MINIATURE INTERNAL COMBUSTION ENGINE-GENERATOR FOR HIGH ENERGY DENSITY PORTABLE POWER

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ABSTRACT

Miniature internal combustion engine/generators provide high energy density for portable power applications, potentially exceeding 1500 Whr/kg for a 72 hr mission. Operation on JP-8 from cold startup to steady operation has been demonstrated at the 300 W scale. Miniature engine/generators can be acoustically silenced for low noise operation.

1.0 INTRODUCTION AND MICE GENERATOR BACKGROUND

Portable electric power is an essential element of the Objective Force. Communications, smart weapons, night vision equipment, and many other tools used by the Objective Force Warrior require portable power. This power is currently supplied by batteries, though the low energy density of batteries significantly limits the duration of missions and represents a substantial fraction of the weight of the load that is carried. A portable power technology having much higher energy density would greatly enhance the ability of the Objective Force to be sustainable, deployable, and responsive.

An alternative to battery technology that has received significant interest and support in the past decade is fuel cells, both PEM and SOFC technologies. PEM fuel cells require methanol fuel unless a reformer is included to allow operation on JP-8. PEM fuel cells are costly because of their use of platinum or other precious metal catalysts. SOFC units can use JP-8, but generally require sulfur to be removed from the fuel prior to delivery to the fuel cell. SOFC units are also limited in the number of on/off cycles before performance degrades significantly. PEM fuel cells offer energy densities that are two to three times that of rechargeable lithium ion batteries for a 72 hour mission, while SOFC units have energy densities that are about twice as high as PEM fuel cells. However, the inability to use JP-8 fuel directly, their high cost, and their limited life (SOFC) are significant impediments to the widespread use of fuel cells in military operations. A technology that avoids these impediments and offers two to three times higher energy densities than PEM fuel cells, but has not attracted the level of interest and support as fuel cells, is internal combustion (IC) engine-generator technology. *IC engine-generator technology can use logistics fuels directly at high efficiency and low cost, and, contrary to expectations, can be designed to have have low acoustic, exhaust, and thermal emissions.*

Aerodyne Research, Inc. (ARI) is developing an innovative motor-generator, consisting of a miniature linear engine coupled with a linear electric alternator, that takes advantage of the high energy content of hydrocarbon fuels while eliminating most of the parts found in a standard internal combustion engine-generator set. This technology, the MICE (Miniature Internal Combustion Engine) generator, has been developed by ARI into a patented design (Annen, et al., 2003), shown in Figure 1.

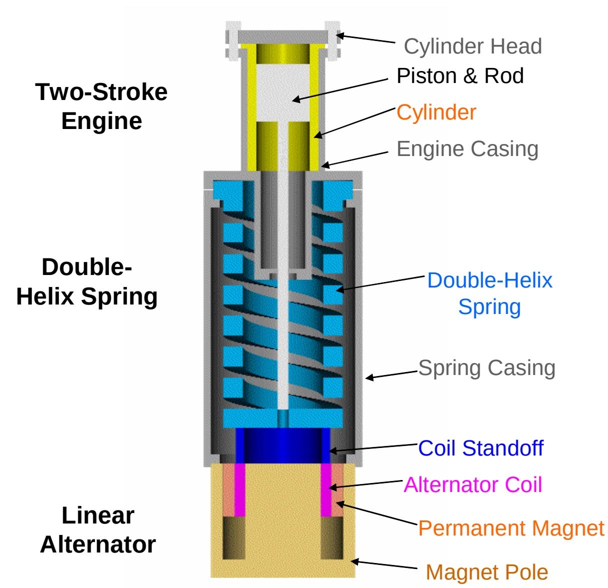

Figure 1 MICE Generator Design

The basic MICE design consists of a free piston two-stroke engine, a spring, and an alternator in a linearly oscillating configuration. MICE is inherently an electric power generator, since there is no mechanical linkage with which to extract power. Pure linear motion is ensured by the use of a unique double helix or multiple helix spring. The pure linear oscillation provides sliding motion with no side forces. Thus, MICE has low frictional losses since there are no bearing surfaces having a direct load. The complexity and cost of the rotary components in the conventional crankshaft-rod-piston arrangement are eliminated, thus also removing the typical failure point in small engines. The low friction characteristics and absence of stresses generated by direct loads allow MICE to operate at very high cycle speeds, leading to high energy and power density,

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particularly at smaller size scales. The pure linear motion, in addition to having low frictional losses, may allow operation with little or no oil lubricant, using a solid film lubricant instead.

Major differences exist between the MICE two-stroke engine and conventional engines. The key difference is that MICE is a free piston design that uses a spring for energy storage. MICE is a high Q system, operating at the resonant frequency of the spring-mass system with very low frictional losses. The free piston design of the MICE generator provides a variable compression ratio and enables the easy use of homogeneous charge compression ignition (HCCI) combustion. HCCI combustion gives the MICE generator its low exhaust emissions and high efficiency characteristics, as well as its multifuel capability including demonstrated JP-8 operation at small size scales (Annen, et al., 2006). The single frequency operation of the MICE generator allows highly effective tuning for good scavenging and low exhaust noise. In addition, very quiet operation can be achieved with specially designed acoustic packaging.

The important features of the MICE concept are therefore:

- Free piston design and variable compression ratio
- Low frictional losses, because of no bearing surfaces with an applied load
- High piston speed and cycle speed giving high power density at small size scales
- Compact, low weight package because the alternator is integrated in the system
- Potential to operate without oil lubrication
- HCCI combustion giving high efficiency, low exhaust emissions, and multifuel capability including JP-8
- Very low noise capability.

2.0 MICE GENERATOR DEVELOPMENT STATUS AND TEST DATA

ARI is developing the MICE generator in three power ranges. Figure 2 shows the 5 - 10 W MICE generator, developed as an alternative power source for micro air vehicles, next to the 300 - 500 W MICE generator which is designed to use both heavy (JP-8, diesel) and light (propane, butane) fuels. An AA battery and ruler provide a dimensional reference. The 300 - 500 W MICE generator in Figure 2 has a diameter of 80 mm (3.1") and a height of 285 mm (11.2"). Extensive testing has been performed on the 300 - 500 W MICE generator using both propane and JP-8 fuels. The third size range, a 100 W MICE generator, was originally developed for the powered prosthesis application under AMRMC STTR funding. The 100 W MICE generator, which was designed to operate with a butane or propane fuel cartridge, is shown in Figure 3 with a military BB-390 battery (5 inch height) for relative size comparison. The 100 W unit has a diameter of 36 mm (1.4") and a height of 130 mm (5.1"). Operation on JP-8 is possible at this size scale with further development. A 100 hour test of the 100 W spring and alternator components was recently completed, and combustion testing of the100 W MICE generator is currently in progress.

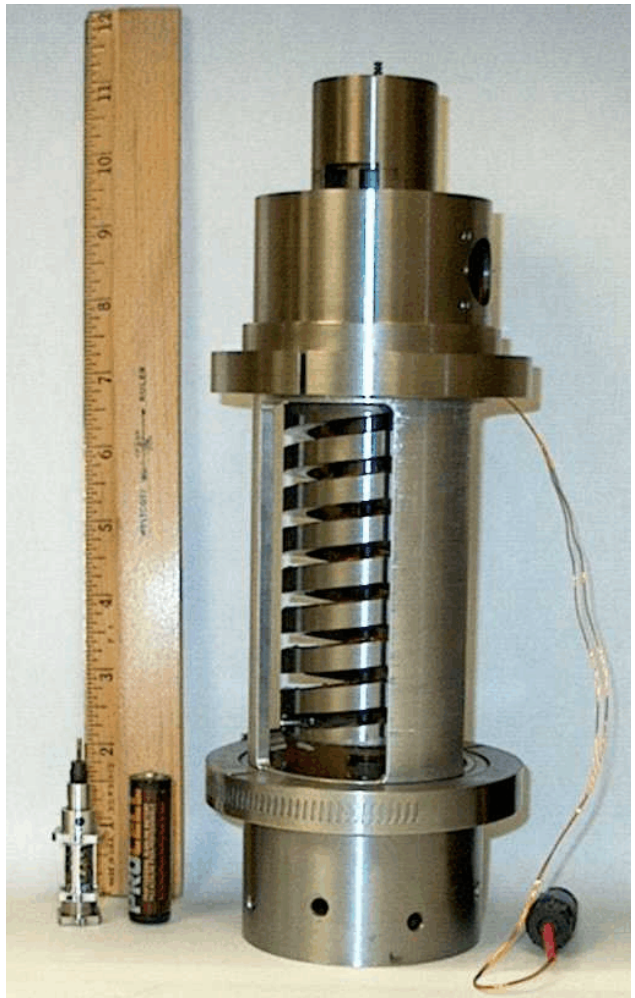

Figure 2 Nominal 300 W and 5 W MICE Generators with AA Battery

2.1 300 W MICE Generator Test Data

We have run our nominal 300 W MICE generator over a wide range of conditions on both propane and Jet-A (a JP-8 surrogate) fuels. The typical cycle frequency at the 300 W power level was 115 Hz, giving a cycle time under 9 ms. Scavenging ratios ranged from 0.85 down to as low as 0.25. (Scavenging ratio defined here as the volume of reactant mixture delivered to the cylinder per cycle divided by the trapped volume of the cylinder.) Equivalence ratios ranged from Φ=0.5 (fuel lean) to Φ=1.35 (fuel rich). Air preheat temperatures ranged from 45°C to 165°C. The geometric compression ratio in most tests was typically between 7 and 9, though the compression ratio at startup on

Figure 3 100 W MICE Generator with BB-390 Battery

propane is typically 4, and the compression ratio exceeded 15 on Jet-A tests. (The actual compression ratio is lower due to leakage between the piston and cylinder.) The high level of exhaust fraction in the cylinder under our typical operating conditions has the effect of greatly reducing the laminar flame speed so that flame propagation cannot be supported. Mixtures having an exhaust fraction, x_b, of 0.39 or higher are projected to have zero laminar flame speed, S_L, based on the correlation of flame speed with exhaust fraction (Heywood, 1988):

$$S_L(x_b) = S_L(x_b\!=\!0)\ (1. - 2.06\ x_b^{0.77})$$

Thus, HCCI combustion with glow plug assist is the type of combustion occurring in the MICE generator.

Figure 4 plots the residual exhaust fraction (1 - scavenging ratio) and the equivalence ratio for combustion conditions from 30 tests with the MICE generator. Also plotted in Figure 4 is the exhaust fraction

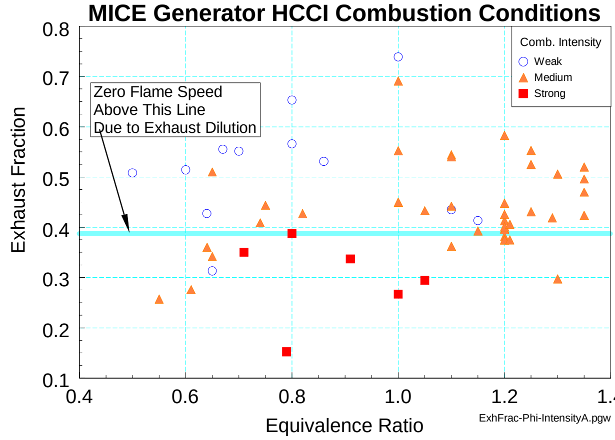

Figure 4 HCCI Combustion Test Conditions. *(Exhaust Fractions Above 0.39 Have Zero Laminar Flame Speed)*

level at which the flame speed is extrapolated to be zero from the above correlation. Figure 4 clearly indicates that the majority of the test conditions could not support flame propagation, thus HCCI combustion is the operative combustion mechanism. We note that for most conditions, glow plug assist is currently necessary to sustain combustion during starting and warmup. The glow plug supplies sufficient heating of the local reactant mixture to shorten the ignition delay and initiate local combustion. The additional pressure rise and compressive heating from this local combustion shorten the ignition delay in the remainder of the mixture, promoting combustion throughout the compressed volume.

Startup of the MICE generator with HCCI combustion requires raising the temperature of the compressed mixture to a level high enough so that a short ignition delay is achieved and strong combustion is obtained. This is achieved by a combination of compressive heating, preheating the inlet air, glow plug heat input, and adjustment of the equivalence ratio to shorten the ignition delay. HCCI combustion at startup is frequently characterized by delayed

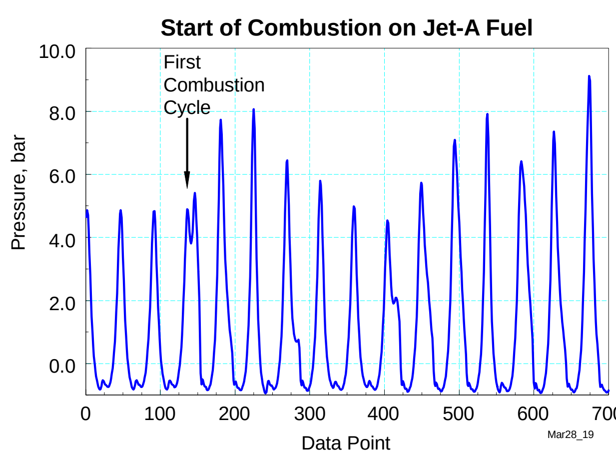

Figure 5 Pressure Data Showing Delayed Combustion in First Combustion Cycle on Startup with Jet-A Fuel

ignition since the compressed mixture temperature is just sufficient to support combustion. Figure 5 shows a segment of cylinder pressure data during startup on Jet-A fuel. The first cycle on which combustion occurred was at data point 150, and this pressure trace shows a double peak caused by delayed ignition on the expansion stroke. The next two cycles showing combustion, at data points 275 and 400, also show delayed ignition that can be visually detected in the pressure trace. After this third delayed ignition cycle, the succeeding cycles show little or no delayed ignition. The most likely cause of the reduced ignition delay for the next several cycles is the increase in reaction rate produced from combustion radicals present in the residual exhaust. Further reductions in the ignition delay would be produced by the increase in compression ratio as the stroke increases due to power output from the two-stroke engine. On a slower time scale, the increase in inlet temperature due to the increase in the engine temperature will produce an additional reduction in the ignition delay.

We have recently upgraded the engine control electronics to allow a rapid modulation of the alternator load in response to cycle-to-cycle variations in the combustion pressure so that the alternator voltage and stroke are kept nearly constant. Figure 6 shows generator current and combustion pressure data from the engine warm up portion of test with our new electronics. Figure 6 includes data for the voltage, which is linearly proportional to the engine stroke, the current, which is modulated by the engine control, and the combustion pressure. The engine control is seen to be very effective at maintaining a constant voltage and stroke as the HCCI combustion pressure varies during engine warmup. The current is modulated by the engine control to maintain constant stroke, compensating for modest cycle-to-cycle variations in the engine power output.

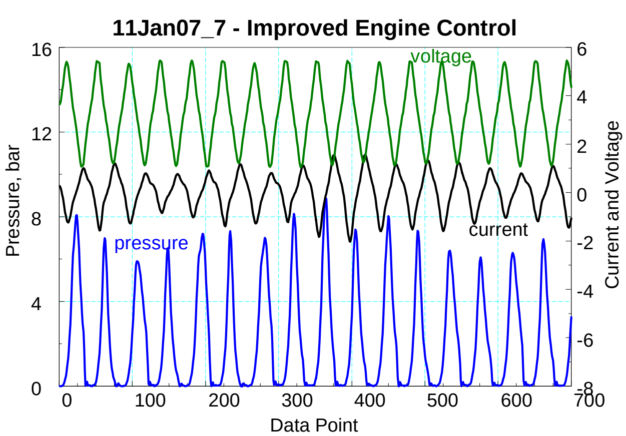

Figure 6 Voltage, Current, and Pressure Data from Test with Improved Electronic Engine Control

Calculations of the two-stroke engine power output were performed for Jet-A and propane combustion conditions to compare with measured power output from tests with the 300 W MICE generator. In a Jet-A test having a scavenging ratio of 0.67 and an equivalence ratio of Φ=0.67 (fuel lean) at a cycle frequency of 110 Hz, an electrical power output of 185 W was measured. Since the alternator efficiency for this MICE generator is measured to be 94%, the mechanical power output of the two-stroke engine for this test was 197 W. In comparison, our two-stroke engine model predicts a mechanical power output of 244 W for these conditions. Thus, the MICE generator achieved 81% of its "rated" power output on Jet-A fuel in this test. Figure 7 shows these measured and predicted power output data points overlaid on calculated curves of power vs. scavenging ratio from our two-stroke engine model. We believe that two main factors are responsible for this modest shortfall in power output. One factor is that the leakage between the piston and cylinder is higher than we designed for, primarily due to thermal expansion differences between the piston and cylinder that we plan to address. The other is that, in part due to this higher leakage, the combustion efficiency is lower than the 95% value used in the two-stroke engine model.

Similar calculations were performed for a propane test having a scavenging ratio of 0.67 and an equivalence ratio of Φ=1.0, also at a cycle frequency of 110 Hz. The electrical power output in this test was measured to be 220 W, giving a mechanical power output of 234 W. Our two-stroke engine model predicts a mechanical power output of 271 W for these conditions, so the MICE generator achieved 86% of its "rated" power output in this test. These measured and predicted data points are also shown in Figure 7.

The energy conversion efficiency (electrical output /chemical energy input) of the MICE generator on Jet-A fuel was 15% with the two-stroke engine set up to give a compression ratio (geometric) of 15. For our alternator efficiency of 94%, the two-stroke engine thermal efficiency is then 16%. Since the two-stroke engine for the MICE generator is at an early stage of development, a thermal efficiency of 20 - 25% or higher can most likely be achieved with future refinement and improvement.

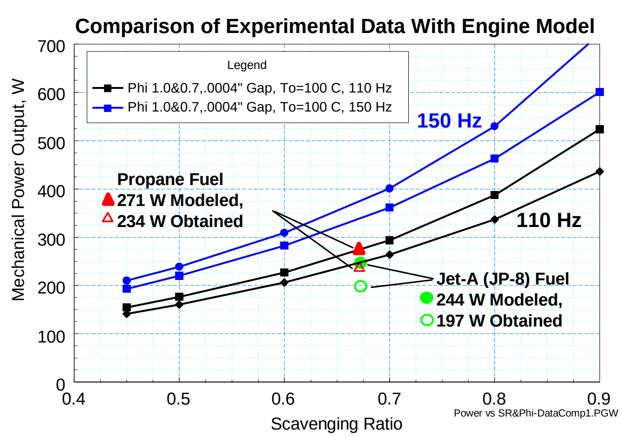

Figure 7 Comparison of Measured and Predicted Two-Stroke Engine Power Output for Jet-A and Propane

The exhaust emissions of the 300 W MICE generator with HCCI combustion are very low, especially for a two-stroke cycle. We measured a CO emission level of 0.17%, which is very low compared with typical values of 0.5 - 3% for two-stroke engines. We also measured an HC emission level of 700 ppm, which is roughly an order of magnitude lower than the 5000 - 10000 ppm HC level typical of small two-stroke engines.

2.2 300 W MICE Generator Acoustic Silencing Tests

As part of an effort to demonstrate the ability to acoustically silence the MICE generator, tests were performed to characterize the acoustic emissions from the 300 W MICE generator with increasing levels of suppression. The unsuppressed MICE generator with no exhaust muffler was measured to have a sound pressure level (SPL) of 111.5 dBA at a distance of 1 ft. The addition of an inexpensive though effective commercial muffler produced an SPL of 91.6 dBA at 1 ft, nearly 20 dBA reduction from the unsuppressed MICE generator. The addition of non-optimized acoustic enclosure using commercially available hardware produced more than 20 dBA additional suppression, for an SPL of 71.2 dBA at 1 ft distance. Figure 8 shows the measured acoustic spectra for the configuration with the muffler and the configuration with the muffler plus an acoustic enclosure. The acoustic enclosure is seen to provide good suppression at the fundamental frequency of 115 Hz as well as throughout the full spectrum. The one exception is higher emission at the 2nd harmonic of 345 Hz with the enclosure. This is due to imperfect dampening of the enclosure, which can be easily remedied with additional effort.

The measured SPL of 71 dBA would be reduced to 58 dBA at 6 ft in an open environment for which $1/r^2$ attenuation is expected. Simple modification of the enclosure by reducing its diameter in a custom design would produce an additional attenuation of more than 10 dBA, for an SPL below 48 dBA at 6 ft. It should be noted that a modest performance penalty due to increased

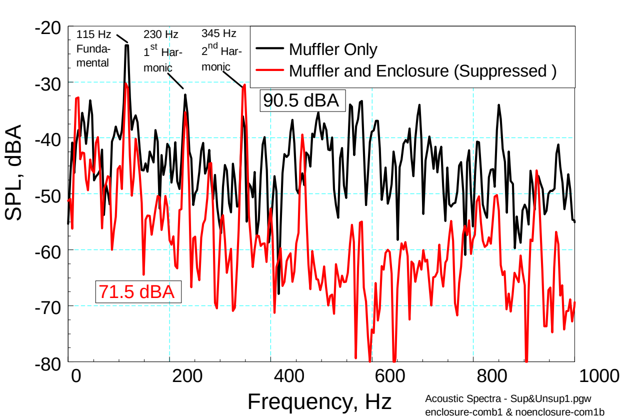

Figure 8 Measured MICE Generator Acoustic Spectra in Silencing Effort

exhaust back pressure does accompany the use of an acoustic enclosure. The measured data, and scaling for standard improvements in the acoustic enclosure design, show that the MICE generator can achieve very quiet operation – acoustic levels below 50 dB at 6 ft.

2.3 100 W MICE Generator Tests

100 W MICE generator tests are currently being performed under ARI internal funding. The 100 W MICE generator design includes several design changes/improvements over the existing 300 W design that improve the alignment of the piston rod with the cylinder, reduce the number of parts, improve the cylinder head seal, and significantly improve the strength of the attachment of the alternator coil to the spring.

A 100 hour test, consisting of 1.2×10^8 cycles, of the spring and alternator components has recently been completed. This test verifies the improved design of the alternator coil assembly and its attachment to the spring. This test also confirms the results of finite element modeling of the spring that indicate that stress concentrations in the current double helix spring design have been virtually eliminated. The spring used in this test was fabricated from Ti 6Al 4V alloy. A second spring fabricated from the higher fatigue strength Ti Beta-C alloy is also being tested.

Combustion testing of the full 100 W MICE generator is currently being performed using propane fuel. This testing has so far indicated good durability of the piston and cylinder with little or no lubrication. The tests have also shown good HCCI combustion characteristics without power to the glow plug in steady operation after startup.

2.4 MICE Generator Development Status Summary

The accomplishments of the MICE generator development program include:

- Demonstrated 185 W electrical power output on Jet-A fuel (JP-8 surrogate) at 68% throttle
- Demonstrated 16% thermal efficiency of 300 W MICE two-stroke engine with CO and HC emissions that an order of magnitude lower than typical two-stroke engines, with expected 25% thermal efficiency of engine with further development
- Demonstrated 94% efficiency of 300 W linear alternator
- Demonstrated full operation of MICE generator from cold startup to net power output operation on Jet-A and propane fuels
- Demonstrated acoustic silencing (71 dBA at 1 ft) and vibration isolation of 300 W MICE generator
- Demonstrated electronic engine load control and smooth transition from startup to net power output

- Demonstrated long life of spring and alternator components in 100 hr (1.2×10^8 cycle) test
- Demonstrated net power output from MICE with propane combustion without lubrication at a cycle speed of 390 Hz (23,400 cpm) at the nominal 10 W size scale
- Demonstrated scaling of MICE generator from nominal 5 W to 500 W sizes

3.0 MICE GENERATOR SYSTEM PACKAGING DESIGNS

Fully packaged MICE generator system designs have been developed in a TARDEC SBIR program for the 300 W and 100 W MICE generators. Size constraints for the small unmanned ground vehicles (SUGVs) that were the focus of this effort required a minor modification to the two-stroke engine to reduce the overall length of the MICE generator. By submerging part of the cylinder within the spring inner diameter, the overall length of the 300 W MICE generator was reduced to 186 mm (7.3") and the overall length of the 100 W MICE generator was reduced to 103 mm (4.1"). This allowed a 300 W packaging design that could fit in the cargo area of the PackBot and Talon SUGVs, and a 100 W (actually derated to 75W for JP-8 fuel) packaging design that could fit within the 4.4" x 2.45" x 5.0" BB-series battery form factor.

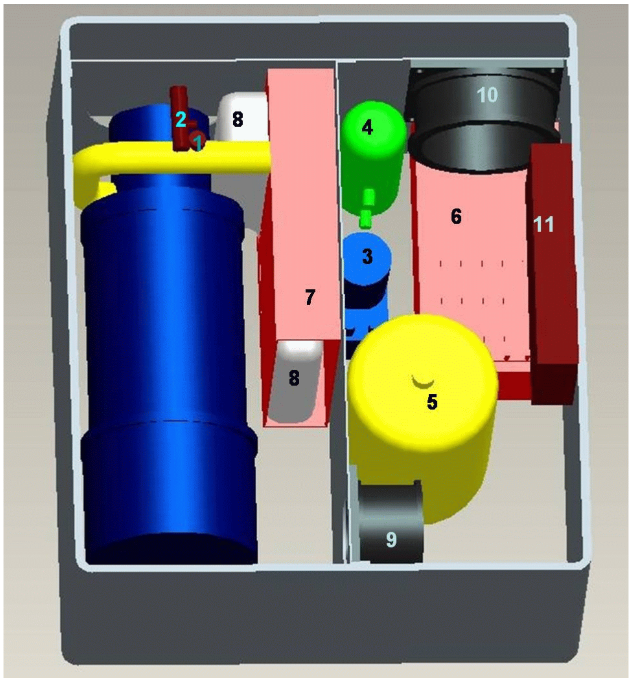

Figure 9 300 W MICE Generator Packaging Design with 9" x 8" x 4" Outer Dimensions; MICE generator is in blue on left; other components are: 1,2- MEMS fuel atomizer & solenoid valve; 3- Fuel pump; 4- Pressurized fuel reservoir; 5- fuel tank, 200 ml; 6– Electronics package; 7- Inlet air heat exchanger shroud; 8- muffler; 9- small fan; 10- large fan; 11- rechargeable battery.

The complete MICE generator system consists of the MICE generator basic unit (illustrated in Figures 1-3) and a number of subsystems that are required for full operation. The full MICE generator system contains:

- MICE generator basic unit (two-stroke engine, double helix spring, alternator)

- Fuel subsystem (fuel pump, fuel atomizer, fuel tubing, optional fuel tank)

- Electronic engine control and electrical power conversion

- Inlet air heat exchanger and cold-start air preheater

- Engine and electronics thermal management subsystem

- Vibration and acoustic suppression (soft spring vibration isolation and exhaust muffler)

- External package with BB-series connectors, controls, meters and indicators

- Rechargeable battery for startup, cold start preheat, and load management.

The packaging design for the 300W MICE generator system is shown in Figure 9 and has external dimensions of 9" x 8" x 4". The package is currently designed to have the controls, connectors, fuel connection, air inlet, and warm air discharge on the front (9" x 8") side, eliminating the need for access or clearance on all other sides. This packaging design includes all of the above subsystems. A central baffle separates the MICE generator basic unit and exhaust system from the fuel and electronic subsystems. An upper baffle forms an exhaust dilution plenum in which the exhaust is mixed with sufficient air to dilute the exhaust flow to a temperature that is 40°C above ambient temperature before being discharged from the package. The MICE generator is supported in the package by a suspension system that provides strong support in the plane normal to its axis of movement, and is very compliant in the axis of movement so that minimal vibration is transmitted to the package. Flexible electrical leads and fuel tubing are used in the design.

The MICE generator package has been designed to use an external fuel supply, though it can include a 1 liter conformal internal fuel tank (replacing the 200 ml cylindrical fuel tank in Figure 9) to allow 6 hours of operation at full power without being connected to an external fuel supply.

The overall packaging design shown in Figure 9 is very open and low risk. The design allows significant opportunity in the future to a) make the package smaller, b) allow much more fuel to be packaged internally, enough for 8 hours duration at full rated power, c) provide additional rechargeable battery capacity for extended silent operation without operating the MICE generator, or d) some combination of reduced size, increased fuel storage, and increased battery capacity. As mentioned above, a similar packaging design has been developed for a 75 W MICE generator (derated from 100 W for operation on JP-8 fuel) that conforms to the BB-series battery form factor.

4. MICE GENERATOR WEIGHT AND ENERGY DENSITY SPECIFICATIONS

The low weight, high energy density, and compact size characteristics are key features of the MICE generator system, in addition to its ability to use JP-8 fuel directly. The nominal 300 -500 W MICE generator has a weight of 3.1 kg (6.8 lb) for the basic unit and a fully packaged design dry weight of 5.0 kg (11.0 lb). The 100 W MICE generator (75 W on JP-8) has a weight of 0.3kg (0.7 lb) for the basic unit and 0.9 kg (2.0 lb) for the fully packaged dry unit.

The energy density characteristics for the 300 W and 75 W MICE generator systems are shown in Figure 10. The energy densities include the weight of the MICE generator system, the fuel, and the fuel tank required for the mission duration. The two-stroke engine thermal efficiencies used in the energy density calculations are 25% for the 300 W system and 23.5% for the 75 W system, based on detailed two-stroke engine model calculations that account for frictional and heat losses. A 95% alternator efficiency (current design) was used for the 300 W system while an 85% efficiency was used for the 75 W system. An AC/DC conversion efficiency of 90% was used for both systems.

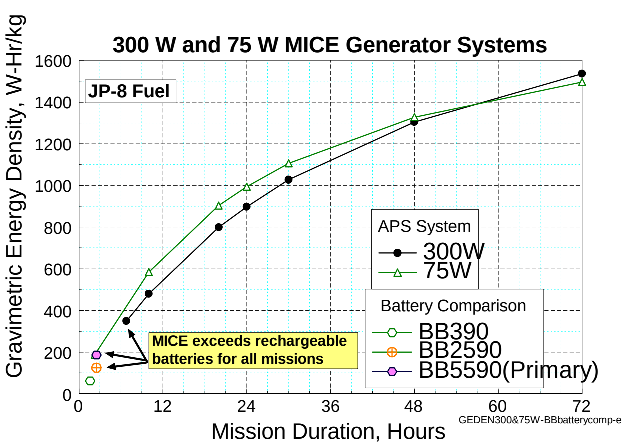

Figure 10 MICE Generator System Energy Density and Comparison with Rechargeable Batteries

As indicated in this figure, the MICE generator energy density exceeds that for BB-series rechargeable batteries for all missions, and greatly exceeds that of rechargeable batteries for mission durations of 12 hr or more. The volumetric energy densities (Whr/liter) of the MICE generator systems with JP-8 fuel is roughly 90% of the gravimetric energy densities. As Figure 10 shows, the energy density of both the 300 W and 75 W systems is above 1500 Whr/kg for missions of 72 hr or longer.

CONCLUSIONS

Internal combustion engine/generators have the ability to use JP-8 fuel directly and to provide high energy density portable power for a wide range of military requirements. IC engine/generators are efficient, light weight, low cost, and can be designed to be very quiet. The MICE generator technology, in particular, has shown the potential for energy densities that are much higher than PEM and solid oxide fuel cells. MICE generator energy densities exceed 1000 Whr/kg for missions longer than 30 hours, and exceed 1500 Whr/kg for missions longer than 72 hours. The MICE generator has demonstrated full operation from cold startup to steady state operation on Jet-A fuel at the 300 W scale in laboratory tests. The MICE generator has also shown the capability for quiet operation, demonstrating 71 dBA at 1 ft in laboratory tests with much lower levels achievable with an improved acoustic design. The MICE generator technology has the potential to meet the portable power needs of US military forces. With additional development to the TRL 6 or 7 level, these high performance characteristics can be demonstrated and quantified.

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