FTA-CA-26-0018-97-1

U.S. Department
of Transportation

APPLICATION OF SUPERCONDUCTING MAGNETIC ENERGY STORAGE FOR THIRD RAIL VOLTAGE SUPPORT

1997

FTA

Federal Transit
Administration

Office of Research, Demonstration and Innovation

Technical Report Documentation Report

1. Report No. FTA-CA-26-0018-97-1	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Application of Superconducting Magnetic Energy Storage for Third Rail Voltage Support		5. Report Date August 21, 1997
		6. Performing Organization Code
7. Authors: Melissa M. Reading, Ph. D *(PG&E), Walt Stolte (Bechtel), John D. Heinzmann (Endecon)		8. Report No. FTA-CA-26-0018
9. Performance Organization Name and Address Bay Area Rapid Transit District 800 Madison Street Oakland, California 94604		10. Grantor Project No.
		11. Contract No.
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Transit Administration (FTA) 400 7th Street, S.W. Washington, D.C. 20590		13. Type of Report and Period Covered Technical Report
		14. Sponsoring Agency Code TR1-20

15. Supplementary Notes

* Principal Contractor: Pacific Gas and Electric Company (PG & E)
3400 Crow Canyon Road
San Ramon, California 94583

16. Abstract

This Report examines the technical and economic feasibility of utilizing Superconducting Magnetic Energy Storage (SMES) technology on the San Francisco Bay Area Rapid Transit system. The problem addressed was the voltage sag on the traction power third rail during times of high current demands by trains on the BART system. The study establishes a functional specification for a storage system to support the transient voltage sag problem in BART's transbay tube. Limited computer simulation runs provided some quantitative understanding of the magnitude of the problem and three vendors who could potentially supply a SMES device provided conceptual designs of units that could meet the functional specifications. The three SMES designs were then compared with three battery system designs and one pulse-duty rectifier design to assess the relative position of SMES technology in relation to more conventional technologies from a performance and economic standpoint.

17. Keywords Rail Transit Electric Power Power Rail Battery Systems Superconducting Magnetic Energy Source	18. Distribution Statement This document available to the public through the National Technical Information Service, Springfield, VA 22161 (703) 487-4650

19. Security Classif (of this report) Unclassified	20. Security Classif (of this page)	21. No. of pages 218	22. Price

DISCLAIMER

The Pacific Gas and Electric Company (PG&E) and the United States Government or any agency thereof, or any of their employees, contractors, subcontractors and their employees, (1) make no representation or warranty, expressed or implied; (2) assume no legal liability for damages, including any consequential damages, even if PG&E and/or the U.S. Government, or any of their representatives, have been advised of the possibility of such damages; or (3) take no responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, method, or process disclosed, nor do PG&E or the U.S. Government represent that its use would not infringe upon the privately held rights of others. Reference herein to any commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement, recommendation, or favoring by PG&E or the U.S. Government, any agency thereof, or any of their contractors or subcontractors.

The work disclosed in this report was done with the support of the U.S. Department of Transportation. However, any opinions, findings, conclusions, or recommendations expressed herein are those of the author(s) and do not necessarily reflect the views of PG&E or the U.S. Government, any agency thereof, or any of their contractors or subcontractors.

CONTENTS

CONTENTS (cont.)

FIGURES

TABLES

ACKNOWLEDGMENTS

The study of SMES as a solution to the BART voltage sag problem was initiated with early contacts between Paul Koeppe of Superconductivity, Inc., and Victoria Nerenberg of BART, and gained PG&E involvement under the aegis of Brian Farmer. Like other application studies of new technologies, it has taken much longer, and uncovered more information, than was originally anticipated.

It has come to its current stage of fruition because of the contributions of many individuals and organizations. All were important to this product, but a premier role was played by two of the SMES vendors who responded at their own expense to the Request for Information, and submitted complete and detailed conceptual designs for SMES installations on the BART system. These vendors were, first, Westinghouse, and second, a consortium headed by Pitt-Des Moines (PDM) that included General Atomics, Advanced Cryo Magnetics, Inc., and CVI, Inc. These two groups, as well as Superconductivity, Inc., have been exceedingly helpful and responsive to inquiries and requests. Their contributions will help to advance the fledgling SMES industry and open up applications for the technology. Although their organizations chose not to respond to the RFI, appreciation is also extended to Kamal Kalafala (then at General Electric) and Garry Morrow of Intermagnetics General for their encouragement and useful technical discussions.

The author acknowledges the efforts of the individuals at BART who contributed their time and expertise to the project: Eugene Nishinaga, Jay Burns, Peter Todd, Kevin Reilly, and Victoria Nerenberg have all been particularly helpful in mobilizing resources, providing information, sharing insights, gaining funding, and fitting SMES tasks into their schedules. Ralph Sullivan was generous with his time and expertise, and very gracious in the assistance he provided with the AC monitoring. Other BART personnel also worked capably on the project.

Robert Schainker of the Electric Power Research Institute has been a consistent and knowledgeable source of strategic and technical advice, as well as a valued guide, and has cofunded the work as well. Other members of the EPRI staff who have contributed of their time, expertise, and judgment on this project are Philip Symons and Stephen Eckroad. Their willingness to assist is appreciated.

Many colleagues at PG&E have also been supportive. First among these is Ray Dracker, who, as program manager for renewables and storage, provided priceless guidance to the project. As directors, Gerry Braun, Dave Christensen, and Tom Hillesland retained an interest in the work and found budget to cofund it for three years. They asked the penetrating questions which catalyzed the growth of the project. As the initial project manager for this BART SMES study, Howard Wenger conducted the pre-engineering scoping which guided the present work. Micro-SMES colleague Ken Lau shared data from his EPRI Benefits Study, valuable wisdom on the distribution system, as well as advice on this manuscript. Bill Lemon and Lloyd Cibulka provided helpful support and discussions.

As an area-crossing project, this work did not fit neatly into any of the project groups, but I was fortunate to have leeway and guidance from first Dan Shugar and then Jimmie Yee as supervisors who could and did help with timely and insightful advice. I particularly value the experience with the electric distribution system which Jimmie and Ken Lau brought to bear on the problem.

Assistance from Walt Stolte of Bechtel and John David Heinzmann of Endecon has been essential to the work, and I thank them both for their contributions of technical expertise and for their willingness to work over the hard spots with me.

GLOSSARY

BART	Bay Area Rapid Transit District and/or its system and trains.
BATC	Bay Area Transit Consultants.
Baytube East	*See KTE.*
Baytube West	*See MTW.*
Contact Rail	A busbar or rail which is used to provide power to train cars via a contact shoe on the trains, e.g., third rail. The contact rails are connected to the positive of the DC traction power system.
Crush Headways	The minimum time between successive trains; for safety reasons, trains cannot run closer together than this spacing. Crush headways are used when clearing the system of a blockage or delay to return to scheduled operation as soon as possible.
Cutoff	The low-voltage limit at which the on-board train drive electronics are set to turn off to protect the equipment. The cutoff is 750 V for the BART train cars.
ESS	Energy storage system, generically encompassing battery, SMES, or other energy storage technologies and their ancillary subsystems.
Full-Load Voltage	*See nominal voltage.*
Gallery	The enclosed space in the transbay tube between the east- and westbound sections of track. The lower gallery is 8 feet wide by 9 feet tall in cross section and houses equipment. The upper gallery is 8 feet wide by 6½ feet tall and is primarily used as an exhaust air duct, but it also houses some wiring and pipes.
Gap Breaker	A circuit breaker used to electrically connect or isolate two sections of rail running in the same direction. Gap breakers are closed during normal operation. *See also tie breaker.*
Headway	The time between adjacent trains. In 1996, projected headways will be 2:15 minutes for BART trains during rush hour.
KTE	BART designation for the traction substation located at the east end (Oakland side) of the transbay tube. KTE is also known as Baytube East. This substation includes two 5-MW traction rectifiers.

LARR	Levelized annual revenue requirement. The amount of money which would be required as income, per year, to pay off the "mortgage" on the capital equipment, and to pay the operations, maintenance, and replacement charges in equal dollar payments each year. Includes estimates of cost of capital, etc.
Light-Load Transition Voltage	The DC output voltage of the traction rectifier at very low current output (a few amperes compared to a full-load current of several thousand amperes). The BART system light-load transition voltage is 1,060 V. For practical purposes and modeling simulation, this is the no-load voltage. Regenerative braking may raise the DC system voltage above 1,060 V.
MCG	BART designation for the gap and tie breaker station located at (approximately) the middle of the transbay tube.
MTW	BART designation for the traction substation located at the west end (San Francisco side) of the transbay tube. MTW is also known as Baytube West. This substation includes two 5-MW traction rectifiers.
Nominal Voltage	The DC system voltage and voltage of a rectifier when delivering rated power and current. The BART system nominal voltage is 1,000 V. Also called full-load voltage.
PCS	Power conditioning system. The PCS can convert the varying DC current from the SMES magnet, or the varying DC voltage from the battery bank, into a constant voltage to apply to the third rail.
Regenerative Braking	The excess kinetic energy of a moving train is converted to electric energy and reinjected into the third rail of the system when a train brakes. This raises the voltage of the rail, and is allowed only insofar as the track voltage is within certain limits. Excess energy which cannot be reinjected into the rail is dissipated in an onboard resistor. BART garners significant energy savings during rush hour periods from its regenerative braking.
Regulation	The decrease in voltage of traction rectifiers with increasing current output, usually expressed as a percent. The BART system (and most other) traction rectifiers have a 6% regulation, i.e., the voltage decreases from 1,060 V to 1,000 V as the current increases from (near) zero to rated current. This is standard transit system terminology. The meaning is very different from the meaning of the term in common utility parlance. Utility engineers would call this quantity "voltage drop at the device." BART traction rectifiers are routinely, if briefly, run at three times the rated current, which would give a 180-V drop in the rectifier alone.

GLOSSARY (cont.)

Running Rail	The steel rails on which the trains are supported and run (i.e., track). The negative return of the DC traction power system is connected to the running rails.
SMES	Superconducting magnetic energy storage, e.g., SMES coil or SMES system. We refer to "small" SMES to distinguish these MW-sec size machines from the 1,000-MWh-size machines which are discussed for utility-scale, load-leveling storage applications.
Solenoid	A coil of wire wound helically on a straight cylindrical form. When current flows through the wire, a magnetic field is set up inside the coil, approximately parallel to the axis of the cylinder, with the field lines closing through the space outside the coil. Thus, the magnetic field lines form a donut shape when current flows in a solenoid.
Tie Breaker	A circuit breaker used to electrically connect or isolate two sections of rail running in opposite directions. Tie breakers are closed during normal operation. *See also gap breaker.*
Toroid	A coil of wire wound around the surface of a donut. It can be thought of as a solenoid whose axis is bent into a circle. When current flows through the wire, a magnetic field is set up which is largely confined to the interior, or "dough" of the donut. The field lines close on themselves in a circle which is inside the toroid.
Traction	Relating to train propulsion, e.g., traction power, traction substation.
Traction Substation	An installation of transformers, rectifiers, switchgear, and other equipment which changes the utility-supplied AC voltage into the DC voltage needed to power the train system. BART traction substations have one or two rectifier units of 3, 4, or 5 MW each.
Voltage Drop	*See regulation.*
Voltage Sag Event	A decrease in the voltage of the DC third rail below the cutout voltage of the motors (750 V). On the BART system, these transient events are very brief, i.e., on the order of a few seconds.

EXECUTIVE SUMMARY

In 1991, a collaborative program began between PG&E and the Bay Area Rapid Transit District (BART), with Electric Power Research Institute (EPRI) cofunding and participation, to scope the application of superconducting magnetic energy storage (SMES) to the BART system, especially the center of the Transbay Tube. Later, the Federal Transit Administration (FTA) joined the effort and provided funding to complete the project and enable the preparation of this report.

The BART objective was to increase train capacity in the Transbay Tube, which links Oakland and San Francisco under the waters of the Bay. The capacity of the current system is limited by the inability to maintain acceptable voltage levels at the train when traffic densities are high and multiple trains simultaneously draw power from the traction power distribution system. This is because excessive loading on the system results in short transients of low voltage below 750-V on the third rail which in turn causes train motors to shut down to minimize damage to the equipment. These occurrences cause excess wear and failure of traction power system components while causing passenger discomfort. While the frequency of these events is currently tolerable, BART anticipates that as system loading increases with the completion of additional line extensions, such events will increase in frequency. BART, therefore, wanted to determine whether wayside storage of electrical energy near the middle of the tube would mitigate the transient low-voltage condition.

The PG&E objective was to perform a detailed scoping study of SMES, leading to demonstration of SMES in a beneficial, customer-sited application. BART was chosen because of its willingness to consider application of this new technology on its system, and because it was believed that there would be relatively frequent occurrences of events on the system that would require an energy storage device to support system voltages. This frequency is higher than would occur in the typical industrial plant, and a higher rate of events would provide increased validity to the demonstration. PG&E also wanted a comparison of other competing technologies on both functional and economic grounds.

While technical and institutional hurdles to time-coordinated testing on the BART AC and DC systems were being addressed, work progressed on the conceptual designs and economics of SMES, battery, and conventional solutions to the presumed problem. Computer simulations allowed identification of situations in which transient voltage sag below 750 V might occur, and permitted a reasonable choice of system energy and power ratings. A functional specification was issued with a Request for Information.

Three SMES vendors responded with conceptual designs and cost information, which provided the first-ever cross-vendor comparison of design alternatives and costs in the micro-SMES area. Bechtel was employed to produce battery and pulse-duty rectifier designs to meet the functional specification. This study also presents a rare look at competing SMES and battery designs for the same application. The seven resultant designs were compared technically and economically.

Technically, the major differences between the solutions were in footprint and in ability to sustain the connection voltage to a close tolerance. SMES and the two battery designs which included power conditioning units were able to hold the energy delivery voltage to within "a few volts." SMES and the pulse-duty rectifier were able to fit into the BART-desired length of the tube gallery, while the battery designs spread out from 2.5 to 9 times longer than desired. Table ES-1 displays the footprints of all seven systems.

Table ES-1

System Footprints

System	Footprint (in feet) (length x width)
Battery Only	458 x 2.5
"DC Battery"	122 x 3.5
Battery-PCS	232 x 3.5
Rectifier	30 x 4
PDM SMES	50 x 4
Westinghouse SMES	61 x 3.8
SI SMES	50 x 4

A wide range of innovative features are found in the three SMES designs. Two are modular, and one is a single coil. Two are solenoidal, and one is toroidal. To enable comparison to the study location in the transbay tube, vendors also submitted designs for an unconstrained location. This gave PG&E a better basis on which to apply the results to a more typical industrial site, lacking in the constraints of space and auxiliary power posed by the tube location. All designs use liquid helium refrigeration systems.

Economically, there was a substantial range of costs. The lowest-cost options were those with the largest footprint and the poorest voltage regulation. With battery systems, significant expenditures would be required in years 7 and 14 for battery replacement to keep the systems operating. This means that in choosing a storage solution, a strategic determination of the actual need for small footprint, the necessity of close-voltage control, and the institutional issues of availability of capital dollars compared to expense dollars would be essential. Table ES-2 exhibits the levelized annual revenue requirement (LARR) for three of the designs.

Table ES-2

Cost and Economic Summary for Battery, Rectifier, and SMES Systems

	"DC-Battery"	System Rectifier	SMES
Capital Cost			
Energy Subsystem	$1,276,000	$2,019,000	$1,565,000
DC Interface	304,000	304,000	304,000
Total	$1,580,000	$2,323,000	$1,869,000
Annual Electricity Cost	$185	$3,500	$36,000
Annual Maintenance Cost	$10,000	$2,000	$12,000
Battery Replacement Cost	$130,000	N/A	N/A
LARR	$174,000	$219,000	$242,000

N/A = Not applicable. Only the battery system incurs major component replacement costs during its service lifetime. Battery replacement at one-third and two-thirds of the 20-year lifetime was assumed here.

Over three-fourths of the LARR for the pulse-duty rectifier is attributable to the costs of cabling and conduit to supply its power from the end of the tube. There is a possibility that the pulse-duty rectifier costs could prudently be lowered from the Bechtel estimate by use of site-specific rather than general system criteria for cable sizes in the design. This would increase the attractiveness of that conventional option if a near-term solution is needed. (It also means that BART is unlikely to ever space out its surface substations at greater distances in favor of intervening SMES units, because the cost balance is very likely to be on the side of the traction rectifiers.) However, if any greater capacity were required of the rectifier, it is unlikely that the transformer would fit into the tube. Furthermore, BART might for other reasons hesitate to run a new 34.5-kV cable in the tube. The LARR for the Bechtel design of the rectifier is $219K.

The SMES system with the lowest cost estimate had an LARR of $242K. Vendor prices for the SMES systems ranged over a factor of 3.6. SMES is in its infancy, and costs are projected to drop substantially with manufacturing experience and the advent of competition. The SMES LARR could be further decreased by roughly $20K in avoided electricity cost if advanced train controls permit the unit to be charged on an as-needed basis rather than full time. Two of the SMES systems, including the lowest price quote, exceeded the specified auxiliary power requirement.

The battery system LARR ranged from $120K for the Battery-Only system to $174K for the Omnion modular PCS battery system ("DC-Battery"). Battery systems exceeded the specified footprint by up to a factor of nine: 442 feet long compared to a preferred length of 50 feet. The simpler the battery system, in terms of supports and power conditioning, the lower its cost and the greater its footprint. As racks and power electronics are added, footprint decreases, voltage setability increases, and price rises. The benchmark battery system used in the cost comparisons is the one with the smallest footprint—122 feet long. In the case of a public transit agency such as BART, where capital costs are paid primarily by federal funding, while expenses are paid from local budgets, the issue of battery replacement cost may become important: If funds were unavailable to replace the batteries, the system lifetime would drop to one-third of its design value.

In light of the results of the time-coordinated AC/DC monitoring of the transbay tube traction power system (reported separately under *Monitoring of the BART Baytube Traction Power System,* PG&E Report 007.5-94.12), where far fewer voltage sag events were detected at the center of the tube than had been expected by BART, it does not now appear that a source of pulsed energy at the tube center would alone be of benefit to BART. It appears that modification of the automatic train control system to inhibit multiple simultaneous high-acceleration starts would be more useful, as would the increased understanding of system operation which could be gained from monitoring track voltage at several points in the tube for several months. (This study agreed with earlier work in finding that the voltage drop was due roughly equally to drop in the substations and drop in the rails, so minimizing voltage drop could also be approached through either of those systems.)

Therefore, the recommendation is that an investigation be made of the contribution which train control could make to elimination of transient voltage sags, quantify system benefits from elimination of such transients, and begin long-term monitoring of track voltages at several points to determine the frequency and depth of sags in the tube as a function of position. Thus, for BART, it appears that the benefit of this effort has been in clarifying the problem rather than in providing a solution.

If, in weighing the feasible complexity of advanced train control, BART decides that a compact, transient, local energy source would still be a desirable adjunct to system operation, then the outlook for SMES is sufficiently favorable to warrant proceeding with a test phase. The test would be done first at the Hayward test track and then at a revenue track location. It is likely that SMES would be proven able to support some range of sags cost-effectively. In the spirit of cross-technology comparison which has animated some of the present work, EPRI would also like to test a battery system at BART. This would have the advantage of providing two qualified solutions from which BART could chose its preferred solution. Such testing does not have high likelihood in the near future.

For PG&E, the benefit has been more in line with our goal of bringing a technology to the state of readiness for use by our customers in power quality. Although we have not achieved the hoped-for test of SMES at a customer site, we have effectively broadened our vendor base and achieved competitive pricing while increasing understanding of how SMES and battery characteristics compare in their ability to fit differing customer requirements. Issues of footprint, cycle life, energy cost, and the trade-offs of modularity are now clearer. In retrospect, the complexity of a transit application was a significant impediment to the rapid due-diligence scoping which we had hoped to achieve. In a more typical industrial application, we expect that the need would be more clearly defined from the outset.

Section 1
INTRODUCTION

BACKGROUND

The overarching objective of this phased study is to bring one application of superconducting magnetic energy storage (SMES) through specification, design, and testing to the point where a decision on a permanent installation is feasible. The study will also establish functional and economic comparison with batteries and non-storage solutions. This study concerns the application of a small SMES device to the Bay Area Rapid Transit (BART) system, and emphasizes the location near the center of the transbay tube which connects Oakland to San Francisco under the waters of the San Francisco Bay. BART experiences occasional transient situations in which third rail voltages fall below 750 volts due to excess demands for current by the transit vehicles. When these situations occur, the onboard traction motor control system cuts power to the motors to minimize damage to the motors. This results in an uncomfortable ride for the passengers while contributing to failures of the onboard traction power subsystems.

The design of BART, which is an electric train system operating at a nominal 1,000 VDC, has all the train current carried from the rectifier substations to the trains by a third-rail system. A spring-loaded shoe from each train car rides along this third rail, and the running rails, or tracks, provide the current return to the rectifier. Unlike some transit systems, BART does not use feeder cables to the track between electrical substations, so as a train leaves an electrical substation, the length of track through which the current must pass increases steadily until the halfway point between substations. Then it decreases again as the next substation is approached. Spacings between substations vary, with one of the largest being the spacing between the substations at the opposite ends of the transbay tube, a span of 3.5 miles. The Ohm's law losses in the rails contribute to the voltage sag problem, so that voltage is likely to be lowest at locations most distant from substations. Figure 1-1 schematically illustrates this voltage drop as one traverses the transbay tube.

The slope of the track and other trains on the system also contribute to voltage sag. When a train is going uphill or is more heavily loaded with passengers, it draws a higher current to meet the demand of increased power. This higher current causes a larger voltage drop in the rails (voltage drop in a section of track equals the resistance of the track times the current flowing). Other trains on the system cause loads on the rectifier substations, whose injection voltage to the rails drops as the power drawn from them increases. As the distance between trains decreases, and the number of trains on the system increases, voltage sags below the 750-V level will thus become more probable. The fact that these loads are all time-varying only adds to the complexity of the situation.

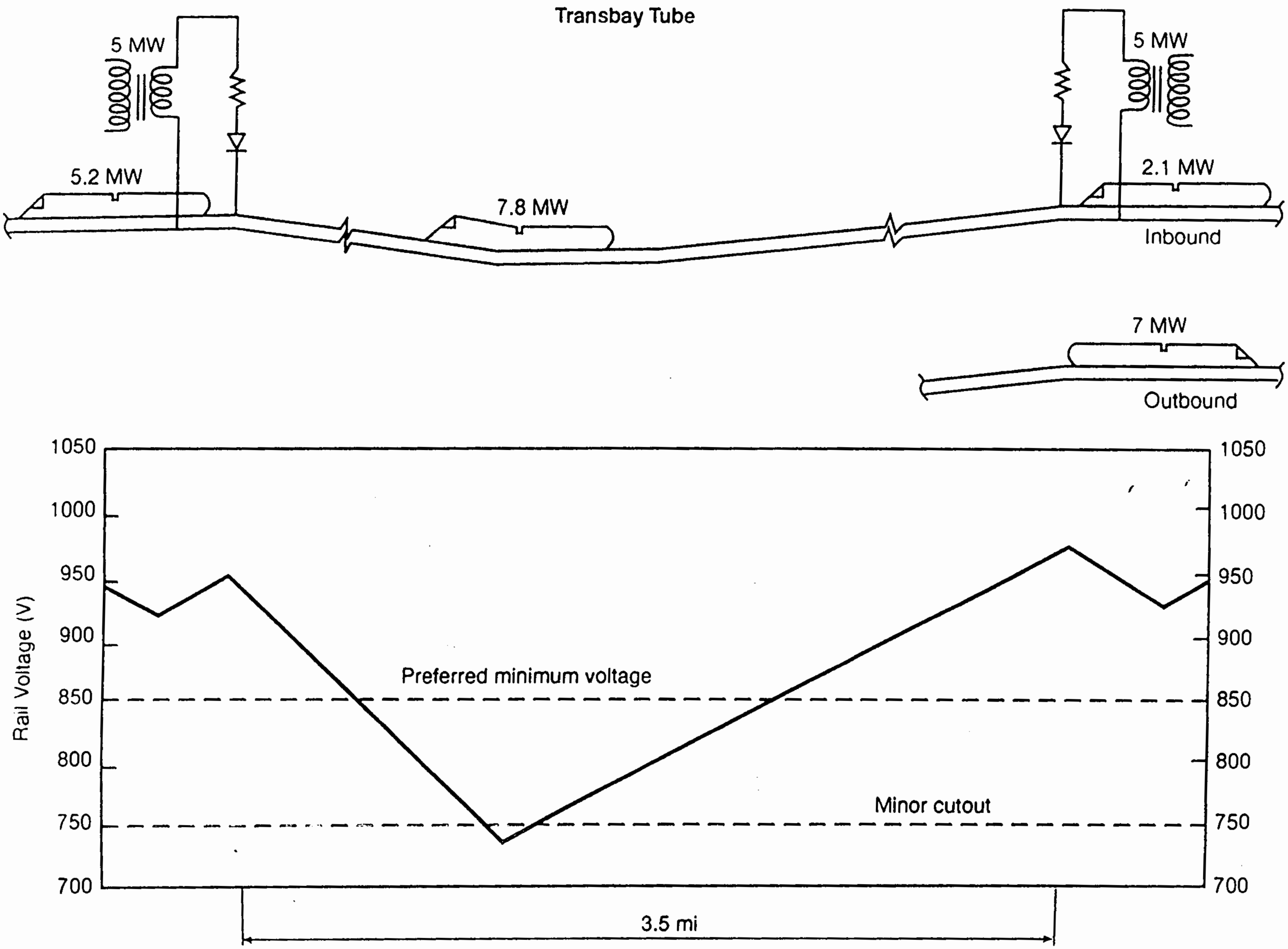


Figure 1-1. Schematic of BART voltage sag.

This voltage sag problem could be addressed in a number of ways: BART has already decreased the resistance of the third rail by adding aluminum cladding to it in the tube area. A new substation could be added in the middle of the tube span, but this is significantly complicated by the underwater location. Perhaps something could be done on the AC side of the BART electrical network to improve the power factor. In this study, we assess the feasibility and cost of providing a storage solution to the voltage sag problem, and we compare this to the cost of a pulse-duty rectifier at the same mid-tube location. With any of these technologies, current would be injected to support the train load for the brief period when the existing supply was insufficient to maintain 750 V at the vehicle. Improvements of the automatic train control system provide a second avenue for mitigation strategies, in addition to the measures described here for the traction power system.

A 1992 PG&E report, *Superconducting Storage for Transit Train Voltage Support: Problem Definition and Technology Survey,* outlines the process by which the choices of the storage technologies which might be applied to the BART voltage sag problem (Heinzmann, Wenger, and Reading 1992) were narrowed. To summarize those results, PG&E settled on SMES and batteries with a non-storage comparison solution. (Although flywheels are a topic of increasing interest, they were eliminated from consideration on the grounds that there was no vendor prepared to supply them at that time.) Comparison of SMES to batteries pits a nascent technology against a mature, century-old one. It reveals differences in ability to meet the specification, as well as in price. The comparison to a non-storage solution provides a benchmark of price and function which allows us to determine whether a storage solution is desirable at all for this application.

In the current phase, referred to as Phase Zero, PG&E defined the problem more precisely through computer simulations; wrote a functional specification for storage solution of the problem; received conceptual designs for SMES, battery, and pulse-duty rectifier solutions to the problem; and performed an economic comparison of the various designs. The work will be described in detail in this report.

HOW VOLTAGE SAG OCCURS

A qualitative description of voltage sag can be made with reference to a schematic graph of the probability of a given third-rail voltage at a particular location. For the purposes of this discussion, a location near the center of the transbay tube will be used (see Figure 1-2).

When there are no trains moving on the system, the voltage will be above 1,060 V. This situation will only rarely occur. When trains are moving on the system but none are within the tube, the voltage will be below 1,060 V because as power drawn from the rectifier substations increases, their output voltage

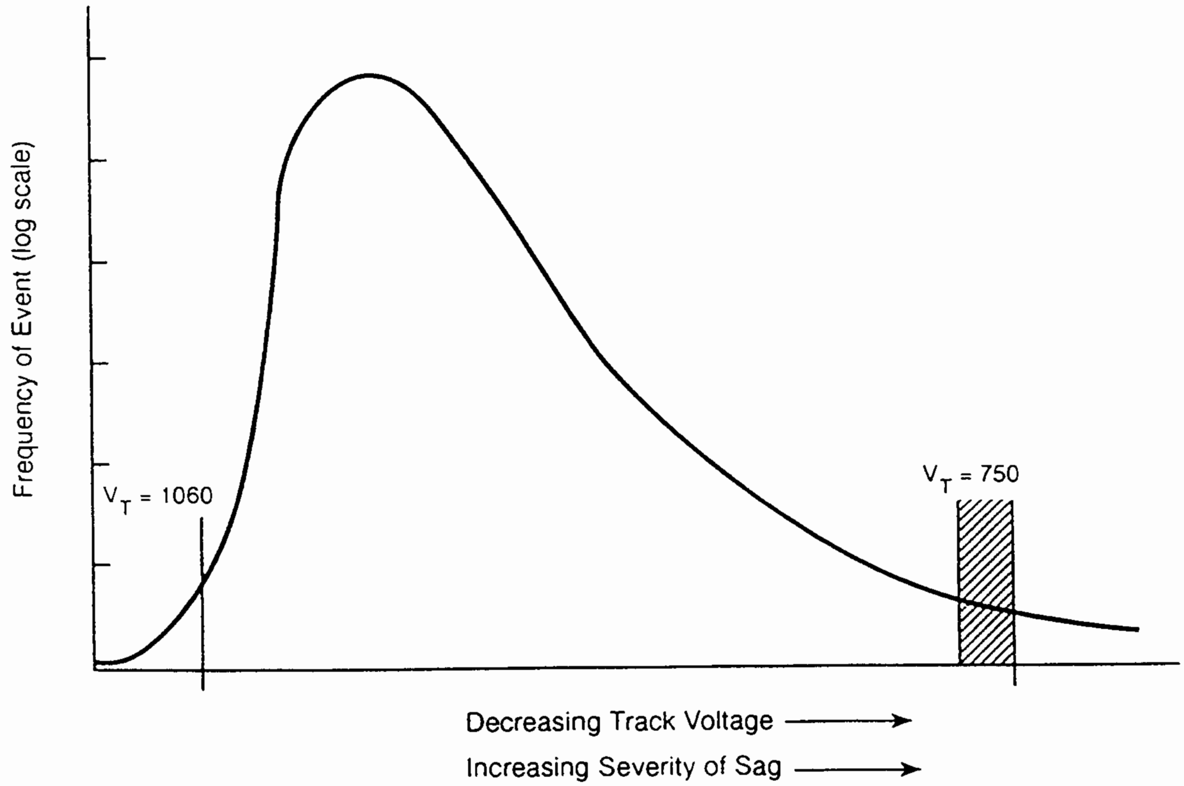


Figure 1-2. Qualitative probability distribution of voltage at MCG. The shaded band shows the range of events addressed by a storage solution at MCG.

drops. When a single train is traversing the tube and drawing its current through the long rails, the voltage at a location near the middle of the tube will drop as the train approaches and track losses steadily increase, and then will rise again as the train recedes toward the opposite end of the tube.

When two trains are passing through the tube in opposite directions, the voltage will drop farther, and will also depend upon the point at which the trains pass. When more than two trains are drawing current primarily from KTE and MTW, the rectifier substations at the east and west ends of the tube, respectively, then the voltage at mid-tube will drop farther yet. If a train accelerates from a halt in mid-tube or climbs one of the uphill slopes in the tube, it will draw a higher current and thus drop the voltage even farther. Consideration of an array of such circumstances leads to a curve like that in Figure 1-2, where the probability of a given voltage at MCG is plotted. This curve should be interpreted only qualitatively.

The events which BART wants to eliminate with a SMES or battery installation are those which lie in the tail of the distribution, in some band of voltage sag severity. The storage capacity of the device will determine the width of the band of events which are eliminated by the device. It is not useful to speak of a "worst case" event, because we are seeking to alleviate those sag events which we can cost-effectively eliminate, not any conceivable event. (For example, events such as a substation or distribution cable being out will occur quite infrequently, but will worsen the sag in each of the train scenarios mentioned above. These rare events will lie well out in the tail of the curve. In fact, the "worst case" is loss of all electric supply to BART: clearly none of these measures is intended to address such a circumstance.)

A relatively small, or sub-scale, device will eliminate a narrow band of sag events, while a larger device will eliminate a broader band. Sizing of the device was based on plausible scenarios of frequency of sag events. To give a concrete but very rough estimate, if these sag events occur once a week now, they might occur once a month with any of these mitigation techniques, and once a year with wayside mitigation such as SMES coupled with advanced train controls. (We do not have sufficient data at this time to state such concrete frequencies with justification.) Extensive monitoring of the existing problem areas, comparison to simulations, and broad suites of simulation runs would be necessary to fully quantify this situation. Such an effort would require a budget of a few hundred thousand dollars.

HOW SMES TECHNOLOGY WORKS

In their article, "Storing Power for Critical Loads," DeWinkel and Lamoree (1993) describe how SMES technology would work. A SMES device would be attached to the third rail through a system controller. This system controller would monitor the third-rail voltage. In the event that third-rail voltage dropped below a specified set point, the controller would advise the voltage regulator, which controls the DC power from the magnet, to inject current into the third rail.

The superconducting coil is charged through a magnet power supply which can be fed from the auxiliary 4,160-V supply or from the third rail itself. Once the coil has been charged, the magnet charger provides a small voltage to overcome resistive losses in the room temperature part of the circuit. This keeps a constant current flowing through the superconducting coil. In the standby mode, the current stored in the magnet circulates through this normally closed switch and back to the magnet. Unless a cryogenic switch is provided, current must also flow through the external leads connecting the magnetic storage system to the power converter, resulting in a slight energy loss. Again the magnet power supply provides a trickle charge to replace the power lost in the non-superconducting part of the circuit.

When the system controller senses that the third-rail voltage has dropped below the set point, the switch in the voltage regulator opens in 200 to 500 microseconds. The system is sized to store sufficient energy to maintain voltage above the minimum for several seconds for predicted loads.

Section 2

BART SYSTEM TECHNICAL DESCRIPTION

BART provides rapid rail train service in the San Francisco Bay Area. A map of the overall BART system routes and passenger stations is shown in Figure 2-1. Operation of the system exhibits typical commuter morning and afternoon peaks in ridership and electrical power consumption.

The BART system includes a 3.5-mile-long tube under San Francisco Bay, which is the primary area of interest of this study. The route of the transbay tube is shown in Figure 2-2. Due to the relatively long distance between the traction rectifier substations, which are at the ends of the tube, the train voltage may drop to undesirably low levels under certain conditions. These conditions may include rush hour traffic and train delays at present and decreased train headways in the future. The train drive electronics will cut out if the voltage falls below 750 V (for the nominal 1,000-VDC system).

The transbay tube is made up of concrete sections, which were lowered and connected underwater during construction of the system. A representative cross section of the tube is shown in Figure 2-3. There are two 17-foot-diameter bores in which the train tracks are located, one for eastbound trains and the other for westbound trains. The space between the two sections of track is called the gallery. The upper gallery is 8 feet wide by 6.5 feet tall and is primarily used as an exhaust air duct, but also houses some wiring and pipes. The lower gallery is 8 feet wide by 9 feet tall in cross section, houses equipment, and serves as an emergency escape route. Any energy storage system or other system postulated as a solution must be located within the lower gallery. There are further space and size limitations. Equipment may not protrude more than 4 feet from the wall so that a 4-foot passageway remains. Also, the equipment may not be more than 8 feet tall so as to clear overhead cables.

Access to the gallery area is limited. Pumps near the ends of the tube reduce the width of the gallery to 30 inches. Thus, system modules and components must be brought in through the personnel doors from the track area. Components must pass through the door (79 inches high by 42 inches wide) and turn into the 8-foot-wide gallery. Details of this area are shown in Figures 2-4a, b, and c. The level of the train floor is substantially higher than the base of the door, and the width of the sidewalk ramp is a nominal 30 inches, but in some places may be as narrow as 27 inches. Installation of components must take into account that no cranes or similar equipment exist in the tube, but temporary rigging is allowed. However, such installation work must be performed during non-revenue hours (midnight to 4 A.M.). Additional requirements include a maximum floor loading of 29 pounds per square inch and bracing for Seismic Zone 4.

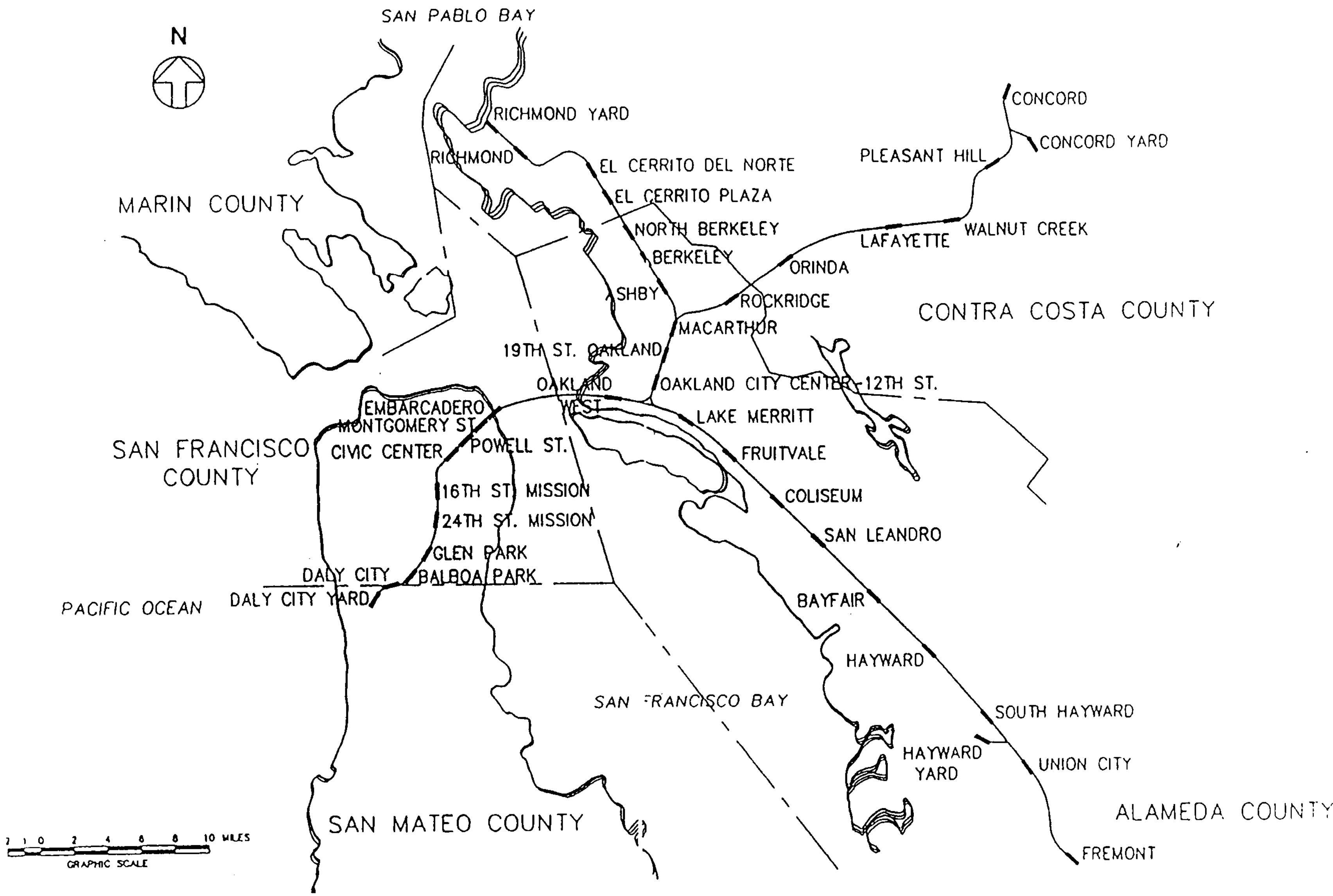


Figure 2-1. BART system routes and passenger stations.

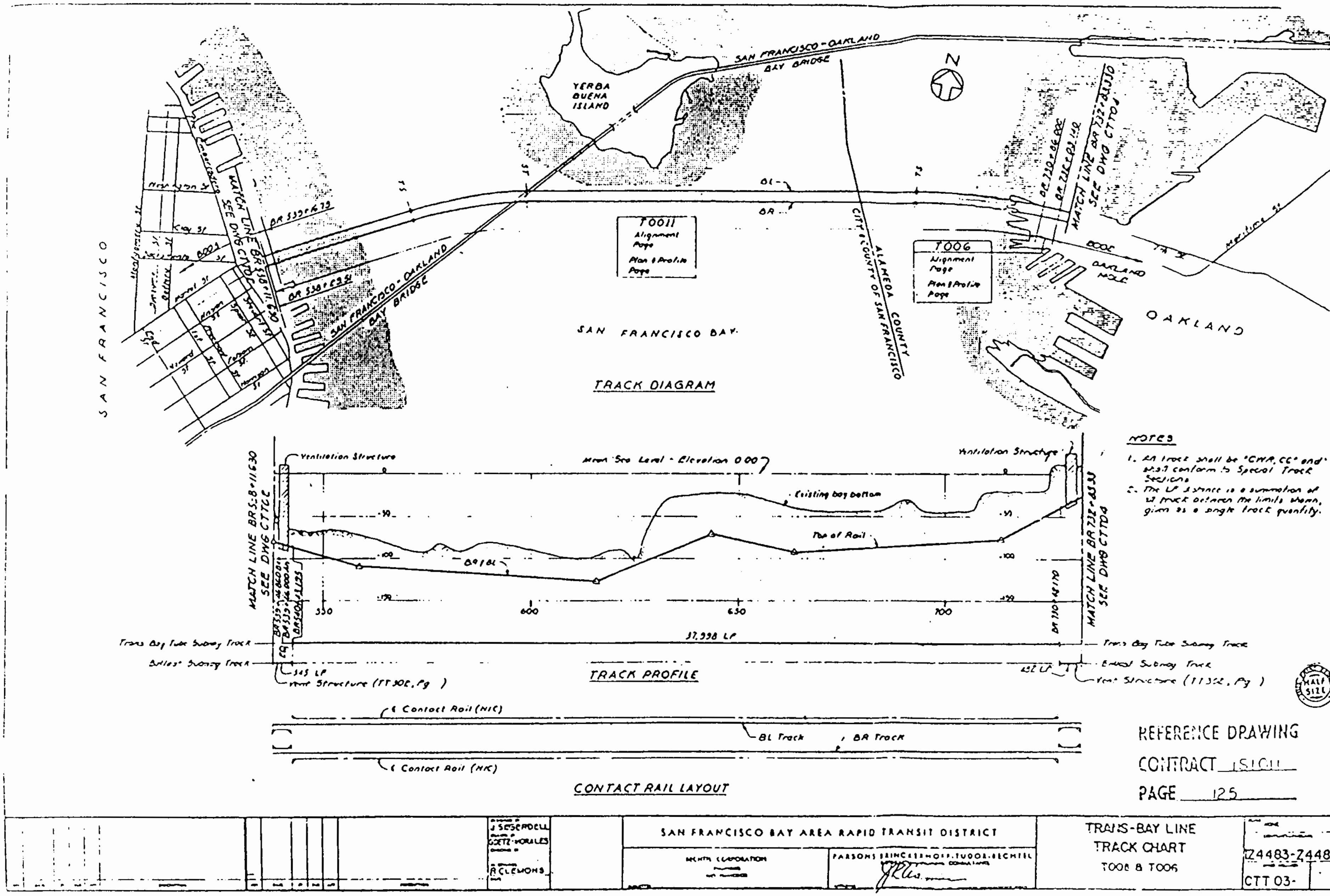


Figure 2-2. Route of transbay tube.

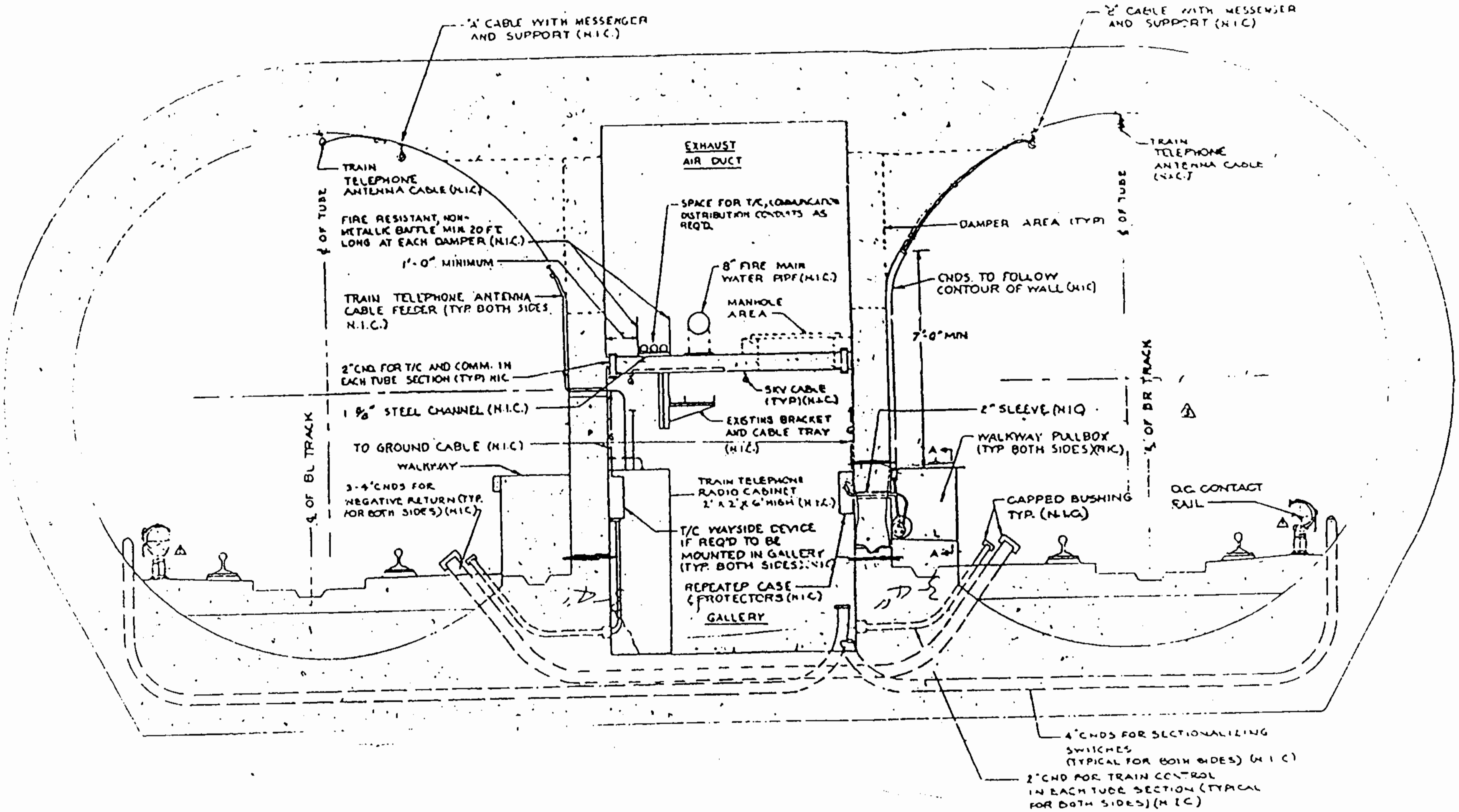


Figure 2-3. Cross section of transbay tube.

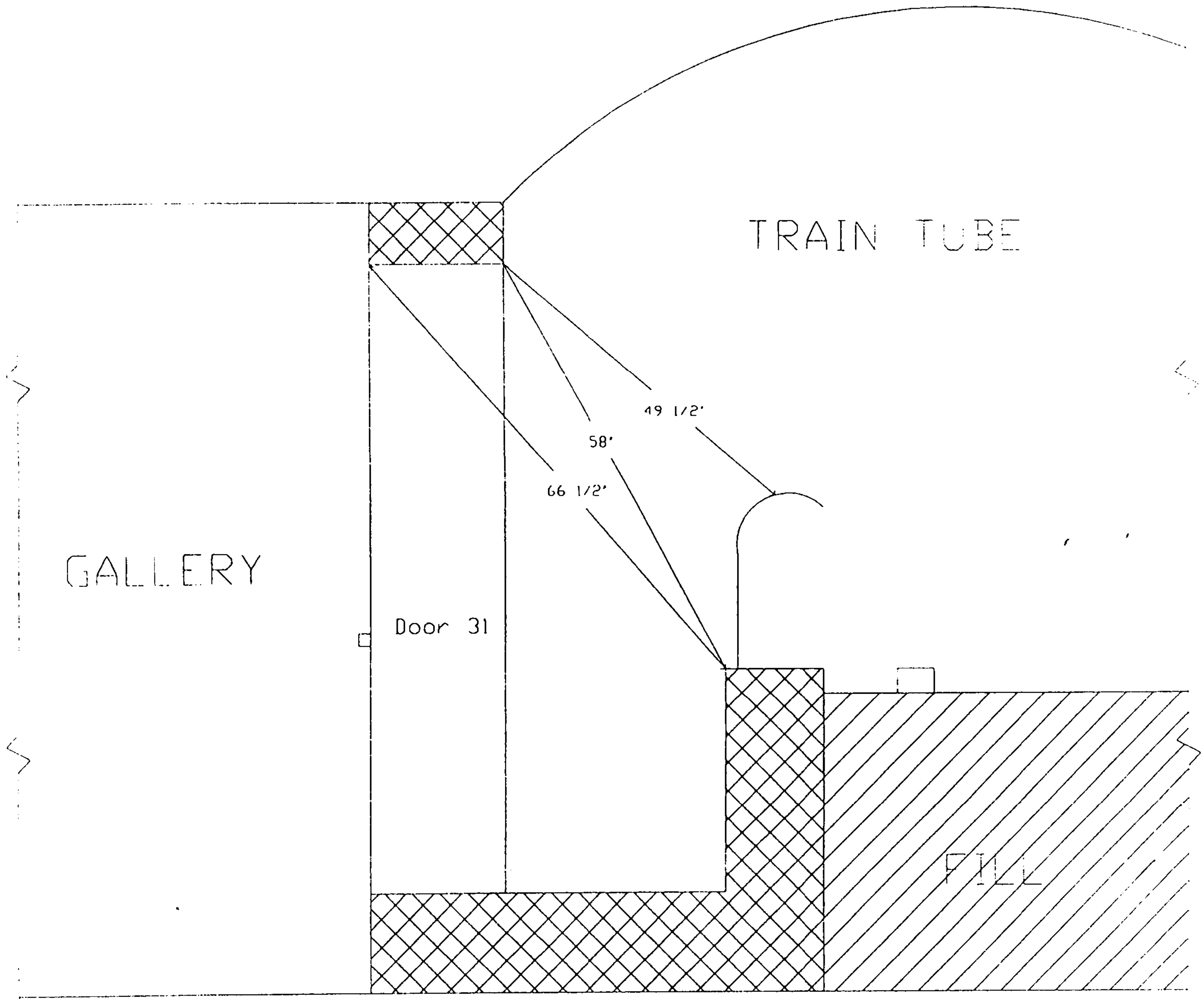


Figure 2-4a. Dimension drawing for access through Door 31, BART transbay tube. Front view from gallery, through door into train tube.

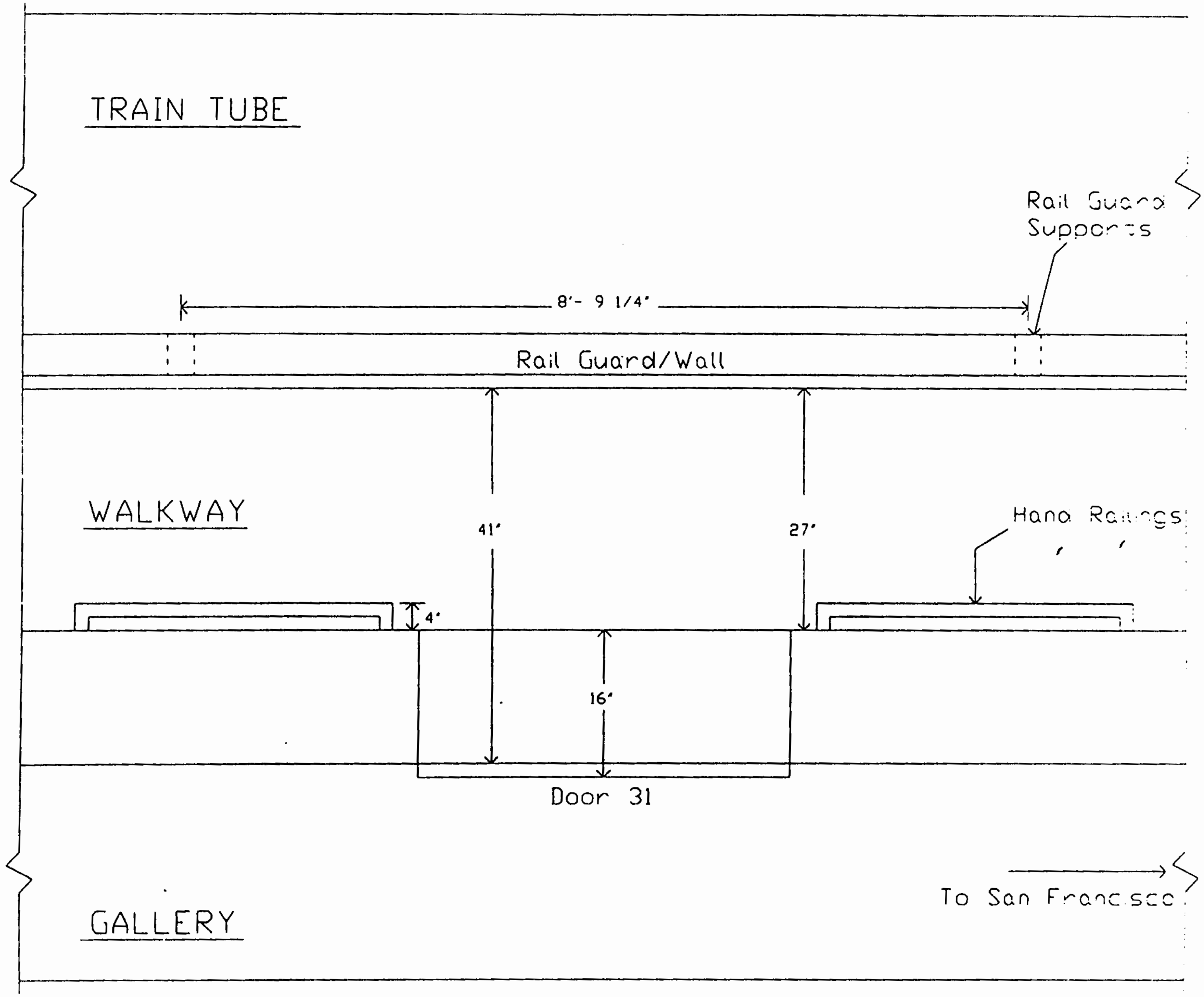


Figure 2-4b. Dimension drawing for access through Door 31, BART transbay tube. Top view, showing detail of walkway, handrails, rail guard, and entryway to gallery.

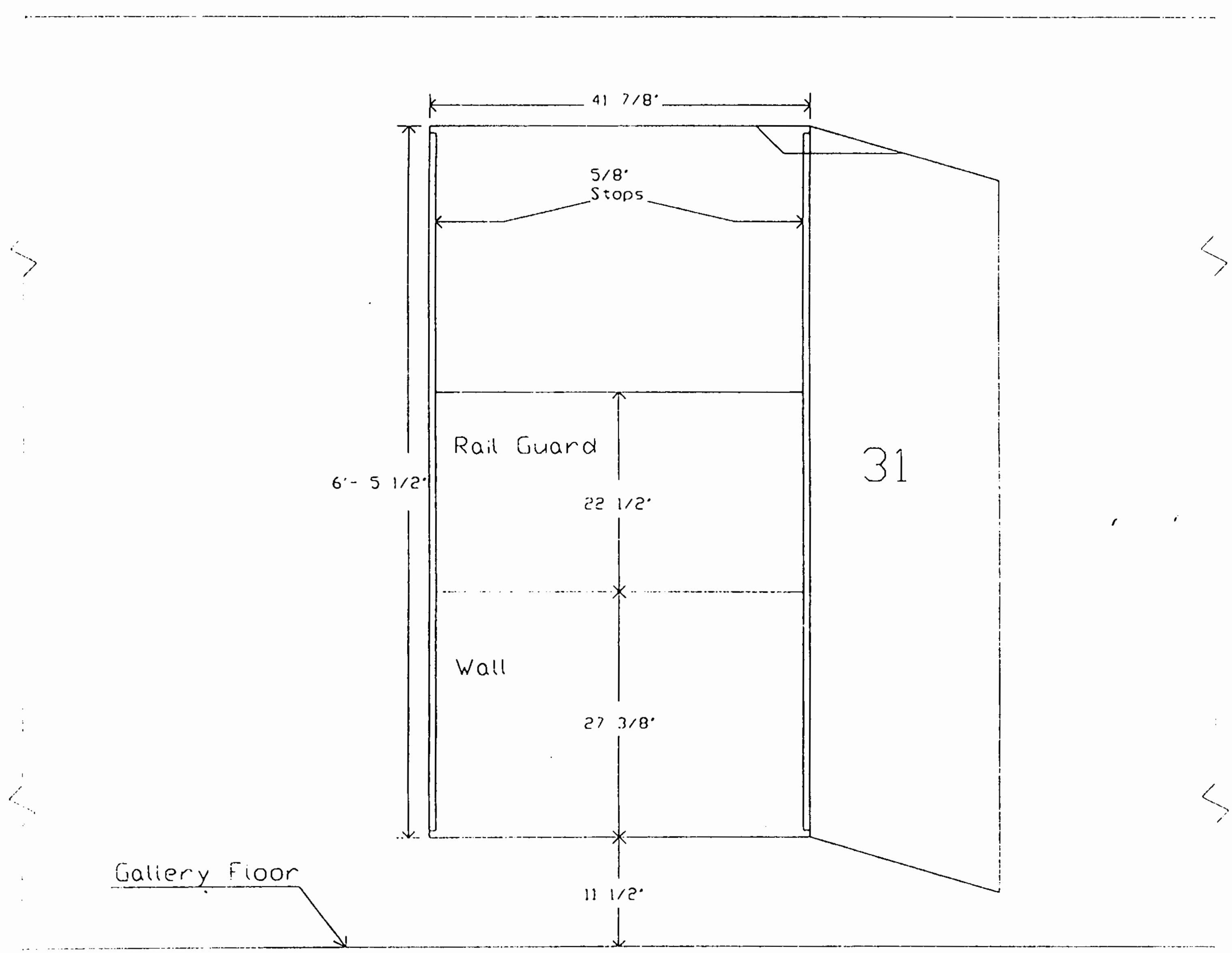


Figure 2-4c. Dimension drawing for access through Door 31, BART transbay tube. Side view (cross section through wall) showing clearance of distances for passage of equipment from railcar into the gallery.

A simplified electrical single-line diagram of the BART system in the area of the transbay tube is shown in Figure 2-5. The traction substations closest to the tube midpoint (MCG) are about 10,000 feet away, at the ends of the tube. Each of these traction substations includes two 5-MW traction rectifiers.

BART refers to the system as a "nominal 1,000-V system" to simplify the variety of voltages which are found. The no-load voltage (e.g., no trains on the system) and braking maximum regeneration voltage are approximately 1,160 V. The light-load transition voltage is approximately 1,060 V. The contact rails are positive and the running rails (tracks) are negative. The negative of the BART DC system is connected to ground through diodes and contactors at each substation. This configuration allows the track to rise up to about 125 V above earth ground potential during normal operation. A flashover and fuse opening on train cars may cause transient voltages of up to 3,000 V to be present between the positive and negative, and transient voltages of up to several hundred volts between the negative and earth ground.

The distance from the MCG (tube midpoint) to either the Baytube East or Baytube West rectifier substation (BART designations KTE and MTW, respectively) is approximately 10,000 feet. The resistances are approximately 0.020 ohm for each of the two contact rails which are in parallel, and 0.022 ohm for the four parallel running rails from MCG to either KTE or MTW (these resistances are for the entire 10,000-foot length of these rails: $R = r/l \times l \quad r/l = 2 \times 10^{-6}$ ohms per foot for the clad contact rail). The available fault current at MCG is approximately 60,000 amps. The inductive time constant of the rails L/R is approximately 0.1 second (L is the inductance of the rails).

Each BART train car has four series-wound DC motors and a chopper controller. The propulsion system typically operates in a constant power mode, so that as the track voltage decreases, the current drawn by a car increases. Beginning at about 850 V, the maximum current that a car is allowed to draw is reduced. Whether train *performance* is reduced at this point depends on whether the limiting amount of current is being drawn (due to acceleration, grade, passenger load, etc.). This is nevertheless referred to as "reduced-performance mode."

Only limited AC power is presently available in the BART transbay tube. An energy storage system may draw up to 15 kVA of auxiliary or charging power from the 4,160-V, 3-phase line existing in the gallery. If higher power is needed, it must either be taken from the DC rail system, or a cable must be run to the 34 kV_{AC} line at MTW or KTE, approximately 10,000 feet.

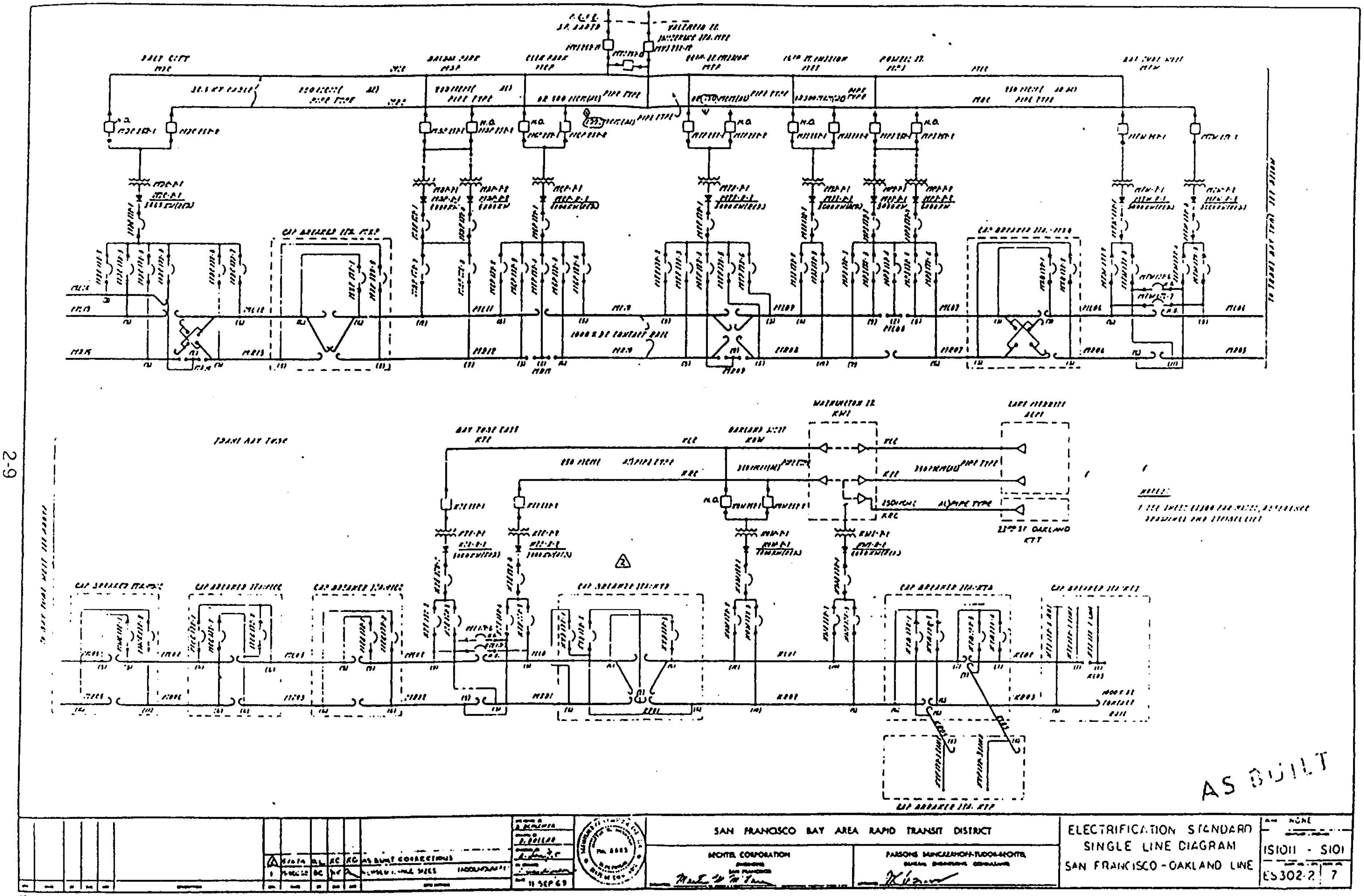


Figure 2-5. Single-line diagram of the BART system (transbay tube).

Section 3

METHODOLOGY FOR SIZING THE STORAGE DEVICE

SIMULATIONS

As a first quantitative step in sizing the storage device, computer simulations of several scenarios of train operation were run. The simulator used was the Traction Electric Load Simulator (TELS 3.0) model which belongs to Parsons, Brinkerhoff, McQuade, and Douglas (PBMQD). This model has been extensively verified with on-train, on-track testing on the BART system, and has been shown to give train minimum voltages which are typically within 1% of the measured values, substation DC root-mean-square (rms) currents within 3% of the measured currents, and rms currents in the 34.5-kV subtransmission system which are in 3-6% agreement with the field test results. TELS 3.0 is run on a desktop 386-class computer.

TELS 3.0 can provide single-case runs as well as statistical runs. In a single-case run, the starting times of trains from opposite ends of the test system are specified, as are the headways in each direction between successive trains. Basic data on the traction power system parameters have been entered in the model. Train control system characteristics for the intended mode of operation are specified. The model then calculates a sequence of 1-second spaced snapshots of system operation. One can select the output parameters of interest, such as train current or train voltage as a function of time or distance. TELS does not account for motor cutout in undervoltage situations. The severity of a voltage sag is indicated by the depth to which the simulated voltage drops, though in actual operation the motors cut out at a nominal 750 V. Some of the parameters which we recorded are listed below:

- Train voltage vs. track position
- Train voltage vs. time
- Train current vs. track position
- Train current vs. time
- Train speed vs. track position
- Train speed vs. time
- MCG gap breaker bus voltage vs. time
- MCG tie breaker current vs. time
- SMES injection current vs. time

TELS 3.0 can be used to model the entire BART system; however, for the purposes of this study, we used a limited track system from the Oakland Wye (designated EOL, end of line) to the Sixteenth Street traction substation in San Francisco (MSS). In most cases, we observed lower voltages in the final track segment between Powell Street (MPS) and Sixteenth Street than we did in the transbay tube. We did not extend the test system to determine whether that track segment is actually even weaker than the tube track segment (there is some BART sentiment to support that possibility), or whether the result was an end effect, an artifact of our limited test system.

In normal system operation, there is an uncertainty in the trains' time of departure from the station. Depending on the relative times of departure of two oncoming trains from their respective ends of the test system, they will pass one another at a different location on the track. For example, if a train leaves the Oakland Wye westbound, the oncoming eastbound train could leave Sixteenth Street simultaneously, or at any later time. Because we are assuming that the trains leave Oakland on a regular schedule, the maximum delay time is equal to the time between westbound trains. Depending on the passing point, the voltage sag will be more or less severe. For example, if the two trains pass each other close to the center of the tube, they will suffer a greater voltage drop because they are conducting their current through a great length of track, with its resistance loss, and the voltage at the time they pass one another will be lower than if they passed one another close to the electrical feed point at the traction rectifier.

For each single-case run, a statistical run can be done where the single case is run repeatedly for all of the possible oncoming train delays (in minimum 1-second increments.) For each delay, the minimum track voltage in each electrically distinct track section is recorded. This gives rise to a statistical distribution of voltage sags for the given scenario as a function of track segment.[1]

A scenario is a specification of headways, train control scheme, train size and loading, duration and location of delays, and feed voltages. To determine the characteristics of a voltage sag event, it is first necessary to specify a scenario in which voltage sag occurs. We tried a number of scenarios before finding one which exhibited voltage sag below 750 V. Table 3-1 summarizes the scenarios which were

---

[1]Although the simulation program gives the complete voltage profile as a function of track distance for a single case, the volume of data which this generates is immense. PBMQD reduces the volume of data by saving only one voltage for each track segment, such as the eastern half of the transbay tube between KTE and MCG. For each track segment, TELS 3.0 saves the value of the lowest voltage attained in that case.

Table 3-1

Voltage Sag Scenarios

Note	Code	Westbound Headway	Eastbound Headway	Delay Location	Delay Duration	Minimum Voltage in Tube
1	NNS	2:15 min	2:15 min	none	none	844-924 V
	NN1	2:15 min	2:15 min	none	none	844 V
2	NDS	1:30 min	2:15 min	Oakland	15 min	778-882 V
	ND1	1:30 min	2:15 min	Oakland	15 min	778 V
3	NDS-A	1:30 min	2:15 min	Oakland	15 min	753-850 V
4	NDS-B	1:30 min	2:15 min	Oakland	15 min	729-830 V
	ND1-B	1:30 min	2:15 min	Oakland	15 min	729 V
5	NS	2:15 min	2:15 min	none	none	819-902 V
	N	2:15 min	2:15 min	none	none	821 V
6	D10	2:15 min	2:15 min	Emb.	10 min	789 V
7	E10	2:15 min	2:15 min	Emb.	10 min	710 V
8	S10	2:30 min	2:30 min	MCG	6 min	< 530 V
	S11	2:30 min	2:30 min	MCG	6 min	691 V
	S12	2:30 min	2:30 min	MCG	6 min	701 V
	S13	2:30 min	2:30 min	MCG	6 min	714 V

Notes:

1. Normal rush hour operation
   NNS: statistical run
   NN1: dynamic simulation with dispatch offset that results in lowest voltage sag in transbay tube
2. Catch-up operations following delay at Oakland Wye
   NDS: statistical run
   ND1: dynamic simulation with dispatch offset that results in lowest voltage sag in transbay tube
3. Catch-up operations (following delay at Oakland Wye) with PG&E voltage 1.5% below normal
   NDS-A: statistical run identical to NDS except for PG&E voltage
4. Catch-up operations (following delay at Oakland Wye) with PG&E voltage 3% below normal
   NDS-B: statistical run identical to NDS except for PG&E voltage
   ND1-B: dynamic simulation identical to ND1 except for PG&E voltage
5. NS: update to case NNS, statistical run, with 1995 train control (normal rush hour operation)
   N: update to case NN1, dynamic run, with 1995 train control (normal rush hour operation)
6. D10: simulation run using 1995 speed limits and 100-foot signaling blocks; 10-minute delay of westbound train at Embarcadero. This control regime results in closer stacking of trains in west end of tube.
7. E10: identical to D10 except using 1992 speed limits and 1,000-foot signaling blocks. This case was run for comparison to D10, however it does not represent a realistic scenario. Dips below 750 V occur only when the tube is more than half filled with trains. In actual operation, trains would be delayed outside the tunnel rather than stacked within the tunnel.
8. Simulations with 1992 signaling. Six-minute train stop at MCG, the transbay tube midpoint.
   S10: No SMES Device
   S11: With SMES Device at MCG set at 775 V
   S12: With SMES Device at MCG set at 800 V
   S13: With SMES Device at MCG set at 850 V

run in this project. (Recall that although actual track voltages never drop below 750 V, the simulation does not include the cutout of train motors for undervoltage: therefore the depth of sag below 750 V is an indication of severity of system overload, but not an actual voltage which would be observed.) The reader will note that some of the "minimum voltage" entries in the final column of the table are ranges rather than single numbers. This occurs in the case of a statistical run because the different offsets of oncoming trains result in different passing points in the tube and different minimum voltages. In fact, examination of the statistical distribution of those minimum voltages can yield important information.

The statistical table of voltages which the TELS 3.0 model provides can be converted into a graph which visually presents, as a function of track segment, the range of voltages which occur in a given operational scenario. For normal rush hour operation, for example, as calculated in case NNS, Figure 3-1 shows the distribution of minimum voltages. The family of curves displays the cumulative probability distribution of various voltage minima as a function of track segment.

Here, the track segments are plotted on the x-axis. Voltage is plotted on the y-axis. Points are plotted for various percentile voltages. The 100% line indicates the voltage below which all offset cases fall: for any offset of trains, the voltage will always have a minimum which falls below this line in the specific track segment. The 5% line indicates the voltage below which only the worst 5% of the offset cases fell for the particular track segment: 95% of the offsets will result in higher minimum voltages in that track segment. The 50% line indicates the median minimum voltage in a given track segment in normal rush hour operation.

In case NDS—catch-up operations following a 15-minute delay at the Oakland Wye—westbound trains are traveling through the transbay tube at crush headways of 1:30 minutes, and eastbound trains are at headways of 2:15 minutes. The cumulative probability of a given minimum voltage for the offsets in this scenario is shown in Figure 3-2, and differs from Figure 3-1. In case NDS, the system is more heavily loaded than in case NNS by virtue of the crush headways in the westbound traffic, and one sees the effect of the heavier system loading in the generally lower voltages observed.

An insight can be gained from examination of these graphs relating to the plausible set point for a SMES device at MCG. Let us look at the eastern half of the tube, which is the track segment between KTE and eol - kow = track segment from Oakland Wye to Oakland West

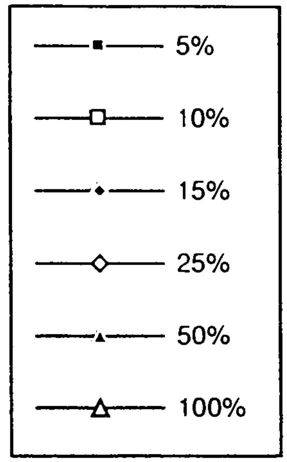
kow - kte2 = track segment from Oakland Wye to Baytube East

kte2 - mcg = track segment from Baytube East to center of tube

mcg - mtw = track segment from center of tube to Baytube West

mtw - mps = track segment from Baytube West to Powell Street

mps - mss = track segment from Powell Street to Sixteenth Street



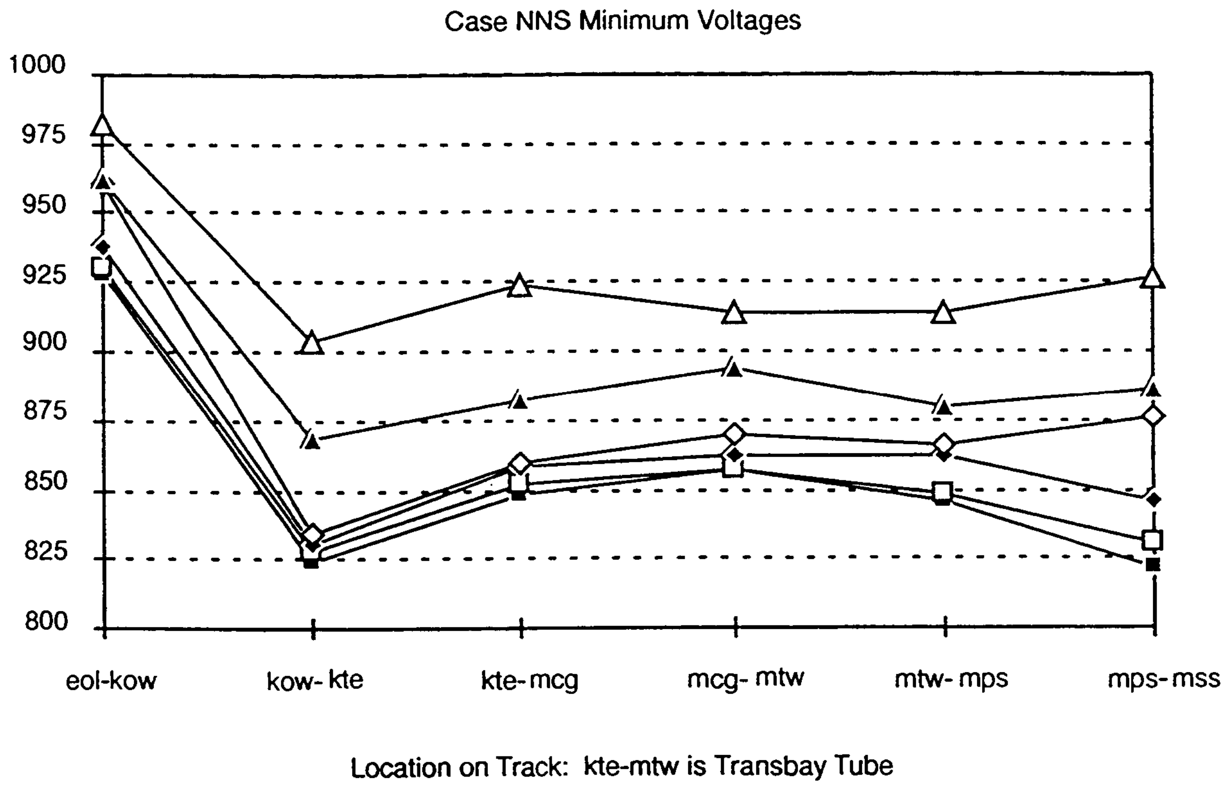


Figure 3-1. Statistical distribution of minimum voltages for case NNS.

eol - kow = track segment from Oakland Wye to Oakland West

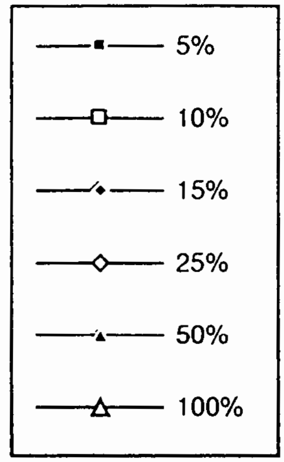
kow - kte2 = track segment from Oakland Wye to Baytube East

kte2 - mcg = track segment from Baytube East to center of tube

mcg - mtw = track segment from center of tube to Baytube West

mtw - mps = track segment from Baytube West to Powell Street

mps - mss = track segment from Powell Street to Sixteenth Street



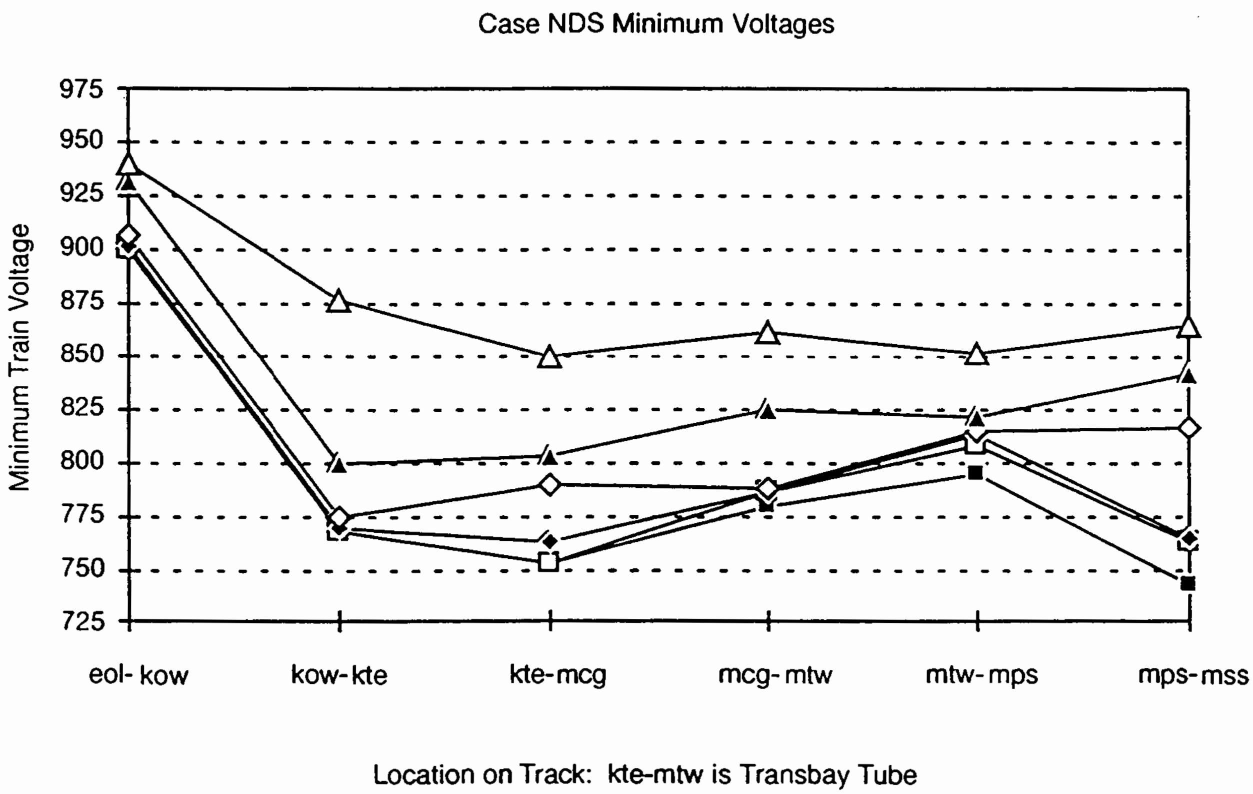


Figure 3-2. Cumulative probability of minimum voltage for case NDS (catch-up operations following a 15-minute delay at the Oakland Wye).

MCG. Assume installation of a SMES unit at MCG, and a set point of 860 V for SMES discharge. If one-fourth of the trains during normal rush hour operation experience a voltage below 860 V somewhere in the eastern half of the tube, then the SMES unit would discharge for one-fourth or fewer of the passing trains. The low-voltage location may be distant from MCG by several thousand feet, and MCG may experience a less severe voltage sag than the lowest point, so the SMES unit might not discharge even though the segment-minimum voltage dropped below the set point. The statistical graphs thus provide information which will assist in setting a storage device at a voltage high enough to maintain minimum track voltages above 750 V, while limiting the number of discharge cycles. Many more simulations would be required to fully quantify this insight. The same is true for a battery storage system. This has implications for battery lifetime and perhaps for SMES refrigeration needs (since AC losses generate heat within the cryostat).

Another point which is evident from these graphs is that the spread of voltages in a given scenario varies by nearly a factor of 2 from one track segment to another. In case NDS, compare the V(100%) - V(5%) values for the segments KOW-KTE and for MTW-MPS: the former is 115 V, while the latter is 63 V. In addition, the weakest point of the system appears to vary from one scenario to another because different operational scenarios load the system non-uniformly.

The effect of a decreased supply voltage from PG&E is modeled in cases NDS-A, NDS-B, and ND1-B. For a 1% drop in supply voltage, there is roughly a 2% drop in track voltage. In these small incremental changes of supply voltage, the minimum track voltage seems to consistently experience double the percent change of the supply. A monitoring program to quantify the relationship between voltage sag events at MCG and parameters of the AC supply system is described in Section 10.

Scenarios With a Train Accelerating From a 6-Minute Stop in the Tube

This final set of scenarios is built upon the case of a train stopped at MCG for 6 minutes. In the case where a train stops near the middle of the transbay tube, the simulation predicts a dramatic voltage sag below the motor cutoff voltage. Records in BART's central computer logs verify that such stops do occur. In Table 3-1, voltages far below 750 V are indicated for a scenario with a 6-minute stop near mid-tube. In actual train operation, of course, the voltage never drops below 750 V: In a small range of voltages near 750 V, the motors cut out and cease to draw current. In contrast, the computer simulation allows the trains to continue to draw the necessary power even at severely reduced voltages. Thus in the simulation results, the depth of voltage sag below 750 V, and its duration, provide an indication of the amount of current which would have to be injected into the rails by a storage device to maintain the voltage at the specified minimum value. In fact, the problem posed to the system by scenario S10 was so severe that it exceeded the computer model's zone of stability, and the run was terminated.

Subsequent to finding a scenario which displayed a voltage sag below 750 V, the TELS 3.0 model was modified to have a constant voltage node at the site of the gap breaker station in the center of the transbay tube. This was intended to represent a SMES device, which can inject current at constant voltage. The model was run again with the same scenario, and the amount of current injected during a sag event was determined. This quantified the amount of energy which a storage device at the gap breaker station would have to inject into the third rail to maintain the voltage above the set point at that location. When a storage device is present to inject current at MCG, then the location where the train experiences its minimum voltage will be some distance from MCG. Therefore, an actual device located at MCG would need to inject current at some voltage higher than 750 V. PBMQD ran cases for three voltage set points: 775 V, 800 V, and 850 V. These cases are designated S11, S12, and S13, respectively.

It is evident that the minimum track voltage was much lower than the voltage at MCG, where the SMES unit clamped track voltage at the specified set point (Table 3-2). The minimum voltage in this scenario occurred in the track segment between MCG and KTE, that is, in the eastern half of the tube.

Table 3-2

System Low-Voltage Log, BART Transbay Tube

Intersubstation Zone Boundaries				Minimum	Time of
From	**Feet**	**To**	**Feet**	**Voltage**	**Occurrence**
EOL	0	KOW	850	960.8	07:12:46
KOW	850	KTE1	10,175	791.8	07:10:42
KTE2	10,176	MCG	19,740	690.8	07:11:48
MCG	19,740	MTW1	29,390	731.1	07:12:35
MTW2	29,391	MPS	35,815	826.5	07:19:49
MPS	35,815	MSS	43,615	822.5	07:24:09

In the scenarios of this series (S10, S11, S12, and S13), one train stops near MCG for 6 minutes, during operations at 2:30 minutes headway. Two additional trains stack up, halted behind it at positions separated by about 1,000 feet. These second and third trains are halted for just under 4 and 2 minutes, respectively, as they await the signal that the track ahead is clear for a sufficient distance for them to accelerate.[2]

The system is competent to support the load of the first and second trains pulling out while the third is still at a halt, but when the third train accelerates, a series of transient overloads occurs. At that time, the power draw on the system is so severe that three trains—the second, third, and fourth—all experience voltages below the motor cutout voltage. The momentary status of the trains on the system at the time of overload is displayed in Figure 3-3, and a schematic of the train positions is shown in Figure 3-4. The positions of the rectifier substations and gap breaker station are shown in Table 3-3.

Table 3-3

Track Positions of the Rectifier Substations and Gap Breaker Station

Station	Position (feet)
KOW	850
KTE1	10,175
KTE2	10,176
MCG	19,740
MTW1	29,390
MTW2	29,391
MPS	35,815
MSS	43,615

[2]Under the current BART control system, the trains accelerate sharply when they start up. BART engineers refer informally to this as a "teenage driver" control scheme. It would be desirable if trains could accelerate at a more gradual rate when the system is heavily loaded. The present day control system does not automatically adjust acceleration rate based on system loading. Such an option may be introduced in the future, and could mitigate the brief transient overloads which presently occur when a heavily loaded train accelerates sharply as other trains also draw on the same rectifier substations.

TRAINS MOMENTARY STATUS AT 07:11:48 BART TRANSBAY TUBE

TRAIN No.	SERVICE ROUTE	LINE SYMBOL	GRADE (%)	LOCATION (ft)	SPEED (mph)	ACCEL (mphps)	No. CARS	TRAIN CURRENT	TRAIN VOLTAGE	VOLT DEVIATION % OF CAR NOMINAL
201	2	M	0.0	1201	33.0	0.00	10	1030	939.6	-6.0
109	1	M	0.1	8663	67.0	0.00	10	1917	889.0	-11.1
202	2	M	0.3	13941	67.0	0.00	10	3037	781.1	-21.9
107	1	M	-0.3	16389	25.5	3.00	10	11130	690.8	-30.9
105	1	M	-2.0	19445	45.5	2.02	10	10852	748.3	-25.2
103	1	M	0.3	23817	56.5	0.90	10	8977	739.3	-26.1
204	2	M	-1.3	28673	64.6	1.14	10	8015	883.3	-11.7
112	1	M	1.3	28852	47.0	0.00	10	2654	898.7	-10.1
206	2	M	-1.0	33139	0.0	0.00	10	353	972.9	-2.7
208	2	M	-0.7	37615	33.0	0.00	10	351	999.7	-0.0
210	2	M	-0.3	43764	35.8	2.19	10	8165	973.8	-2.6

Figure 3-3. Momentary status of BART system trains at the time of overload (case S11).

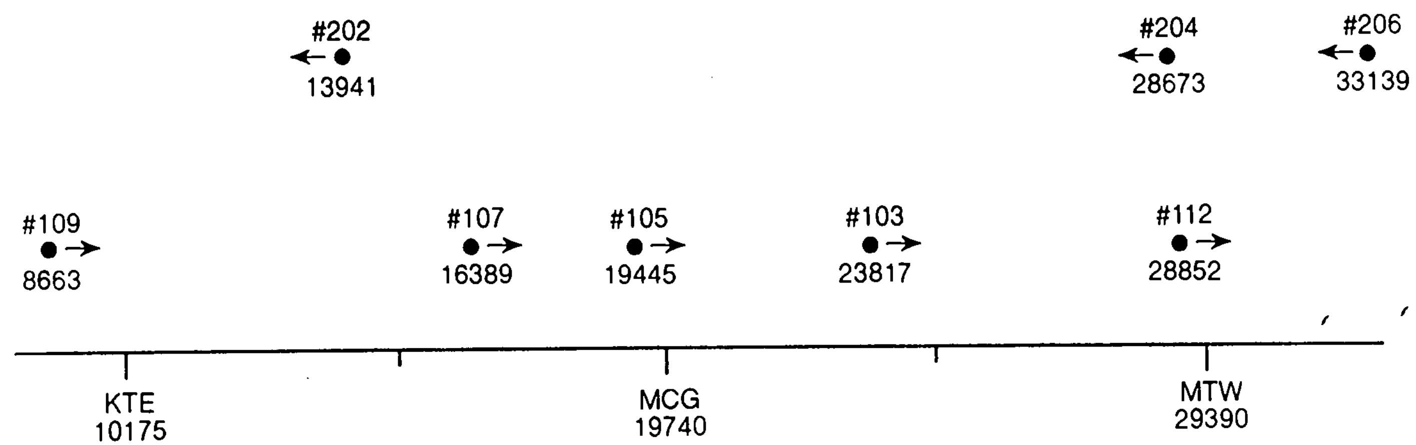


Figure 3-4. Train positions at the time of system collapse (case S11).

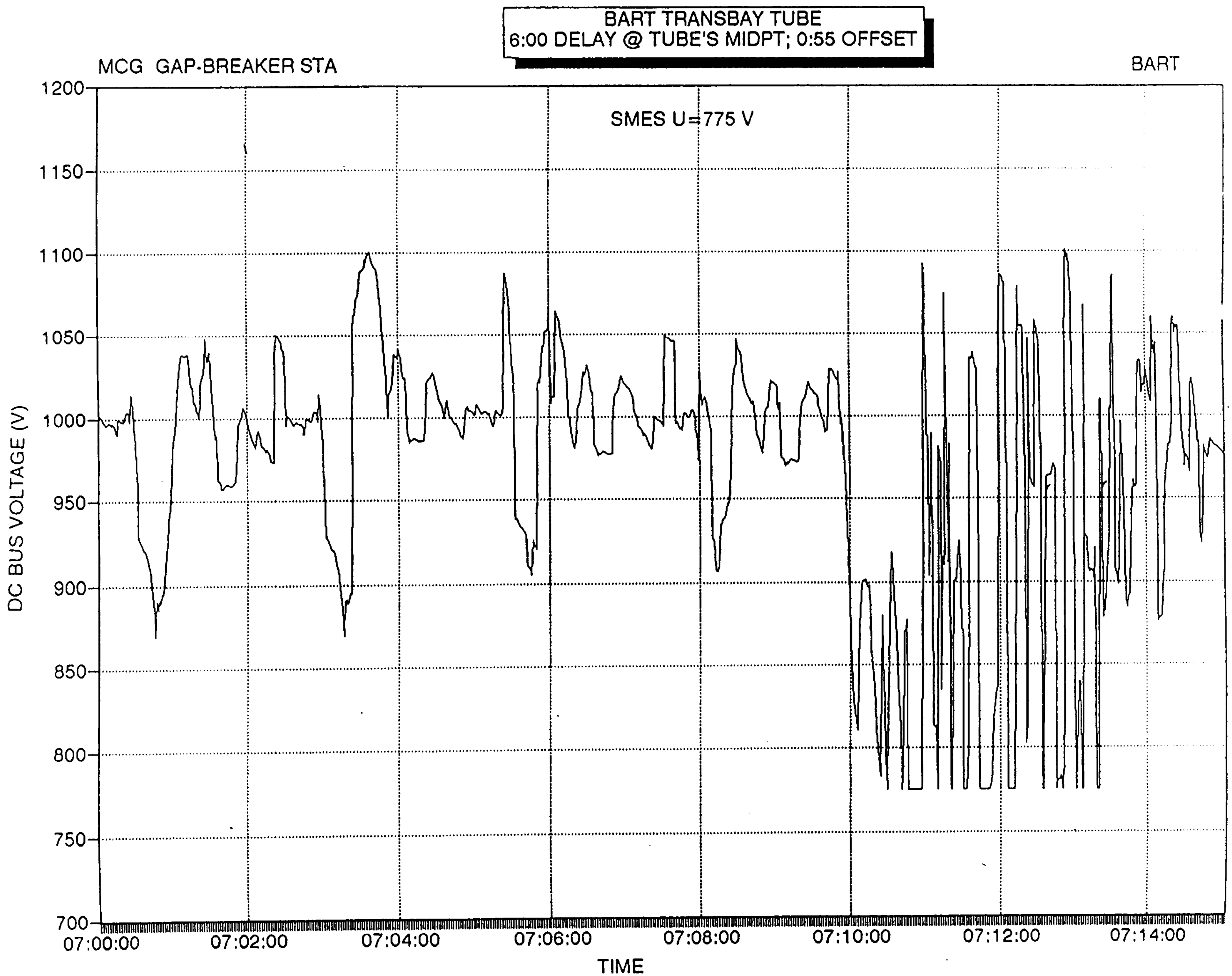
From Figures 3-3 and 3-4, one can see that the load on the system includes trains very near to KTE and MTW (the rectifier substations at the ends of the tube), as well as a train near MCG, and an additional train about 3,700 feet to either side of MCG. These five trains are moving westbound toward San Francisco from Oakland. In addition to these trains, two eastbound trains are within the tunnel: one is roughly halfway from MCG to KTE, and the second has just entered the tube from San Francisco.

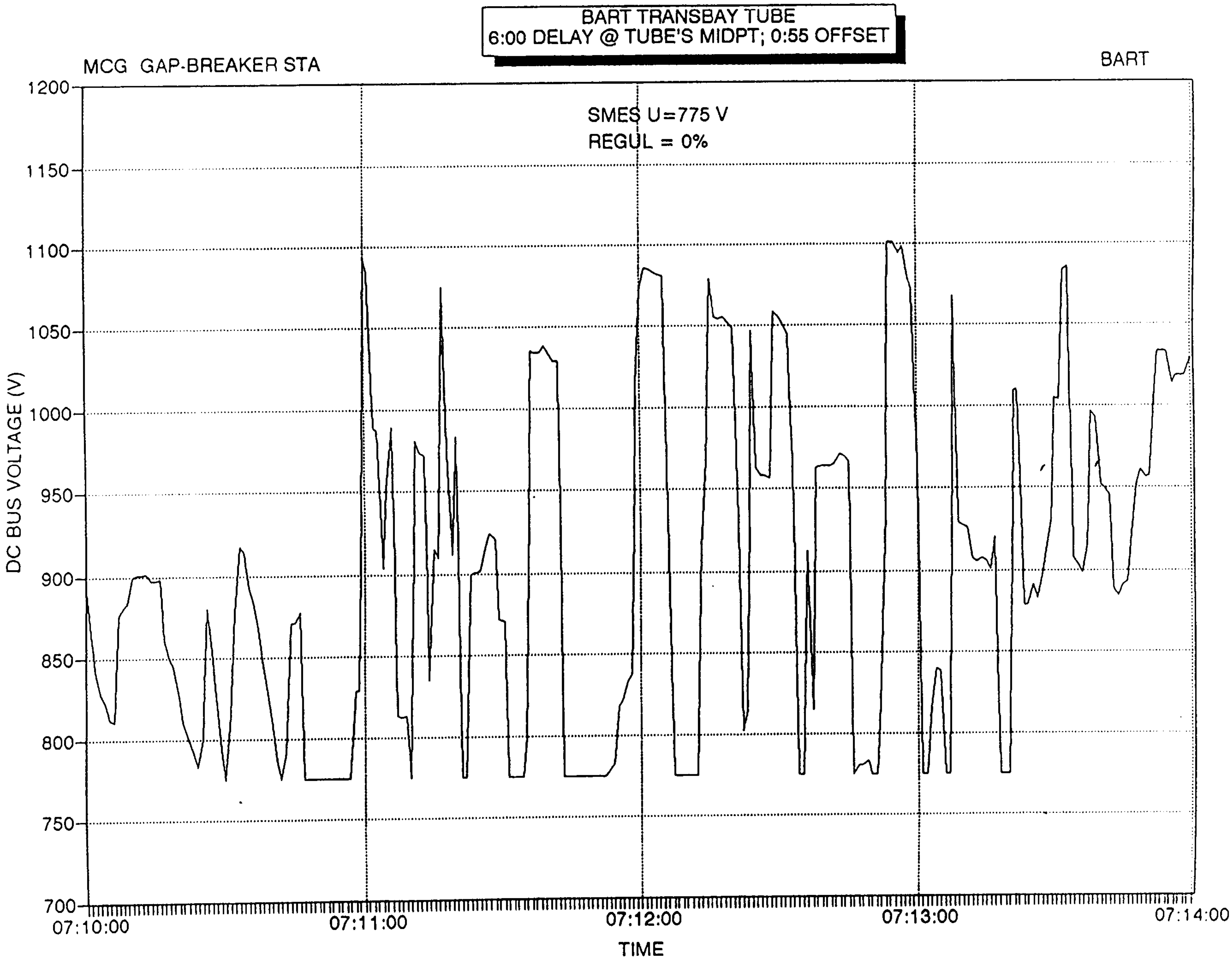
The momentary loading of the two rectifier transformers at MTW at time 07:11:48 averaged 161% of nominal rated power, while the momentary loading of the two rectifier transformers at KTE at that time averaged 106% of rated full load. It is not the overloading of the rectifier transformers alone which is responsible, however, for the transient voltage sag phenomenon, but the concentration of trains at great distances from the supply points at KTE and MTW, and the resulting large voltage drop in the rails.

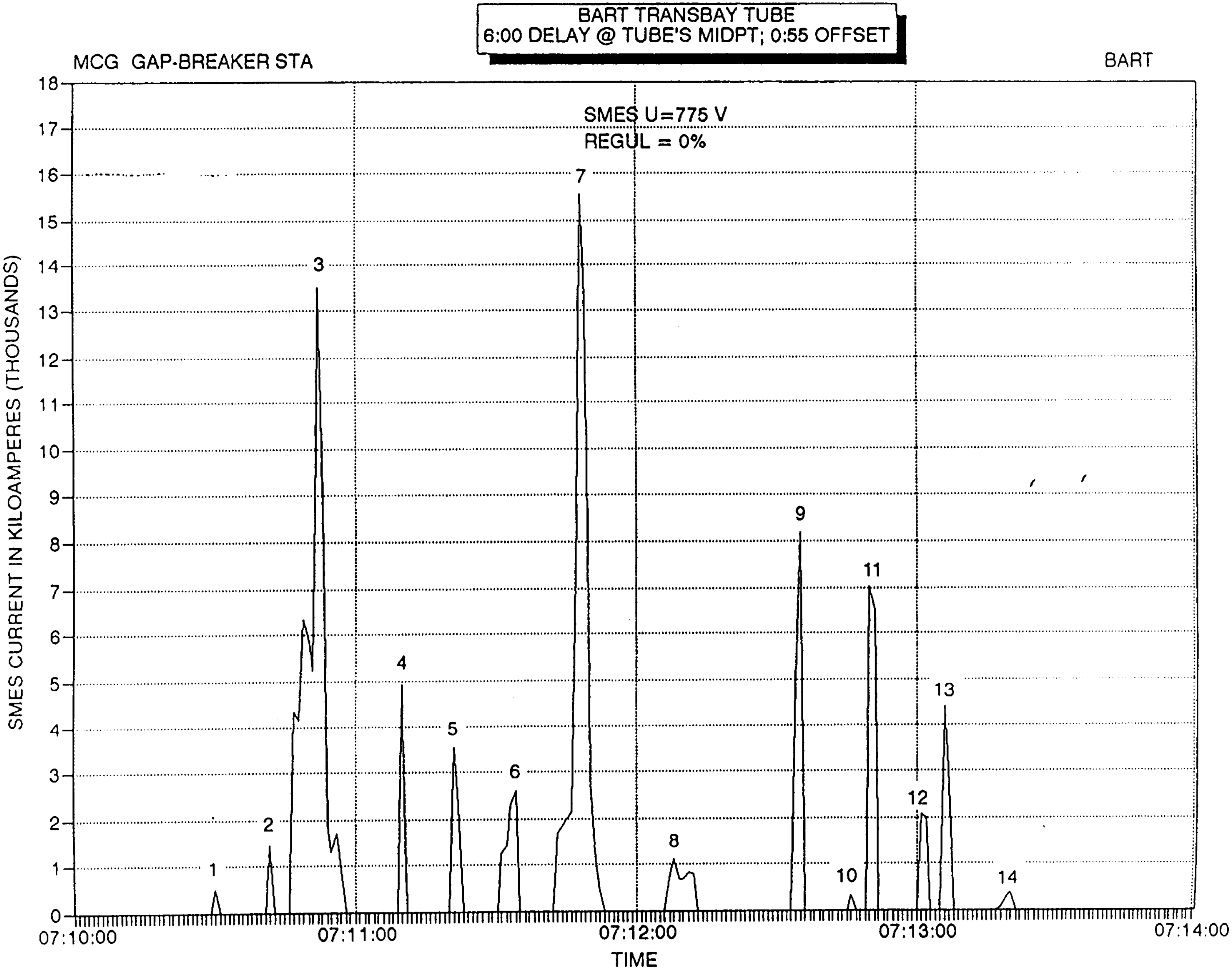
What happens as the third train accelerates from a halt is quite complex, and results in a system crisis which lasts for several minutes and has several severe voltage sags which last up to 11 seconds apiece. In such an operational event, the loads of each individual car's motors would rapidly switch in and out, the track voltage would fluctuate rapidly above and below 750 V at a given car, and train motion would be unpredictable and jerky for the duration of the crisis.

Because of the severity of the system loading, the TELS 3.0 computer simulator was unable to complete the run of scenario S10 (no SMES unit). With installation of a constant voltage node at MCG to represent the SMES unit, the model was able to complete a run. The DC bus voltage at MCG as a function of time for case S11 appears in Figure 3-5. This covers the first 15 minutes of that simulation. (Voltages at MCG from 07:15 to 07:29 resemble those prior to 07:06 and are not shown here.) The overload crisis is evident beginning just after 07:10, and appears in expanded form in Figure 3-6. Of course, the reason for the flat-bottomed profiles is that the model was instructed to hold the voltage at MCG at or above the SMES set point.

Similarly to the manner in which TELS 3.0 calculates rectifier station loading, the simulator calculated the total current required at each second to maintain the DC bus voltage at MCG above the set point of the SMES. A plot of SMES current as a function of time during the crisis in case S11 appears in Figure 3-7. During a span of 3 minutes, there are 14 peaks where the SMES unit supplies current to the


BART TRANSBAY TUBE
6:00 DELAY @ TUBE'S MIDPT; 0:55 OFFSET
MCG GAP-BREAKER STA
BART
SMES U=775 V
DC BUS VOLTAGE (V)
1200
1150
1100
1050
1000
950
900
850
800
750
700
07:00:00
07:02:00
07:04:00
07:06:00
07:08:00
07:10:00
07:12:00
07:14:00
TIME


BART TRANSBAY TUBE
6:00 DELAY @ TUBE'S MIDPT; 0:55 OFFSET
MCG GAP-BREAKER STA
BART
SMES U=775 V
REGUL = 0%
DC BUS VOLTAGE (V)
1200
1150
1100
1050
1000
950
900
850
800
750
700
07:10:00
07:11:00
07:12:00
07:13:00
07:14:00
TIME


BART TRANSBAY TUBE
6:00 DELAY @ TUBE'S MIDPT; 0:55 OFFSET
MCG GAP-BREAKER STA
BART
SMES U=775 V
REGUL = 0%
SMES CURRENT IN KILOAMPERES (THOUSANDS)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
07:10:00
07:11:00
07:12:00
07:13:00
07:14:00
TIME
1
2
3
4
5
6
7
8
9
10
11
12
13
14

rail. These peaks range from a fraction of a kiloamp at a duration of a second, to nearly 16 kA with a duration of 11 seconds. In case S12, where the SMES support point is set at 800 V, the peaks are slightly higher, rising to a current above 17 kA in one case. For the duration of the crisis, the total energy out of the SMES for case S11 is 147 MJ, and it is 207 MJ for case S12.

In an effort to stay within the budget constraints of the simulations task, PG&E decided to assume that this scenario provided us with a plausible distribution of events which could individually represent single voltage sags on the system. Furthermore, a decision was made that in some overload crises, there could be multiple peaks. These are major assumptions. However, it was the judgment of the project team, including BART technical personnel, that we were not specifying a mitigation technology which would handle a crisis as severe as the one which this scenario posed for the system. The next section describes how we used these results and assumptions to arrive at a specification for a SMES device.

TRADE-OFFS

To systematize the data provided by the graph of SMES current versus time during this overload event (case S11), we numbered the peaks sequentially in time, recorded the total duration and peak current of each peak, and graphically integrated their areas. This basic information appears in Table 3-4. These data were sorted by duration of sag, energy per peak, and peak current. Bar graphs depicting the frequency of these quantities were then plotted (Figures 3-8, 3-9, and 3-10). Even in an overload situation of this magnitude, the severe voltage sag events are very transient in nature. Of 14 peaks, 10 last 3 seconds or less, and all are less than 11 seconds in length; 10 peaks likewise are of 5 kA or lower current and 6 MJ or lower energy. These sharp transients appear to be attributable to the abrupt onset of the acceleration of the BART cars.

It would have been desirable at this point to probe further in scenario space for cases where a single voltage sag occurred, and even to run a large enough set of cases to get a more definitive picture of the statistical rates of occurrence of these phenomena, but project budget constraints precluded that course of action. The team decided instead to rely upon the accumulated experience of BART personnel indicating that single spike events do occur with appreciable frequency, and to make the assumption that such events assort roughly as the individual spikes of our overload event in case S11. PG&E further assumed that if there were a significant system backup, sags could occur at roughly the frequency of oncoming trains.

Table 3-4

Analysis of Peaks in SMES Support Episode (Case S11)

Peak No.	Duration (seconds)	Energy (MJ)	Current (kA)
1	1	0.4	0.40
2	1	1.1	1.45
3	11	35.9	13.50
4	1	3.9	5.00
5	3	4.6	3.60
6	5	5.9	2.60
7	10	37.9	15.70
8	6	3.8	1.15
9	2	10.4	8.25
10	1	0.2	0.35
11	2	10.5	7.00
12	2	3.2	2.10
13	2	5.7	4.40
14	3	0.6	0.40

Notes:

1. Case S11 = with SMES device
2. Analysis of peaks in 4-minute SMES episode

Peak#	Duration (seconds)	Energy, MJ	Current, kA
1	1	0.4	0.40
2	1	1.1	1.45
4	1	3.9	5.00
10	1	0.2	0.35
9	2	10.4	8.25
11	2	10.5	7.00
12	2	3.2	2.10
13	2	5.7	4.40
5	3	4.6	3.60
14	3	0.6	0.40
6	5	5.9	2.60
8	6	3.8	1.15
7	10	37.9	15.70
3	11	35.9	13.50

Note: Analysis of peaks in 4-minute SMES episode.

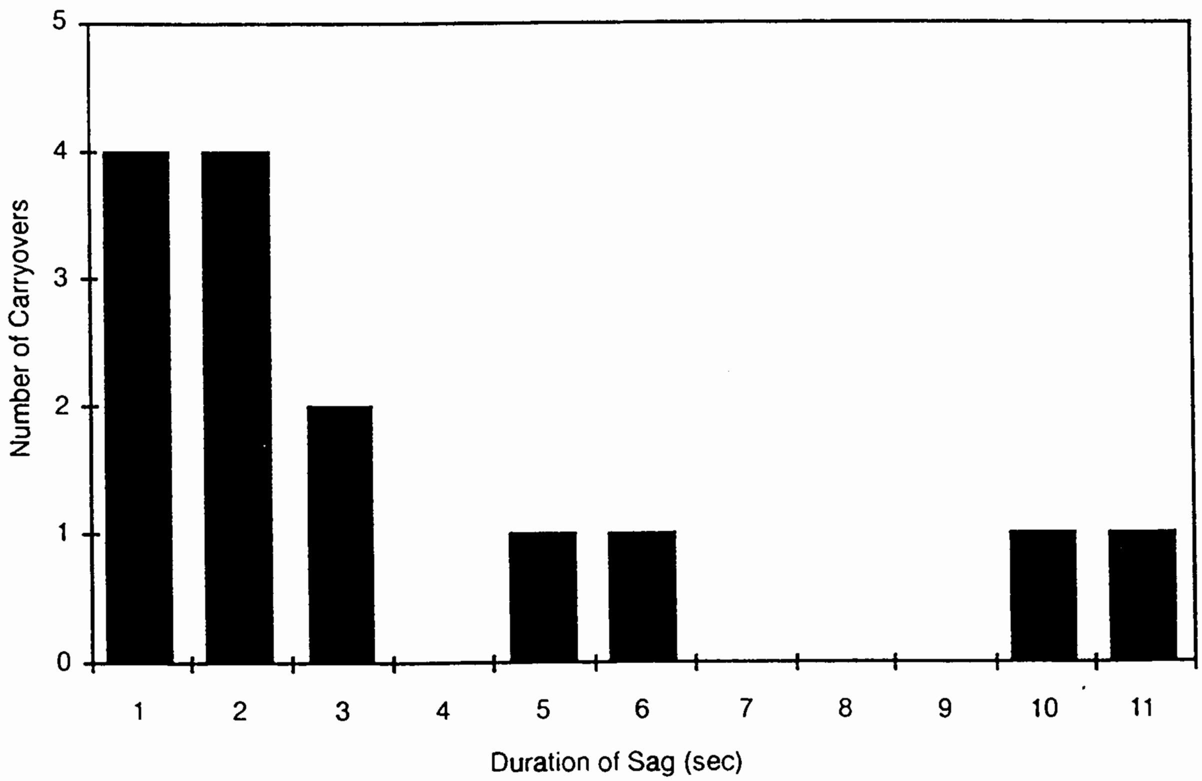


Figure 3-8. Support peaks sorted by duration of sag (case S11, with SMES device).

Peak#	Duration (seconds)	Energy, MJ	Current, kA
10	1	0.2	0.35
1	1	0.4	0.40
14	3	0.6	0.40
2	1	1.1	1.45
12	2	3.2	2.10
8	6	3.8	1.15
4	1	3.9	5.00
5	3	4.6	3.60
13	2	5.7	4.40
6	5	5.9	2.60
9	2	10.4	8.25
11	2	10.5	7.00
3	11	35.9	13.50
7	10	37.9	15.70

Notes: Analysis of peaks in 4-minute SMES episode.

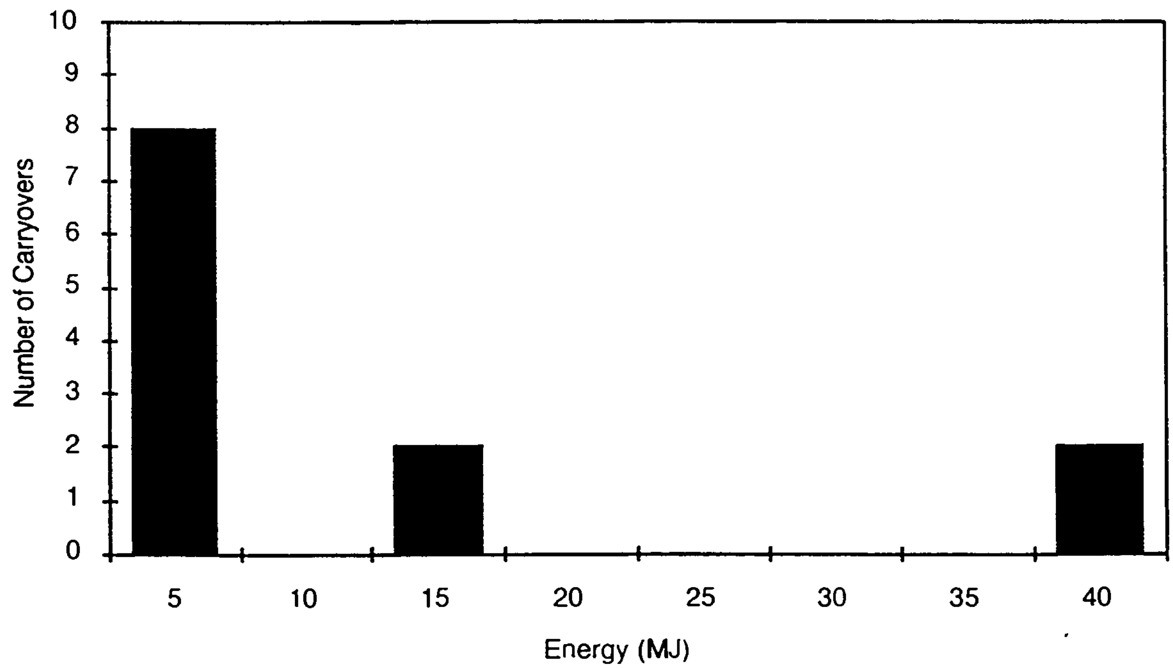


Figure 3-9. Support peaks sorted by energy per peak (case S11, with SMES device).

Peak#	Duration (seconds)	Energy, MJ	Current, kA
10	1	0.2	0.35
1	1	0.4	0.40
14	3	0.6	0.40
8	6	3.8	1.15
2	1	1.1	1.45
12	2	3.2	2.10
6	5	5.9	2.60
5	3	4.6	3.60
13	2	5.7	4.40
4	1	3.9	5.00
11	2	10.5	7.00
9	2	10.4	8.25
3	11	35.9	13.50
7	10	37.9	15.70

Notes: Analysis of peaks in 4-minute SMES episode.

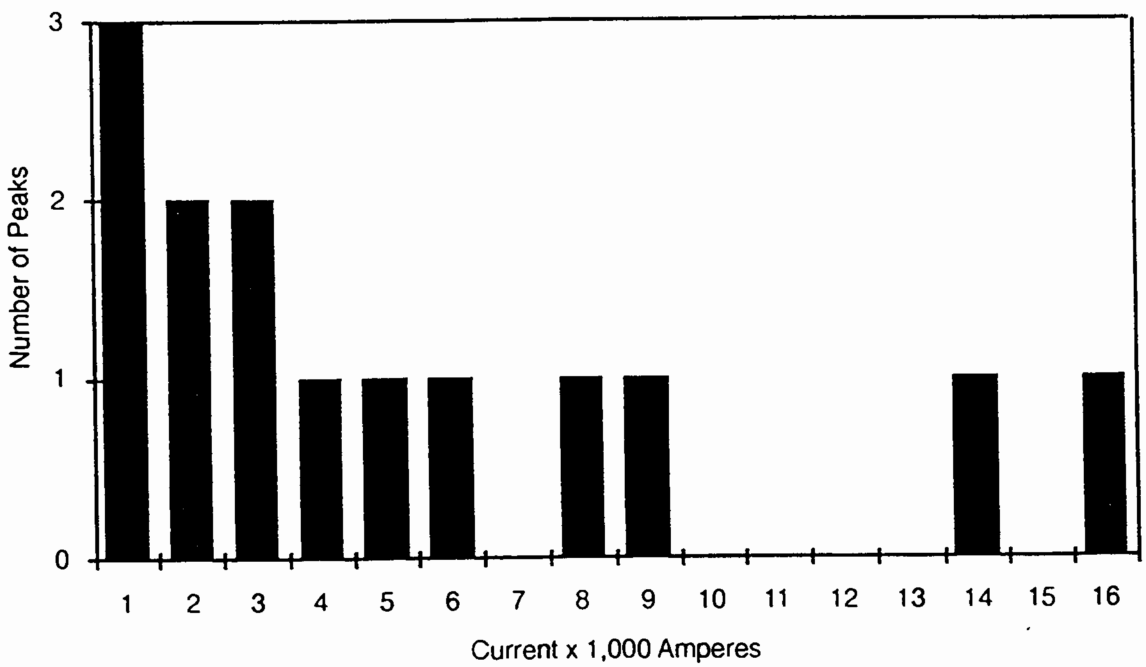


Figure 3-10. Support peaks sorted by peak current value (case S11, with SMES device).

With crush headways of 90 seconds, this would give a minimum interval between sags of 90 seconds. BART personnel specified that to meet BART criteria of usefulness, the device should be able to cover events as large as 8 MJ, which would include 10 out of 14 of the peaks which appeared in simulation case S11.

Thus, the final specification of an 8-MJ device, capable of delivering a peak current of 4,000 amps in a triangular pulse of 5 seconds, was set to include the majority of the spikes in crisis case S11. The repetition rate and life cycle were set to include one "bad rush hour" per week, and seven transient sag events during that overload condition.

There is an additional difficulty. With the SMES support voltage set at 775 V or 800 V, in a scenario as severe as case S11 and with a single SMES unit at MCG, there will still be positions on the track where a train could experience a voltage below the motor cutout of 750 V. For the present, PG&E assumes that in most cases of only moderate system overload, as opposed to case S11, voltage sags below 750 V will occur close enough to the gap breaker station so that the drop in the track voltage between MCG and the train is less than the difference between the SMES set voltage and the motor cutout voltage. Substantial numbers of additional scenarios to quantify and verify this assumption would need to be run to determine the statistics of location and severity of sag, as well as the degree to which the SMES unit supported each. This extensive simulation effort is not within the scope of this study.

It is important to note here that our voltage monitoring data reveal no sags at MCG below 750 V in a period of 4 months. This leaves open several possibilities:

1. The tie breaker location, MCG, where we monitored DC rail voltage, may be slightly stiffer than locations a few thousand feet away.
2. Motor cutout may occur at a broader range of voltages than car specifications indicate.
3. Present day system loading is less severe than in case S11.

Notwithstanding the fact that our test trains stopped only momentarily, and only at the onset of morning rush hour, rather than for 6 minutes and at the height of the traffic peak as in S11, the discrepancy between our expectations and the monitoring results is dramatic.

It appears to be of substantial importance for BART to institute a program of long-term voltage monitoring at locations where simulations indicate the likelihood of voltage sag problems. Measured confirmation of simulations results should precede investment of funds for mitigation.

Section 4
FUNCTIONAL SPECIFICATION

This section describes the highlights of the functional specification which arose in part from the trade-offs discussed in Section 3 and in part from system-related information garnered from BATC (Bay Area Transit Consultants) and other Bechtel sources.

A functional specification was written which embodied the system constraints and requirements outlined in Section 3. It was sent to prospective SMES vendors in a software response format which ensured that responses would be comparable to the maximum extent feasible. The specification also served as the document to which Bechtel designed the battery system options and the non-storage solution. The complete functional specification is in Appendix A. The most notable electrical features of the functional specification are the energy, power, and pulse characteristics, and the frequency of sag events. These parameters are listed in Table 4-1.

Table 4-1

Functional Specification Parameters

Parameter	Value
Available Energy	8 MJ
Maximum Current	4,000 amps
Delivery Voltage	Adjustable from 775 V to 825 V
Pulse Duration	5 seconds
Pulse Shape	Triangular
Pulse Repetition	7 pulses, with 90 seconds between pulses, maximum one such series per day, and maximum 350 pulses per year

The power and energy, controls and monitoring, and most of the electrical requirements of the functional specification apply equally in the transbay tube and in an unconstrained location on the BART system; BART believes that there are other locations on the system which experience voltage sags. However, stringent requirements of size, shape, and auxiliary power load are unique to the tube location. In particular, the doorway through which the device would be installed in the tube gallery is 79 inches high by 42 inches wide, and the gallery width is 8 feet, of which 4 feet must be left free for passage of maintenance personnel and equipment. The allowable auxiliary power draw on the 4,160-V, 3-phase line in the transbay tube gallery is 15 kVA, and the device is disconnected automatically in the emergency situation where ventilation fans are fed from one side of the tube only. Higher power needs may be supported from several more costly options: (1) by a cable run to the 34.5-kV AC distribution line at the ends of the tube, (2) by a cable run to the PG&E 12.47-kV AC distribution line at the Baytube West structure (loads less than 1 MW only), or (3) by drawing power directly from the BART DC third rail.

Section 5

SMES ALTERNATIVES

The three SMES designs which were submitted in January 1993 in response to PG&E's Request for Information (RFI) varied widely not only in cost, but also in technology employed and the degree to which they met certain requirements of the functional specification. Thus, it is particularly important to exercise caution in making direct comparisons of price between vendors because the prices represent rather different units.

The basic areas of difference in technology which strongly influence price are, first, modular vs. single unit; second, toroidal vs. solenoidal; third, shielded vs. unshielded; and fourth, adherence to auxiliary power restriction in transbay tube area vs. increased power draw. In each case, the first of the two choices leads to a higher-cost installation, but may have benefits which the second alternative lacks.

Conceptual designs were provided by Pitt-Des Moines (PDM), Westinghouse, and Superconductivity, Inc. (SI). While PDM submitted a single design for both the tube and unconstrained locations, SI and Westinghouse submitted separate designs for the two sites. SI and PDM based their designs on solenoidal coils, whereas Westinghouse used a toroidal configuration. The PDM and Westinghouse designs would require more auxiliary power than specified in the RFI; SI proposes taking the refrigeration power from the third rail, and thus meets the specification for auxiliary power from the 4,160-V line. The SI and Westinghouse designs will have lower external fields than the PDM design; for Westinghouse, because of the toroidal configuration, and for SI, because of external shielding used in the tube location. Modularity differs among the designs: in the transbay tube location, both Westinghouse and SI use multiple coils, whereas PDM uses a single coil. In the unconstrained location, Westinghouse reverts to a single coil as more economical. There appears to be a large cost penalty for modularity, yet it could have the benefit of reliability enhancement if coils are connected in parallel as in the SI design.

In this section, we summarize the most salient features of each of the SMES designs, and then compare them in Section 6. Detailed design information for PDM and Westinghouse is in Appendices B and C. The entire text of the subcontracted design from SI appears in Appendix D.

SUPERCONDUCTIVITY, INC.

SI manufactures and sells megajoule-class SMES units for the industrial power quality market. SI was instrumental in initiating the BART-PG&E collaboration on this project. SI chose to use its standard equipment to the maximum extent feasible in its response to the RFI, but redesigned the refrigeration system to allow it to run from the third rail rather than from the 4,160-V line. In this way, SI was able to stay within the meager 15-kVA auxiliary power specification.

Overall System Design

In the transbay tube location, the SI design fits within the specified footprint (50 feet by 4 feet). In an unconstrained location, SI would mount the components in a 50-foot container with a 10-foot width. SI proposes a system of four identical magnets, each in its own cryostat, and each equipped with its own refrigeration system. The four magnets would be connected in parallel to the tracks. For the unconstrained site, SI employs its standard voltage regulators to connect each magnet to the tracks, and charges the magnets from an auxiliary AC line. For the transbay tube, SI proposes combining voltage regulator and magnet charger functions into a two-quadrant chopper for each magnet, so that the magnets can be charged directly from the tracks. DC motors powered from the tracks are used for the refrigerators in the transbay tube, so that the AC auxiliary power is reserved for the control system. The overall SI system design is summarized in Table 5-1.

Table 5-1

Overall SI System Design

Overall System Design	Transbay Tube Site (4 Solenoids)	Unconstrained Site (4 Solenoids)
Net Effective Stored Energy	8 MJ	8 MJ
Peak Discharge Power Rating	3.2 MW	3.2 MW
Recovery Period Between Cycles	Less than 90 seconds	Less than 90 seconds
System Footprint	50' L x 4' W x 8' H	50' L x 10' W x 10' H
System Weight	32,000 lb (system) and 80,000 lb (shielding). Total: 112,000 lb	40,000 lb (no shielding)
Auxiliary Power Requirements	80 kW @ 800 to 1,000 VDC	250 kW @ 480 VAC
Availability for Test Program	18 months after date of order	8 months after date of order

Cryostat and Refrigeration Design

Each cryostat assembly is a vacuum-insulated vessel which contains the superconducting magnet in a bath of liquid helium (Figure 5-1). The 600-liter reserve inventory of helium in the inner vessel allows for 40 to 45 hours of time in which the refrigeration system can be shut down without loss of magnet cooling. The cryostat design also allows manual additions of liquid helium from a portable dewar.

Cost Estimates

SI did not provide a price breakdown for its designs. The system price, in an unconstrained location, is $3.4M, whereas the price of a system in the transbay tube is $5.6M. Neither price includes an allowance for site installation costs. See Table 5-2 for cost estimates.

Table 5-2

SI Cost Estimates

Site	Transbay Tube	Unconstrained Site
Capital Cost Estimate for 1993 Delivery	$5,584K	$3,408K
Indirect Costs (including design, engineering, assembly, transportation, management, fees, contingencies, taxes, insurance, etc.)	Included in price.	Included in price.
Cost per unit, in quantities of 2-5	10% discount	10% discount

Maintenance Costs

System maintenance cost is expected to be approximately $12K per year, including labor but not travel for personnel to perform the work. Electricity cost must be added to this for an operation and maintenance (O&M) total. At $0.06/kWh, the SI unit would consume $35,700/year in electricity in the transbay tube site, and $88,300/year at the unconstrained site.

PITT-DES MOINES

The consortium headed by PDM brings separate areas of expertise to the design. PDM is an engineering construction firm which specializes in field installation of large vacuum and cryogenic systems. PDM serves here as system integrator. CVI, Inc., a wholly owned subsidiary of PDM, is a supplier of helium refrigerators and nitrogen reliquefiers. Advanced Cryo Magnetics, Inc. (ACMI), designs and builds

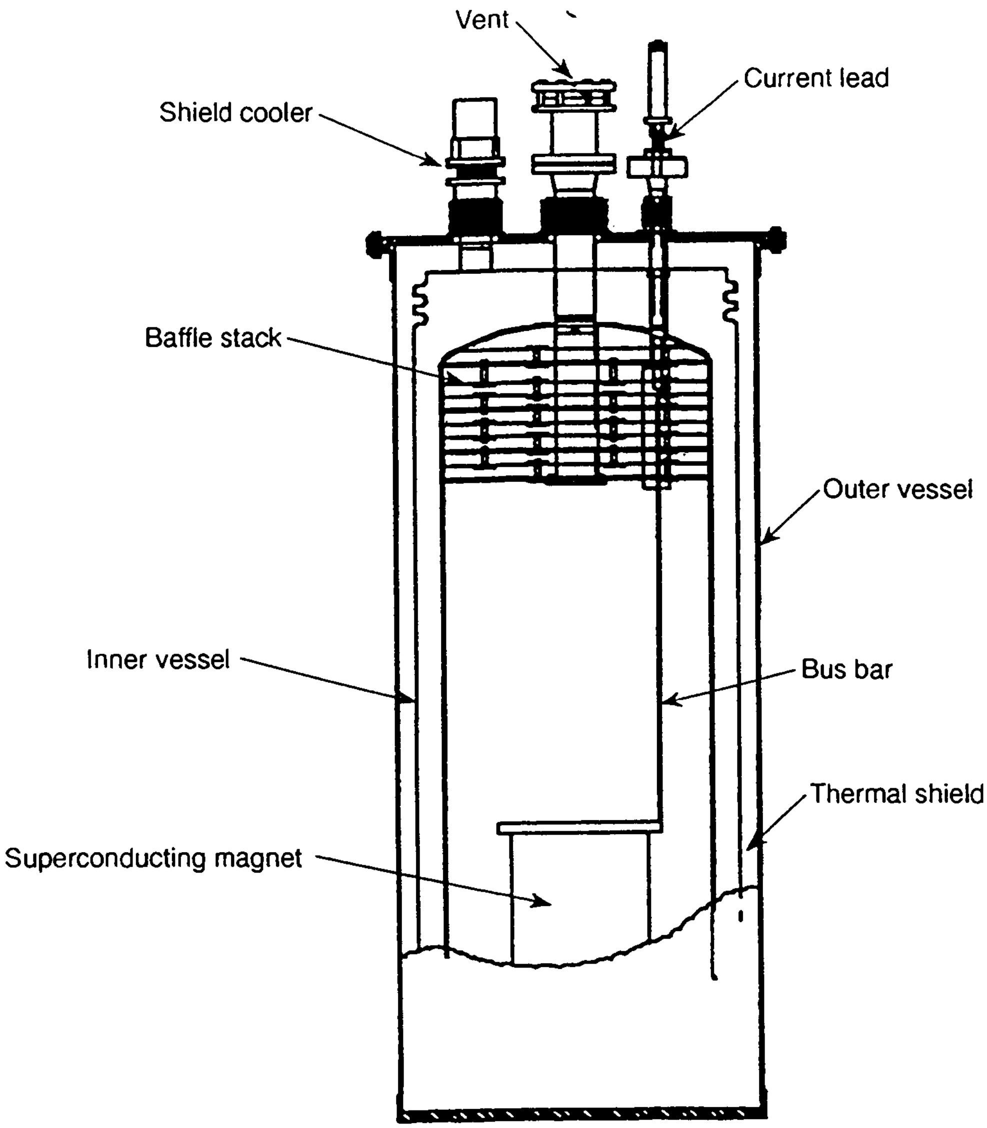


Figure 5-1. SI cryostat.

superconducting magnets and cryostats. General Atomics supplies the power conditioning, control, and monitoring systems, and was prime contractor under Los Alamos National Laboratory (LANL) for the 30-MJ, 10-MW Bonneville SMES unit which was field tested in 1980.

Overall System Design

PDM chose a single large solenoid for the storage element in its design and optimized it to fit through the restrictive access door. The footprint fits within the specified space (50 feet by 4 feet). A single design was submitted by PDM for both the transbay tube and unconstrained locations. PDM elected to design its refrigeration system to run from the 4160-V line in the tube, and in doing so they exceed the 15-kVA limit which BART has assigned for auxiliary power draw from that supply. The PDM design is summarized in Table 5-3.

Table 5-3

Overall PDM System Design

Overall System Design	Transbay Tube and Unconstrained Sites (Single Long Solenoid)
Net Effective Stored Energy	9.65 MJ
Peak Discharge Power Rating	4.7 MW
Recovery Period Between Cycles	6 to 80 seconds
System Footprint	50' L x 4' W x 8' ± H
System Weight	27,000 lb
Auxiliary Power Requirements	41.5 kW (avg.) @ 120/240/480 V
Availability for Test Program	3/94

Refrigeration Design

The PDM refrigeration system is intended for continuous duty at variable capacity. Its electricity consumption has a maximum of 66 kW, with an average value of 41 kW. This exceeds the specification in the tube by a maximum factor of 4.5, and average factor of 2.7. The current leads are proposed to be optimized for low heat leak in standby mode or in operating mode at zero current. (PDM proposes that the unit be charged only when train control foresees its use; otherwise, it should be maintained uncharged to reduce losses.) No gas supply is required for one year.

Power Electronics

PDM would recharge the magnet from the track at any site. It uses a two-quadrant current chopper, which utilizes insulated gate bipolar transistors (IGBTs), and a 250-Hz switching frequency, which will provide acceptable levels of harmonic injection at all BART signaling frequencies.

Cost Estimates

PDM has optimized its system for lowest cost. For 1995 delivery ($1993), PDM provides a budgetary cost estimate of $1.6M, fully installed in either the transbay tube or an unconstrained location. The single solenoidal configuration without shielding minimizes cost, while extracting the penalty of larger fringe fields from the magnet. See Table 5-4 for cost estimates.

Table 5-4

PDM Cost Estimates ($1993)

Delivery Year	1993	1995	1997
Total System Cost, single unit	N/A	$1,620K	$1,580K
Indirect costs (including design, engineering, assembly, transportation, management, fees, contingencies, taxes, insurance, etc.)	N/A	Included in price	Included in price
Cost per unit, in quantities of 2-5		$1,400,000	$1,365,000

N/A = Not applicable

Maintenance Costs

PDM estimates a yearly maintenance cost of $12K, with an operations cost of $36K for electricity based on $0.10/kWh.

WESTINGHOUSE

Overall System Design

Westinghouse submitted a toroidal design to satisfy its perceived need to minimize external DC magnetic fields. Although Westinghouse used a single large toroid in the unconstrained location, which lowered the costs relative to a modular system, space constraints were met in the transbay tube by supplying three smaller toroids connected in series. With the exceptions of the magnets and cryostats, all of the subsystems for the two designs are identical. It is remarkable that the 10-Gauss line for the in-tube design lies less than 2 feet from the wall of the cryostat. At a footprint of 61 feet by 3.83 feet by 6 feet, the in-tube design is slightly narrower and lower, but somewhat longer than specified. This length, however, does not overstep any physical constraint of the gallery. Although Westinghouse predicates its design upon consumption of 110 kW from the 4,160-VAC line, exceeding the specification sevenfold, the company could run its refrigeration from the rails. Cost implications of that alternative are unknown. Westinghouse has previously constructed a cryogenic toroid of this energy storage level. Details of the overall system design are presented in Table 5-5.

Table 5-5

Overall Westinghouse System Design

Overall System Design	Transbay Tube (3 small toroids)	Unconstrained Site (1 large toroid)
Net Effective Stored Energy	9.3 MJ (3 x 3.1 MJ)	9.3 MJ
Peak Discharge Power Rating	3.2 MW	3.2 MW
Recovery Period Between Cycles	90 seconds	90 seconds
System Footprint	61' L x 3.83' W x 6.0' H	27' L x 13' W x 9' H
System Weight	66,640 lb	75,689 lb
Auxiliary Power Requirements	110 kW at 4,160 V	110 kW at 4,160 V
Availability for Test Program	6/94	6/94

Magnet Design

Each magnet is a segmented toroid with 8 series connected segments. Both site designs use niobium titanium (Nb-Ti) cabled conductor. Several novel design features minimize refrigeration load. An illustration of a segmented toroid is shown in Figure 5-2.

Refrigeration Design

Westinghouse has chosen commercially available refrigeration units. A novel feature of the design is the use of BSCCO-2212 high-temperature superconductor lead material to minimize heat leak.

Power Electronics Design

Westinghouse proposes use of a two-quadrant chopper to interface between the SMES units and the BART track using gate-controlled thyristor (GTO) technology. In designs for both sites, magnet recharge energy would be drawn from the third rail.

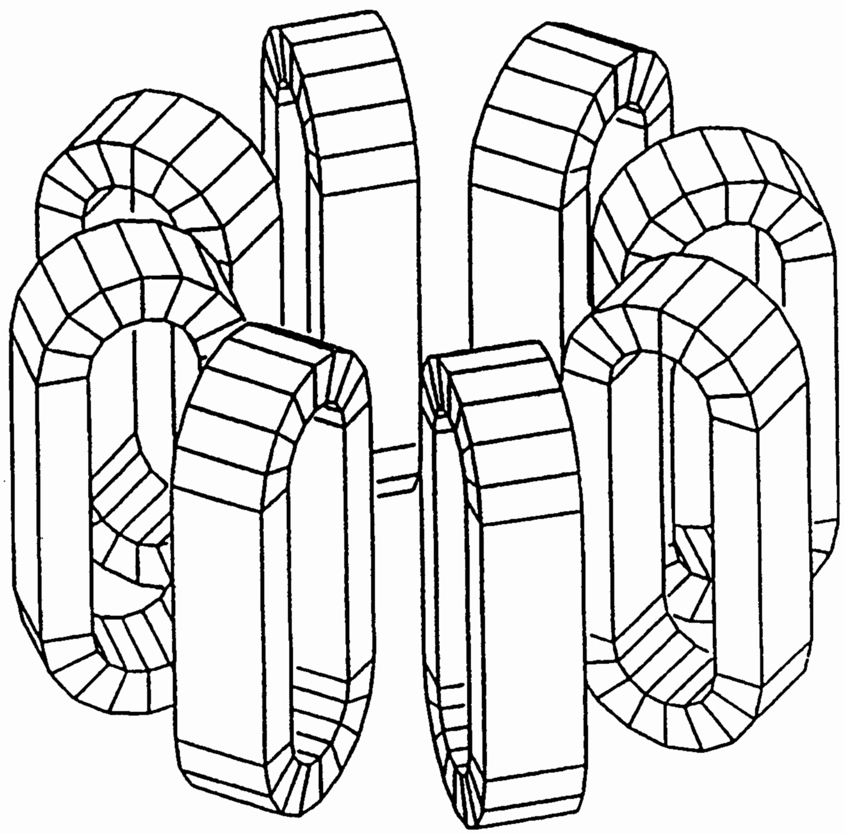


Figure 5-2. Westinghouse segmented toroid.

Cost Estimates

Westinghouse budgetary cost estimates for the transbay tube site and for an unconstrained site are $4.9M and $3.2M, respectively. The $1.7M difference between these costs breaks down into a $0.7M incremental cost for the tri-modular system over the single toroid system, and $1.0M extra in indirect costs (design, engineering, assembly, transportation, management, fees, contingencies, taxes, insurance, etc.) for the modular system compared to the single large toroid. Notable in the Westinghouse cost table is the rapid drop in cost for the system in quantities from 2 to 5. This likely implies that the single-system cost includes an allowance for a large proportion of the one-time engineering costs. The $3.9M and $2.4M costs for later units bring the toroidal system closer to competitive pricing with a large solenoid. (Note: subsequent Westinghouse work at detailing and cost-optimization of the toroidal design indicates that prices much nearer the PDM price are achievable.) See Table 5-6 for site cost estimates.

Table 5-6

Westinghouse Cost Estimates

Site	Transbay Tube	Unconstrained Site
Delivery Date	1993	1993
Total System Cost, Single Unit	$4,870K	$3,179K
Indirect costs (including design, engineering, assembly, transportation, management, fees, contingencies, taxes, insurance, etc.)	$2,380K included in total system cost	$1,364K included in total system cost
Cost per unit, in quantities of 2-5	$3,903K	$2,444K

DC INTERFACE

The DC interface, designed by Bechtel, is common to all of the systems evaluated and forms the connection between the system and the BART DC rail system. The total installed cost of the DC interface subsystem is $304K. Details are presented in Table 5-7.

Table 5-7
Vendor Cost (Bechtel), DC Interface Subsystem ($1993)

QTY BY: ENGINEERING
EST BY: R. H. ALMOGELA
DATE: FEBRUARY 18, 1993

PROJECT DESCRIPTION: TRANSBAY TUBE POWER QUALITY STUDY
CLIENT: BAY AREA RAPID TRANSIT DISTRICT(BART)
LOCATION: SAN FRANCISCO AREA, CALIFORNIA

ITEM	DESCRIPTION	QTY	UNIT MEAS	UNIT COST MTL	UNIT COST MHR	UNIT COST ALLOW	TOTAL MHR	$/MHR	<---- COSTS IN U.S. $ ----> MATERIAL	LABOR	ALLOW	TOTAL COSTS
1	6000A DC main circuit breaker @ MCG	1	ea	27,000	200.00		200	37.12	27,000	7,400		34,400
2	Negative grounding Device	1	ea	35,000	200.00		200	37.12	35,000	7,400		42,400
3	Negative Junction Box, nema 12	1	ea	2,000	24.00		24	37.12	2,000	900		2,900
4	4" RGS conduit sleeves, 4 ft long w/insulated bushings on each end.	6	ea	80	4.00		24	37.12	480	900		1,380
5	1/C #750 kcmil neg return cable, XLP	1,000	lf	6.50	0.20		200	37.12	6,500	7,400		13,900
6	#750 kcmil cable terminations	20	ea	65	4.00		80	37.12	1,300	3,000		4,300
7	Core drill subway wall for 4" dia. rgs conduit	6	lot	100	16.00		96	37.12	600	3,600		4,200
8	Local controls -- allowance	1	lot	25,000					25,000			25,000
9	Bus Duct, 6000A 1200VDC complete w/ fittings and supports.	30	lf	1,500	16.00		480	37.12	45,000	17,800		62,800
10	Allowance for additional material handling in and out of the transbay tube. BART to provide train w/operator w/o cost to contractor.	1	lot		500.00		500	37.12		18,600		18,600
11	6000A, 1200VDC Non-loadbreak negative fused disconnect.	1	ea	3800	40.00		40	37.12	3,600	1,500		5,300
	TOTAL DIRECT COST						1,844		146,680	68,500		215,180
	SALES TAX @ 8.25% on material								12,100			12,100
	INDIRECT COST @ 35% on Labor $ only.									23,980		23,980
	CONTINGENCY @ 10%											25,130
	ENGINEERING AND MANAGEMENT COST @ 10%											27,640
											Rounding	(30)
	DC INTERFACE SUBSYSTEM TOTAL COST											304,000

The DC interface consists of a DC breaker, negative disconnect, negative grounding device, and bus to the rails. This DC interface subsystem is common to all of the solutions evaluated (Battery-Only, "DC-Battery," Battery-PCS, SMES, and conventional rectifier). An 8,000-amp bus duct is used to connect the battery, SMES, or rectifier to a new 6,000-amp main breaker and then to the existing gap breaker, B01, at MCG. A negative grounding device will be connected to the negative bus. Ten 750-kcmil, 5-kV cables will be installed for negative return between the running rails and the battery (or other system) negative. Three 4.5-inch-diameter holes will be core-drilled from the gallery to each track for these cables.

Modifications to the existing supervisory control and data acquisition (SCADA) system, local control/graphic panel, and local control wiring are required. Modification of the central SCADA system located at Lake Merritt is excluded from the current design and cost estimate, though it would need to occur. Modifications to train signaling may be required and would be developed during detail design.

Consideration should be given to reconfiguring the cable bus connecting the existing gap breakers so that one feeder breaker is provided for each of the contact rails (ML06, MR06, ML03, and MR03) at MCG. This would provide the same flexibility as at other BART traction substations. To achieve this, one additional 4,000-amp DC breaker would be required. The total additional cost is estimated to be on the order of $100K ($1993).

Section 6

COMPARISON OF SMES ALTERNATIVES

In this section, direct comparisons of the designs are made, with reference to accompanying tables which present the designs from the three vendors in a combined format.

OVERALL SYSTEM DESIGN

Unconstrained Site

The PDM design has a higher power rating than the other two designs. PDM uses IGBTs in its power electronics, while SI and Westinghouse use GTOs. The PDM unit has the potential of very fast recharge, if the track voltage could withstand that draw. PDM is the lightest of the three systems and has the lowest auxiliary power requirement. These features may be attributed to the single cryostat, with consequent low surface-to-volume ratio and reduced number of leads. Also, a solenoid requires less physical support than a toroid. See Table 6-1 for vendor comparison of the overall designs.

Table 6-1

Vendor Comparison, Overall System, Unconstrained Site

Vendor	PDM	SI	Westinghouse
Net Effective Stored Energy	9.65 MJ	8 MJ	9.3 MJ
Peak Discharge Power Rating	4.7 MW	3.2 MW	3.2 MW
Recovery Period Between Cycles	6 to 80 seconds	Less than 90 seconds	90 seconds
System Footprint	50' L x 4' W x 8' ± H	50' L x 10' W x 10' H	27' L x 13' W x 9' H
System Weight	27,000 lb	40,000 lb (no shielding)	75,689 lb
Auxiliary Power Requirements	41.5 kW (avg.) @ 120/240/480 V	250 kW @ 480 VAC	110 kW @ 4,160 V

Transbay Tube Site

SI has dropped its refrigeration load by a factor of 3 compared to its unconstrained design, and is drawing this power from the DC track rather than from an AC source. The systems are comparable in footprint, depending on the details of equipment layout. See Table 6-2 for vendor comparison of the overall designs.

Table 6-2

Vendor Comparison, Overall System, Transbay Tube Site

Vendor	PDM	SI	Westinghouse
Net Effective Stored Energy	9.65 MJ	8 MJ (4 x 2 MJ)	9.3 MJ (3 x 3.1 MJ)
Peak Discharge Power Rating	4.7 MW	3.2 MJ	3.2 MW
Recovery Period Between Cycles	6 to 80 seconds	Less than 90 seconds	90 seconds
System Footprint	50' L x 4' W x 8' ± H	50' L x 4' W x 8' H	61' L x 3.83' W x 6' H
System Weight	27,000 lb	32,000 lb (system) and 80,000 lb (shielding). Total: 112,000 lb	66,640 lb
Auxiliary Power Requirements	41.5 kW (avg.) @ 120/240/480 V	80 kW @ 800 to 1,000 VDC	110 kW at 4,160 V

MAGNET DESIGN

Unconstrained Site

Niobium titanium Rutherford-type cable is used by all three vendors. The single large Westinghouse toroid requires nearly twice the amount of cable as the PDM solenoid requires. All three vendors are operating at similar maximum field strength in their coils, in the range of 4.6 to 5.5 Tesla, probably set by the tolerance of the conductor. The maximum current in the coil varies widely with design, from a high of 5,700 amps for PDM to a low of 1,250 amps for SI. All vendors use detection of imbalance between segments of the coil to determine whether the magnet is operating in a stable superconducting mode, and would dump the stored energy to an external resistor in the event of quench. See Table 6-3 for vendor comparison of the magnet designs.

Transbay Tube Site

In the transbay tube site, PDM and SI use the same magnets which they utilize in an unconstrained site. Westinghouse replaces the single larger toroid of the unconstrained site with three smaller toroids connected in series. In these smaller toroids, for the sake of compactness, the maximum magnetic field strength in the coil has risen from the 5.5 Tesla of the larger coil to 7.5 Tesla. In the case of quench in the transbay tube, all three designs contain the helium which may be vaporized, rather than releasing it into the gallery. See Table 6-4 for vendor comparison of the magnet designs.

Table 6-3

Vendor Comparison, Magnet Design, Unconstrained Site

Vendor	PDM (1 Long Solenoid)	SI (4 Solenoids)	Westinghouse (1 Toroid)
Conductor Length	Approx. 5,000 meters of cable	Proprietary information	27,750 feet
Number of Turns	1,500	Proprietary information	2,304
Length of Coil	2.13 meters	Approximately 3 feet	67.0 inches
Inner Diameter of Coil	0.76 meters	28 inches	10.25 inches
Maximum Magnetic Field Strength in Coil	4.6 Tesla	5 Tesla	5.5 Tesla
Maximum Current in Coil	5,700 amps	1,250 amps	4,000 amps

Table 6-4

Vendor Comparison, Magnet Design, Transbay Tube Site

Vendor	PDM (1 Long Solenoid)	SI (Modular: 4 solenoids)	Westinghouse (Modular: 3 Toroids)
Conductor Length	Approx. 5,000 meters of cable	Proprietary information	3 x 13,500 feet
Number of Turns	1,500	Proprietary information	3 x 2,592
Length of Coil	2.13 meters	Approximately 3 feet	26.0 inches
Inner Diameter of Coil	0.76 meters	28 inches	8.72 inches
Maximum Magnetic Field Strength in Coil	4.6 Tesla	5 Tesla	7.5 Tesla
Maximum Current in Coil	5,700 amps	1,250 amps	4,000 amps

REFRIGERATION DESIGN

Unconstrained Site

All vendors use liquid helium cryosystems: none use supplemental liquid nitrogen cooled shields. SI, with 4 x 25 = 100 W at 4.2K, and Westinghouse, with 114 W at 4.6K, use similar amounts of cooling. The current leads proposed by the three vendors employ different strategies in their loss trade-off approaches. The dimensions of the PDM and SI cryostats are remarkably similar despite the factor of 4 difference in the storage capacity of the coil contained within. This is due to the SI strategy of providing for long carryover times in case of refrigerator failure by storing a substantial volume of liquid helium within the cryostat. The electric load of the refrigeration systems seems to vary roughly as the number of leads from warm to cold, so that the SI load is roughly four times the PDM load. This also translates directly into a fourfold increase in annual electricity consumption/cost for SI. All vendors use commercially available refrigeration systems. A comparison of the cryosystems for the unconstrained site designs appears in Table 6-5.

Transbay Tube Site

Table 6-6 gives a cross-vendor comparison of the cryosystems proposed for the transbay tube site. Rows of the table which are unchanged from the preceding table are omitted. In the transbay tube site, SI estimates a 45-hour duration of carryover in the cold condition after loss of power to the refrigerator. This is attributable to its large volume of liquid helium. SI upgrades to a boiler-rated cryostat in its tube design, so that vaporized helium will be retained in the cryostat rather than venting to the atmosphere as it does in the unconstrained site design. Also, SI modifies the leads and refrigeration so that the electric load of the refrigeration system drops from the previous 160 kW to 60 kW. This brings all the systems to a smaller range of values of projected annual energy consumption for refrigeration: 357 to 606 MWh per year.

Table 6-5

Vendor Comparison, Cryosystem, Unconstrained Site

Vendor	PDM	SI	Westinghouse
Type of Refrigeration	Helium refrigerator	1. Refrigerator: Process Systems (Koch) Model 1200. Collins cycle liquefier/refrigerator. 2. Shield Cooler: Gifford-McMahon cycle, single stage.	Closed-cycle helium liquefaction
Type of Liquid Coolant(s)	liquid helium/gaseous helium	Helium	Liquid Helium
Volume of Coolant(s)	gaseous helium, 55 ft^3 @ 20 atm	750 liters per cryostat (total 3,000 liters)	1,640 liters
Expected Rate for Resupply of Coolant(s), liters/time interval	No resupply is required for 1 year	250 liters per cryostat/year (total 1,000 liters/year) during annual maintenance of refrigeration system.	16 liters/hour *Note: this is probably the recondensation rate, not the resupply rate.*
Cooling Capacity of Refrigerator, $W_{thermal}$	10 W recondensation 600 W load stream cooling 50 W shield cooling	Refrigerator 4 liters/hr or 25 W refrigeration @ 4.2 K	114 W at 4.6°K
Duration of Carryover in Cold Condition After Loss of Power to Refrigerator	TBD	60 hr	TBD
Current Lead Material	steel/brass/copper	Conventional copper vapor cooled current lead. Current leads made with HTSC will be available in late 1993.	BSCCO-2212
Current Lead Features	Low heat leak in standby mode or operating mode with zero current	Automatic flow controller to minimize helium flow rate. HTSC leads under design.	HTSC lead, reduced heat leak
Cryostat Dimensions	100" L x 44" W x 80" H	Cylinder, 40" OD and 96" high	67.5" L x 67.5" W x 109" H
Cryostat Weight	4,000 lb, plus coil of 11,000 lb	4,000 lb	21,343 lb (includes cold mass)
Electric Load of Refrigeration System	40.75 kW (avg) 65.75 kW max	160 kW	100 kW
Projected Annual Electricity Consumption of Refrigeration System	356,970 kWh, including water cooling and instrument air	1,401,600 kWh	606,000 kWh

TBD = To be determined
HTSC = High-temperature superconductor

Table 6-6

Vendor Comparison, Cryosystem, Transbay Tube Site

Vendor	PDM	SI	Westinghouse
Type of Refrigeration	Helium refrigerator	1. Recondenser: Gifford-McMahon cycle, 3 stage with final Joule-Thompson stage. 2. Shield Coolers: Gifford-McMahon cycle, single stage.	Closed-cycle helium liquefaction
Volume of Coolant(s)	Gaseous helium, 55 ft^3 @ 20 atm	600 liters per cryostat (total 2,400 liters)	270 liters/module, 810 liters total
Cooling Capacity of Refrigerator, $W_{thermal}$	10 W recondensation 600 W load stream cooling 50 W shield cooling	1. Recondenser: 3 W @ 4.2 K 2. Shield Cooler: 200 W @ 55 K	114 W at 4.6°K
Duration of Carryover in Cold Condition After Loss of Power to Refrigerator	TBD	45 hr	TBD
Cryostat Dimensions	100" L x 44" W x 80" H	Cylinder, 40" OD and 96" high	3 x (46" L x 46" W x 42" H)
Cryostat Weight	4,000 lb plus coil of 11,000 lb	5,000 lb	3 x 4,098 lb (includes cold mass)
Electric Load of Refrigeration System	40.75 kW (avg) 65.75 kW max	60 kW, to be drawn off DC rail system as long as voltage is above minimum value.	100 kW
Projected Annual Electricity Consumption of Refrigeration System	356,970 kWh, including water cooling and instrument air	525,600 kWh	606,000 kWh

TBD = To be determined

POWER ELECTRONICS DESIGN

Westinghouse and PDM utilize a consistent power electronics design at both sites. SI changes its power electronics scheme for the site in the transbay tube. In the unconstrained site, SI charges the magnet from the AC line instead of the third rail. Thus, the magnet provides no additional load to the traction power substations and no additional track losses. However, it would incur an extra site-dependent cost for installation of a supply circuit. Both PDM and Westinghouse adopt the strategy of being capable of recharge from the third rail at any rate up to the discharge rate. This would allow them to charge their devices "on demand" when a future BART advanced control system saw a sag coming, or when a train actually stopped in the tube. The unit could charge within a period of 5-10 seconds and be ready to prevent voltage sag transients as the queue of trains restarted. More analysis would be necessary to determine whether this quick recharge would be compatible with system operations, but its load should look about like the acceleration of a single train, and therefore be acceptable under all but the most severe cases of system loading. SI limits its recharge rate to match the specification that the unit recharge in the probable 90-second minimum period between successive sags. With recharge power coming from the AC system, this slower recharge could also be necessary to avoid causing an AC voltage sag. Table 6-7 compares the designs at an unconstrained site.

Table 6-7

Vendor Comparison, Power Electronics, Unconstrained Site

Vendor	PDM	SI	Westinghouse
Power Source for Recharge	Third rail	AC power	BART third rail
Setability of Voltage Level for Recharge	850 V ± 25 V	Will not be charging from DC track system	± 25 V
Maximum Recharge Power	1.3 MW	4 x 62.5 kW peak or 0.25 MW	0.11 MW → 3.2 MW
Criteria for Recharge	I magnet < 5,700 A, 860 > V track > 825 V, SMES = operate	N/A	Rail voltage above set point
Maximum Discharge Power	4.7 MW (5700 amps, 825 V)	4000A @ 800 V = 3.2 MW	3.2 MW
Maximum Discharge Voltage	825 V	850 V	Set point (nominal 800 V)

N/A = Not available

In the transbay tube case, the BART third-rail DC system provides recharge power for all three designs. In this case, SI can recharge in under 10 seconds. All vendors use a current chopper, voltage-controlled scheme for their power electronics at the tube site. Table 6-8 compares the designs' power electronics for the transbay tube application, omitting rows which are unchanged from Table 6-6.

Table 6-8

Vendor Comparison, Power Electronics, Transbay Tube Site

Vendor	PDM	SI	Westinghouse
Power Source for Recharge	BART third rail	BART third rail	BART third rail
Maximum Recharge Power	1.3 MW	1.06 MW (4 sections to have staggered charging)	0.11 MW → 3.2 MW

MAINTENANCE PROCEDURES

PDM and SI anticipate that the SMES system will be a low-maintenance installation, with PDM expecting yearly and SI semi-annual inspection and maintenance. Both vendors remark that it would be desirable to de-energize the magnet when workers are in its vicinity. This would be in part for human exposure reasons, and in part because steel tools can experience a strong pull in such large magnetic fields. This would be a much smaller problem with the Westinghouse toroidal design because of its inherently lower fringe fields. As noted earlier, the field drops to 10 Gauss within less than 2 feet of the cryostat in the Westinghouse design.

COST ESTIMATES

The cost of the systems in the unconstrained location varies by over a factor of 2, while in the transbay tube site it varies by over a factor of 3. These dramatic differences may be attributed to pricing policy, ability to amortize engineering costs over many units, in-house maturity of component technologies, relative amounts of conductor used, and cost savings of single units compared to multiple modules. This section will attempt to interpret some of the differences in cost, at the risk of having to do some guesswork on matters which are hidden from direct examination.

The fact that SI considers its cost breakdowns to be proprietary information inhibits direct comparison of component prices among the three designs. However, SI alone does respond to the incremental cost questions. The reader should notice that vendors chose to respond to prices in different years, but that all are in 1993 dollars.

Unconstrained Site

Comparison of the costs in the unconstrained site with those in the transbay tube site reveals that PDM prices hold at $1.6M per unit irrespective of site, while both SI and Westinghouse prices increase in the transbay tube. To speculate, PDM may consider that the cost of sheltering the unit in an unconstrained site (container or building and slab) balances the 50% productivity factor for working in the tube for installation. (Because work in the transbay tube can be performed only on graveyard shifts, when the transit system is not operating, and because of the time necessary to transport workers and materials to the site, the ratio of time worked to time charged used by Bechtel in its cost estimates is 0.5. This is called a productivity of 50%.) In the case of Westinghouse, the design is going from a single unit to three small modules. The effort to make these modules compact increases the amount of conductor required. The modularity increases the fabrication cost.

In the unconstrained site, however, Westinghouse prices for the unit in quantities of 2 to 5 drop substantially, from $3.1M to $2.4M per unit, a drop of $0.7M. PDM prices drop only from $1.6M to $1.4M in going from a single unit to quantities of 2 to 5. This brings Westinghouse, with its single toroid design, within a factor of 1.7 of the PDM price. (Subsequent Westinghouse work at detailing and cost-optimization of the toroidal design indicates that prices much nearer the PDM price are achievable. This lends credence to our decision to base cross-technology comparisons on the PDM pricing.)

In the unconstrained site, the 1993 SI price of $3.4M is close to the single-unit Westinghouse price. This indicates that the cost penalty due to the SI design's modularity may roughly cancel the cost penalty due to the Westinghouse design's toroidal configuration. The price drop for SI as more units are purchased is smaller than for Westinghouse, so that with multiple purchases, the Westinghouse price advantage increases. With all these comparisons stated, it should also be borne in mind that SI prices may have an edge in credibility owing to the fact that they are actually selling units at the present time. The PDM and Westinghouse prices are not quotes for procurement, but rather are based on conceptual-level designs for budgetary purposes.

See Table 6-9 for a comparison of vendor costs at an unconstrained location.

Table 6-9

Comparison of Vendor Costs, Unconstrained Site

Vendor	PDM	PDM	SI	SI	Westinghouse	Westinghouse
Year of Delivery	1993	1995	1993	1995	1993	1995
Total System Cost, single unit	N/A	$1,620K	$3,408K	$3,238K	$ 3,179K	TBD
Cost of Coil and Cryostat	N/A	$600K	*	*	$ 762K	TBD
Cost of refrigeration system	N/A	$350K	*	*	$ 411K	TBD
Cost of Power Electronics		$560K	*	*	$ 642K	TBD
Cost of fusing and switching		$55K	$115.5K	$115.5K	included in power electronics above	TBD
Incremental Cost of additional 1 MJ of energy storage	N/A		$100K		TBD	TBD
Incremental Cost of additional 1 MW of power capability		$55K	$850K		TBD	TBD
Indirect costs (including design, engineering, assembly, transportation, management, fees, contingencies, taxes, insurance, etc.)	N/A	included	Included in price.	Included in price.	$ 1,364K	TBD
Cost Per Unit in Quantities of 2-5		$1,400K	10% discount	10% discount	$ 2,444K	TBD

N/A = Not available
TBD = To be determined
*SI considers its cost breakdown to be proprietary.

Transbay Tube Site

In the Transbay Tube, the cost for the Westinghouse system rises significantly, while the cost of the SI unit rises still higher. The difference between the SI costs in and out of the tube is nearly $2.6M. The SI cost increase may be attributable to four factors: (1) the more complex, more efficient cryogenic system which SI includes in its tube design to meet the auxiliary power specification; (2) the greater difficulty of installation in the tube; (3) the shielding which SI uses to mitigate the DC magnetic field in the close confinement of the tube; and (4) the change in their power electronics. SI estimates the total shield cost for the system in the tube to be $280K. The Westinghouse price increase is primarily an indication of the penalty for modularity in the coil and cryostat themselves, although it likely also contains a component for the higher fields and increased amount of conductor required to make toroids fit through the tube doorway.

The vendor cost estimates for the Transbay Tube location are shown in Table 6-10. In contrast to the rectifier and battery costs, which are presented in Section 7, the SMES cost for installation is probably less reliable. Rectifier and battery installation costs as defined by Bechtel are fully detailed, and include productivity factors for working in the tube, etc. (These were determined in consultation with Bay Area Transit Consultants (BATC), of which Bechtel is a member. BATC is working on the BART extensions program, and thus its costs are highly credible.) The SMES vendors, on the other hand, devoted varying amounts of effort and detail to their estimates of installation costs. Thus, the SMES costs may not actually include sufficient allowance for installation or for the labor productivity differences between tube and unconstrained location. It should also be borne in mind that only one of the three SMES vendors has actually sold units in this size range to date, and that is SI, so there may be costs which are not included in the conceptual designs. On the other hand, PDM sells its systems fully installed and so would shoulder the burden of any underestimation in this area.

Nevertheless, for purposes of this study, the lowest-price SMES design will be compared to the battery and rectifier alternatives.

Table 6-10

Comparison of Vendor Costs, Transbay Tube Site

Vendor	PDM	PDM	SI	SI	Westinghouse	Westinghouse
Year of Delivery	1993	1995	1993	1995	1993	1995
Total System Cost, single unit	N/A	$1,620K	$5,584K	$5,305K	$ 4,870K	TBD
Cost Per Unit in Quantities of 2-5		$1,400K	10% discount	10% discount	$ 3,903K	TBD

N/A = Not available
TBD = To be determined

Maintenance Costs

Maintenance costs vary little between SI and PDM, the two vendors who supplied estimates, however, the operations cost of electricity to power the refrigeration units varies.

Section 7

BATTERY ENERGY STORAGE SYSTEMS

Three battery energy storage system designs were developed by Bechtel. The first connects a battery directly across the BART DC rail system (Battery-Only System). The second design uses battery/power electronics modular units ("DC-Battery" System). The third uses external batteries and larger power electronics units (Battery-PCS System). Design tables are in Appendix E.

BATTERY-ONLY SYSTEM

Battery System Modeling

Lead-acid batteries have a very high energy density, but poor power performance compared to SMES. To meet the *power* requirements of this application, it is necessary to store far more *energy* than required in the series of voltage sags defined in the functional specification. Furthermore, in a battery system, as current drawn increases, the battery voltage drops. This is unlike the case of SMES, where output voltage is held steady by the power electronics.

To account for battery voltage drop with increasing current draw, Bechtel used a simplified computer model. The simplified circuit shown in Figure 7-1 was used for this modeling. The resulting voltages and currents, with and without the energy storage system, are shown as functions of time in Figure 7-2. A pulse-duty traction rectifier at MCG was also modeled. The resulting voltages and currents, with and without the additional rectifier, are shown as functions of time in Figure 7-3.

Comparing Figures 7-2 and 7-3 shows the effects of including practical impedances for a rectifier or a direct-connected battery. For 6% regulation, there is a voltage span of 50 V (i.e., 6% of the voltage at the 4,000-amp rated current). This probably is the upper limit for practical systems so as not to supply current at voltages attained during normal operation of the trains.

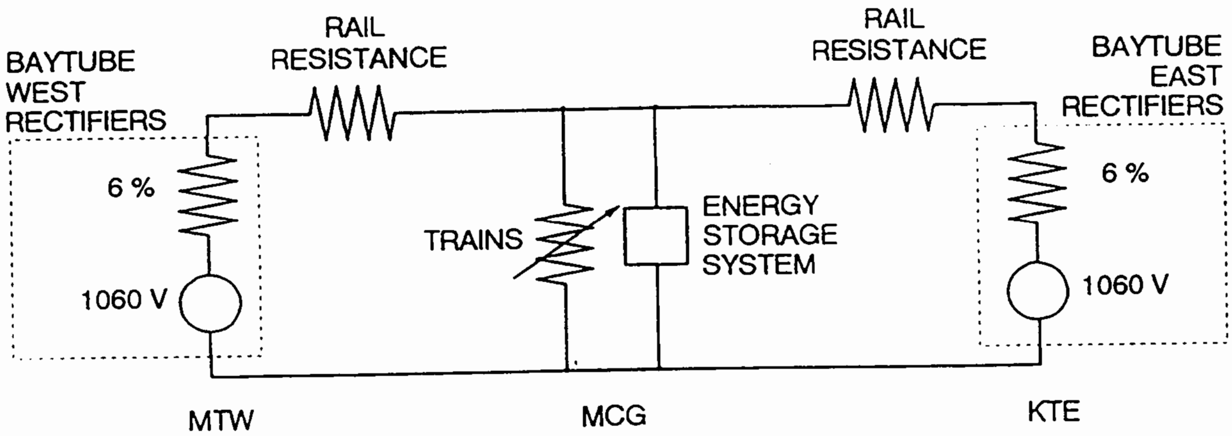


Figure 7-1. Circuit for battery modeling (Battery-Only system).

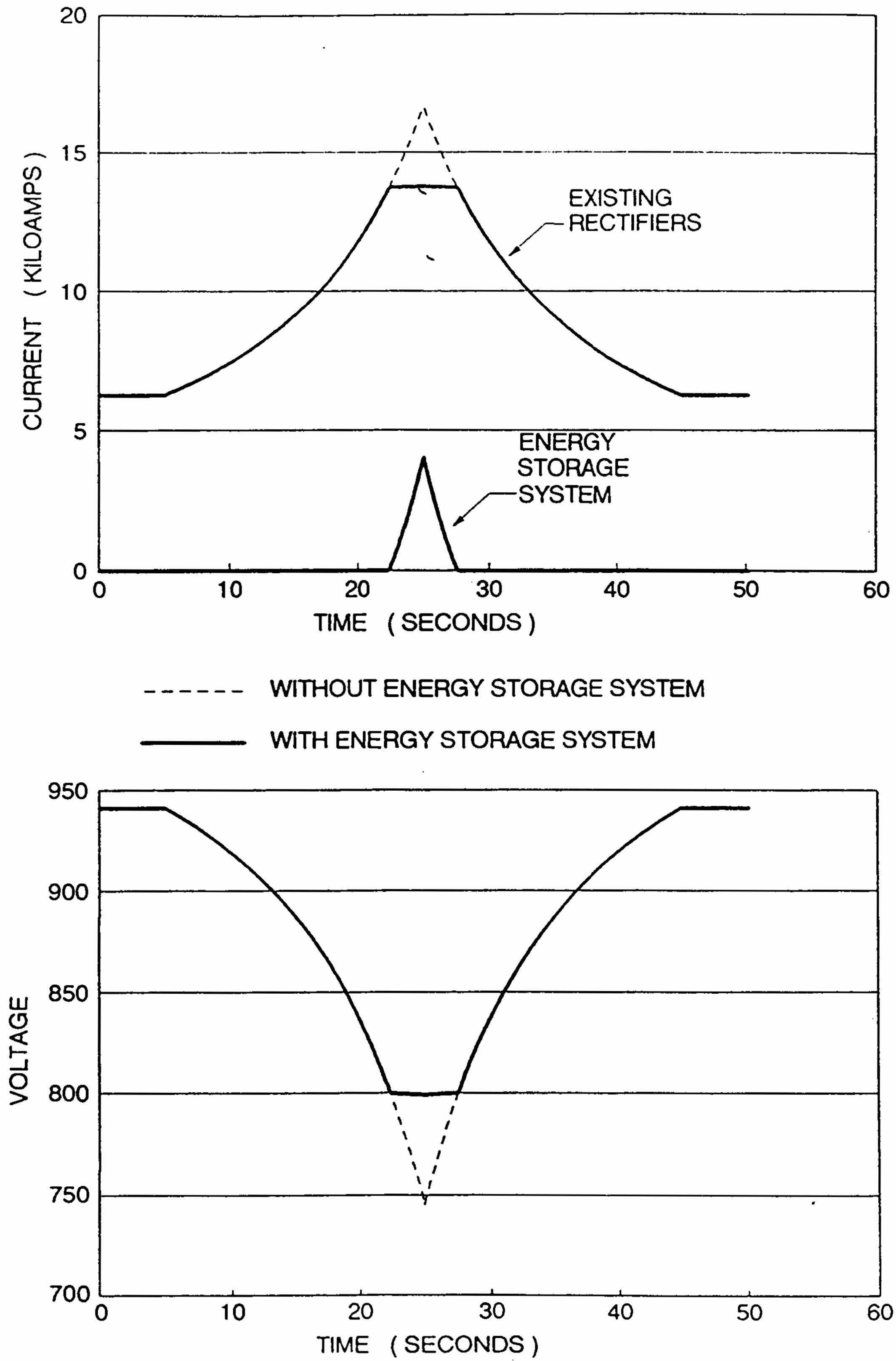


Figure 7-2. Modeled voltage and current for zero-impedance energy storage system.

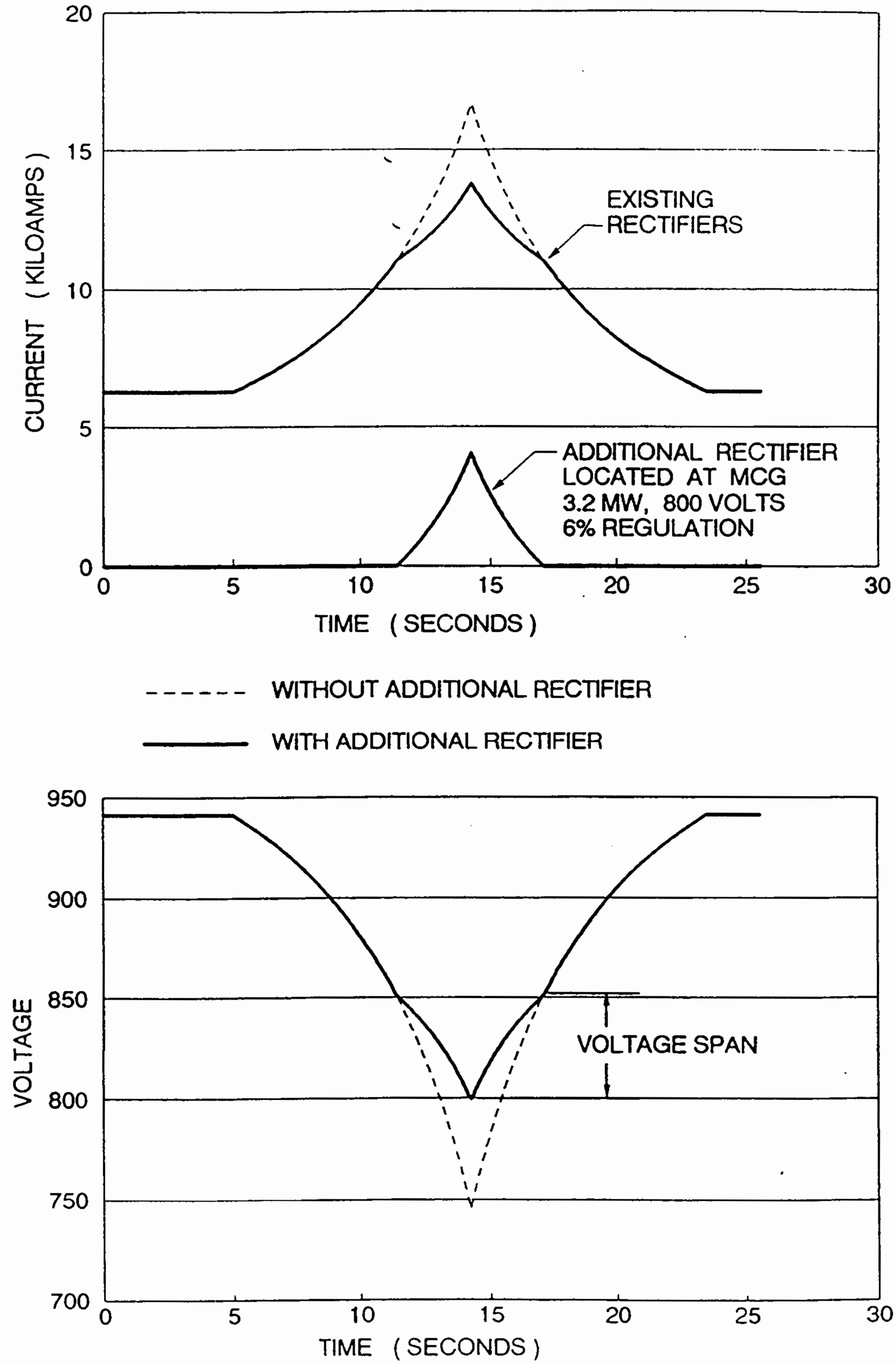


Figure 7-3. Modeled voltage and current for 6% impedance rectifier at MCG.

System Design

Electrical Design. The basic electrical configuration of the Battery-Only design is shown in Figures 7-4 and 7-5. Many lead-acid cells are connected in series to attain the desired voltage. Several of these "strings" are connected in parallel to attain the desired resistance of 0.012 ohm.

The operation of the Battery-Only system is such that it begins to discharge and supply current to the BART system when the rail voltage falls below the battery's open circuit voltage. A blocking diode is included to prevent charging of the battery from the rail system: charging is provided by a small, separate rectifier. The battery would be connected to the BART rail system through the DC interface subsystem described in Section 5. The battery could be recharged directly from the rail system; however cell life can be increased by recharging with a more controlled charge profile. The conceptual design includes recharge of the battery by a separate 5-kW rectifier fed from the 4,160-V auxiliary power line.

For purposes of the conceptual design, Bechtel selected a Delco 2000 battery, a 6-cell car battery. The resistance of a cell is 580 micro-ohms. Computer modeling indicated that 20 parallel strings, of 72 modules each, are needed to attain a battery resistance of 0.012 ohm and duplicate the performance of the 3.2-MW traction rectifier (Figure 7-3).

Physical Design. A number of commercially available battery racks could be used to stack the battery modules, but because the area at the base of the gallery wall was not being used for other equipment, an unstacked configuration was selected to minimize cost. The physical configuration of one of the battery strings is shown in Figure 7-6, along with the positive and negative conduits, a fused disconnect switch enclosure for the positive string cable, and a junction box for the negative cable. The intermodule straps are sketched.

The overall battery extends 458 feet along the gallery wall. This overall length greatly exceeds the specified preferred length of 50 feet. Using a three-tier rack, two modules deep, would give an overall length of approximately 150 feet. Attaining an overall length of 50 feet would require use of a five-tier rack, seven modules deep.

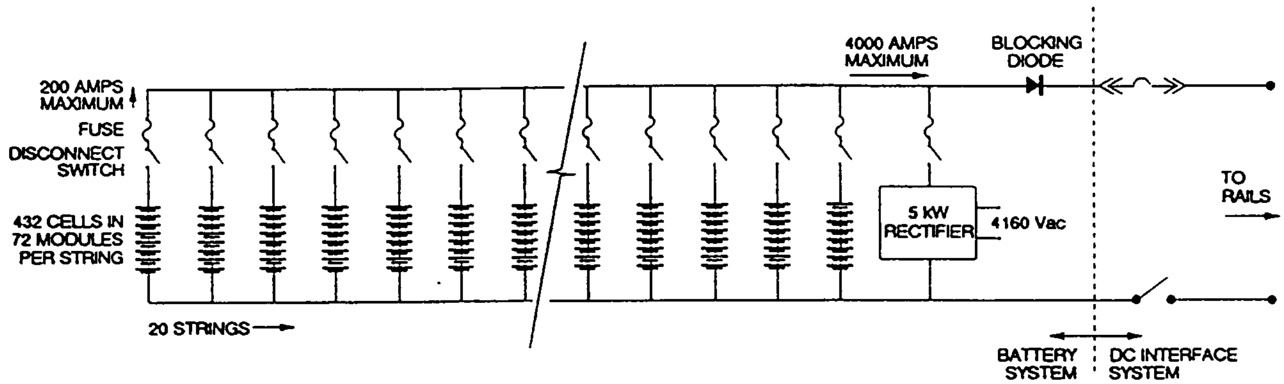


Figure 7-4. Electrical configuration of the Battery-Only design.

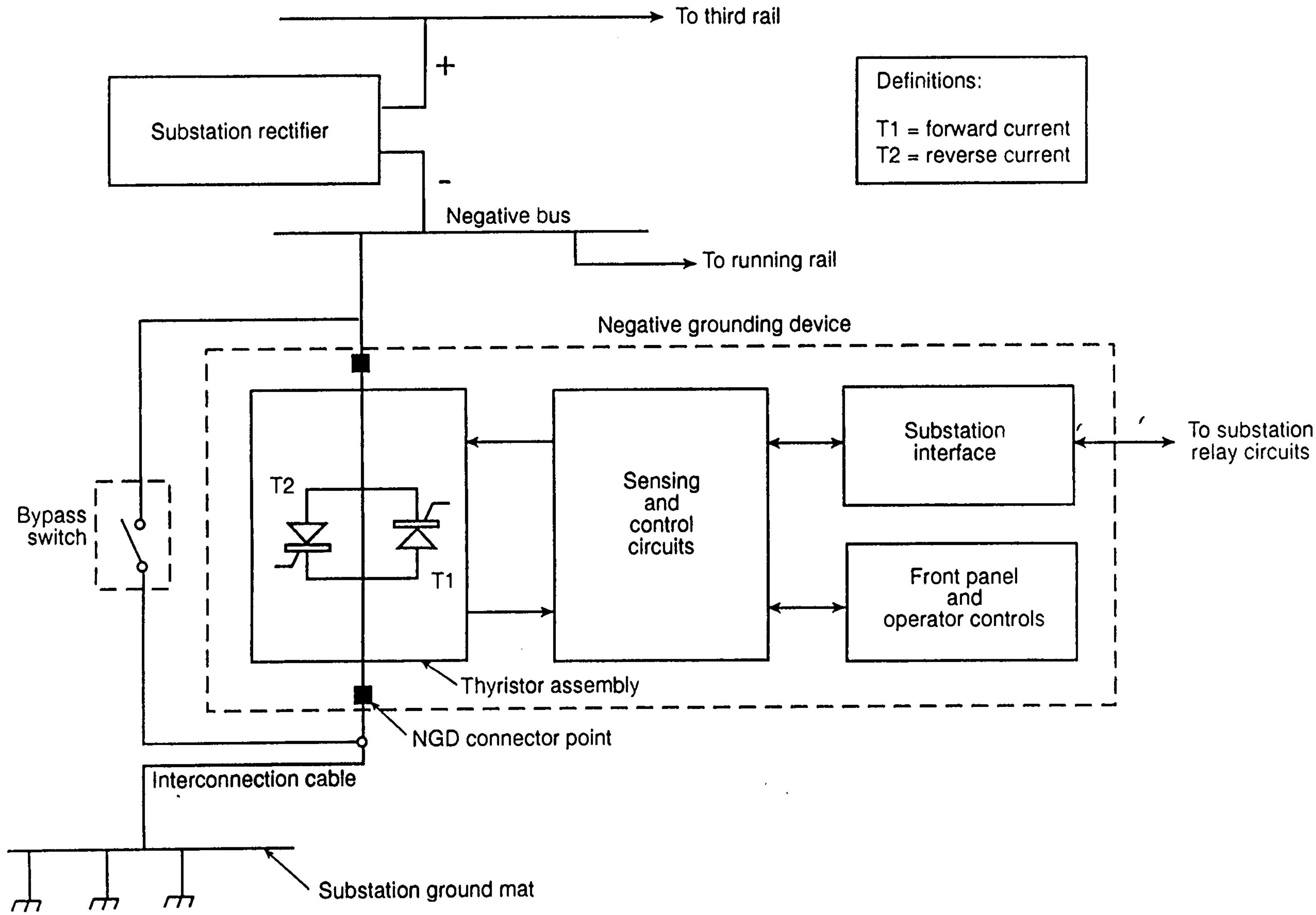


Figure 7-5. General arrangement and interconnections for BART rectifier grounding device.

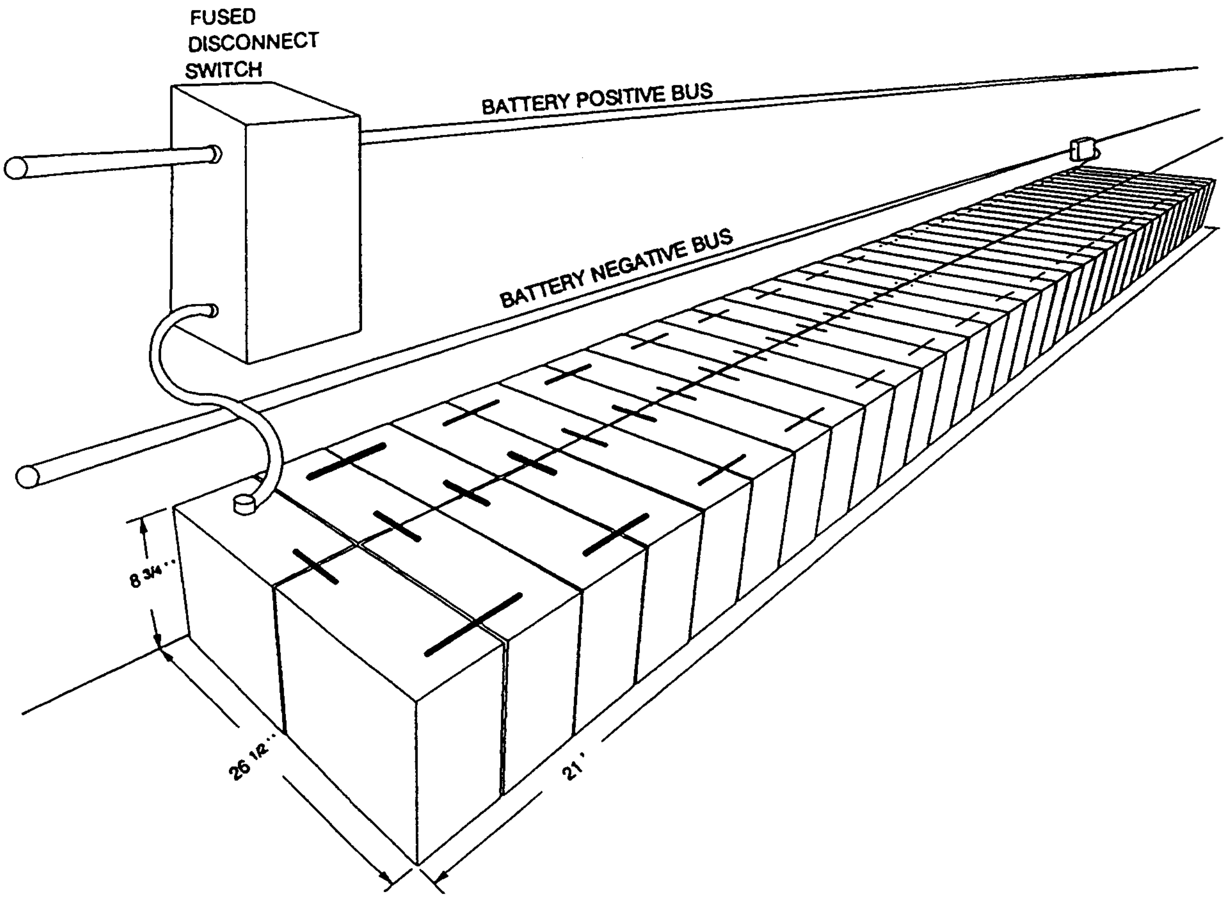


Figure 7-6. Physical configuration of one string for Battery-Only design.

Cost Estimates

The location of the site in the middle of the transbay tube generally increases the systems' total installed costs relative to those of a more typical surface installation. The total installed cost of the Battery-Only system, including the DC interface subsystem, is shown in Table 7-1. Because the cells must be replaced twice during the 20-year life of the project, a levelized annual revenue requirement (LARR) analysis offers a more meaningful insight into the system costs than does an installed cost. (In fact, for a transit system such as BART, where capital dollars come primarily from federal agency funds and operating dollars come from local budgets, the replacement of batteries may pose a difficult budgetary hurdle.)

Other Cost Factors

Electricity cost to cover losses in the batteries is a negligible $92 per year. The Delco 2000 is a flooded electrolyte cell, with a bi-directional valve, but with no provisions to add water. Routine maintenance will entail only visual inspection of the modules to detect reversing cells. The Battery-Only installation is estimated to require 96 hours for inspections, 56 hours for module replacement (plus $1K in materials), and 4 hours of miscellaneous items annually. Assuming a fully burdened rate of $50 per hour, the estimated annual maintenance cost is $9K.

In the present application, the life of the cell is limited by calendar life rather than cycle life. The economic analyses are based on a 6.33-year life for the cells. The estimated LARR of the Battery-Only system is $120K. Details and assumed economic parameters are presented in Table 7-2. The debt, discount, and escalation rates are as provided by PG&E, except for the 3% escalation rates for batteries.

DC-BATTERY SYSTEM

Unlike the Battery-Only system, the power electronics in the "DC-Battery" system track the voltage of the discharging battery and maintain an 800-V output at the DC interface. In addition, fewer battery modules are required (about half as many as for the Battery-Only design). The "DC-Battery" design described here is an example of a rack-mounted battery with pull-out trays: it is the most expensive of the three battery solutions.

System Design

The design of the "DC-Battery" system is based on the AC Battery™ being developed by Omnion Power Engineering Corporation of Mukwonago, Wisconsin (Myer 1992). Omnion's approach uses factory-assembled modular units to provide battery energy storage. A number of units may be paralleled to attain desired power and energy levels.

Table 7-1
Battery–Only System Cost Summary ($1993)

QTY BY: ENGINEERING
EST BY: R. H. ALMOGELA
DATE: FEBRUARY 18, 1993

PROJECT DESCRIPTION: TRANSBAY TUBE POWER QUALITY STUDY
CLIENT: BAY AREA RAPID TRANSIT DISTRICT (BART)
LOCATION: SAN FRANCISCO AREA, CALIFORNIA

ITEM	DESCRIPTION	QTY	UNIT MEAS	UNIT COST MTL	UNIT COST MHR	UNIT COST ALLOW	TOTAL MHR	$/MHR	COSTS IN 1993 $ MATERIAL	COSTS IN 1993 $ LABOR	COSTS IN 1993 $ ALLOW	TOTAL COSTS
1	Battery Sets											
	a) Battery Modules (20 sets w/ 72 modules per set) (FOB Anaheim, Ca.)	1,440	ea	50	1.00		1440	37.12	72,000	53,500		125,500
	b) Straps, 4"x1"x0.25" incldg bolts and washers.	720	ea	0.35	incld.				250			250
	c) Straps, 7.75"x1"x0.25" incldg bolts and washers	700	ea	0.65	incld.				460			460
	d) Steel channel guard, cover, etc.	20	lots	400	incld.				8,000			8,000
2	200A, 1200VDC Non-loadbreak fused disc., nema 12	20	ea	600	16.00		320	37.12	12,000	11,900		23,900
3	15A, 1200VDC Non-loadbreak fused disc., nema 12	1	ea	200	6.00		6	37.12	200	200		400
4	Transformer, 15 KVA 4160V-120V	1	ea	4,000	30.00		30	37.12	4,000	1,100		5,100
5	Charger unit, 800V DC output(5kw approx.)	1	ea	650	30.00		30	37.12	650	1,100		1,750
6	Paneboard, 24 ckts, 225A mains, 120v, nema 12	1	ea	2,500	48.00		48	37.12	2,500	1,800		4,300
7	1/C #250kcmil feeder cable, XLP	5,500	lf	3.80	0.18		990	37.12	20,900	36,700		57,600
8	#250kcmil cable terminations	80	ea	65	4.00		320	37.12	5,200	11,900		17,100
9	Cable tray, ventilated and fireproofed w/ fittings and supports.	1,000	lf	16	2.50		2,500	37.12	16,000	92,800		108,800
10	Ground Wire, 1/c #250 kcmil including connections	500	lf	2.50	0.40		200	37.12	1,250	7,400		8,650
11	Eye Wash, misc.	1	lot	1,000					1,000			1,000
12	4000A Diode	1	ea	1,000	6		6	37.12	1,000	200		1,200
	TOTAL DIRECT COST						5,890		145,410	218,600		364,010
	SALES TAX @8.25% on material								12,000			12,000
	FREIGHT COST ALLOWANCE										9,000	9,000
	INDIRECT COST @ 35% on Labor $ only.									76,510		76,510
	CONTINGENCY @10%											46,150
	ENGINEERING AND MANAGEMENT COST @ 10%											50,770

Rounding	(440)
ENERGY STORAGE SUBSYSTEM	558,000
DC INTERFACE SUBSYSTEM	304,000
TOTAL SYSTEM COST	862,000

Table 7-2

Economics of Battery-Only System ($1993)

	Estimated Cost
Capital Costs	
Materials	$199,000
Labor	577,000
Batteries	86,000
Operating Costs	
Materials	$92/year
Labor	$0/year
Maintenance Costs	
Materials	$0/year
Labor	$7,800/year
Batteries	$1,050/year
Battery Replacement Costs	
Labor	$108,000
Batteries	82,940
Levelized Annual Revenue Requirement	$120,000

Estimate Basis:	February 1993	Debt Rate:	6.5%
Start-up:	February 1993	Discount Rate:	6.5%
Plant Life:	20 years		
Battery Life:	6.67 years	Escalation Rates:	
		Materials:	4.5%
		Labor:	5.0%
		Batteries:	3.0%

Electrical Design. Discussions with Omnion indicate that the IGBT power conditioners used in its present AC Battery design could be reconfigured into DC-DC choppers to provide the DC output required. A total of 16 units are required. Each unit contains 48 Delco 2000 battery modules connected in series. Delco performed high-rate discharge tests for the BART application and provided the data shown in Figure 7-7. As with the Battery-Only design, the cells are limited by power capability rather than energy storage capability.

The units could be configured to charge from the BART DC rail system. The cell life can be extended by use of a prescribed recharge regime which would require a relatively low power level, e.g., 300 W per unit. Because operation of the PCS at this low power level may be difficult to control, a small rectifier would be included in each unit. Each unit requires low-voltage AC power for controls and cooling fans. The addition of a few-hundred-watt charger would not require a major change. The low-voltage power for the Omnion units would be derived from the 4,160-VAC line via a transformer and distribution panel. Similar to the Battery-Only design, the DC outputs from the 16 units would be collected by a bus and brought to the DC interface subsystem. Omnion estimates that its power conditioner/chopper design will be able to maintain the 800-V output, "plus or minus a few volts," from zero to 4,000 amps.

Physical Design. For purposes of the conceptual design, Omnion proposes that the unit be the same size as its AC Battery™ unit. Each unit is 4.8 feet long by 3.3 feet deep by 4.3 feet high (Figure 7-8). Each unit weighs 3,600 pounds, including the 48 battery modules. The floor loading of each is approximately 250 pounds per square foot. The units will be oriented with their 4.8-foot side parallel to the gallery wall and project 40 inches from the wall. A 3-foot space is included between adjacent units, making the overall length 122 feet.

This overall length exceeds the specified preferred length of 50 feet. Using zero spacing between units could give an overall length of 77 feet, but would make maintenance and inspection of battery modules vastly more difficult. It would be possible to redesign the unit enclosures and reconfigure the battery modules. Stacking the modules in six layers would give an overall system length of 59 feet and a height of 6½ feet. This would make the units much more costly and difficult to install and maintain.

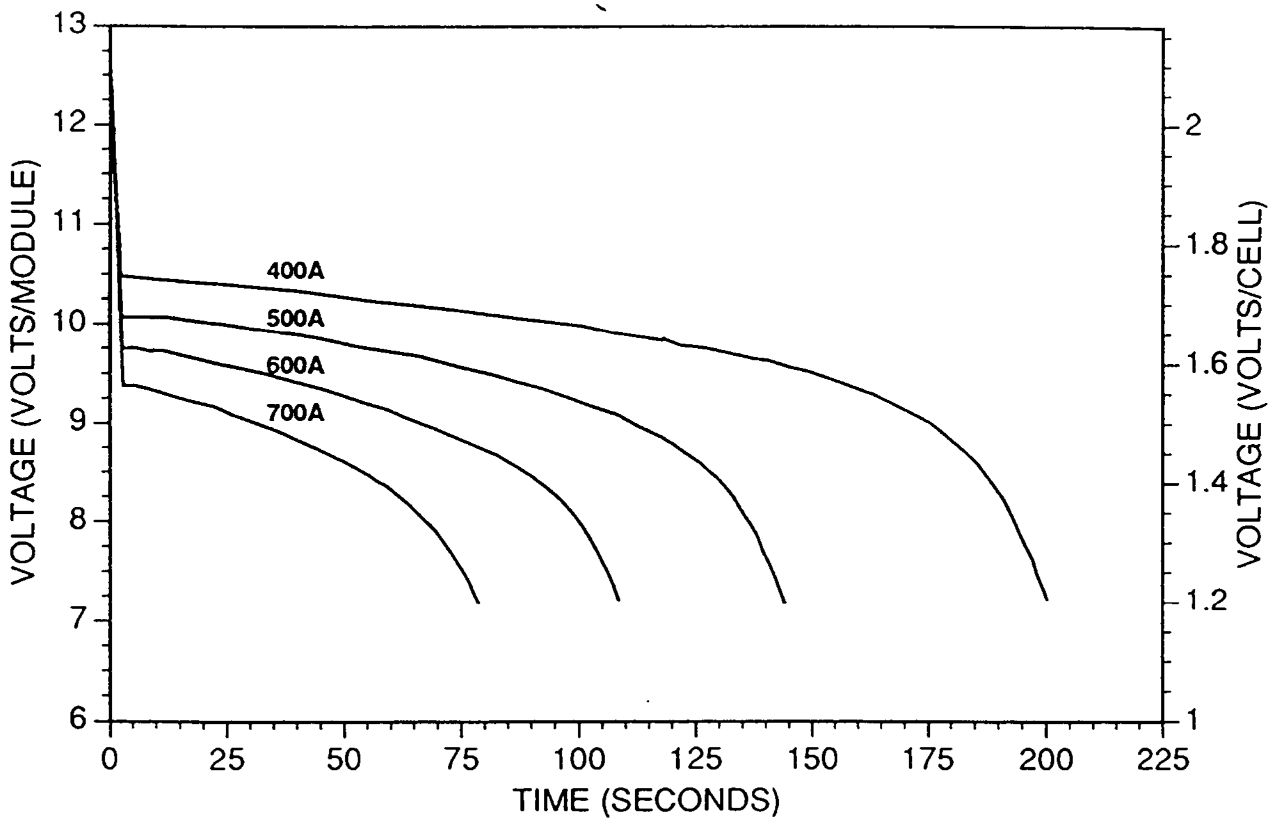


Figure 7-7. Delco battery module constant-current discharge data ("DC-Battery" system).

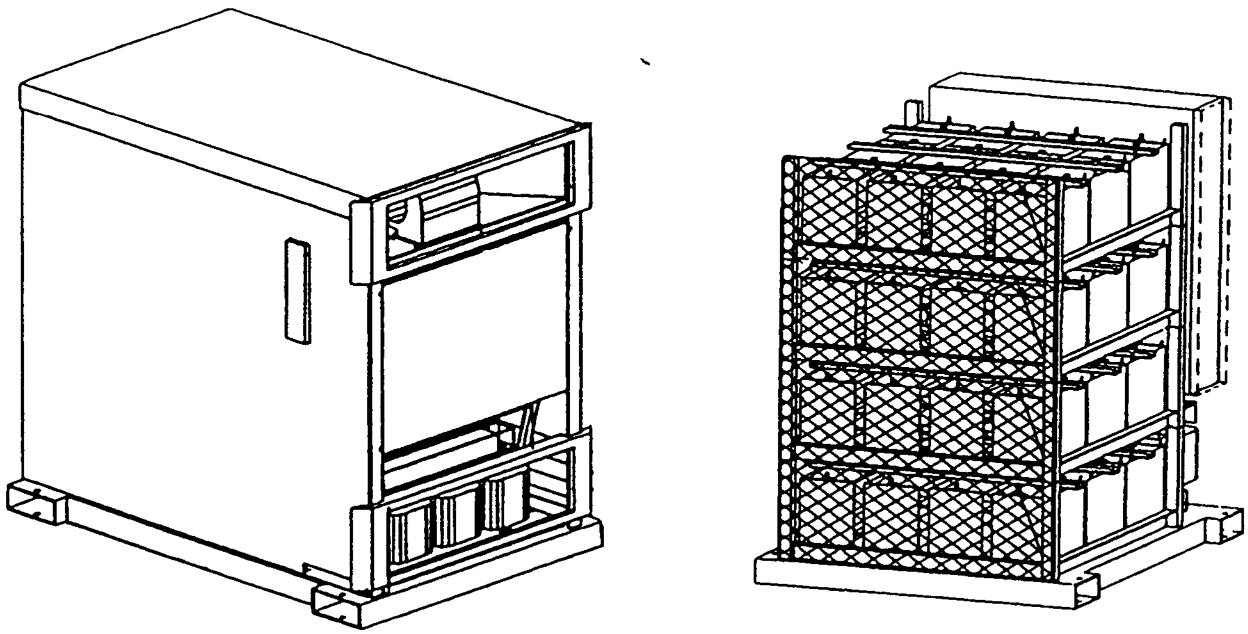


Figure 7-8. Omnion AC Battery unit design proposed for the DC-Battery system.

Hans Meyer, "AC Battery Development Project," presented at the Utility Battery Storage Systems Program Review, Valley Forge, PA, November 17, 1992.

Cost Estimate

Cost estimate details for the "DC-Battery" system are shown in Table 7-3. Omnion's estimated cost for the 16-unit system is $600K to $700K. For purposes of the conceptual design, $656K was used ($41K/unit), FOB Wisconsin, including design engineering. Omnion estimates that it could deliver the units 20 to 30 weeks after receipt of order.

Other Cost Factors

Battery maintenance and replacement differs from the Battery-Only system because there are roughly half the number of Delco 2000 modules, and access to modules in the cabinets is more difficult for both inspections and replacements than for the open-access batteries. The estimated annual maintenance cost is $10K for the "DC-Battery" system. As mentioned, the entire complement of cells must be replaced twice during the life of the project. There are fewer modules in this case than for the Battery-Only case, but installing and deinstalling modules in the cabinets is estimated to take 50% more labor. This leads to an estimated cost per replacement of $130K. The estimated LARR of the "DC-Battery" system is $174K. Details and assumed economic parameters are presented in Table 7-4.

BATTERY-PCS SYSTEM

The Battery-PCS (power conditioning system) is a combination of the Battery-Only and "DC-Battery" systems. For this design, larger and fewer power electronic units are used. The batteries are external to these units and are configured essentially the same as for the Battery-Only system, lying on the floor of the gallery rather than in racks or cabinets.

System Design

The design of the PCS is based on the photovoltaic PCS being supplied to the PVUSA Project at Kerman, California, by Omnion. As in the other two battery energy storage system designs, Delco 2000 battery modules are used.

Electrical Design. Discussions with Omnion indicate that the power conditioners which they designed for use at Kerman could be reconfigured into DC-DC choppers to provide the required DC output. Omnion's Kerman units are rated for 275 kW_{AC} continuous output. For the pulse duty cycle in the BART application, Omnion would increase the rating of the bridges so that six two-bridge units are required. The effect of this overrating on reliability is uncertain. Each bridge is fed by 48 Delco 2000 battery modules connected in series.

Table 7-3
DC–Battery System Cost Summary ($1993)

QTY BY ENGINEERING
EST BY R. H. ALMOGELA
DATE FEBRUARY 18, 1993

PROJECT DESCRIPTION: TRANSBAY TUBE POWER QUALITY STUDY
CLIENT: BAY AREA RAPID TRANSIT DISTRICT (BART)
LOCATION: SAN FRANCISCO AREA, CALIFORNIA

ITEM	DESCRIPTION	QTY	UNIT MEAS	UNIT COST			TOTAL MHR	$/MHR	<-------- COSTS IN 1993 $ ---->			TOTAL COSTS
				MTL	MHR	ALLOW			MATERIAL	LABOR	ALLOW	
1	Omnion battery / chopper units, 200KW (FOB Wisconsin)	16	ea	41,000.00	300.00		4,800	37.12	856,000	178,200		834,200
2	Transformer, 15KVA 3PH, 4160V-120V	1	ea	4,000.00	30.00		30	37.12	4,000	1,100		5,100
3	Paneboard, 24 ckts, 225A mains, 120V, nema 12	1	ea	2,500.00	48.00		48	37.12	2,500	1,800		4,300
4	1/C #250 kcmil feeder cable, XLP	2,200	lf	3.80	0.18		396	37.12	8,360	14,700		23,060
5	#250 kcmil cable terminations	64	ea	65.00	4.00		256	37.12	4,160	9,500		13,660
6	Cable tray, ventilated and fireproofed w/ fittings and supports.	260	lf	16.00	2.50		650	37.12	4,160	24,100		28,260
7	Ground Wire, 1/C #250 kcmil including connections	130	lf	2.50	0.40		52	37.12	330	1,900		2,230
8	Portable Eye Wash, misc.	1	lot						1,000			1,000
	TOTAL DIRECT COST						6,232		680,510	231,300		911,810
	SALES TAX @8.25% on material								56,140			56,140
	FREIGHT COST ALLOWANCE										6,000	6,000
	INDIRECT COST @ 35% on Labor $ only.									80,960		80,960
	CONTINGENCY @10%											105,490
	ENGINEERING AND MANAGEMENT COST @ 10%											116,040

Rounding	(440)
ENERGY STORAGE SUBSYSTEM	1,276,000
DC INTERFACE SUBSYSTEM	304,000
TOTAL SYSTEM COST	1,580,000

Table 7-4

Economics of DC-Battery System ($1993)

	Estimated Cost
Capital Costs	
Materials	$867,000
Labor	668,000
Batteries	46,000
Operating Costs	
Materials	$185/year
Labor	$0/year
Maintenance Costs	
Materials	$0/year
Labor	$9,600/year
Batteries	$600/year
Battery Replacement Costs	
Labor	$57,600
Batteries	44,235
Levelized Annual Revenue Requirement	$174,000

Estimate Basis:	February 1993	Debt Rate:	6.5%
Start-up:	February 1993	Discount Rate:	6.5%
Plant Life:	20 years		
Battery Life:	6.67 years	Escalation Rates:	
		Materials:	4.5%
		Labor:	5.0%
		Batteries:	3.0%

As with the "DC-Battery" system design, the Battery-PCS system includes a small charger in each unit to extend cell life by use of a prescribed recharge regime. Each unit requires low-voltage AC power for controls and cooling fans, and the addition of a few-hundred-watt charger would not require a major change. The low-voltage power for the units would be derived from the 4,160-VAC line via a transformer and distribution panel.

Similar to the other designs, the DC outputs from the six units would be collected by a bus and brought to the DC interface subsystem. As in the "DC-Battery" design, Omnion estimates that its design will be able to maintain the 800-V output, "plus or minus a few volts," from zero to 4,000 amps.

Physical Design. For purposes of the conceptual design, Omnion proposes that the unit be essentially the same size as its power conditioner for the PVUSA Project at Kerman. Each unit is 9 feet long by 3.5 feet deep by 6 feet high (Figure 7-9). Two battery sets feed each PCS. The configuration of the Delco 2000 battery modules resembles the Battery-Only design, except that there are 48 modules per set and each set has a 14-foot length. The overall length of each unit (PCS plus two sets of batteries) is 37 feet. Allowing 2 feet between units yields an overall length of 232 feet for the Battery-PCS system. As for the Battery-Only design, the battery modules could be installed in racks to shorten the overall length, at a penalty in cost. Each PCS unit weighs 4,000 pounds.

Cost Estimate

Cost estimate details for the Battery-PCS system are shown in Table 7-5 and detailed in Appendix E. Omnion estimated the cost for the six-unit system would be $400K to $500K. For purposes of the conceptual design, $450K was used ($75K/unit), FOB Wisconsin, including design engineering.

Other Cost Factors

As in the other battery designs, operating cost of electricity is a negligible amount. Battery maintenance and replacement operations are the same as for the Battery-Only case, except that this design uses 576 Delco 2000 modules (versus 1,440). Maintenance is estimated to require 40 hours for inspections, 12 hours for module replacement (plus $200 in materials), and 24 hours for the power electronics. This yields an estimated annual maintenance cost of $4K for the Battery-PCS system. Replacing the entire complement of cells is estimated to cost $77K per replacement. The LARR of the Battery-PCS system is $133K. Details and assumed economic parameters are presented in Table 7-6.

The competing features of footprint cost and regulation of the three battery designs appear together in Table 7-7 for ease of comparison.

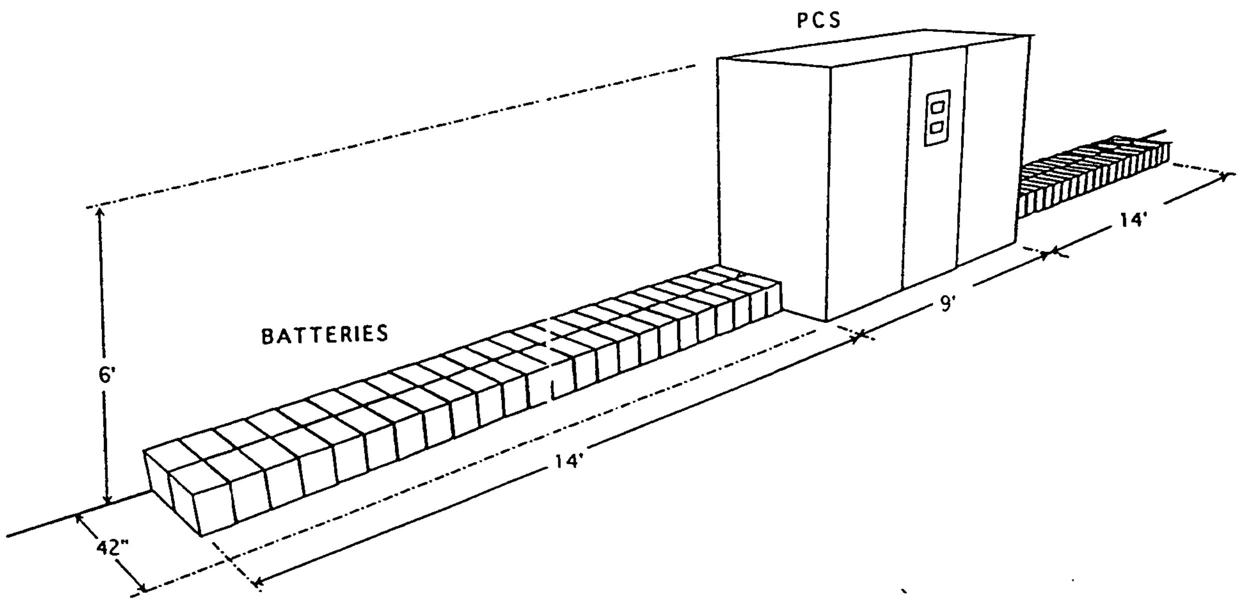


Figure 7-9. Physical configuration of one unit of the Battery-PCS system.

Table 7-5
Battery–PCS System Cost Summary ($1993)

QTY BY: ENGINEERING
EST BY: R. H. ALMOGELA
DATE: FEBRUARY 18, 1993

PROJECT DESCRIPTION: TRANSBAY TUBE POWER QUALITY STUDY
CLIENT: BAY AREA RAPID TRANSIT DISTRICT (BART)
LOCATION: SAN FRANCISCO AREA, CALIFORNIA

ITEM	DESCRIPTION	QTY	UNIT MEAS	UNIT COST MTL	UNIT COST MHR	UNIT COST ALLOW	TOTAL MHR	$/MHR	COSTS IN 1993 $ MATERIAL	COSTS IN 1993 $ LABOR	COSTS IN 1993 $ ALLOW	TOTAL COSTS
1	Omnion Chopper PCS units	6	ea	75,000.00	320.00		1920	37.12	450,000	71,300		521,300
2	Battery Sets (12 each)											
	a) Battery modules (12 sets w/48 modules per set)	576	ea	50.00	1.00		576	37.12	28,800	21,400		50,200
	b) Straps, 4"x1"x0.25" incldg bolts and washers	288	ea	0.35	incld.				100			100
	c) Straps, 7.75"x1"x0.25" incldg bolts and washers	280	ea	0.65	incld.				180			180
	d) Allowance for steel channel guard, cover, etc.	12	lots	300.00	incld.				3,600			3,600
3	Transformer, 15 KVA, 4160V – 120V	1	ea	4,000.00	30.00		30	37.12	4,000	1,100		5,100
4	Paneboard, 24 ckts, 225A mains, 120V	1	ea	2,500.00	48.00		48	37.12	2,500	1,800		4,300
5	1/C #250 kcmil, feeder cable, XLP	1,600	lf	3.80	0.18		288	37.12	6,080	10,700		16,780
6	Cable terminations for #250 kcmil	96	ea	65.00	4.00		384	37.12	6,240	14,300		20,540
7	Cable tray, ventilated and fireproofed w/ fittings and supports	500	lf	16.00	2.50		1,250	37.12	8,000	46,400		54,400
8	Ground wire, 1/c #250 kcmil including connections	250	lf	2.50	0.40		100	37.12	625	3,700		4,325
9	Portable Eye Wash, misc	1	lot	1,000.00					1,000			1,000
	TOTAL DIRECT COST						4,596		511,125	170,700		681,825
	SALES TAX @8.25% on material								42,170			42,170
	FREIGHT COST ALLOWANCE										6,000	6,000
	INDIRECT COST @ 35% on Labor $ only.									59,750		59,750
	CONTINGENCY @10%											78,970
	ENGINEERING AND MANAGEMENT COST @ 10%											86,870

Rounding	415
ENERGY STORAGE SUBSYSTEM	956,000
DC INTERFACE SUBSYSTEM	304,000
TOTAL SYSTEM COST	1,260,000

Table 7-6

Economics of Battery-PCS System ($1993)

	Estimated Cost
Capital Costs	
Materials	$683,000
Labor	542,000
Batteries	34,000
Operating Costs	
Materials	$185/year
Labor	$0/year
Maintenance Costs	
Materials	$0/year
Labor	$4,400/year
Batteries	$450/year
Battery Replacement Costs	
Labor	$43,200
Batteries	33,176
Levelized Annual Revenue Requirement	$133,000

Estimate Basis:	February 1993	Debt Rate:	6.5%
Start-up:	February 1993	Discount Rate:	6.5%
Plant Life:	20 years		
Battery Life:	6.67 years	Escalation Rates:	
		Materials:	4.5%
		Labor:	5.0%
		Batteries:	3.0%

Table 7-7

Comparison of Battery Designs

	Battery-Only	DC-Battery	Battery-PCS
Regulation	6%	~0.5%	~0.5%
No. of Cells	1,440	768	576
Length	458 feet	122 feet	232 feet
Capital Cost (w/o interface)	$558K	$1,276K	$956K
LARR	$120K	$174K	$133K
Replacement Battery Cost	$191K	$102K	$76K

RECTIFIER SYSTEM

Design Basis

Bechtel also evaluated solutions to the BART transbay tube voltage sag problem using conventional, non-storage equipment. Addition of a traction rectifier at the tube midpoint (MCG) was selected as the most promising non-storage solution and evaluated in detail. (The contact and running rails in the tube have been designed to lower their resistance, and adding more conductor did not appear to be cost effective.) What Bechtel evaluated was not a standard, continuous-duty rectifier, but rather a rectifier which could be far more compact and inexpensive owing to its being used only in pulse-duty mode, as were the energy storage systems described previously.

The rectifier was specified to meet the same requirements as the energy storage systems: delivery of up to seven pulses at 800 V with a peak current of 4,000 amps, an energy of 8 MJ, a pulse duration of 5 seconds, and 90 seconds between pulses. This duty cycle is less severe than conventional traction rectifier specifications: basically components can be run at ratings far above their thermal limits for continuous use when they cycle on for such brief periods. However, the rectifier is also required to be sufficiently compact to enable its installation in the gallery of the transbay tube, a requirement which is more severe than for conventional traction rectifiers.

The basic performance of a rectifier at MCG was modeled along with the Battery-Only system. A conventional 6% regulation was used. This results in a voltage span of 50 V, for a current variation of zero to 4,000 amps.

System Design

Telephone discussions and meetings were held with IMPulse NC, Inc., of Mount Olive, North Carolina, a manufacturer of traction rectifiers, compact mine rectifiers, and similar equipment. IMPulse indicated that it could fabricate the required equipment. Its initial design was based on a 15-kVAC supply (Figures 7-10 and 7-11). However, the peak power involved, 3.2 MW, is more than could be supplied by the 12.7 kV available at the west ventilation structure and therefore requires that AC power be supplied at 34.5 kV. IMPulse revised its design, but not the equipment layout drawing. This drawing was marked up by Bechtel to reflect the final design.

The largest item of equipment is the rectifier transformer, consisting of three dry-type, single-phase units. The individual transformers can be moved through the gallery door. The transformer cabinet is too large to fit through the doorway, and must be assembled in place. The completed transformer cabinet is 168 inches long by 48 inches deep by 76 inches tall. The rectifier cabinet is as illustrated, 96-inches long by 42 inches deep by 76 inches tall. The 15-kV breaker was replaced by a 34.5-kV breaker. This is more compact than a standard breaker cabinet, which would be 5 feet wide by 7 feet deep by 7 feet tall. For this location, a customized cabinet would have to be no more than 4 feet wide. The transformer weighs 15,000 pounds, and the rectifier unit weighs 10,000 pounds.

In the Bechtel design, AC power for the rectifier is supplied from the Baytube East Substation (KTE). Modifications to the existing KTE substation are required to terminate the 34.5-kV cables. The connection is made at breaker KTE 252-1. Three 250-kcmil single-conductor cables are installed in a 6-inch rigid galvanized steel conduit from KTE to the gap breaker station (MCG). The conduit is wall-mounted in the lower gallery. Cable splice boxes are provided every 2,500 feet between MCG and KTE. Cable shields in the splice box located at the midpoint are grounded through spark gap arresters. The 34.5-kV cables will be connected to the new 34.5-kV, 1,200-amp main breaker located at MCG. The main breaker is furnished with protective relays.

Modifications to this Bechtel design could lower the costs of a rectifier solution. First, Bechtel specifies three 250-kcmil cables. This meets the BATC specification for rectifier transformer substation feed. However, it is wildly oversized for this pulse-duty application. Cable size could be decreased, and conduit size decreased: since the lion's share of the rectifier cost is in cable and cable-pulling labor, this could net appreciable savings. (BART may have space in existing conduit, which would provide a further dramatic cost reduction.) As a separate issue, it may also be unnecessary to include spark gap arresters in an underground installation. BART will need to evaluate the appropriateness of BATC standards for this unusual application.

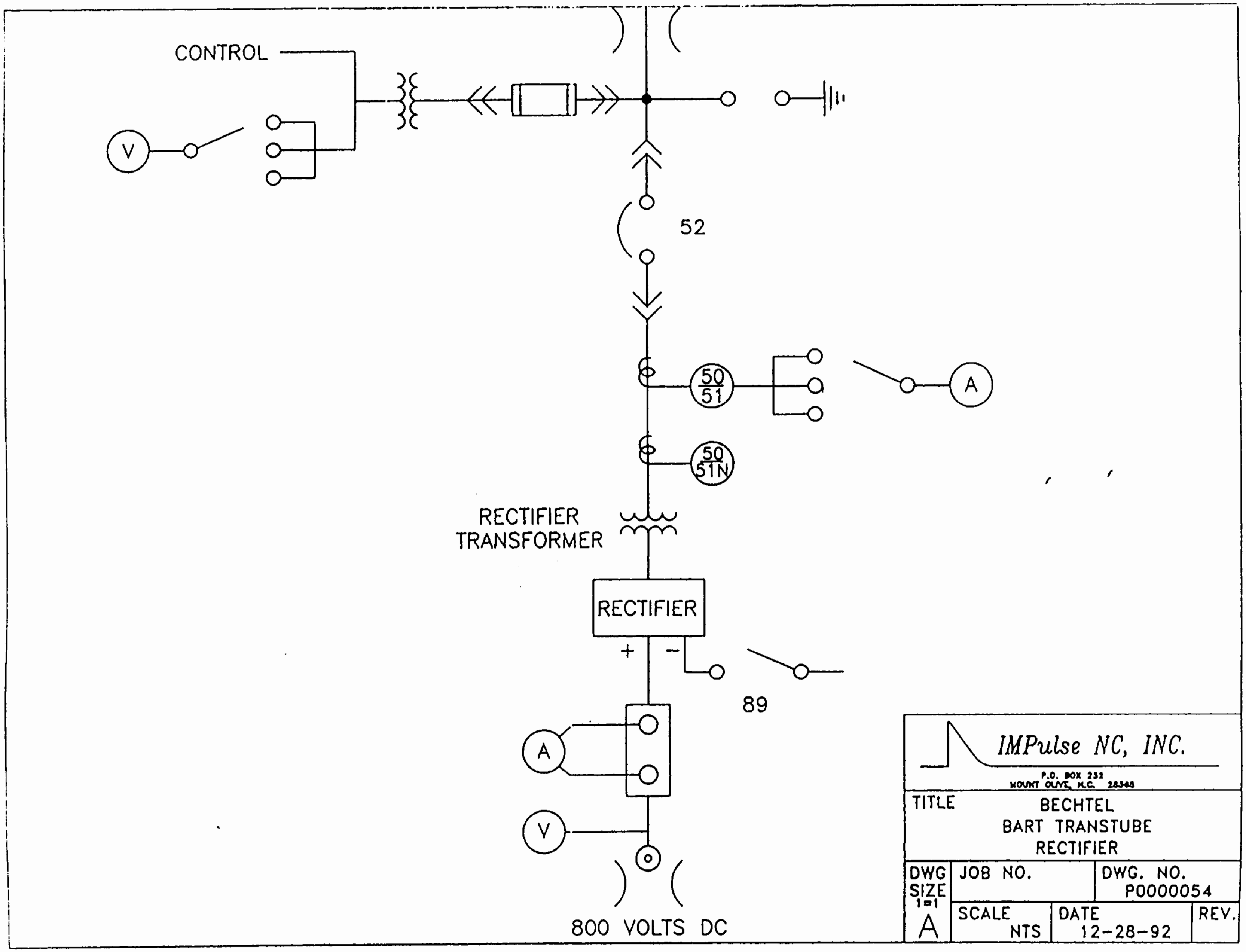


Figure 7-10. Electrical configuration of the traction rectifier design for the transbay tube.

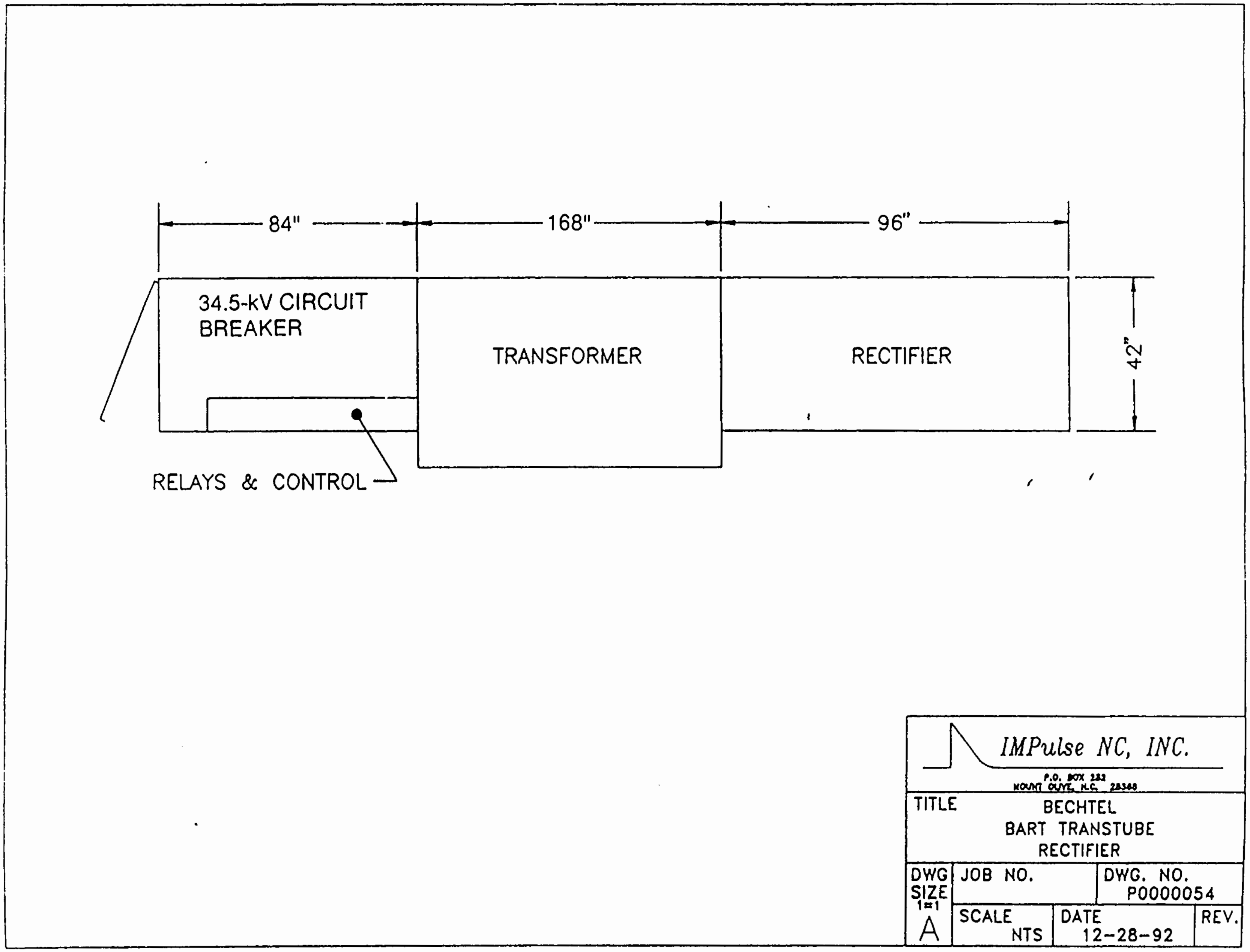


Figure 7-11. Physical configuration of the traction rectifier design for the transbay tube.

As for the battery energy storage systems, the output of the rectifier is connected to the BART rails through the DC interface subsystem.

Cost Estimate

Cost estimate details for the Rectifier system are shown in Table 7-8. The basis of the estimate is the same as for the battery system cost estimates. IMPulse estimated the cost for the rectifier system to be $220K, FOB North Carolina. This cost includes a negative disconnect, and the cost of the equivalent disconnect in the DC interface subsystem is deducted from the rectifier cost in the table.

Other Cost Factors

The major operating cost is due to magnetization losses in the rectifier transformer. These are estimated to be 35 MWh per year and, at $0.10/kWh, lead to an operating cost of $3,500 per year. Maintenance is estimated to require 40 hours, for an annual maintenance cost of $2K. The LARR of the rectifier system was calculated to allow comparison with the battery systems which require periodic cell replacement expenditures. The estimated LARR of the rectifier system is $219K. Details are presented in Table 7-9.

CONCLUSIONS ON BATTERY AND RECTIFIER DESIGNS

The capital costs and LARR for the five systems evaluated are summarized in Table 7-10. The Battery-Only system is the low-cost approach despite the large cost associated with periodic replacement of the battery. However, its regulation and footprint may be unacceptable to BART. The Battery-Only design has a 6% regulation, as does the rectifier system, which means that it needs to switch in to operation 50 V above the minimum tolerable voltage to support a load of 4,000 amp at 800 V.

The three PCS-based designs ("DC-Battery," Battery-PCS, and SMES) are able to maintain a constant 800-V output, plus or minus "a few volts" from zero to full current. It may be possible to design a rectifier system with 4% or even 3% regulation, but it is unlikely that it would fit into the gallery of the transbay tube. The Battery-Only system could be designed to have any practical regulation by increasing the number of parallel strings. Some 84 strings of Delco 2000 modules would be required to attain 1.5% regulation (with a corresponding increase in cost and footprint).

In general, PCS-based designs would deliver up to their rated current (e.g., 4,000 amps), and then protective circuitry would limit the current to the rated value despite any further decreases in load resistance. The Battery-Only and rectifier systems could continue to increase current beyond the rated 4,000 amps as load resistance decreased, but with a decreasing voltage. The ratings of the rectifier diodes would likely limit the maximum current from the rectifier system. Attaining the 6% regulation with the

0075944

Table 7-8
Rectifier System Cost Summary ($1993)

QTY BY: ENGINEERING
EST BY: R. H. ALMOGELA
DATE: FEBRUARY 18, 1993

PROJECT DESCRIPTION: TRANSBAY TUBE POWER QUALITY STUDY
CLIENT: BAY AREA RAPID TRANSIT DISTRICT (BART)
LOCATION: SAN FRANCISCO AREA, CALIFORNIA

ITEM	DESCRIPTION	QTY	UNIT MEAS	UNIT COST MTL	UNIT COST MHR	UNIT COST ALLOW	TOTAL MHR	$/MHR	COSTS IN 1993 $ MATERIAL	COSTS IN 1993 $ LABOR	COSTS IN 1993 $ ALLOW	TOTAL COSTS
1	34.5 kv 1200A Vacuum Circuit Breaker	1	ea	45,000	120.00		120.00		45,000	4,500		49,500
2	3 MW Transformer/Rectifier unit	1	ea	220,000	800.00		800		220,000	29,700		249,700
3	Spark Gap Arresters	3	ea	2,500	20.00		60		7,500	2,200		9,700
4	6" Rigid galvanized steel conduit w/ ftgs. & suppts.	10,000	lf	35	0.98		9,800		350,000	363,800		713,800
5	Metal Splice Box, 2'H x 4'W x 18'L, nema 4	3	ea	3,000	36.00		108		9,000	4,000		13,000
6	1/c #250 kcmil, 34.5kv EPR insulated	30,100	lf	5.60	0.14		4,214		168,560	156,400		324,960
7	35kv cable terminations	12	ea	100	16.00		192		1,200	7,100		8,300
8	34.5kv Splice Kits	9	ea	150	20.00		180		1,350	6,700		8,050
9	Allowance for misc. modifications to existing equipt. (e.g. substa. KTE, SCADA @ LMA, etc.)	1	lot	25,000					25,000			25,000
10	Deduct for negative disconnect	(1)	ea	3,800	40.00		(40)		(3,800)	(1,500)		(5,300)
	TOTAL DIRECT COST						15,434		823,810	572,900		1,396,710
	SALES TAX @8.25% on material								67,960			67,960
	FREIGHT COST ALLOWANCE										3,000	3,000
	INDIRECT COST @ 35% on Labor $ only.									200,520		200,520
	CONTINGENCY @10%											166,820
	ENGINEERING AND MANAGEMENT COST @ 10%											183,500

Rounding	490
RECTIFIER SUBSYSTEM	2,019,000
DC INTERFACE SUBSYSTEM	304,000
TOTAL SYSTEM COST	2,323,000

Table 7-9

Economics of Rectifier System ($1993)

	Estimated Cost
Capital Costs	
Materials	$1,086,000
Labor	1,236,000
Batteries	N/A
Operating Costs	
Materials	$3,500/year
Labor	$0/year
Maintenance Costs	
Materials	$0/year
Labor	$2,000/year
Batteries	N/A
Battery Replacement Costs	
Labor	N/A
Batteries	N/A
Levelized Annual Revenue Requirement	$219,000

N/A = Not Applicable

Estimate Basis:	February 1993
Start-up:	February 1993
Plant Life:	20 years
Battery Life:	6.67 years

Debt Rate:	6.5%
Discount Rate:	6.5%
Escalation Rates:	
Materials:	4.5%
Labor:	5.0%
Batteries:	3.0%

Table 7-10

Cost and Economic Summary

	Battery-Only	DC-Battery	Battery-PCS	Rectifier	SMES
Capital Cost					
Energy Subsystem	$558,000	$1,276,000	$956,000	$2,019,000	$1,565,000
DC Interface	304,000	304,000	304,000	304,000	304,000
Total	$862,000	$1,580,000	$1,260,000	$2,323,000	$1,869,000
Annual Electricity Cost	$92	$185	$185	$3,500	$36,000
Annual Maintenance Cost	$9,000	$10,000	$5,000	$2,000	$12,000
Battery Replacement Cost	$191,000	$130,000	$77,000	N/A	N/A
LARR	$120,000	$174,000	$133,000	$219,000	$242,000

N/A = Not Applicable

Battery-Only system required a large number of cells which are not deeply discharged in this application. The maximum cell current for this design (i.e., 4,000-amp pulses) is 200 amps. As can be seen from Figure 7-7, the cell is capable of 700 amps (or more for short pulses). This corresponds to a 14,000-amp system current, but at a voltage of 665 V. The present Battery-Only design could deliver up to 8,000 amps while maintaining the voltage above the 750-V train chopper cutoff voltage.

Bechtel used a higher cost for its PCS system than did any of the SMES vendors. Using the cost of the SMES PCS for the Battery-PCS system would lower the cost of this energy storage subsystem by 53% and decrease the LARR of the Battery-PCS system by 33%, to $90K.

After completion of the designs and cost estimates, it was noted that the DC cabling and cable trays comprised a substantial part of some of the system costs (almost half of the Battery-Only direct costs). It is possible that a trade-off between battery rack costs (along with some increase in maintenance cost) and the low density designs used herein could lead to lower costs for the battery energy storage systems. (A more compact racked design would have shorter cable runs.)

One aspect of the study relates to installations at locations other than the Transbay Tube gallery. The gallery presents difficult working conditions. At a location that is readily accessible, a labor productivity factor of 1 would be used. This essentially cuts the labor costs in half and results in the capital costs shown in Table 7-11. Additionally, the costs for the rectifier system reflect a reduction in the length of the AC feeder from 10,000 feet to 100 feet, which results in a major decrease in cost. The effect on maintenance and battery replacement costs were not calculated, but they would be similarly reduced. The numbers in the table neglect the costs of any building to house the system, a function provided by the gallery.

Table 7-11

Approximate Effect on Cost for Easily Accessible Site

	Battery-Only	DC-Battery	Battery-PCS	Rectifier	SMES
Capital Cost					
Energy Subsystem	$380,000	$1,088,000	$816,000	$436,000	$1,565,000
DC Interface	218,000	218,000	218,000	218,000	218,000
Total	$598,000	$1,306,000	$1,034,000	$654,000	$1,783,000
Percent Decrease	31%	17%	18%	72%	5%

An ancillary aspect of the study relates to the incremental costs of an additional megajoule of energy storage and an additional megawatt of power. For the three battery systems and the rectifier system, Bechtel expects no additional cost for an additional megajoule (or several megajoules) of storage capacity, as long as the energy is delivered as more pulses and not as higher voltages or currents. However, that specification was per pulse, and would thus play into either the current or the duration of the pulse.

Bechtel estimated the effect of providing an additional megawatt of power: The FOB cost of the rectifier was estimated to go up by about 20%, and the feeder cable size may have to be increased. But PG&E believes that the cable is already very much oversized for intermittent use, and that it could easily accommodate an additional megawatt. However, it may no longer be possible to fit the transformer into the gallery. The FOB costs of the power electronics portions of the "DC-Battery" and Battery-PCS systems would also increase by about 20%. The battery costs would not increase, but the ratings and costs of cabling, switches, and similar items in the storage and DC interface subsystems may increase. Approximately 25 (versus 20) parallel strings would be required for the Battery-Only case (maintaining 6% regulation). A more definitive answer would require redesigning the systems. The increase in cost for the SMES system was estimated to be $55K, the increase in PCS cost at $55/kW.

Section 8

COMPARISON OF DC TECHNOLOGIES

MATURITY

While there are substantial differences between SMES, battery, and pulse-duty rectifier designs within a given technology, there are even greater differences between technologies. One of the more dramatic contrasts is in maturity.

SMES technology does not have long-term field experience. Lifetimes of superconducting magnets and cryogenic systems are extrapolated from the behavior of the magnets at Fermi Lab, where similar sized magnets have been operating for the past 15 to 20 years. But these are in a laboratory environment, clean and attentively maintained. The BART tube constitutes a significantly different environment: very dirty, difficult access, with drafts which will pull the sooty dust inside equipment cabinets. Recent experience with kaolin separation using superconducting magnets more closely approaches this element of the transit environment, and the experience there indicates good reliability and robustness, even in a dusty industrial installation. Thus, there are good reasons to believe that SMES technology can operate reliably in the tube environment. Batteries currently are used in the tube to power various auxiliary and standby equipment, so BART has experience with battery lifetime and maintenance in the tube. The pulse-duty rectifier would resemble other BART equipment, and its durability and operability in transit environments is not in question. As a public agency, BART places a very high value on reliability.

SMES prices are far less certain than those of batteries or the rectifier. As a new technology, SMES is still at the top of its price curve and subject to significant price decreases. In a recent PG&E report (Lau, Pupp, and Schoenung 1993), Susan Schoenung of W. J. Schafer and Associates makes detailed cost calculations on the price of cold-supported SMES units over the coming decade. Her results indicate that the cost of a SMES unit in the 1- to 3-MW range, in constant 1992 dollars, will drop to one quarter of today's cost by the time 200 units are built. For one to a few second discharge times, this may drop to one-fifth of the present-day cost. About half of the price drop is expected to occur within the 3 years from 1992 to 1995.

In interpreting these costs, it is not certain whether it would be appropriate to take the PDM cost and discount it to one quarter of its present value to obtain a price for the year 2002, or whether the starting value should be the present-day price of the SI system. A second uncertainty is whether the vendor-quoted prices for 1994 delivery should be considered to be base-year or third-year costs. Since Schoenung's cost-decline curve is based on manufacturing experience, it is likely appropriate to use

1994 as the base year, in light of the very few SMES sales to date. If indeed PDM costs will drop by the factor which Schoenung predicts, and if they are base-year costs as quoted, SMES will become an extremely attractive option for transit applications. Even if SMES costs drop only to one-fourth of the present-day SI prices (or to half of the PDM price), SMES will still compete very favorably with the other technologies considered in this report.

ECONOMICS

The cost estimates of the designs vary greatly in the level of detail, so in addition to the future cost decreases, there are uncertainties in the 1994 installation costs of the systems. The SMES system costs were determined on a less detailed level than either the battery or rectifier costs. Bechtel's determination of rectifier installed cost is likely to be highly accurate and comprehensive within its assumptions and choice of standards. Bechtel's determination of battery cost is very complete in terms of labor rates, productivity factors, and auxiliary equipment installation, but does rely on a minor level of extrapolation for some equipment prices: it should be quite solid overall.

Among the SMES design teams, PDM alone includes installation of the unit in its pricing. The PDM response to the RFI states clearly that it includes system integration, transportation, installation, and checkout of the system in the Transbay Tube, using BART-provided transportation in the tunnel itself. This means that PDM would bear any penalty for error in its estimation of installation labor cost or productivity. On the other hand, the PDM price is clearly identified as a budgetary cost estimate rather than a quote for procurement. In favor of the reliability of the PDM price is the fact that most of the components of the PDM system are currently in commercial production and sold by the members of the team.

Prices from SI do not include installation. However, because SI currently is actively marketing SMES units, and has sold some, the SI prices do reflect a true market price rather than a budgetary estimate.

Westinghouse identifies its price as a budgetary cost estimate, not a bid. Because the company is still involved in refinement and detailed specification of its design, its prices are perhaps the least certain of the three vendors. Westinghouse does not include installation in its cost estimate.

In summary, the SMES prices are the least certain among the DC technologies by reason of the immaturity of the technology, the fact that some of the systems are first-of-a-kind for their vendors, and the unknowns of installation difficulty.

TECHNICAL ASPECTS

The SMES, battery, and rectifier options meet the functional specification to varying degrees. Perhaps the issues of footprint, lifetime, and voltage drop at the device are among the more telling ones. Among these, footprint and lifetime are easily evaluated, but voltage drop at the device raises complex and important issues.

System Footprint

The SMES and Rectifier systems fit within the specified floor space (4 feet by 50 feet) of the functional specification to within a 20% tolerance (See Table 6-2). The rectifier is the most compact of all at 4 feet by 29 feet by 7 feet. However, the battery systems vary dramatically, ranging up to a floor length of over 450 feet.

Among the battery systems, the Battery-Only system, which is the least costly by about a factor of 2, would take 458 linear feet of the gallery, in a 2.3-foot swath along one wall. While this does not violate any physical constraint of the BART gallery, it exceeds *by nearly an order of magnitude* the preferred BART dimensions. This design was meant to probe the low price limits of battery support to voltage sag, but clearly fails to meet the footprint spec. Decreasing the length of the system by stacking the batteries in racks would correspondingly increase the price of the system, unless savings from decreased cable runs offset rack costs appreciably. The "DC-Battery" system, which combines rack-mounted batteries with modular power conditioning units, comes the closest to meeting the footprint specification at 3.3 feet by 122 feet by 4.3 feet. It is also the most expensive of the battery systems, suffering the penalties of both multiple power conditioners and battery racks. However, this is still a factor of 2.4 longer than BART prefers. The third battery system, the Battery-PCS system, comes in at intermediate values of both length and price: a system size of 3.5 feet by 232 feet by 6 feet results from lining the batteries up along the wall on the floor of the tube, without racks, beside their respective power conditioner cabinets.

System Lifetime

The system lifetime of the rectifier is 30 years, which is consistent with long experience with similar equipment. The lifetime of the SMES systems is expected to be a minimum of 20 years, which was the value in the functional specification. SMES system lifetime may significantly exceed that number, but experience with the components of this new technology is of insufficient duration to establish that with certainty. The battery systems will require replacement of the batteries themselves twice in the 20-year specified lifetime according to manufacturer expectation of battery service life.

Voltage Drop in Device

Most important is the issue of voltage drop in the device as current is drawn: transit parlance calls this "regulation," whereas utility engineers refer to it as "voltage drop" (and save the term "regulation" to apply to a different phenomenon). Here the term is used to indicate the slope of the voltage vs. current graph with increasing current. As described in Section 7 on the Battery-Only design, the inherent internal resistance of the batteries will cause the voltage out of the system to drop as the current draw increases. This will have an unwanted effect: to support the track voltage at 825 V or above at MCG, for example, it will be necessary to have the battery system switch in at a track voltage of about 875 V. This may prove to be a problem because of overuse of the battery. In the normal rush hour operation scenario, case NNS, the track voltage drops to a value of 875 V somewhere in the MCG to KTE track segment in 40% of the train passages through the tube (see Figure 3-1). It drops to a value of 875 V in the MCG to MTW segment in 30% of the cases. Thus, in a significant number of the cases of normal rush hour train passage, the battery will actually switch into operation and support the voltage at tube center as rush hour trains pass. This could prove to severely limit battery lifetime. Although rough estimates by Bechtel support the feasibility of the design and the relatively low probability that this will be a problem, it is an issue which would bear further scrutiny if such a design were seriously considered.

The pulse-duty rectifier system has a similar voltage vs. current characteristic, since both were designed to mimic the 6% voltage drop of the present-day rectifier substations. In the case of the rectifier, this is also an issue which would require further analysis. If, to support track voltage above 750 V at locations a few thousand feet from MCG, the rectifier support voltage had to be set at 825 V, then the cut-in voltage would have to be set at 875 V.

Transients which drop below 750 V are brief—usually 1 to 5 seconds, possibly as long as 11 seconds—but there are no statistics on duration of voltage drop below 875 V at the gap breaker station. In some of the simulation results of train voltage versus track position, there are events in the tube where train voltage drops below 875 V for much longer than 5 seconds. For example, in case S11 (the voltage collapse crisis with 775-V SMES support), where the voltage at MCG drops below 775 V for a total of 13 seconds, it drops below 850 V for a total of 36 seconds during the 60 seconds following 07:10. It is below 875 V for 45 seconds out of that minute. The resulting prolonged operation of the rectifier might cause it to exceed its thermal limits, which were established by the 5-second transient specification. This would more likely affect the semiconductor components than the transformer, with its large thermal mass. It could necessitate upgrade of the silicon-controlled rectifiers (SCRs), or it could decrease transformer life.

In that same case, the lead train (number 112, labeled "first in delay queue") traverses the distance between track location 20,000 foot and location 25,000 foot at a speed of 68 mph, which is 100 feet per second. During that 50-second interval, the train experiences a voltage below 850 V for a total of 25 seconds. If a traveling train experiences a fluctuating voltage of this level, then MCG, as a vulnerable location far from supply points, probably experiences voltage levels which are similar or worse. Even in case ND1 (recovery from a delay at the Oakland Wye), train line voltage plotted against distance reveals a period of about 7 seconds when the voltage drops below 850 V just east of MCG. (This same case exhibits no sag below 750 V.) Thus, these events are found in many operational scenarios.

Before specification of a pulse-duty rectifier could confidently be made, it would be necessary to quantify the actual duty which it would experience. If the transformers of the present design were shown to be thermally inadequate for the expected duty, it could pose size problems for a system design which would fit into the transbay tube gallery.

For the SMES units and for the battery systems with power conditioning, voltage drop is not an issue. Owing to the characteristics of the power conditioning units, these systems can deliver up to their rated current at a very constant voltage (likely better than 1%). Thus, the SMES systems, or the battery systems with power conditioners, will be able to switch in at virtually the support voltage level, rather than 50 V above it as with the rectifier and battery only systems, and as a consequence will support a significantly smaller number of events.

Furthermore, in the case of SMES, no damage to the unit is expected under an overload scenario. In contrast to the rectifier case, where thermal ratings could be exceeded, or to the battery, where life could be shortened by overuse, if the SMES unit is charged, it will discharge when triggered. If a subsequent demand comes before recharge, the SMES unit will simply not support it. The number of pulses which a SMES unit can sustain before any lifetime limiting effects set in is likely to far exceed the number specified for 20 years of operation. Thus the unit lifetime is not compromised by system operation. An issue of refrigeration sufficiency could arise (from AC losses in the magnet) with very frequent discharge of a SMES unit.

The battery systems with power conditioners ("DC-Battery" and Battery-PCS designs) will not be subject to the excess numbers of discharges which the Battery-Only system would have to endure owing to its high effective internal resistance. They will discharge only to forestall actual voltage sag events below motor cutout. Thus their lifetimes should be as specified.

RISKS

Operation

On the basis of PG&E's in-house testing of an SI SMES unit in 1990-91 (Wenger and Heinzmann 1992), SMES is highly likely to meet the technical specification and respond reliably to thousands of discharge cycles. SI experience with installing its units for AC industrial power quality applications over the past year support PG&E test results. On the basis of PBMQD computer simulations to date (see Section 3), sag events which need support will be spaced sufficiently for AC losses to be handled by the SMES refrigeration systems.

Battery Lifetime

The risk is very low that the batteries with power conditioners will be lifetime-compromised and thus perform below manufacturers specs. The risk is somewhat higher for the Battery-Only system, owing to the large voltage drop with current in the battery. Bechtel's rough calculations indicate that this is an unlikely problem.

Seismic Sensitivity

All the designs considered for this study appear to be robust from a seismic viewpoint.

Rectifier Operation

More information is needed to quantify the risk of thermal overload in the rectifier. It may be the crucial weak point in what otherwise appears to be a good conservative solution to the BART voltage sag problem in the transbay tube.

SAFETY ISSUES

DC Magnetic Fields

The issue of electromagnetic field effects must be addressed in a discussion of SMES safety. There is significant public concern over the possibility that power frequency (50-60 cycle) electromagnetic fields might cause deleterious health effects. The jury is still out on that issue, with well-designed, large-scale studies showing conflicting results. Furthermore, this study does not deal with power frequency fields. The SMES unit would have a DC, or static, magnetic field when it was in a charged state (i.e., a magnetic field whose direction and magnitude are constant in time). In the period of charge or discharge of a few seconds several times a week, there would be a transient field of constant direction but changing magnitude as the magnetic field grew or collapsed. As a train passed the device, it would experience a time-varying field owing to traveling through the space-varying field of the magnet. To what can we compare these fields? Could they be decreased? What are their magnitudes? Are they a cause for concern?

These fields can be compared to the static field of the earth, to which we all have lifelong exposure, and we can compare them to various standards which have been proposed. The magnetic field of the earth is roughly half a Gauss at the surface. Magnetic field is measured in Tesla or Gauss (1 Tesla = 10,000 Gauss). Safety guidelines for exposure to static magnetic fields have been published by the American Conference of Governmental Industrial Hygienists. The static magnetic field experienced during an MRI scan (magnetic resonance imaging; for routine medical diagnosis) is 1-2 Tesla. The guideline states the following:

> Routine occupational exposures should not exceed 60 milli-Tesla (mT), equivalent to 600 Gauss, whole body or 600 mT (6,000 Gauss) to the extremities on a daily, time-weighted average basis. A flux density of 2 Tesla (20,000 Gauss) is recommended as a ceiling value. Safety hazards may exist from the mechanical forces exerted by the magnetic field upon ferromagnetic tools and medical implants. Workers having implanted cardiac pacemakers should not be exposed above 1.0 mT (10 Gauss). At higher flux densities, perceptible or adverse effects may also be produced resulting from forces upon other implanted ferromagnetic medical devices (e.g., suture staples, aneurysm clips, prostheses).

Other organizations have published their own recommendations. See Appendix A for a table of values and sources.

External fields can be decreased. Magnetic materials such as iron or some steel can contain or shield magnetic fields. The iron used as reinforcement in concrete, such as in the sections of the Tansbay Tube, would also act to shield penetration of magnetic fields from the gallery to the track area. Joints between sections of the transbay tube are strengthened by half-inch boiler plate lining the gallery for a 15-foot section. Thus, there are possibilities for installing SMES coils where there would be significant shielding from the structure of the tube itself. Two of the vendors have proposed that the SMES device could be charged only "on demand," when the train control logic predicted that a voltage sag was likely. In that case, there would be no external magnetic field at all, except for the few brief periods each day or week when a low track voltage was anticipated, but advanced train control would be necessary.

What is the magnitude of the DC magnetic field from a SMES unit? Three SMES designs have substantial differences in external magnetic fields. With its toroidal approach, the Westinghouse design has a remarkably low external static magnetic field of 10 Gauss at less than 2 feet from the cryostat (no external shielding). Thus, fields in the track area from the SMES unit would be comparable to the magnitude of the earth's magnetic field. SI calculates that with its proposed shielding in place, its open solenoid configuration would give fields of 10 Gauss or less in the compartment of a passing train, thus meeting the stringent pacemaker standard. The PDM design, an open solenoid with no additional shielding, would, in the absence of structural shielding, result in a DC field which exceeded 100 Gauss within the nearer third of the track bore. The 10-Gauss line, in the absence of structural shielding, would fall outside the confines of the tube structure. Detailed calculations would be necessary to determine the extent to which these fields would be decreased by the presence of structural rebar or boiler plate; it is likely to be a significant diminution of their magnitude. If it is assumed that the PDM single long solenoid could be installed in a boiler plate section, and that further shielding would cost roughly what the SI modular shielding costs, then at a supplemental cost of about $280K, the PDM external fields could possibly be dropped to values comparable to the SI design. Detailed calculations would be required to verify this hypothesis.

What does this mean? The highest fields experienced by passengers from any of the SMES designs will be far below the occupational exposure limits. The Westinghouse and SI designs will observe the most stringent limit, that which warns pacemaker and prosthetic implant users. The PDM design may result in fields in the passenger compartment of trains which significantly exceed the 10-Gauss pacemaker limit. (Note: Recently, the American Conference of Governmental Industrial Hygienists has decreased the recommended exposure limit for static magnetic field exposure of the general unsuspecting public to 5 gauss from the former 10-gauss value. This is in response to a recent study in Italy in which pacemakers from 15 manufacturers were tested for their operation in a static magnetic field. Pacemaker operational parameters are programmed from outside the body with a static magnetic field which activates a magnetic reed relay switch inside the device. Some were found to change state at values of magnetic flux between 5 and 10 gauss, but none below 5 gauss. This indicates that SMES would need to be well enough shielded, or sited sufficiently distant from the track, for passengers to experience fields only below 5 gauss.)

Workers in the gallery of the Transbay Tube would be much closer to the device than passengers of trains, and would experience higher static magnetic fields when the unit was charged. In the case of the Westinghouse toroidal units, this is not an issue, since even at a distance of 2 feet from the cryostat, the DC magnetic field is below a 10-Gauss value. In the case of the SI and PDM solenoidal designs, there is a danger from the strong pull which the static magnetic field will exert on tools. A loosely held or carelessly placed wrench would tend to be attracted with an ever-increasing force towards the cryostat. SI suggests placing exclusion gates at either end of the SMES installation, which would trigger automatic discharge of the unit while any worker was in the exclusion area. Because there is only very light traffic of personnel through the gallery, this is a practical solution. (The median week may see one worker walk the gallery from end to end, usually at midday.)

Cryogenic Fluids

All three vendors address the issue of escape of cold helium gas in the gallery. This is a concern because if helium were to displace air in a segment of the gallery, it would provide a suffocating atmosphere. The amount of liquid helium which would be present in the SI design is 600 liters in each of the four modular cryostats, for a total of 2,400 liters of liquid helium. (With a density of 0.12 g/cm^3 at the boiling point, that helium would fill the gallery to a length of 870 feet at standard temperature and pressure in still air conditions. Ventilating fans at each end of the tube create a constant air flow in the gallery of 2,900 cfm. Ignoring mixing, this would be a flow of only 40 linear feet per minute.) All three designs specify cryostats built to boiler code, so that they could maintain the helium under pressure as a gas.

Battery Leakage

Bechtel's battery designs have a plastic liner beneath the lead-acid batteries to contain any acid spills. Lexan plastic sheets are placed on top of the modules to provide for personnel electrical safety. The float voltage, charge regime, and temperature are anticipated to be below the TVG (temperature, voltage, gassing) curve, so hydrogen evolution should not occur. However, several hydrogen monitors are included in the design, and are interlocked to turn off the charger if hydrogen above 1% is detected. This would eliminate the possibility that explosive concentrations of hydrogen could build up. The planned voltages are also below the threshold voltage for production of stibine, a poisonous gas. The design includes wall-mounted emergency eye wash stations in case of acid accidents. (Such eye wash stations also accompany some other, much smaller battery installations in the tube gallery.)

Section 9

CONCLUSIONS AND RECOMMENDATIONS

AC MONITORING

This report has focused on the DC side of the BART electrical system and its interaction with train operations. A companion report, *Monitoring the BART Baytube Traction Power System*, describes the time-coordinated monitoring of both the DC and AC sides of the BART electrical system in the vicinity of the transbay tube (Heinzmann 1995). This monitoring occurred in the second and third quarters of 1993. The complete test plan for that monitoring program appears in this report as Appendix F.

In brief, that effort found that voltage sags at the center of the transbay tube were far less frequent than had originally been thought. So there is little likelihood that a wayside energy storage solution at MCG would eliminate the jerky train motions which were the impetus for this work.

CONCLUSIONS

This phase of the study has established a functional specification for a storage system to support the transient voltage sag problem in BART's transbay tube. A limited set of computer simulation runs has provided some quantitative understanding of the conditions under which low-voltage transients are likely to occur. Three vendors have provided conceptual designs of SMES units to meet the functional specification, and Bechtel has provided three battery system designs as well as a pulse-duty rectifier design. Economic comparison of the various solutions has been made. What conclusions can be drawn at this point?

It is fairly likely that any of the seven design solutions to the low-voltage transient problem could technically solve the problem which was posed, although some questions remain on the functionality of the Battery-Only and rectifier designs. It is highly likely that either SMES or battery systems with power conditioners would work well. The battery systems have much larger footprints than specified. The SMES designs appear to be more costly than the battery and rectifier designs with present-day costs, but projections of costs over time indicate that SMES could be the least expensive technology 5 years from now. However, the results of the companion study of time-coordinated monitoring on the BART system cast doubt that the problem addressed by this study is the problem which BART actually experiences. For this reason, a local transient energy source no longer appears to be a certain single solution to the jerky train motion which BART train operators report.

The level of complexity of the BART system has limited the scope of this study to a small set of the possible ways that low-voltage transients could be eliminated or reduced. A promising line of inquiry for BART could be to investigate the contribution which advanced train control (ATC) could make, either alone or in conjunction with a wayside energy source. It would be desirable for ATC to limit train acceleration rates when substation loadings were high, when track segment congestion occurred, or when a train stopped far from a rectifier substation. If SMES were still deemed desirable after implementation of ATC, then it would be helpful to have an ATC which would allow the SMES system to charge on demand (as referred to in Section 5); refrigeration load could be reduced by charging the unit only when use was anticipated, and savings on electricity consumption would subtract directly from the LARR for the device. Such charge-on-demand would also eliminate the DC magnetic field from the device except for its brief periods of charge (less than 1% of the time) and thus aid in avoidance of controversy.

If, in weighing the complexity of ATC, it is decided that a compact, transient, local energy source would still be a desirable adjunct to system operation, then the outlook for SMES is sufficiently favorable to warrant proceeding with a test phase. Such a test phase would allow the refinement of our quantitative understanding of the problem through further simulations and monitoring. This would improve our statistical knowledge of where, when, how frequently, for what duration, and to what depth, transient low-voltage conditions occur on the BART system. It is expected that SMES would be proven able to support some range of these sags.

The Electric Power Research Institute (EPRI), our cofunder in this study, also has an interest in piggybacking a battery test on the SMES test at BART. This would utilize much of the same test plan and connection hardware. It would have the advantage of providing two qualified solutions from which BART could chose its preferred solution.

RECOMMENDATIONS

In the original plan for implementation of SMES at BART, it was planned to follow this study with, first, a test of SMES at the BART test track, and, second, a test installation of SMES on the BART revenue track at a surface location which suffers voltage sags. Both of these tests would have employed a leased sub-scale SMES device (smaller than described in the functional specification).

In Phase 1A, measurements at the test track would have determined whether voltage sag was mitigated at the set voltage of the SMES device, characterized single train loads, and quantified magnetic fields in trains passing the device. This test would have determined whether the DC magnetic field impacted the on-board train controllers, acquired field data to determine the simulation parameter refinements for the

SMES device, and performed AC monitoring in the transbay tube and at the test site on the revenue track. Additionally, the testing would have determined the hurdles to revenue track testing, selected a revenue track test site, and performed computer simulations of the BART line which included the selected site.

In Phase 1B, the same sub-scale device was to have been tested on the revenue track. This would have provided on-system operational experience with SMES. This activity would have acquired data on the number of carryovers, duration, energy supplied, etc. We would have obtained information on maintenance and reliability, and monitored magnetic fields on trains passing the SMES device. A refined specification and design for a BART-optimized SMES device and refined cost information for a full-scale test would have resulted, and simulations to test refined parameters would have been performed.

In Phase 2, a full-scale SMES device would have been tested on the BART system. After qualification testing at the test track, it would have been placed on the revenue track at the same location where the sub-scale device had been tested, and would have been tested over several months. At the end of this testing, BART would have had sufficient cost and performance information to make a decision on procurement of SMES for permanent system support.

However, because the results of the AC monitoring program (Heinzmann 1995) differ so markedly from the voltage profiles on which initial assumptions were based, and because of our insights from the simulations on the contributions which AATC could make to mitigation of sharp transient loading of the system, it is no longer anticipated that we will proceed with these further phases. They are briefly outlined above only to aid others who may later scope similar applications. BART will benefit in its development of advanced train control and from the insights on train operations gained in this study.

Section 10
REFERENCES

DeWinkel, C., and J. D. Lamoree. June 1993. "Storing Power for Critical Loads." *IEEE Spectrum* Vol. 30(6):38-42.

Heinzmann, J. D. 1995. *Monitoring of the BART Baytube Traction Power System.* Report 007.5-94-12 prepared for Research and Development, Pacific Gas and Electric Company, San Ramon, California.

Heinzmann, J. D., H. Wenger, and M. M. Reading. 1992. *Superconducting Storage for Transient Train Voltage Support: Problem Definition and Technology Survey.* Report 007.4-91.3 prepared for Research and Development, Pacific Gas and Electric Company, San Ramon, California.

Lau, K., R. Pupp, and S. Schoenung. 1993. *Micro-SMES Distribution and Customer Systems Applications Assessment Study.* Report 007.5-93.3 prepared for Research and Development, Pacific Gas and Electric Company, San Ramon, California.

Myer, H. 1992. "AC Battery Development Project Status." Presented at the Utility Battery Storage Systems Program Review, Valley Forge, Pennsylvania, November 17, 1992.

Wenger, H. J., and J. D. Heinzmann. 1992. Superconducting Storage Testing at PG&E: Demonstration of an Emerging Technology for Critical Power Applications. Report 007.3-92.3 prepared for Research and Development, Pacific Gas and Electric Company, San Ramon, California.

Appendix A

FUNCTIONAL SPECIFICATION

FUNCTIONAL SPECIFICATION
for an
ENERGY STORAGE SYSTEM

- - BART Transbay Tube Power Quality Study - -

BACKGROUND

The Bay Area Rapid Transit District (BART) system includes a 3½ mile long tube under San Francisco Bay. Due to the relatively long distance between the traction rectifier substations at each end of the tube, the train voltage may drop to undesirably low levels under certain conditions. These conditions may include rush hour traffic and train delays, at present, and decreased train headways in the future. The train drive choppers will cut out if the voltage falls below 750 volts (for the nominal 1000-volt DC system). This results in jerky motion of the trains and increased maintenance, as well as passenger discomfort and anxiety. A study is currently being performed to evaluate energy storage and conventional equipment solutions to this voltage sag condition in the BART transbay tube. Both Superconducting Magnetic Energy Storage and Battery Energy Storage systems are being evaluated. The study is sponsored by BART, Pacific Gas and Electric Company's Department of Research and Development (PG&E R&D) and the Electric Power Research Institute (EPRI).

ESS REQUIREMENTS

General

The ESS system shall be designed for unattended operation and control, a 20-year design life, minimum maintenance, 90% availability, and 90% starting reliability.

Components shall be designed and installed in a manner to allow convenient access, safe operation and ease of maintenance. The ESS and its equipment shall be designed to ensure that normal ESS operation, faults or malfunctions will not affect the rail system or train operation, or result in an unsafe condition.

Power and Energy

Simulation modeling has been used to determine the parameters for voltage sag events, and to estimate the power and energy requirements for the energy storage and conventional solutions. Statistical variations in train operations preclude prescribing a precisely defined power or current versus time profile for the ESS discharge. The device must satisfy the following requirements: The ESS shall be capable of delivering an eight (8) megajoule pulse of energy. The pulse duration is five (5) seconds. The required maximum current is 4,000 amps. The ESS terminal voltage shall be 800 volts at the maximum current. This delivery voltage shall be field adjustable from 775 to 825 volts. Even if the rail voltage drops below the set point, the SMES should continue to inject at maximum current until exhausted.

The ESS shall be capable of delivering up to seven (7) such pulses with 90 seconds between pulses. The ESS may recharge between the pulses. There will be no more than one such series of seven pulses per day, and no more than 350 pulses per year.

Recharge of the ESS at high power from the dc rail system during rush hour train traffic can lower the track voltage to an undesirable level. Therefore, it is required that the ESS design and/or its control system include provisions to prevent recharge from lowering track voltage below 825 volts. Possible options include:

- Delay recharge from the tracks until the track voltage is above 850 volts for five (5) seconds and stop the recharge if the track voltage falls below 825 volts. These voltage points shall be field adjustable ± 25 volts.

- Recharge from the 4160 V_{AC} auxiliary power line. This is subject to the 15 kVA limitation on total power drawn from the auxiliary power line.

- Recharge from 12.47 or 34 kV_{AC} will be permitted, but this would require installation of a cable to the Baytube West (East) substation, approximately 10,000 feet, and may make the ESS unduly expensive.

- Any other recharge scheme/schedule that does not reduce the voltage on trains below 825 volts for the train schedules postulated.

Electrical

The ESS shall be connected to the BART dc track system. A simplified electrical single line diagram of the BART system in the area of the transbay tube is shown in Figure 1. The no-load voltage (e.g., no trains on the system) and braking maximum regeneration voltage are approximately 1160 volts. The light-load transition voltage is approximately 1060 volts. The contact rails are positive and the running rails (tracks) are negative. The negative of the BART dc system is connected to ground through diodes and contactors at each substation. This configuration can allow the track to rise up to about 125 volts above earth ground potential during normal operation. In the event of a flashover and fuse operation on train cars, transient voltages of up to 3,000 volts may be present between the positive and negative, and transient voltages of up to several hundred volts may be present between the negative and earth ground. The distance from the MCG (tube midpoint) and either the Baytube East or Baytube West rectifier substation is approximately 10,000 feet. From the midpoint to either rectifier substation the resistances are approximately 0.02 ohms for each of the two contact rails which are in parallel and 0.0218 ohms for the four parallel running rails . The available fault current at the ESS interface is approximately 60,000 amps. The L/R is approximately 0.1 seconds.

The point of electrical power interface for the ESS positive terminal shall be the contact rail in the west-bound bore of the transbay tube at approximately the midpoint of the transbay tube. (The MCG tie breaker provides the connection between the east- and west-bound bores; see Figure 2.) The point of electrical power interface for the ESS negative terminal shall be the track in the west-bound bore. (Track cross-bonds in tube Sections 29 and 32 provide connection between the bores.) Spare conduits (but not cables) exist between the rails and gallery, and shall be used for connection of the ESS. Each 4-inch conduit can hold three 750 kcmil cables.

The ESS shall include fault protection, a visible means of disconnect and lockout on the interface with the BART dc power system. The fault protection shall be on the positive and may be a circuit breaker or a fuse. The fault protection shall be coordinated with existing BART equipment, shall be rated for dc service and shall be capable of interrupting the 60,000-amp dc fault current available at the MCG tie breaker. Disconnects shall be provided on both the positive and negative conductors. Non-load-break disconnect devices shall be key (or otherwise) interlocked to prevent opening under load. Disconnect conductor separation shall be clearly visible; flags or indicators are not acceptable. These disconnects shall be capable of being locked open for

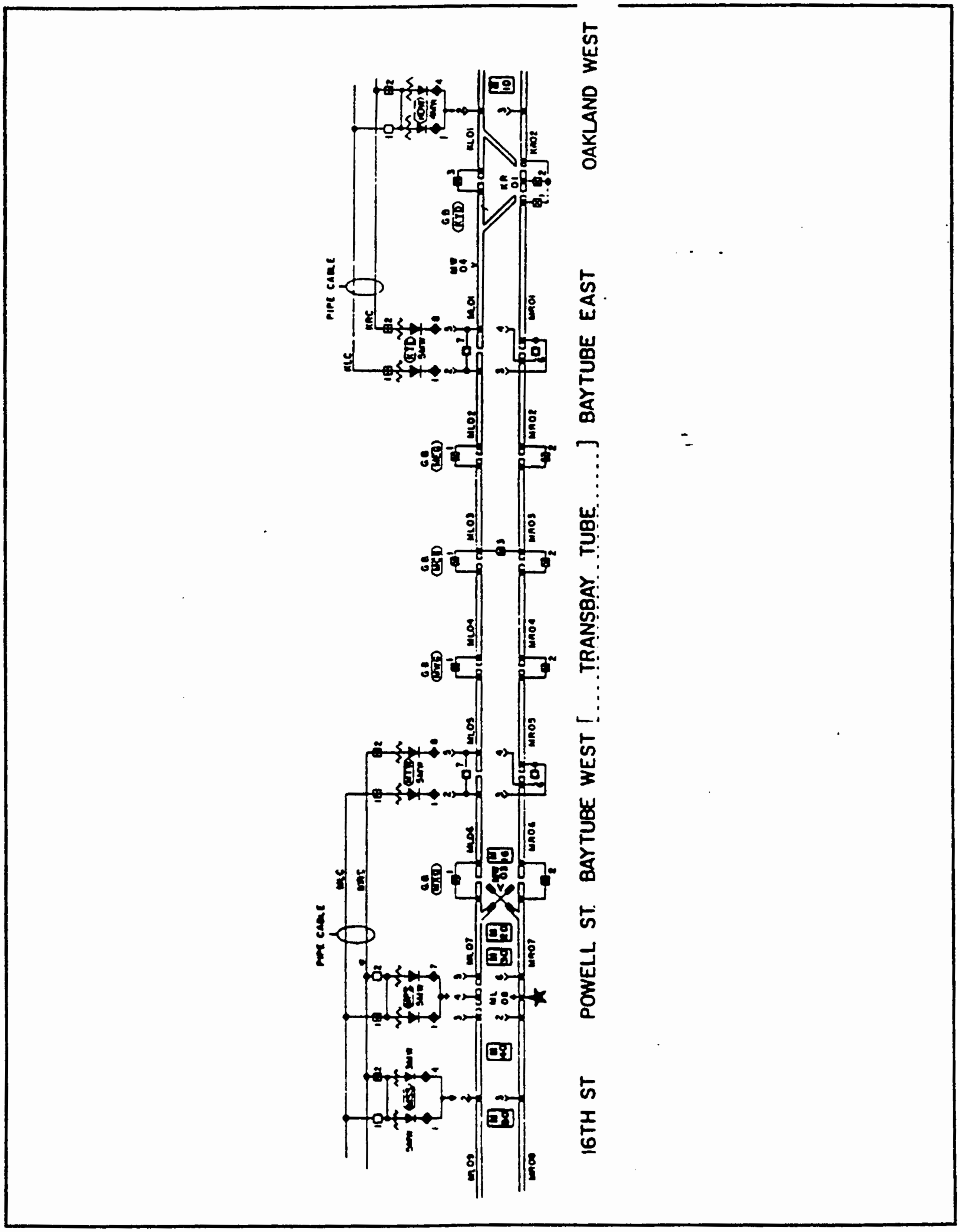


Figure 1 BART System Single-Line Diagram

maintenance work. The ESS shall include means of disconnecting upon receipt of a control signal from BART.

The ESS design or a transient surge suppression device(s) shall protect the ESS from high-voltage transients which may occasionally be present on the BART system (from positive to negative). The ESS and/or surge suppression device shall be capable of withstanding and protecting against 3000 volts for 8 milliseconds or 6000 volts for 50 microseconds with a 1.2 microsecond rise time.

The impedance between the negative and ground in the ESS shall be greater than 1 megohm (so as not to interfere with the BART ground fault detection system).

The ESS ripple and/or ac voltage and current injection onto the BART dc track system shall not disrupt BART signalling. In particular, BART signalling frequencies of 5184, 5600, 5842, 5920, 6624, 7776, 8400, 8763, 8880 and 9936 Hz. shall be avoided and ESS injection of current at any of these frequencies shall be 30 ma or less.

Wiring which may be exposed to mechanical damage shall be placed in galvanized rigid steel conduits. Positive and negative cabling shall be run in separate conduits and the 1000-volt dc power cabling shall have 5 kV insulation. Control wiring in the proximity of power wiring shall have 2 kV insulation. Insulations and jackets shall be flame retardant and shall be capable of passing the flame test of IEEE Standard 383.

The ESS shall have no exposed current carrying or voltage bearing parts or surfaces.

Polychlorobiphenyls (PCBs) shall not be used in transformers or other components.

The ESS may draw up to 15 kVA of auxiliary (or charging) power from the 4,160-volt, 3-phase line existing in the BART transbay tube gallery. The system must include a suitable circuit breaker and enclosures, plus any step-down transformers needed by the ESS. The 4,160-volt line is usually reliable, but the ESS shall disconnect from this line when the ventilation fans are operated in an emergency mode (power fed from one side). A signal for this will be provided by BART. If higher power is needed, a cable must be run to the 34 kV_{AC} (or for up to 1 MW, to the 12.47 kV_{AC}) in the Baytube West (East) substation, approximately 10,000 feet, or it must be derived from the BART dc track system.

Additionally, the ESS may draw up to 400 watts (for instrumentation, datalogging, controls, etc.) from the 120-volt, single-phase line existing in the BART transbay tube gallery. The system must include a suitable circuit breaker and a ground fault detection/alarm system.

Appropriate warning signs shall be affixed to the equipment and cabinets which contain possibly dangerous high voltages.

Controls and Monitoring

The system shall be designed for remote and local automatic, and unattended operation.

The system shall include, as a minimum, the following three modes:

> Shutdown - dc contactors/breakers open; non-critical power supplies de-energized; control system power may remain energized. This mode includes both normal shutdown and system trips requiring reset.
>
> Standby - dc contactors/breakers open, non-critical power and control system power energized.
>
> Operate - contactors/breakers closed and system available to deliver power to or be charged by the BART dc system.

In the operate mode, the ESS shall automatically discharge if the track voltage falls below 800 volts. This initiate voltage shall be field adjustable from 775 to 825 volts. In the operate mode, the ESS shall also automatically recharge, subject to the ESS control system design and the limitations imposed on page 2.

The ESS shall include provisions for an orderly and safe shutdown, even in the absence of BART-supplied power.

The ESS shall go to the shutdown mode under the following conditions and remain in the shutdown mode until a reset signal, either local or remote is initiated:

- Front panel emergency trip switch
- Remote disable (no reset required)
- Absence of track voltage.
- DC ground fault (equipment cubicles shall be relay grounded)
- ESS internal control logic trouble
- Equipment overtemperature
- Internal smoke detector
- Other ESS alarms
- Interlocked door is opened. A "defeat" feature shall allow for maintenance
- Failure to restart after 3 automatic restart attempts

For faults or failures which are transient in nature, the ESS may attempt to restart after a 30-second time delay without requiring a manual reset.

The following local controls shall be located on a control panel on or adjacent to the ESS:

- On/Off control switch or pushbuttons
- Emergency Trip (lock-out) pushbutton
- Reset toggle or pushbutton.
- Remote reset cut-out switch - local/remote control switch

The ESS shall respond to the remote control signals to set/reset the mode. The control design shall be such as to prevent externally supplied or "front panel" local signals from causing the system to operate in an unsafe manner.

The local control panel shall also include lights or other display devices to indicate system status/mode and the status of alarms (e.g., dc ground fault, internal control logic malfunction, overtemperatures, door interlocks, etc.). A remote monitor panel shall be installed in the west ventilation structure and duplicate the local display readouts.

All sensors and transducers shall be easily and safely accessible for calibration. Similarly, all test points in the ESS shall be easily and safely accessible for testing, maintenance and troubleshooting by BART maintenance personnel.

Control and instrumentation wiring shall be physically separated from power and high voltage wiring by use of separate compartments or enclosures, or by use of separate wireways and appropriate barrier strips within a common enclosure. Appropriate transducers and isolation shall be used between high voltage circuits, and control and instrumentation circuits.

Mechanical/Physical

The ESS shall be located in the gallery of the BART transbay tube, section 30. Figure 2 shows the general layout of the tube and existing breakers and conduits, as well as a cross-section of the tube. The gallery is 9-feet tall by 8-feet wide.

The installed ESS shall not project more than 4 feet from the wall (due to the need for passage of personnel and equipment) and shall not be more than 8 feet tall (to clear existing conduit and equipment). It is preferred that the installed ESS be less than 50 feet long.

The maximum size of any equipment module or component will be restricted by the door size of 6' 7"H x 3' 8"W and 8-foot gallery width. Additionally, plans for the installation of ESS components must take into account that no cranes or similar equipment exists in the tube. Temporary rigging for installation and maintenance will be allowed.

The maximum floor loading for the ESS is 29 pounds per square inch.

All components and installed equipment must be braced for Seismic Zone 4.

All waste heat from the ESS shall be rejected to the air in the gallery. The air flow in the gallery is 2,900 cfm and the temperature in the gallery averages 59°F (15°C) and rarely ranges more than 5°F above or below that value. For a non-tube location, ambient temperature can range from 17°F to 110°F.

Other Requirements

Both Superconducting Magnetic Energy Storage (SMES) and Battery Energy Storage (BES) systems are covered by this functional specification. However, certain requirements are unique to each of these two types of systems.

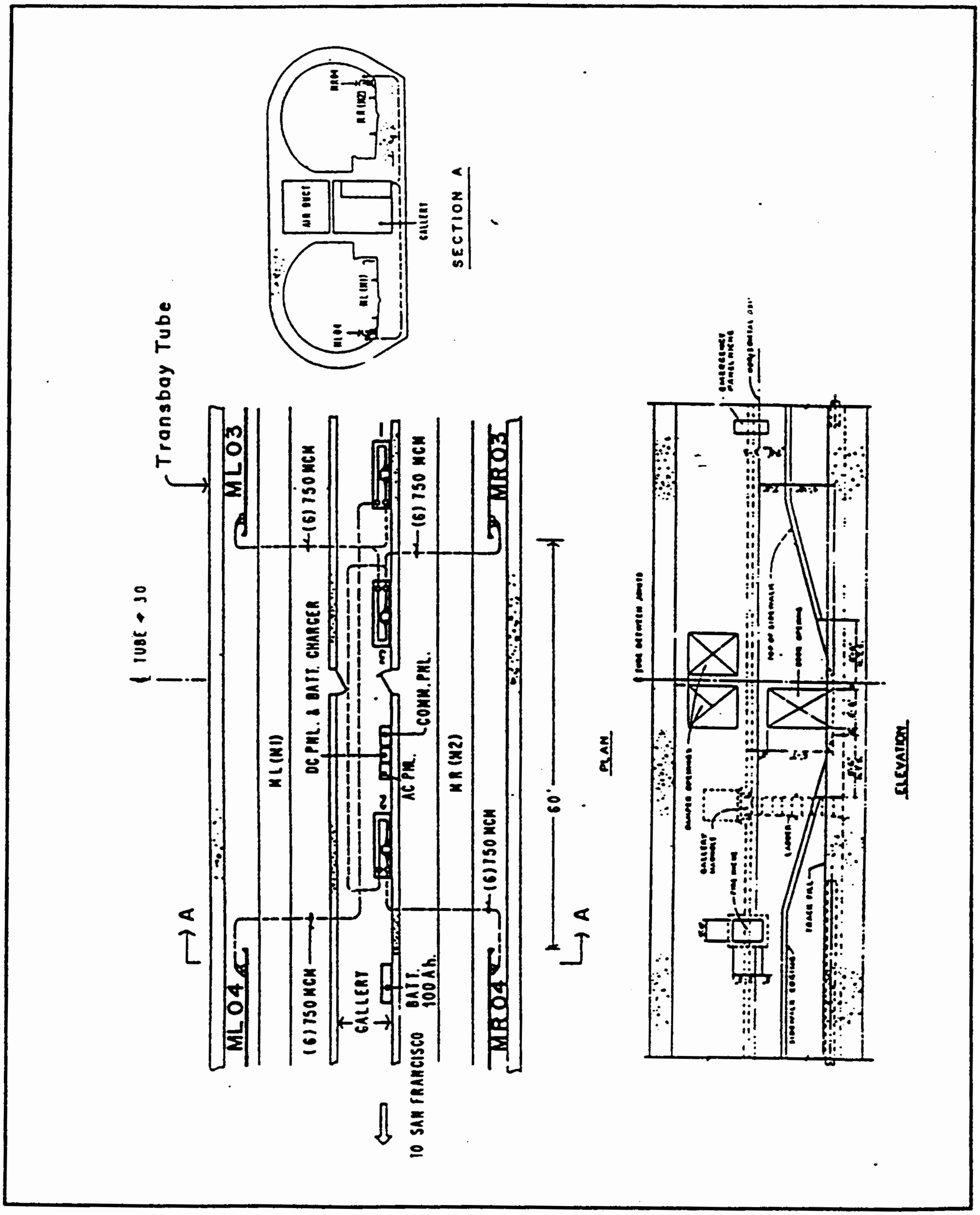


Figure 2 General Layout of BART Transbay Tube in MCG Area

Superconducting Magnetic Energy Storage System Requirements

Due to a lack of sufficient scientific evidence indicating precise biological effects or dose responses associated with specific field strengths, there are few adopted standards for magnetic field exposures outside specialized environments at the present time. Other variables (such as time of exposure or time rate of change) may be more significant than field strength alone. However, the SMES system shall include shielding to minimize stray fields; appropriate warning signs shall be posted in the area; and manuals and training for BART personnel shall address exposure limits, as summarized below. These consist of a combination of the guidelines from U. S. Department of Energy [USDOE], Stanford Linear Accelerator Center [SLAC], and Lawrence Livermore National Laboratory [LLNL].

Field Strength (Tesla)	Exposure Criterion for Static Fields
0.001	Exclusionary warning for pacemaker users; cautionary warning for prosthetic implants [LLNL]
0.01	Whole body limit, 8-hour day exposure [USDOE]
0.05	Action limit-Training & medical surveillance required; Sickle cell patients prohibited [LLNL]
0.06	Time weighted average (TWA) exposure for trunk
0.1	Extremities limit, 8-hour day exposure [USDOE]
0.2	Whole body limit, short duration (minutes) [SLAC]
0.5	TWA basis changes from 40-hour week to 8-hour day for fields in excess of this value [LLNL]
0.6	TWA exposure criterion for the extremities [LLNL]
2	Peak exposure criterion [all]

In addition to these limits on static DC field intensity, limits on DC time-varying magnetic fields have been proposed based on limiting induced body currents to less than 0.01 amps/m^2. For critical regions (i.e., head and heart), this translates to 1.3 Tesla/second. The SMES system design shall be such as to limit stray fields to remain below this limit for both BART maintenance personnel in the gallery and passengers on passing trains. [Initial "zeroth"- order estimates for a 10 kA, 2-foot coil indicate that the closest passenger passing the coil at 80 mph would be exposed to 4 x 10^{-5} Tesla/second, well below the proposed limit.]

The SMES design shall be such as to prevent BART maintenance personnel from exposure to cold or hazardous fluids or gasses and from touching cold surfaces that may cause injury.

The requirement for an orderly and safe shutdown, even in the event of loss of BART-supplied power, includes coil quench.

The SMES system design shall preclude the accumulation of suffocating levels of gases from the coil system in the event of failure or normal warmup for maintenance.

Battery Energy Storage System Requirements

The battery system design shall preclude the accumulation of dangerous concentrations of hydrogen. This shall include an alarm if the hydrogen concentration level exceeds 1000 ppm/v and cessation of charging if the hydrogen level exceeds 2000 ppm/v.

If the battery cells contain antimony or arsenic, the battery system design shall preclude the accumulation of stibine (SbH_3) or arsine (AsH_3) gases above the National Institute for Occupational Safety and Health threshold value-time weighted averages (TLV-TWA) of 0.1 ppm/v for stibine and 0.05 ppm/v for arsine.

If the battery open-circuit voltage is above 600 volts, the battery system design shall include a sectionalizing switch to reduce the voltage to below 600 volts for maintenance.

Appendix B

PDM DESIGN TABLES

Table B-1

Overall System Design for PDM/GA/ACMI/CVI

Net Effective Stored Energy, in MJ	9.65 MJ
Peak Discharge Power Rating, in MW	4.7 MW
Recovery period between cycles, m:sec	6 to 80 SEC
System Footprint, L x W x H in feet	50' x 4' x 8' ±
System Weight, in pounds	27,000 lb
System Lifetime, in years	> 30 yr
System cycle life, # of discharge cycles	> 100,000
Auxiliary power requirements, watts@volts	41.5 KW @ 120/240/480 V
Seismic characteristics, installed.	Zone 4
Date when a system could be supplied for test program: month/year	3/94

Table B-2

Magnet Design for PDM/GA/ACMI/CVI
9.65-MJ-Long Solenoid

Conductor type	multi-element, Rutherford cable
Conductor length	approx. 5000 meters of cable
Number of turns	1500
Length of coil	2.13 meters
Inner Diameter of coil	0.76 meters
Maximum magnetic field strength in coil	4.6 Tesla
Maximum current in coil	5700 amps
Quench Protection:	The magnet is designed never to quench and also to be fully self-protected in the event of an accidental quench.
quench detection procedure	precision balanced bridge
dump procedure	dump to a resistive element
recovery time, procedure	In the event of a quench, the magnet temperature reaches approx. 60K. The magnet is re-cooled with bulk cryogenics and refrigerator cooling re-established. This procedure takes about 24 hours.
damage detection	If a quench damaged the magnet, the most likely damage is a short, which is detected by increasing the consumption during charge.

Table B-3

Refrigeration design for PDM/GA/ACMI/CVI

Type of refrigeration	helium refrigerator
Type of liquid coolant(s)	liquid helium/gaseous helium
Volume of coolant(s)	gaseous helium, 55 ft^3 @ 20 Atm
Expected rate for resupply of coolant(s), liters/time interval	no resupply is required for 1 year
Cooling capacity of refrigerator, $W_{thermal}$	10 watts recondensation 600 watts load stream cooling 50 watts shield cooling
Duration of carryover in cold condition after loss of power to refrigerator, hr:min	
Current Lead material	steel/brass/copper
Current Lead features	low heat leak in stand-by mode or operating mode with zero current
Cryostat dimensions, L x W x H, in inches	100" x 44" x 80"
Cryostat material	stainless steel
Cryostat weight, in pounds	4000 lb plus coil of 11,000 lb
Electric load of refrigeration system, kW	40.75 KW (avg) 65.75 KW max
Duty cycle of refrigeration system	continuous/variable capacity
Projected annual electricity consumption of refrigeration system, kWh	356,970 KW hr including water cooling and instrument air
Is refrigeration system commercially available?	yes
Is system shipped cold or warm?	magnet can be shipped cold
Can cryostat be tipped for diagonal entry into Tube gallery?	yes, but not necessary

Table B-4

Power electronics design for PDM/GA/ACMI/CVI

Recharge issues:	
Power source for recharge	Track
Setability of voltage level for recharge	850 V ± 25 V
Maximum recharge power, MW	1.3 MW
Criteria for recharge	I magnet < 5700 A, 860 > V track > 825 V, SMES = operate
Discharge issues:	
Ramp rate, MW/sec	80 MW/sec
Maximum discharge power	4.7 MW (5700 A, 825 V)
Maximum discharge voltage	825 V
How do you avoid overvoltage at the end of discharge?	Current chopper regulates discharge voltage to 800 V ± 25 V
Other issues:	
Spurious current injection at signaling frequencies, ma/specific frequency	< 20 mA at all signaling frequencies
Are notch filters required?	no
Is there a warm bypass switch?	yes
Is there a cold bypass switch?	no

Table B-5

Switching and Fusing Design for PDM/GA/ACMI/CVI

Fault protection: fuse or circuit breaker type	Fast action circuit breaker
Disconnect method	Motorized disconnect
Lockout type	Kirk key interlocks

Table B-6

System Monitoring and Control for PDM/GA/ACMI/CVI

Permanent system monitoring	
Digital data link to control center	Output current and voltage
Digital data link to control center	Magnet current and voltage
Digital data link to control center	Fault detection system
Early phase datalogging for research purposes:	
Lecroy oscilloscopes with mass storage via IBM PC	Output current and voltage
Lecroy oscilloscopes with mass storage via IBM PC	Magnet current and voltage
Thermocouples with a chart recorder	Semiconductor temperatures

Table B-7

Maintenance Procedures for PDM/GA/ACMI/CVI

Magnet	Inspect and clean yearly
Refrigerator, Cryostat, Leads	Routine maintenance, inspect, replace worn parts and clean system yearly
Power electronics	Inspect and clean yearly
Monitoring system, including calibration	Calibrate yearly
Special safety procedures for maintenance personnel	Normal remote shutdown and manual safeing via Kirk key interlocks requires no special procedures. On-line maintenance will require high voltage and high magnetic field safety procedures.

Table B-8

Capital Cost Estimates (in 1993 dollars) for PDM/GA/ACMI/CVI

	1993 delivery	1995 delivery	1997 delivery
Total System Cost, single unit	n/a	$1,620K	$1,580K
Cost of Coil and Cryostat	n/a	$600k	$600k
Cost of refrigeration system	n/a	$350k	$380k
Cost of Power Electronics		$560 k	$530 k
Cost of fusing and switching		$55 k	$50 k
Incremental Cost of additional 1 MJ of energy storage	n/a		
Incremental Cost of additional 1 MW of power capability		$55 k	$50 k
Indirect costs, including design, engineering, assembly, transportation, management, fees, contingencies, taxes, insurance, etc. (this may be lumped or broken out)	n/a	included	included
Cost per unit in quantities of 2-5		$1,400,000	$1,365,000

Table B-9

Maintenance Costs Per Year (in 1993 dollars) for PDM/GA/ACMI/CVI

	1993 delivery	1995 delivery	1997 delivery
Total system	$12k		
Refrigeration system	$9k		
Power electronics	$2 k		
Monitoring system	$1 k		
Electricity Cost @ $0.1/kWh	$36,000		
Daily operations (labor hours)	0 hr nominal with automated system		

Appendix C

WESTINGHOUSE DESIGN TABLES

Table C-1A

Overall System Design for Westinghouse (Unconstrained Site)

Net effective stored energy, in MJ	9.3 MJ
Peak discharge power rating, in MW	3.2 MW
Recovery period between cycles, m:sec	1 min. 30 sec.
System footprint, L x W x H in feet	27' x 13' x 9'
System weight, in pounds	75,689 lb
System lifetime, in years	20
System cycle life, # of discharge cycles	7500
Auxiliary power requirements, watts@volts	110 KW at 4160 V
Seismic characteristics, installed.	TBD
Date when a system could be supplied for test program: month/year	6/94

Table C-1B

Overall System Design for Westinghouse (Transbay Tube)

Net effective stored energy, in MJ	9.3 MJ (3 x 3.1 MJ)
Peak discharge power rating, in MW	3.2 MW
Recovery period between cycles, m:sec	1 min. 30 sec.
System footprint, L x W x H in feet	61' x 3.83' x 6.0'
System weight, in pounds	66,640 lb
System lifetime, in years	20
System cycle life, # of discharge cycles	7500
Auxiliary power requirements, watts@volts	110 KW at 4160 V
Seismic characteristics, installed.	TBD
Date when a system could be supplied for test program: month/year	6/94

Table C-2A

Magnet Design for Westinghouse (Unconstrained Site)

Conductor type	NbTi Copper Stabilized Cable
Conductor length	27,750 feet
Number of turns	2304
Height of coil	67.0"
Inner diameter of coil	10.25"
Maximum magnetic field strength in coil	5.5 Tesla
Maximum current in coil	4000 A
Quench protection:	
quench detection procedure	Voltage Taps
dump procedure	Isolate coil, dump coil through external resistor
recovery time, procedure	TBD
damage detection	Loss of vacuum, loss of cryogen, asymmetric coil voltage, temperature rise, helium vessel pressure

Table C-2B

Magnet Design for Westinghouse (Transbay Tube)

Conductor type	NbTi Copper Stabilized Cable
Conductor length	3 x 13,500 feet
Number of turns	3 x 2592
Height of coil	26.0"
Inner diameter of coil	8.72"
Maximum magnetic field strength in coil	7.5 Tesla
Maximum current in coil	4000 A
Quench protection:	
quench detection procedure	Voltage Taps
dump procedure	Isolate coil, dump coil through external resistor
recovery time, procedure	TBD
damage detection	Loss of vacuum, loss of cryogen, asymmetric coil voltage, temperature rise, helium vessel pressure

Table C-3A

Refrigeration Design for Westinghouse (Unconstrained Site)

Type of refrigeration	Closed cycle Helium Liquefaction
Type of liquid coolant(s)	Liquid Helium
Volume of coolant(s)	1640 liters
Expected rate for resupply of coolant(s), liters/time interval	16 liters/hour
Cooling capacity of refrigerator, Wthermal	114 watts at 4.6°K
Duration of carryover in cold condition after loss of power to refrigerator, hr:min	TBD
Current lead material	BSCCO-2212
Current lead features	HTSC lead, reduced heat leak
Cryostat dimensions, L x W x H, in inches	67.5" x 67.5" x 109"
Cryostat material	Stainless Steel
Cryostat weight, in pounds	21,343 lb. (includes cold mass)
Electric load of refrigeration system, kW	100 KW
Duty cycle of refrigeration system	0.88 at 65% capacity; 0.12 at 100% capacity
Projected annual electricity consumption of refrigeration system, kWh	606,000 kWh
Is refrigeration system commercially available?	Yes
Is system shipped cold or warm?	Warm
Can cryostat be tipped for diagonal entry into Tube gallery?	Not Applicable

Table C-3B

Refrigeration Design for Westinghouse (Transbay Tube)

Type of refrigeration	Closed cycle Helium Liquefaction
Type of liquid coolant(s)	Liquid Helium
Volume of coolant(s)	270 liters/module, 810 liters total
Expected rate for resupply of coolant(s), liters/time interval	16 liters/hour
Cooling capacity of refrigerator, $W_{thermal}$	114 watts at 4.6°K
Duration of carryover in cold condition after loss of power to refrigerator, hr:min	TBD
Current lead material	BSCCO-2212
Current lead features	HTSC lead, reduced heat leak
Cryostat dimensions, L x W x H, in inches	3 x (46" x 46" x 42")
Cryostat material	Stainless Steel
Cryostat weight, in pounds	3 x 4098 lb. (includes cold mass)
Electric load of refrigeration system, kW	100 KW
Duty cycle of refrigeration system	0.88 at 65% capacity; 0.12 at 100% capacity
Projected annual electricity consumption of refrigeration system, kWh	606,000 kWh
Is refrigeration system commercially available?	Yes
Is system shipped cold or warm?	Warm
Can cryostat be tipped for diagonal entry into Tube gallery?	Yes, can be tipped completely on side

Table C-4A

Power Electronics Design for Westinghouse (Unconstrained Site)

Recharge Issues:	
Power source for recharge	BART Third Rail
Setability of voltage level for recharge	± 25 V
Maximum recharge power, MW	0.11 MW → 3.2 MW
Criteria for recharge	Rail Voltage Above Set Point
Discharge Issues:	
Ramp rate, MW/sec	3.2 MW / 5 sec. (0.64 MW/sec)
Maximum discharge power	3.2 MW
Maximum discharge voltage	Set Point (nominal 800 V)
How do you avoid overvoltage at the end of discharge?	Voltage Controlled Scheme - maximum discharge voltage = 800 V
Other Issues:	
Spurious current injection at signaling frequencies, ma/specific frequency	TBD
Are notch filters required?	TBD
Is there a warm bypass switch?	Yes
Is there a cold bypass switch?	No

Table C-4B

Power Electronics Design for Westinghouse (Transbay Tube)

Recharge Issues:	
Power source for recharge	BART Third Rail
Setability of voltage level for recharge	± 25 V
Maximum recharge power, MW	0.11 MW → 3.2 MW
Criteria for recharge	Rail Voltage Above Set Point
Discharge Issues:	
Ramp rate, MW/sec	3.2 MW / 5 sec. (0.64 MW/sec)
Maximum discharge power	3.2 MW
Maximum discharge voltage	Set Point (nominal 800 V)
How do you avoid overvoltage at the end of discharge?	Voltage Controlled Scheme - maximum discharge voltage = 800 V
Other Issues:	
Spurious current injection at signaling frequencies, ma/specific frequency	TBD
Are notch filters required?	TBD
Is there a warm bypass switch?	Yes
Is there a cold bypass switch?	No

Table C-5A

Switching and Fusing Design for Westinghouse (Unconstrained Site)

Fault protection: fuse or circuit breaker type	Fuse and Contactor
Disconnect method	Noload Disconnect
Lockout type	TBD

Table C-5B

Switching and Fusing Design for Westinghouse (Transbay Tube)

Fault protection: fuse or circuit breaker type	Fuse and Contactor
Disconnect method	Noload Disconnect
Lockout type	TBD

Table C-6A

System Monitoring and Control for Westinghouse (Unconstrained Site)

Permanent system monitoring	
{instrument}	{measurement}
TBD	TBD
Early phase datalogging for research purposes:	
{instrument}	{measurement}
TBD	TBD

Table C-6B

System Monitoring and Control for Westinghouse (Transbay Tube)

Permanent system monitoring	
{instrument}	{measurement}
TBD	TBD
Early phase datalogging for research purposes:	
{instrument}	{measurement}
TBD	TBD

Table C-7A

Maintenance Procedures for Westinghouse (Unconstrained Site)

Magnet	TBD
Refrigerator, cryostat, leads	TBD
Power electronics	TBD
Monitoring system, including calibration	TBD
Special safety procedures for maintenance personnel	TBD

Table C-7B

Maintenance Procedures for Westinghouse (Transbay Tube)

Magnet	TBD
Refrigerator, cryostat, leads	TBD
Power electronics	TBD
Monitoring system, including calibration	TBD
Special safety procedures for maintenance personnel	TBD

Table C-8A

Capital Cost Estimates (in 1993 dollars) for Westinghouse (Unconstrained Site)

	1993 delivery	1995 delivery	1997 delivery
Total system cost, single unit	$ 3179 K	TBD	TBD
Cost of coil and cryostat (includes vacuum, dump, & instrumentation systems)	$ 762 K	TBD	TBD
Cost of refrigeration system	$ 411 K	TBD	TBD
Cost of power electronics	$ 642 K	TBD	TBD
Cost of fusing and switching	included in power electronics above	TBD	TBD
Incremental cost of additional 1 MJ of energy storage	TBD	TBD	TBD
Incremental cost of additional 1 MW of power capability	TBD	TBD	TBD
Indirect costs, including design, engineering, assembly, transportation, management, fees, contingencies, taxes, insurance, etc. (this may be lumped or broken out)	$ 1364 K	TBD	TBD
Cost per unit in quantities of 2-5	$ 2444 K	TBD	TBD

Table C-8B

Capital Cost Estimates (in 1993 dollars) for Westinghouse (Transbay Tube)

	1993 delivery	1995 delivery	1997 delivery
Total system cost, single unit	$ 4870K	TBD	TBD
Cost of coil and cryostat (includes vacuum, dump, & instrumentation systems)	$ 1436 K	TBD	TBD
Cost of refrigeration system	$ 411 K	TBD	TBD
Cost of power electronics	$ 642 K	TBD	TBD
Cost of fusing and switching	included in power electronics above	TBD	TBD
Incremental cost of additional 1 MJ of energy storage	TBD	TBD	TBD
Incremental cost of additional 1 MW of power capability	TBD	TBD	TBD
Indirect costs, including design, engineering, assembly, transportation, management, fees, contingencies, taxes, insurance, etc. (this may be lumped or broken out)	$ 2380 K	TBD	TBD
Cost per unit in quantities of 2-5	$ 3903 K	TBD	TBD

Table C-9A

Maintenance Costs per Year (in 1993 dollars)
for Westinghouse (Unconstrained Site)

Total system		TBD	TBD
Refrigeration system		TBD	TBD
Power electronics		TBD	TBD
Monitoring system		TBD	TBD
Electricity cost		TBD	TBD
Daily operations (labor hours)		TBD	TBD

Table C-9B

Maintenance Costs per Year (in 1993 dollars)
for Westinghouse (Transbay Tube)

Total system	TBD	TBD	TBD
Refrigeration system	TBD	TBD	TBD
Power electronics	TBD	TBD	TBD
Monitoring system	TBD	TBD	TBD
Electricity cost	TBD	TBD	TBD
Daily operations (labor hours)	TBD	TBD	TBD

Appendix D

SI DESIGN

Response to Micro-SMES Conceptual Design for BART Voltage Sag Problem

Superconductivity, Inc.

January 15, 1993

Overall System Design

Superconductivity, Inc. (SI) proposes to make use of as much standard SSD® equipment as possible, particularly for the "unconstrained" site. Thus, the price will be kept relatively low, and the system can be delivered in a short time frame. Therefore, the emphasis within this document will be placed on the application rather than the technology.

Specifically, SI proposes to install a system of four identical magnets, each placed in its own cryostat and equipped with a cryogenic refrigeration system. These four magnets will be connected in parallel to the tracks. For the unconstrained site, SI's standard (patented) voltage regulators will be used to connect each magnet to the tracks, and four standard AC/DC magnet chargers will be used to charge the magnets. For the "Transbay Tube" (Tube), SI proposes to combine each voltage regulator and magnet charger into one two-quadrant chopper connected to the magnet and the tracks, so that the magnets can be charged directly from the tracks. DC motors powered from the tracks will be used for the refrigerators, and the 15 kVA AC power source will only be used for the control system.

Figure 1 shows a sketch of the system for the Transbay Tube and the unconstrained site, including basic dimensions of the components and cabinets. The total system will fit into the designated space in the Tube.

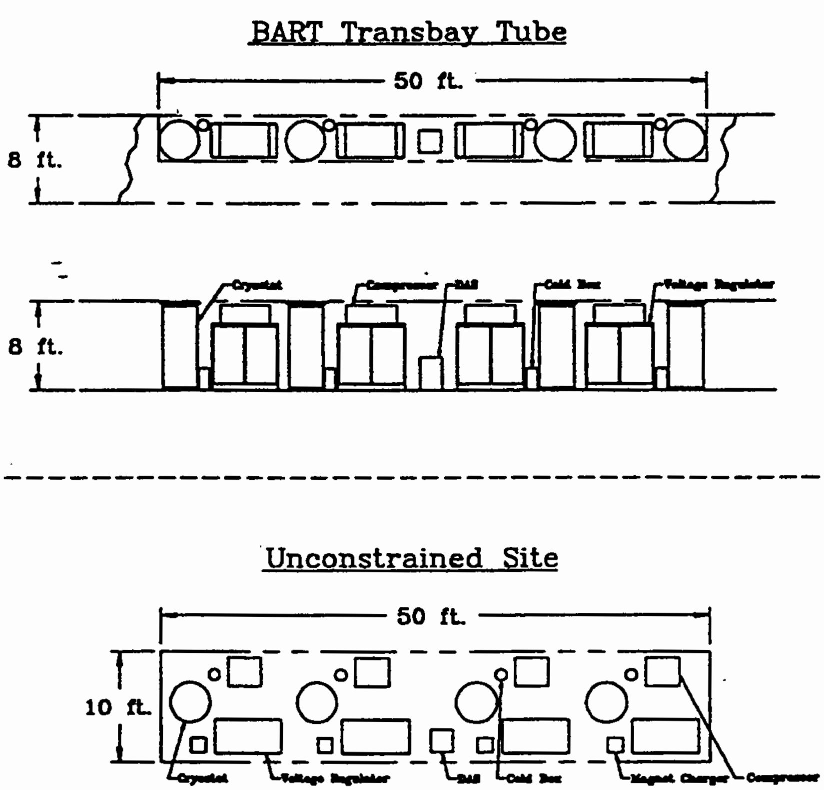


Figure 1

Control. A current-to-voltage converter (or voltage regulator), permits the magnet to provide energy directly to the DC track system and obtain recharge energy from the tracks as well.

The present implementation of this converter in SI's commercial SSD installations functions by using a gate controlled thyristor (GTO) switch in the external circuit of the magnet. A capacitor bank is connected, via steering diodes, in parallel with the GTO switch. The voltage level in the capacitor bank is sensed by a control circuit which turns off the GTO when the voltage drops below a pre-set level and turns it on when the voltage rises above the upper setpoint. Each cycle of the switch transfers energy from the magnet to the capacitor bank. The capacitor bank, in turn, is the energy source for the load. As the voltage level in the capacitor changes in response to the load, the SSD's voltage regulator acts to maintain a pre-set level.

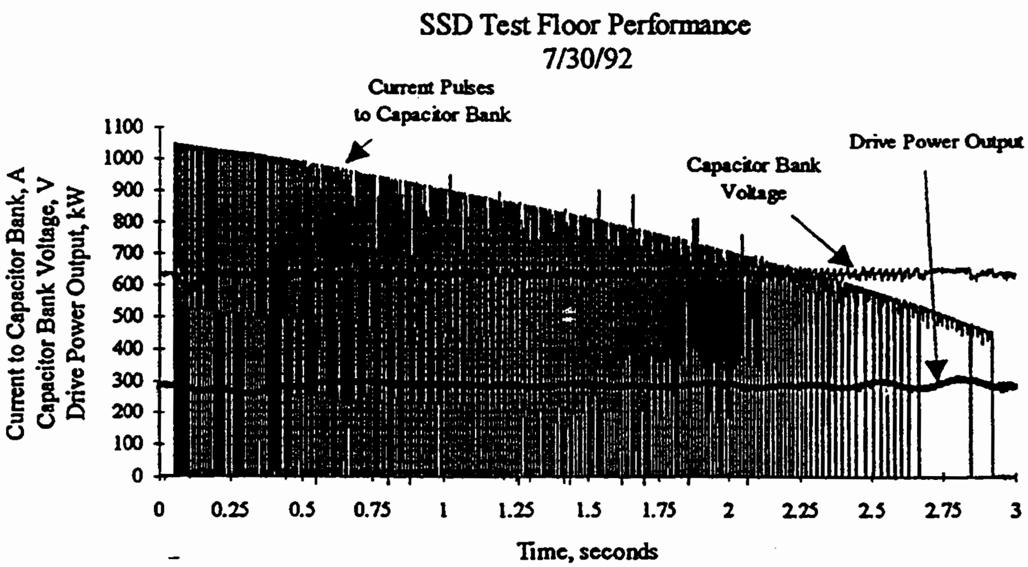


Figure 2

Figure 2 shows test data that illustrate the transfer of energy from the magnet to a load. The test floor system uses a motor drive SSD connected to a 300 kW(400 hp) motor-generator set. This particular test involved disconnecting the line input from the drive and allowing it to operate on stored energy from the magnet. The disconnection period spans the plot from 0.05 to 2.92 seconds. The drive output remains nearly constant while the switching operation of the voltage regulator can be seen in the pulses of current into the drive's capacitor bank. The capacitor bank voltage shows a periodic variation in response to the energy transferred from the magnet. This voltage profile is similar to what the voltage of the tracks will be while the magnets are discharging when a train is passing by. Power drawn from the magnet is constant in this test. Of course, this current waveform will be different for the BART application because of the rapid increase and decrease of the required power. The control of the GTO switch for this trackside application is explained in detail in the section on power electronics.

Operations. The SSD is designed for hands-off operation. The daily operation of the system can be remotely monitored by SI and, as an option, by BART. Important events are recorded by utilizing the onboard computer and data acquisition system. The SSD's proven availability in field operations is well over 95%, thus exceeding the ESS requirements. Starting reliability is near 100%.

The SSD has four modes of operation:

1. Standby Mode—The SSD is in Standby Mode when the BART track voltage is normal and energy is stored in the magnet and available to provide power to the tracks.

2. Tracks Support Mode—The SSD is in Tracks Support Mode when the voltage on the tracks falls below a minimum voltage and the available stored energy is being delivered to the tracks.

3. Recharge Mode—The magnets will be recharged provided the tracks voltage equals or exceeds 850 VDC.

4. Shutdown Mode—The SSD is in Shutdown Mode when stored energy is not available for Tracks Support Mode or the SSD has been shut down.

Table 1A: Unconstrained Site

Overall System Design	
Net Effective Stored Energy, in MJ	8 MJ
Peak Discharge Power Rating, in MW	3.2 MW
Recovery period between cycles, m:sec	Less than 1 min:30 sec
System Footprint; L x W x H in feet	50' x 10' x 10'
System Weight, in pounds	40,000 lbs. (no shielding)
System Lifetime, in years	> 20 years
System cycle life, # of discharge cycles	> 1,000,000
Auxiliary power requirements, watts@volts	250 kW @ 480 VAC
Seismic characteristics, installed.	Conforms to Zone 4
Date when a system could be supplied for test program: month/year	Eight months after date of order

Table 1B: Transbay Tube Site

Overall System Design	
Net Effective Stored Energy, in MJ	8 MJ
Peak Discharge Power Rating, in MW	3.2 MJ
Recovery period between cycles, m sec	Less than 90 seconds
System Footprint, L x W x H in feet	50' x 4' x 8'
System Weight, in pounds	32,000 lbs. system and 80,000 lbs. shielding. Total weight is 112,000 lbs.
System Lifetime, in years	>20 years
System cycle life, # of discharge cycles	>1,000,000
Auxiliary power requirements, watts@volts	80 kW @ 800 to 1000 VDC
Seismic characteristics, installed.	Conforms to Zone 4
Date when a system could be supplied for test program: month/year	18 months after date of order

Regarding magnetic fields, SI has adopted magnetic field safety guidelines published by the American Conference of Governmental Industrial Hygienists (ACGIH). The 1990-1991 **Threshold Limit Values for Chemical Substances and Physical Agents and Biological Exposure Indices** (ISBN: 0-936712-86-4), states:

"Routine occupational exposures should not exceed 60 milli-Tesla (mT), equivalent to 600 Gauss, whole body or 600 mT (6,000 Gauss) to the extremities on a daily, time-weighted average basis. A flux density of 2 Tesla (20,000 Gauss) is recommended as a ceiling value. Safety hazards may exist from the mechanical forces exerted by the magnetic field upon ferromagnetic tools and medical implants. Workers having implanted cardiac pacemakers should not be exposed above 1.0 mT (10 Gauss). Perceptible or adverse effects may also be produced at higher flux densities resulting from forces upon other implanted ferromagnetic medical devices; e.g., suture staples, aneurysm clips, prostheses, etc."

The appropriate magnetic field limit for the general public is the 10 Gauss pacemaker limit. SI's design philosophy for both the Transbay Tube site and the unconstrained site is to limit exposure to non-SI personnel to the 10 Gauss limit. In the Tube site this will require extensive magnetic shielding. Even with magnetic shielding, the field near cryostats will be too large to allow passage through the gallery with the magnets energized. At this conceptual phase we are envisioning the installation of gates at each end of the SMES system. Before personnel are allowed to proceed beyond the gates, they would have to de-energize the magnets.

The magnetic field exposure at the unconstrained site can be limited to the 10 Gauss level by a combination of shielding and exclusion fencing. The unshielded 10 Gauss level for each magnet is at a distance of approximately 17 feet from the magnet centerline as shown in ***Figures 3*** and ***4***. If available space at the unconstrained site will not allow exclusion for the full 17 feet, a shield can be used to pull the 10 Gauss line closer to the cryostat. The shielding in this case would not be as extensive as that required for the Transbay Tube application.

All cryogenic components have been designed to stay within their elastic region during warm-up. No permanent deformations should occur on cool-down or warm-up. Therefore, warm-up, cool-down cycles should have minimal impact on the system's lifetime.

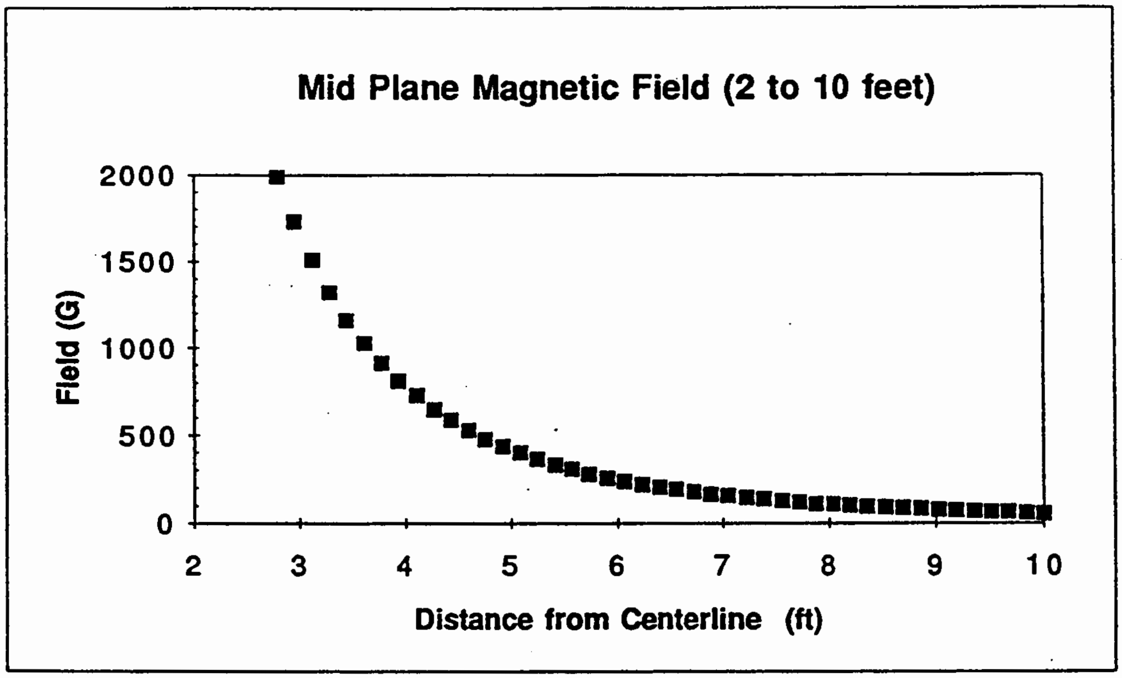


Figure 3

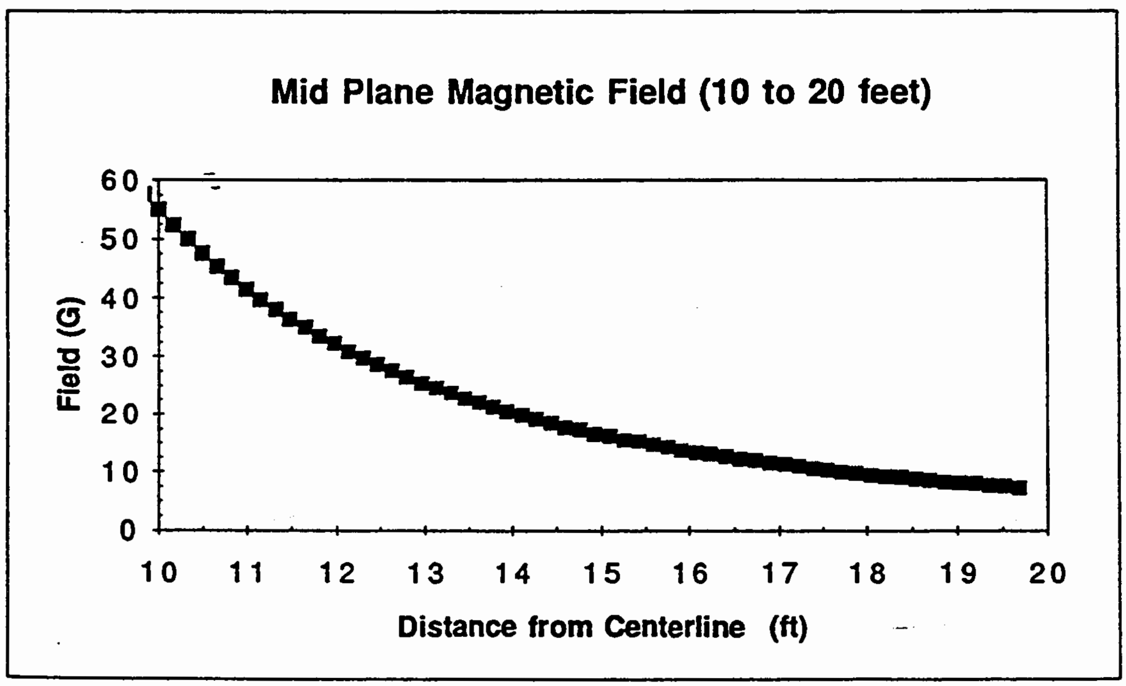


Figure 4

Magnet Design

SI proposes to install a system of four identical magnets at the "unconstrained" site and in the Transbay Tube. Each magnet will be supplied in its own cryostat and be equipped with a cryogenic refrigeration system.

The design operating current for these magnets is 1250 A. The energy stored in the magnet is dependent on the current and the inductance. The inductance of the magnet is about 3.8 Henries so when the magnet is charged to a current of 1250 A, the stored energy is 2.97 MJ.

As shown in ***Figure 5***, the superconducting magnet is constructed by winding cable made of niobium titanium/copper composite superconducting wires onto a former. The winding is restrained at the top and bottom by the flanges. The ends of the cable are connected to busbars which are superconducting Nb_3Sn and copper composite. These busbars connect to current leads in the upper part of the cryostat. The magnet is mounted into the cryostat with a lower mounting fixture and centered with a centering fixture.

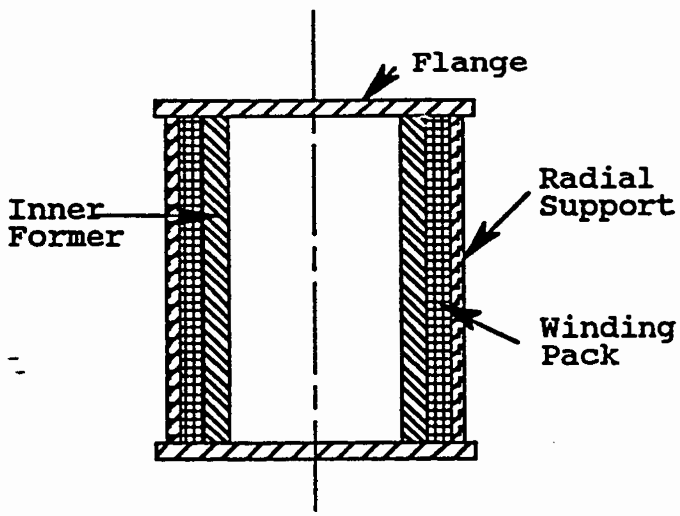


Figure 5

The superconducting magnet is designed for a lifetime of deep, highly repetitive discharge cycles. The superconducting magnet is of rugged design, existing in an inert and stable cold environment. While energized in this low-temperature environment, it suffers no mechanical, electrical or chemical degradation.

As the magnet is charged, it will be compressed axially towards the midplain and expand radially outward. The radial support around the winding helps bear the radial load. At full charge, maximum axial stresses in the winding are about 17,000 psi and maximum tangential stresses in the winding pack (due to expansion in the radial direction) are approximately 15,000 psi.

Magnets operating in similar stress regimes have accumulated 10 years of operation with one minute charge-discharge rates at Fermi National Laboratory with no observable degradation.

Table 2A: Unconstrained Site

Magnet Design	
Conductor type	Rutherford type cable composed of strands employing filamentary NbTi alloy in a copper matrix
Conductor length	Proprietary information
Number of turns	Proprietary information
Height of coil	Approximately 3 feet
Inner Diameter of coil	28"
Maximum magnetic field in coil	5 T
Maximum current in coil	1250 A
Quench Protection:	
quench detection procedure	Detection of a voltage imbalance between symmetric sections of the coil.
dump procedure	External contactor opens and shunting resistor absorbs energy in magnet. Vaporized helium is vented into atmosphere.
recovery time, procedure	Magnet is cooled down to 20 K using integral refrigeration system. Estimated time: 48 hours. After 20 K point is reached, the cryostat is re-filled with liquid helium and magnet is re-energized.
damage detection	If magnet damage is suspected, a high voltage ringer can be applied to the external voltage taps. Asymmetric waveforms are an indication of insulation failure.

Table 2B: Transbay Tube

Magnet Design	
Conductor type	Rutherford type cable composed of strands employing filamentary NbTi alloy in a copper matrix
Conductor length	Proprietary information
Number of turns	Proprietary information
Height of coil	Approximately 3 feet
Inner Diameter of coil	28"
Maximum magnetic field in coil	5 T
Maximun current in coil	1250 A
Quench Protection:	
quench detection procedure	Detection of a voltage imbalance between symmetric sections of the coil.
dump procedure	External contactor opens and shunting resistor absorbs energy in magnet. Vaporized helium is stored within the cryostat. No helium is vented during quench event.
recovery time, procedure	Magnet is cooled down to 20 K using integral refrigeration system. Estimated time: 48 hours. After 20 K point is reached, the cryostat is re-filled with liquid helium and magnet is re-energized.
damage detection	If magnet damage is suspected, a high voltage ringer can be applied to the external voltage taps. Asymmetric waveforms are an indication of insulation failure.

Cryostat and Refrigeration Design

Each cryostat and magnet assembly will be equipped with a refrigeration system. The following description applies to a single cryostat.

The cryostat assembly is a vacuum-insulated vessel which contains the superconducting magnet in a bath of liquid helium. The cryostat assembly is shown in ***Figure 6***.

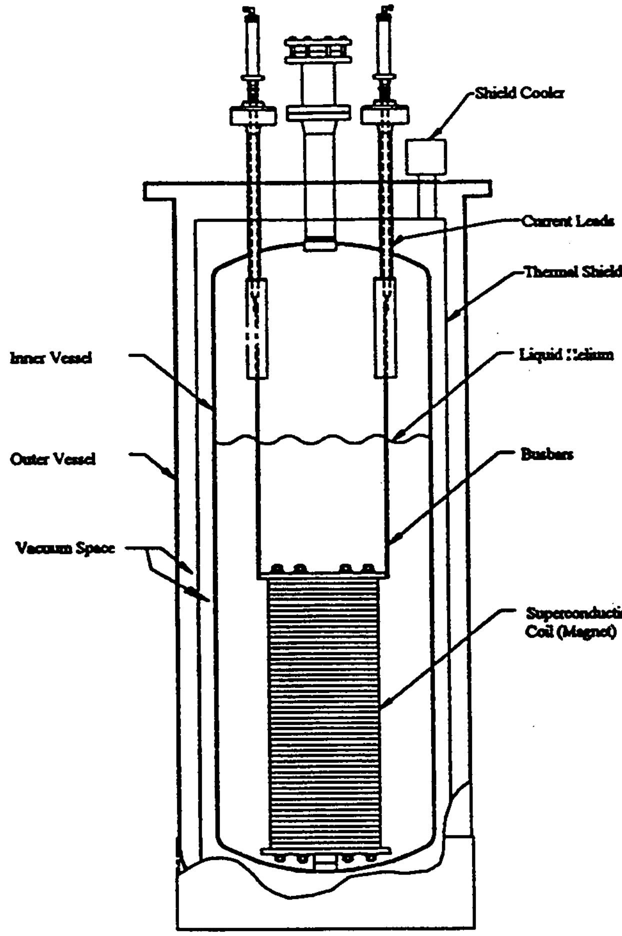


Figure 6

The inner (helium) vessel contains a reserve inventory of approximately 600 liters of liquid helium. This reserve inventory of helium allows for 40 to 45 hours of time in which the refrigeration system can be shut down without the loss of magnet cooling. The cryostat is designed so that liquid helium can be transferred into it from a portable dewar. These dewars can be delivered within 24 hours in the continental U.S., therefore, extending indefinitely the time the refrigeration system can be shut down, while keeping the SSD fully operational. Both inner and outer vessels of the Cryostat Assembly are constructed from stainless steel. The inner is an ASME code-stamped vessel constructed in accordance with the ASME Boiler and Pressure Vessel Code Section VIII, Division 1. The normal operating pressure of the inner vessel is 2.5 to 5 psig.

Table 3A: Unconstrained Site

Refrigeration design	
Type of refrigeration	1. Refrigerator: Process Systems (Koch) Model 1200. Collins cycle liquefier/refrigerator. 2. Shield Cooler: Gifford-McMahon cycle, single stage.
Type of liquid coolant(s)	Helium
Volume of coolant(s)	750 liters per cryostat (total 3000 liters)
Expected rate for resupply of coolant(s), liters/time interval	250 liters per cryostat/year (total 1000 liters/year) during annual maintenance of refrigeration system.
Cooling capacity of refrigerator, $W_{thermal}$	Refrigerator 4 liters/hr or 25W refrigeration @ 4.2k.
Duration of carryover in cold condition after loss of power to refrigerator, hr:min	60 hrs
Current lead material	Conventional copper vapor cooled current lead. Current leads made with high temperature superconductors will be available in late 1993.
Current lead features	Automatic flow controller to minimize helium flow rate. High temperature superconducting leads will be available in late 1993.
Cryostat dimensions, L x W x H, in inches	Cylinder, 40" OD and 96" high
Cryostat material	Stainless steel
Cryostat weight, in pounds	4,000 pounds
Electric load of refrigeration system, kW	160 kW.
Duty cycle of refrigeration system	100%
Projected annual electricity consumption of refrigeration system, kWh	1,401,600 kWh
Is refrigeration system commercially available?	Yes
Is system shipped cold or warm?	Warm
Can cryostat be tipped for diagonal entry into Tube gallery?	Yes

Table 3B: Transbay Tube Site

Refrigeration design	
Type of refrigeration	1. Recondenser: Gifford-McMahon cycle, 3 stage with final Joule-Thompson stage. 2. Shield Coolers: Gifford-McMahon cycle, single stage.
Type of liquid coolant(s)	Helium
Volume of coolant(s)	600 liters per cryostat (total 2400 liters)
Expected rate for resupply of coolant(s), liters/time interval	250 liters per cryostat/year (total 1000 liters/year) during annual maintenance of refrigeration system.
Cooling capacity of refrigerator, $W_{thermal}$	1. Recondenser: 3 W @ 4.2 K 2. Shield Cooler: 200 W @ 55 K
Duration of carryover in cold condition after loss of power to refrigerator, hr:min	45 hrs
Current lead material	Combination of metallic and ceramic superconductors connected to a copper upper stage.
Current lead features	The ceramic superconducting leads greatly reduce the heat input to the cryostat and allow a recondenser to be substituted for the Koch 1200.
Cryostat dimensions, L x W x H, in inches	Cylinder, 40" OD and 96" high
Cryostat material	Stainless steel
Cryostat weight, in pounds	5,000 pounds
Electric load of refrigeration system, kW	60 kW, to be drawn off DC rail system as long as voltage is above minimum value.
Duty cycle of refrigeration system	100%
Projected annual electricity consumption of refrigeration system, kWh	525,600 kWh
Is refrigeration system commercially available?	Yes
Is system shipped cold or warm?	Warm
Can cryostat be tipped for diagonal entry into Tube gallery?	Yes

Power Electronics Design

As noted before, SI proposes to use slightly modified standard voltage regulators and standard magnet chargers for the unconstrained site application. The voltage regulator consists of a GTO switch as shown in ***Figure 7*** and a PWM controller. There are three modes of operation of the voltage regulator:

1. Magnet Current Freewheeling Mode: The GTO is kept on if the magnet current needs to be freewheeled.

2. Magnet Discharge Mode: The GTO is switched on and off if the magnet energy needs to be discharged into the BART system. The PWM controller senses the magnet current I and the DC voltage V and issues appropriate PWM turn-on/off signal to the GTO switch to vary the discharge duty cycle γ and, therefore, the discharging average current and average power profile according to a predefined template as specified for the project.

3. Magnet Charge Mode: The GTO is kept on and the magnet charger will charge the magnet at a voltage of 50V, which results in a recharge time of about 50 to 60 seconds.

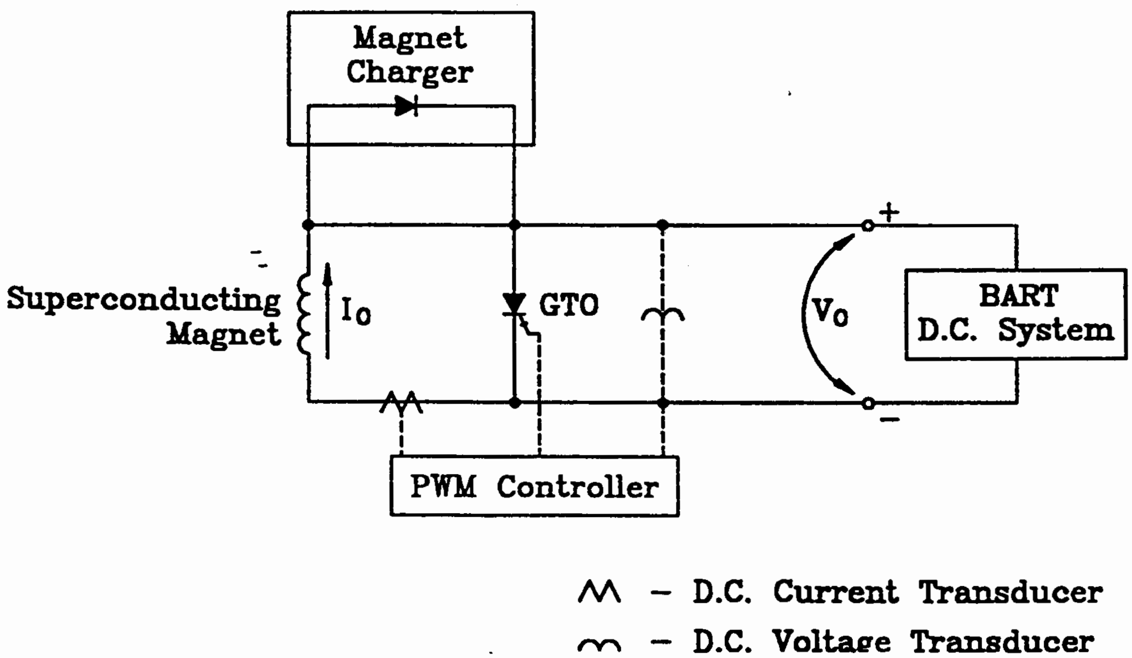


Figure 7

For the Transbay Tube application, each superconductive magnet will be charged and discharged through a voltage regulator consisting of a two-quadrant DC-DC chopper circuit. The modularity of the superconductive magnet/voltage regulator circuit guarantees independent control of energy transfer to or from each of the magnets. This means that each of the magnets will have its own voltage regulator circuit. The schematic of the magnet and the voltage regulator connection is shown in ***Figure 8***. The voltage regulator consists basically of two controllable switches, A1 and A2, and two diodes, D1 and D2.

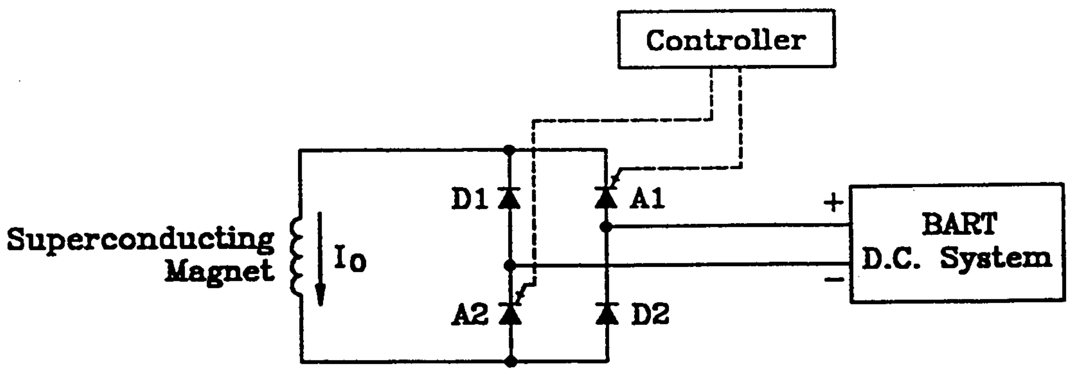


Figure 8

As in the unconstrained site, there are three modes of operation of the voltage regulator:

1. Magnet Current Freewheeling Mode: A2 turned on, A1 turned off - D1, A2 in conduction

2. Magnet Discharge Mode: A1, A2 turned off - D1, D2 in conduction

3. Magnet Charge Mode: A1, A2 turned on - A1, A2 in conduction.

The charging and discharging procession of the magnet will be controlled by pulse width modulator (PWM). The duty cycles consist of charging/discharging modes and freewheeling mode. An example will illustrate this aspect. The controllable switches A1 and A2 will be modulated at a constant frequency close to 500 Hz. The constant switching time period can be denoted by τ. When the magnet is being charged, A2 is always turned on (for the entire duration, τ) and A1 is turned on for a duration of $\gamma\tau$ ($\gamma < 1$). Thus, if the coil current has an approximate DC value of I and the DC system voltage is V, the average charging power during the interval τ is (γ) X(I) X (V). A control of the duty cycle γ (by means of pulse width modulation of the switch A1) therefore permits SI to control the average charging power and, hence, the magnet DC current profile.

Recharging will start after the tracks' voltage has been above 850 VDC for 5 seconds. The controls for the recharge cycle will be set so that the 90 seconds maximum recharge time will be met, while the track voltage equals or exceeds 825 VDC (field adjustable $\pm$25 VDC). In the case of discharging the magnet, by keeping A1 always turned off and pulse width modulating the duty cycle of A2 the magnet energy discharging curve can be tailored in a similar manner.

The controller senses the magnet current and DC voltage values and issues appropriate PWM signal patterns to turn on/off the controllable switches A1 and A2.

Table 4A: Unconstrained Site

Power electronics design	
Recharge issues:	
Power source for recharge	AC power
Setability of voltage level for recharge	Will not be charging from DC track system.
Maximum recharge power, MW	4 x 62.5 kW peak or 0.25MW
Criteria for recharge	N/A
Discharge issues:	
Ramp rate, MW/sec	Full power can be delivered in approximately 5 micro-seconds (delay in semiconductor device's switching time is ~ 5μsec.).
Maximum discharge power	4000A @ 800V = 3.2MW
Maximum discharge voltage	850 V
How do you avoid overvoltage at the end of discharge?	Not Applicable.
Other issues:	
Spurious current injection at signaling frequencies, ma/specific frequency	Not anticipated. Subject to further analysis. See comments in text below.
Are notch filters required?	See comments on page 16.
Is there a warm bypass switch?	Yes
Is there a cold bypass switch?	No

Table 4B: Transbay Tube

Power electronics design	
Recharge issues:	
Power source for recharge	DC Track
Setability of voltage level for recharge	850V DC
Maximum recharge power, MW	1.06 (4 sections to have staggered charging)
Criteria for recharge	Magnet current < 1250 A and DC track voltage ≥ 850V DC
Discharge issues:	
Ramp rate, MW/sec	Full power can be delivered in approximately 5 micro-seconds (delay in semiconductor device's switching time is ~ 5μsec.
Maximum discharge power	4000A @ 800V = 3.2MW
Maximum discharge voltage	850 V
How do you avoid overvoltage at the end of discharge?	Not Applicable
Other issues:	
Spurious current injection at signaling frequencies, ma/specific frequency	Not anticipated. Subject to further analysis. See comments in text below.
Are notch filters required?	See comments below table.
Is there a warm bypass switch?	Yes
Is there a cold bypass switch?	No

Current Harmonics and Surge Suppression

By choosing an appropriate switching frequency for the controllable switches, harmonic injection can be avoided at all of the specified critical frequencies of the BART signaling system. For example, if we chose 500 Hz switching frequency for the controllable switches, harmonics will be present at 5000, 5500, 6000, 6500, 7000, 7500, 8000, 8500, 9000, 9500 and 10,000 Hz, besides some other harmonics which are beyond the BART signaling range. None of the above mentioned frequencies should interfere with the BART signaling system. However, a small capacitor bank will be added, as shown below in ***Figure 9***, filter out the effect of harmonics in general.

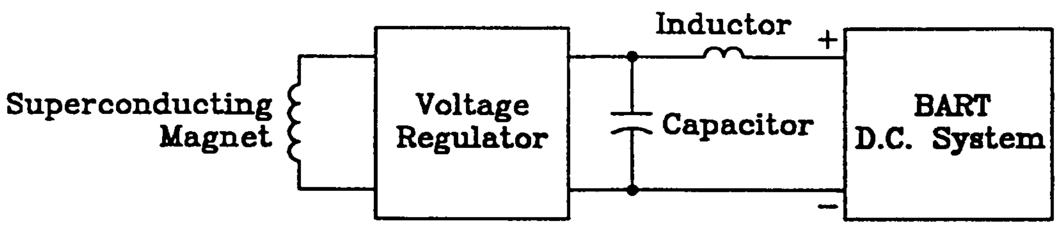


Figure 9

The superconducting magnet and the voltage regulator semiconductor devices can withstand 3000 V surges without any extra protection. The capacitor bank, however, will aid in the surge suppression mechanism. The voltage regulator will be designed with a 6000 V voltage stand-off rating. If additional surge suppression is required, then an inductor, as shown above, can be used.

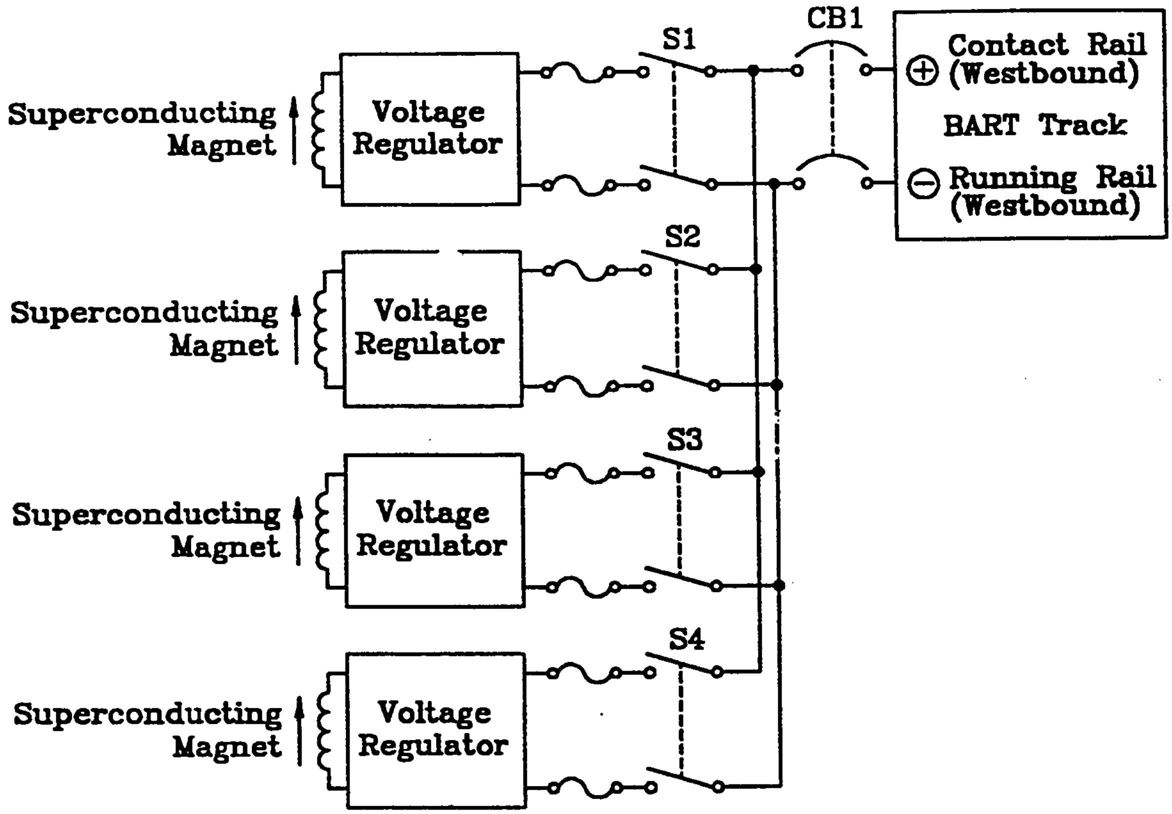
A detailed study of the project will include the evaluation of the possibility of adding a notch filter in addition to the DC capacitor bank. The notch filter, if used, will be designed to prevent the injection of current harmonics in the range of BART signaling frequencies.

Switching and Fusing Design

The magnet system will connect to the BART rail system through a main circuit breaker. The breaker will be electrically interlocked to the ESS controller such that opening of breakers will inhibit the release of energy from any of the four magnets. The switching and fusing is shown schematically in ***Figure 10.*** The ESS controller will also be capable of opening the breaker on a command signal from BART. Since SI's magnet system is inherently current limited by the amount of current flowing in the magnets, the fault current and peak voltage conditions cited in the ESS specification will govern the selection of the breaker.

The individual (4) magnet/voltage regulator pairs will be connected together on a DC bus, which in turn connects them to the main circuit breaker. Each voltage regulator is connected to the bus through fuses and a manual disconnect switch. The fuses are electrically interlocked to the controller; if a fuse element opens, an indicator on the fuse signals the controller so energy cannot be released from the associated magnet. Likewise, the disconnect switches are electrically interlocked so that if they are opened, energy cannot be released.

Switching and Fusing Design



(S1–S4)=Mannual Disconnects
Non Load Break
1500A Rating
1500VDC Rating

(CB1)=Electricaly Operated
Main Breaker
2000A Rating Continuous

500A Fuses

Figure 10

Switching and Fusing Design	
Fault protection: fuse or circuit breaker type	Main circuit breaker with fuses for each individual magnet/regulator.
Disconnect method	Electrically operated main breaker and manually operated fused disconnects.
Lockout type	Conventional lockout ring.

System Monitoring and Control:

Each magnet is controlled at the voltage regulator control panel. Control push buttons, selector switches, level meters and indicator lights are mounted on the front of the voltage regulator. The layout is illustrated in ***Figure 11*** below. A remote monitor panel will be installed in the west ventilation structure and duplicate these local display outputs. Control of the overall magnet system will be provided with a controller similar to those in the voltage regulators. It will control the sequence of operation among the magnets and also respond to control signals from BART. This provides the intermediate link between the magnet and the BART system. It will control the overall magnet system and response.

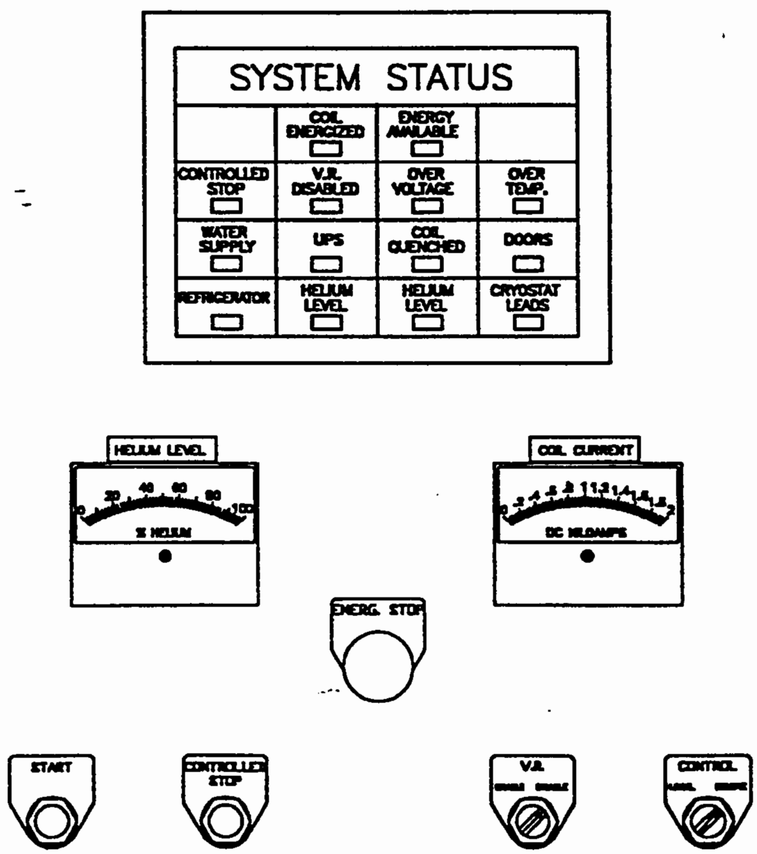


Figure 11

When the system is operating properly, as shown in ***Figure 11***, only two indicator lights will be lit: COIL ENERGIZED and ENERGY AVAILABLE. The two meters will also verify normal operations: the COIL CURRENT meter will be at full scale with the indicator needle over 1, and the HELIUM LEVEL meter will indicate anywhere between 55% to 100%. There are twelve other indicating lights - six warning (yellow) and six fault (red) indicators. Typically, these lights will remain unlit. Interpretations of the warning and fault lights are given below:

Warning Indicators

These conditions will not shut the system down, but may inhibit restarting it. Interpretations of the warning lights are:

Controlled Stop: When the CONTROLLED STOP (yellow) button has been depressed, the coil current will start decreasing and this light will come on. When the system is in this state, the DC magnet charging power supply is no longer enabled. Magnet energy is being consumed by components in series with the magnet, primarily the GTO switch.

VR Disabled: The selector switch must be in the ENABLE position for the system to provide power when the BART tracks need it. If for some reason it is necessary to inhibit the discharge of the magnet, the selector switch is placed in the DISABLED position. The yellow light alerts the operator of this condition.

Water Supply: There are several conditions which activate this light. The most likely cause is that the water chiller has failed to operate properly. The other most likely condition is lack of, or low, water flow through the GTO cooling block. If the system is shut down with the CONTROLLED STOP or EMERGENCY STOP button and the WATER SUPPLY indicator is lit, the system cannot be restarted until the water condition is cleared.

UPS: This UPS is used to back up the control and computer circuitry in the event of a long duration outage. If the light is blinking, the 120 V supply to the UPS is in question. If the light stays on continuously, there is a problem with the UPS itself.

Refrigerator: The helium refrigerator performance is monitored by its own PLC control system. Different conditions can trigger this warning light.

Helium Level: If the liquid helium level drops to 75% or less of the proper level, this light will be illuminated. This light will inhibit restart of the system.

Fault Indicators

These will de-energize the magnet immediately through a dump resistor in series with the magnet. The system is prevented from restarting until the fault is cleared.

Four of the six lights—OVER-VOLTAGE, COIL QUENCHED, CRYOSTAT LEADS and OVERTEMP—are triggered by events which have a short lifetime. These conditions are usually cleared by the time a restart is initiated. However, they do warrant investigation by an SI field service representative. The other two lights—DOORS and HELIUM LEVEL—are of a different nature. Their condition will still exist at the time of discovery. Interpretations of the fault light are:

Overvoltage: An overvoltage condition across the capacitor bank will trigger a "crowbar" thyristor which short circuits the GTO switch. The energy of the magnet is dissipated through the dump resistor.

Coil Quenched: The magnet developed a small voltage across it, i.e., part of it begins to leave the superconducting state. The energy is removed through the dump resistor. This condition is not likely.

Cryostat Leads: The cryostat leads connect the magnet to the room temperature conductors. The current flowing through them produces a voltage which is related to the amount of cooling they receive. If the voltage drop across one of the leads exceeds a preset level, this light is activated. The energy in the magnet will be dissipated through the dump resistor. An SI field representative will investigate the shutdown.

Overtemp: The temperature of the GTO switches are monitored. If it rises above 175°F, the light comes on. The magnet is de-energized automatically by dissipating the energy through the dump resistor. The most likely cause for this condition is loss of water cooling.

Doors: The voltage regulator door has a Position Sensor Switch. It is kept locked to prevent inadvertent access to the high voltage and current components. If the door is not properly closed, the system cannot be started. If it is opened while the magnet is energized, all the energy will be dissipated in the dump resistor. The DOORS protective feature can be disabled with a switch inside the Control Cabinet.

Table 6: Both Sites

System Monitoring and Control:	
Permanent system monitoring	
Data Acquisition System (DAS): Industry standard PC in ruggedized case monitoring 16 isolated analog signals and 40 isolaed digital signals.	Measurements include: Magnet, current(s) Current transferred to train Track voltage Helium system(s) status Controller alarms
Permanent system control	
Controller: Allen-Bradley PLC	Measurements include: Coil Status DC Overvoltage Magnet lead overtemperature GTO(s) overtemperature Helium level
Data logging:	A telephone modem will be installed on the DAS for remote monitoring of events and system status. Additional data sampling channels can be provided for research purposes if needed.

Maintenance Procedures

Scheduled Maintenance. The SSD is a hands-off, maintenance-free system from the user's perspective. All SSD system maintenance can be provided by SI. The SSD remains on-line ready to provide power when during most required maintenance procedures.

The status of all SSD support systems is monitored continuously via the Data Acquisition System (DAS). Should a condition occur requiring the on-site attention of an SI technician, one will be dispatched within 12 hours.

The SSD system is relatively maintenance-free. The magnet has no moving parts, no electrochemical reactions or other processes that cause wear or require replacement. The voltage regulator consists principally of solid state devices, and should be periodically inspected for dust, dirt and other contaminates which may be present.

Unscheduled Maintenance: Unscheduled maintenance events will be addressed without delay by SI field service representatives. The onboard DAS will notify SI immediately of any abnormal activity. SI will interrogate the SSD from its facilities in Madison and implement the appropriate response.

Significant differences between the Transbay Tube and the unconstrained site in maintenance procedures are not foreseen at this time. Required training of BART personnel will be minimal, because of SI's design philosophy and remote DAS. If so desired by BART, SI can provide the necessary training to re-start the system and do routine maintenance on the refrigeration system.

Table 7

Maintenance Procedures:	
Magnet	None
Refrigerator, cryostat, leads	Semi-annual maintenance on refrigerator; annual inspection of cryostat and lead connections.
Power electronics	Semi-annual cleaning and annual check of connections.
Monitoring system, including calibration	Semi-annual cleaning; annual check of connections.
Special safety procedures for maintenance personnel	De-energize magnet when working close to cryostat.

Cost Estimates

The prices for the proposed systems specified in this proposal are $5,584,000 for the Transbay Tube installation and $3,408,000 for the unconstrained site. The price difference is accounted for by the modifications to the standard SSD system for installation in the Tube. One modification consists of increasing the cryostat vessel pressure rating sufficient to contain vaporized helium in the event of a quench within the cryostat. The other modification is the incorporation of shielding to contain the magnetic field. Shielding costs are estimated as detailed design has not been performed. Neither of these prices include site installation or operation and maintenance costs.

We anticipate prices will decrease in the 1995 and 1997 time frames. Estimates of these decreases are, however, highly speculative. Cost reductions achieved due to volume production and design refinements of SSD systems may be offset by price increases in major components such as superconducting wire and stainless steel. For planning purposes, 5% reductions in 1995 over 1993 pricing and a further 5% reduction when comparing 1997 prices to 1995 may be reasonable.

As described earlier, the approach taken to meet the requirements of the Transbay Tube site consists of four parallel SSD modules each operating at 1250 A and storing 2M J of available energy.

For the unconstrained site the number of modules can be increased or decreased depending on the site requirements. Individual modules to be used in the unconstrained site are priced at $850,000 each for 1993 delivery. The modules are capable of stand-alone operation.

Table 8A: Unconstrained Site

Cost Estimates (in 1993 dollars)			
Capital costs:	1993 delivery	1995 delivery	1997 delivery
Total system price, single unit	$3,408,000	$3,238,000	$3,076,000
Cost of coil and cryostat	*	*	*
Cost of refrigeration system	*	*	*
Cost of power electronics	*	*	*
Cost of fusing and switching	$115,500	$115,500	$115,500
Incremental cost of additional 1 MJ of energy storage	$100,000		
Incremental cost of additional 1 MW of power capability	$850,000		
Indirect costs, including design, engineering, assembly, transportation, management, fees, contingencies, taxes, insurance, etc. (this may be lumped or broken out)	Included in price.	Included in price.	Included in price.
Cost per unit in quantities of 2-5	10% discount	10% discount	10% discount

**Proprietary information*

Table 8B: The Transbay Tube

Cost Estimates (in 1993 dollars)			
Capital costs:	1993 delivery	1995 delivery	1997 delivery
Total system price, single unit	$5,584,000	$5,305,000	$5,040,000
Cost of coil and cryostat	*	*	*
Cost of refrigeration system	*	*	*
Cost of power electronics	*	*	*
Cost of fusing and switching	$115,500	$115,500	$115,500
Incremental cost of additional 1 MJ of energy storage.	$100,000		
Incremental cost of additional 1 MW of power capability	$1,400,000**		
Indirect costs, including design, engineering, assembly, transportation, management, fees, contingencies, taxes, insurance, etc. (this may be lumped or broken out)	Included in price.	Included in price.	Included in price.
Cost per unit in quantities of 2-5	10% discount	10% discount	10% discount

****Proprietary information***

***Requires the use of another 13 ft. of tunnel space beyond the 50 ft. being used for the proposed system.*

Table 9A: Unconstrained Site

Maintenance Costs per year:			
Total system	$12,000*		
Refrigeration system	~ $8,000		
Power electronics			
	~ $4,000		
Monitoring system			
Electricity Cost*	$35,700		
Daily operations (labor hours)			

** Labor costs only (excludes travel costs). Total system includes power electronics, monitoring and regrigeration*
***Based on 6¢/Kwh*

If the helium liquefication system is used for the unconstrained site, the electricity cost becomes $88,300/year.

Table 9B: Transbay Tube Site

Maintenance Costs per year:			
Total system*	$12,000*		
Refrigeration system	~ $8,000		
Power electronics			
	~ $4,000		
Monitoring system			
Electricity Cost*	$35,700		
Daily operations (labor hours)	0		

** Labor costs only (excludes travel costs). Total system includes power electronics, monitoring and refrigeration.*
***Based on 6¢/Kwh*

Appendix E

BATTERY AND RECTIFIER DESIGN TABLES

Request for Information: Battery Energy Storage Systems

Overall System Design	Bat. Only	DC Bat.	Bat.- PCS
Net Effective Stored Energy, in MJ	7,100	3,800	2,800
Peak Discharge Power Rating, in MW	10	3.2	3.2
Recovery period between cycles	n/a (1)	n/a (1)	n/a (1)
System Footprint, L x W x H in feet (2)	458 x 2.3 x 0.8	122 x 3.3 x 4.3	232 x 3.5 x 6
System Weight, in pounds	86,700	57,600	58,700
System Lifetime, in years	30 (3)	30 (3)	30 (3)
System cycle life (# of disch. cycles)	n/a (4)	n/a (4)	n/a (4)
Aux. power requirements, W @ volts	5 kW@4160	5 kW@4160	5 kW@4160
Seismic characteristics, installed.	Zone 4	Zone 4	Zone 4
Date when a system could be supplied for test program: month/year	present (5)	present (6)	present (6)

(1) Recharge at night.
(2) Could be reduced if space is at a premium.
(3) Assumes battery replacement at specified periods.
(4) For the shallow discharge experienced by the cell in these designs, time (not # of cycles) limits life.
(5) Cells commercially available.
(6) 20 to 30 weeks after receipt of order for PCS.

Cell Design	Bat. Only	DC Bat.	Bat. - PCS
Manufacturer	Delco		
Model No.	2000		
Type	Flooded electrolyte (with valve)		
100 hour capacity (Ah)	115		
Internal resistance (micro-ohms)	580		
Cells per module	6		
Total number of modules	1,440.	768	576

System Monitoring and Control	Bat. Only	DC Bat.	Bat. - PCS
Permanent system monitoring:			
Digital data link to control center	Output current and voltage		
"	DC interface status		
"	Charger status		
"	n/a	PCS overtemp	PCS overtemp
"	n/a	PCS control	PCS control
Local	Hydrogen gas concentration		
Early phase datalogging for research purposes:	none		

Maintenance Procedures	Bat. Only	DC bat.	Bat. - PCS
Batteries	6 inspections per year	6 inspections per year	6 inspections per year
Power electronics	n/a	6 inspections per year	6 inspections per year
Monitoring system, including calibration	Yearly inspection	Yearly inspection	Yearly inspection
Special safety procedures for maintenance personnel	none	none	none

Request for Information: Rectifier

Overall System Design	Rectifier
Net Effective Stored Energy, in MJ	n/a
Peak Discharge Power Rating, in MW	3.2 MW
Recovery period between cycles, m:sec	n/a
System Footprint, L x W x H in feet	29 x 4 x 7
System Weight, in pounds	25,000
System Lifetime, in years	30
System cycle life, # of discharge cycles	n/a
Auxillary power requirements, watts@volts	3.4 MW @ 34.5 kV
Seismic characteristics, installed.	Zone 4
Date when a system could be supplied for test program: month/year	present (1)

(1) Commercially available.

System Monitoring and Control:	Rectifier
Permanent system monitoring	
Digital data link to control center	Output voltage and current
"	DC interface status
"	Rectifier overtemperature
"	Rectifier control
Early phase datalogging for research purposes:	none

Maintenance Procedures:	Rectifier
Power electronics	Yearly inspection
Monitoring system, including calibration	Yearly inspection
Special safety procedures for maintenance personnel	none

Appendix F

AC MONITORING TEST PLAN

AC MONITORING TEST PLAN

1. General description of test

   Equipment will be installed at four locations on the BART traction power system and two PG&E feed points to the traction power system. This equipment will monitor voltage, current, real and reactive power for at least one BART business cycle (one week). Voltage sag events in the transbay tube will be captured and the data collected from all six locations at the time of each event will be compared to determine the relative contribution made by each section of the traction power system from the PG&E feed points to the center of the tube.

   Train operating and event data recorded by BART during the test period will be made available to PG&E for the purpose of their study.

2. Test objective

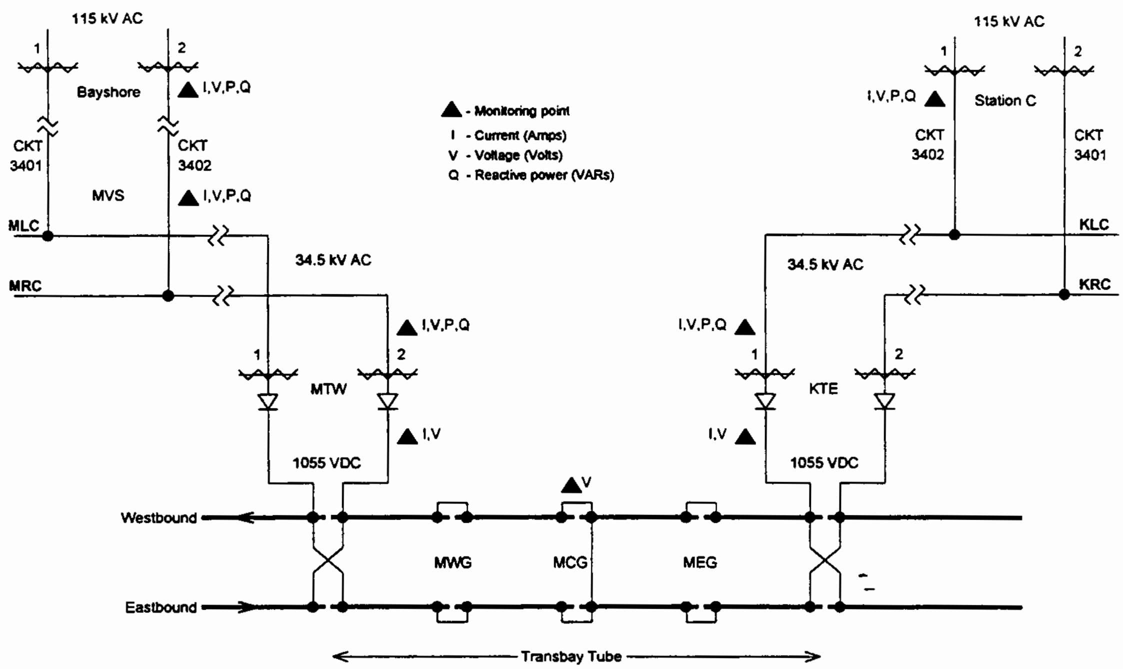
   Observe the contribution made by major components of the traction power system to voltage sags in the transbay tube and determine whether any measures on the AC side of the system could help mitigate the problem.

3. Test location

   The locations of the test equipment and the data to be monitored are summarized in the table and sketch below.

Location	**Line/ CKT**	**Symbol**	**Owner**	**AC Volts**	**AC Amps**	**AC KW**	**AC kVARs**	**DC Volts**	**DC Amps**
Bayshore	3402		PG&E	X	X	X	X		
Valencia St.	2 (MR)	MVS	BART	X	X	X	X		
Baytube West	2	MTW	BART	X	X	X	X	X	X
Baytube Middle	1	MCG	BART					X	
Baytube East	1 (KL)	KTE	BART	X	X	X	X	X	X
Station C	3402		PG&E	X	X	X	X		

Note that only the one line (of the two lines at each location) that feeds the westbound track of the baytube will be monitored. Only the A phase of these lines will be monitored due to the lack of 3-phase PTs or PDs at all points and budget constraints.



4. Test duration

Once the test equipment has been set up and verified on both sides of the bay (sequence detailed in section 8 below), continuous monitoring will be performed for one week (one BART business cycle). In the unlikely event that no significant voltage sag event occurs during that time, the duration of the test may be extended a few days in the interest of capturing a more significant event.

5. Equipment and connections

PG&E will supply all test equipment, wiring, connection hardware and tools required for equipment connection. BART will also supply any tools it deems necessary for installation, especially tools needed for station shut-down, live circuit testing and grounding, etc.

Astro-med multi-speed chart recorders with electrically isolated inputs will be used at all five locations outside of the tube. A Campbell Scientific Inc. datalogger with cassette recorder will be used at the middle of the tube.

In the interest of keeping the budget down, existing BART meter and relay CTs, PTs and PDs will be used to sense AC voltage and current. Existing BART current shunts and potential transducers will be used to sense DC voltage and current at the rectifying substations. Only single phase measurements of the A phase will be made.

The AC voltage and current signals from the CTs, PTs and PDs will be monitored directly by the chart recorders using RMS inputs. AC real and reactive power monitoring will be done using Ohio Semitronics Watt/VAR transducers with DC outputs to the chart recorders.

PG&E will fabricate a voltage divider and isolation circuit to measure DC voltage at the middle of the baytube. The isolated DC signal will be fed to the datalogger.

At the rectifying substations (KTE and MTW), connections to the PD will be made with ring connectors on the back of the under-voltage relay. Connections to the CT will be made with ring connectors in series with the backup overcurrent relay for phase A. Connections to the DC current shunt and voltage transducer will be made with ring connectors on the backs of the ammeter and voltmeter respectively.

Connections Made Inside C02 Cabinet

<table>
<tr><th>Quantity</th><th>Sensor</th><th>Relay/meter</th><th>Station</th><th>Panel</th><th>Terminal(s)</th><th>Conductor(s)
Phase (& Neut)</th></tr>
<tr><td rowspan="2">Aφ Voltage</td><td rowspan="2">20,125:115 V
Potential Device</td><td>227-1 Under-voltage relay</td><td>KTE</td><td>MR-3</td><td>8 (line)
9 (gnd)</td><td>LC4 (line)
LC0 (gnd)</td></tr>
<tr><td>227-2 Under-voltage relay</td><td>MTW</td><td>MR-4</td><td>8 (line)
9 (gnd)</td><td>RC4 (line)
RC0 (gnd)</td></tr>
<tr><td rowspan="2">Aφ Current</td><td rowspan="2">600:5 A Current Transformer</td><td>251B-A/1 Backup over-current relay</td><td>KTE</td><td>MR-3</td><td>9</td><td>25</td></tr>
<tr><td>251B-A/2 Backup over-current relay</td><td>MTW</td><td>MR-4</td><td>9</td><td>45</td></tr>
<tr><td rowspan="2">DC Bus Voltage</td><td rowspan="2">Voltage transducer</td><td>V-1 DC Volt meter</td><td>KTE</td><td>MR-1</td><td>8 (+)
10 (-)</td><td>V1 (+)
V2 (-)</td></tr>
<tr><td>V-2 DC Volt meter</td><td>MTW</td><td>MR-2</td><td>8 (+)
10 (-)</td><td>V1 (+)
V2 (-)</td></tr>
<tr><td rowspan="2">DC Bus Current</td><td rowspan="2">Current Shunt</td><td>A-1 DC Ammeter</td><td>KTE</td><td>MR-1</td><td></td><td>A1 (+)
A2 (-)</td></tr>
<tr><td>A-2 DC Ammeter</td><td>MTW</td><td>MR-2</td><td></td><td>A1 (+)
A2 (-)</td></tr>
</table>

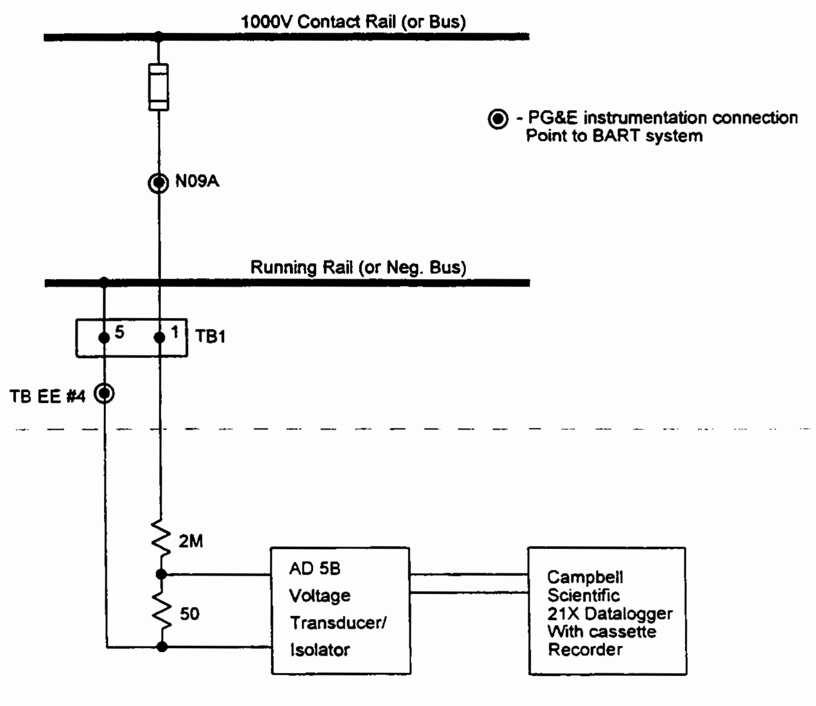
At the Valencia Street switching station and PG&E sub-stations, the connections will be made at the metering state block. The current connection will be made using a make-before-break "stab" and the voltage connections will be made with insulated alligator clips.

Connections Made on Front of MVS Meter & Relay Board, Panel 2

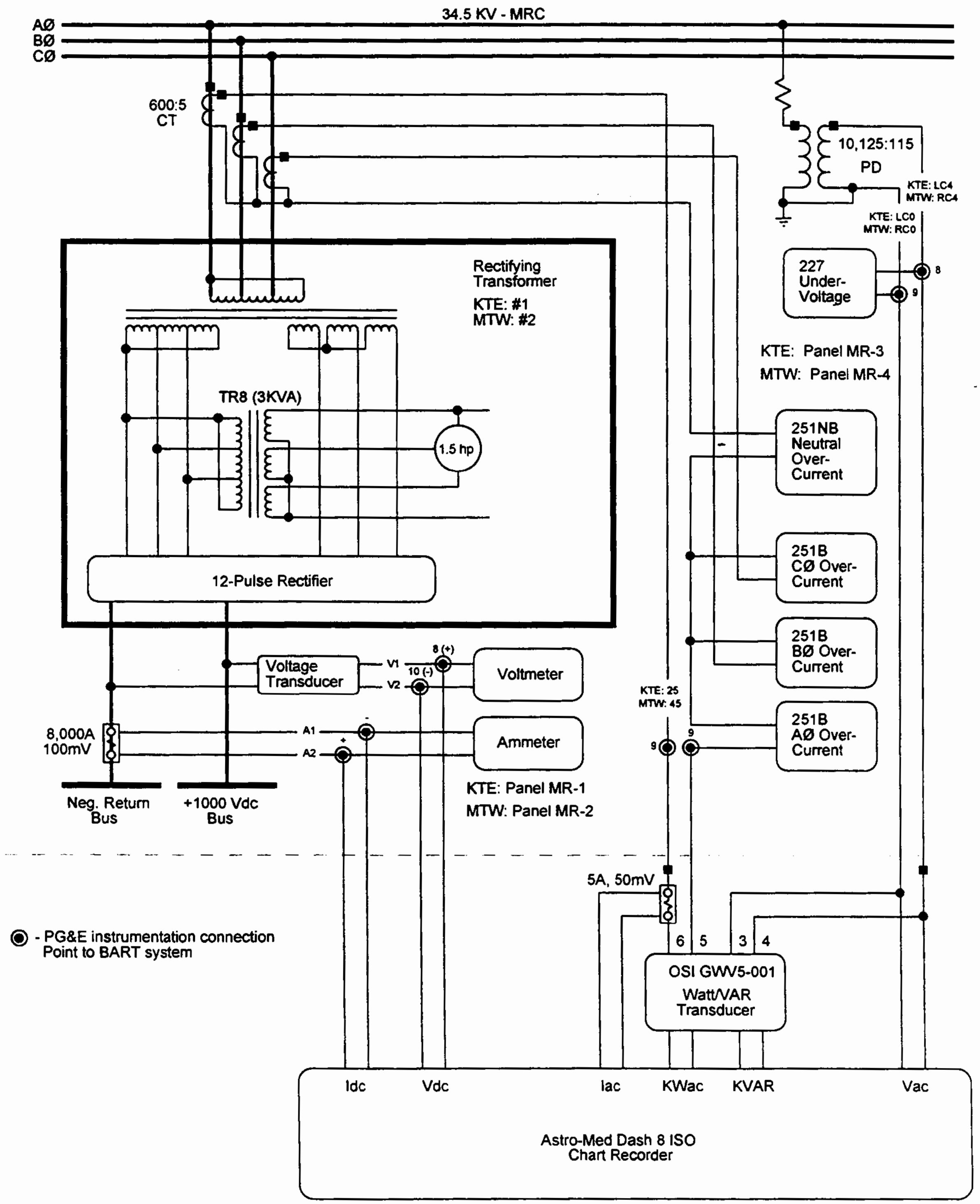
Quantity	Sensor	Relay/meter	Panel	Terminal(s)	Conductor(s) Phase (& Neut)
Aφ Voltage	20,125:115 V Potential Transformer	TS-12, State block for PG&E meters	MR-2	A (line) J (neut) (Insulated alligators)	14 (line) 10 (neut)
Aφ Current	1200:5 A Current Transformer	TS-12, State block for PG&E meters	MR-2	E (Stab)	75

At the baytube center gap breaker station (MCG), connections will be made using banana plugs into jacks number 1 (+) and 3 (-) inside the low voltage compartment of breaker number one (B01). There is a fuse between jack 1 and the positive bus.

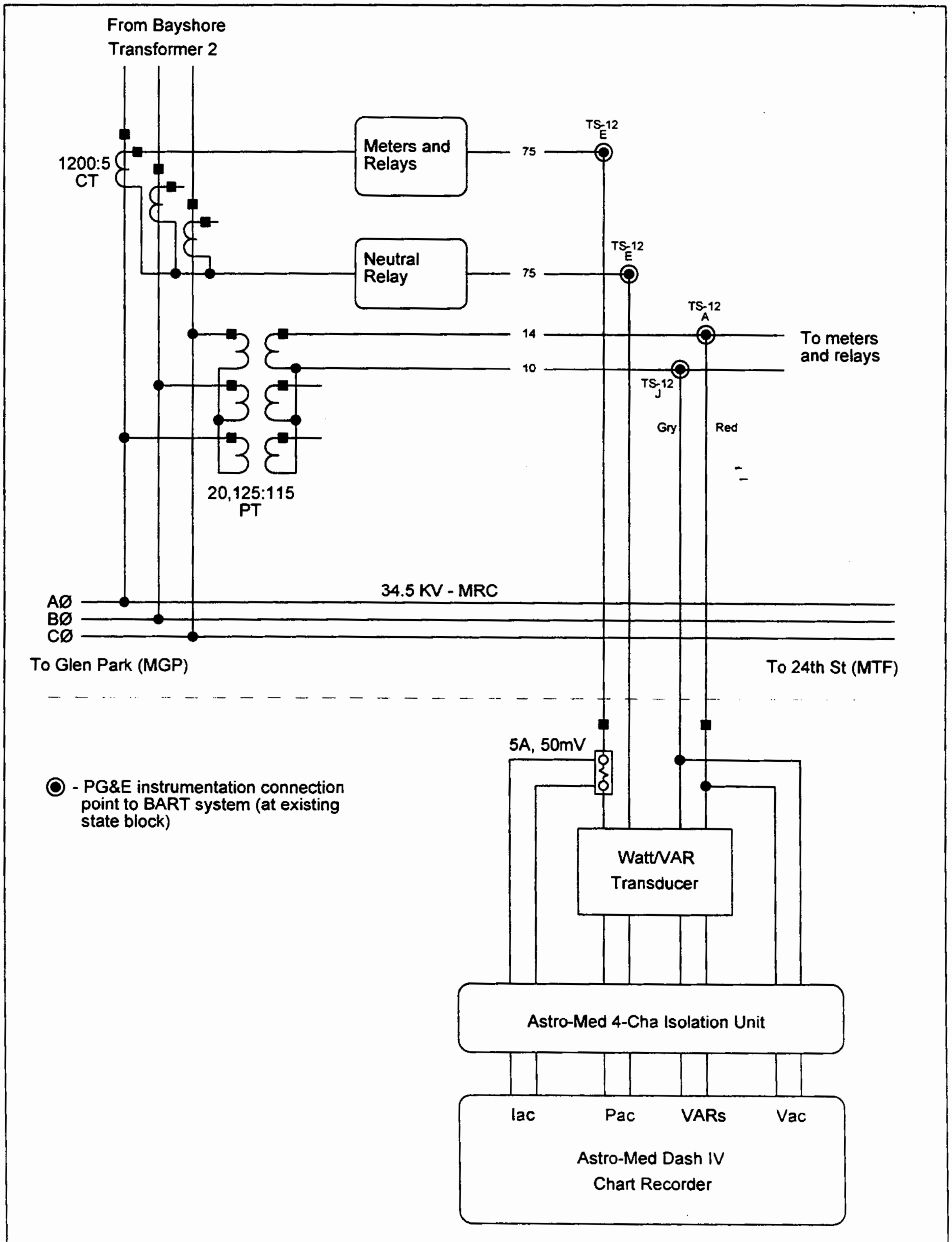
Diagrams of these connections follow:



Hook up of datalogger at gap breaker station in middle of tube (MCG)



Hook up of chart recorder to rectifying substations at baytube East and West (KTE & MTW)



Hook up of chart recorder to Valencia Street switching station (MVS)

6. Personnel

- BART Maintenance for connection to BART
- PG&E Personnel for test direction and connection to PG&E equipment (John David Heinzmann, et al.)
- BART Engineering for monitoring and coordinating the test (Abdul Shaihk, et al)

7. Test criteria

A successful test will be measured by the continuous collection of chart recorder and datalogger data for all quantities monitored with high speed capture of voltage sag events and the ability to compare monitored levels from all sites at the times of these events.

8. Test sequence

Equipment installation is currently scheduled to begin June 1, 1993. Equipment vendors have indicated that all equipment being purchased and rented for this test will be available in time for this test date. In the event that there are uncontrollable delays, the test date would have to be adjusted.

The test sequence will be:

- Install datalogger at MCG. Look at waveform to datalogger with oscilloscope.
- Install instrumentation on the East side of the bay (KTE and PG&E station C)
- Monitor for several days, with daily visits to instrumentation to adjust trigger levels and get comfortable with the setup.
- Visit datalogger at MCG and swap tapes
- Install instrumentation on the West side of the bay (MTW, MVS and PG&E Bayshore sub)
- Monitor both sides of bay for one week with visits to each site as necessary to check on equipment and examine results
- Remove all equipment

9. Operational effect on BART equipment and system

Equipment installation and connections at each of the stations described above will be made during the grave yard shift. The substations will be shut down while the equipment is being connected and disconnected to the BART system. Therefore, BART's revenue operations will not be affected.