Powering the U.S. Army of the Future

The Boeing Company

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INTRODUCTION

The U.S. Army faces the challenge of integrating into Multi-Domain Operations (MDO), which increases demands on electrical power systems during operations across land, sea, air, space, and cyberspace arenas. Power demands across the board, from dismounted soldiers to forward operating bases (FOB), are anticipated to grow significantly to support state-of-the-art and emerging equipment required for modern warfare. Ongoing innovations in power generation and energy storage technologies can enable the Army to provide solutions that reduce equipment weight for dismounted soldiers and improve the logistic chain by reducing the fuel consumption necessary to operate remote bases. This paper addresses non-traditional power generation for FOB, as well as solutions for 'silent watch' operation of tanks and Bradley vehicles.

Boeing has done extensive work in the development of power systems based on fuel cell technology operating with hydrocarbon and non-hydrocarbon fuels. Boeing developed a regenerative power system based on solid oxide fuel cell (SOFC) technology under the DARPA Vulture program (a solar-powered aircraft). This closed-loop system utilized solar energy during the day to run the solid oxide stacks as an electrolyzer to decompose water into pressurized hydrogen and oxygen gas for storage, then operated as a fuel cell during the night to power the aircraft using the stored hydrogen and oxygen. Following that work, Boeing matured SOFC technology for a power plant operating on diesel fuel under the NASA FUELEAP (Fostering Ultra-Efficient Low Emitting Aviation Power) contract.

<u>Forward and Operating Bases</u> – These bases require 100s of kW to 10 MW of continuous electric power to sustain operations. Today, these bases are supported by large diesel-powered gen-sets that are noisy, inefficient and emit high-temperature exhaust. Recent developments in SOFC technology enable a power plant, with a low acoustic signature, that is at least 50% more

efficient than current diesel gen-sets. Our concept for FOB utilizes an SOFC gen-set operating at elevated pressure to provide electric power with a fuel-to-electric conversion efficiency of >60% (LHV). The fuel savings offered by an SOFC gen-set reduce operating costs and reduce the frequency of high-risk fuel transport in contested regions. Additional information about the SOFC-based power system for FOB is presented later in this paper.

Mobile Platforms (Silent Watch) – Mobile platforms, such as tanks and Bradley Fighting Vehicles, are required to operate in 'silent watch' mode where they remain stationary and quiet for extended periods observing adversaries, mapping the battlefield, and communicating with their command post. In 'silent watch' mode, the main engine remains off to conserve fuel and reduce acoustic and IR signatures. The use of batteries is limiting because the vehicle would need to periodically abandon 'silent watch' mode as it turns on its engine to recharge the batteries. An SOFC-based auxiliary power unit, operating on diesel fuel, enables extended periods of 'silent watch' with low acoustic and IR signatures. This unit can be rated from 1 kW to 20 kW and provide power to communications, surveillance equipment, and essential vehicle functions. The SOFC power plant can operate at ambient pressure, eliminating the need for noisy compressors, and provide an impressive fuel-to-electric conversion efficiency of >40% (LHV). Additional information about the SOFC-based power system for Mobile Platforms is presented later in this paper.

FORWARD OPERATING BASES

The proposed power generation concept for Operating Bases leverages Boeing's extensive experience with SOFC-based power plants from the DARPA Vulture and NASA FUELEAP programs. The key enabling technology for both of these programs is a highly efficient SOFC stack that is made even more efficient (per the Nernst Equation) by pressurizing the reactants. The

DARPA program utilized hydrogen as the fuel, but an SOFC can also operate on reformed heavy hydrocarbon fuels (reformate). Boeing demonstrated pressurized operation on simulated reformate with an SOFC stack to validate the concept and its performance potential as part of the FUELEAP program.

The key to SOFC power system efficiency is a high-performance solid oxide stack, where efficiency improves as stack operating pressure increases. Two significant challenges with solid oxide stacks are seals and the thermal stress induced by thermal expansion mismatches between materials utilized in stack fabrication. The stack operates over a wide temperature range, which complicates the selection of material to seal mated surfaces that have different coefficients of thermal expansion (CTE). The SOFC stack design must ensure that CTE differences between stack materials do not result in damage during power system startup. Stack temperature is raised slowly during startup to manage thermal stresses, but this results in startup times that can exceed one hour. Boeing has worked closely with suppliers to develop seal materials for both anode-supported and electrolyte-supported stacks. However, an emerging development in SOFC stack technology is metal-supported cells. This technology simplifies sealing between cells and also enables much faster startup times. Boeing is currently collaborating with a supplier to mature this technology.

System Configuration – Boeing developed a power system architecture, shown in Figure 1, that operates on logistic fuel (diesel or JP8) reformate and utilizes waste heat from the stack to drive a compressor to pressurize incoming reactants to increase system efficiency. Inlet air is pressurized by a compressor that is driven by a turbine utilizing heat generated from catalytic combustion of the SOFC products created during system operation. Fuel reformation is required to break down the hydrocarbon fuel into constituents that the SOFC can utilize, such as hydrogen and carbon monoxide. The proposed concept accomplishes this by using highly efficient steam reformation with water as an oxidizer. The steam reformer is integrated with the catalytic combustion chamber to provide the heat necessary for reformation. A high-temperature blower diverts some of the fuel cell anode exhaust to the reformer to provide water and heat.

Employing pressure vessel containment enables the proposed concept to operate at pressures of greater than 10 bars, which results in a system efficiency greater than 60% (LHV).

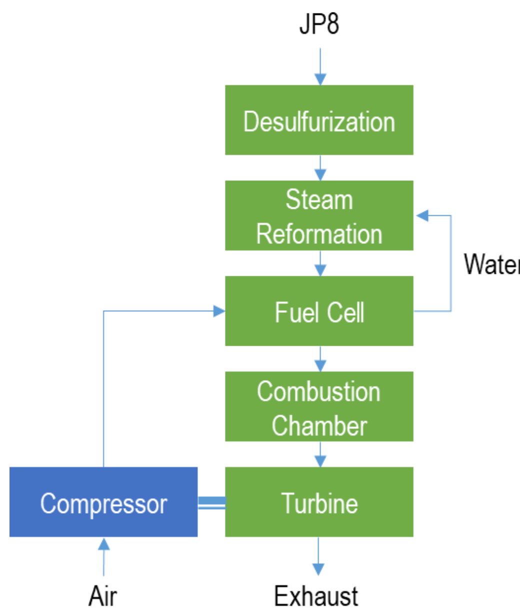

Figure 1 Forward Operating Base SOFC Power System Architecture

The remaining reaction products, apart from water, are catalytically combusted to generate heat for steam reformation and to drive the turbomachinery. Anode exhaust water that is not used in steam reformation is condensed and filtered for human consumption or used in other base functions such as centralized hygiene and construction purposes. The SOFC power system generates approximately 6 gallons of potable water for every 10 gallons of fuel consumed. Water recovered from the power generation process could be filtered to remove contaminants before treatment with minerals such as fluoride and calcium to produce potable water for drinking, food preparation, and personal hygiene. However, as much as 20% of the water may be lost in the filtration process, which is expected to include reverse osmosis.

Heavy hydrocarbon fuels for military applications contain as much as 3,000 ppmw sulfur. Sulfur compounds are known to poison the catalytic activity of many metals, including the anode materials of fuel cells. Work is underway to develop liquid and gas phase adsorptive desulfurization for JP8 to levels that would be acceptable to a SOFC (< 10 ppmw), potentially requiring desulfurization both upstream and downstream of the reformer. In large applications, such as Operating Bases, the sulfur absorbing beds can be thermally regenerated as needed. Approximately 5% of the fuel is lost in the desulfurization process and is represented as a loss in overall system efficiency.

System Efficiency – Figure 2 illustrates that the proposed SOFC based gen-set can achieve efficiencies that are 50% to 100% higher than that of diesel or gas turbine gen-sets. It is important to note that Operating Base gen-sets typically operate significantly below full load conditions. Unlike diesel and gas turbine generators, an SOFC-based power source remains highly efficient under reduced load.

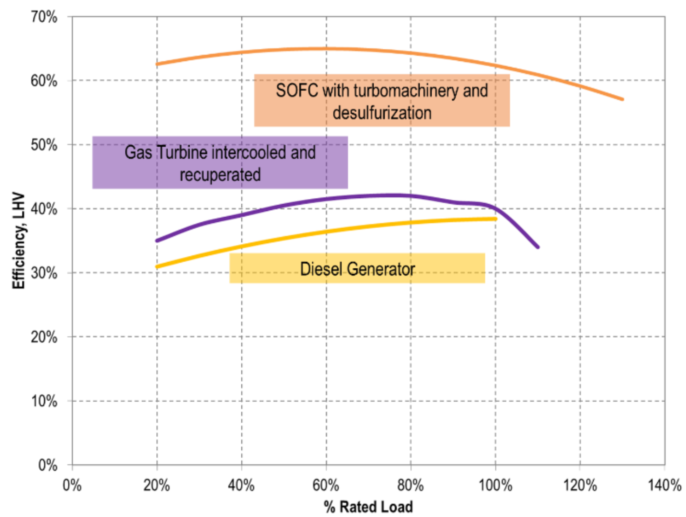

Figure 2 Efficiency of Large Generators (100 kW+) Operating on JP8

Logistics – The dramatic increase in efficiency offered by the proposed SOFC gen-set represents a significant reduction in fuel consumption. The proposed SOFC gen-set would require less frequent resupplies, which reduces the risk of bodily harm and loss of equipment during dangerous resupply convoys in contested areas. In the Iraq and Afghanistan campaigns, diesel fuel required by the FOB cost many billions of dollars. Table 1 shows a yearly cost savings potential of $2.8 billion (2007 dollars) by transitioning to an SOFC based gen-set from the current diesel gen-set for Harvest Falcon bases that support 1,100 soldiers (75 in Iraq and 43 in Afghanistan).[1]

[1] "Sustain the Mission Project Energy Costing Methodology," Steve Siegel, Energy and Security Group, DoD, May 23, 2007.

Table 1 Potential Yearly Fuel Cost Savings in Iraq and Afghanistan in 2007 using an SOFC Based Gen-Set

	Diesel Gen-Set	SOFC Gen-Set	Savings
Iraq – Total Savings of $1.3 Billion per Year			
Fuel Convoys (No)	3,285 / year	1,408 / year	1,877
Fuel Cost	$2.26 B ($17.17 / gallon)	$967 M ($17.17 / gallon)	$1.3 B
Afghanistan – Total Savings of $1.5 Billion per Year			
Fuel Convoys (No)	1,884 / year	807 / year	1,077
Fuel Cost	$2.63 B ($34.90 / gallon)	$1.13 B ($34.90 / gallon)	$1.5 B

Estimates in 2009 suggested 0.026 and 0.042 soldiers were killed in each convoy in Iraq and Afghanistan, respectively.[2] Based on the reduced number of convoys projected in Table 1, that results in the potential to save 93 lives per year (2007).

Noise (Acoustic Signature) – Based on experimental data from components for similar systems, the noise level of the proposed SOFC system is expected to remain below 55 dB with modest acoustic treatment, which is well below the current regulated noise thresholds for diesel power generators, and significantly under the range of typical fielded diesel gen-sets (approximately 65 to 85 dB).

MOBILE PLATFORMS (SILENT WATCH)

An SOFC-based power system for mobile platforms could use the same SOFC stacks as the FOB, but the system would be scaled down to meet power requirements as low as 1 kW. The turbomachinery of the larger system would be eliminated to further reduce noise (< 50 dB) and overall system weight and volume. The resulting system, shown in Figure 3, would have a fuel-to-electric conversion efficiency of 40% (LHV). A battery would be used to provide power during start-up and abnormal transient conditions and will recharge during normal operation.

[2] "Sustain the Mission Project: Casualty Factors for Fuel and Water Resupply Convoys," David Eady, Steven Siegel, R. Bell, and Scott Dicke, Army Environmental Policy Institute, September, 2009.

Air is pressurized by a fan or small compressor and directed to both the fuel cell stack and the auto-thermal reformer (ATR). An ATR is less efficient than a steam reformer but was selected for this application because it is lighter and more compact. The fuel is desulfurized in a liquid state and directed to the reformer before entering the fuel cell stack. A catalytic combustion chamber takes the effluent of the fuel cell to generate additional heat for the incoming reactants and the reformation process. Water for reformation is supplied by directing some of the fuel cell anode exhaust to the reformer. Depending on operational needs, the sulfur sorbent beds can either be regenerated in situ, thereby requiring two beds, or cartridges can be used and replaced as needed.

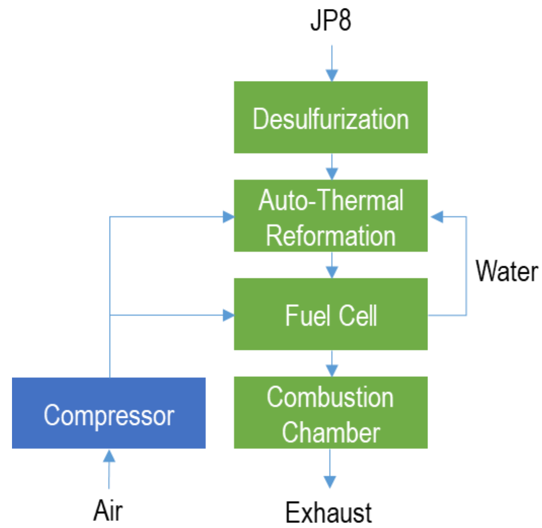

Figure 3 Mobile Platform SOFC Power System Architecture

METRICS

Power, efficiency, weight, and volume metrics are provided in Table 2 below.

Table 2 Metrics for the Forward and Remote Operating Base and Silent Watch Proposed Power Generation

Parameters	**Power Generation FOB**	**Power Generation Silent Watch**	**Comments**
Specific Energy	NA	NA	It's a power generation system not energy storage system
Power Output	100 kW to 10 MW	1 kW to 10 kW	
Efficiency	>60%	~40%	
Weight	~1510 kg.	~34 kg	• For 250kW FOB system • For 2 kW Silent Watch system
Volume	~3,000 liters	~50 liters	
Endurance	NA	250 hours	Sulfur filter needs replacement for silent watch. FOB system has regenerative sulfur bed

Environmental Considerations – SOFC power systems are relatively impervious to ambient temperature and can operate from subzero to ~50°C based on sizing of the balance of plant heat exchanger capabilities. The solid oxide stacks operate ~700°C and are well insulated to prevent heat loss to the environment as this reduces the overall system efficiency. Air intake filters can be used to prevent ingestion of particulates.

Solid oxide cells use a ceramic electrolyte which is susceptible to breakage in high vibration and shock environments. However, the newly emerging metal-supported cell technology previously discussed, should allow the stack to sustain higher vibration and shock loads.

Maintenance – An SOFC power plant used in a FOB requires no scheduled maintenance except replacement of air filters as the sulfur beds can be designed to be regenerative. However, a mobile SOFC system will require the sulfur filter be changed approximately every 200 hours, depending on the amount of sulfur in the fuel. We anticipate the SOFC stacks to be operational for approximately 5000 hours, however performance degradation (loss in efficiency) based on the duty cycle may require earlier replacement of stacks.

Safety Issues – No system safety issues are expected.

Personnel Training – Basic system operation training, which will include startup and shutdown of the SOFC system, will be required. Field maintenance training will be limited to changing of the air and sulfur filters. Comprehensive maintenance, where balance of plant components and stacks are to be replaced, will be conducted at a maintenance depot or the factory.

POWER MANAGEMENT

Power conditioning and management are required for fuel cells and batteries as they provide DC power at an output voltage that varies with load. Battery output voltage is a function of its state of charge (SOC) and the load impedance, whereas fuel cell output voltage changes with load per its current-voltage (I-V) curve. Existing AC and DC electrical loads are designed to operate over a specified voltage range. Power conditioning of fuel cell and battery output is necessary to minimize impacts to these loads.

Boeing has successfully developed and patented a high-efficiency DC-to-DC boost converter with a conversion efficiency that could reach 99%. This boost converter reduces cooling requirements and energy losses in the system. Large AC loads in FOB require the inversion of DC output from the SOFC gen-set. The solar power industry has made tremendous advances in inverter design, achieving converter efficiencies as high as 99% using IGBTs as power semiconductors. The U.S. Army should consider changing to DC loads because advances in power electronics have enabled the development of power converters with very high efficiency.

DEVELOPMENT

Development of both platforms discussed in this paper falls under the Tier 1 category. With adequate funding, we can demonstrate an operational system, for both products, within 6 years and have an operational system ready for procurement by 2035. A high level development plan is shown in Figure 4.

Figure 4 Development Plan for the Proposed Forward Operating Base and Silent Watch Power Systems