White Paper

Solid Oxide Fuel Cell (SOFC) Technology

For Powering the U.S. Army of the Future

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1. INTRODUCTION

This paper describes solid oxide fuel cell (SOFC) technology and its features, discusses the technological status and examines the key parameters of the technology critical to supporting the U.S. Army power and energy (P&E) needs for multi-domain operations (MDO) in the 2035 timeframe.

2. SOFC TECHNOLOGY AND FEATURES

A SOFC is a solid-state energy conversion device that produces electricity by electrochemically combining a fuel with air across an oxide electrolyte. A SOFC cell consists of a dense oxide electrolyte sandwiched between two electrodes - the anode and cathode and in a stack of cells, an interconnect connects the anode of one cell to the cathode of the next in electrical series. A SOFC system for a specified power generation application combines SOFC stack(s) with other required components (referred to as balance of plant or BOP) such as reformer if any and equipment for fuel cleanup (for fuel processing), blowers/compressors (for fuel/air delivery), heat exchangers/recuperators/combustors (for thermal management), power electronics (for power conditioning), and controller (for system control). The SOFC operates at high temperatures, between about 650°C and 1000°C depending on cell design and selected materials. At present, the most common materials for the SOFC are yttria stabilized zirconia (YSZ) for the electrolyte, nickel-YSZ for the anode, lanthanum strontium cobalt iron perovskite oxide (LSCF)-YSZ for the cathode and stainless steel or conducting ceramic for the interconnect depending on the operating temperature. Figure 1 shows examples of SOFC cell, multi-cell stack and power system.

The key features of the SOFC are solid state construction (ceramic and metal) and high operating temperature (650°C-1000°C). The combination of these features leads to a number of advantages for the SOFC including cell/stack design flexibility, multiple manufacturing options, multi-fuel capability and operating temperature choice. Multi-fuel capability is especially an important feature of the SOFC. Like other types of fuel cell, the primary fuel for the SOFC is hydrogen. However, suitable fuels for the SOFC also include natural gas, biogas, coal gas, alcohols, diesel, etc. For fuels such as natural gas, the SOFC can operate directly on reformates (without required cleanup of carbon monoxide and carbon dioxide) from external reformation of the fuel or via internal reforming (on fuel feeds with significant amount of water or carbon dioxide) or direct fuel utilization (on fuel feeds with no water or carbon dioxide).

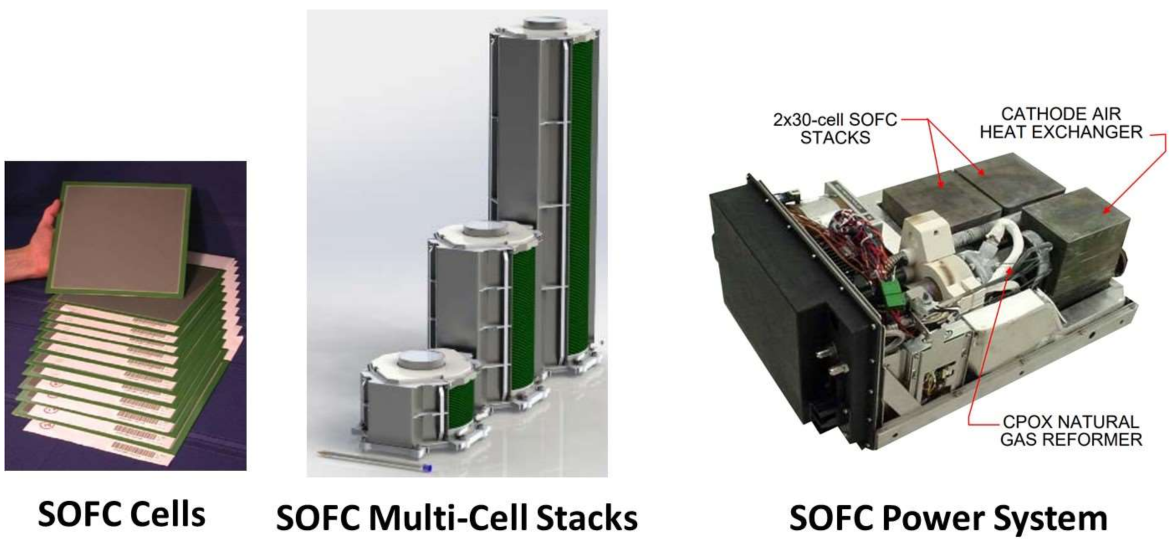

Figure 1. Examples of SOFC cell, multi-cell stack and power system

With these advantages, the SOFC currently have been considered and developed for a broad spectrum of power generation applications ranging from small watt-sized devices to large multi-MW power plants. Furthermore, the SOFC could play an important role in advanced energy systems to be developed for the future. The SOFC could serve as a technology base for future affordability as summarized in Figure 2.

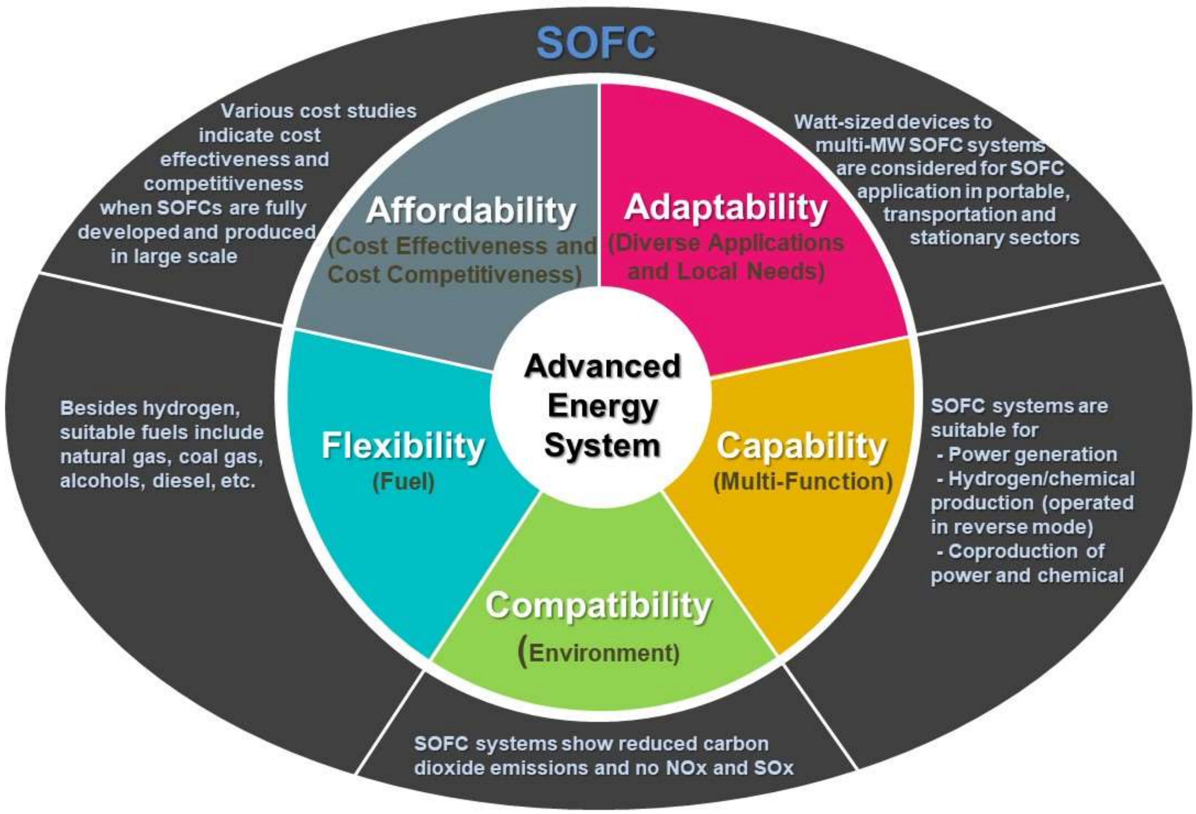

Figure 2. Characteristics of Future Energy Systems and SOFC Technology

3. TECHNOLOGICAL STATUS AND CHALLENGES

The SOFC has been considered and developed for a wide range of commercial applications and markets and has been evaluated for a number of military applications.

(i) **Commercial Applications**: Commercial applications considered for the SOFC cover all market sectors (portable/mobile, transportation and stationary) (Table 1). Many of the applications for the SOFC have progressed to hardware demonstration and prototype/pre-commercial/early-commercial stages with systems of power level up to 200 kW while several applications, especially those with large power outputs, are at the conceptual/design stage (Figure 3). Figure 4 shows selected examples of SOFC prototypes and commercial systems with power levels of 5 W to 50 kW.

Table 1. SOFC Power System Commercial Markets and Applications

Market	Application	Power Size	Status
Portable	Consumer electronic devices, mobile portable power	1-100W	Demonstration, precommercial
	Portable power, battery chargers	200-500 W	Demonstration, commercial
Transportation	Range Extenders Automobile and Truck APU	5-50 kW	Demonstration
	Aircraft APU	Up to 500 kW	Concept
Stationary	Residential/micro CHP, uninterruptible	1-10 kW	Prototype, precommercial
	CHP and DG	100 kW-1MW	Demonstration, precommercial, concept
	Base load	100-500 MW	Concept

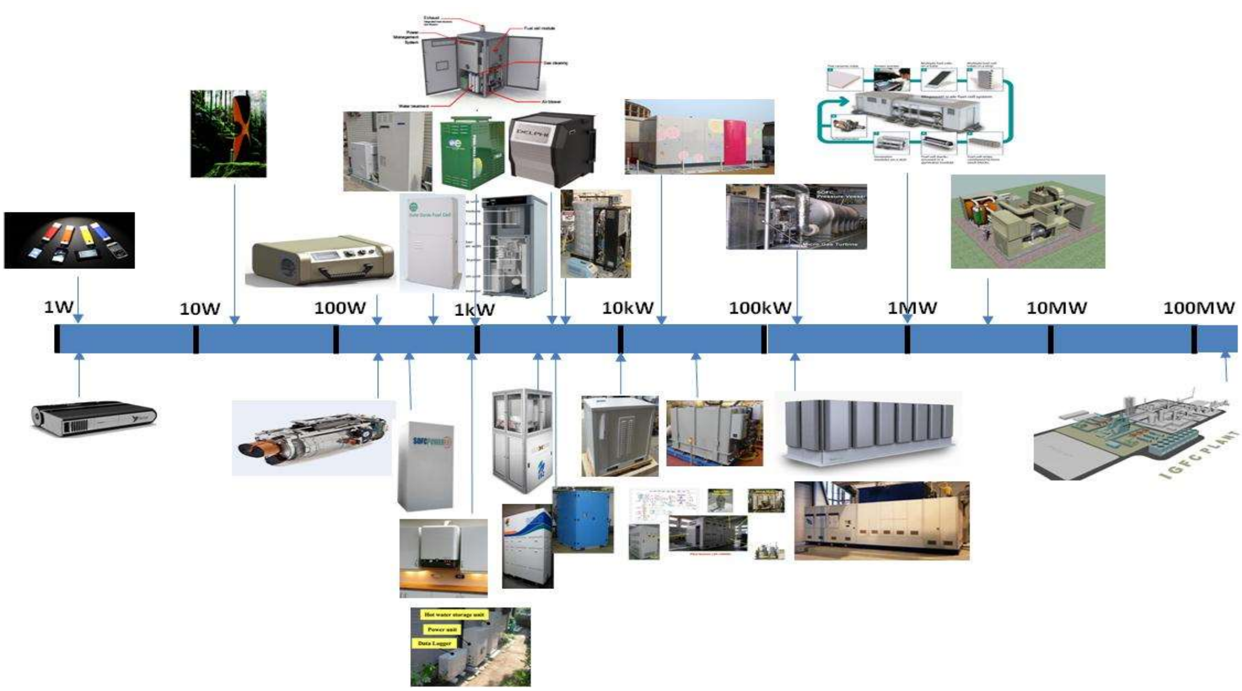

Figure 3. Examples of SOFC Hardware Demonstrator, Prototype, Pre-Commercial, Commercial and Conceptual Systems from Watt to Multi-Megawatt Power Outputs

Significant advancements have been made in the past few years in several technological areas critical to the development of the SOFC for commercial applications. However, further improvements are needed in several areas for cells and stacks, relating to the key drivers (efficiency, reliability and cost) to enable commercialization (Figure 5). These areas are:

Figure 4. Examples of Prototype/Commercial SOFC Systems (not in same scale)

Figure 5. Key Areas for Improvement in Key Drivers to Enable SOFC Commercialization

- *Power density* (increase), especially under practical operating conditions such as high fuel utilization, to increase power output per unit cell area (efficiency), thus lower number of cells per stack (cost).
- *Material content* (decrease), especially interconnect quantity, to minimize stack weight and volume (cost), thus smaller stack mass that requires, e.g., thermal management such as cooling (efficiency).

- *Cell size* (increase), especially for scale-up to large power systems, to decrease parts count (cost), thus reduced cell-to-cell connections and potential mal-distributions, e.g., cell stacking and gasflow distribution (reliability).
- *Reproducibility* (increase), especially stacking reproducibility, to improve stack yields based on acceptance criteria for the intended application (reliability), thus minimal rejects (cost).
- *Life* (increase), especially cell life, to prevent untimely failures (reliability) and performance losses during long-term operation (efficiency).
- *Degradation* (decrease), especially performance poisoning caused by chemical interactions and impurities, to meet cell/stack specifications (reliability) and minimize excessive performance losses (efficiency).

(ii) **Military applications**: All branches of the U.S. armed forces have been involved in the development of SOFC technology to support the military's need for modular, secure and reliable power. Main areas of interest include soldier palm power, portable power, unmanned aerial, ground and undersea vehicles, prime power and backup power for facilities and APUs, range extenders for transportation. The main reasons for the interest are the SOFC's high power density and its capability to operate on logistic fuels. The development of the SOFC for military applications generally has leveraged the progress of the technology from the commercial sector. To date, under the support from the U.S. Department of Defense (DOD), several portable SOFC power systems have been developed and are now available and several hardware systems have been demonstrated for operation with logistic fuels. Figure 6 shows as an example two 350-W systems, one for battery charging and one for unmanned aerial (UAV) and unmanned ground (UGV) vehicles developed under DOD support. The main challenge currently facing the SOFC for military applications is to meet the highest standards of required performance, reliability and robustness to ensure the protection of warfighters.

(A) (B)

Figure 6. 350-W SOFC Systems; (A) for battery charging, (B) for UAVs and UGVs

4. SOFC BASED SYSTEMS FOR DISTRIBUTION INFORMATION ENABLED MDO

The following parameters of the SOFC are examined to assess the technology for its potential to support the U.S. Army P&E needs for the MDO concept:

(a) Specific Energy and Power Output: It has been shown that the SOFC can be designed and developed for a broad spectrum of power system sizes with power outputs ranging from W to multi-MW levels. The key challenge is to develop and optimize the system configuration to meet the specifications of the intended applications. Specific energy of a SOFC system depends on cell performance, stack specific power and mission profile. Specific energy of SOFC systems can be very high (e.g., several kWh/kg vs. lithium batteries 100-250 Wh/ kg).

(b) Efficiency: A SOFC stack can produce electricity with power generation efficiency of >60%. Typical efficiency in the range of 30%-50% has been demonstrated for SOFC systems.

(c) Weight and Volume: It has been shown that weight and volume of the SOFC can be significantly reduced via design changes and performance improvement. For example, a recent modified SOFC stack design that has been developed for commercial applications demonstrated

6X increase in power to weight ratio (specific power) (from 76W/kg to 467 W/kg) and 4X increase in power to volume ratio (volumetric power density) (from 185 W/L to 778 W/L). The SOFC has the potential for exceptionally high specific power and volumetric power density. For example, based on a recent demonstration of high performance of thin-film SOFCs on direct utilization of methane and an advanced lightweight and compact stack design, the specific power and volumetric power density of the SOFC are estimated to be about 2.58 kW/kg and 1.90 kW/L, respectively.

(d) Endurance: In term of endurance, SOFC technology being developed for commercial applications has made significant progress in the past ten years. SOFC cells and stacks have demonstrated long-term (>10,000 hours) operation with significantly reduced performance degradation. One example is the operation of a large and tall SOFC stack (16 cells of cell active area of 550 cm^2) with natural gas reformate (at 0.85 V/cell and 0.364 A/cm^2) for more than 17,000 hours that exhibited a degradation rate of <0.5%/1000 hours.

(e) Durability: The SOFC can be designed for operation in harsh/hazardous environment and ruggedness under mechanical load/shock. One example to show the potential for durability of the SOFC is the solid oxide electrolysis cell (SOEC, i.e., SOFC operated in reverse or electrolysis mode) being developed for oxygen production from carbon dioxide for Mars in-situ resource utilization (ISRU) applications. This SOEC has been successfully tested in Mars environment (CO_2 atmosphere, atmosphere temperature of -60^o C, atmosphere pressure of 0.088 psi, clogging filter, etc.) and demonstrated for mechanical ruggedness under load and vibration during liftoff and landing.

(f) Vulnerability to Attack and Disruption: The SOFC, like any fuel cell, has the characteristics of modularity, i.e., cells can be made in modular sizes. Thus, fuel cell size can be easily increased or decreased. The SOFC can be designed to follow loads with fast response time without significant efficiency loss at part-load operation. The SOFC can be configured into a distributed system or can be designed to generate power on site, eliminating the need for critical electrical transmission. The technology is thus less vulnerable to attack and disruption.

(g) Portability/Mobility: Because of all the components are solid, the SOFC cell/stack can be designed and configured for minimum size and weight appropriate for incorporation in portable/mobile systems. The SOFC can be developed for mobile and portable application and several systems in the 1-500 W power range have been demonstrated. One example is a 2.5 W mobile power that has the specifications: USB 2.0 interface, standard +5 V output, >2.5 W peak power, 55,000 mWh of energy in a single butane canister, volume of 202 cm^3 (including butane canister) and weight of 235 g (including butane canister).

(h) Supply and Maintenance Concerns: There are no major challenges for SOFC technology regarding material and fuel sourcing and rarity of materials. The SOFC contains no noble metals such as platinum and other rare materials and the materials for constructing the fuel cell come from several sources in the U.S. and other areas around the world. Because of its fuel flexibility, the SOFC has the ability to adjust to fuels from various fuel sources. Also, there is no need of water supply when the SOFC operates in direct fuel utilization mode (on fuel feeds with no water).

(i) Investment and Unit Cost: The federal government, especially the U.S. Department of Energy, has been funding (about $700M for the last 20 years) the development of SOFC technology for commercial applications. Other funding sources are cost shares from industry and private investments. Funding to develop the SOFC for military applications is relatively small. Significant and sustainable funding will be needed to develop the SOFC with the required properties for MDO. Many cost estimation studies have indicated that the SOFC when fully developed and produced in large scale will have competitive costs. Cost estimates for kW class

SOFC stacks range from \$200/kW-\$400/kW. Stack cost can be reduced by improving cell performance and stack design and system cost by simplifying system configuration.

(j) Safety Issues: The major hazards associated with a SOFC system are dangerous substances (mainly, fire and explosion and harmful effects of exposure), electric shock and general safety hazards (for example, manual handling). Safety guidance on controlling the risk from fire and explosion, particularly when hydrogen is the fuel, has been developed for fuel cell technology in general and SOFC technology in particular. General guidance describing how risk from the other significant hazards should be controlled is already available.

(k) Personnel Training Requirements: Personnel training requirements for SOFC deployment and use, besides operation procedure training, mainly relate to safety and safe operation of the system.

(l) Policy and Regulatory Concerns: There are no major policy and regulatory concerns regarding deployment of fuel cell technology in general and SOFC technology in particular. Current policies from the federal government and many states support research, development and deployment of fuel cell technologies. Regulations, codes, and standards are actively being developed by local/state/federal government entities, trade organizations and industry.

It can be seen from the above examination that SOFC technology has the potential to be developed into a power system that meets the requirements for MDO applications. Based on the current status of the technology, the SOFC can be considered for both tiers: Tier 1 for demonstration of SOFC systems (kW to 100 kW class) and Tier 2 for demonstration of mobile SOFC systems (1 W-500 W) and large systems (1 MW – 10 MW).

REFERENCES

A list of references for certain information and data included in this paper is available upon request.