COMERCIALIZATION OF A MEMS SOLID OXIDE FUEL CELL FOR PORTABLE POWER APPLICATIONS

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Abstract: Lilliputian Systems has pursued a unique approach to deliver on the promise fuel cells offer to relieve the pain of limited batteries in portable electronics devices. High-energy butane fuel and high-efficiency solid oxide fuel cells (SOFCs) are combined to provide a platform with compelling energy density. Lilliputian leverages microfabrication techniques to solve the challenges of extreme insulation, high-temperature multi-chip sealing, and severe thermal expansion stresses. These integrated technologies are then assembled into a complete system in order to deliver a product which can power the latest smartphones for weeks.

Keywords: Portable Power, USB, Smartphone, Fuel Cell, SOFC, Butane, MEMS, Glass Seal, Simulation

INTRODUCTION

Modern consumer electronics boast an impressive range of capabilities, with the ability to wirelessly accomplish almost anything imaginable, with new capabilities added daily. Unfortunately, the battery life required to support these capabilities gets worse every year. On-the-go users are often tied to a wall plug for hours to recharge their devices. Fuel cells have long held out the promise of cutting that final cord, but have thus far fallen short of delivering a compelling power source for Consumer Electronics (CE) devices. Lilliputian Systems has overcome that barrier by choosing the highest energy density fuels, combined with the most efficient and dependable fuel cells, in a MEMS-enabled compact form factor, in order to deliver a powerful user experience.

Portable Power Market

Recent trends in the CE market have resulted in increased energy requirements for billions of portable devices. Moreover, the increase is both rapid and accelerating due to four unique trends.

CE devices (i) have become more power consumptive, (ii) are increasingly used away from stationary power sources, (iii) are equipped with more numerous, more power hungry features and applications, and (iv) are being used more frequently. Several studies have confirmed this fact. Detailed analyses by Lilliputian[1], Parks Associates[2], Strategy Analytics[3-5], and Cisco[6], have attempted to quantify this increase in demand. Shown in Figure 1, the results show a large and growing energy demand gap of a heavy user's daily mobile phone requirement. Batteries are simply unable to meet this growing energy demand.

Fuel Cell Solutions

The need for better solutions to power portable electronics has long been apparent[7]. Fuel contains up to 100x the energy stored in batteries, primarily due to the use of "free" ambient air. However, fuel-based systems suffer from two significant drawbacks. First, the fuel is converted into electricity at low efficiencies when compared to batteries. Second, the generator takes up a majority of the volume in portable applications, so that there is limited available space for the fuel. These drawbacks combined often eliminate the initial energy advantage.

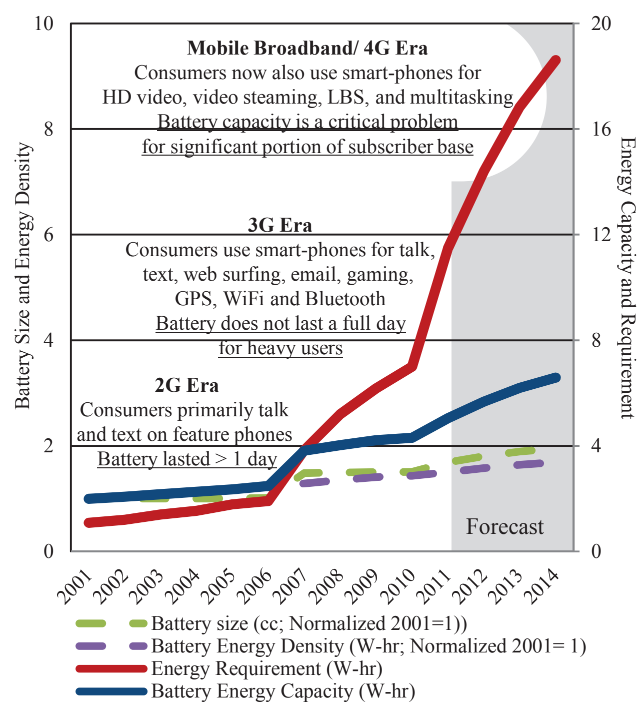

Figure 1: Energy needs and capacities of cellphones vs. time. [1]

	Low End	High End	Mean
Fuel Utillization or Pre-Processing Efficiency	20.0%	100.0%	60.0%
Core Fuel Cell Efficiency	25.0%	65.0%	45.0%
System Electrical Efficiency	50.0%	85.0%	67.5%
Fuel Volume Percentage of Total System	5.0%	50.0%	27.5%
Net Energy Density Delivered	0.13%	27.6%	5.0%
Heat Generated Per Watt Delivered	39.0	0.8	4.5

Table 1: Performance limiters for fuel cell systems

Fuel cells have been touted as the solution to this challenge, but only a small number of fuel cell products aimed at CE devices have reached the general public, and none have been a commercial success. Despite the initial promise of high efficiency, fuel cells also suffer from an accumulation of losses between the raw fuel energy and the net energy delivered to the user. Though each system and each fuel cell is a little different, the losses broadly fall into the four categories shown in Table 2. Even in the very best case across the board, the energy delivered is almost 4x lower than the starting fuel energy. In practice, each approach tends to excel in some areas and lag in others. In the "mean" case, the losses are 20x. The few commercial products which have been offered at any level have yet to even achieve this "mean" performance. Consequently, it should not be surprising that fuel cells have thus far been unsuccessful in the CE market.

TECHNOLOGY CHOICES

Overcoming the challenges highlighted by Table 2 requires a relentless focus on maximizing the performance in every phase of the system. Lilliputian chose to pursue a system based on a high energy density fuel, in the form of butane, combined with a fuel cell type which provides high utilization and efficiency, a solid oxide fuel cell (SOFC).

Butane Fuel

Butane was selected as the primary fuel because of its high energy density (~7,400 W-Hr/L) and impressive safety record built up over almost one hundred years of widespread consumer use in lighters, cooking, lighting, and various specialized applications. Butane safety stems in large part because

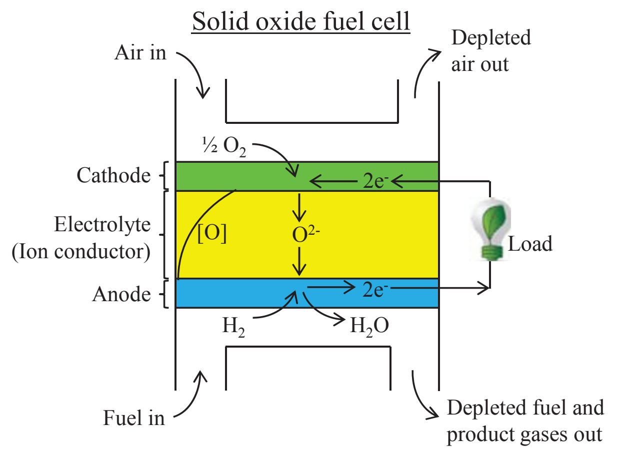

Figure 2: SOFC operating principle

it is difficult to ignite. Butane's autoignition point is approximately 405 °C, higher even than untreated wood[8]. The tradeoff for that safety is the need to operate at temperatures well in excess of 400 °C, with catalysts requiring 600 °C for efficient conversion.

Solid Oxide Fuel Cell

Lilliputian selected SOFCs based on their compatibility with butane fuel, solid state construction (enabling simple device design), resilience to environmental contamination and humidity, and high efficiency (due to high fuel utilization and high power densities). SOFCs are defined by their use of a ceramic oxide solid as their electrolyte membrane, typically Yttrium-Stabilized Zirconia (YSZ). Sandwiched around the YSZ electrolyte are two electrodes which perform the electrochemical reactions to complete the circuit and convert chemical energy into electrical energy.

Fuel cells operate by creating opposing gradients of chemical concentration and electrical potential. When an ion diffuses due to the concentration gradient, the associated charges are transported against the electric field, generating electrical power. In the case of SOFCs, the mobile ion is O^{2-}, and the oxygen gradient is created by providing air on one side (the cathode) and a fuel mixture which consumes any free oxygen on the other side (the anode). Any fuel which burns oxygen will produce power in an SOFC.

SOFC's many positive attributes come at the cost of an operating temperature of at least 500 °C, and generally perform best in the range 700-800 °C.

LILLIPUTIAN SYSTEM DESIGN

Consumers do not care about butane, fuel cells or MEMS directly. They need a device which is compact and high-energy, that they can use as if it were a portable wall outlet, with little regard to the internal workings of the system. The "outlet" should deliver

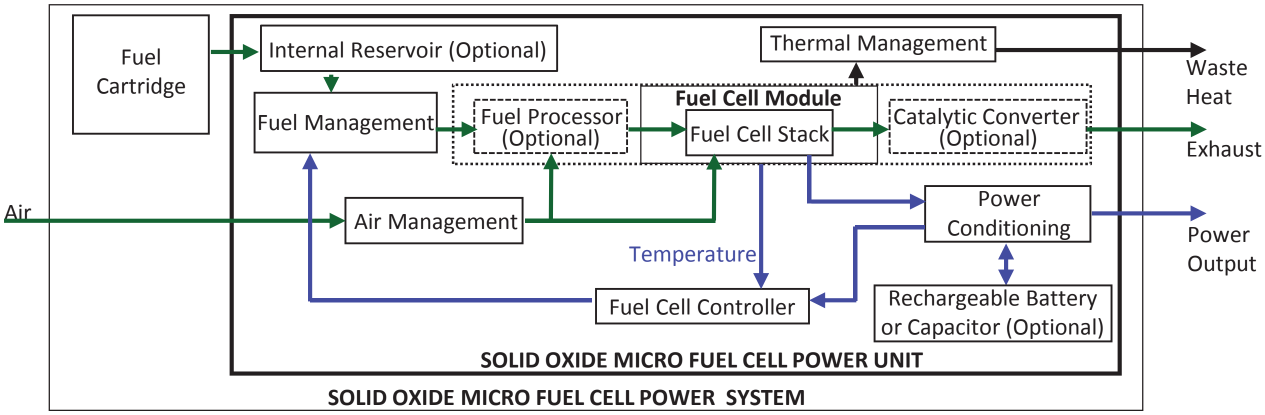

Figure 3: Butane Fuel Cell System block diagram.[9]

power immediately, and deliver as much power as the device can accept, or as little as it needs.

Figure 3 shows the high-level system design for a small portable butane SOFC system. The user's needs are first met by a rechargeable battery, which is able to immediately provide power, regardless of the fuel cell state. Behind the battery, the fuel cell operates independently to recharge the battery as needed.

The core of Lilliputian's butane fuel cell system is a "Generator Chip" (GC) containing the functionality of the dotted box in Figure 3, shown schematically in Figure 4, including fuel processing, fuel cell, catalytic converter, and the extreme insulation required to deliver >700 °C in an efficient portable device.

The operation of the GC is as follows:

(1) Fuel is mixed with a small amount of Air and fed into the Fuel Processor,
 (1b) Fuel breaks down into simpler fuels, Hydrogen (H2) and Carbon Monoxide (CO), which are easier for the Fuel Cell to use,
(2) Air is provided to the other side of the Fuel Cell,
(3) Fuel and Air react across the Fuel Cell membrane, producing Electrical Power at the terminals,
(4) Remaining Fuel mixes with Remaining Air and is burned and cleaned in the Catalytic Converter,
(5) Clean Exhaust leaves the GC.

Extreme Insulation

Butane and SOFCs are both selections that require operation at temperatures of at least 500 °C, and up to 1000 °C. Delivering 2-3 Watts of electricity to a CE device at efficiencies of at least 25% limits the heat available to sustain those temperatures to be no larger than 6-9 Watts. Those scant Watts are shared amongst the primary thermal loss pathways of conduction through any insulation, infrared radiation, conduction through tubing and wiring, and forced convection of hot exhaust gasses.

Vacuum insulation is a requirement to allow for compact construction. For our application, vacuum levels under 1 millitorr essentially eliminate the first thermal loss pathway. This demands the development of thermally and chemically-stable vacuum-tight sealing materials, however there is little choice; even aerogel insulation would need to be unacceptably large to meet the heat loss requirement.

Radiation of infrared light, if allowed to escape, would still cause up to 200 Watts of heat loss from our compact GC. To minimize this pathway, highly reflective shields surround the hot region as completely as possible; only the tube structure is allowed to pierce the shielding. Even with this

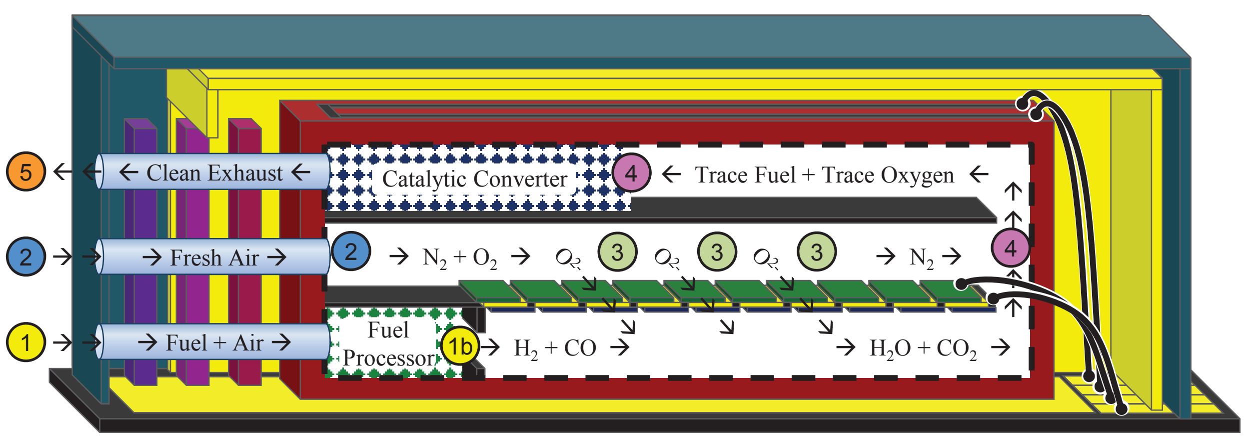

Figure 4: Schematic of Lilliputian's Generator Chip

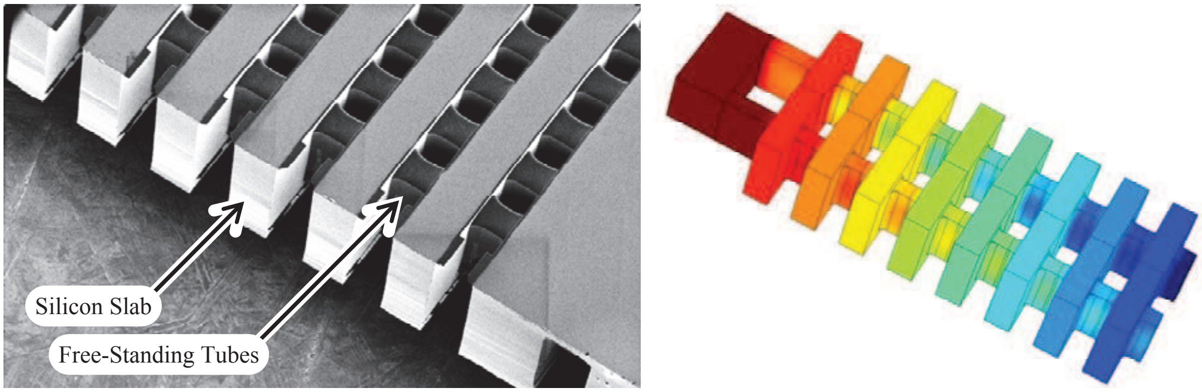

Figure 5: (Left) Electron-micrograph of MEMS Tubes, (Right) Modeling of heat recovery characteristics.

approach, the light that escapes through gaps for the tubes and wire traces dominate the remaining heat loss.

Convective heat loss from the required gas flows contains less energy than the preceding mechanisms, but is one of the most challenging pathways to eliminate. This ultimately forces the choice to use silicon-based MEMS because it enables the complex device geometries needed to achieve sufficiently high levels of recovery with minimal physical conduction.

Previous work at MIT developed a manufacturing approach to build thin-walled tubes with excellent insulation and heat recovery using silicon MEMS[10]. Advancements on that work shown in Figure 5 are able to provide gas flow with minimal physical conduction using thin-walled tubes of insulating silicon nitride. Silicon heat transfer bars are provided perpendicular to the tubes to provide efficient recovery of the heat from the exhaust stream back into the input gas streams. The geometry is optimized to maximize recovery without undue pressure drop, radiation leakage or physical conduction. The losses from this pathway are the second largest overall.

Physical connections in the form of tubing and wires are minimized to the extent possible. However, the tubing is constrained as described above, and the wiring must be large enough to provide low resistance

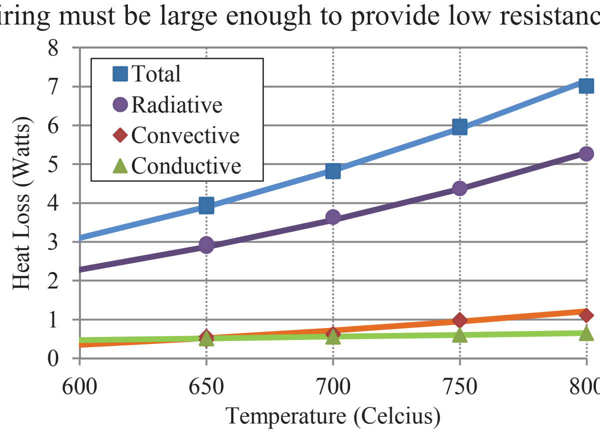

Figure 6: Extreme insulation measured on a representative Generator Chip.

for extracting the power produced and providing power to the startup heater. Thermal resistance and electrical resistance are governed by the same geometric dependencies, limiting the optimization available.

The cumulative heat losses from this suite of extreme insulation approaches results in 3-7 Watts over the temperature range of interest for our system, as shown in Figure 6. This matches well with the heat generated from the SOFC and the catalytic reactions, creating an autothermal system.

Sealing Glass

Vacuum insulation has tremendous advantages, as mentioned previously, but requires hermetic sealing between the multiple components that comprise the GC in order to maintain the vacuum level over the life of the device. The exclusive use of silicon as the primary structural material throughout the GC limits the stress on the seal, but that seal is still subject to a challenging set of requirements, including:

- 800-1000 °C operation with thermal cycling
- Oxidizing and reducing environments
- Mechanical stress from 1 atm internal pressure

Traditional wafer bonding technologies, such as silicon fusion bonding, would meet these requirements, but they require extremely clean and flat surfaces. Unfortunately, fuel cell manufacturing requires extensive processing to create the electrode, and there are numerous electrical interconnects that cross bond lines. Producing sufficiently high yield with conventional bonding would pose significant challenges. Glass seals are a more natural technology fit, but no commercially available sealing material was identified which met all of the aforementioned requirements. Therefore, Lilliputian developed a novel sealing glass which is able to provide the required characteristics at very high yields. Figure 7 shows a cross-section from a six-die stack assembled with this glass.

Figure 7: Cross section of an assembled silicon die stack using Lilliputian's glass seal.

SOFC on Silicon Pre-Cracked Structure

Integrating SOFCs onto a silicon substrate is required by the tube and bonding approaches described above. Early work at Lawrence Livermore National Laboratories demonstrated SOFCs fabricated on a silicon substrate [11, 12], but the large thermal expansion mismatch between the silicon and the YSZ electrolyte caused the membranes to fail after repeated thermal cycling. Between 0 and 900 °C, over 1 GPa of stress is developed in a YSZ film deposited on silicon. Shown in Figure 8 is the first thermal cycle of a YSZ film deposited on a silicon wafer. Initially the stress is 400 MPa compressive. As the wafer heats up, the film becomes more compressive until it exceeds the yield stress. Despite being a crystalline ceramic, the stress levels are high enough to induce plastic deformation in the film between 400 and 900 °C, as well as some additional stress relaxation at 900 °C. During the subsequent cool down, the thermal expansion mismatch drives the previous highly compressive stress in the film into a highly tensile state, ultimately resulting in significant fracturing in the film.

Cracking in a fuel cell is fatal because it allows gas to bypass the electrochemical circuit and simply combust through the membrane directly. To prevent this, Lilliputian invented a "Pre-Cracked" structure where the YSZ film is constructed with closely spaced seams prior to thermal cycling, with seals under each seam.[13] The Pre-Cracked structure is completed by removing the underlying silicon to form a free-standing composite membrane.

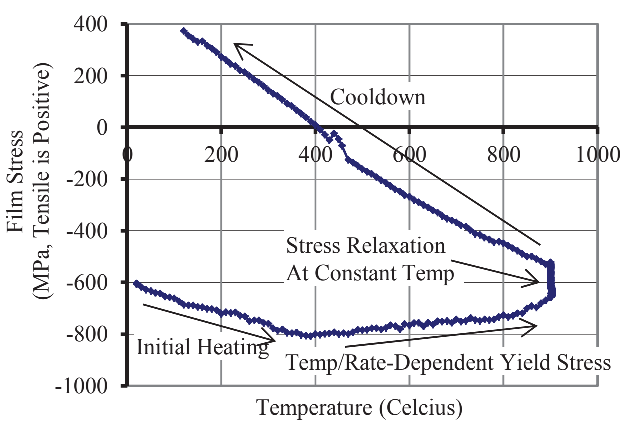

Figure 8: Stress vs. Temperature during the first thermal cycle of an example YSZ film. Thickness 2 µm, heating and cooling rates of 6 °C/min, dwell time of 3 hrs.

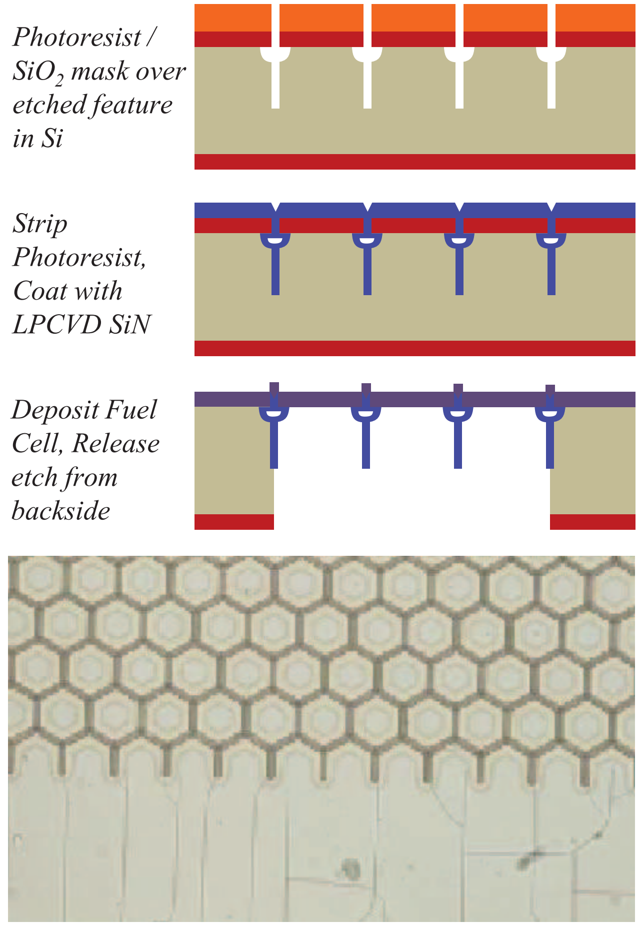

Figure 9: Simplified process flow for the Pre-Cracked fuel cell and a micrograph of the edge of a Pre-Cracked region

Figure 9 shows a simplified process flow, and a micrograph of the edge of a Pre-Cracked region. Outside of the patterned area, numerous cracks are clearly visible, but within the "Pre-Cracked" area, no unintentional cracks form. The small YSZ "tiles" are supported on a silicon nitride lattice, which is supported in turn by silicon walls to form YSZ/nitride composite "membranes". The membranes can then be replicated in a large array to cover arbitrarily large surface areas. In this way even 1,000,000 crack-free tiles can be readily combined onto a single silicon die.

Pumps, Valves and Electronics

Lilliputian's GC contains tremendous technology innovations, many of which were covered above, but it is useless to a consumer without a system surrounding it. Much like the engine block of a car, which performs a similar fuel-to-work conversion, it is surrounded by a far larger volume of auxiliary "Balance of Plant" (BoP) components which deliver the desired user experience.

Figure 10: Prototype Lilliputian complete system.

At a minimum, the BoP must provide the GC with three gas input streams (fuel, air for reforming, and air for the SOFC cathode), one electrical startup heater, and one fuel cell output power converter. In the Lilliputian system, those needs are met with an air pump which supplies both air streams, a fuel valve which meters fuel out of the pressurized butane cartridge, and a number of DC/DC converters to shuttle power around the system. All of these operations are managed by a sophisticated embedded controller. Shown in Figure 10 is a fully functional early prototype of the Lilliputian system.

CONCLUSION

Portable fuel cells have the potential to cut the final cord connecting consumer electronics users to the wall. Lilliputian is fulfilling this potential at a time when people are increasingly dependent on their amazing devices, and increasingly frustrated by the frequent need to hunt for a “non-mobile” plug to keep their devices powered. Relentless pursuit of the highest performance choices in the form of butane fuel, SOFC fuel cells and MEMS combine to provide a technology basis capable of finally delivering on the fuel cell promise; however, those choices come with complications. Integration of the core Generator Chip required solving an extreme insulation challenge, developing a new sealing approach, and leveraging ceramic fuel cell materials onto silicon. Even after surmounting these integration barriers, the Generator Chip had to be incorporated into a full system to deliver the required user experience reliably and at a competitive price.

Over the past several years, Lilliputian Systems has created the many innovations required to bring this complex system to high-volume manufacturing, and ultimately to the mobile world, enabling long-lasting portable power for consumer electronics devices.

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