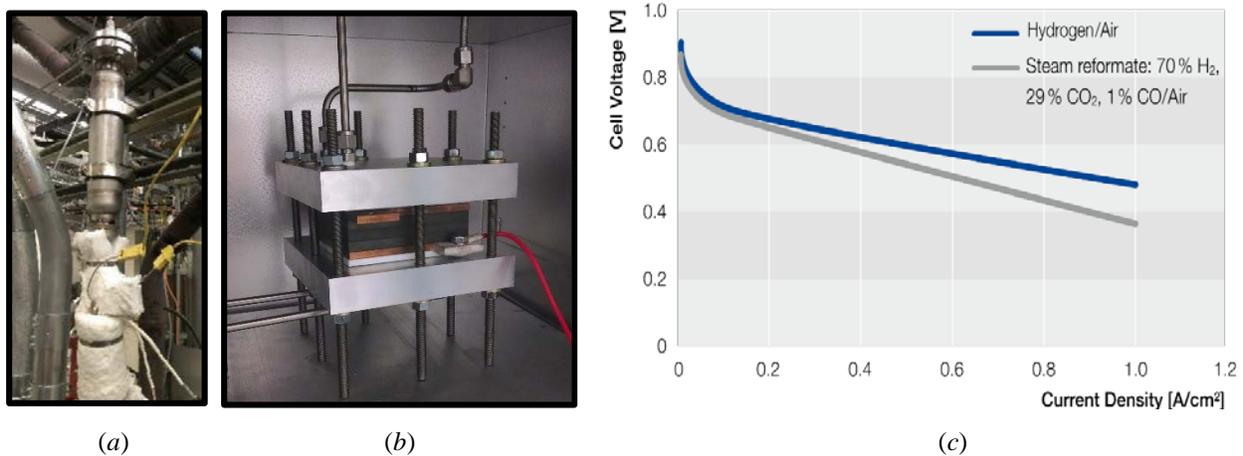


Figure 5: Combined shift reactor and HTPEM system under development for testing with engine-derived syngas. Part (a) shows the prototype shift reactor attached to an SI engine, part (b) shows the prototype HTPEM fuel cell using BASF MEAs, and part (c) shows performance data for the MEAs using hydrogen and shifted reformat as fuels [6].

## Conclusions

Having performed a range of analytical and experimental studies under the exploratory grant, we believe we have the problem framed sufficiently to undertake a three-year, systematic exploration and demonstration. Our overall objective is to determine the best way to combine piston-cylinder, internal-combustion-based reaction with electrochemical reaction. We believe the tools required to

perform this task are available to us, primarily the knowledge base, a HTPEM fuel cell, two engines and dynamometers, and the appropriate emissions and diagnostic measurement systems. To achieve this, a proposal has been submitted to the GCEP program.

## References

1. B. Johnson and C. Edwards, "Exploring the Pathway to High Efficiency I.C. Engines through Exergy Analysis of Heat Transfer Reduction," SAE Int. J. Engines 6(1):2013.
2. K.-Y. Teh, "Thermodynamics of Efficient Simple-Cycle Combustion Engines," Ph.D Dissertation, Dept. of Mechanical Engineering, Stanford University, May 2007.
3. S. L. Miller, M. N. Svrcek, K.-Y. Teh, and C. F. Edwards, "Requirements for Designing Engines with Reversible Reactions," *Energy*, Vol. 36, pp. 99-110, 2011.
4. K. Yamada and M. Suzuki, "Perspectives for Decentralized Power Generation with Fuel Cell," keynote presentation at the World Engineers Convention, WEC2011, Geneva Switzerland, Sept. 2011.
5. R. Pass, and C. F. Edwards, "Exergy Analysis of a Solid-oxide Fuel Cell, Gas Turbine, Steam Turbine Triple-Cycle Power Plant", Proceedings of the ASME 2012 International Mechanical Engineering Congress and Exposition.
6. G. Roberts, B. Johnson, and C. Edwards, "Prospects for High-Temperature Combustion, Neat Alcohol-Fueled Diesel Engines," SAE Technical Paper 2014-01-1194, 2014.
7. G. Blanquart, P. Pepiot-Desjardins, and H. Pitsch, "Chemical mechanism for high temperature combustion of engine relevant fuels with emphasis on soot precursors," *Combustion and Flame* 156:588-607, 2009.

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