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**Federal Railroad
Adminstration**

Assessment of Micro-Superconducting Magnetic Energy Storage (SMES) Utility in Railroad Applications

A Report to Congress

**Office of Research
and Development**

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LIST OF ABBREVIATIONS & ACRONYMS

AC	Alternating Current
ARPA	Advanced Research Projects Agency
ConnDOT	Connecticut Department of Transportation
DC	Direct Current
DNA	Defense Nuclear Agency
DOD	Department of Defense
DOE	Department of Energy
EPRI	Electric Power Research Institute
ETM	Engineering Test Model
FRA	Federal Railroad Administration
GBFEL	Ground-Based Free Electron Laser
HARC	Houston Advanced Research Center
Hz	Hertz
J	Joule
kg	Kilogram
kV	Kilovolt
kWh	Kilowatt-hour
LANL	Los Alamos National Laboratory
LIRR	Long Island Rail Road
MARC	Maryland Rail Commuter
M/G	Motor/Generator
MJ	Megajoule
MW	Megawatt
NEC	Northeast Corridor
NJT	New Jersey Transit
PCCIE	Power Conditioning and Continuation Interfacing Equipment
PCU	Power Conditioning Unit
SDIO	Strategic Defense Initiative Office
SEMS	Superconducting Energy Management System
SEPTA	Southeastern Pennsylvania Transportation Authority
SMES	Superconducting Magnetic Energy Storage
UPS	Uninterruptible Power System
USAF	United States Air Force
W	Watt

Executive Summary

At the direction of the U.S. Congress, the Federal Railroad Administration (FRA), with technical support from the Volpe National Transportation Systems Center (Volpe Center), investigated the feasibility of using micro-Superconducting Magnetic Energy Storage (SMES) technology to provide cost-effective energy regeneration and energy savings capability along the Northeast Corridor (NEC) for both Amtrak and commuter rail operations. The approach has been to review the current technical literature and other background information on SMES concepts, materials, designs, and benefit/cost projections. In addition to this independent review, comments from recognized experts in government, industry and academia were solicited and their input was considered by the FRA and the Volpe Center in assessing micro-SMES technology maturity and suitability to improve or upgrade the efficiency of rail operations along the NEC between Washington and Boston.

On the NEC, trains currently use a combination of friction and dynamic braking as the means for slowing down and stopping. In dynamic braking, the traction motors function as generators converting the kinetic energy of the train into electrical energy. This energy is then dissipated as heat in resistor grids. There is an opportunity to recover this energy and to reuse it to reduce the amount of energy purchased for propulsion via redistribution or an energy storage system such as micro-SMES.

Based on this preliminary review and technical analysis, it appears that SMES technology with current capabilities does not presently "provide cost-effective regeneration and energy savings capability along the NEC for either Amtrak or commuter rail." First, SMES devices store too little energy for their size, weight and, most importantly, cost to be useful as bulk energy storage units either on board a trainset or on the wayside. Second, the electrical distribution network serving the NEC is sufficiently dense that it can absorb any energy transferred from regenerative trains. Third, existing SMES prototypes have only recently been introduced to the commercial environment for utility or critical facilities power quality applications and are still under test and evaluation. No one is currently pursuing near-term commercial SMES configurations appropriate for railroad energy savings applications.

Since micro-SMES systems are an emerging and still rapidly evolving technology, currently being introduced in selected market areas, there is little operating experience to date for micro-SMES power applications. As a result, it is difficult to assess the potential for economies of scale in capital, operating and maintenance cost pricing. However, researchers have identified design goals and options for improving the cost and performance of current micro-SMES systems in the areas of energy capacity, size, cost, safety, and efficiency.

It is clear that both technology push and market pull are necessary if micro-SMES systems are to be introduced into transportation and power niche markets. Although SMES units of the size defined as "micro" (20 megajoules, i.e., 20 megawatt-seconds of energy capacity) do not appear appropriate for cost-effective energy regeneration, because of their relatively low energy storage capability, large SMES units or massively parallel micro-SMES with a storage capacity on the order of 1000 megajoules may be useful in particular applications where the potentially large capital investment can be justified.

Section 1 - Introduction

The U.S. Congress, in a Conference Report accompanying the Department of Transportation and Related Agencies Appropriations Act, 1997, P.L. 104-205, directed the Federal Railroad Administration (FRA) to prepare a report on the "feasibility of utilizing micro-Superconducting Magnetic Energy Storage (SMES) technology to provide cost-effective regeneration and energy savings capability along the Northeast Corridor (NEC) for both Amtrak and commuter rail operations."

In response, the FRA, with technical support from the Volpe National Transportation Systems Center, has conducted a literature search, and has solicited information and comments from a number of organizations with expertise in SMES technology and/or railroad operations. These organizations include SMES industry representatives, university researchers, government agencies, and an electrified railroad operator. This review and assessment was conducted based on the available information gathered and upon simulation data generated by modeling of train performance on the NEC.

The utility industry and Federal agencies have been developing SMES and micro-SMES prototypes since the 1970s. Micro-SMES applications, limited to less than 20 megajoules (MJ), are currently focused on those installations where power quality is critical to the operation of a facility or to the control of an industrial process. For these critical applications, the installation or process must be protected from voltage fluctuations and momentary power outages of the utility power system. Computer controlled facilities and industrial processes are typical of installations where power quality is critical. Almost all of these systems now make use of an uninterruptible power supply consisting of lead-acid battery power, sometimes in conjunction with emergency diesel engine generators operating in parallel to the utility power supply. However, the requirements for industrial power quality applications differ significantly (in the number of charge/discharge cycles) from the energy regeneration and energy savings requirements of the electrified railroad industry.

This review and assessment has focused primarily on the use of micro-SMES devices for capturing, storing, and resupplying regenerated braking energy of electrified trains. Other railroad applications such as uninterruptible power supplies may potentially benefit from the capabilities associated with magnetic energy storage, but these were beyond the scope of this study.

Section 2 - Background of SMES and Micro-SMES Development

Section 2.1 - Background

Superconducting Magnetic Energy Storage (SMES) technology is based on the simple physical principle that a wire carrying a direct current (DC) creates a magnetic field that stores energy. If the wire is wound in a coil, the stored energy in the coil increases in proportion to the number of coil turns and to the square of the current. However, current flowing in an ordinary wire (e.g., copper) generates resistance losses that dissipate the stored energy. When a superconducting material is used as the conductor, the resistance loss is reduced to negligible level at or below the critical superconducting temperature (usually near absolute zero) for the specific material. Such a coil can store the energy indefinitely so long as it is kept in a superconducting state, via a cryogenic refrigeration system.

In its simplest configuration, a SMES system is an energy accumulator consisting of a superconducting coil that stores energy in the magnetic field generated by a direct current flowing in the coil. The SMES is attached, via a power conditioning unit (PCU), to the power source, usually an electric utility power grid, and to the system being served. Its key feature is that energy can be stored indefinitely, and the energy in the superconducting coil can be extracted very quickly. A SMES can respond very rapidly to either supply power to a load, or absorb power from a grid, with the key limitation being the switching time and capacity of the solid-state power conversion equipment. In addition to the superconducting coil and the PCU, the SMES plant also has a cryogenic refrigeration system to keep the superconductor at cryogenic temperatures. Since a SMES needs to be maintained at cryogenic temperatures, it needs a refrigeration system which requires a fair amount of power to operate. Depending on the system design and operating sequence, the thermodynamic losses associated with the cold-to-warm interface can significantly reduce the energy savings capability.

Because of its fast response, a SMES of sufficient capacity can also be used to enhance power transmission line electrical stability and power quality. Typically, SMES units can respond to a grid transient and deliver full power in less than 100 milliseconds. Therefore, not only can a SMES insert real power into or absorb real power from a grid, but it can also provide line stability and increase power quality. This is the application which currently has the largest interest among utilities and their customers.

The perception when SMES was initially proposed in the late sixties and early seventies was that electricity would primarily be produced by nuclear generating plants, while fossil fueled powered plants would serve only to provide peaking duty (at times of high demand). To minimize the use of the fossil-fueled peaking units, utilities would try to smooth the daily differences between peak demand and available supply by any or all means, including energy storage. Competitive energy storage systems, some of which are also in a developmental stage, include pumped-hydro, batteries, flywheels, ultra capacitors, and compressed air.

Because of these perceived needs, early SMES designs focused on large-scale systems capable of storing 18,000 gigajoules (5000 MWh) or more. However, the superconducting coils needed for such large units were orders of magnitude larger than anything built at that time. Such SMES units were viewed as too large and expensive for the amount of load leveling required in utility applications.

In 1972, the U.S. Atomic Energy Commission requested the Los Alamos National Laboratory (LANL) to determine the relative value of SMES in comparison to other storage technologies, and to assess the utility conditions in which it would have to operate. The study quickly focused on transmission line power quality rather than load leveling because the bulk energy storage requirement was manageable by other means. In 1976, LANL initiated a program to design and construct a 30 megajoule (8.3 kWh) SMES unit to provide stability support to the Bonneville Power Authority's Pacific Intertie. The unit, located in Tacoma, Washington, operated for about a year. The need for the SMES unit, which existed in 1976, was subsequently eliminated by the introduction of much more cost-effective equipment, namely solid state power control.

In 1987, the Defense Nuclear Agency (DNA) was tasked by Department of Defense's (DOD) Strategic Defense Initiative Office (SDIO) to undertake a dual-use (military-electric utilities) program to demonstrate a 72 gigajoule (20 MWh) SMES Engineering Test Model (ETM). It was to provide 72 gigajoules (20 MWh) of usable energy storage, with PCU capabilities of 400 megawatts for 100 seconds for the military demonstration and 10 megawatts for 2 hours for the electric utility demonstration. The SMES-ETM was to demonstrate a dual-use technology that could be scaled up to 3,600 - 18,000 gigajoule (1000 - 5000 MWh) plants. It was to develop the design, engineering, fabrication, and construction technologies necessary for a full-scale plant. Based on costing studies, it was anticipated that for SMES technology to be economically viable, 3,600 gigajoule (1000 MWh) or larger systems would need to be developed.

For military purposes, these SMES units were to provide power sufficient for a ground-based, free-electron laser (GBFEL) directed-energy weapon under development by SDIO. To power the GBFEL, a SMES with an energy capacity of about 3,600 gigajoules (1000 MWh) was required. For electric utilities, these large SMES plants were to provide diurnal storage of electrical energy to level the typical day-night cycle of usage. The electric utilities were interested in SMES only if the plants were cost effective, efficient, reliable, easily sited, and environmentally acceptable.

After a preliminary costing study, two contractors (Bechtel and Ebasco) were selected for the SMES-ETM, Phase I, concept definition. Both teams proposed solenoidal coil designs with diameters of over 100 meters, and heights of over 5 meters. These teams proposed to use thousands of liters of helium to cool the superconducting coils.

In 1990, SDIO canceled the GBFEL program. Consequently, in June 1991, DNA canceled the SMES-ETM program. Subsequently, in late 1991, at the direction of Congress, DNA resumed the SMES-ETM program. Because the cost estimates for Phase II increased to more than five times the original cost estimate of $54 million, a Risk Reduction Program was undertaken as well as a survey of military and electric utility applications. Although a number of potential military applications were identified, such as the Navy's next generation all-electric aircraft carrier, no formal military requirements for SMES were found. The survey of electric utilities showed them to be turning away from diurnal energy storage toward a focus on energy management, primarily because of the high cost and low energy density of SMES units.[1] Hence, researchers changed their focus and proposed a change from the acronym SMES to SEMS (Superconducting Energy Management System). Numerous power quality applications were identified. Transmission line stability enhancement is likely to be the first commercial application of SEMS in the utility sector. Many alternating current (AC) transmission lines are limited in power capacity by stability constraints. As transmission networks become increasingly interconnected this increases in importance (especially under the stability risks posed by the contemplated environment of retail power wheeling). Because of its fast response (within 100 milliseconds or six cycles) to inject or absorb power, a SEMS plant can significantly enhance transmission line stability.

In September 1993, the U.S. Air Force Power Conditioning and Continuation Interfacing Equipment (PCCIE) Materiel Group at McClellan AFB initiated a 3-year program to field and evaluate micro-SMES devices. PCCIE concentrated development on "dual-use" (government and commercial) power quality applications of micro-SMES. The PCCIE goal was to demonstrate that micro-SMES devices are capable of providing quality electrical power and short-term system power backup in case of power outages. Final reports documenting the results of the technology demonstration programs are scheduled for completion in March 1997.

The PCCIE micro-SMES Technology Insertion Program identified several sites for demonstration of micro-SMES technology. These are the DOE Brookhaven National Laboratory, Upton, New York; McClellan AFB, Sacramento, California, and the Defense Megacenter at Tinker AFB, Oklahoma. Superconductivity Inc., of Middleton, Wisconsin, built and installed the first three systems. Intermagnetics General Corp., of Latham, New York, has been selected to install the fourth unit at Wright Laboratory, Tyndall AFB, Florida, around May 1997.

The SMES industry, based on its success in demonstrating small scale prototype systems, now believes that commercialization of SMES can follow a steady approach of demonstrating better and bigger units that can be tailored to specific applications.[2]

Section 2.2 - References

1. "Summary of the DNA SMES Development Program," Ullrich, George W., Defense Nuclear Agency, 1995.

2. "Superconducting Storage Systems: An Overview," Luongo, Cesar, Bechtel Corp., 1995.

Section 3 - Micro-SMES System Description

Micro-SMES systems are defined as superconducting magnetic energy storage devices with energy capacities less than 20 megajoules (5.5 kWh).[1] However, there is no technical barrier here. Conceptually, a SMES can be any size. Micro-SMES units are now commercially available from several U.S. vendors, with power capacity and energy storage ratings of up to 2 megawatts and 3 megajoules, respectively. Energy can be conveniently quantified as a joule (J), equivalent to a watt-second, or alternatively, in larger quantity, as a kilowatt-hour (kWh). The power level of an energy storage device defines the rate (joule per second) at which the storage device can be charged and discharged. Power is usually given in terms of watts (W). Energy is equivalent to power multiplied by time.

Section 3.1 - General Description

Superconducting magnetic energy storage (SMES) devices are designed and configured to store energy in the form of an intense magnetic field created by circulating a current in a superconducting coil. The energy stored in the coil is proportional to the coil inductance (a measure of how much impediment a coil presents to rapid current buildup) times the square of the circulating current. This energy can be stored indefinitely because the superconducting coil does not provide any resistance to the circulating current. But, to maintain this state of superconductivity, energy must be supplied from outside to operate a cryogenic refrigeration system. As an energy storage device, SMES is conceptually similar in function to a conventional battery, except that it can be rapidly charged and discharged.

Certain materials become superconducting when cooled below a characteristic temperature (usually near absolute zero). To achieve and maintain superconductivity, a SMES system requires that the coil be immersed in a bath of cryogenic fluids (liquid helium or nitrogen) which is then enclosed in a vacuum sealed thermos or cryostat. In addition, refrigeration and thermal isolation equipment is needed to maintain the temperature within the cryostat below that which is required for superconductivity. The micro-SMES systems evaluated in the field to date use superconducting magnets made from a niobium-titanium alloy wire. For the niobium-titanium alloy to become superconducting, it must be cooled to liquid helium temperatures (4° Kelvin or minus 269° Celsius or minus 452° Fahrenheit).

To extract the energy from the coil, wire leads must be connected to the coil in the cryostat. These leads connect the coil to the power conditioning unit and, while the SMES is in the fully charged standby state, the leads still carry the full current. These connections are a major source of heat creeping into the cold mass of the superconductivity material. Heat entering the superconductor through these leads greatly increases the heat removal load on the cryogenic system.

Power conditioning equipment is used to extract energy from the SMES and to condition it properly in terms of voltage, current, and phase, if the load requires it. This equipment contains rectifiers and inverters. These devices are used to control the flow of energy to and from the SMES unit.

Strong mechanical forces, called Lorentz forces, are associated with the large direct currents circulating in the SMES coil. The cryostat structure must restrict these internal forces. Movement of coil wire in response to these forces generates heat (in the cooled mass) which must be extracted at high cost. Furthermore, the coil support structure itself can become a path for heat leakage into the superconductor.

Section 3.2 - Cryogenic System

The cryogenic system is designed to keep the conductor of the coil cold enough to remain superconducting. For low temperature superconducting material, such as niobium-titanium alloy, the conductor is typically maintained at about 4° Kelvin above absolute zero in a bath of liquid helium. Other more elaborate methods of cooling, such as cryogenic pumps, are possible, but they add to the degree of system complexity, manufacturability, and cost. High-temperature superconductors are being developed that can attain useful current-carrying characteristics at temperatures between 20 to 70° Kelvin (which can be attained with liquid nitrogen rather than helium). These materials have yet to show the current and magnetic field density required of SMES.

A superconducting coil will become resistive when its temperature rises above a critical temperature, and at that time the coil is no longer superconducting (i.e., said to be "quenched"). If the coil is carrying a significant current at the time of a quench, the coil may be damaged to the extent that it may release cryogenic fluids and even cause an explosion. Therefore, a SMES unit must be carefully monitored and the energy stored in the SMES unit must be dissipated as heat in resistor banks prior to or during a quench.

The cryogenic system must continually remove any heat generated in the superconducting material to avoid any significant temperature rise in the conductor. Heat is generated in the superconductor when the magnetic field in the coil changes, as happens with each charge and discharge cycle. As the duty cycle of the SMES unit increases, the load on the cryogenic system also increases. Heat is also continuously introduced into the cold mass through the leads, which run from inside the cryostat out into the ambient temperature environment outside the cryostat. These resistive leads must be sized large enough to reduce the resistive losses from the large currents associated with SMES operation, but with this large conductor cross-section comes increased thermal losses through conduction. This heat must be continuously removed from the cold mass to maintain superconductivity. Due to the extremely low temperatures, and the inefficient methods available for cooling at those temperatures, the cryogenic system must use approximately 1,000 watts of power to remove 1 watt of heat from the cold mass.

Power required to run low temperature superconductor "refrigeration systems" is relatively significant, especially for SMES units of the micro size (less than 20 MJ). The commercially available micro-SMES units, which are designed to provide 3 MJ of energy, have cryogenic loads in excess of 30 kW.[2] For larger SMES units, it is expected that this cryogenic load will decrease on a per megajoule basis. The cryogenic load for the large 1800 MJ SMES under development by Anchorage Municipal Light and Power in Alaska is expected to be approximately 2 MW.

The prototype systems demonstrated recently were configured as power quality and uninterruptible power systems. These systems had low duty cycles (short term and infrequent) where excessive charge/discharge heat losses and efficiencies were not a major concern. A railroad-based SMES unit must have a cryogenic system that can handle the heat generation associated with the more severe power and duty cycle requirements of railroad operations.

Section 3.3 - Importance of the Power Conditioning Unit (PCU)

Power conditioning equipment is used to convert energy from the superconducting coil to a form required in the application. This typically involves rectifiers (AC to DC) and inverters (DC to AC). These devices are used to control the flow of energy to and from the SMES unit. Switching frequency, switching time, voltage, current, and other factors influence the design and configuration of the power conditioning unit for SMES interfaces. Because the primary function of the SMES device is to supply or store power instantaneously when needed, the energy stored in the SMES must be "conditioned" and delivered to the load promptly. The cost of the power conditioning unit is determined by the power rating and response time requirements and often is a substantial portion of the cost of the SMES system.

In addition to the power electronics, switchgear and power transformers will be required to interface a SMES with a high voltage power distribution system. For railroad usage, switchgear would be necessary to isolate the SMES unit from a railroad's catenary power distribution system in cases of faults, or during maintenance activities associated with individual electrical catenary sections or the SMES unit itself. A power transformer would be required to transform the output of the PCU up to the voltage level of the catenary distribution system. These components can add significantly to the cost and size of the integrated SMES station.

Advances are continuously being made in power electronics technology. The power levels, switching frequency, duty cycles, and manufacturability of these devices are improving every year. Improvements in power electronic devices may reduce the cost of SMES but may also reduce the need for energy storage/management concepts as well.

Section 3.4 - Safety-Related Systems

The tremendous energy and associated mechanical forces of a SMES system must be monitored and controlled to keep the magnet from quenching and to control the charging and discharging cycles of the magnet. The circulating current, output voltage, output current, superconductor temperature, operating condition of the cryogenic system, operating condition of the PCU, and the condition of the interface system, all must be monitored to ensure that the SMES system is operating properly and safely. If one or more of the critical systems becomes unstable, an orderly shutdown and discharge of the SMES unit must be initiated. These monitoring systems add to the complexity of a SMES and must be maintained to provide high availability.

Section 3.5 - Micro-SMES System Configuration

SMES systems could be designed and configured to be transportable, or to be operated at a fixed location. However, many of the physical attributes will be determined by the amount of energy storage required, and the desired power charge or discharge rate. For example, a tested prototype of a 3 megajoule micro-SMES UPS installation, including the power electronics but excluding other required energy storage devices and emergency backup generators, could be housed in a trailer-size container. Space optimization designs could reduce the required footprint of the SMES unit; however, many other factors influence the minimum space needed for safe system operation. The magnetic fields associated with the high currents in the winding may adversely affect the performance of any nearby microprocessor controlled subsystems, and therefore the latter must be adequately shielded and/or situated a minimum distance from the winding. These high magnetic fields must also be considered when locating a SMES device near an area where there could be exposure to workers and to the public. Maximum exposure guidelines do exist for public and worker exposure to magnetic fields. [3]

The superconducting coil can be wound in many forms, but typically takes the form of a solenoid or a toroid. A solenoid coil is wire wound around a long cylinder. A toroid coil is wire-wrapped in a donut shaped configuration. Each winding configuration has inherent benefits and shortcomings. Size, conductor volume, field strength, and modularity are all factors that are affected by winding configuration.

A solenoid has a major benefit of requiring the least amount of conductor material for a given amount of energy storage. Toroidal coils require more conductor than solenoids and are generally more expensive for a given amount of stored energy, but toroids have the benefit of confining most of the magnetic fields generated to the toroid volume, thereby reducing the strength of the magnetic fields far from the unit.

Section 3.6 - Cost and Size of SMES Units

SMES units are now commercially available from several U.S. vendors, with power ratings up to 2 megawatts and energy storage capacity ratings of up to 3 megajoules. The costs of these units range from $745,000 to $1,000,000 and thus give us an average cost of energy storage capacity of near $300,000 per MJ capacity. [4] The costs of the power electronics is estimated to be between $200 and $300 per kW. For a two-megawatt (MW) system, the power electronics would cost between $400,000 and $600,000. Commercially available micro-SMES systems can be housed in a 40-foot trailer. [5] The superconducting coils are approximately 1 meter in diameter and 1.5 meters in height. The remainder of the trailer is used to house the control equipment, the power electronics, and the cryogenic system. Space optimization designs might reduce the volume required for these commercially available SMES designs.

Babcock & Wilcox is working with Anchorage (Alaska) Municipal Light and Power to install the first commercial mid-size utility SMES system. This system is a 1800 MJ (0.5 MWh) 30 megawatt system. This project is partially supported by a Technology Reinvestment Program grant from the U.S. DOD and ARPA. The initial estimated cost for this project was $25 million based upon factory assembled units. The system developers now assume the assembly of the coils will occur on site. To store 1800 MJ of energy, the dimensions of the solenoidal superconducting coil will be approximately 6 meters in diameter and 2 meters in height. The weight of just the superconducting coil assembly is expected to exceed 110,000 kg (243,000 lbs). [6] The area required for housing the entire SMES unit, including power electronics, cryogenic system, and monitoring system is expected to be at least 100 square meters (over 1,000 square feet).

System development and installation costs are expected to reach $50 million for the Anchorage SMES system. For this demonstration unit, the cost per MJ is estimated to be approximately $28,000. Project completion is expected sometime in the year 2000.

Section 3.7 - References

1. "Superconducting Storage Systems: An Overview," Luongo, Cesar, Bechtel Corp., 1995.

2. "Frequently Asked Questions Regarding Intermagnetics' Micro SMES System," White Paper No. 2, Kalafala, Kamal, Intermagnetics General Corp., 1995.

3. "Threshold Limit Values (TLVs) for Chemical Substances and Physical Agents," American Conference of Governmental Industrial Hygenist (ACGIH), 1995-1996.

4. "Power Equipment Market Growing in Size, Tension," New Technology Week, Mark Crawford, October 28, 1996.

5. "Air Force micro-SMES Program Demonstrates Successful Application Of the Dual Use Initiative," Lt. Col. Michael Gravely, Air Force PCCIE Materiel Group, Power Quality Assurance Magazine, Jan/Feb 1995.

6. "B&W/ ML&P SMES System," Ron Kunz, SMES Project Manager, Babcock & Wilcox, January 13, 1997.

Section 4 - Electric Traction Power and Energy Usage in the Northeast Corridor

The railroad network in the portion of the country known as the Northeast Corridor (NEC) between Washington and Boston handles a great deal of intercity passenger and commuter rail service. Consequently, much of the network is electrified, much with overhead catenary wires and some also with third rail.

Amtrak's lines between Washington and New Haven and between Harrisburg and Philadelphia have overhead catenary, and catenary is currently being installed between New Haven and Boston. There are also electrified commuter lines with catenary operated by New Jersey Transit (NJT), Southeastern Pennsylvania Transportation Authority (SEPTA), Maryland Rail Commuter (MARC) and Connecticut Department of Transportation (ConnDOT). The Long Island Rail Road (LIRR) and Metro-North Commuter Railroad use third-rail electrification.

Metro-North uses some dual-mode locomotives that are powered by both a diesel engine and electrified third-rail, but all the rest of the passenger operations in the NEC use locomotives and multiple-unit cars powered by either diesel engines or by electrification. Freight operations in the NEC are powered exclusively by locomotives with diesel engines.

Section 4.1 - Configuration of the Electrification System

The electric traction power system used in the NEC is a diverse system. The reason for this diversity is mostly historical in that corridor electrification occurred over several decades and with different railroad ownership. Amtrak trains now running over the mainline part of the NEC must operate with different catenary voltages and frequencies. In the territory south of New York, the catenary system operates at a nominal voltage of 12 kilovolts (kV) and at a frequency of 25 Hz (alternating current cycles per second). In the region between New York and Washington, frequency converters are used to produce the single-phase 25 Hz power. These synchronized converters are installed at a few locations along the corridor and their outputs are interconnected to a railroad-owned 138 kV, 25 Hz, single-phase transmission system. The transmission system feeds numerous traction substations where the 138 kV primary is stepped down by transformers to the catenary voltage of 12 kV. Direct current (DC) power transmitted by third-rail is also used in certain areas in and around New York. For example, the LIRR is a third-rail system which operates at a nominal voltage of 650 volts DC.

The electrification system between New York and New Haven now operates at 12.5 kV, 60 Hz. The new system between New Haven and Boston will operate at 25 kV, 60 Hz when electrification is completed in that part of the NEC. The electric power feed north of New York is connected directly to the utility at each traction substation location. At each utility supply point, a single-phase connection is made to the railroad load. The electricity produced by the utility system is so-called three-phase power, but an electrified railroad requires single-phase power for its traction power. To balance the railroad load evenly over the three phases, the utility chooses to connect adjacent catenary electrical sections to different phases. The utility must also make sure that each phase of their 3-phase distribution system is continuously isolated from the other phases. Therefore, phase breaks are used on the catenary system to electrically isolate each railroad section from adjacent sections, and thereby preserve the separation of the utility phases from each other. Typical distances for phase breaks are 15 to 25 miles. The impact of the requirement for phase breaks is that each section of catenary is electrically isolated from its adjacent sections. As the portion of the NEC between New Haven and Boston is electrified, 10 or more additional traction substations, and electrically isolated sections, will be installed.

Section 4.2 - Operational Loads of the Electrified Territory

Transmission and distribution systems have inherent operating costs associated with delivering power. Resistances in the transmission and distribution cabling, inefficiencies in the transformers, current leakage to ground, and internal motor losses all add to the inefficiencies of the system. For instance, in the southern portion of the NEC, between New York and Washington, the lengthy transmission and distribution system, which provides 25 Hz power to the catenary system, has steady state losses due to system inefficiencies of around 10 to 15 megawatts. This power must be continuously supplied by the frequency converters to maintain the operation of the transmission and distribution system, whether trains are running or not.

The electrification system between New York and New Haven is connected directly to the utility at each traction substation location. Each substation provides power for an electrical section of track. Each electrical section is typically 15 to 25 miles in length. Phase breaks are used on the catenary system to electrically isolate each electrical section from adjacent sections. The inherent losses for these electrical sections are similar to those encountered on the southern portion of the NEC. Current leakage to ground, cabling losses, and transformer inefficiencies all add to the losses of the distribution system. For each electrical section, the losses associated with the operation of the substation and the distribution system are expected to consume 500 kW of power continuously.

Because of the population densities associated with the towns and cities along the NEC between and including Boston and New York, the utilities have constructed power generation plants and utility transmission and distribution grids which are capable of providing excess power to all major residential, commercial and industrial loads. Because of the large generating capacity and numerous transmission and distribution interconnections, utility consultants describe this system as “stiff,” a term used to describe the ability of the grid to maintain a constant voltage under varying load. Loads of the size expected by railroad operations are not expected to adversely impact utility grid operations.

Section 4.3 - NEC Rolling Stock and Power Distribution System

Current practice for passenger train operation is to use a combination of friction and dynamic braking as the means for slowing and stopping trains. In dynamic braking, the traction motors function as generators, and they convert the kinetic energy required to brake the train into electrical energy. This energy is then dissipated through conversion into heat by being fed into resistor grids, which are typically located somewhere on the locomotive or power car.

Storing regenerated braking energy at a wayside installation would only be of use if trains are capable of transferring braking energy from the traction motors back into the catenary. Currently, the trains that operate on the NEC do not have the necessary power conditioning equipment to transfer energy back into the electrification system. Thus dynamic braking energy can now only be dissipated as heat. If fed back into the catenary distribution system, the electrical energy regenerated from braking must match the phase and frequency and be similar in harmonic content to the distribution power. Railroad motive power is designed to accept fairly wide variations of voltage and frequency to accommodate the power characteristics typical of long-block catenary systems. The onboard regeneration equipment must be able to sense the voltage and phase angle of the supply power and feed back the regenerated energy at a higher voltage and with matched phase and frequency. Since much of the rolling stock is capable of operating on the entire NEC, which is comprised of a diverse power distribution system (12 kV 25 Hz, 12.5 kV 60 Hz, 25 kV 60 Hz, 650 V DC), all of these regenerative scenarios must be considered.

Modern propulsion control system technology enables the braking energy to be fed back into the catenary or third rail where such energy can either be used to power other trains or be transferred back into the electric utility power system. The cost associated with retrofitting the commuter rail and intercity rail fleet with modern propulsion control systems has not been considered. There are many different types of rolling stock currently being run on the NEC. Each car type would require a different level of retrofitting, based on the existing propulsion system on each car, to make regenerative braking possible. Amtrak's new high-speed trainset, the American Flyer, is being specifically designed with regenerative capability.

Section 4.4 - Braking Energy Requirements for Typical Passenger Trainsets

The amount of energy consumed during acceleration and dissipated during braking by each train depends upon the composition of the train (termed "consist") and its operating characteristics. Although there are a number of different types of trains running on the NEC, the problem can be simplified by grouping these trains into three distinct groups. The three groups of trains would have consists with the following characteristics:

- Intercity train operating up to a maximum speed of 125 mph (Amtrak - present),
- Intercity train operating up to a maximum speed of 150 mph (American Flyer),
- Commuter service train operating up to a maximum speed of 80 mph (Commuter).

The propulsion energies associated with the Amtrak-present trainset is representative of not only the existing train configuration for Amtrak service between New York and Washington but also the high speed non-electric locomotive service on the Empire corridor. The commuter trainset is representative of the SEPTA, Metro-North, LIRR, and NJT configurations currently used in commuter rail operations. The American Flyer trainset is expected to be in revenue service by

1999. Using information gathered from Amtrak, the required train braking power and potential regenerative energy for the three train configurations have been estimated and are given below:

BRAKING PERFORMANCE FOR NOMINAL DECELERATION					
Consist	Braking Time min	Maximum Total Power kW	Maximum Total Energy kWh (MJ)	Regenerative Power at Max Speed kW	Regenerative Energy kWh (MJ)
Amtrak -present	2.1	8853	172 (619.2)	3092	112 (403.2)
American Flyer	2.5	11812	257 (925.2)	7755	189 (680.4)
Commuter	1.7	6312	106 (381.6)	5032	88 (316.8)

The total energy required to brake a specific train from a given speed is dependent on the kinetic energy of the train. The kinetic energy of the train is proportional to train mass and the square of its speed, and it is this kinetic energy that must be dissipated during braking. Railroads may choose to operate in a manner to maximize the amount of energy that is converted to regenerative energy and thereby minimize the amount of energy absorbed by the friction brakes. If the braking rate can be limited so that the use of friction brakes is not required toward the total braking effort, the fraction of energy available for regeneration increases. At very low braking rates, most of the required braking energy would be converted into regenerative energy. The maximum available regenerative braking force is limited by the braking tractive effort of the propulsion system. The traction motors can only regenerate energy at the power rating of these machines. This power limit cannot be exceeded without damaging the motors. If a higher braking rate is required, friction brakes must be used to absorb the additional energy required.

Section 5 - Suitability of Micro-SMES Use in Railroad Applications

An energy storage device, such as a superconducting magnetic energy storage system (SMES), could conceivably be installed along the wayside, or on board a trainset, to absorb available regenerated braking energy and then return this energy to provide some of the power demand when accelerating. In the case of diesel powered (non-electric) train operation, the SMES device would have to be installed on board the train because there is no catenary or third rail network available to pass energy from the train to a wayside device.

Section 5.1 - Requirements for On-Board Energy Storage Systems

Onboard energy storage devices must have a capacity of between 200 and 600 MJ to be useful as a supply of energy to the train propulsion system. Ideally, an onboard energy storage device should be capable of absorbing all the regenerated energy of the train. The magnitude of this energy could range from 300 to 800 megajoules, depending on train consist configurations. But any storage device should not impact the overall performance of the train. The key issues associated with locating the SMES unit on board the train include size, weight, cost, and energy/power rating of the SMES.

Commercially available micro SMES units, with energy capacities up to 3 MJ, have costs which are on the order of $300,000 per MJ capacity. Larger SMES units, such as the 1800 MJ power quality unit being developed for the Anchorage utility, has an estimated cost of about $30,000 per MJ (over $50 million). Therefore, the estimated cost of a SMES unit with a capacity of between 200 and 600 MJ, for onboard energy storage, is expected to cost between $6 million and $18 million, which will exceed the cost of the locomotive itself.

The weight of the coil for the 1800 MJ power quality SMES unit being developed for the Anchorage utility is expected to be 110,000 kg (243,000 lbs), not including the cryogenic equipment, magnetic field shielding and power electronics equipment. The dimensions of this coil will be approximately 6 meters in diameter and 2 meters in height. The weight of the coil for a 600 MJ SMES unit is estimated to be over 50,000 kg (110,500 lbs). A solenoidal coil with an energy capacity of 600 MJ is expected to have dimensions of at least 3 meters in diameter and 2 meters in height. The power conditioning unit and cryogenic system would occupy at least an additional 20 square meters of space. Finally, other onboard systems, such as the safety critical control equipment, need to be protected from the intense time-varying magnetic fields associated with SMES. This will require spatial isolation and soft iron shielding plates, which will add additional weight.

Therefore, an onboard 600 MJ SMES energy storage unit is estimated to occupy at least 35 square meters (nearly 400 square feet) of space, and would weigh in excess of 60,000 kg (132,000 pounds). Because of these estimated weight and footprint requirements, at least one separate rail car (i.e., distinct from a locomotive or power car) would be required to house this SMES unit. The cost of this type of compact SMES would be expected to be much higher than comparable wayside designs.

A further concern is the steady state power requirements of the cryogenic systems needed to keep the coils cold. The shock and vibration environment associated with steel-wheeled train operations will increase the heating loads associated with coil movements. While the coil is in standby mode, the losses associated with the cryostat and the additional heavy car must be supplied by the locomotive's installed engine. It is therefore critical that these power demands be minimized. For these reasons, a SMES for railroad energy storage applications is not likely to become practical as an onboard device.

SMES is not the only technology capable of storing large amounts of energy for an indefinite period of time. Flywheels, cryogenic capacitors, and advanced batteries may also be capable of storing sufficient amounts of energy for railroad traction applications.

The FRA is supporting research at the University of Texas into flywheel energy storage systems as applied to high speed non-electric locomotives. The target system would augment the tractive power available from either a gas turbine or a lightweight diesel engine providing the accelerating performance of a locomotive with twice as much installed power. The flywheel or paralleled flywheels would provide power during acceleration and would recharge during cruise or braking. The intent of the system would be to provide the performance of a high-powered locomotive without the high fuel consumption. A proposed system being built for demonstration in 1998 or 1999 would have around 600 MJ (166.67 kWh) of energy storage and be able to provide 3MW of additional power for over two minutes during acceleration, roughly doubling the power rating for the locomotive.

This device, including an associated high-speed alternator, would fit in the approximately 9 square meters available and would weigh less than 10,000 kg (22,000 pounds). Alternative designs would use many smaller flywheels capable of providing similar power augmentation and energy storage. These smaller devices are being developed for electric vehicles for roadway applications and as alternatives to battery power supplies and have promise for cost reductions due to economies of scale in manufacturing quantities.

Section 5.2 - Requirements for Wayside Energy Storage Systems

Few electrified railroad locomotives or multiple-unit cars currently in U.S. revenue service are capable of easily transmitting braking energy back into the railroad power distribution system. As electrically powered rolling stock is modernized, propulsion system designs will most likely include this important capability. Once braking energy is fed back into the catenary distribution system, the energy must either be:

- transported and consumed by another traction system load
- fed back into the utility power grid for re-use elsewhere
- stored in an energy storage device
- dissipated as heat in a bank of resistors located in a wayside facility.

The electric traction power system used in the NEC is a diverse system. The operating characteristics of the traction power system south of New York is considerably different than the traction power system north of New York. Therefore, energy storage requirements are different for the two portions of the NEC, and will be considered separately.

Section 5.2.1 - Energy Storage Requirements for the South End of the NEC

In the portion of the corridor south of New York, the traction power system is electrically continuous. Therefore, regenerated braking energy, which is fed back into the catenary, can be transported and consumed by another traction system load. As mentioned earlier, a continuous, steady state 10 to 15 MW load exists on this traction power system. This load is due to operating losses and inefficiencies of the transmission and distribution system. Therefore any braking energy generated by a decelerating train could be used to offset the energy required to operate the traction power transmission and distribution system. In addition, in the southern portion of the NEC the steady state load, including traction power loads of accelerating trains, is always at least 30 MW, and sometimes in excess of 300 MW. Therefore, there will never be a need to store energy or sell power back to the utility in the NEC south of New York.

The traction power supply frequency south of New York is 25 Hz. The local utilities generate power at 60 Hz. Motor/generator (M/G) sets are used to convert 60 Hz utility power to 25 Hz railroad traction power. The motor/generator sets, currently operating in the portion of the corridor between New York and Washington, cannot send back energy to the utility because of physical limitations in the control systems. Also, the M/G sets are operating at reduced load because of their aged condition, and future plans of the railroads may include replacement of these maintenance intensive machines with solid state, modern traction distribution substations which will be capable of converting the utility supplied power into either 25 Hz or 60 Hz energy. With this upgrade, sectionalizing of the existing transmission and distribution system may be required. This capital improvement would make energy sell-back technically feasible.

Section 5.2.2 - Energy Storage Requirements for the North End of the NEC

The traction power transmission and distribution system between Boston and New York is electrically segmented. Each traction substation (existing or planned) is connected directly to the utility grid. Each substation provides power for an electrical section of track, which is typically 15 to 25 miles in length. As mentioned previously, the steady state load for each electrical section is expected to be in excess of 500 kW. This load can be attributed to the inefficiencies of the traction power transmission and distribution system. During the regeneration of train braking energy, energy could be supplied to the transmission system to reduce the amount of energy supplied by the utility. If another train is operating in the same electrical section, the steady state load of the transmission system, and the load of any train accelerating in the same block could be provided, at least in part, by the regenerated energy. If the regenerated power is greater than the load on the electrical section, the additional energy would need to be returned to the utility grid, stored, or dissipated as heat.

In the portion of the NEC between Boston and New York the proposed new traction substations, if appropriately designed, could transfer energy back into the utility power grid. Older traction substations could also be modified to backfeed energy into the utility power grid.
The receptivity of the utility grid is determined by the typical load characteristics of the area supplied by the transmission lines. The impact of 3 to 10 MW of regenerative power on the utility power grid in the Northeast should be minimal due to the high capacity and loads or relative "stiffness" of the utility grid.

If the grid is not receptive to braking energy of trains, the railroads could chose to store this regenerated energy in a wayside energy storage device or dissipate this energy dynamically as heat. This would be determined on a strict economic basis, i.e., how much could be saved by storage versus the cost of storage. The yearly savings associated with energy storage needs to be significant to offset the large initial capital costs associated with the installation and construction of SMES units, and the yearly maintenance and operational costs.

The micro-SMES units commercially available, which have power ratings up to 2 MW and energy ratings up to 3 MJ, have costs of about $300,000 per MJ capacity.[1] The 1800 MJ, 30 MW SMES unit being developed for the Anchorage utility is expected to cost more than $50 million. Therefore, the cost of the mid range SMES (600 to 2000 megajoule) is estimated to be approximately $28,000 per MJ.

If a wayside energy storage system was sized based on the scenario of one Amtrak high-speed train simultaneously braking with two commuter trains, then the maximum power demand on the energy storage device would be about 20 MW and the total regenerative energy could be up to 1224 MJ (340 kWh). Based upon the development and installation costs of the Anchorage demonstration unit, the cost of a 1200 megajoule 20 megawatt railroad SMES unit is estimated to be in excess of $30 million.

In comparison to the capital costs associated with a 1200 MJ SMES energy storage device, the value of the kinetic energy stored in a high-speed train (600 MJ or 166.67 kWh) is $11.66 (at $.07 per kWh. For every charge and discharge cycle of the SMES unit, the railroad then has a potential savings of $23.33. Without considering the operational and maintenance costs, this would mean the devices would need to be cycled almost 1.3 million times to recover the capital investment. In reality, all the savings would be expended to pay for the energy required to run the refrigeration/cryogenic subsystem and other ancillary equipment.

The commercially available 3 MJ micro-SMES units have cryogenic loads in excess of 30 kW. The cryogenic loads of the 1800 MJ Anchorage SMES unit are not known at this time but are estimated to be proportional to the energy, power and duty cycle of the unit. A 1200 MJ SMES unit developed for railroad duty cycles could be expected to have cryogenic steady state loads of at least 1.5 MW. The annual operational costs of this cryogenic system would be approximately $920,000. To recover just the operating costs, the SMES unit would need to cycle 108 times per day. To achieve this level of discharge and charge cycles, 108 high-speed trainsets and 216 commuter trains would have to traverse the electrical section. Train traffic densities of this magnitude are not encountered on any electrical section north of New York. Current traffic densities are less than 40 percent of that required to recover the operating costs of a SMES unit.

Because of the demanding duty cycle on a railroad, current designs of the cryogenic subsystem would consume much of the regenerated energy to remove the heat generated by the AC losses during each charge and discharge cycle. Advancements in conductor design are required to minimize the AC losses associated with the charge and discharge cycle. Other improvements are also required to reduce the size, weight, efficiencies and safety of SMES systems.

In power quality applications, many industrial customers are willing to run the SMES units at a net energy loss because interruption of power and subsequent uncontrolled shutdown is extremely costly. In contrast, because momentary loss of traction power does not affect the safety of the railroad passengers, the capital investment for any energy storage device can only be justified through whatever cost savings may exist, if any.

Section 5.3 - Safety and Environmental Issues Associated with SMES Systems

The magnetic fields generated by superconducting magnetic energy storage systems and the cryogenic subsystem associated with SMES units introduce potential safety and environmental issues into the railroad environment.

Various technical summaries provided by Federal (USAF, DOE) and private-nonprofit (e.g., EPRI or HARC) sponsors of SMES technology development efforts, as well as prospectus information from manufacturers of commercial micro-SMES units (Superconductivity, Inc., American Superconductor, Intermagnetics General, Babcock & Wilcox) mention the following environmental advantages over competing alternatives:

- no air pollutant emissions compared to diesel generators for backup power,
- no toxicity concerns associated with lead acid batteries.

However, they omit to mention the specific environmental and potential safety hazards associated with high magnetic fields. Relatively large (5 - 10 meters mentioned for commercial designs) "exclusion radius" or safe standoff zones are required where the magnetic fields are above the recommended 5 to 10 gauss. Within the "exclusion zone" rather high static magnetic fields and rapidly time-varying magnetic fields, due to rapid charge/discharge cycles, are present which can create both health and electronic compatibility hazards. Therefore, a SMES installation requires special fencing, posting of warning and area controls to protect susceptible individuals, and the need for field management and mitigation installations, which add to the cost and/or weight of the system.

The anticipated SMES units depend on very strong static magnetic fields (possibly up to 5.5 Tesla or 55,000 gauss), several times more than can be obtained in ordinary circumstances as with an iron core magnet. The field strengths vary depending on the number of magnet coils, coil size, current, design, configuration and the distance from the superconducting coil. Some designs involve several coils with bucking fields, or toroidal configurations which confine the fields better, to manage the static field problem. AC fields are also associated with transients and eddy currents induced into the metallic structure and conductors from the charge/discharge cycles thereby giving rise to stray (external) fields.

For any SMES design, the static magnetic field strength must be modeled with the objective of mitigation and control of magnetic fields. Access restrictions to the high field area by posting perimeter warnings may be required (standoff limit of 5-10 gauss). The radius of this standoff zone can range from a few to several tens of meters, depending on the specific micro-SMES design, solenoid size, and current-carrying capacity. Static field management options do exist, but add to the size and complexity of system.

There are operational and work safety concerns associated with high static magnetic fields, including:

- the need for nonmagnetic tools to be used within the stand-off zone, in order to avoid having the tools "fly-off" to the magnet potentially causing worker injury;
- the need to protect magnetic and electronic media from electro-magnetic fields; and
- the need for nonmagnetic or for shielded monitoring instrumentation and power subsystems.

In addition, system safety analyses were performed by the Science Applications International Corporation (SAIC) for the U.S. Air Force, and by the University of Wisconsin for Superconductivity, Incorporated. [1] The analysis findings suggested that the hazards associated with handling cryogenic fluids (cold burns and materials embrittlement hazards), pressurized helium boil off and potential blowoff, and superconducting magnet coil quenching, would require trained maintenance workers and a new system safety plan for rail and transit operations if using SMES units.

Section 5.4 - References

1. "System Safety Program Plan and SMES Site System Safety Plan For Micro Superconducting Magnetic Energy Storage (SMES) Technology Insertion Program at Tinker Air Force Base," Thomas R. Abel, Science Applications International Corporation, July 1995.

Section 6 - Findings and Conclusions

At the request of the U.S. Congress, the FRA, with technical support from the Volpe National Transportation Systems Center, has undertaken a review of the current technical literature on micro-SMES concepts, materials, designs, and of cost/benefit projections. Well-reasoned inputs from recognized experts in government, industry, and academia, backed up by technical supporting information, were also provided to and considered by the FRA in assessing micro-SMES technology maturity and suitability to railroad operations on the Northeast Corridor.

Section 6.1 - Findings

1. Research, design and development of superconducting magnetic energy storage systems have occurred through public and private funding since the 1970's. The initial public thrust of SMES development was to provide load leveling for utilities. The U.S. DOD focus was to provide energy to a ground-based free-electron laser weapon system.

2. Micro-SMES device concepts have been defined by industry consensus as devices with capacities less than 20 MJ. Currently available, through several SMES vendors, are micro-SMES devices rated up to 3 MJ.

3. To be useful for intercity and commuter railroad applications, as an onboard energy storage device, 3 MW of peak power and 500 MJ of energy capacity would be desirable.

4. Modifications would be required to the propulsion systems of existing rolling stock operating on the NEC if braking energy is to be returned to the catenary.

5. Amtrak's new high-speed trainset, the American Flyer, will have braking energy regeneration capability.

6. The footprint of the micro-SMES systems, rated up to 3 MJ, are typically up to 400 square feet. The power-conditioning unit of the micro-SMES system consumes the largest portion of this space.

7. University researchers have identified design improvements which may lead to improvements in cost, efficiency, manufacturability, and size of SMES system and subsystems.

8. Commercially available micro-SMES units are not now suitable as onboard energy storage devices because the low energy density of the units and because coil vibration and movement will cause heating which would reduce the effective storage capacity and could lead to a loss of superconductivity.

9. Railroad requirements for energy storage applications are significantly different than the power quality requirements of the utility industry. The heat generated within the superconductor by the nearly continuous charge and discharge cycles on a railroad may not be efficiently handled by the current refrigeration designs.

Section 6.2 - Conclusions

1. Micro-SMES devices do not now have the energy storage capacity required for either onboard or wayside regenerated braking energy storage in a railroad application. Due to fundamental technological limits, this situation is not expected to change significantly in the next five years.

2. Based upon current technology, a SMES device with the capacity required to absorb energy of a single train is too large to fit on board a train.

3. Based on current operating practices, once energy is fed to the catenary there is no apparent reason to store it. Rather, Amtrak or any other power system operator on the NEC would seek first to consume the energy with a railroad-related load and, if no railroad load exists, then feed the power back into the commercial grid.

4. Based on this preliminary review and technical analysis, it appears that a micro-SMES technology insertion program to "provide cost-effective regeneration and energy savings capability along the Northeast Corridor (NEC) for both Amtrak and commuter rail" is premature. Existing micro-SMES prototypes have only recently been introduced to the commercial environment for utility or critical facilities power quality applications and are still under test and evaluation. These devices routinely operate at a net energy loss.

5. SMES as an uninterruptible power supply for train control systems has not been addressed, as this was viewed as beyond the scope directed for this report. Further, we have assumed that this is a relatively mature application and that the market place will determine the migration into the railroad industry.

6. Safety concerns regarding the cryogenic system and the high magnetic fields must be evaluated prior to any in-service demonstration.

7. Improvements to existing designs would be required prior to the initiation of any demonstration program. These improvements should be based upon the expected requirements of a railroad energy storage device.

Section 7 - References and Industry Feedback

A literature search was conducted to identify articles related to research and development activities associated with superconducting magnetic energy storage systems. In addition to this literature search, the FRA solicited information and comments from a number of organizations with expertise in SMES technology and/or railroad operations. In response to this solicitation for comments and information, 17 industry representatives of government, industry, or academia provided feedback to the FRA.

In addition to the information provided by these individuals, the literature search identified over 20 additional articles relevant to SMES and micro-SMES research, design and development.

Section 7.1 - List of Articles- Organized by Industry/Government/Academia Representative

American Superconductor Corporation

"HTS SMES Magnet Design and Test Results," S.S. Kalsi, D. Aized, B. Connor, G. Snitchler, J. Campbell, R.E. Schwall, and J. Kellers, American Superconductor Corp., Th. Stephanblome and A. Tromm , Germany, P. Winn, Applied Engineering Technologies.

Mtechnology, Inc.

"The Future Prospects for Large Scale Applications of Superconductivity," D. Bruce Montgomery, MIT, Plasma Fusion Center, 1996.

Intermagnetics General Corporation

"Superconducting Magnetic Energy Storage for Substation Applications," Michael Parizh, A. Kamal Kalafala, and Robert Wilcox, Intermagnetics General Corporation. Presented at Applied Superconductivity Conference, Pittsburgh, PA 1996.

"Superconducting Magnetic Energy Storage for Power Quality Applications," A.K. Kalafala, F.S. Murray, M.B. Parizh, M.W. Sampson, E.A. Scholle, and R.E. Wilcox, Intermagnetics General Corporation. Presented at the International Workshop on High Magnetic Fields, 1996.

"Micro Superconducting Magnetic Energy Storage (SMES) System for Protection of Critical Industrial and Military Loads," A.K. Kalafala, J. Bascunan, D.D. Bell, L. Blecher, F.S. Murray, M.B. Parizh, M.W. Sampson, and R.E. Wilcox, Intermagnetics General Corporation, 1995.

"Micro SMES and Its Role in Improving Power Quality," White Paper No. 1, Kalafala, Kamal, Ph.D., Intermagnetics General Corporation, 1995.

"Frequently Asked Questions Regarding Intermagnetics' Micro SMES System," White Paper

No.2, Kalafala, Kamal, Ph.D., Intermagnetics General Corporation, 1995.

University of Wisconsin-Madison

"Micro SMES Magnet Configurations For Reduced Stray Field Applications," Mostafa K. Abdelsalam, Applied Superconductivity Center, Univ. of Wisconsin-Madison. 1995.

"Yoke Shield Design for Micro SMES Magnets Using Finite Element Modeling," Sean He and Mostafa K. Abdelsalam, Applied Superconductivity Center, Univ. Of Wisconsin-Madison, 1994.

"Conductor Joint Performance During the EBASCO Team SMES POPE (Proof of Principle Experiment)," D.W. Scherbarth, O.R. Christianson, E.F. Daly, T. Kupiszewski, and D. Marschik of Westinghouse Science and Technology Center, J.M. Pfotenhauer, M.K. Abdelsalam, O.D. Lokken, and J.S. Waldrop of Univ. of Wisconsin-Madison, 1995.

"Micro SMES Magnet Configurations for Reduced Stray Field Applications," Mostafa K. Abdelsalam, Applied Superconductivity Center, University of Wisconsin-Madison, 1995.

Bechtel

"Review of the Bechtel Team's SMES Design and Future Plans for a Technology Demonstration Unit," Cesar Luongo and the Bechtel SMES Team, 1995.

"Tests on a 200kA Cable-in-Conduit Conductor for SMES Application," Scott D. Peck, John C. Zeigler, Cesar Luongo, 1994.

"Superconducting Storage Systems: An Overview," Cesar A. Luongo, Bechtel Corp, 1995.

"Current Redistribution During Quench in a SMES Coil with Separated Conductor and Dump Shunt," Ales M. Bulc of Bechtel, William V. Hassenzahl of LLNL, Miljutin Zeljeznov, Univ. Of Ljubljana, Slovenia, 1994.

"Storing Electricity as Magnetic Energy," Cesar A. Luongo, Bechtel, 1995.

"A Computational Quench Model Applicable to the SMES/CICC," Cesar A. Luongo, Chih-Lien Change, and Kenneth D. Partain, Bechtel, 1994.

"Composite Structures for Superconducting Magnetic Energy Storage Systems," Craig Mix, General Dynamics and Cesar Luongo, Bechtel, 1994.

Babcock & Wilcox

"30 MW Babcock & Wilcox SMES Program for Utility Applications," Xianrui Huang, Stephen

F. Kral, Gregory Lehmann, Yury M. Lvovsky and Minfeng Xu, Babcock & Wilcox, 1995.

"Superconducting Power Delivery Systems For Transmission and Distribution Applications," S.F. Kral, M. Aslam, P.F. Ribeiro, X. Huang, M. Xu, Babcock & Wilcox, Accelerator & Magnet Systems, Lynchburg, VA 24502.

"Protection Study of the Babcock & Wilcox SMES Coil," Xianni Huang of Babcock & Wilcox, 1995.

"Transient Stability of SMES Monolith Conductor with Normal Stabilizer," Yury M. Lvovsky, Joseph A. Waynert, Stephen F. Kral, Babcock & Wilcox, 1995.

"Design of a High-Temperature Superconductor Current Lead for Electric Utility SMES," R.C. Niemann, Y.S. Cha, J.R. Hull of Argonne National Laboratory, C.M. Rey, K.D. Dixon of Babcock & Wilcox, 1995.

"B&W/ ML&P SMES System," Ron Kunz, SMES Project Manager, Babcock & Wilcox, January 13, 1997.

Massachusetts Institute of Technology

"Field Analysis for a SMES Magnet with Radial Force Balance," Joseph L. Smith, Jr., Dept. Of Mechanical Engineering, Massachusetts Institute of Technology, 1995.

Lockheed Martin

"Global Cost Optimization of 1-10 MWh Toroidal SMES," Dennis W. Lieurnace, Lockheed Martin Advanced Development Operations.

"Design and Cost Studies for Small Scale Superconducting Magnetic Energy Storage (SMES) Systems," D. Lieurance, F. Kimball, and C. Rix of Martin Marietta, and Cesar Luongo of Bechtel, 1995.

US Air Force PCCIE Materiel Group

"US Air Force Micro Superconducting Magnetic Energy Storage Technology Insertion Program," Joe Burgan, USAF, Thomas R. Abel, SAIC.

"Air Force Micro-SMES Program Demonstrates Successful Application Of the Dual Use Initiative," Lt. Col. Michael Gravely, Air Force PCCIE Materiel Group, *Power Quality Assurance* Magazine, Jan/Feb 1995.

"System Safety Program Plan and SMES Site System Safety Plan For Micro Superconducting

Magnetic Energy Storage (SMES) Technology Insertion Program at Tinker Air Force Base," Thomas R. Abel, Science Applications International Corporation, July 1995.

Other

"When Reliable Power is Not Good Enough," Dr. Thomas L. Baldwin, Ken Tison, pgs. 1724 - 1731, Proceedings of the American Power Conference, 1995.

"Cooling of Small SMES System with Forced Flow Supercritical Helium," R.M. Schottler, Technical University of Munich, 1994.

"Exploratory Assessment of the Dynamic behavior of Multimachine System Stabilized by a SMES Unit," J.B. Simo of University of Laval (Quebec), I. Kamwa of IREQ, Hydro-Quebec, 1995.

"The Performance of High-Power GTOs Operated as Fast Turn-Off Thyristors," Joachim Holtz, Michael Stamm of the University of Wuppertal, and Oskar Stielau of South African Iron and Steel, 1994.

"A Protection System for Small High Power SMES with Power Semiconductors Working at Cryogenic Temperature," J. Karner, H. Lorenzen, F. Rosenbauer, J. Schaller and R. Schottler, Technical University of Munich, 1995.

"Fast Switching Characteristics of Magnetic Persistent Current Switch for SMES," N. Sadakata, K. Uchiyama, K. Goto, T. Saito, O. Kohno of Fujikura Ltd, Y. Kouno, M. Matsukawa, K. Noto of Iwate University, H. Honma, T. Tatsuki of Tohoku Electric Power Co., 1995.

"Magnetic Shielding of Small High Power SMES," Uwe Brammer and Hans W. Lorenzen, Technical University of Munich, 1995.

"Design of SMES with Reduced Stray Field," Gerald Schonwetter and Juergen Gerhold, Institute of Electromagnetic Energy Conversion, Technical University, Graz, Austria, 1995.

"The Advantages of Using High-Temperature Superconductors in High-Duty-Cycle Applications of SMES," S.M. Schoenung and R.L. Bieri of W.J. Schafer Associates, T.C. Bickel of Sandia National Laboratories, 1995.

"Structure and Cost Scaling for Intermediate Size Superconducting Magnetic Energy Storage (SMES) Systems," M.S. Lubell and J.W. Lue, Oak Ridge National Laboratory, 1995.

"Summary of the DNA SMES Development Program," George W. Ullrich, Defense Nuclear Agency, 1995.

"Input Circuit of Superconducting Magnetic Energy Storage for DC Lines," K. Takeno, S. Ohtsu, and T. Yamashita of NTT Interdisciplinary Research Laboratories, 1994.

"SMES Solenoids with Reduced Stray Field," Gerald Schonwetter, Institute of Electromagnetic Energy Conversion, Technical University, Graz, Austria, 1994.

"An Application of Dual-Time-Scale Simulation to Power System Problems Including Power Electronics Devices," F. Naito and J. Toyoda, Dept. of Electrical Engineering, Tohoku University, 1995.

"Quench Initiation and Propagation Study (Quips) for the SMES-CICC," C.A. Luongo and K.D. Partain of Bechtel, J.R. Miller and G.E. Miller of National High Magnetic Field Laboratory, M. Heiberger of General Atomics, and A. Langhorn of Startech, Inc., 1994.

"A Soft Switching AC/DC Converter with Energy Recovery Snubber Circuit for Superconducting Magnetic Energy Storage," T. Ise, M. Nakade, and Y. Murakami, Dept. of Electrical Engineering, Research Center for Superconducting Materials and Electronics, Osaka University, 1994.

"Power Equipment Market Growing In Size, Tension," *New Technology Week*, Mark Crawford, October 28, 1996.

Section 7.2 - Government, Industry and Academia Responses Received

1. Air Force, SM-ALC/LIET, Launce (Joe) Burgan, Micro SMES/ Alternative Energy Program Manager
2. American Superconductor Corp., Keith Kuzmin, Senior Business Analyst
3. Babcock & Wilcox, Naval Nuclear Fuel Division, Product Development Department, Ron Kunz, SMES Project Manager
4. Bechtel, Dr. John R. Gilleland
5. Bechtel, Dr. Cesar Luongo
6. Houston Advanced Research Center (HARC), Technology Development Laboratory, Thomas L. Mann
7. Intermagnetics General Corporation, Dr. John Steckly
8. Massachusetts Institute of Technology, Plasma Fusion Center, Dr. Joseph Minervini
9. Massachusetts Institute of Technology, Plasma Fusion Center, Dr. Yuki Iwasa
10. Massachusetts Institute of Technology, Department of Electrical Engineering and Computer Science, Dr. Richard D. Thornton
11. Mtechnology, Inc., Dr. Bruce Montgomery
12. Superconductivity, Inc., Warren E. Buckles, Director of Engineering
13. Superconductivity, Inc., James P. Losleben, National Sales Manager
14. Utilicorp United, WestPlains Energy, Sam Wheeler, Director of Technology
15. Amtrak, John Popoff, Program Director Electrification, High Speed Rail Group
16. Foster Miller, Inc., Dr. David Cope and Dr. Richard Wiesman
17. University of Wisconsin, Dr. John Pfotenhauer