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Air-Steam Hybrid Engine: An Alternative to Internal Combustion

MARCH 2011

FTA Report No. 0013
Federal Transit Administration

PREPARED BY

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Courtesy of BRASH

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Air-Steam Hybrid Engine: An Alternative to Internal Combustion

Cleaner, More Efficient, Multi-Fuel Compatible, Retrofitable

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Metric Conversion Table

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC

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13. ABSTRACT

In this Small Business Innovation Research (SBIR) Phase 1 project, an energy-efficient air-steam propulsion system has been developed and patented, and key performance attributes have been demonstrated to be superior to those of internal combustion engines. A mixed air-steam propellant system can provide immediate power without a boiler, and that power can be varied simply by modifying the ratio of water and air in the propellant mix. Next steps for this innovation include more detailed performance verification and an analysis of scaling this promising technology to propel buses and trains for mass transit use. Successful validation would lead to a vehicle retrofit of a smaller, lighter, more fuel efficient engine in a standard mid-size or full-size vehicle. That engine could operate on a variety of fuels other than refined petroleum. These goals are consistent with the DOT SBIR subtopic narrative, "Economical and durable technologies and devices for improving safety for riders and transit agency employees, reducing noise and energy consumption, or improving the rider experience. The innovations must be adaptable to existing bus and rail transit vehicles and systems."

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EXECUTIVE SUMMARY

More than one quarter of all energy consumed in the U.S. is used to support the transportation sector, and, as shown in Figure 1, nearly all of that transport energy is derived from petroleum.[1]

Why does transportation rely nearly exclusively on petroleum, when other sectors rely primarily on other sources of energy? A major part of the answer lies in the timed ignition needs of internal combustion engines, which require a highly-refined and volatile fuel to provide timely detonation of the fuel/air mixture.

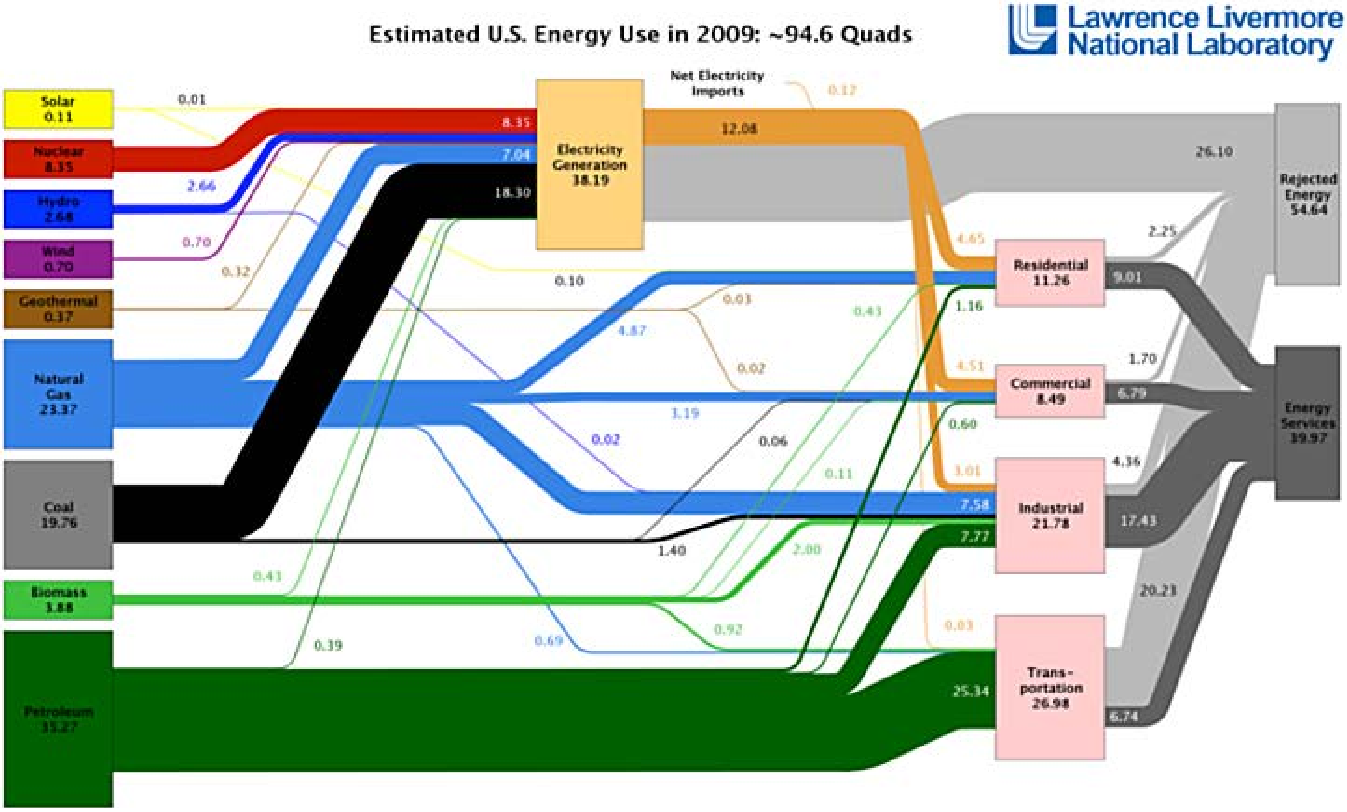

Figure 1

Energy Usage in the United States

However, the detonation of refined fuels is not a necessary condition to produce useful prime-mover work. That work can be extracted from heat alone, and that heat can be generated from semi-solid bio-fuels if the work is performed by an external combustion (EC) engine.

EC engines have been in use for centuries and still produce 80 percent of electrical capacity in the U.S.,[2] but EC engines have been disfavored for transportation applications because of startup delay, constant "tending," and perceived lower fuel economy. The patented BRASH (Binary Recovery, Air-Steam Hybrid)

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[1] "Petroleum Basic Statistics," September 2008, Energy Information Administration, U.S. Department of Energy, October 14, 2008, http://www.eia.doe.gov/basics/quickoil.html.

[2] "Net Generation by Energy Source: Total (All Sectors)," March 11, 2011, U.S. Dept. of Energy, Energy Information Administration, Energy Source Table, http://www.eia.doe.gov/cneaf/electricity/epm/table1_1.html.

engine technology resolves each of these concerns and presents the first clear alternative to internal combustion in more than 50 years. It is projected to produce higher fuel efficiency, greater power, and lower emissions than a comparable internal combustion (IC) engine. It should be particularly well-suited to larger vehicles such as buses. The BRASH engine is a binary recovery, air-steam hybrid engine. The combination of air and water in an EC engine provides immediately available power and should produce much greater fuel economy than a conventional steam or IC engine. More significantly, the BRASH engine can provide more power with lower emissions from a wider range of fuels than an internal combustion engine. A simplified schematic of the BRASH engine is shown in Figure 2, illustrating the following principles:

- Accelerator regulates flow of air, water and fuel to heater, based on load and wheel speed.
- Water and fuel are metered to maintain heater temperature within optimal performance band.
- Output demand determines air-water fraction.

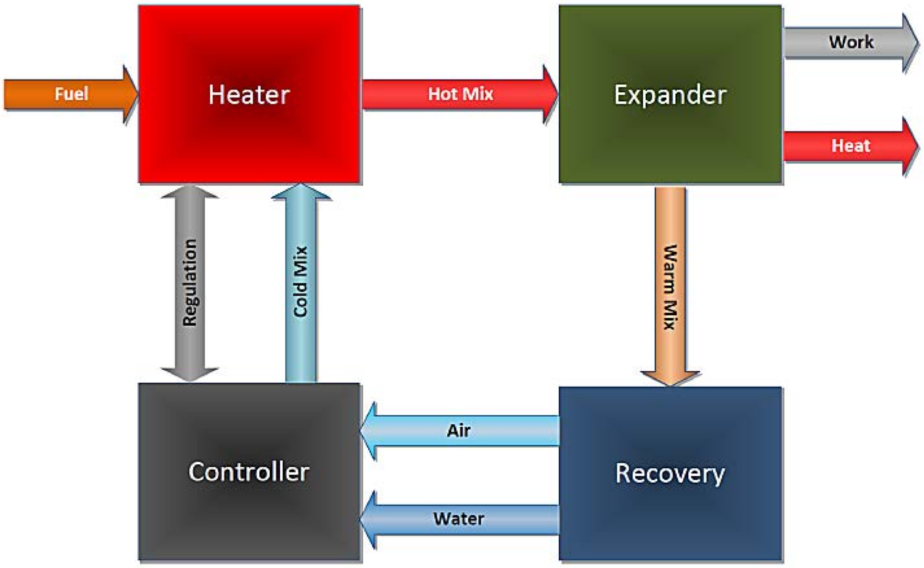


Figure 2

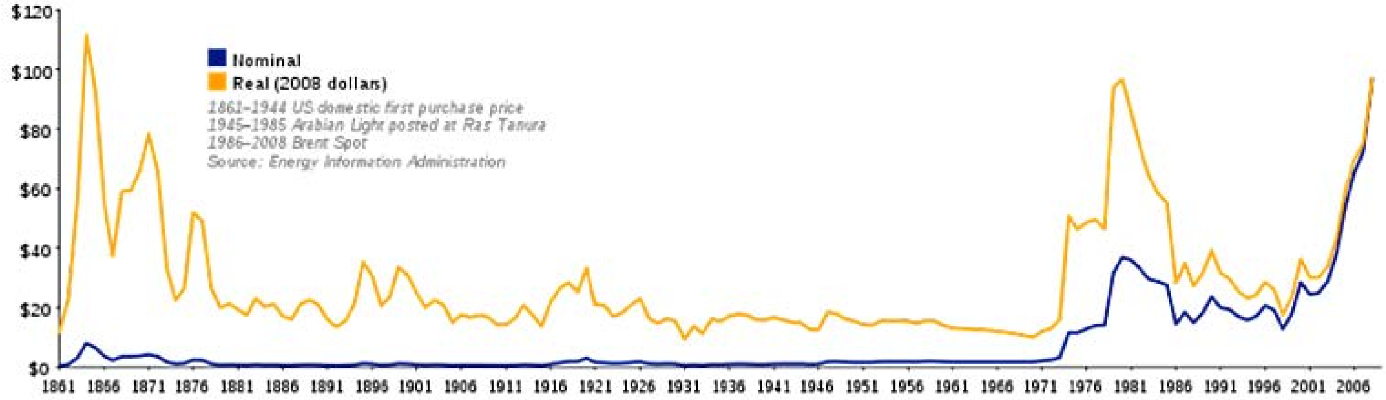
Simplified Model of Air-Steam Hybrid Engine

Any fuel that can be metered (liquid, solid, or gas) can be used, and the heat from combustion is used in direct proportion to work done. Fuel is consumed in direct proportion to demand. Fuel economy with this air-steam system is much higher than steam alone because air requires less heat to move a piston, and the system's superior thermal management will yield practical fuel economy 3–4 times that of an internal combustion engine of comparable torque.

SECTION 1

Context for BRASH: Societal Challenges and Needs

Economic growth in the developed world has been highly dependent on petroleum distillates for nearly a century.[3] As Figure 3 shows, for most of that century, the price of oil has remained stable ($10–$30 per barrel, in 2008 dollars) and relatively low. Since the oil embargo of the 1970s, and later political instability in large oil-producing regions, the price of oil has fluctuated significantly. Over the last 40 years, each sharp increase in oil prices has been followed by a steep decline in economic activity.



1861–1944 US domestic first purchase price
1945–1985 Arabian Light posted at Ras Tanura
1986–2008 Brent Spot
Source: Energy Information Administration

Figure 3

Historic Crude Oil Prices

The long-term trend in oil prices reflects the growing concern that oil quantities are finite, while worldwide demand continues to grow.[4] M. King Hubbert first posited in 1956 that U.S oil production was approaching a maximum rate, and past that point, when demand exceeded supply, prices would rise rapidly, to unprecedented levels.[5] Since Hubbert, this model has been extended to worldwide oil reserves and the popular notion of "peak oil."[6]

Figure 4 shows projections of world oil production beyond 2010. Most models show a decline in supply over the next 20 to 30 years.[7] This decline in production

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[3] "Analysis of the Impact of High Oil Prices on the Global Economy," International Energy Agency (IEA), http://www.iea.org/textbase/npsum/high_oil04sum.pdf.

[4] *E&P Magazine*, "Geologists Positive about Future of Oil and Gas," June 10, 2009.

[5] Marion King Hubbert, "Nuclear Energy and the Fossil Fuels Drilling and Production Practice," June 1956, Spring Meeting of the Southern District, Division of Production, American Petroleum Institute, San Antonio, Texas, Shell Development Company, pp. 22–27. http://www.hubbertpeak.com/hubbert/1956/1956.pdf, retrieved April 18, 2008.

[6] Adam R. Brandt, "Testing Hubbert,"*Energy Policy* 35(5), May 2007, pp. 3074–3088.

[7] "Medium-Term Oil Market Report," July 2007, IEA, Public Access–Oil Market Report, http://omrpublic.iea.org/.

would coincide with far greater fuel demand, as China, India and other parts of the developing world are beginning to embrace the automobile.[8]

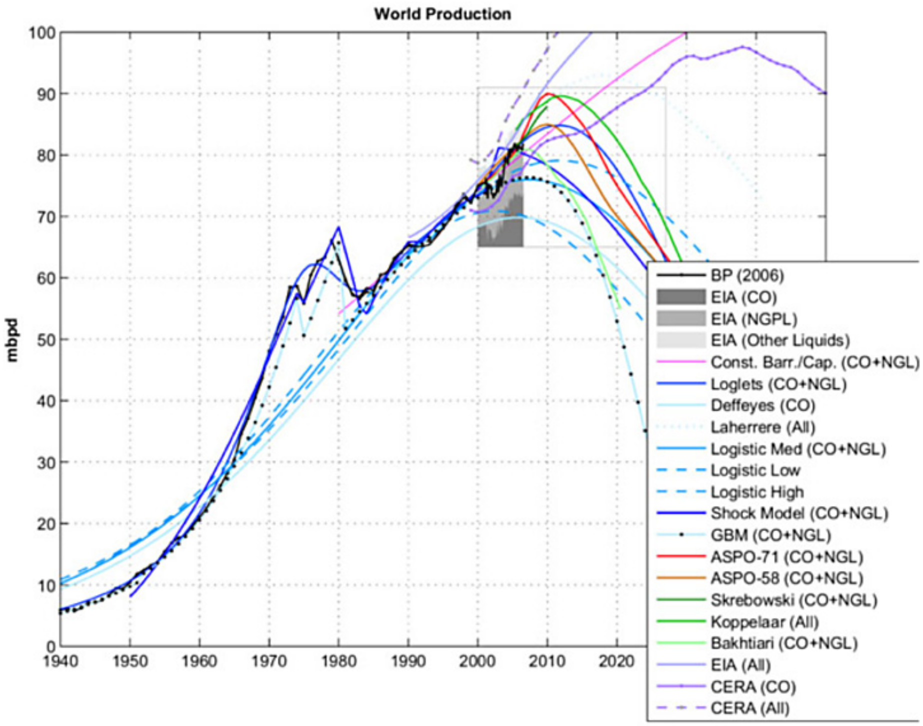

Figure 4

Projections of World Oil Production

The other trend of note related to petroleum usage is the rise of atmospheric CO_2 and the growing risk of climate change. Figure 5 shows the consistent rise in atmospheric CO_2 at the remote Mauna Loa observatory. The rise in CO_2 levels is attributed to fossil fuel combustion, most notably coal-fed power plants and gasoline powered automobiles.

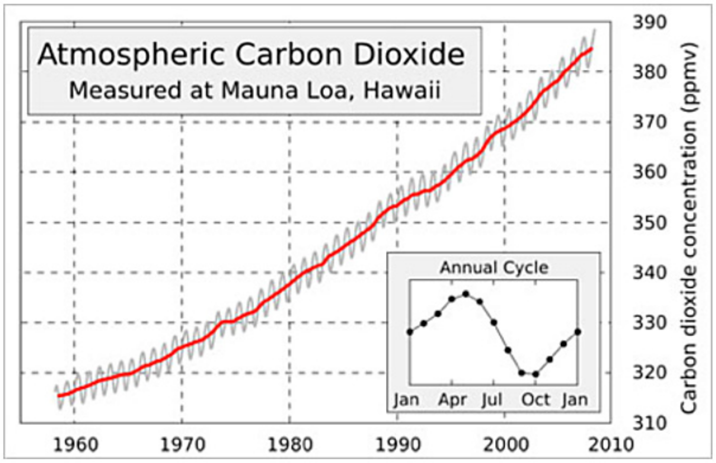

Figure 5

Measured Atmospheric CO_2

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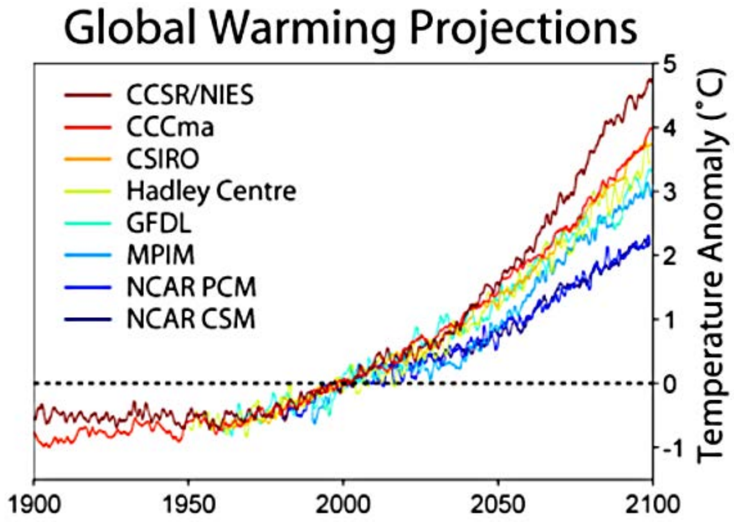
[8] Plunkett Research (2008), "Automobile Industry Introduction."

As shown in Figure 6, the rise in atmospheric CO_2 levels correlates with increases in global temperatures. As CO_2 continues to increase, the expectation is further increases in average global temperatures.[9]

Figure 6

Global Warming Projections



The economic modeling and the environmental modeling point to one conclusion: petroleum distillates may be the current source for nearly all of our transportation fuel supplies, but its primacy cannot be sustained. Whether from a perspective of limited supply and growing demand or the perspective of a growing environmental impact, refined petroleum does not provide solutions, only difficult and growing problems.

Three popular initiatives—petroleum alternatives, improved fuel economy, and alternative electric vehicle power—cannot solve world's thirst for petroleum distillates:

- Petroleum alternatives, like biodiesel or ethanol, put fuel in competition for land with our food supply.[10]
- Noble efforts to increase vehicle fuel economy domestically cannot offset the surging worldwide demand for more vehicles (Figure 7).[11]

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[9] IPCC, "Summary for Policymakers," Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Intergovernmental Panel on Climate Change (IPCC)" 2007. http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-spm.pdf, retrieved July 3, 2009.

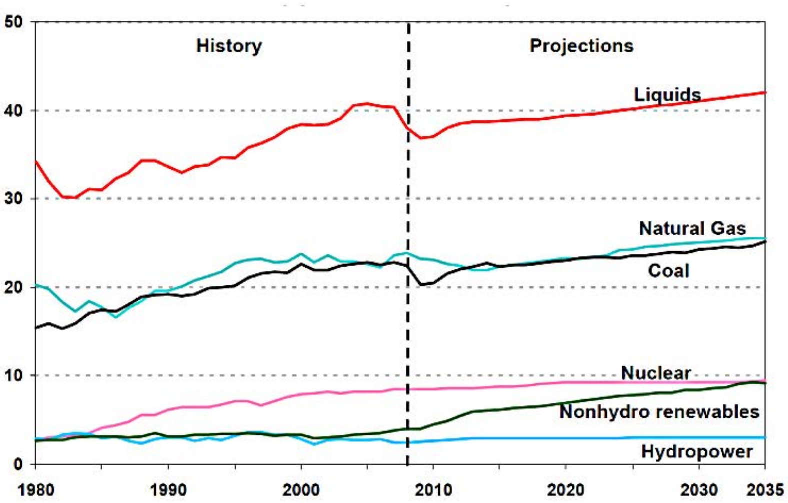
[10] *The New York Times*, "Food and Fuel Compete for Land," December 18, 2007. http://www.nytimes.com/2007/12/18/business/18food.html.

[11] U.S. Information Administration, Analysis & Projections, http://www.eia.gov/oiaf/forecasting.html.

- Domestic migration to electric vehicles is constrained by gross vehicle weight and range,[12] and electric hybrids are still priced at a premium over their non-hybrid versions.[13]

Figure 7

U.S. Energy Consumption by Fuel (1980–2035)



The goal of lower national fuel consumption is built on the false premise that the transportation sector requires highly-refined fuel. Transportation requires highly-refined fuels only if the motive power is derived from timed detonation of a fuel/air mixture in the cylinder head. In other words, the problem is not so much the petroleum itself, but rather the virtually universal dependence on internal combustion (IC) engines that require petroleum fuels.

If motive power were to come instead from external combustion, a far wider array of gas, liquid, and solid biomass/renewable fuels could be used. The goal could shift from "miles per gallon" to "effective production cost per 100 miles driven" for a new class of fuels measured by the pound and favored by the rate of production and CO_2 absorption during growth.

In sum, the goal is to reduce the amplitude and slope of the red ("Liquids") line in Figure 7 and increase the same parameters of the green ("Nonhydro renewables") line significantly. By migrating to EC vehicles, more of the green renewables line can be used in the transportation sector.

The driving force behind the world economy is energy. It is axiomatic that lower fuel production costs and consumption equals higher economic productivity. The solution for the transportation sector is to migrate toward less refined, self-renewing fuels,

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[12] *The New York Times*, "Will Lithium-Air Battery Rescue Electric Car Drivers from 'Range Anxiety'?" May 7, 2010. http://www.nytimes.com/cwire/2010/05/07/07climatewire-will-lithium-air-battery-rescue-electric-car-37498.html.

[13] ConsumerAffairs.com, "Consumer Reports Sizes Up Hybrid Costs," March 2006. http://www.consumeraffairs.com/news04/2006/03/cr_hybrids.html.

and that can come only through the technical migration toward external combustion. BRASH (Binary Recovery, Air-Steam Hybrid) technology provides that path.

SECTION

2

Technology Background

With few exceptions, all mechanical work is derived from heat, and all that heat is generated by combustion. The earliest effective engines were steam engines, first put to practical use at the time of U.S. independence. Steam engines remained the dominant source for motive power for the next century, until its slow but steady displacement by IC engines in the automobile.

Henry Ford was first inspired to develop steam traction engines as a better solution than plow horses:[14]

> I felt perfectly certain that horses, considering all the bother of attending them and the expense of feeding, did not earn their keep. The obvious thing to do was to design and build a steam engine that would be light enough to run an ordinary wagon or to pull a plow. I thought it more important first to develop the tractor. To lift farm drudgery off flesh and blood and lay it on steel and motors has been my most constant ambition.

Ironically, by the 1920s, steam traction engines were completely displaced by IC tractors, largely the product of the same Henry Ford and his Fordson brand of tractor.[15]

The IC engine was smaller, lighter, and cheaper to produce—and considered safer. Gasoline- and diesel-powered tractors were more expensive to operate, but the most compelling argument for switching was safety in the hands of a lower-skilled operator, who no longer had to constantly watch gauges and adjust temperatures and pressures.

Similar differences existed in the broader automotive market, and the advent of the electric starter effectively ended consumer interest in EC steam cars.

Still, near the end of the steam car era, Stanley, Doble, White, and others offered technically-competitive options. The Doble Model E (Figure 8) weighed more than 5,500 pounds but achieved in the 1930s the same fuel economy of a comparable IC engine in a contemporary SUV—16 mpg. The Doble was powered by a four-cylinder engine of 190 cubic inches displacement, about the size of an Accord engine, but the Doble weighed 67 percent more than the Accord. As for emissions, one Doble Model E (currently owned by Jay Leno) recently passed California emissions testing with no modifications.[16]

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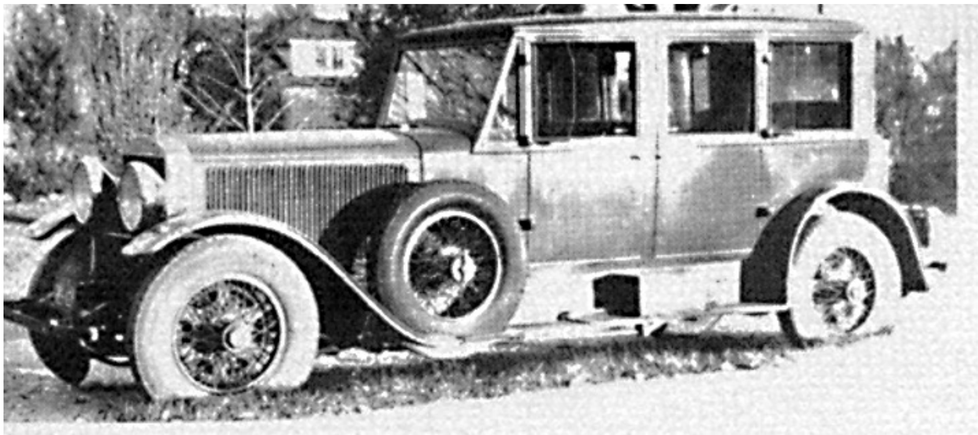
[14] Henry Ford, *My Life and Work*, 1922.

[15] Spencer Yost, *Antique Tractor Bible*, 1998.

[16] "Jayo's Garage: 1925 Doble Series E Steam Car," http://www.jaylenosgarage.com/at-the-garage/steam-cars/1925-doble-series-e-steam-car/.

Figure 8

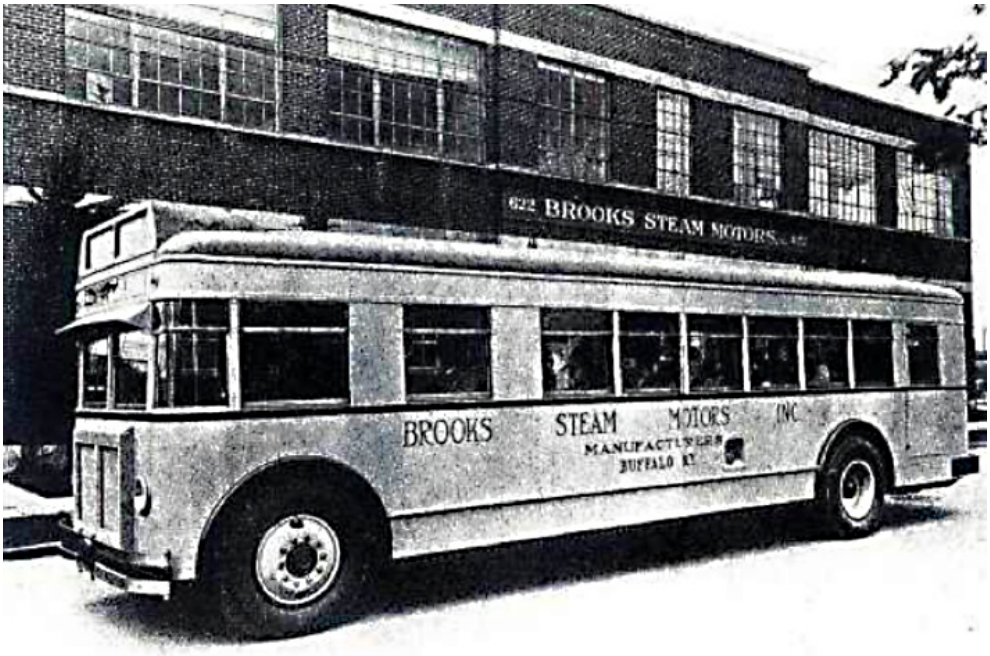
Doble Model E



Doble and Brooks also built passenger buses similar in capacity and weight to contemporary buses. The Brooks shown in Figure 9 was powered by a 400-cubic-inch V8 steam engine and carried 29 passengers at 60 mph while turning at 2000 rpm. As a cruel twist of fate, the public unveiling of the Brooks Steam Bus was announced in October 1929, two weeks before the stock market crash and the onset of the Great Depression.[17] The company did not survive.

Figure 9

Brooks Steam Motors Bus



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[17] Wikipedia, “Brooks Steam Motors,” http://en.wikipedia.org/wiki/Brooks_Steam_Motors.

The suitability of steam power for mass transit use can be seen from comparison of a very powerful contemporary Ford V-8 Diesel engine (from the Excursion SUV) to the Besler V-Twin Steam engine, circa 1938:

	Ford Turbo Diesel	**Besler Steam**
Configuration	V-8	V-2
Displacement (cu.in.)	445	80
Horsepower	175	150
Torque (ft-lbs)	420	1200
Engine wt, w/ transmission (lbs)	930	80

The Besler is roughly one quarter the size and weight of the V-8 Turbo-Diesel, but has equivalent horsepower and three times the available torque (the primary determinant of performance). The Detroit Diesel Series 60 six-cylinder engine commonly used in mass transit vehicles produces marginally more torque (1450 ft-lbs) than the Besler, from twice the horsepower and with much more fuel.

Steam engines make greater use of the energy contained in the fuel by separating the heating phase of the Carnot cycle from the expansion phase and metering fuel burn to more closely match demand. A steam engine presents maximum torque at low speed and greater horsepower and torque than comparable IC engines.

Another EC technology gaining resurgent interest is compressed air power. Recent reports of collaboration between MDI of France and Tata Motors of India suggest a new approach toward EC engines.[18] Tata Motors, a major producer of vehicles on the Indian subcontinent, intends to produce the MDI Air Car in the near future, with anticipated fuel economy of 106 mpg. The latest iteration of the MDI Air Car, shown in Figure 10, has a projected range of 848 miles from 8 gallons of fuel, or 106 mpg, for a 4-passenger vehicle weighing 1870 pounds.[19] The MDI City Car relies on a six-cylinder 75 HP engine/expander to achieve this performance and in the "process [produce] emissions of only 0.141 lbs of CO_2 per mile. That is … less than [half] the cleanest vehicle available today." (Toyota Prius 07 Emissions: 0.34 lbs of CO_2 per mile.)

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[18] Autobloggreen, "A New Agreement between Tata Motors and MDI Bring the Air-Car Closer to Reality," March 21, 2007.
http://green.autoblog.com/2007/03/21/a-new-agreement-between-tata-motors-and-mdi-bring-the-air-car-cl/.

[19] Motor Development International (MDI), OneFlowAIR, http://www.mdi.lu/english/oneflowair.php.

Figure 10
MDI Air Car

The schematic for the MDI power plant is shown in Figure 11. The stored air is heated to combustion temperatures and allowed to expand mechanically. This is the practical definition of an EC engine, where combustion provides heat but the working fluid or propellant is not generated by the combustion process itself.

Separating the heating step from the expansion step does not, in itself, yield higher fuel economy or lower emissions. But the regulation of fuel flow to maintain optimum propellant temperature immediately prior to expansion provides both maximum fuel economy and lowest possible emissions. In contrast, an IC engine ignites fuel at 1800°F and immediately conducts that heat away through its water jacket to drop cylinder temperatures to 200–300°F. EC engines preserve that heat for useful work.

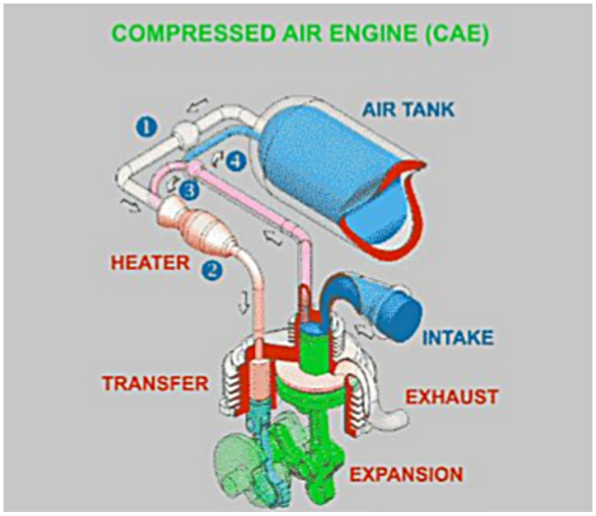


Figure 11
MDI Air Engine Schematic

Both air and steam engines provide an alternative to the conventional IC engine. Both operate from a variety of fuels and offer the potential of lower emissions and higher fuel economy. Steam is the more robust of the two (the Besler Steam Twin is much more energetic than the MDI six-cylinder), but the compressed air engine offers an operational simplicity and a lower weight because no boiler or condenser is required. Unfortunately, it can never provide the power and acceleration of steam.

The best of both worlds would be a blending of air and steam into a single engine that offers all of the benefits, but without the weight and heat management issues of a boiler and with significantly more power than an air engine alone.

SECTION

3

The Air-Steam Hybrid Solution

Air and water are completely different in their physical properties, except when they operate as working fluids at high temperatures and pressures. At steam operating pressures and temperatures, their behavior largely follows ideal gas behavior, and each is miscible in the other at all proportions. The arrow in Figure 12 indicates the rough path for expansion of the hot, high-pressure propellant and shows near ideal gas behavior for steam at these elevated temperatures and pressures.

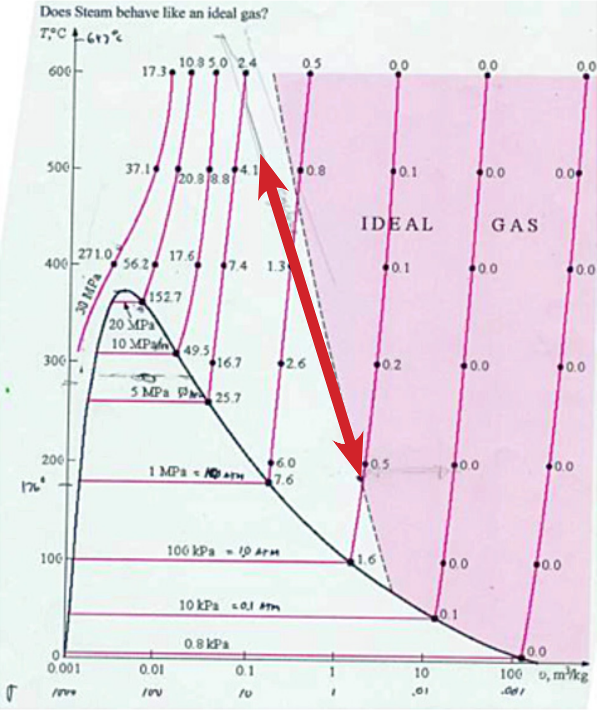


Figure 12

Does Steam Behave Like an Ideal Gas?

Getting to steam operating temperatures and pressures requires that significantly more heat be applied to water than air at STP (standard temperature and pressure). Air requires only 6.42 kcal/mole to reach these operating temperatures, while water (steam) requires 523.6 kcal/mole (due to the 512 kcal heat of vaporization). In this development, a baseline flow of air is used to entrain water into the heater section. Fuel is consumed in direct proportion to the water fraction to maintain the heater at a near constant temperature. The heat required to maintain "hot air" temperatures is a small fraction of the heat required to maintain steam temperatures, as shown in Figure 13.

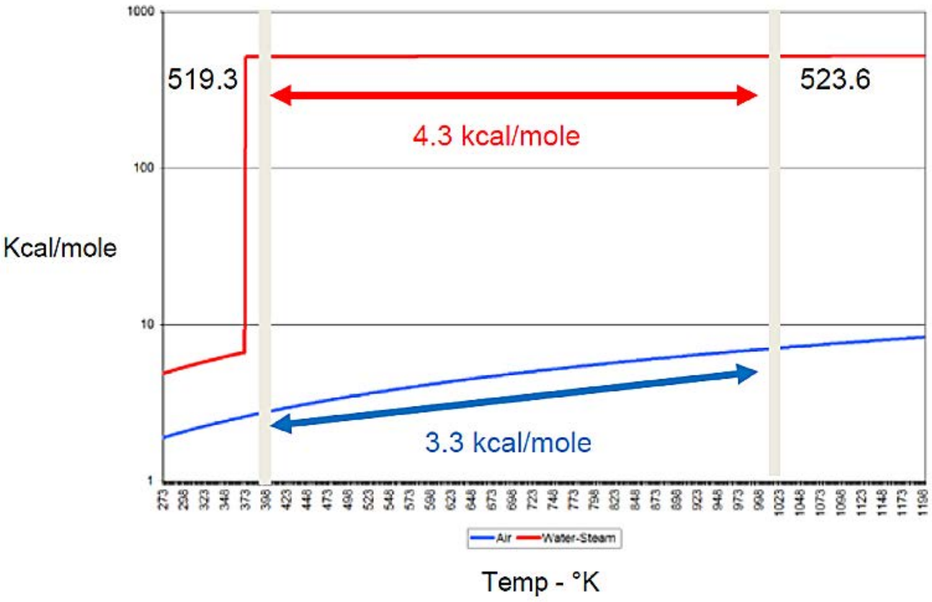


Figure 13

Heat Required to Raise Air and Water Temperature to 1000°K

The compressed air fraction provides a safe and consistent flow pressure into the hot section. The water, once heated to working steam temperature provides a more robust working fluid.

The hot mixed propellant is injected into the expander, moving a piston, and converting heat to motion. The expanded propellant thereby drops to condensing temperatures, allowing the water portion to drop to a sump for pumped return to the injector. The expanded air fraction is then recompressed for return to the injector.

The use of an air fraction allows for immediate injection of work-appropriate amounts of water into the hot section: no boiler, no steam under pressure, no fuel wasted (heating steam without immediate purpose). The use of a water fraction (and proportional fuel flow) allows for variable power from a constant temperature system. The binary (air-steam) propellant allows for a closed-loop, condensing recovery system, extending range and economy.

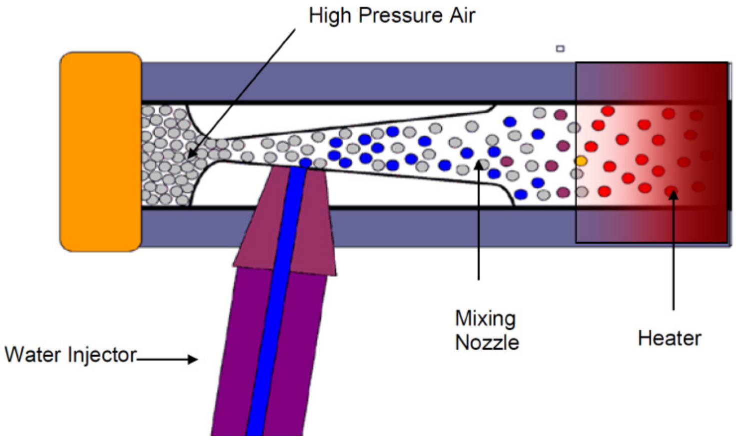


Figure 14

Schematic of Injector Nozzle Used to Mix Air and Water

The sum of the process is as follows:

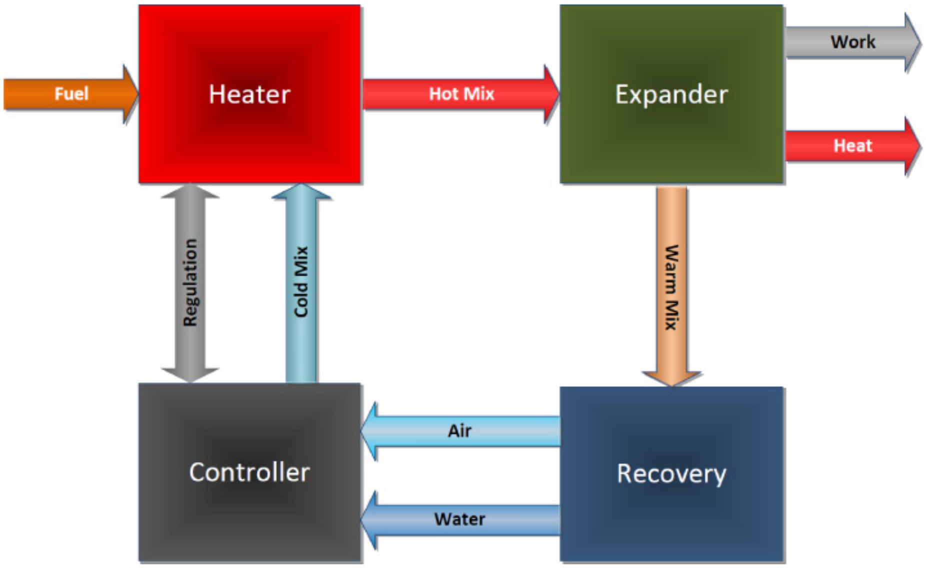
Key start begins a modest fuel burn that immediately provides initial hot air flow through the engine.

- Depressing the accelerator increases the water fraction and fuel flow (in direct proportion).
- The vehicle moves forward under (air/steam/fuel) power in direct proportion to wheel turn.
- The hot mix expands, and the expanded mix condenses the water fraction.
- A small parasitic load recompresses the small air fraction to reinjection pressures.
- Removing the foot from the accelerator returns the flow to hot air only, sweeping residual moisture from the cylinders and preventing hydraulic lock (during next cold start).

The engine can operate on any fuel whose flow can be regulated (semi-solid, liquid, gas). Combustion occurs at high temperature at one atmosphere, so much cleaner burning than internal combustion.

Figure 15

Air-Steam Hybrid Schematic



Accelerator regulates flow of air, water, and fuel to heater, based on load and wheel speed. Water and fuel are metered to maintain heater temperature within optimal performance band. Output demand determines air-water fraction.

Any discussion of fuel efficiency relative to current IC engine technology must first re-emphasize the multi-fuel capability of EC engines. In a market so dominated by one fuel, customers have accepted the term "miles per gallon" as the basis for comparison. But in an open market with many different fuels and widely different heat content (BTU/lb), the only common and appropriate denominator is “miles per dollar” (closer to “fuel economy”).

To the extent that any EC solution gains market acceptance and the market responds with new and different fuel blends, the law of supply and demand dictates that fuel prices for all will drop. Until then, the remainder of this efficiency discussion will assume all engines require the same petroleum-based fuel.

The long-accepted estimate of fuel efficiency for the IC engine is about 25 percent, with the remaining 75 percent of the heat content dissipated in equal parts through the hot exhaust, the radiator, and mechanical losses in the engine. Much has been done to raise that efficiency, but what remains is one power stroke in four and a high temperature detonation whose heat content is quickly and intentionally dissipated through conduction.

In sharp contrast, a steam engine is designed to preserve as much heat as possible from combustion and then mete out that heat through the expansion of the working fluid. Instead of a 25 percent heat loss through conduction through a radiator, conductive loss is limited to 10 percent in efficient steam engines. The greatest loss is through the vaporization of water to steam (at 30%), yielding useful work of 35 or 40 percent higher than internal combustion. Steam vehicles often report significantly lower practical fuel economies, as the whole boiler is heated for a relatively short trip (another reason to avoid using a boiler.)

Hot air engines involve no change of state, therefore avoiding the loss associated with vaporization. That can mean fuel efficiencies approaching 65 percent, except as noted with the MDI engine, a lower power-to-weight capability.

The combination of air and steam into a single engine type is expected to yield economies between 35 and 65 percent, varying with wheel load. A 50 percent net efficiency would double fuel economy over a comparably-sized IC engine, but, as shown with the Doble and Besler examples, the EC engine can be much smaller, yielding even greater economies.

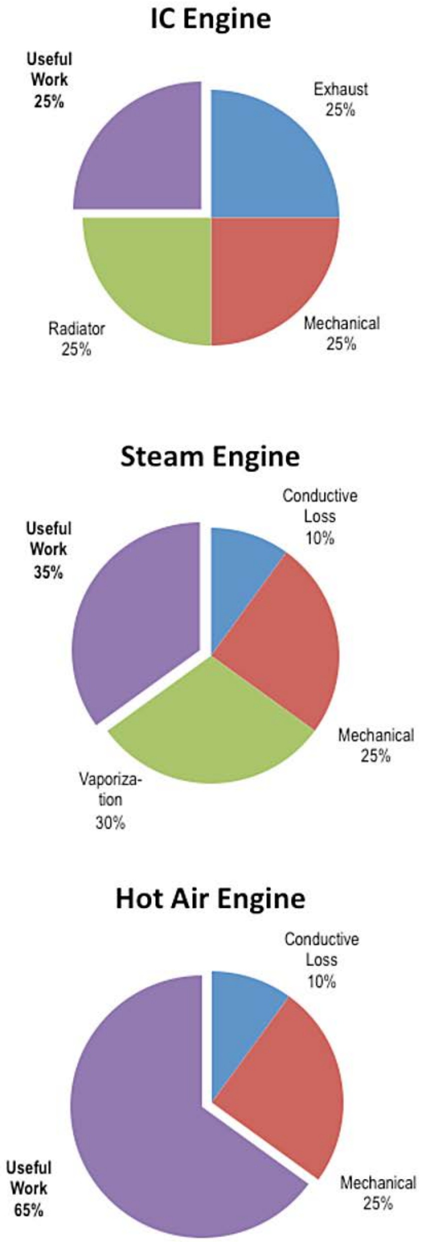


Figure 16

Fuel Efficiency by Engine Type

Derivative Uses

As much as this study is focused on large, motive power applications, it should be noted that an equally important opportunity for this technology is in stationary power applications, similar in configuration to combined heat and power units, referred to generally as micro-CHPs. Rapid start-up, high torque, quiet operation, and multi-fuel compatibility make it well suited to an integrated heat and electrical power installation.

Its ability to produce a full range of power options (mechanical, pneumatic, heat and, through attached accessories, electrical and hydraulic) in a small, modular man-portable configuration also make it particularly well suited to temporary or tactical power requirements. Although beyond the scope of the DOT goals for vehicular use, this stationary power application's potential may be strategically important in market acceptance and adoption by expanding the range of applications and, thereby, providing economies of scale in all aspects of development, production, and commercialization activities for all applications.

SECTION

4

BRASH Test Plan

This Phase I effort followed the Technical Objectives outlined in the proposal, as follows.

Practical Objectives

1. Modify the Smart™ sized test vehicle (Figure 17), installing a 10–20 HP equivalent heater; a 650 cc displacement; 2 HP (nominal) Quasiturbine™ steam engine; pressurized air and water tanks; electronic flow regulation of air, water, and fuel via laptop-based LabVIEW software; and solenoid valves.
2. Perform test runs to validate the system operation and determine key baseline performance parameters, such as:
    a. minimum air fraction to maintain engine operation, upper limits for operating temperatures, maximum allowable flow rates for water (without reducing effective propellant flow at temperature)
    b. upper limits of vehicle speed, while varying gross vehicle weight and course incline
3. Following baseline performance assessment, further objectives included:
    a. an analysis of component placement for ease of maintenance and replacement
    b. an estimation of comparable volumes and weights to an equivalent IC powertrain in order to verify retrofitability
    c. an estimation of effective fuel economy while using propane fuel on closed track mileage runs

Figure 17

Smart™ Car-Sized Test Vehicle

4. Over the course of multiple test runs, a cumulative assessment of component performance and reliability would lead to a gross verification of BRASH engine integrity and range. That, in turn, could lead to off-site vehicle demonstrations to federal agencies, potential industry partners, and investors.

Analytical Objectives

1. The BRASH engine model has been demonstrated only at a bench level with rudimentary understanding of its operating principles. A key objective in this vehicle build is to increase the thermodynamic modeling of this technology, including an analysis of mass flow (air, water, fuel) and resulting power.
2. Early test data would lead to analysis of specific on-vehicle capacities (for air, water, and fuel) and flow rates for same, in order to estimate operating range, recovery strategies and rates (recompression and condensation), and the parasitic loads (e.g., alternators, pumps) to sustain useful operation for many hours.
3. Over time, the vehicle testing under various test conditions (e.g., varying gross vehicle weight, wheel load, engine temperature, propellant mix) will lead to a body of data to support more complete modeling of water fraction *vs.* torque *vs.* temperature. These data are essential to real-world estimation of fuel economy, as this technology scales to larger practical vehicle applications.
4. With the modeling from #3 in place for steady-state operation, practical track runs with frequent starts and stops can further shape the model for real-world use.
5. The analysis from steps #1–4 will provide sufficient basis for estimating the mass flow, heat, component capacity, recovery factors, and fuel economy for scaling this 2 HP test data to larger vehicles, in two decade steps: first to a 20 HP pickup truck, and then further modeling and custom buildup of a 200 HP power plant, with a DOT-identified industrial partner.
6. This analytical plan is consistent with the overall SBIR program plan; as the 2HP effort is confined to Phase I, the 20 HP build and test plan would be accomplished in Phase II, and the design and build of the 200 HP power plant would be accomplished in Phase III with an established industry partner.

The work effort toward completion of these tasks has proceeded on two tracks: mechanical modifications to the April test vehicle and electronic control and measurement.

Mechanical Modifications and Test Configuration

The test vehicle is a modified electric car about the size of a Smart™ car. Earlier modifications included removal of the electric drive train, exposing a large working space behind the cab. This rear space over the rear left wheel contains a 2HP Quasiturbine™ steam engine,[20] selected for its compact design and suitable power range for this 700-pound vehicle. The placement over the left wheel permits direct drive to that wheel via electric clutch and chain drive.

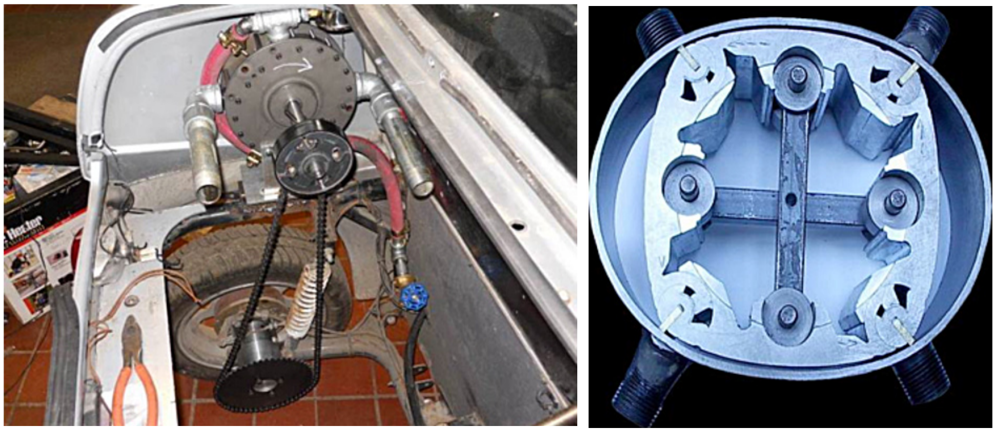


Figure 18

Quasiturbine™ Rotary Expander Installed and Interior View

In the center of center of this rear space, a heavily-modified propane space heater rated at 30,000–80,000 BTU/hr (equivalent to 11–31 boiler horsepower [bhp]) was installed. Heaters of this type generally are designed to efficiently distribute heat into an adjoining space. This heater was heavily modified with high temperature insulation and outer shells to retain useful heat to the 20-ft stainless steel coil passing through its core.

Figure 19

Quasiturbine™ Rotary Expander Installed and Interior View

Figure 20 shows the back of the vehicle with fenders and trim removed, revealing the expander and heater (with recent refinements). Also visible under the heater is the pressurized water tank (painted grey). The open space to left of the heater is reserved for drive components. The space to the right of the heater is reserved for recovery and recompression of the expanded propellant. (Recompression is outside of the current scope to simplify the testing and analysis. See discussion section for more information.) Other system components include air cylinders and electronic controllers that are mounted forward of the rear firewall in the cab or under the front hood.

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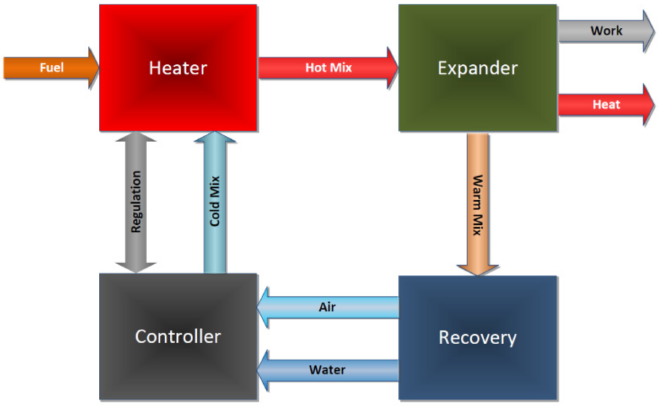
[20] Quasiturbine™ Product Details, http://quasiturbine.promci.qc.ca/.

Figure 20

Test Configuration

Figure 21

System Components



The main system components are shown. Minor components and linkage to mechanical output are not included in this report for the sake of simplicity.

Electronic Control and Measurement

No realistic progress toward a vehicle demonstrator with known and regulated fuel use can proceed without electronic regulation. In this build, the LabVIEW program and system components from National Instruments were used to create a "glass cockpit" of vehicle controls and performance measurement.[21] The simplified schematic in Figure 22 shows the planned integration of electronics in this development. LabView-compatible components will replace all mechanical flow and measurement components.

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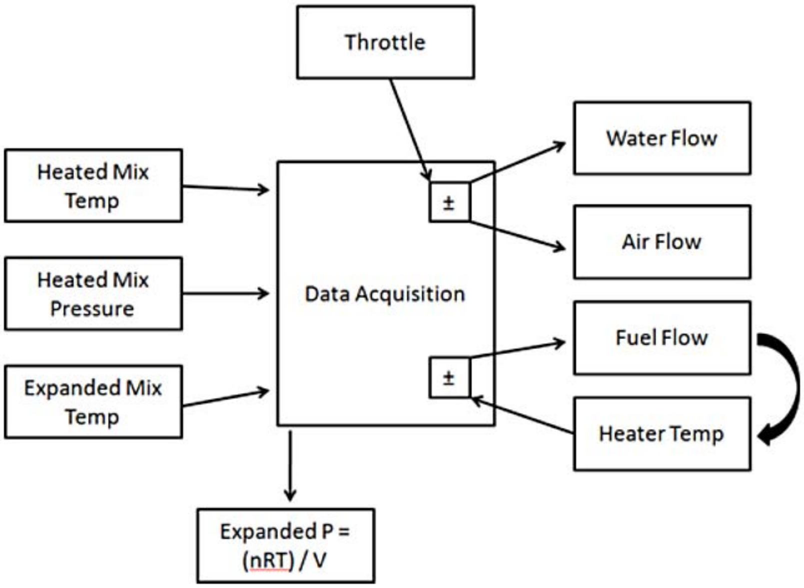
[21] More information can be found at National Insturments: The LabVIEW Environment http://www.ni.com/labview/.

Figure 22

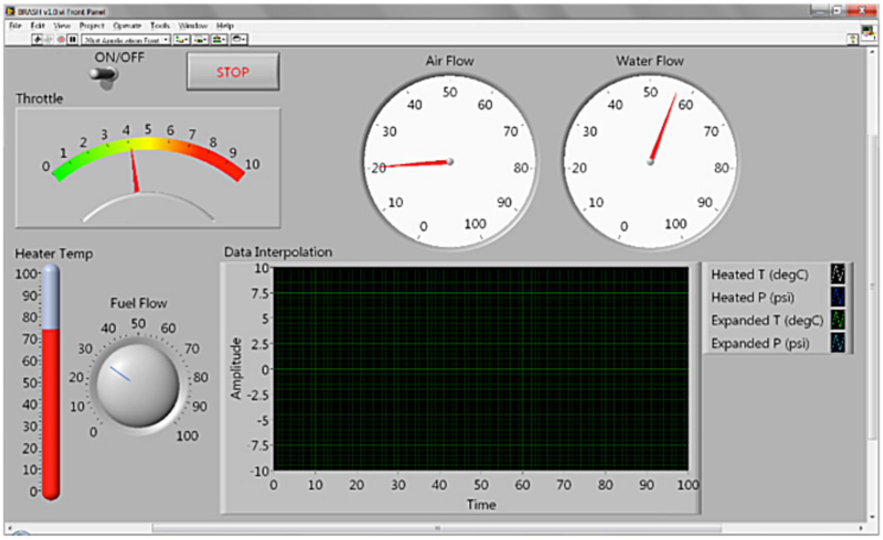
Electronics Schematic for Air-Steam Hybrid



For the vehicle driver, the dashboard collection of gauges has been replaced with a laptop screen similar to the one pictured in Figure 23.

Figure 23

Front Screen Display for Air-Steam Hybrid



Certain features on this front screen will reflect user input (On/Off, Throttle), while others reflect the dependent variables in the process (Heater Temp, Fuel Flow Air and Water Flow). Shown on the bottom screen will be running time-series data on speed, wheel load, temperature, specific fuel consumption and the other variables important to the analytical process. The front screen display is generated from programming and controls on the back screen display.

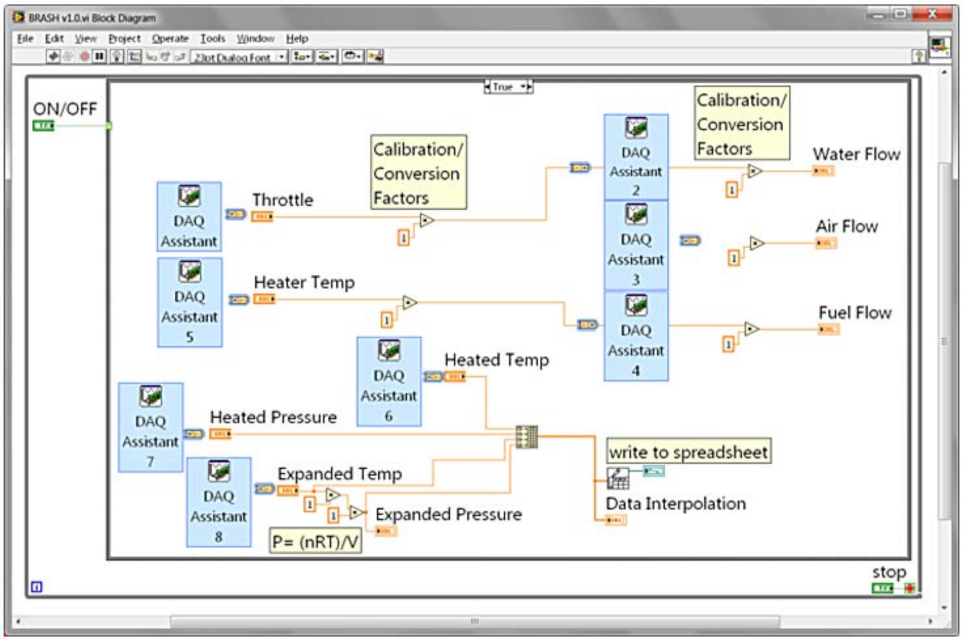


Figure 24

Back Screen Display for Air-Steam Hybrid

LabVIEW software and controllers were chosen because of National Instruments' status as the industry leader in rapid control prototyping and In-Vehicle data-logging solutions. BKi purchased the LabVIEW componentry through the University of Connecticut, Mechanical Engineering Department, as part of UConn's ongoing support of the project.

By the end of the contract term in October 2010, the air and water regulation components were complete and operational, but the fuel regulation and engine speed components were not yet fully operational. To generate the most meaningful data under these circumstances, the test vehicle was configured for extended operation to determine specific fuel, water, and air consumption rates. The combination of these rates provided the basis for initial estimates of power and efficiency.

Summary of Effort

Mechanical Modifications

1. Removal of original electrical drive components, reinforcement of frame
2. Installation of Quasiturbine™ 2HP engine; modified heater; pressurized water tank; all pneumatic, water, and fuel lines
3. Baseline validation testing using manual controls
4. Installation of electronically-regulated flow controllers

Electronic Modification

1. Acquisition of computer, electronic regulators, and control software
2. LabVIEW systems programming
3. System checkout

Testing and Analysis

1. Static Safety Testing
2. Baseline vehicle drivetrain testing
3. Vehicle static testing (Runs #3 & #5)

Summary of Requirements/Goals

1. Safe operation of vehicle during static and motive applications
2. Qualitative demonstration of BRASH engine capability to move test vehicle on flat and inclined road surface
3. Quantitative determination of air, water, and fuel consumption during timed static test
4. Quantitative determination of air, water, and fuel consumption while varying water and fuel fractions

Summary of Testing

Two experiments were performed in late November, the first to establish minimum fuel and propellant flow rates for sustained operation at low speed (air-rich mode), and the second to establish reasonable upper limits of fuel and propellant flow at higher engine speeds (steam-rich mode). Variation in the air-steam mix is the underlying theory of operation for the BRASH engine: the air fraction provides a baseline flow for initial start-up and low-speed operation, but the addition of water (as steam) to the propellant results in a significant boost in range and power. These two tests have verified this underlying theory.

Test Conditions

The two test runs summarized in this report are #3, on November 22, 2010, and #5, on November 26, 2010. Both tests were performed at the Depot D campus of the University of Connecticut in Storrs. The testing was performed outside in seasonal conditions: 45-50°F, with light winds.

Figure 25

Vehicle Test Setup

Each run was a dynamic test with no load on the two-cylinder Quasiturbine™ engine. The propane cylinder was suspended from a scale for the duration of the test. Propane fuel consumption was monitored continuously by digital scale with a display accuracy of 0.01kg.

Each test run lasted for the duration of one high pressure air cylinder. Air cylinder start (full) and end (empty) were determined at the start and finish of each run, using the same scale and accuracy. Water levels initially were determined volumetrically, but the results were too inconsistent. Displaced volume of liquid water proved a poor measure of the quantity heated to steam and carried forward for productive work. For this reason, water is an estimated quantity based upon fuel quantity burned, less heat absorbed by the air fraction. (Further integration of the LabView controller software in the next phase will obviate this work-around.)

Each of the complete test runs may be viewed at Brash Engines website, http://www.brashengines.com/. Photos from each run appear in the figures that follow. Tables 1 and 2 summarize the productive mass flow for air, water, and propane fuel to produce work from the engine for the test duration.

The cab interior in Figure 26 shows the high pressure air cylinder below the steering wheel and the laptop computer (regulating propellant flow) in passenger seat space. The LabView controllers reside in the protective case under the laptop.

Figure 26

Vehicle Cab with Controller Laptop

During each test, hot propellant was allowed to expand and vent to ambient, in order to simplify the thermodynamic model and analysis. (Note the plumes of water vapor from each exhaust hose and the small puddles of water under each hose in Figure 27.)

Figure 27

Exhaust Plumes from Expander

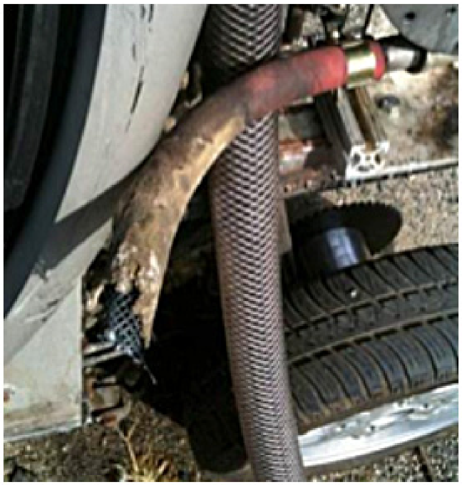
Development plans include recovering the expanded propellant, separating into water and air phases, and then recompressing the air fraction for re-use. This will both improve efficiency and eliminate the visible vapor plume.

Test Assumptions

Another estimation used in this study is the efficiency of heat transfer for the propellant, through the 20-ft coil of stainless steel, inside the insulated heater. Figure 28 shows an early "air-only" test run with the current heater. The hose failure and melting of the steel wire mesh inside (note formed ball in the mesh) indicates 1300°K temperatures exiting the hot section.

Figure 28

Hose Failure Due to Overheating



Effective heat transfer (as Figure 28 shows) does not equal efficient heat transfer, but the ability to deliver 1300°K air from a well-insulated burner suggests a highly efficient transfer of heat. The analysis of results assumes a value of 90% efficiency. (See Appendix A for a discussion of heat transfer efficiency.)

#3 Low Speed Test

On November 22, 2010, Run #3 tested the lower operating limits of the test setup. Low limit in this context meant sufficient pressure to maintain expander rotation, but low steam and fuel burn. The test commenced with a full air cylinder weighing 6.61 Kg. At the end of the test, the empty cylinder weighed 4.60 Kg. Over the 7 minutes and 15 seconds of testing, 0.06 Kg of propane was consumed.

The mass of air and fuel was determined from before/ after run test weights. As stated earlier, determining the quantity of steam produced from the pressurized water tank was problematic because of the quantity of stored water, the resistance to water flow under dynamic pressures, and the potential for some fraction of the water (in liquid state) to be entrained in the propellant mix.

To solve for this unknown, the energy required to raise the known quantity of air from ambient to 1000°K (3.3kcal/mol or 0.467 BTU/g) was subtracted from the energy content of the propane consumed (44 BTU/g), and then the efficiency of the heat transfer process was de-rated by 10 percent to yield a net quantity of 1438 BTUs to elevate ambient temperature water to 1000°K steam. The result is an estimated 12.5 grams of water consumed in the 7-minute test.

Table 1 summarizes these data and shows a high reliance on the air fraction for the work performed by the 2 HP engine. The air cylinder used in this test has a measured free volume of 45 cubic feet (1274 liters at STP), which means sustained flow rates of 6.2 cubic feet per minute (cfm) or 175 liters per minute. In contrast, the 12.5 grams of water, passed through as steam, produced an estimated equivalent gas volume of 15.5 liters at STP. Note the modest levels of water vapor in Figure 29. Why the greater air fraction, relative to water flow, in this test?

Table 1

Analysis of Mass Flow Data at Low Speed

11/22/2010 - #3 Low Speed Run, Air Pressure 60 psi, Water Head Pressure 60 psi

Component (BTU)	Start	End	Net	Energy[1] (BTU)	Power (BTU/min)	Power (HP)	Efficiency[3]
Air (Wt 0.00Kg)	**6.61**	**4.60**	2.01	938	**129.4**	3.0	**36%**
Water[2] (Wt 0.00Kg)			0.0125	1,438	**198.3**	4.7	**54%**
Propane (Wt 0.00Kg)	**15.62**	**15.56**	0.06	2,640	**364**	8.6	90%
Time (hr:mn:sc)	12.30.00	12:37:15	0:07:15	n/a	n/a		

[1] Energy value based upon absorbed heat (italicized) from STP to 1000°K (0.446 BTU/g for Air, 115 BTU/g water).

[2] Determined by difference from propane and air energy, assumed value @ 90%.

[3] Arbitrary estimated efficiency of heat transfer, not effective work.

Figure 29

Low-Speed Test Results in Little Water Vapor

In this baseline experiment, the single cylinder provides 60 psi air flow and 60 psi static "head" pressure on the water column. The air flow from the cylinder is biased toward the generally less restrictive flow path for air. The water column under the same pressure presents a higher viscosity medium, passing through a greater number of valves and restrictions. At the point of injection, the air fraction flows more freely into the hot section. In order to bias the mix toward greater water fraction (and greater power), the head pressure on the water column must be increased over the 60 psi air line pressure.

Run #4 (not documented here) evaluated head pressures from 110 psi to 70 psi and determined that modest differential pressures retarded the flow from the air fraction and boosted flow of the water fraction. Still higher differential pressures effectively stopped air flow altogether, reverting the engine operation to "steam only." For Run #5, an additional cylinder was used to apply a 70 psi static head pressure on the water column, a 10 psi differential over the 60 psi air line pressure.

#5 Variable High Speed Test

On November 26, 2010, Run #5 tested the higher differential water pressure as a means to increase the effective water fraction in the propellant mix. The test commenced with a full air cylinder weighing 6.54 Kg. At the end of the test, the empty cylinder weighed 4.72 Kg. Run #5 was interrupted after 2:43 minutes to refill the water tank, and then testing resumed for an additional 9:07 minutes. Over the whole test, 0.27 Kg of propane was consumed.

Using the same analytical basis as Test #3, Test #5 data indicate a substantial increase in work capacity (as measured by fuel consumed and steam generated) over the #3 baseline.

Table 2

Test #5 Results with Increased Water and Fuel

11/26/10 - #5 Variable High Speed Run, Air Pressure 60 psi, Water Head Pressure 70 psi

Component (BTU)	Start	End	Net	Energy[1] (BTU)	Power (BTU/min)	Power (HP)	Efficiency[3]
Air (Wt 0.00Kg)	6.54	4.72	1.82	*849*	71.8	1.7	7%
Water[2] (Wt 0.00Kg)			.0860	*9,890*	835.8	19.7	83%
Propane (Wt 0.00Kg)	15.20	14.93	.27	<u>11,880</u>	1,004	23.7	90%
Time (hr:mn:sc)	13.30.00	13:41:50	0:11:50	n/a	n/a	n/a	n/a

[1] Energy value based upon absorbed heat (*italics*) from STP to 1000°K (0.446 BTU/g for Air, 115 BTU/g water). <u>Underlined</u> value is released heat at generally accepted 44 BTU/g.

[2] Determined by difference from propane and air Energy, assumed value @ 90%.

[3] Arbitrary estimated efficiency of heat transfer, not effective work.

The increase in pressure on the water column by 10 psi reduced air flow by 9 percent but increased the steam fraction considerably and thereby increased the effective boiler horsepower nearly three-fold to 23.7 bhp (assuming 90% heat transfer). These data are summarized in Table 3.

Table 3

Comparison of Mass Flows, Runs #3 and #5

Component	Run #3 BHP	Run #5 BHP	Net Chng BHP	Run #3 Mass Transfer (kg)	Run #5 Mass Transfer (kg)	Net Change Mass Transfer (kg)
Air	***3.0***	***1.7***	-45%	2.010	1.82	-9%
Water	***4.7***	***19.7***	422%	0.013	0.086	588%
Propane	**<u>8.6</u>**	**<u>23.7</u>**	276%	0.060	0.270	350%
Duration (mn)	7.25	11.80	163%	7.25	11.80	163%

This difference in steam fraction and power is more clearly seen in Figure 30 (and on the source video at the Brash Engines website).

Figure 30

Three Images from Run #5

As with Run #3, start up from Time Zero was immediate: burner on, air flow begins, and water flow under pressure commences immediately. Another impressive feature of the mix air-steam propellant system is the ability to start, stop and rapidly accelerate, as shown in the full Run #5 video. Run #5 serves as validation that this patented technology has unique performance benefits over air, steam, or internal combustion alone.

Lessons Learned

A comparison of the two test runs verifies some key points:

1. The same power plant can produce variable power and fuel economy based upon power demand and air/steam mix.
2. Although imprecise at this point in testing, fuel consumption appears directly proportional to engine speed. The engine/expander will spool up, spool down, stop and restart in a manner consistent with fuel and propellant flow. The Run #5 video on the Brash Engines website verifies this conclusion.
3. The use of a defined static air pressure "head" over the water column, at a pressure higher than the defined air line dynamic pressure, provides a safe and predictable bias toward flow from the water fraction.
4. Although the current test configuration offers sufficient performance for this initial demonstration phase, the following observations are in order:
    a. The heater path is too long, creating latent response issues.
    b. The air/water injector is not optimized for proper mix or flow capacity.
    c. The incomplete integration of LabVIEW compromises the quality of data.
    d. The absence of a measured variable load on the expander compromises any analysis of power and fuel economy.

5. The design migration to a vehicle installation was premature. The project should move back to a lab bench study to refine the regulation of components, complete the recovery and recompression portions of the system, and use electromechanical loads to estimate power and useful work for specific quantities of fuel, water, and air.
6. The Quasiturbine™ engine technology is promising but too immature for larger-scale modeling. Later phases of the project should rely on more conventional multi-cylinder piston-type expander.

Estimated Fuel Economy

Mass transit authorities have relied on large diesel engines, such as the Detroit Diesel Series 50 and Series 60 engines, for more than 30 years. Reports on fuel economy vary from a high of 6.0 miles per gallon (Diesel) for longer-range commuter services in California[23] to a low of 2.28 miles per gallon (Diesel) for city buses with frequent stops in New York City.[24] In both cited studies, the migration to compressed natural gas (CNG) has resulted in lower fuel economies on a Diesel Gallon Equivalent (DGE) basis.

Table 4 summarizes this study (columns 2 and 3) and the next proposed phase (columns 4 and 5), the performance of the current fleet of mass transit buses (columns 6 and 7), and the likely outcome if the Besler engine (described earlier) were employed with the air-steam hybrid technology (columns 8 and 9).

Table 4

Comparison of Fuel Economies

1	2	3	4	5	6	7	8	9
Example	***#3***	***#5***	***Bench***	***S-10***	***SB Bus***	***NYCT***	***@50% eff***	***@30% eff***
Air	8.6	23.7	40	80			300	500
Configuration	Current	Current	UC #1	UC #2	MC1102			
Engine	Quasi	Quasi	6 cyl	6 cyl	DD S.60		Besler	Besler
HP	2	2	20	40	350		150	150
Torque					1450		1200	1200
Fuel	Prop	Prop	Prop	Mix	Diesel	Diesel	Mix	Mix
g/min	8.2	23	40	80	540		300	500
BTU/hr	21.6	60.7	105.6	211.2	1140.0		792	1320
GGE/hr	0.2	0.5	0.9	1.9	10.0		6.95	11.58
mpg @ 60mph	316.0	112.6	64.8	32.4	6.0	2.3	8.64	5.18
GGE/100 mi	0.3	0.9	1.5	3.1	***16.7***	***43.9***	***11.58***	***19.30***
$ per GGE	3.0	3.0	3.0	3.0	3.5	3.5	1.6	1.6
$/100 mi	0.9	2.7	4.6	9.3	***58.3***	***153.5***	***18.53***	***30.88***

The Besler engine is shown in two columns. The left column reflects the higher efficiency anticipated with the air-steam hybrid mix, described earlier as at or near 50 percent. The right column reflects the historical efficiency realized with steam engine technology. The italicized numbers near the bottom of the column show that even at historical efficiencies, the Besler engine would offer equal or better Gasoline Gallon Equivalent (GGE)/100 mile ratings of the current diesel technology, but migrating toward less refined and (therefore) less expensive fuels would significantly reduce the operating cost ($/mile).

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[23] Demonstration of Caterpillar C-10 Dual-Fuel Engines in MCI 102DL3 Commuter Buses, National Renewable Energy Laboratory, http://www.nrel.gov/docs/fy00osti/26758.pdf, p. 7.

[24] R. Barnitt, "New York City Transit (NYCT) Hybrid (125 Order) and CNG Transit Buses Final Evaluation Results," November 2006, National Renewable Energy Laboratory K. Chandler Battelle, Technical Report NREL/TP-540-40125 November, 2006, http://www.nrel.gov/vehiclesandfuels/fleettest/pdfs/40125.pdf, p.*vii*.

There are, of course, two orders of magnitude difference between the results of Runs #3 and #5 and the daily demands of city and commuter buses, but the mere existence of the Besler Twin and the Brooks V-8 400 HP engine suggests an opportunity for fuel economy and fuel variety.

Proposed further support for the next phase of development will advance the air-steam hybrid technology by an important order of magnitude. This would provide the data confidence to scale to larger vehicle operation and garner the interest of one or more engine or vehicle OEMs.

Figure 31

MTA/New York City Transit Orion VII Next Generation Hybrid Transit Bus

Next Development Phase

The next phase of development will incorporate a modern six-cylinder steam engine design with a displacement of 53 cubic inches and capable of sustained 15-25 HP operation. The expander will be supplied by Steam Engine Power, Inc. (http://www.steamenginepower.com). This expander will drive an alternator/generator to measure effective work output in watts, as well as provide sufficient power to satisfy the system parasitic loads of battery recharge, exhaust air recompression, and all other pump and valve operations.

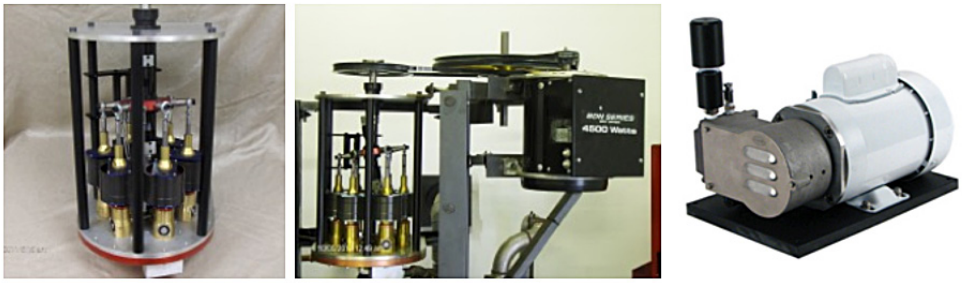

Figure 32

(l to r): Six-Cylinder Expander, Power Generation Load, Small 24 VDC Compressor

Static pressure for the water column will still be supplied via compressed air cylinder, but the dynamic air flow will be supplied by an oil-less air compressor of the size and type shown. This 24 VDC compressor will recompress the recovered air exiting the expander to 40–60 psi pressure and support flows of 3–4 cubic feet per minute (cfm). These three components are off-the-shelf enhancements to the system, but custom engineering of a new more powerful and more responsive heater, completion of the electronic integration, and design and fabrication of the recovery/recompression components are necessary tasks that must be included to make the next generation assembly work to its potential. This work will be accomplished largely by Mechanical and Electrical Engineering students at the University of Connecticut, under the supervision of faculty and Brash Engines personnel.

When this build is complete, all operations will be under LabVIEW control. All expander operations will be measured for power and work. Once the bench version is in control, a modified version will be installed in a small pickup truck (e.g., Chevrolet S-10) for further verification of system performance and robustness.

During this phase, a new and promising technology will be investigated: a new and faster class of solenoid valves from National Instruments. These solenoid valves, with an unprecedented 3 msec response time, have the potential of allowing air-steam retrofit in existing engine blocks. The solenoid valves could replace the spark plugs in conventional IC engines and provide the equivalent timed injection of hot propellant mix as the timed firing of a spark plug in the presence of a fuel air mix.

If possible, these fast solenoids, and the black box programming to control them, could allow very easy portability to larger vehicles, and easier retrofit. Potentially, a V-6 engine could operate 4 cylinders for expansion, and the remaining two cylinders could be used as direct drive compressors with different, but equivalent, solenoid valves controlling the compression process.

SECTION
5

Development Plan and Next Steps

This current effort is a key first-proof of concept for this air-steam hybrid technology, but our goals extend well beyond this two-seat, 2 HP demonstrator. The lessons learned in electronic integration will allow rapid migration to larger platforms, using the same basic controls but scaling the expander, heater, and other mass-flow components to vehicle-appropriate size. That project, identified as "20 HP Vehicle" and other near-term derivative projects are listed in Table 5.

Table 5

Project Funding Summary

BRASH Project	Proposed Funding Source	Funds Req'd $K	Project Description
20 HP Vehicle	DOT/USPS	300	SUV-size proof-of-concept for reliable highway performance, mail/delivery vehicle size
200 HP Vehicle	DOT/DOD	600	Proof-of-concept mass transit bus-retrofit, scaled to city bus capacity and suitable for replacement of over-the-road diesel engines
Stationary Power Unit: Micro-CHP Equivalent	DARPA	300	Proof-of-concept mass transit bus-retrofit, scaled to city bus capacity and suitable for replacement of over-the-road diesel engines
Alternative Processed Solid Fuel	DOE EPA DOA	600	Processed mix of hydrolyzed wood pulp, processed solid waste, and other combustible solids in an extrudable mass with alcohol solute/vehicle—demonstrate utility in vehicles as a high energy content, clean burning fuel for EC engines
Binary Solid/ Gas Fuel	EPA / Waste Management/ BFI	400	Demonstrate effective pyrolysis of processed solid fuels in a binary fuel burner; conventional fuel (gasoline, natural gas) provides primary heat source for pyrolysis temperatures.
Proof of Concept OEM Power Plant	Vehicle OEM (e.g., Ford, GM Caterpillar)	1200	Development of direct replacement BRASH engine alternative to existing OEM IC engine
Black Box Integration of Controller Software	Vehicle OEM (e.g., Ford, GM Caterpillar)	1600	Development of commercial BRASH system alternative to existing OEM IC engine

The issuance of U.S. Patent #7,743,872 five months ago has two important consequences for this project. First, it serves to validate the underlying technology: the combination of air and steam in an EC engine is better than steam or air alone. Second, it provides a basis for full and open discussions with government agencies and large commercial interests in the transportation and power sectors.

Our efforts at promotion have been delayed, pending successful demonstration of the Smart™ car vehicle to allow the first detailed real-world performance data to be distributed.

Coupling that performance data with the option of migration away from refined petroleum should spark significant interest. If we can move to a high lignin-processed wood pulp that costs $0.45 per gasoline gallon equivalent (an arbitrary value for example only) and consumes more CO_2 while growing than is consumed in processing as a fuel and produced from combustion, then we succeed as a project and as a global game-changing technology for many uses. Improvements in fuel economy are important, but of greater importance is the migration to low-process biomass fuels.

SECTION

6

Potential Applications and Societal Value

The whole premise behind the BRASH air steam hybrid is that external combustion offers a more benign and environmentally-appropriate way to power large vehicles and other portable equipment than refined petroleum-powered internal combustion:

- Combustion heat can be derived from any fuel source, including processed solids from fast-growing renewables such as poplar trees, waste corn stalks, or switch grass.
- That combustion heat is applied at a rate consistent with the work to be done, and not to support idling and other unproductive fuel use.

Using a mix of air and steam as working fluids in the engine allows:

- Immediate startup from an "air-only" start
- Managed system pressure through use of a defined head air pressure
- Managed fuel burn as the air-steam fraction is adjusted to match wheel load
- Adjusted wheel load reduces fuel burn

Integration of modern control circuitry with external combustion also brings a level of performance, operational simplicity, and safety heretofore unavailable.

SECTION

7

Phase I Conclusions

The last steam train in scheduled service in the U.S. departed on October 11, 1962.[25] One year earlier, Robert Noyce received the first patent for an integrated circuit.[26] But for that brief one-year overlap, the most powerful motive power technology was never harnessed by the black box controls that grew out of Noyce's invention, so the diesel-powered IC engine, championed by Henry Ford, won out.

Now, nearly 50 years later, the modern IC engine cannot operate efficiently without the benefit of black box electronics—but that technology still presents intractable challenges of supply, safety, and environmental impact. The air-steam hybrid technology may offer an alternative, and a glimpse of that potential is presented here and viewable in Run #5 on the Brash Engines website at http://www.brashengines.com/.

While demonstration in a test vehicle provides a strong visual message that BRASH technology works, the commercial success of this technology will depend upon reliable, repeatable measurement of power and economy. For that data, the Phase 2 effort will require a return to laboratory bench testing and effective demonstration of recovery of the water and air fractions.

The results of this Phase I project collectively demonstrate the technical feasibility and commercial potential of the BRASH air-steam hybrid engine technology. The initial DOT SBIR funding has been highly effective in facilitating this important proof of concept and laying the groundwork for further technology refinement and application.

As described earlier, the next steps are clear and appear to combine achievable and rapid major advances with low developmental risk. SBIR Phase 2 support is needed for those advances, due to the still-early stage of development that restricts access to private capital.

The immense potential value of this technology has been enhanced and verified in Phase I; there is now a clear and low-risk path ahead to larger-scale testing, further component and controls refinement, specific applications prototyping, and pre-commercial deployments.

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[25] William Rosen, *The Most Powerful Idea in the World*, Random House, 2010, p. 311.

[26] U.S. Patent 2,981,877.

APPENDIX

A

Heat Transfer Efficiency, Modeling Runs #3 and #5 @ 50% and 90%

Much of the analysis for Runs #3 and #5 is based on an assumed efficiency of 90% for heat transfer from the combustion of propane to heating of the water/air mix in the coil. As a test for the reasonableness of that assumption, the same data have been modeled at a much lower 50% factor below:

11/22/10 - #3 Low Speed Run, Air Pressure 60 psi, Water head pressure 60 psi

Component (BTU)	Start Wt	End Wt	Net Wt	Energy[1] (BTU)	Power (BTU/min)	Power (HP)	Efficiency[3]
Air (Wt 0.00Kg)	6.61	4.60	2.01	938	129.4	3.0	36%
Water[2] (Wt 0.00Kg)			0.0125	380	52.3	1.2	14%
Propane (Wt 0.00Kg)	15.62	15.56	0.06	**2,640**	364	8.6	50%
Time (hr:mn:sc)	12.30.00	12:37:15	0:07:15	n/a	n/a	n/a	n/a

#5 Variable High Speed Run, Air Pressure 60 psi, Water head pressure 70 psi

Component (BTU)	Start Wt	End Wt	Net Wt	Energy[1] (BTU)	Power (BTU/min)	Power (HP)	Efficiency[3]
Air (Wt 0.00Kg)	6.54	4.72	1.82	849	71.8	1.7	7%
Water[2] (Wt 0.00Kg)			0.0440	5,060	427.6	10.1	43%
Propane (Wt 0.00Kg)	15.2	14.93	.27	**11,880**	1004	23.7	50%
Time (hr:mn:sc)	13.30.00	13:41:50	0:11:50	n/a	n/a	n/a	n/a

[1] Energy value based upon absorbed heat (italics) from STP to 1000°K (0.446 BTU/g for Air, 115 BTU/g water) Underlined value is released heat at generally accepted 44 BTU/g.

[2] Determined by difference from Propane and Air Energy, assumed value @ 90%.

[3] Arbitrary estimated efficiency of heat transfer, not effective work.

The two known quantities in each run is the weight of the air moving through the system and the weight of the propane heating that air. The variable is the quantity of water heated to steam temperatures and above. In Run #3, at 90% efficiency, that mass of water calculates to 12.5 grams; at 50% it drops to 3.3 grams. In Run #5 at 90% efficiency, that mass of water calculates to 86 grams; at 50% it drops to 44 grams.

As the comparison tables below show, the uncertainty in the efficiency of heat transfer is manifest only in the mass of water heated to steam to do useful work.

Data @ 90% Efficiency

Component	Run #3 BHP	Run #5 BHP	Net Chng BHP	Run #3 Mass Transfer (kg)	Run #5 Mass Transfer (kg)	Net Change Mass Transfer (kg)
Air	3.0	1.7	-45%	2.010	1.82	-9%
Water	4.7	19.7	422%	0.013	0.086	588%
Propane	8.6	23.7	276%	0.060	0.270	350%
Duration (mn)	7.25	11.80	163%	7.25	11.80	163%

Data @ 50% Efficiency

Component	Run #3 BHP	Run #5 BHP	Net Chng BHP	Run #3 Mass Transfer (kg)	Run #5 Mass Transfer (kg)	Net Change Mass Transfer (kg)
Air	3.0	1.7	-45%	2.010	1.82	-9%
Water	1.2	10.1	817%	0.003	0.044	1233%
Propane	8.6	23.7	276%	0.060	0.270	350%
Duration (mn)	7.25	11.80	163%	7.25	11.80	163%

Regardless of the specific efficiency, Run#3 reflects an air-rich propellant mix, while Run #5 was clearly the more powerful and steam-rich propellant. If 50% efficiency is a more realistic figure than 90% , the only consequence is more water passing through the heater, expander, and recovery tank. The only consequence for overall system efficiency is the slight but added work required to move the additional water, by pump, to the top of the water column.

APPENDIX

B

Acronyms

BHP	Boiler Horsepower
BRASH	Binary Recovery, Air-Steam Hybrid
BTU	British Thermal Unit
CC	Cubic centimeter
CFM	Cubit feet per minute
CHP	Combined heat and power
CNG	Compressed natural gas
CO_2	Carbon dioxide
CU	Cubic
DARPA	Defense Advanced Research Projects Agency
DGE	Diesel gallon equivalent
DOT	Department of Transportation
EC	External combustion
EIA	Energy Information Administration
EPA	Environmental Protection Agency
FTA	Federal Transit Administration
GGE	Gasoline gallon equivalent
HP	Horsepower
IC	Internal combustion
K	Kelvin
Kcal	Kilocalorie
MPG	Miles per gallon
MPH	Miles per hour
OEM	Original equipment manufacturer
PSI	Pounds per square inch
RPM	Revolutions per minute
SBIR	Small Business Innovation Research
STP	Standard temperature and pressure

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