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Feasibility study for SOFC-GT hybrid locomotive power part II. System packaging and operating route simulation

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ABSTRACT

This work assesses the feasibility of Solid Oxide Fuel Cell-Gas Turbine (SOFC-GT) hybrid power systems for use as the prime mover in freight locomotives. The available space in a diesel engine-powered locomotive is compared to that required for an SOFC-GT system, inclusive of fuel processing systems necessary for the SOFC-GT. The SOFC-GT space requirement is found to be similar to current diesel engines, without consideration of the electrical balance of plant. Preliminary design of the system layout within the locomotive is carried out for illustration. Recent advances in SOFC technology and implications of future improvements are discussed as well. A previously-developed FORTRAN model of an SOFC-GT system is then augmented to simulate the kinematics and power notching of a train and its locomotives. The operation of the SOFC-GT-powered train is investigated along a representative route in Southern California, with simulations presented for diesel reformate as well as natural gas reformate and hydrogen as fuels. Operational parameters and difficulties are explored as are comparisons of expected system performance to modern diesel engines. It is found that even in the diesel case, the SOFC-GT system provides significant savings in fuel and CO_2 emissions, making it an attractive option for the rail industry.

1. Introduction

As discussed in Part I of this work, the transportation of goods by rail has historically been a major portion of the overall freight transportation system in the United States. Although its use declined for some years in favor of trucks, freight transport by rail has recently begun to be more widely utilized again and is now more prevalent than trucking, on a ton-mile basis [1]. Thus, it is reasonable to assume that transport by rail will continue to have a major role in our nation's freight-carrying infrastructure.

A complete understanding of the emissions impact of locomotives is still an active research area, but it is becoming increasingly clear that a significant stress is imparted on the environment and the health of those living near the rail lines' centers of operation. Recent studies carried out in the Southern California area highlight impacts on the population living near rail operations centers, caused mostly by the emission of diesel particulate matter (PM). In one year, these PM emissions from the Ports of Los Angeles and Long Beach have been estimated to be responsible for 29 deaths, 750 asthma attacks, and as many as 6600 lost work days [2]. Another study at the BNSF rail yard in San Bernardino, California found that in the neighborhoods nearest to the rail yard, the risk of lung cancer was nearly double the background risk; nearly 36,000 residents living within one mile of the rail yard were estimated to have an increased cancer risk between 10 and 50% of the background [3]. Clearly, the current locomotive-based emission of PM proves to be a concern, with a significant environmental justice impact.

In addition to PM emissions are concerns regarding fuel efficiency, fuel cost, and emissions of greenhouse gases, including CO_2 in particular. It is estimated that one gallon of diesel fuel typically produces 10,217 g of CO_2 [4]. In 2005, 5714 trillion BTUs of diesel fuel were utilized by the freight rail industry, or approximately 4.44 billion gallons [5]. This represents a potential emission of 45.36 million tons, or approximately 7.4% of the total national emission of CO_2 in the same year [6]. Given the current emphasis on reduction in Greenhouse Gas emissions, it is reasonable to assume that locomotives may be required to reduce their GHG emissions. In addition, there is evidence that the industry is moving forward with plans to address the concern, as the development of General Electric's Evolution and Evolution Hybrid locomotives seem to indicate [7–9]. Moreover, current EPA guidelines provide restrictions on locomotive emissions of CO, unburned hydrocarbons, and NO_x, all of which have been discussed in Part I. The consideration of the

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impact of diesel fuel use and emissions signature from the rail industry provide strong motivating factors for the investigation into alternative systems for powering the industry's locomotives.

Thus, the need for more locomotives with a smaller environmental impact has been recognized. Given how thoroughly the diesel engine has penetrated the locomotive market as the engine technology of choice, the development of strategies to improve diesel technology is a logical first step for improving the fuel efficiency and emissions characteristics of locomotives. However, future efficiency and emissions requirements may exceed the capabilities of diesel technology requiring an investment in new technologies and capabilities that may be applicable to the railway prime mover. Early investment in emerging technologies, such as solid oxide fuel cells, may provide more options and open the door to greater improvements. The fuel cell has already been identified as having an opportunity to completely replace the entire diesel and electric power system for a locomotive [10].

Research to-date has nearly exclusively considered low-temperature fuel cells in this application. Application-based research for high-temperature fuel cells has additionally focused on stationary power applications. In spite of this focus, the locomotive application of fuel cells has been studied since the 1980's, especially in the context of use for the Canadian rail system [11–13]. Although the particular fuel cell type, fuel, and system configurations varied, these early models and studies did conclude that the use of a fuel cell system in this application was possible, and could have substantial benefits, but that the economic viability was a hurdle which would have to be overcome. These findings are common to many previous fuel cell systems analyses, especially given the early stage of development of fuel cell technologies and the lack of mass production capability for this technology. Scott et al. further emphasized that life-cycle considerations made the option more competitive [14]. Their conclusions also pointed to increased viability in the case of possible levies based on emission rates.

Significant investment in the practical application of fuel cells to American railway applications has been accomplished by Vehicle Projects, LLC. In 2002, Vehicle Projects developed the first fuel cell locomotive, building a 17 kW mine cart for use in Ottawa. Vehicle Projects are currently nearing completion of a fuel cell-battery hybrid switcher locomotive, based on the design of a diesel-battery hybrid. The Department of Defense is also working with Vehicle Projects to develop a 1.2 MW locomotive that is designed for freight transport but can also be utilized as a base power plant, thereby providing dispatchable emergency power for the military [12]. The design process for the near-complete railyard switcher locomotive has been well-documented, including much discussion of feasibility and physical constraints [15–17]. The wide range of interests and attention to detail in many of these investigations is a positive indicator of the applicability, potential, and interest in this technology.

Note that all of the above studies and developments have only considered low-temperature fuel cells, primarily using PEM technology. This may be due to a need for quick startup in these applications or may be motivated by the desire to study a fuel cell type of a particular industrial partner or that is closer to commercialization and mass production. Regardless of the motivation, there has consistently been some concern about the power density of the fuel cell system, as there is limited space available on a locomotive for the prime mover, and fuel cells tend to have lower power density than diesel engines. PEM fuel cells have traditionally had the highest power density of any fuel cell type. However, recent SOFC developments suggest that SOFC technology can achieve very high power density [18]. In addition, SOFCs are expected to have higher efficiency (lower polarizations) and are inherently much more fuel-flexible, which could reduce the size requirements of the onboard fuel and fuel processing system, further alleviating the physical constraints on the system.

Further integrating the SOFC with a gas turbine to create a hybrid SOFC-GT system could provide even greater efficiency and power density, as typical combined efficiencies of such systems are higher than SOFC systems alone, surpassing 70% [19,20]. In addition, the use of diesel fuel, enabled by SOFC fuel flexibility, will aid in the transition to a new engine technology and will support higher fuel energy density compared to hydrogen. SOFC technology has proven high efficiency and low emissions, which can alleviate concerns about fuel use and environmental impact. All of these factors support the consideration and motivate the analysis of a diesel-fueled SOFC-GT locomotive engine. The current novel analysis is intended to determine whether or not recent advances in SOFC-GT technology enable it to positively contribute to clean and efficient future freight rail applications. In this work, this analysis is presented as a two-part process: first, the physical constraints on the sizing of the system are examined, followed by an investigation into the operational capability of the system. Similar to Part I, the simulations in this work do not yet consider the integration of the reformer, but analyze a scenario in which fossil fuel reformates are generated offboard and supplied to the locomotive fuel tank.

2. Calculations for physical constraints

2.1. Satisfying space constraints

A major consideration for the feasibility of an SOFC-GT system applied to locomotive power is to determine whether there is sufficient space available in the engine compartment of a current locomotive design. The integration of the SOFC-GT system should be as seamless as possible; thus, it would be undesirable to use multiple locomotives to provide the same power as a single diesel engine-powered locomotive. In addition, it would be desirable for the fuel system to not impose a volumetric or mass constraint that would require pulling a fuel tender. All of the components necessary for the SOFC-GT unit, fuel storage, and fuel processing systems, as well as balance of plant components are considered for placement within the confines of a typical locomotive engine compartment.

Diesel fuel is desired for operation of the SOFC-powered locomotive because it allows rail operators to continue to use a familiar fuel for which there exists a substantial and satisfactory infrastructure. Other fuels, such as bio-fuels, LNG, CNG, or even H_2 could be readily applied to future use; however, early introduction of such fuels is unlikely due to the additional challenges of establishing an entire fuel provision infrastructure. In the long-term, SOFC technology could enable a transition to alternative fuel use in rail applications due to inherent fuel flexibility.

For reference, most of the comparisons in this work have been made to the AC4400CW and ES44AC/DC locomotives designed by GE and their associated GE7FDL and GEVO-12 (a modified GE7FDL) engines. The GE7FDL engine used on the AC4400CW is a 4500 hp (3355 kW) engine, weighing 19,736 kg, and measuring 4.90 m long by 1.74 m wide by 2.98 m tall, inclusive of the exhaust stack [21]. This 16-cylinder engine is replaced by the 12-cylinder, 4400 hp GEVO-12 on the ES44AC/DC, for which specifications are currently unavailable. However, the total engine compartment, which includes more than the diesel engine itself, provides a floor space of approximately 11 m^2 and a volume of around 53 m^3.

In this application, both volumetric and footprint constraints must be met, since overall locomotive width and height are limited by external infrastructure constraints such as tunnel dimensions.