BRAKING PERFORMANCE TEST PROCEDURE FOR HYBRID VEHICLE ENERGY STORAGE SYSTEMS: CAPACITOR TEST RESULTS

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INTRODUCTION

Hybrid gas-electric automobiles have been commercially available for several years. Because of good market acceptance, partly due to exceptional fuel economy, several manufacturers plan to introduce new models over the next several years. Hybrid city-transit buses are now in operation in several cities with demonstrated fuel economy improvements and emission reductions. Other "heavy-hybrid" vehicles are presently under development, for example a 60,000-pound refuse truck. This hybrid application, where there are typically 800 to 1000 start-stop cycles each day, has great potential to achieve lower fuel consumption, reduced brake maintenance, and decreased operating noise.

These hybrid vehicles derive performance advantages from use of an on-board, fast-response energy storage reservoir. The reservoir must be capable of being filled in a few seconds during regenerative braking, store the energy without sizable losses for seconds to minutes, then release the energy in ~5 to 20 seconds to support vehicle acceleration. In effect the reservoir load-levels the power requirements of the vehicle. Provided that the storage reservoir operates with high efficiency, a smaller internal combustion (IC) engine becomes practical, one sized for the average rather than peak-power demands. A separate electric motor is used to meet load dynamics. An added benefit is that the IC engine, when optimized to run only within a narrow RPM range, can achieve much higher efficiency and lower emissions than in an engine-only vehicle.

Different hybrid vehicle energy storage technologies have been demonstrated. Batteries have been by far the most popular approach. Electrochemical capacitors, often referred to as supercapacitors or ultracapacitors, have been recognized for several years as offering superior performance to competing battery technology due to their exceptional power performance, high cycle life, long operational life, and safe environmentally friendly design. Batteries offer clear energy density advantages while capacitors can offer maintenance-free power density advantages. Efficient energy capture, storage, and delivery are key elements for operational success of the capacitor system and should be used partly to identify the quality of an energy storage product.

This paper describes a simple test procedure to quantify the performance of a storage capacitor during hybrid vehicle braking. The procedure overcomes limitations of earlier approaches like use of projections based on Ragone plots, pulse-power figures-of-merit values, and matched-load power calculations. The approach allows the various capacitor technologies to be objectively evaluated, and in fact, could be extended to include other technologies like batteries and flywheels.

TEST PROCEDURE

The test approach simply relies on measuring the maximum energy that can be captured by a capacitor when charged from one-half rated voltage to rated voltage. In practice, the device is held at one-half rated voltage for 30 minutes, charged at constant current to the rated voltage, then immediately open-circuited for five minutes. The time integral of the charging power determines the regenerative captured energy. The voltage after the five-minutes of open circuit (assumed to be equilibrated) is used to determine the quantity of stored energy from the energy-voltage relationship obtained at a low charge rate where resistive and charge redistribution effects are small and can be neglected. Capacitor charge rates (stopping times) important for hybrid vehicle applications generally span the 3 to 30 second range.

Capacitor mass or volume can be used to normalize stored and captured energy, which provides opportunities to compare braking performance of the various technologies or products. Importantly, capture efficiency comparisons will allow estimates to be made of the relative size of each anticipated thermal management system. Thus the energy storage system mass and volume can be estimated for a specified range of stopping times and capacitor operating temperatures.

TEST RESULTS

Test data for a commercial 1200 F, 2.3 V capacitor cell are shown in **Figure 1**. Captured energy is the total energy accepted by the capacitor, which is dissipated or stored. Stored energy is the quantity of energy that ends up in the capacitor and available to perform work like vehicle acceleration. Referring to the figure, ~6.5 kJ/kg of energy is stored in the capacitor during a 300 second stop, ~6 kJ/kg during a 30 s stop, and ~3 kJ/kg during a 3 second stop. The decrease is associated with resistive losses and porous electrode behavior. This information is normalized by mass and shown as fractional utilization of the total storage in Figure 2.

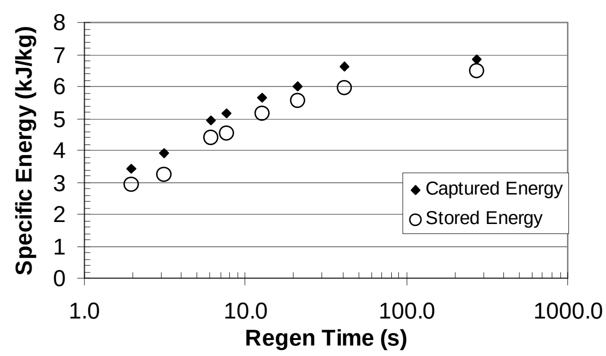

Figure 1: Captured and stored energy by a capacitor rated at 1200 F and 2.3 V at various regen braking times. Voltage starts at one-half the rated voltage and reaches rated voltage during the regen time.

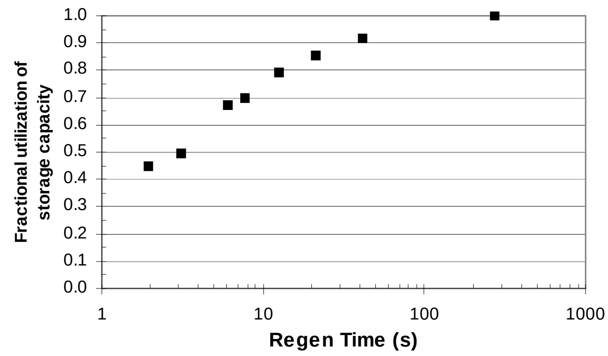

Figure 2: The ratio of energy stored to the maximum possible stored at different regen times. For example, with 3-s braking, the capacitor stores only ~50% of its low-rate (long regen time) value.