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WAYSIDE ENERGY STORAGE STUDY
Volume I - Summary

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16. Abstract

Volume I summarizes an in-depth application study which was conducted to determine the practicality and viability of using large wayside flywheels to recuperate braking energy from freight trains on long downgrades.

The study examined the route structures of nine U.S. railroads and identified various wayside energy storage system (WESS) configurations. The optimum means of transferring energy from the train to the wayside was by means of a high-voltage ac catenary from either regenerative electric locomotives or modified dual-mode (diesel-electric/electric) locomotives.

The application of WESS was then analyzed for four specific routes of typical U.S. railroads. These routes and the annual returns on investment (ROI's) resulting from WESS deployment on existing railroads were as follows: Atchinson, Topeka, and Santa Fe (Los Angeles to Belen), 27.1 percent; Black Mesa and Lake Powell, 17.3 percent; Conrail (Pittsburgh to Harrisburg), 22.0 percent; Union Pacific (Los Angeles to Salt Lake City) 20.2 percent.

This report occupies 4 volumes as follows: Volume I - Summary, Volume II - Detailed Description and Analysis, Volume III - Engineering Economics Analysis: Data and Results, and Volume IV - Dual-Mode Locomotive: Preliminary Design Study. Volume III is available in photocopy or microfiche from the National Technical Information Service, Springfield, VA 22161

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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

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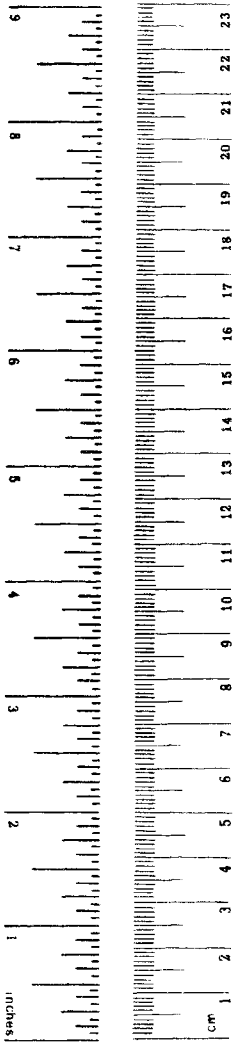
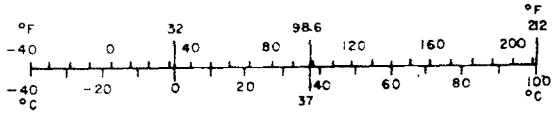
*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



PREFACE

This final report summarizes the results of the Wayside Energy Storage Study. It is submitted to the Transportation Systems Center by the AiResearch Manufacturing Company of California, a division of The Garrett Corporation, in accordance with U. S. Department of Transportation Contract No. DOT-TSC-1349. The final report comprises four volumes as follows:

Volume No.	Title
I	Summary
II	Detailed Description of Analysis
III	Engineering Economics Analysis Data and Results
IV	Dual-Mode Locomotive Design Study

The Wayside Energy Storage Study represents the joint efforts of the AiResearch Manufacturing Company of California and Bechtel Incorporated; the Bechtel staff assisted in the railroad location survey, the electrification studies, and the wayside station design.

The continued assistance and guidance of the Transportation Systems Center (TSC) Technical Monitor, Mr. John M. Clarke; the Federal Railroad Administration (FRA) Functional Coordinator, Energy/Environment, Mr. John Koper; and several members of the TSC and FRA staffs were invaluable to the success of the study.

The interest and support for the Wayside Energy Storage Study given by Mr. Peter L. Eggleton, Director General, Transport Canada Research and Development Centre, and his staff have been helpful and have shown that the concept is also applicable outside the United States. Interest in the wayside energy storage concept has also been expressed by Mr. W. Latscha, General Manager, Swiss Federal Railways.

Major contributions were made by many U.S. railroads, who contributed comprehensive information that was used to establish and maintain the necessary data base. These railroads also acted as sounding boards in the review of flywheel energy recuperation concepts developed in the study. Their comments and suggestions have been incorporated into the final recommendations of the program, with the result that the concept favored for subsequent development, demonstration, and deployment is representative of equipment that railroads would consider for future procurement. The following railroads have given substantial assistance to AiResearch in the study:

Atchison, Topeka, and Santa Fe

Black Mesa and Lake Powell

Burlington Northern

Conrail

Denver and Rio Grande Western

Duluth, Missabe, and Iron Range

Southern

Southern Pacific

Union Pacific.

Many material and equipment suppliers were helpful in defining locomotive modifications, wayside electrification, and the flywheel stations. The suppliers contributing to the study were the following:

Edison Institute

English Electric Corporation

General Electric Industrial Sales Division

General Electric Locomotive Department

General Motors Electro-Motive Division

Lukens Steel Company

Morrison and Knudsen

Reliance Electric

Southern California Edison

Westinghouse Electric Industry Products.

CONTENTS

CONTENTS (Continued)

ILLUSTRATIONS

ILLUSTRATIONS (Continued)

TABLES

SECTION 1

INTRODUCTION

This study quantifies the benefits to be derived by recuperation of braking energy from freight trains descending long grades. This energy, now wasted by dynamic or friction braking on the diesel-electric and electric locomotives, represents a valuable resource that should be conserved. As an example, in the hour it takes a large freight consist to descend Cajon Pass near San Bernardino, California, enough electrical energy can be generated to supply a residential community of 30,000 for 1 hr. Storing this energy for use by an ascending consist would substantailly reduce energy costs for the railroad. For the Cajon Pass example, about $500 in savings for diesel fuel would be realized from the recuperative braking of each large consist.

The energy storage concept could be supplanted by the availability of a receptive electric utility tied to the electric lines used for regenerated electric power on the grades; however, this mode of operation is possible with only a few utilities that have policies permitting them to accept power from intermittent sources. Also, if the utility accepts such power, it is bought back at a price substantially below the cost of newly generated and distributed power from the utility, often at zero credit to the consumer.

Yet another approach to recuperation of braking energy is the scheduling of train operations so that a receptive (ascending) train is available when a train is descending the grade. Such an energy interchange would require an unrealistically precise scheduling of train operations. In practice, it would be necessary for one train to wait at the start of the grade for the second train to reach the grade. Based on actual railroad dispatching data, these waiting periods often would be of several hours duration. Also, in the real world of freight railroads, several other factors appear to make the interchange of energy directly between trains impractical. The most important of these factors are the following:

- Many grades are single track and require consecutive train operations
- Most railroads have a greater flow of freight in one direction than in the return direction
- The times required to ascend and descend a grade are usually different

Consequently, it appears desirable to provide an energy storage system at grades possessing the proper combination of elevation change, traffic density, and length. These energy storage systems should be installed at the wayside rather than onboard the locomotives. This is because the required level of energy storage (up to 3 Mwhr per locomotive) makes the size and weight prohibitive for vehicle installation.

ENERGY STORAGE ALTERNATIVES

Several energy storage techniques are available for wayside energy storage. Important concepts considered in the study were:

Lead-acid batteries

Advanced concept batteries (Na-S, Ni-Zn, etc.)

Pumped hydro storage

Compressed air storage

Regeneration to the utility

Flywheels

The relative merits of each technique are outlined in Section 2 of this report and are analyzed in detail in Volume 2.

PROGRAM OBJECTIVES

The Wayside Energy Storage Study has been structured to provide the necessary detailed information, based on actual railroad route and operational data, for ascertaining the feasibility and applicability of the WESS concept to U.S. railroads. The study has been based on the use of state-of-the-art technology that could be demonstrated at a test track within 36 months and deployed on actual railroad grades in just over 5 years.

The overall objectives addressed in the Wayside Energy Storage Study were:

(a) Develop the WESS concept in sufficient detail to define the hardware and identify the technical risks.

(b) Determine the extent of deployment opportunities on potential grades of U.S. railroads.

(c) Establish the economic viability of the WESS concept on typical U.S. freight railroads using life-cycle cost and return-on-investment analyses.

(d) Plan a comprehensive program leading to widespread WESS implementation.

PROGRAM OUTLINE

The statement of work for this AiResearch study comprised the following 11 items:

Item 1, Locations--Conduct a site survey of the route system of U.S. railroads to identify and classify potential locations for WESS application.

Item 2, Systems--Devise concepts of complete systems, from locomotives to wayside, for WESS application to both electrified and diesel electric railroads.

Item 3, Calculations--Perform power and energy calculations for proposed system configurations at candidate WESS sites and compare with fuel (energy) consumption for existing operations.

Item 4, Locomotives--Define modifications that must be made to diesel-electric locomotives to deliver and receive energy to or from the WESS.

Item 5, Wayside--Evaluate and determine optimum concepts for delivery of electric energy from locomotives to the wayside stations.

Item 6, Stations--Define concepts for the flywheel wayside stations, including interfacing electrical machinery and controls and various flywheel designs.

Item 7, Controls--Derive optimum methods of regulating the flow and storage of energy for various train configurations and timetables for the WESS concept.

Item 8, Energy Supplement--Determine strategies for use of utility energy to precharge WESS flywheels and to supplement flywheel energy for ascending consists.

Item 9, Electrified Railroads--Derive concepts for the use of WESS to provide peak load-shaving on electrified railroads.

Item 10, Engineering Economics--Conduct an engineering economics study to determine the economic viability that results from WESS deployment at grades of typical U.S. railroads.

Item 11, Development Program--Provide plans and cost estimates for follow-on tasks of development, demonstration, and deployment of WESS concept.

Reference to the above-listed items of the study will be made throughout the final report to show the specific efforts that have been directed toward each particular work item.

PROGRAM METHODOLOGY

The methodology followed by AiResearch and Bechtel in performing the study program is shown in Figure 1. The initial data-gathering tasks shown at the left side of Figure 1 were accomplished by a series of visits with the engineering and operating personnel of the following railroads:

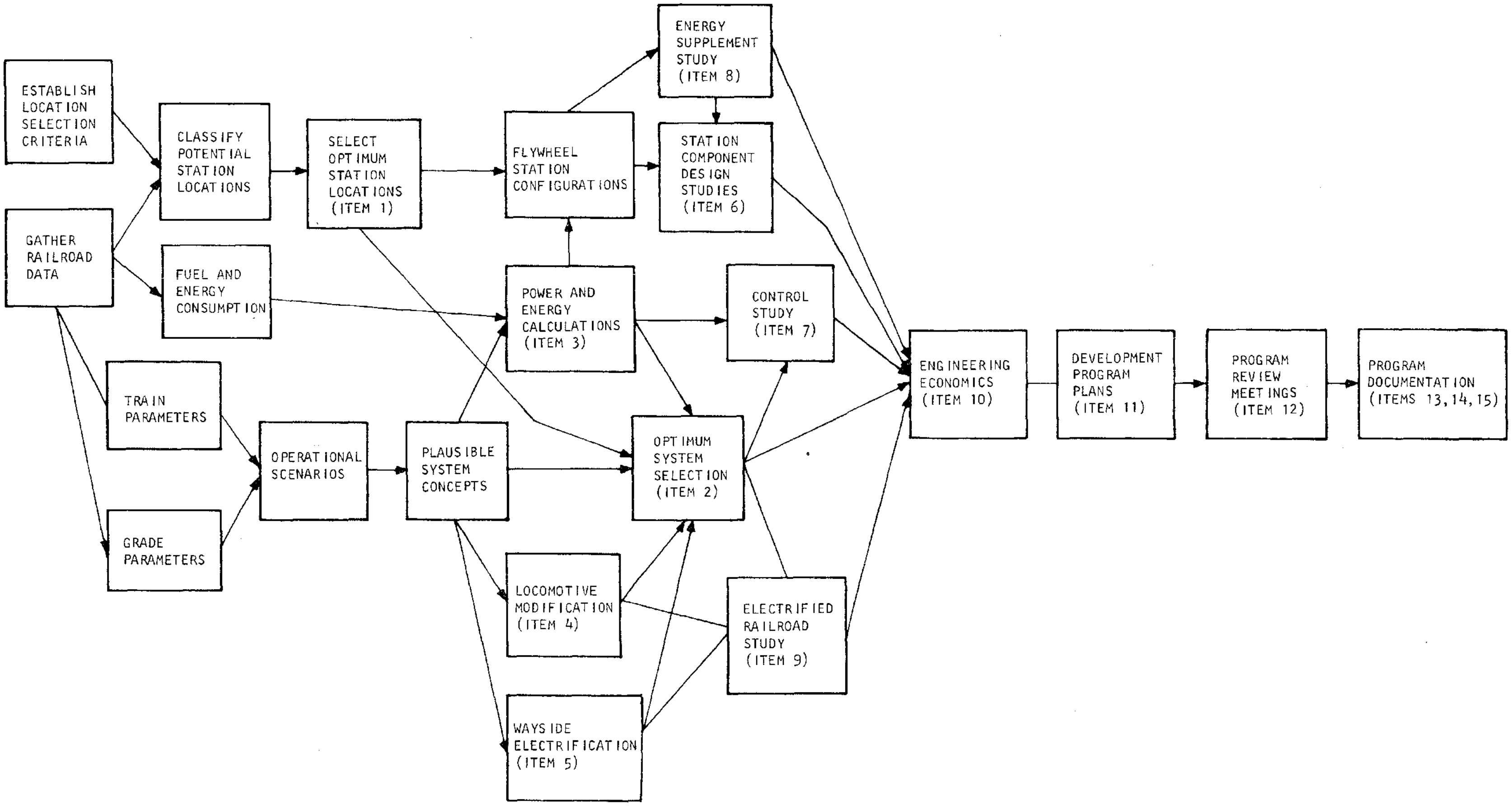


Figure 1. Wayside Energy Storage Study Methodology

Black Mesa and Lake Powell

Conrail

Duluth, Missabe, and Iron Range

Southern

Southern Pacific

Union Pacific

In addition, detailed track and operational data were obtained by FRA from the following railroads:

Atchison, Topeka, and Santa Fe

Burlington Northern

Denver and Rio Grande Western

This information was then used to complete the location study (item 1), and as an input to study items 2 through 5. The interaction and dependencies of activities are shown in Figure 1. With the station configurations and energy requirements determined, it was then possible to complete items 6 through 8. At the same time, study of the operation of WESS as a peak-shaver on electrified railroads (item 9) was accomplished. The important engineering economic analysis (item 10) was then completed, using inputs from items 1 through 9. Finally, as shown in Figure 1, development plans were formulated (item 11); this task was followed by various program review and documentation activities (items 12 through 15).

TRAIN PERFORMANCE CALCULATOR

A task was added to the WESS program by AiResearch as part of the power and energy calculations (item 3) to permit more accurate and complete assessment of energy savings based on actual railroad operations. During the initial work on energy calculations, it was found that the energy economics of WESS were strongly influenced by the operating timetable of the railroad. To determine the interactive effects of as many as 60 trains per day on a WESS grade, it was necessary to use a train performance calculator (TPC) with the capability of calculating energy at the WESS station for many trains at the same time. The AiResearch and Bechtel TPC programs do not have this capability, nor does the TSC program. Therefore, AiResearch decided to generate a new TPC with the required capability of simultaneously calculating the energy requirements in a complete railroad division. The new AiResearch TPC can calculate the energy requirements of up to 100 trains operating on 10 separate electrified sections. These individual train energy values can be summed by the computer to provide the energy values that would be experienced at WESS stations on the route.

The AiResearch TPC has been used to calculate the complete energy profile for a full day of operation on the Pittsburgh to Harrisburg section of Conrail, based on actual dispatcher's records. This unique TPC has been developed by AiResearch within the resources of the Wayside Energy Storage Study contract. In the interest of making this important tool available to TSC, FRA, and other agencies, the new TPC listing is presented in Volume 2.

FORMAT OF THE FINAL REPORT

The sheer volume of material generated during the 1-year Wayside Energy Storage Study has necessitated publishing this report in three volumes. This volume briefly describes the work conducted, the results achieved, and the conclusions reached. The main body of technical data, including the new TPC, is contained in Volume 2. The extensive engineering economics analysis data and results are contained in Volume 3.

SECTION 2

SYSTEM DESIGN AND CONCEPTS

The study of the wayside energy storage system (WESS) design involved the following interacting program work items:

Item 2	System Study
Item 4	Dual-Mode Locomotive
Item 5	Wayside Electrification
Item 7	Controls
Item 8	Energy Supplement
Item 9	Electrified Railroads

The approach used for the study and the results obtained are described in the following paragraphs.

APPROACH

The systems study first examined all the plausible energy storage means that had potential for application to WESS. Next, the various methods of transmitting the recuperated energy back and forth to the wayside at the grade were analyzed. Overall system configuration tradeoff studies then were conducted and optimum arrangements were selected. At this point, the operational constraints indicated by meetings with railroads were applied to the system concepts and used to develop the most practical operational concepts. Then consideration was given to the electric locomotives that would be used for WESS on electrified railroads. Finally, the dual-mode locomotive concept was developed.

PLAUSIBLE ENERGY STORAGE SYSTEMS

Prior to embarking on the detailed study of flywheel-configured WESS stations, a final comparative analysis was made to establish that no other energy storage technique should be considered.

The important criteria that were used in assessing the relative merits of an energy storage device for WESS are:

- Round trip efficiency
- Energy density
- Power density

- Deep discharge cycle life
- Initial cost
- Maintenance cost

The use of these criteria in the analysis resulted in the identification and consideration of the following energy storage techniques:

> Batteries--Electrochemical storage batteries represent the most common energy storage technique in use today; however, they suffer from the disadvantage of low round trip efficiencies of about 60 percent. In addition, a high-quality, lead-acid battery has a deep discharge cycle life of less than 1500 cycles. Thus, since a lead-acid battery used for WESS could be used in 40 or more deep discharge cycles per day, the economic life of such a battery would be only 38 days or less. Consideration also was given to projected new battery types such as nickel zinc, zinc chloride, and sodium sulfur, which are expected to become available within the next 10 to 15 years (ref 1)*. Although these battery types promise higher energy and power densities than the lead-acid battery, their deep discharge lives are not expected to exceed 2500 cycles.
>
> Pumped Hydroelectric--The pumped hydroelectric system could be used for WESS, especially since mountainous terrain is involved, but investigations by AiResearch and Bechtel have shown that installation costs are about twice that for a flywheel system; the round trip efficiency is only approximately 76 percent, as compared to the flywheel round trip efficiency of 91.2 (measured at the distribution side of the input/output electric machine that couples energy to the flywheel). It is recognized that costs of these schemes are very much dependent on the terrain encountered.
>
> Regeneration to the Utility--This technique is technically attractive, because of its high round trip efficiency of 92 percent; however, in economic terms, it suffers from the disadvantage of not getting a full credit for the energy returned. (Usually only 60 percent is credited for a railroad operation). There also would be no credit for the demand portion of the utility charge, which normally accounts for 50 percent of the utility bill.
>
> Compressed Air Storage--An economic analysis of the use of axial-flow compressor/turbine installations storing air at high pressure was performed by AiResearch but not carried out in detail since consideration of the efficiency of this system showed that a round trip efficiency (at the distribution side of the input/output electric machine) of only 34 percent could be expected.

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*References are listed in Section 8.

Flywheels--The flywheel has the high round trip efficiency of 91.2 percent (measured at the terminals of the flywheel machine) and does not suffer from the disadvantages of direct regeneration to the utility in terms of credit for regenerated energy. The life of the system is in excess of 10^6 deep discharge cycles and the energy/power densities are at least competitive with those of the battery.

As a result of this analysis, summarized in Table 1, AiResearch has determined that, within existing technology, the flywheel represents the most economic and efficient method of storing energy for reuse at a later time not exceeding 24 hr.

TABLE 1

ALTERNATIVE STORAGE CONCEPTS

Storage Concept	Round Trip Efficiency	Installed $/kwhr	Cycle Life	Service Life
Battery	60	70	1000	2 Months
Pumped hydroelectric	76	1000	10^6	30 Years
Regeneration to utility	92	120*	10^6	30 Years
Compressed air	37	N/A	10^6	30 Years
Flywheel	91.2	270	10^6	30 Years

*Site-dependent

ENERGY TRANSMISSION CONCEPTS

A key decision in the Wayside Energy Storage Study was the determination of the most practical and cost-effective means of transmitting energy to and from freight trains on a grade. At the locomotive, during braking, this energy exists in dc electrical form and also could be utilized by a subsequent ascending locomotive in the same form. Thus, it appeared logical to analyze various means of electric transmission of energy to the wayside.

The basis of all the systems is that the potential energy of the descending train is converted to electrical energy and transmitted to the wayside station where it is stored in a flywheel. Subsequently, this process is reversed and stored energy is transferred to an ascending train. All systems therefore require an electrical distribution system matched to onboard locomotive and wayside equipment.

The following arrangements were considered for transmitting electrical power to the wayside:

- Low-voltage dc through a third rail
- High-voltage dc through a catenary
- Linear induction motor
- High-voltage ac through a catenary

The technical tradeoffs involved with the various means of electrification are summarized in the following paragraphs and described in detail in Volume 2.

Low-Voltage Dc Third Rail

Low-voltage dc suffers from the major disadvantage of being suitable only for extremely short sections. This is because of the high currents involved. In addition, current collection at the locomotive is beyond the present state of the art.

High-Voltage Dc Catenary

A high-voltage (3-kv) dc catenary would require modifications to both electric and diesel locomotives. For the more important latter case, a dc-to-dc converter would be required on each locomotive; the complexity of this approach was found to be prohibitive from a cost standpoint. Furthermore, with the relatively high currents involved, fault discrimination on the distribution system would pose serious problems.

Linear Induction Motor

A brief analysis was made of the use of a linear induction motor (LIM) for transmission of energy from train to wayside and back. This concept, at first glance, appears attractive since energy can be transmitted across the LIM air gap inductively without need for a catenary and pantograph; however, a combination of low round trip efficiency of the distribution system itself (32 percent compared with 96 percent for a 50-kv catenary) and extremely high installation costs make this system unattractive.

High-Voltage Ac Catenary

The high-voltage (25 or 50 kv) ac catenary is the standard main line electrification technique in the U.S. and throughout the world. It has the advantage of adequate line regulation over significant distances, simple fault protection, and readily available system hardware. The use of such a system would, however, involve the extensive modification of existing diesel locomotives in order to make them compatible.

Although none of the above systems could be considered ideal for the wayside energy storage system, an analysis of the tradeoffs involved led to the selection of the 25- or 50-kv ac catenary.

The overhead line equipment was designed and costed by Bechtel. The system is designed for 70-mph multiple pantograph operation. The simple catenary construction is used in which the contact wire is supported from a single messenger wire by droppers. This is similar to the arrangement used on the Black Mesa and Lake Powell railroad as shown in Figure 2.

The support structures will be wooden poles, except in the Pennsylvania area where steel poles are considered more appropriate.

The costs of electrification used in this study (including catenary, utility tie-in, signaling, and substations) are as follows:

One track	$238,000/route mile
Two tracks	$400,000/route mile
Four tracks	$500,000/route mile

Other electrification studies (ref 2) have shown that the cost of electrification in 1977 dollars could vary, as shown in Table 2.

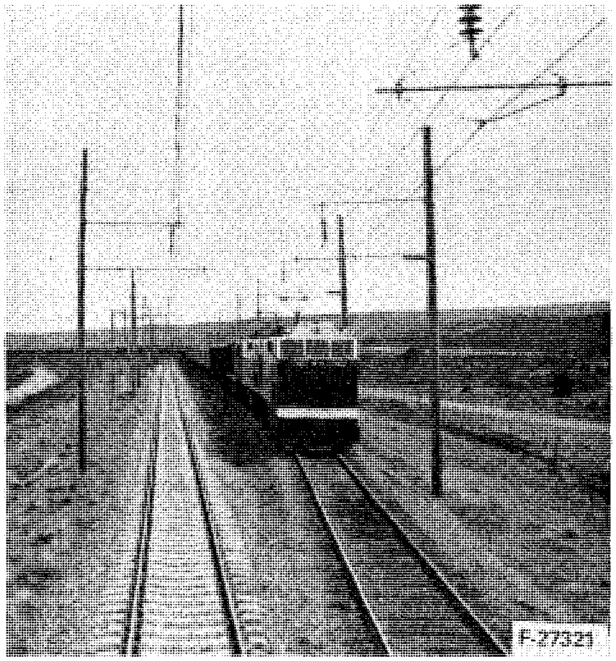

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Figure 2. BM&LP High-Voltage Catenary

TABLE 2

RANGE OF ELECTRIFICATION COSTS FROM REFERENCE 2

	Cost (1977 $)	
	Single Track	Double Track
Low estimate	$125,000	$205,000
High estimate	$371,000	$495,000

The costs quoted in Table 2 do not include the utility tie-in, which has been costed separately in this study and included in the cost-per-route-mile figures quoted above for each configuration under consideration. Therefore, AiResearch has taken conservative (high) figures when charging the cost of electrification to WESS. This is demonstrated in the study when, for comparison purposes, the return on investment (ROI) for electrification only is considered and the result is an unusually low ROI.

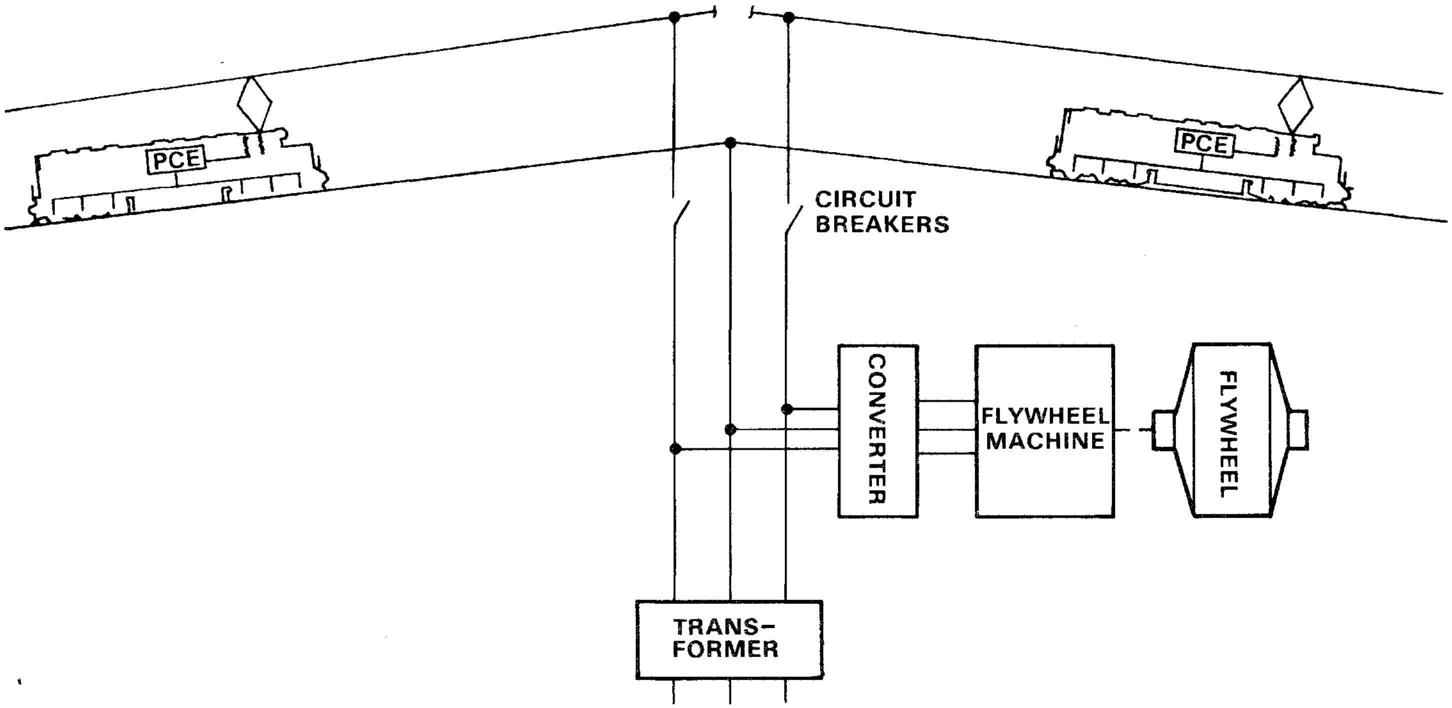
SYSTEM CONFIGURATIONS

With the decision to use a high-voltage ac catenary energy transmission system for WESS, the next consideration was the definition of the entire system to be deployed at typical grades.

Two basic railroad systems were considered, those that are or will be electrified at 25 to 50 kv and those that are and will be operated by diesel-electric traction. Examples of the former that have attractive grades are the presently electrified (at 50 kv, 60 Hz) Black Mesa and Lake Powell Railroad and the Pittsburgh to Harrisburg Division of Conrail, which is a candidate for 25-kv, 60-Hz electrification. All large western railroads are examples of railroads that will probably continue to be operated by diesel-electric locomotives like Union Pacific, Southern Pacific, Santa Fe, Burlington Northern, and Denver and Rio Grande Western.

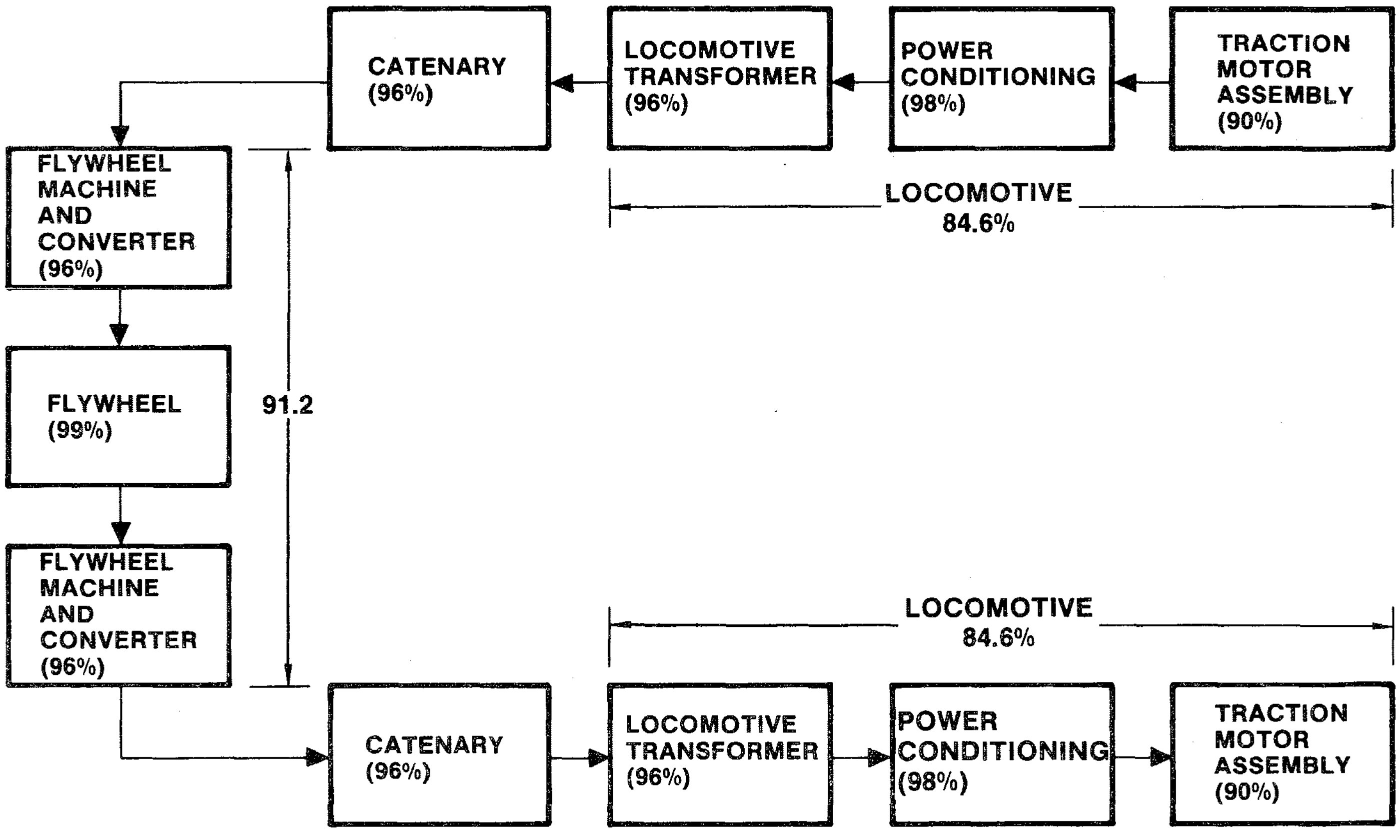
An analysis of the overall system tradeoffs using the ac catenary led to the adoption of the system shown in Figure 3. On each locomotive it is necessary to have a fully controlled thyristor converter, i.e., with thyristors in each bridge arm; a transformer; and a pantograph. At the wayside, a single-phase constant frequency to three-phase variable frequency converter is used to interface with the 3-phase ac synchronous flywheel machine. The detail of the comprehensive analysis that led to the adoption of this overall system is contained in Volume 2.

The overall round trip efficiency (i.e., wheel of descending locomotive to wheel of ascending locomotive) of this system was determined to be 60 percent, as shown in Figure 4.



- COMPATIBLE WITH STANDARD MAIN LINE ELECTRIFICATION
- MINIMIZED HARDWARE REQUIREMENT
- TRANSFORMER CONFIGURATION MINIMIZES UTILITY UNBALANCE
- ALLOWS REGENERATION ACROSS PHASE BREAK

Figure 3. Optimum WESS Regeneration System



- **OVERALL ROUND TRIP EFFICIENCY 60%**

Figure 4. WESS Efficiency with High-Voltage Ac Catenary

OPERATIONAL CONSIDERATIONS

As a result of the broad contacts that were made with railroad companies and the experience at Bechtel and AiResearch, a number of technical and operating constraints, within which WESS must be deployed and operated, were identified early in the program. The constraints were identified and treated as defined below.

Adhesion

Existing practice on U.S. railroads is to dispatch at 18 to 20 percent adhesion. AiResearch uses 20 percent in the study, except where motor modifications allow complete weight transfer compensation. In that case, 22 percent is used for traction and 18 percent is used for braking.

Head End Brake Limitation

AiResearch calculations are based on never exceeding a head-end braking force of 240,000 lb, although normally 210,000 lb is the limiting figure in the study calculations (ref 3).

Axle Load Limitation

The maximum axle load used in this study is 68,300 lb.

Dedicated Locomotives

As previously discussed, it is necessary to modify locomotives in order to make them compatible with the WESS concept. In order to minimize the total cost of locomotive modifications, it is necessary to accept the operational inconvenience of a dedicated fleet of locomotives. Discussions with railroads indicated that provided the system was economically attractive, locomotives dedicated to long routes would be acceptable.

Examples of routes for which dedicated fleets are assumed to be acceptable are the following:

Harrisburg - Pittsburgh	Conrail
Los Angeles - Salt Lake City	Union Pacific
Salt Lake City - Omaha	Union Pacific
Los Angeles - Belen	Santa Fe
Colton - El Paso	Southern Pacific
Sacramento - Ogden	Southern Pacific

Electrification

It has been established by direct contact with the Federal Railroad Administration that most of the grades suitable for WESS are on routes that are part of an electrification network identified for preliminary evaluation purposes under the Railroad Revitalization and Regulation Reform Act. This is hardly surprising since both WESS and electrification require a high traffic flow to be cost effective. This reinforces the case for allowing the WESS system to be compatible with the mainline electrification systems proposed for use in the U.S. and other interested countries.

Electric Utilities

The specification and choice of equipment for use in forming the interface with the electric utility must be of a standard acceptable to the utility. The question of harmonic generation, proximity of high lines, supply capacity, and rate structure were identified as serious constraints on the system. Some problems identified were of a political rather than technical nature and have not been resolved.

The main involvement of the utility is in the question of acceptance of and payment for energy regenerated back to the utility although the questions of power factor, harmonic generation, and load sharing apply whether regeneration occurs or not.

Signals and Communications

At the present time, most railroads use dc track circuits for wayside signaling, and 60-Hz carrier systems are used for in-cab signaling. Data are transmitted between signal locations by overhead open-wire lines running along the right-of-way. Where relatively long distances are encountered, communications are handled either by microwave data link or open-wire overhead lines. These and other types of signaling and communications systems are vulnerable to interference brought about by electrification catenary systems and each one must be considered with appropriate corrective modifications to be compatible with electrification. The electromagnetic and electrostatic fields developed by a catenary system can, and usually do, induce currents and voltages in signaling and communications systems. Care must be taken to keep these effects within tolerable limits.

Operating Scenarios

Within the system concept developed for WESS, three operating scenarios were considered, as described below:

> Dual-Mode Locomotives--Under normal operations the routes under consideration are assumed to be operated by dual-mode locomotives, these being standard diesel locomotives retrofitted with pantograph, transformer, and thyristor converter to enable the locomotive to operate either as an electric locomotive, when on a WESS grade, or as a diesel locomotive when not "under the wire". The changeover

from electric to diesel operation will be accomplished automatically upon reaching the end of the electrified section or when the flywheel is nonreceptive. The power rating of these locomotives remains unchanged in the diesel (primary) mode at 2600 rail horsepower (rhp); however, in the electric (secondary) mode, it is increased to the traction motor limit of 4000 rhp. Due to this increased power rating of the locomotive when connected to the catenary, the number of locomotives required to operate a given route is reduced, and therefore so is the number of locomotives to be modified.

An important spin-off from this scenario is that it allows an evolutionary concept of electrification. That is, a railroad operating dual-mode locomotives could electrify only the grades on its chosen route at a substantial return on investment (ROI). Then, the sections in between the major grades gradually could be electrified. This electrification concept allows the railroad to gain experience of electric operation before committing themselves to very large investments.

Electric Helper--When ascending/descending a WESS grade, the motive power is made up of diesel locomotives and the addition of up to two electric locomotives at the grades. The latter are designed for operation at 50/25 kv ac, 60 Hz, with high tractive effort, limited speed, and high power. At the extremities of the WESS sections, the electric locomotives are detached to await the next train in the opposite direction. The number of diesel locomotives in use is less than that normally used because in most railroading operations the ruling grade determines the number of locomotives required. When WESS is deployed, the gradient duty is eased by the use of electric locomotives with high tractive effort. This scenario is labor-intensive and allowance was made for having the electric locomotive crewed for 72 man-hours per day in order to take account of travelling time to and from the possibly remote location of the WESS grade.

All Electric--The entire railroad operation was assumed to be electrified and diesel power is used only for yard switching and spur lines. WESS would not impose any particular procedure on the railroad method of operation other than the input of data to the wayside energy storage system communications (WESSCOM) link if such a system is provided (see below).

The three scenarios described above are summarized in Table 3. Each of these operating methods involves a change in the economics, cost, and procedures and must be evaluated in detail for each grade under consideration. It also will be clear that the true cost of adoption cannot be considered on a grade-by-grade basis because locomotive fleet sizes depend on traffic flows between classification yards.

It was clearly recognized that the electrification of single grades and their consideration in isolation was not only impractical, but misleading. The approach adopted was to consider each scenario applied to complete routes as shown later in this report.

TABLE 3

SUMMARY OF WESS SCENARIOS

Scenario	Title	Whole Route Electrified	New Vehicles Required	New/ Modified Vehicles Usable on Other Routes	Additional Operating Labor Required	Diesel Locomotives Saved	Special Stops Required
1	Dual-Mode Locomotives	No	No	Yes	No	Yes	No
2	Electric Helper	No	Yes	No	Yes	Yes	Yes
3	Electric Railroad	Yes	Yes	No	No	Yes	No

Communication System

A wayside energy storage system communications (WESSCOM) link is essential in situations where there is no utility tie-in to the system. The benefits of such a system are not so clear cut when a utility tie-in is available and WESSCOM could be used only to optimize peak-shaving. The benefit of WESSCOM then would be the difference between a best guess at the required average demand by an operator and the computer-predicted average demand.

A utility tie-in is not essential to the railroad/WESS operation in scenarios 1 and 2 of Table 3. The cost of provision of such a tie-in was weighed against the anticipated benefits in the study. In cases where the decision was against having the utility tie-in, it was imperative that the flywheel was not taken below its minimum design speed by an excessive energy demand from an ascending train. This could be achieved by opening the protection circuit breakers in the feeder station without recourse to a train/wayside communication system; however, this might result in loss of power and a delay before diesel power was available. Furthermore, it is necessary to keep the system available at all times to accept regenerated energy, which would not be the case if the feeder station circuit breakers were used to protect the flywheel from underspeed. It has been concluded that a communication system is a necessity at installations without a utility tie-in.

Where a utility tie-in is available, such as in scenario 3, the WESSCOM system has to be evaluated against the quality of human judgment. In a complex railroad operation where trains do not run to fixed timetables, it is most probable that minimization of the peak demand could only be handled by a computer.

The case for WESSCOM was considered for each scenario at each grade location.

Summary of Impact on Railroad Operations

The deployment of WESS on an operating railroad is expected to have a minimal effect on existing railroad operations, with the exception of the electric helper scenario. The operation of either electric or dual-mode locomotives over WESS grades can be accomplished with essentially no change in operating procedures. The system has been structured to minimize crew training required and to leave train-handling techniques unaltered.

ELECTRIC LOCOMOTIVES

The electric locomotive considered for use in the WESS study was a regenerative version of the GE Model E60, which is the only recently designed electric locomotive in regular service in the U.S., as shown in Figure 5. The

Figure 5. General Electric E60C Locomotive In Service at Black Mesa and Lake Powell

essential change to the E60 locomotive for the WESS application is the substitution of thyristors for the diodes in the lower arms of the six individual semiconverters that power the six traction motors. This change permits the converter to operate as a line-commutated inverter during electric braking operation, thereby coupling power back into the ac catenary.

The cost of regenerative electric locomotives similar to the modified GE E60 has been obtained from two sources. The first is the A. D. Little projection of $180 per rail horsepower in 1976, which should be escalated to $191 per rail horsepower with 10 percent added for modification to provide regenerative capability for 1977 (ref 2). This results in an estimated cost of $1,071,000 for a 5100 rail horsepower locomotive. The second source used for the cost of an E60 is based on the most recent purchase of these locomotives. In 1976, Black Mesa and Lake Powell Railroad purchased three E60 units for $750,000 each. With adjustment for inflation, today's cost should be about $795,000. The estimated cost for this modification is 10 percent of new cost, resulting in a regenerative locomotive cost of $875,000.

In keeping with the conservative approach used by AiResearch in the WESS economic analysis, the higher cost of $1,071,000 suggested by A. D. Little was used for regenerative electric locomotives.

DUAL-MODE LOCOMOTIVES

The preliminary design study of the dual-mode locomotive (Figure 6) resulted in the recommendation of a configuration suitable for either retrofit of existing locomotives (which could take place at the time of a major overhaul) or application to new diesel-electric locomotives. The locomotives selected for modification in the study were the General Motors Electro-Motive Division (EMD) model SD40 or SD40-2--present workhorses of U.S. freight railroad operations. Similar modifications can be made with other common freight locomotives. These proposals for modification have been presented to the technical staffs of both EMD and GE.

The dual-mode locomotive design is such that motive power can be derived either from the diesel engine or from the catenary, but never both together. As a result, no change need be made to the existing alternator, since no harmonics resulting from braking will be applied.

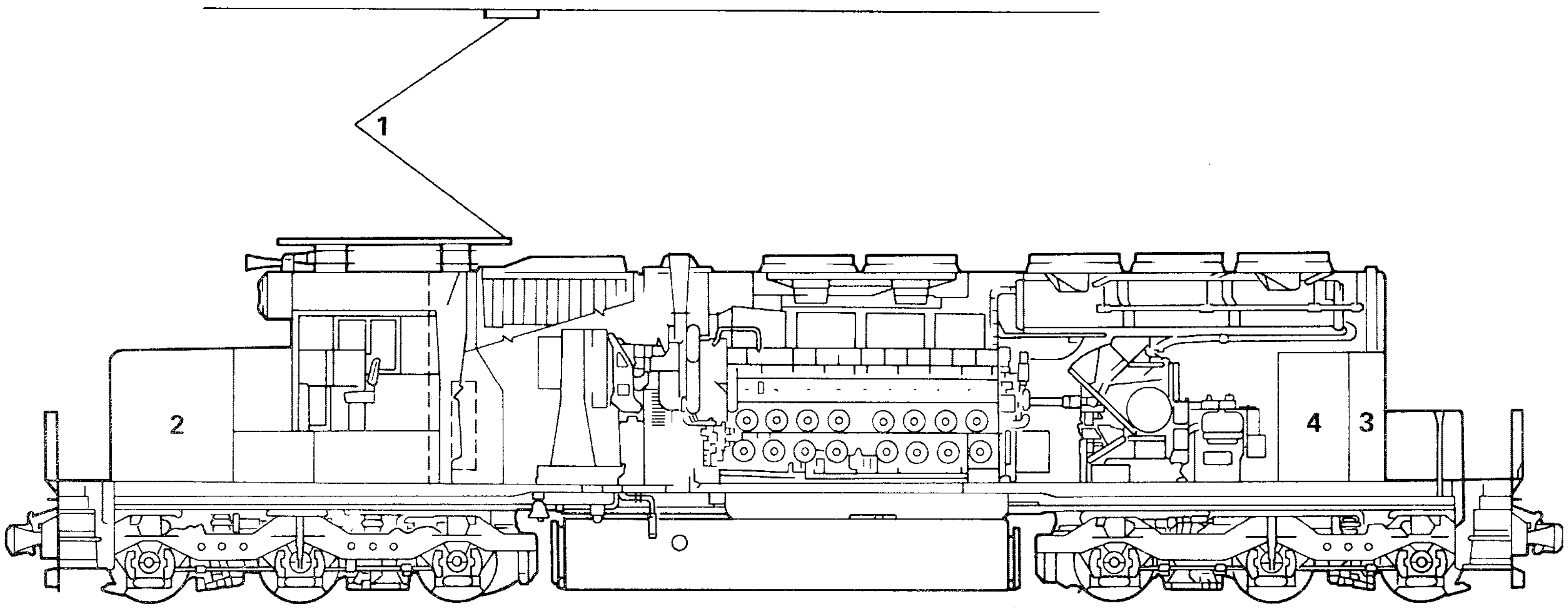
The retrofit modification of the locomotive can be considered in three parts, as follows:

(a) Repositioning of existing equipment

(b) Addition of new equipment

(c) Modification of existing equipment

This modification process is expected to be greatly simplified in the case of a new locomotive.



1 PANTOGRAPH
2 TRANSFORMER
3 CONVERTER
4 CHOKE

Figure 6. Dual - Mode Locomotive

Inspection of SD40 locomotives has confirmed that space is available within the existing locomotive to handle the new equipment, provided that certain equipment is repositioned.

A proposed layout of equipment is shown in Figure 6. The main transformer will be housed in the short hood compartment (see Figure 7). This necessitates the removal of ballast; repositioning of the sand box, battery, and a terminal box inspection cover; and lengthening of existing short hood (see Figure 8). The traction motor smoothing inductor and thyristor converter will be located in the compressor compartment (see Figure 9).

The cab roof will require strengthening to allow the roof equipment to be mounted and to afford protection to the crew in the event of a mishap resulting in the pantograph being forced down toward the cab area.

The estimated cost of the retrofit conversion of an SD40 locomotive to a dual-mode configuration is $211,000 for a fleet modification of 50 to 400 locomotives. The cost includes installation of the new components, pantograph, transformer, converter, etc., as well as the modification of traction motors to a separate field excitation configuration and rework of the locomotive controls. The details of this cost estimate are presented in Volume 2.

LOCOMOTIVE COSTS

To establish the credibility of the locomotive costs used in this study, AiResearch analyzed the reason for the difference in cost between diesel and electric locomotives currently available in the U.S. and compared them with the cost of the proposed dual-mode locomotive and the relative cost levels in Europe.

U.S. and European locomotive fleets are based on a 3000-hp diesel locomotive and a 5000-hp electric locomotive. These power ratings are the most common on both continents. In Europe, the electric and diesel locomotives cost approximately the same. In the U.S., the cost of the electric locomotive is approximately twice that of the diesel locomotive, and yet the cost of the electric locomotive is approximately the same as that of the European version. The reason for the difference is the mass production of the U.S. diesel fleet, which halves the cost of the U.S. diesel locomotive. European practice is to buy locomotives in quantities of 50 to 100; each order is generally for a new model; whereas in the U.S., standard diesel locomotives are mass-produced at the rate of five per day; however, there is no prospect of achieving the mass production levels for electric locomotives that currently exist for the diesel locomotive. Therefore, the U.S. electric locomotive is twice the cost of the U.S. diesel locomotive.

To rationalize this cost differential with the projected dual-mode locomotive cost, an essential element is the fact that the dual-mode locomotive utilizes parts in common with the mass-produced diesel locomotives. The incremental cost of the dual-mode locomotive therefore reflects the cost of the

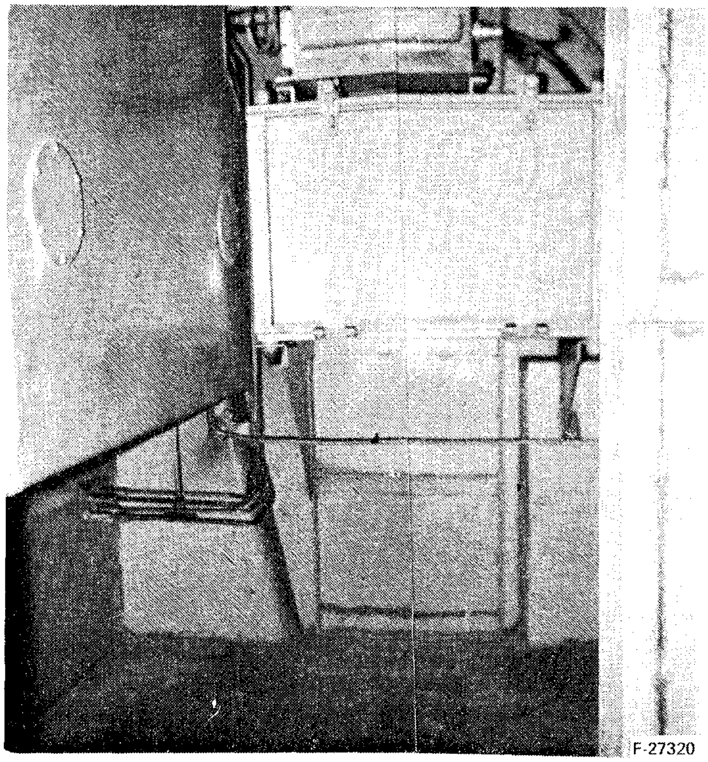


Figure 7. SD40 Short Hood Compartment

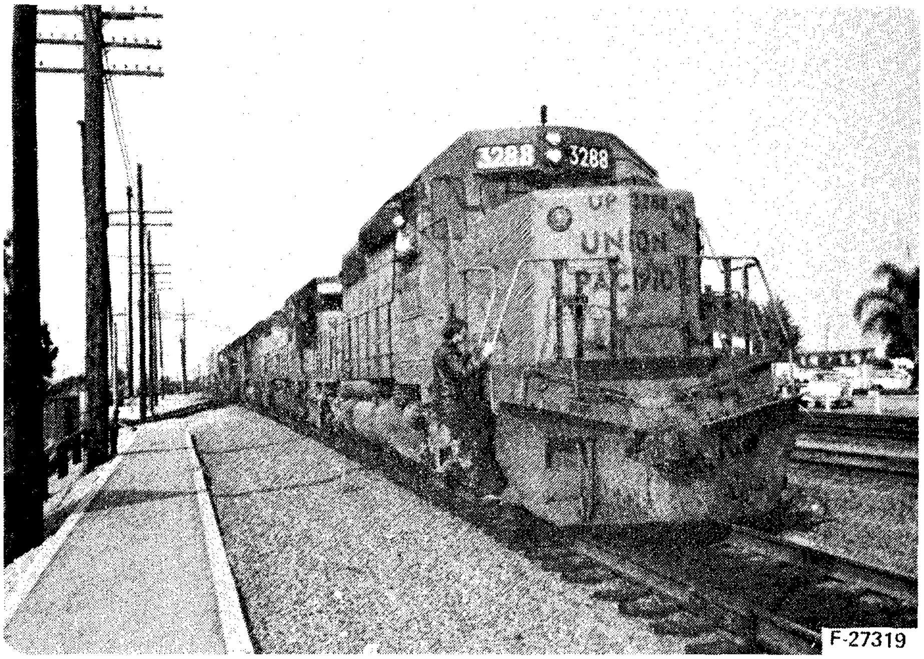


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Figure 8. Short Hood of SD40 Locomotive

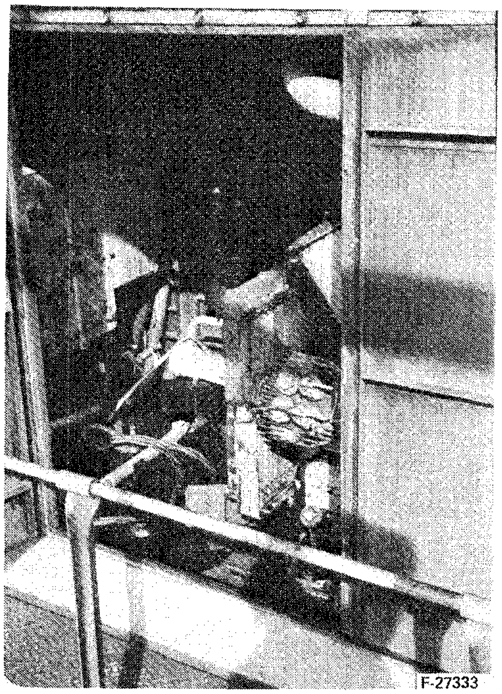

Figure 9. SD40 Compressor Compartment

electrical equipment and labor elements of its installation. Therefore, the following schedule of locomotive costs is compatible:

3000-hp diesel locomotive	$530,000
3000-/4400-hp dual-mode locomotive	$741,000
5100-hp regenerative electric locomotive	$1,071,000

<u>Locomotive Fleet Size</u>

The number of locomotives required for a given train weight is determined by two factors:

(a) The minimum speed required on the ruling grade.

(b) The minimum speed required on level track to achieve the required average speed.

The dual-mode locomotive has a higher power capability in the electric mode than in the diesel mode and on this basis, the locomotive fleet can be reduced in size from the existing straight diesel fleet size. If all the grades are electrified and therefore negotiated in the electric mode, then the governing criterion for the number of locomotives becomes the minimum

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speed required on level track. Therefore, there are a minimum number of grades that may be electrified on each route and still allow the full locomotive saving to be legitimately claimed. The point is reached where, in the diesel mode, the number of locomotives required to negotiate the remaining non-electrified ruling grade is less than, or equal to, the number of locomotives required on level track.

A similar argument applies to the electric helper scenario.

The following statistics for locomotive utilization have been obtained from an FRA report (ref 4):

	Min.	Max.	Avg.
Electric locomotives/1000 MGTM	1.94	4.22	3.6
Diesel locomotives/1000 MGTM	2.80	9.90	6.8

Average values have been used in this study; this probably represents a conservative (high) approach because it is to be expected that the main lines considered for WESS operation would operate at above-average efficiency.

SECTION 3

WESS APPLICATION TO INDIVIDUAL GRADES

LOCATION STUDY

Methodology

A search for favorable locations within the U.S. where railroad energy storage installations would be both feasible and beneficial was conducted at an early stage of the study (item 1). AiResearch was constrained by the contract statement of work not to involve more than "...nine railroad companies or other elements of the general public".

The methodology used to conduct the location study (Figure 10) comprises five distinct phases:

(a) Preliminary calculations

(b) Data acquisition

(c) Identification of prime candidate grades

(d) Individual grade ranking

(e) Identification of WESS routes.

Preliminary Calculations

Before approaching railroads, it was necessary to understand the scale of the systems under consideration and to decide the necessary magnitude of the variables. Such variables as change in elevation, length of grade, weight, and number of trains had to be allotted minimum values in order to be able to define to the railroads the information required. It became clear that there was no minimum value for each variable because a high traffic level could, for instance, counteract a small elevation change (as was later seen to be the case on the Harrisburg-Pittsburgh route); however, system costs and savings are dependent on the scenario adopted and it was necessary from the outset to assume what was later to be termed the "electric helper" scenario in order to get the preliminary calculations under way.

Based on these preliminary data, AiResearch established that, in general, elevation changes in excess of 300 ft at a rate of 1.5 percent with an annual traffic density at 20 x 10^6 tons would be of specific interest with regard to the application of WESS.

Data Acquisition

At the request of AiResearch, six railroads were approached by TSC. The railroads were:

Southern Pacific Transportation Company (SP)

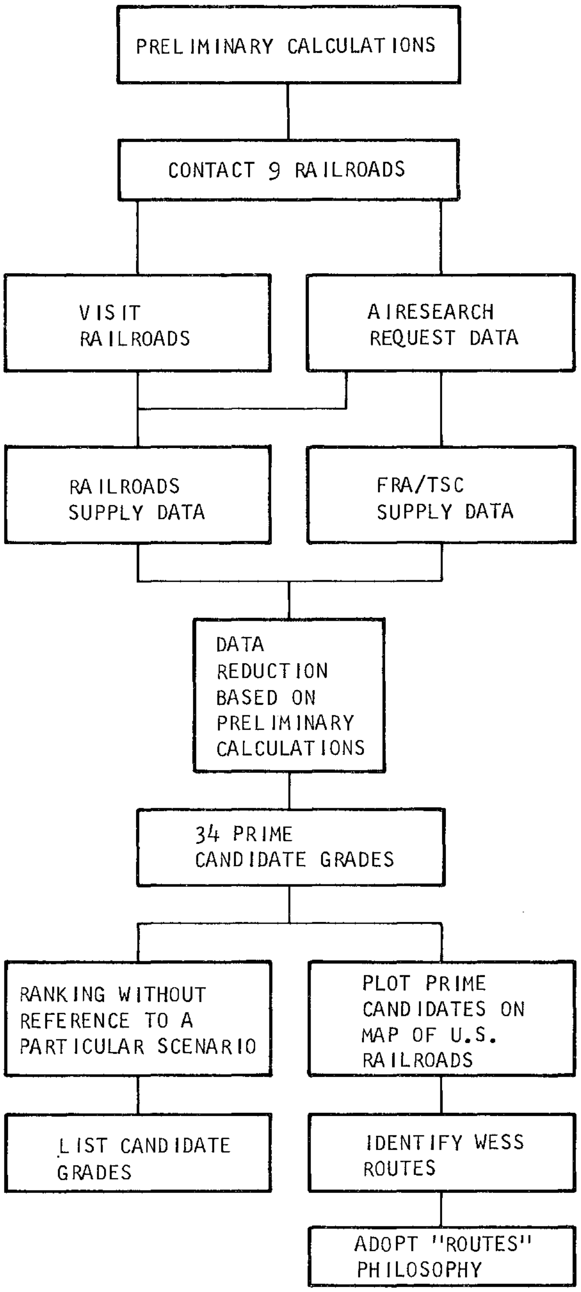


Figure 10. Location Study Methodology

Union Pacific Railroad (UP)

Southern Railway (SR)

Consolidated Rail Corporation (Conrail)

Atchison, Topeka, and Santa Fe Railway Company (AT&SF)

Burlington Northern (BN)

AT&SF and BN declined to participate because of the heavy workload of their engineering staffs; however, a series of meetings was arranged with the other railroads. An informal approach was made to Duluth, Missabe, and Iron Range Railroad with the railroad agreeing to participate. The final meeting in the series took place on August 11, 1977.

Each grade was allotted a grade identification number (GIN) from initial information on traffic density and grades. Preliminary calculations were used as a primary screening process to reduce the number of grades to be considered to manageable proportions, as follows:

SP - 4 grades

UP - 9 grades

SR - 1 grade

DMIR - 1 grade

Conrail - 1 grade

The method of presenting the information collected is shown typically in Figures 11 and 12 where a location map is followed by the grade data.

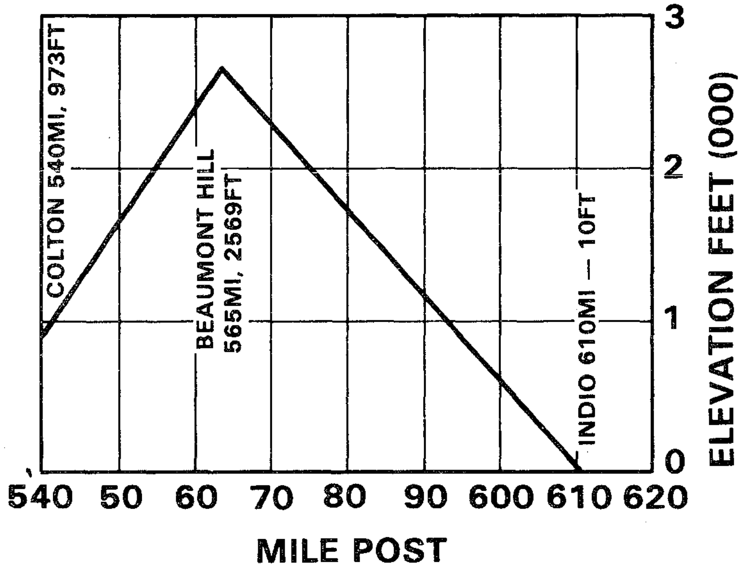
The location study, as originally structured, was intended to cover approximately 50 percent of the major routes in the United States (see map of Figure 13) with approximately 80 percent of the western railroads covered. This was because these railroads consume 50 percent of the fuel used for rail traction. Clearly, the inability of BN and AT&SF to participate was a serious blow to the proposed comprehensive coverage. In an effort to minimize the loss of coverage, AiResearch studied the routes operated by those two railroads and Denver and Rio Grande Western, and requested that TSC obtain as much information as possible from FRA records.

Information also was obtained from Black Mesa and Lake Powell Railroad and Transport Canada. The primary screening process then was applied to the U.S. grades identified during this indirect approach to the railroads and further primary candidate grades were identified as follows:

AT&SF - 10 grades

BN - 4 grades

Figure 11. Beaumont Hill Location Map



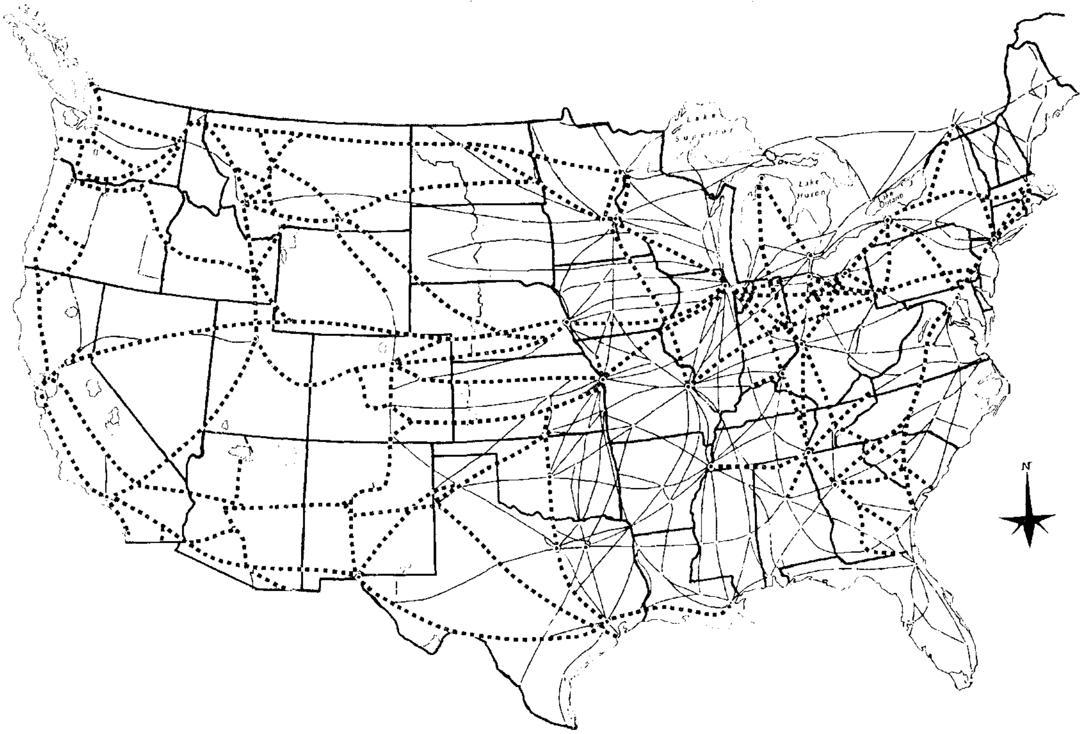
SOUTHERN PACIFIC RAILROAD

BEAUMONT HILL

TRAFFIC DENSITY

**EAST BOUND 27x10^6
TON/YEAR
WESTBOUND 33x10^6
TON/YEAR**

Figure 12. Beaumont Hill Grade Profile



KEY

·················· **ROUTES COVERED BY LOCATION STUDY**

——————— **ROUTES NOT COVERED BY LOCATION STUDY**

Figure 13. Routes Originally Proposed for Location Study

D&RGW - 2 grades

BMLP - 2 grades

It should be noted here that AT&SF subsequently agreed to cooperate in this study and have provided much valuable information.

Ranking Individual Grades

Having established the existence of 34 prime candidate grades on U.S. railroads, it was necessary to rank these grades in order of merit as directed by the contract statement of work. To meet this requirement, AiResearch presented a list of the most attractive grades, based on the best information available at the time. This was done to remove the dependence on a particular operating scenario. Ignoring the motive power costs, it is shown that the costs and benefits of operating a particular grade are related as follows:

Cost of electrification is proportional to length of grade (l) and number of tracks (n).

Flywheel costs, and therefore capacity, are proportional to elevation change (h).

Energy savings are proportional to elevation change (h) and traffic density (T).

Therefore, the benefit-to-cost ratio of WESS grades may be expressed as being proportional to

$$\frac{Th}{nl+h}$$

Using this method, the benefit/cost ratio was derived for each grade and a list of the primary candidate grades with their ranking factor is shown in Table 4.

Identification of WESS Routes

The 34 prime candidate grades were displayed on a map of U.S. railroads, Figure 14, and were compared with a possible U.S. electrified network. It was noted that, with the exception of three grades, the prime candidate grades are located on routes considered to have electrification potential. This is hardly surprising since both WESS and electrification require a high traffic density to be economically viable.

The routes with WESS potential (i.e., routes with many WESS prime candidate grades between major classification yards) were identified and classified by characteristics such as high speed medium traffic, medium speed high traffic, etc. The ten routes are:

Los Angeles-Belen (AT&SF)

Los Angeles-Salt Lake City (UP)

TABLE 4

WESS PRIME CANDIDATE GRADES

Grade Index No.	Railroad	Identification	Ranking Factor
035	Union Pacific	Baker - Weatherby	32.4
036	Union Pacific	Union Junction - Powder River	69.7
037	Union Pacific	La Grande - Duncan	32.88
056	Union Pacific	Cheyenne - Laramie	112.75
061	Union Pacific	Echo - Wahsatch	57.5
063	Union Pacific	Orr - Milepost 40	43.8
088	Union Pacific	Elgin - Crestline	27.8
089	Union Pacific	Borax - Las Vegas	27.12
090	Union Pacific	Kelso - Nipton	27.46
121	Southern	Braswell Mountain	37.4
145	DM&IR	Duluth	33.8
175	Southern Pacific	Cascades (South)	41.2
176	Southern Pacific	Cascades (North)	39.7
183	Southern Pacific	Sierras (Roseville - Sparks)	41.6
195	Southern Pacific	Colton - Indio	58.0
202	Denver & Rio Grande Western	Helper - Springville	34.1
206	Denver & Rio Grande Western	Denver - Granby	30.6
220	Burlington Northern	Wenatchie - Skykomish	*
222	Burlington Northern	Easton - Auburn	*
226	Burlington Northern	Garrison - Missoula	*
227	Burlington Northern	De Smet - Dixon	*
230	Consolidated Rail Corp.	Harrisburg - Pittsburgh	10.8
240	Atchison Topeka & Santa Fe	San Bernardino - Victorville	69.5
242	Atchison Topeka & Santa Fe	Needles - Goffs	50.7
243	Atchison Topeka & Santa Fe	Flagstaff - Canyon Diablo	50.3
244	Atchison Topeka & Santa Fe	Bellemont - Flagstaff	50.2
246	Atchison Topeka & Santa Fe	Eagle Nest - Williams Junction	55.8
247	Atchison Topeka & Santa Fe	Hackberry - Pica	56.1
248	Atchison Topeka & Santa Fe	Topock - Kingman	56.3
251	Atchison Topeka & Santa Fe	Gallup - Belen	54.3
252	Atchison Topeka & Santa Fe	Belen - Silio	29.1
255	Atchison Topeka & Santa Fe	Vaughn - Fort Sumner	56.9
261(a)	Black Mesa & Lake Powell	Page - Milepost 31	+
(b)	Black Mesa & Lake Powell	Milepost 44 - Kayenta	

*Traffic data not available

+The ranking technique cannot be applied to BM & LP since the railroad is electrified and this distorts the rankings. This is because the simplistic approach adopted is only valid when comparing similar (in this case diesel) railroads.

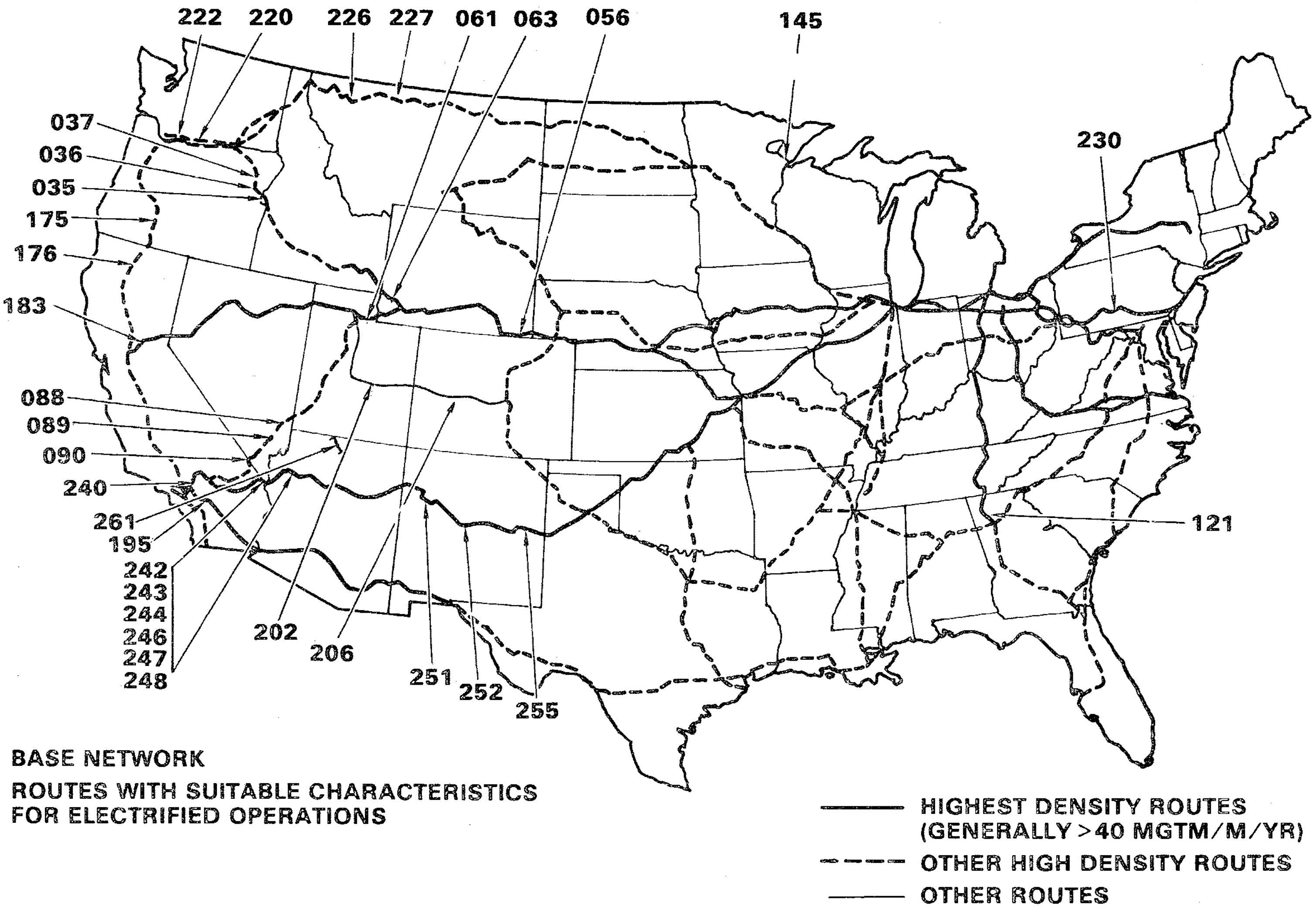


Figure 14. Prime Candidate Grades for WESS Deployment on Possible National Electrified Network

The preliminary calculations identified the range of flywheel sizes and power ratings required to be compatible with the WESS system. Table 5 shows the energy regenerated from a single train on the 10 most attractive grades.

FLYWHEEL STATION STUDY

On the basis of the energy calculations made for the individual grades, the sizing of the flywheels required for energy recuperation was determined. A design study then was conducted (item 6), which resulted in the definition of a typical flywheel station in sufficient detail to support the preparation of cost estimates.

Flywheel Sizing

The first determination was the flywheel energy storage capacity for a typical wayside station. The flywheel to be used for recuperation of braking energy in the WESS system was sized by examining the energy storage requirements from a single train on typical grades. A set of data showing the energy storage requirements for the 10 most attractive grades was shown in Table 5.

It also was assumed that on the intensively used routes under consideration there generally will be an ascending train taking at least part of the regenerated energy from a descending train. Therefore, the flywheel generally would not be required to take more than the energy resulting from the descent of more than two trains.

Then, using the baseline assumption that the flywheel should be capable of storing the energy from two trains for subsequent reuse by ascending trains, it can be seen that flywheel capacities range from 21.0 through 5.4 Mwhr. These values appear to be representative of the requirements for all WESS sites considered.

Thus, it was assumed that a flywheel of 5.5 Mwhr storage capability would be a typical size for cost-estimating purposes (multiple-flywheel installations used where required), although in practice each flywheel would be sized to its specific grade application.

The power required of the flywheel station determines the capacity of the converter and electric machine that couples energy into and out of the flywheel. Required power was found to vary from 4 to 11.6 Mw, depending on the scenario, for the 34 prime candidate grades. On this basis, the assumption was made that the flywheel machine must have a 1-hr capacity of 7.5 Mw operating over the usable flywheel speed range. Again, the flywheel machine used in each WESS installation would be sized for that particular requirement.

The typical flywheel system storage capacity of 5.5 Mwhr and power rating of 7.5 Mw were used to determine the cost per kwhr of the flywheel assembly and the cost per kw of the flywheel machine and converter. These values then were used to determine the cost estimates of the wayside stations for each grade considered in the study.

TABLE 5

ENERGY REQUIREMENTS FOR THE
TEN MOST ATTRACTIVE GRADES

Grade Index No.	Railroad	Energy Storage from Single Train, Mwhr	Flywheel Capacity, Mwhr
056	UP	4.9	9.8
175	SP	10.5	21.0
195	SP	6.4	12.3
206	DRGW	9.6	19.2
230	Conrail	3.0	6.0
240	ATSF/UP	6.9	13.8
242	ATSF	5.3	10.6
248	ATSF	2.7	5.4
261(a) (b)	BM&LP BM&LP	8.3	16.6

Flywheel Background

The use of large flywheels for energy storage is not a new concept. At least three recent applications of large flywheels are known. The characteristics of these flywheel systems are shown in Table 6.

The Navy catapult system has been used on aircraft carriers to launch aircraft. This flywheel rotor is a complex steel forging with heavy hubs to provide the high power level. The catapult flywheel rotor has an energy density of over 10 whr per pound. Both the General Atomic and Tokamak flywheels described in Table 6 are used in nuclear fusion experiments to provide huge pulses of electric power from generators, of which the flywheels act as rotors. The energy densities of the nuclear program flywheels are quite low because their designs are compromised to provide the high pulse power generating capability.

Based on Table 6, it is theoretically possible to combine the weight of the Tokamak rotor with the energy density of the Navy flywheel. The resulting rotor would have an energy storage capacity at full speed of 10.3 Mwhr. If this flywheel then were operated over a 2:1 speed range, its usable capacity would be 7.7 Mwhr, which would be suitable for the majority of WESS applications. Because the catapult flywheel design requires expensive forgings, a simpler design, better suited to the WESS application, was developed.

Flywheel Design

Three basic flywheel designs for 5.5-Mwhr usable energy storage were considered in the study as follows:

(a) All-steel flywheel constructed of axial discs with a peripheral speed of 1440 fps.

TABLE 6

LARGE FLYWHEEL SYSTEM

Description	Flywheel Capacity, Mwhr	Power Rating, Mw	Rotor Weight, ton	Rotor Speed, rpm	Rotor Diameter, ft
Navy Catapult	0.113	70	5.5	6000	7
General Atomic	0.444	260	200	400	20
Tokamak	1.25	475	500	375	22

(b) A composite (fiberglass/epoxy) flywheel comprised of several concentric annular cylinders mounted upon an aluminum spoked hub.

(c) A hybrid design that would contain a steel flywheel core surrounded by a multilayer composite cylinder.

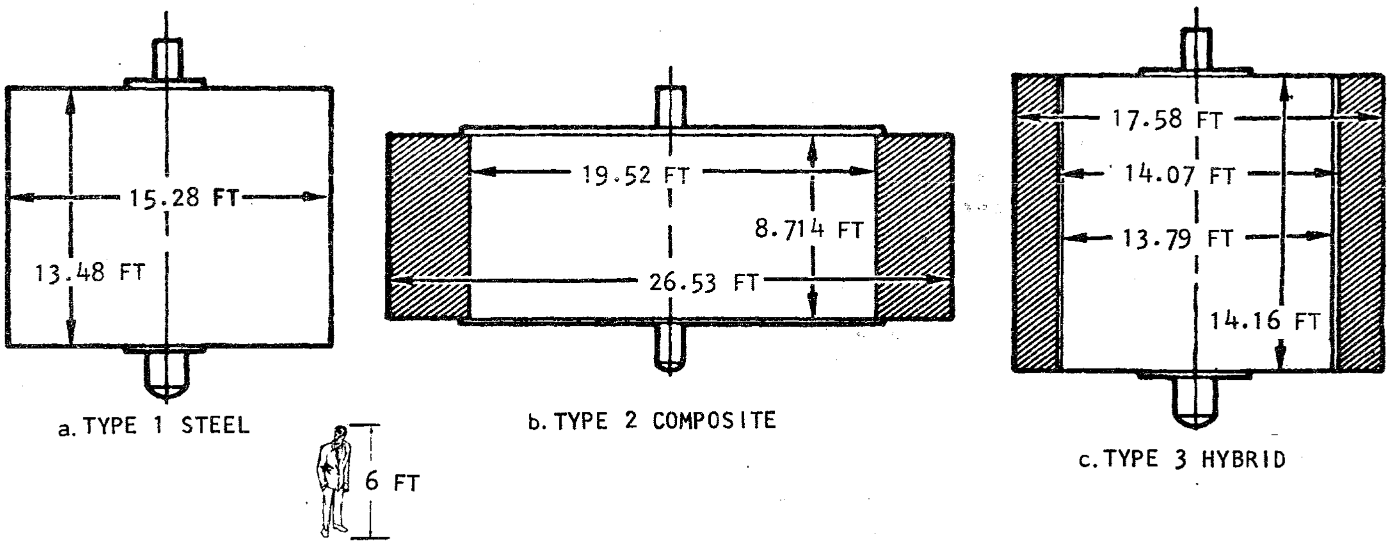
The geometries of these three flywheels designed for operation in the range from 900 to 1800 rpm are shown in Figure 16.

A study was conducted to determine which of the three flywheel designs appeared to be the most practical for WESS. The steel flywheel represents state-of-the-art technology and can be built with little techical risk. This flywheel type weighs over 600 tons but can be shipped in pieces and assembled at the site, as was done with the two Tokamak flywheels.

The composite flywheel is based on present technology, which is being used to fabricate 1- to 4-kwhr rim-type flywheels. It would weigh only about 150 tons; however, no experience exists in building up composite structures anywhere near the size and weight of the WESS flywheel. The high technical risk factor involved in fabrication will probably require the completion of several years of successful evolutionary development for resolution. If such a development program takes place (as has been proposed by the Department of Energy), it may be possible in the 1985 to 1990 time frame to deploy composite flywheels at WESS sites. The cost of the composite flywheel is currently unknown, but may be competitive with steel.

The hybrid steel and S-glass flywheel in many ways has a combination of the worst characteristics of steel and composite construction. It weighs over 600 tons and is larger than the steel flywheel. In addition, the technical risks of the all-composite rotor also exist for the hybrid design.

From the foregoing, it was clear that the only logical choice of flywheel design for serious consideration at present is the steel flywheel. In 1985, another assessment of composite flywheel technology should be made; if sufficient progress has been made in fabrication technology, a change can be made to composite flywheels for WESS.



a. TYPE 1 STEEL

b. TYPE 2 COMPOSITE

c. TYPE 3 HYBRID

Figure 16. 1800-rpm Flywheel Geometries

The optimum flywheel design for the WESS application was found to be a steel flywheel with a rotor weight of 604 tons. The construction of this steel flywheel (Figure 17) is an axial stack of 69 steel disks bolted together by 24 highly tensioned steel bolts located near the outer periphery, where stress levels are reduced. The selected flywheel rotor material is a high-purity grade of 4340 steel currently available in mill run quantities at approximately 60 cents per pound. The steel will be flame cut and machined to 3-in.-thick, round disks that are 13.5 ft in diameter. (This dimension was determined by the limitation of heat treating facilities.) The top and bottom disks shown in Figure 17 are forgings with integral hubs. The characteristics of the recommended steel flywheel are shown in Table 7.

TABLE 7

CHARACTERISTICS OF OPTIMUM STEEL FLYWHEEL

Total Capacity	7.33 Mwhr
Usable Capacity (2 to 1 speed range)	5.5 Mwhr
Maximum Speed	2037 rpm
Diameter	13.5 ft
Length	17.28 ft
Weight	604.4 tons
Peripheral speed	1440 ft/sec
Vacuum requirements	10 torr
Loss at 100 percent speed	136 hp
Loss at 50 percent speed	48 hp
Moment of inertia	855,800 lb-ft-sec^2
Spin-down time (100 to 50 percent speed)	87 hr

The WESS flywheel assembly shown in Figure 17 will be installed at the WESS site by stacking and bolting the flywheel disks into the housing located in a concrete pit below grade level. The bottom bearing of the flywheel is a hydrostatic bearing that supports the weight of the flywheel, while the top bearing is a roller bearing. Flywheel ancillaries provide lubrication and evacuation of the flywheel. It is anticipated that the flywheel can be left untended, with only an annual inspection and routine maintenance required. Complete details on the flywheel assembly are included in Volume 2. A cost analysis also is furnished; it shows the complete cost of the installed and tested flywheel assembly, less the flywheel machine and station construction, to be $270 per kwhr of usable capacity. This cost figure has been used in the WESS economic analysis.

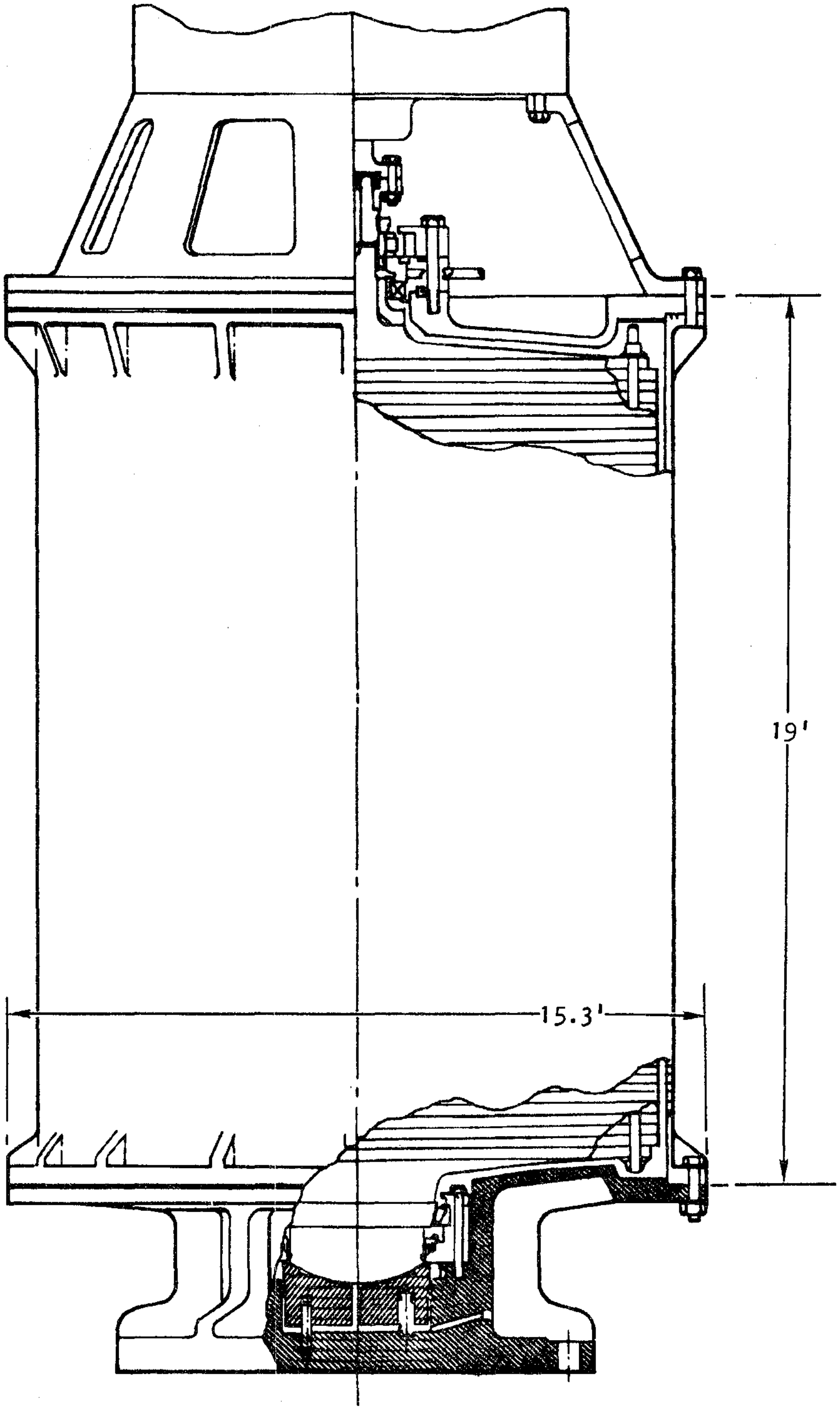


Figure 17. Optimum Steel Flywheel for WESS

Flywheel Machine

The 7.5-Mw flywheel machine used for estimating purposes is a conventional utility type of brushless (rotating rectifier), synchronous, four-pole, electrical machine that can be operated either as a motor or generator at a 7.5-Mw power level over the full flywheel operating speed range (from 1018 to 2037 rpm). The typical efficiency of this air-cooled machine at rated power level is 97 percent. The machine is mounted with a vertical rotational axis above the flywheel in the space shown in Figure 18. The weight of the 7.5-Mw machine is 150,000 lb.

Since the flywheel machine is typical of small utility generators, cost estimates for the 7.5-Mw capacity were obtained from the large machinery departments of General Electric and Westinghouse. The average cost for machines of this type in the 7.5-Mw capacity range was found to be $60 per kw. This cost also was used in the economic analysis.

Flywheel Converter

The static power converter connects the flywheel machine to the railroad electrification system. In the optimum system configuration of Figure 3 it converts two-phase, high-voltage, 60-Hz power to variable-frequency, three-phase power to operate the flywheel machine. The output frequency range of the converter in normal operation varies from 34 to 68 Hz at a continuous power rating of 7.5 Mw as the flywheel is operated over its 2:1 speed range. In addition, the converter must provide controllable, low-frequency power capable of being varied from about 1 to 34 Hz at reduced power levels for flywheel startup. Such startups will occur infrequently such as after inspection or an unscheduled shutdown.

The converter comprises (1) a rectifier section that converts two-phase, 60-Hz power to dc and (2) an inverter section that generates the variable-frequency output. The converter is very similar to AiResearch reversible 60-Hz substations that have an estimated cost of $30 per kw in capacities from 5 to 10 Mw. This value was used in the economic analysis.

Flywheel Station Construction

The construction of a WESS flywheel station at a remote site was analyzed by Bechtel based on their broad experience in products such as pumped hydroelectric stations. The flywheel assembly building concept recommended by Bechtel is shown in Figure 18. The flywheel is located in a concrete pit below grade to preclude any safety hazard due to flywheel failure; the flywheel machine and system ancillaries are located in the steel building above grade.

The plan layouts of the flywheel building and the adjacent converter building are shown in Figure 19. The overall WESS site, the building, adjacent electrification equipment, and access to the site are shown in Figure 20.

The $160,000 cost derived from the Bechtel estimates for construction of the flywheel energy storage station does not include the cost of electrification; this cost is separately estimated under item 5, Wayside.

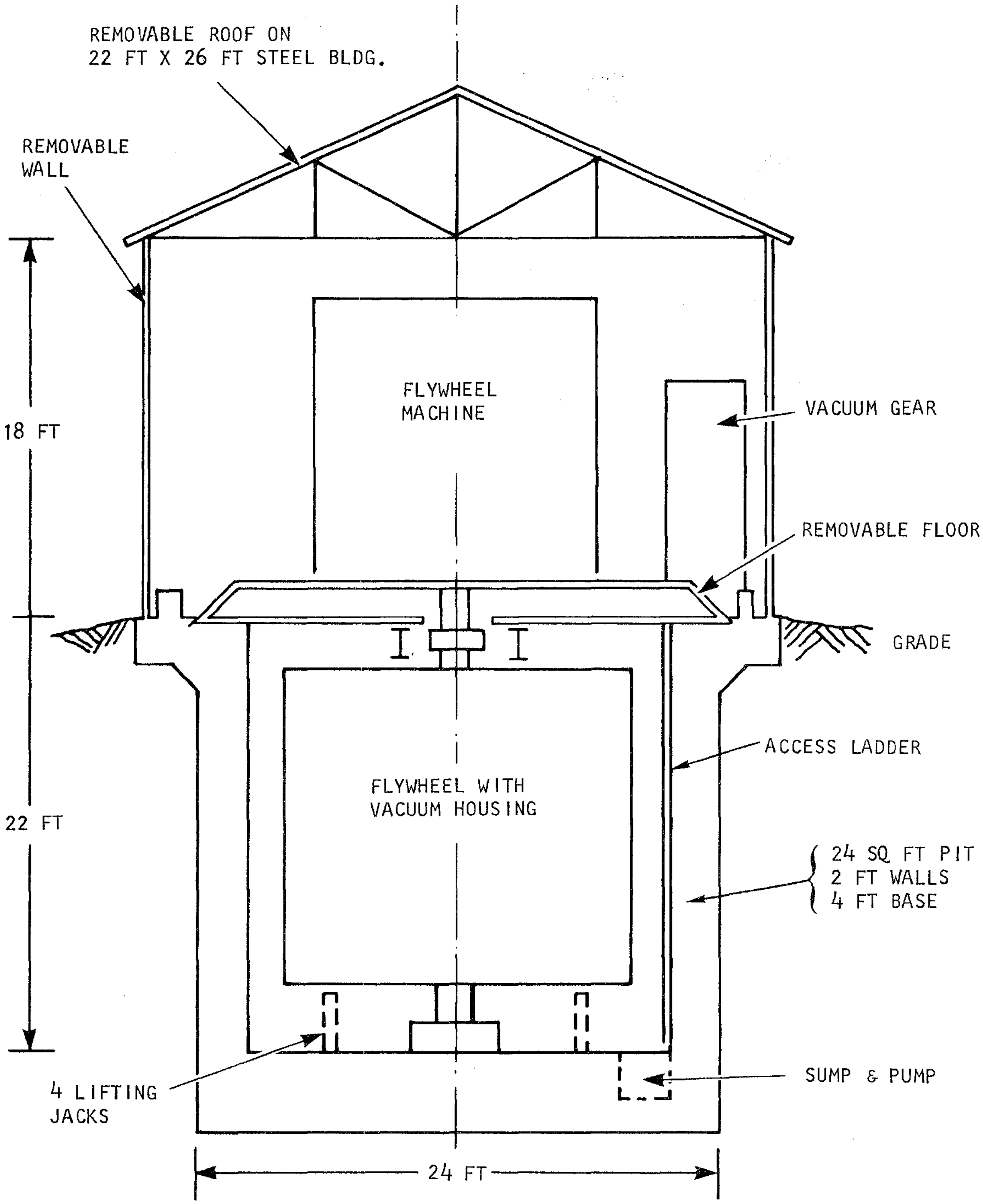
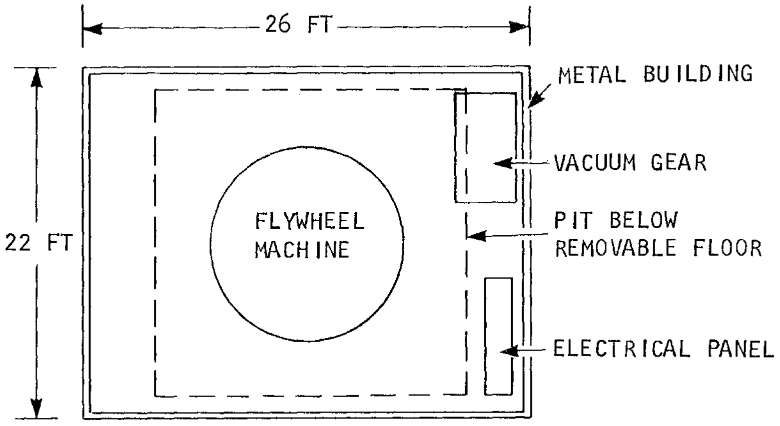
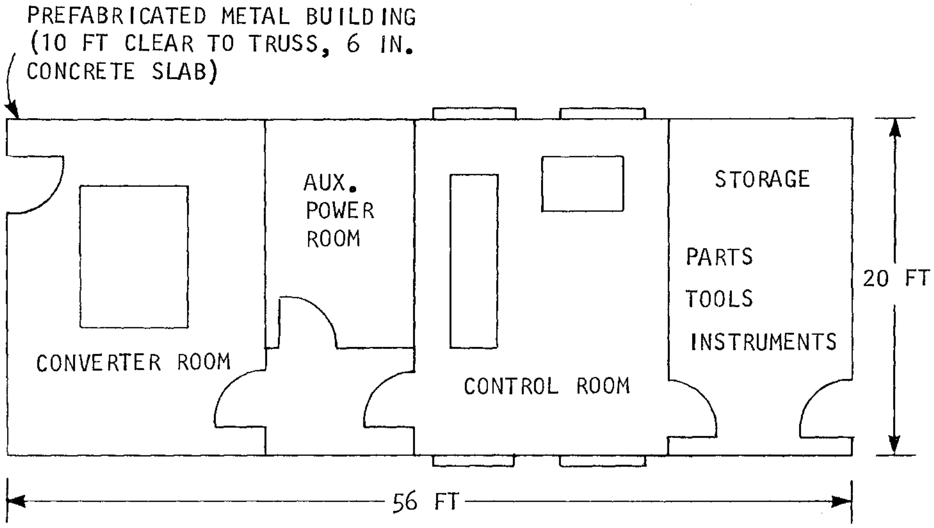


Figure 18. Flywheel Housing



a. PLAN - FLYWHEEL BUILDING



b. CONVERTER BUILDING

Figure 19. Flywheel and Converter Building Plans

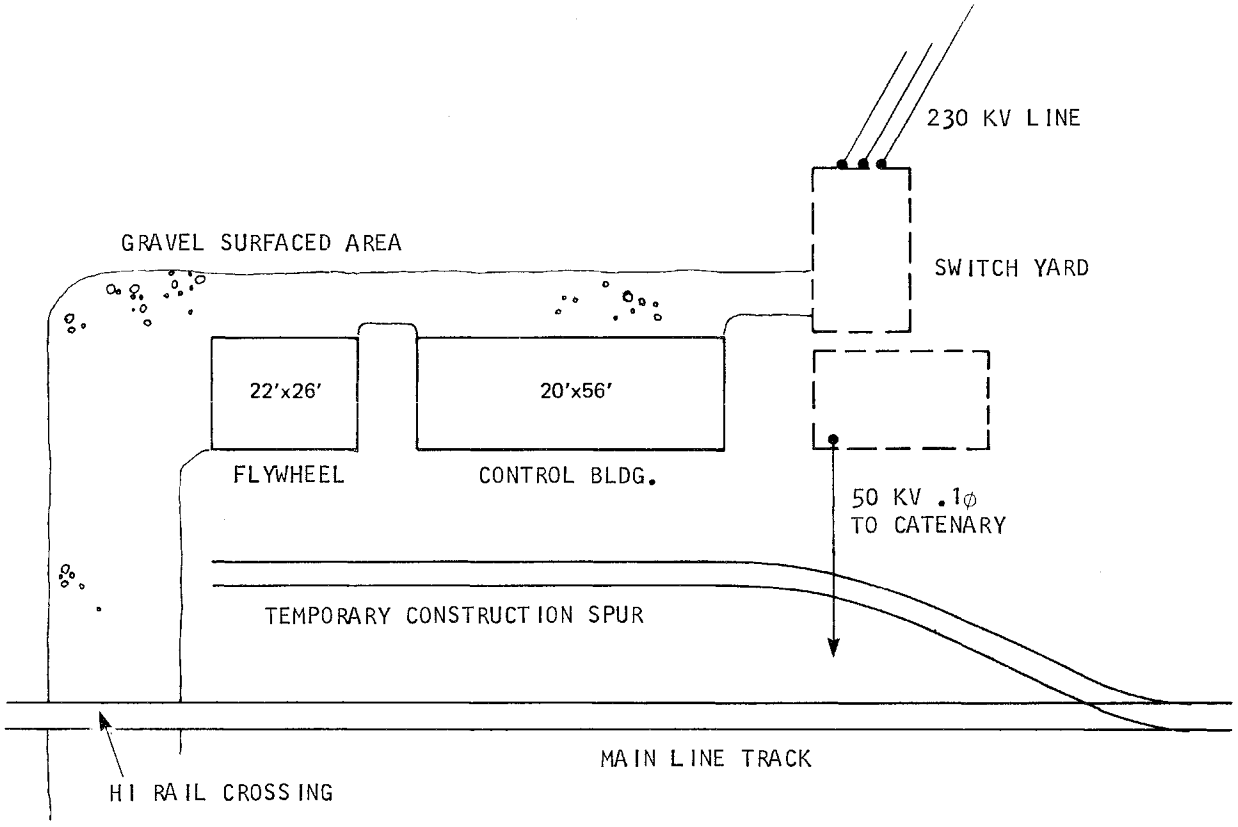


Figure 20. WESS Site Plan

SECTION 4

ECONOMIC SOURCES AND METHODOLOGY

The potential benefits of wayside flywheel stations are largely economic. No particular social benefit results from the deployment of WESS, although reduced fuel consumption is a desirable material goal. The major savings are locomotive fuel or energy and reduced size of the locomotive fleet; other savings are reduced track maintenance, reduced brake system and wheel maintenance, and possible higher and more uniform consist speeds. These savings must be compared on a time-consistent basis with the initial investment cost and maintenance costs for the flywheel system equipment (items 3 and 10).

The comparison of savings to costs has been performed by using several accepted economic techniques. The wayside energy storage system can be considered economically viable if (1) the savings exceed the costs sufficiently to provide a reasonable return on invested capital, including interest charges, and (2) savings compensate for the uncertainties associated with the introduction of new technology.

ECONOMIC ANALYSIS TECHNIQUES

The economic techniques to be employed in this study were agreed upon by TSC and FRA at an early stage. These techniques and their salient features are summarized in Table 8.

In order to simplify the calculation of return on investment (ROI) in the economic analysis, it was assumed that all investments were made in year zero of the 30-year economic life of the system. (The year zero was defined as 1990 for the purpose of this study, this being the earliest that a production WESS system could be deployed). Savings were calculated at the mid-year point for each of the 30 years.

The inflation factors included in Table 8 were agreed upon with TSC and FRA and represent the results of a survey of the numerous studies carried out over the past three years under various Department of Transportation study contracts.

SOURCE OF ECONOMIC DATA

In order to undertake a credible economic analysis, it is necessary to establish a firm foundation of base costs from which to work. The major cost elements have been grouped together with the source of the associated data in Table 9.

ECONOMIC ANALYSIS METHODOLOGY

To accommodate the large amount of data involved in the economic analysis, AiResearch generated a computer program, for which a simplified flow chart is

TABLE 8

SUMMARY OF ECONOMIC ANALYSIS TECHNIQUES

Analysis	Computation Technique	Discount or ROI, Percent	Inflation, percent			
			Diesel Fuel, Percent	Electricity	Maintenance	General Price Level, Percent
OMB-A94	Net present value, constant $	10	2	1	2	0
4R Act	Internal rate of return	Output	0	0	0	0
Sensitivity 1	Internal rate of return	Output	8	7	8	6
Sensitivity 2	Internal rate of return	Output	10	7	8	6

TABLE 9

SOURCES OF ECONOMIC DATA

Cost Element	Cost Data Source
Electric and diesel locomotives - initial and maintenance costs	Engineering cost data acquisition for railroad electrification (ref 2)
Electrification costs	Bechtel Incorporated under subcontract to AiResearch
Flywheel costs	AiResearch
Locomotive modifications	AiResearch
Diesel oil and electrical energy	Energy costs for railroad electrification (ref 5)

shown in Figure 21. This enabled sensitivity studies to be made on the following cost elements:

Flywheel cost ±50 percent

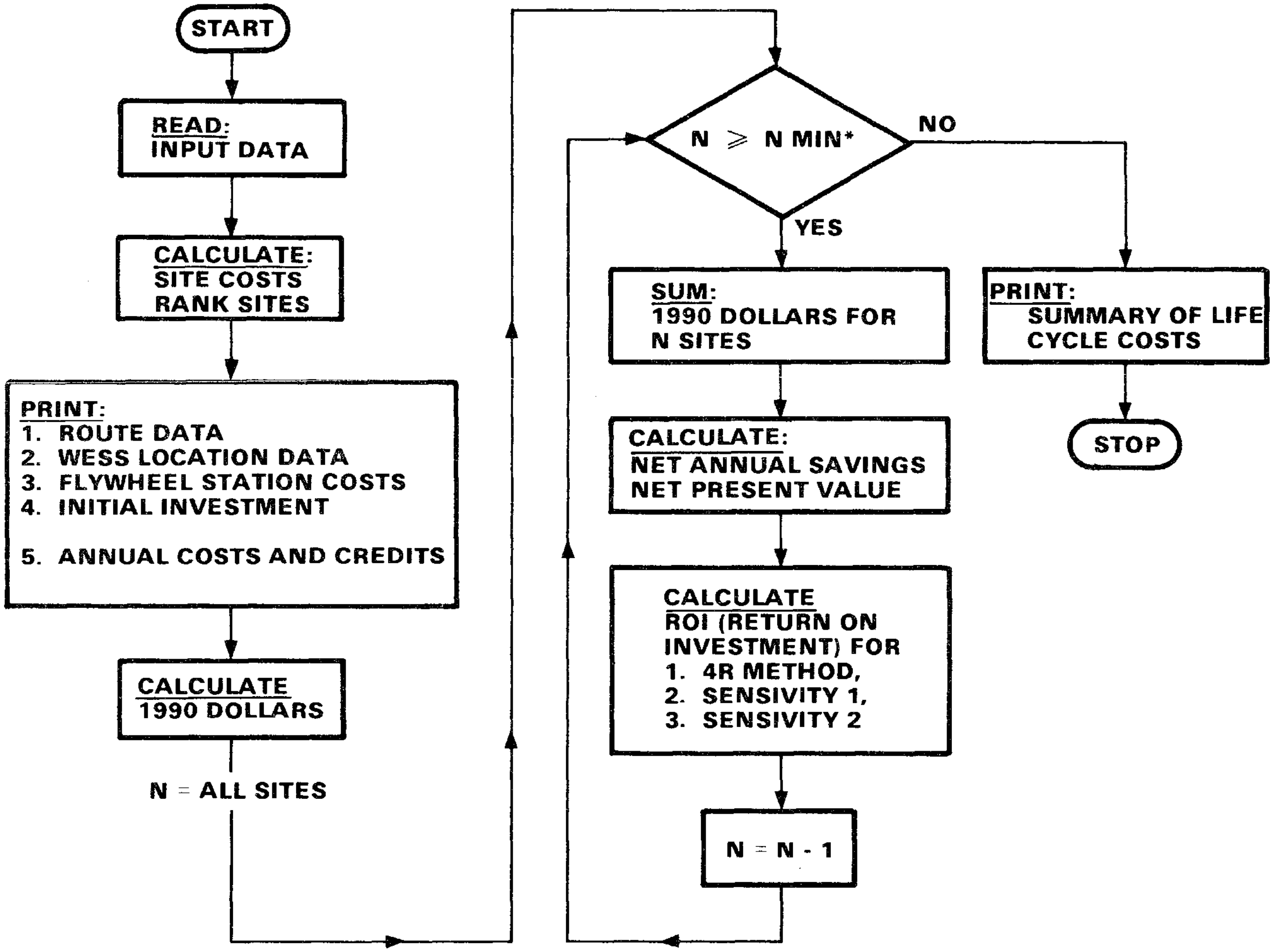
Dual mode locomotive cost ±50 percent

Energy saving ±25 percent, -50 percent

For each route, the analysis was repeated for a diminishing number of grades in an effort to determine the maximum ROI attainable on that route. Where savings in locomotives had been claimed due to the increased tractive effort available at a given speed, it was mandatory to consider the ruling grades. This aspect is considered in detail in Volume 2 of this report.

ENERGY COST TO RAILROADS

The energy costs to railroads are now becoming a more significant proportion of the operating costs, accounting for some 8 percent of the total operating bill. Since diesel fuel oil is expected to rise in price at a higher rate than electrical energy, the attraction of using electrical energy instead of diesel fuel will increase as the years advance. This is shown in Figure 22. Part of the WESS concept is that, while on the WESS grade, the energy deficiency between that demanded by the ascending train and that available in the flywheel will be taken from a utility tie-in rather than from the diesel engines. No credit for this cheaper alternate power source was taken in the calculations in order to be conservative.



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*N_{MIN} = MINIMUM NO OF SITES CONSIDERED AS A GROUP

Figure 21. Simplified Flow Chart

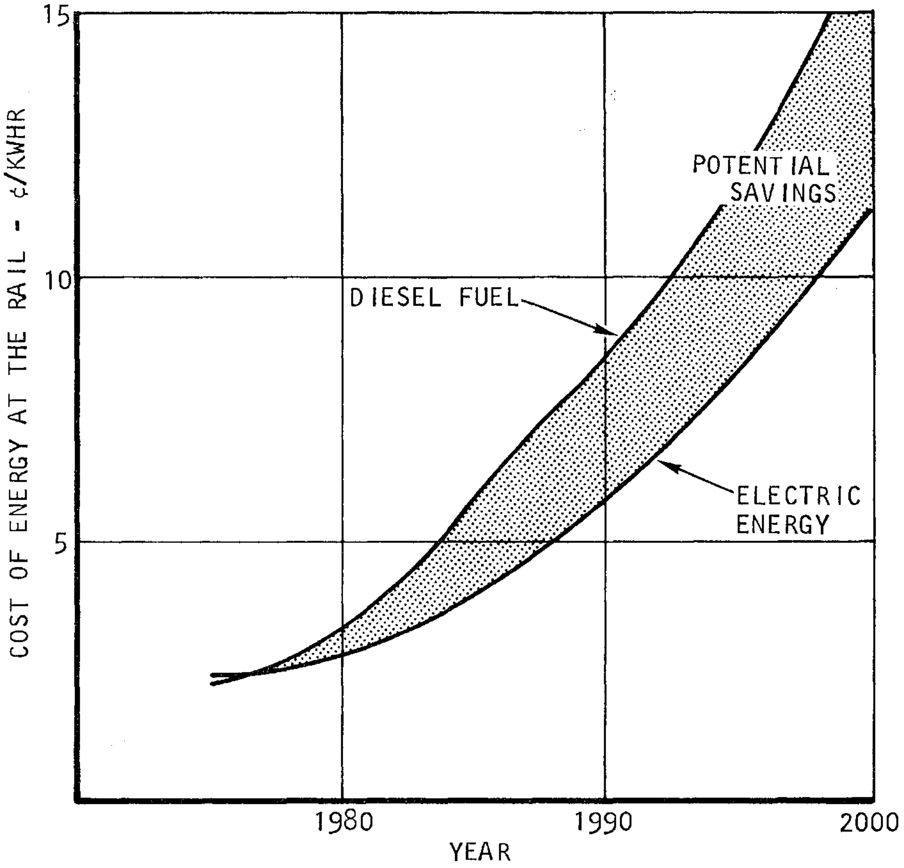

Figure 22. Comparison of Railroad Diesel Fuel and Electric Energy Cost Projections (Reference 4)

Major Credit Elements

There are two major credit elements to be considered:

(a) Energy saving

(b) Reduction in locomotive fleet size

Early in the study, it became apparent that differences in operating technique from railroad to railroad and in fact, from engineer to engineer, make it difficult to quantify precisely the energy saving that can be consistently achieved from a train of given weight operating over a known route. Later in the study, a sensitivity analysis showed that this possible variation did not significantly affect the results of the economic study.

When the concept of the dual-mode locomotive was formulated, it was decided to allow the locomotive rating in the secondary (electric) mode to be determined by the rating of the traction motors, rather than to be limited by the prime mover. This was fully discussed in Section 2 of this volume and results in the following significant economies in the railroading operation:

Reduction in fleet size

Reduction in number of new locomotives to be purchased annually

Reduction in locomotive fleet maintenance

Reduction in fuel wasted during unnecessary idling

The following less significant savings also may be realized, but have not been quantified in this study:

Reduced track maintenance

Reduced crew costs

Reduced switching cost

Major Cost Elements

There are three major cost elements to be considered:

Flywheel cost

Locomotive modification cost

Electrification costs

The first two elements have been the subject of detailed analyses by AiResearch; they are summarized in this report and are fully described in Volume 2. The electrification costs (catenary, feeder stations, signalling, utility tie-ins, etc.) have been generated by Bechtel Incorporated under subcontract to AiResearch. The basis for the costs derived is also covered in Volume 2.

The flywheel cost used for the baseline analysis was $270 per usable kwhr. This cost includes installation and test of the flywheel and its housing and ancillaries at the WESS site.

The regenerative ac electric locomotive cost used for the study was $1.07 million, which, as explained above and in Volume 2, represents a conservative (high) estimate.

The dual-mode locomotive modification cost used for the baseline analysis was $0.211 million; details of this modification are presented in Volume 2.

The cost of electrification, as generated by Bechtel, was somewhat different for each route, depending on the track configuration and the signalling system currently installed. The electrification costs include the following:

Catenary
Utility tie-in
Substation
Signalling and communications

The costs used for the economic analysis for the selected routes were the following:

Railroad	Electrification Cost
AT&SF	$400,000 per route mile
BM&LP	Already electrified
Conrail	$500,000 per route mile
UP	$238,000 per route mile

SECTION 5

WESS APPLICATION TO SPECIFIC RAILROADS

Based on the location study, one may logically conclude that rather than apply WESS to specific grades, prime consideration should be given to routes that lie between major classification yards. The four such routes considered in the study are analyzed below.

Generally, the results of the economic analysis show that WESS applied to today's railroads has an attractive return on investment (ROI). Except for the special case of BM&LP, these WESS installations provide an ROI in excess of 20 percent. Other routes, such as those identified in the location study and those on railroads not considered in this study, would be expected to reflect this minimum ROI.

ATCHISON, TOPEKA, AND SANTA FE RAILROAD

The Los Angeles-Belen route, which forms part of the AT&SF major artery, is characterized as a 100-percent, high-speed manifest service that operates typically at 2.6 hp/GT; it currently has a total traffic level of some 50 × 10^6 GTT/year. The route negotiates the Southern Rocky Mountains and Southern California mountains during its 900 route miles of predominantly double track. A total of 18 potential WESS sites has been identified on this route.

Traffic is expected to increase at an annual average rate of 2 percent until at least 1990 (ref 6). Traffic projections beyond 1990 are not available and therefore zero growth has been assumed after 1990. The results of the power and energy calculations are shown in Table 10 for the entire route.

TABLE 10

ANNUAL ENERGY SAVING FOR LOS ANGELES-BELEN ON 18 WESS SITES

Scenario	Annual Energy Saving at 1990 Traffic Levels
Dual-mode	27.82 Mgal
Electric helper	25.04 Mgal
Electrified railroad	291,000 Mwhr

The baseline case economic analyses, which use the best available data for each scenario, are given in Figures 23 through 26. They show the benefit of installing the WESS system at a varying number of locations, starting with all sites, and successively deleting the least attractive site until only the ruling grades (where applicable) remain.

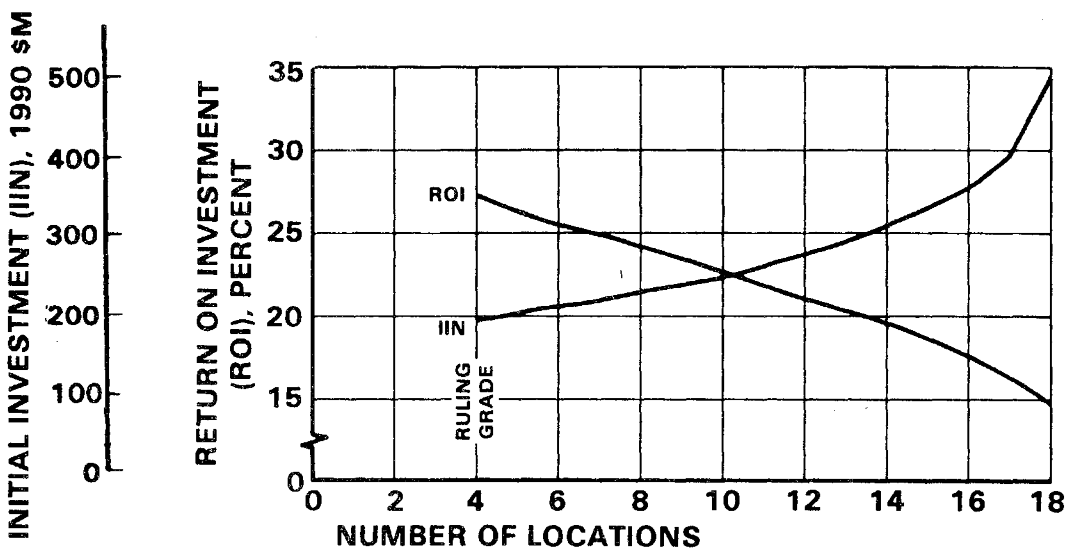

Figure 23. Los Angeles-Belen Dual-Mode Locomotive, Baseline Case

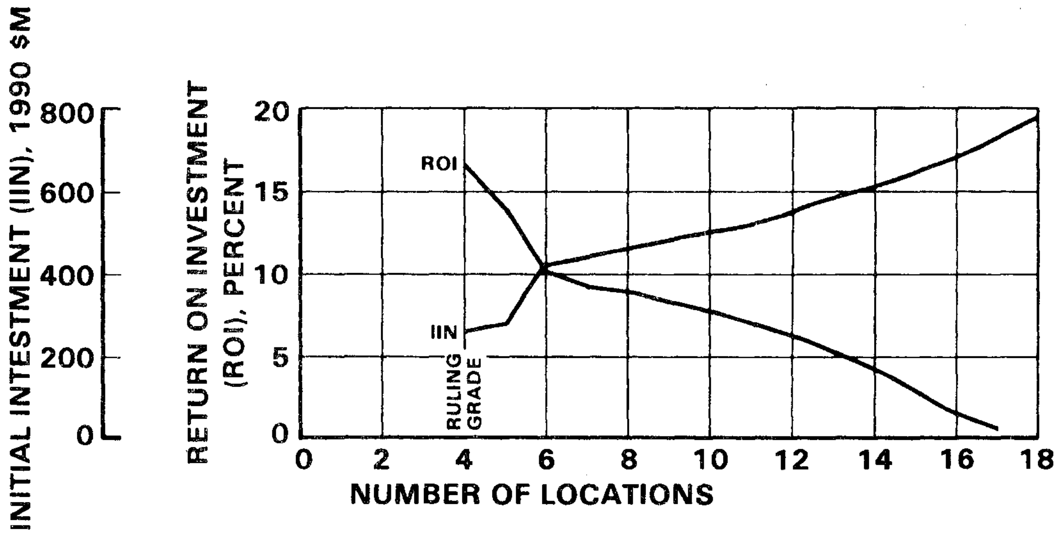

Figure 24. Los Angeles-Belen Electric Helper, Baseline Case

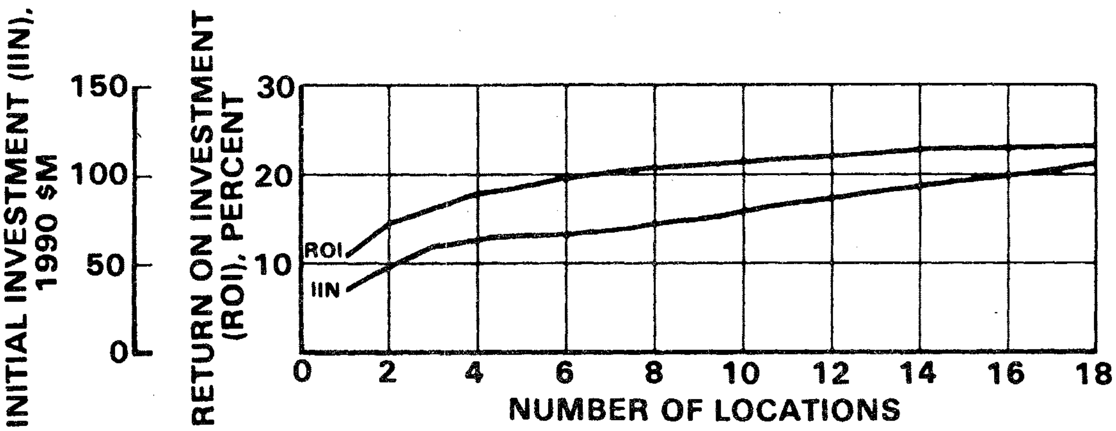

Figure 25. Los Angeles-Belen Electrified Railroad, Baseline Case

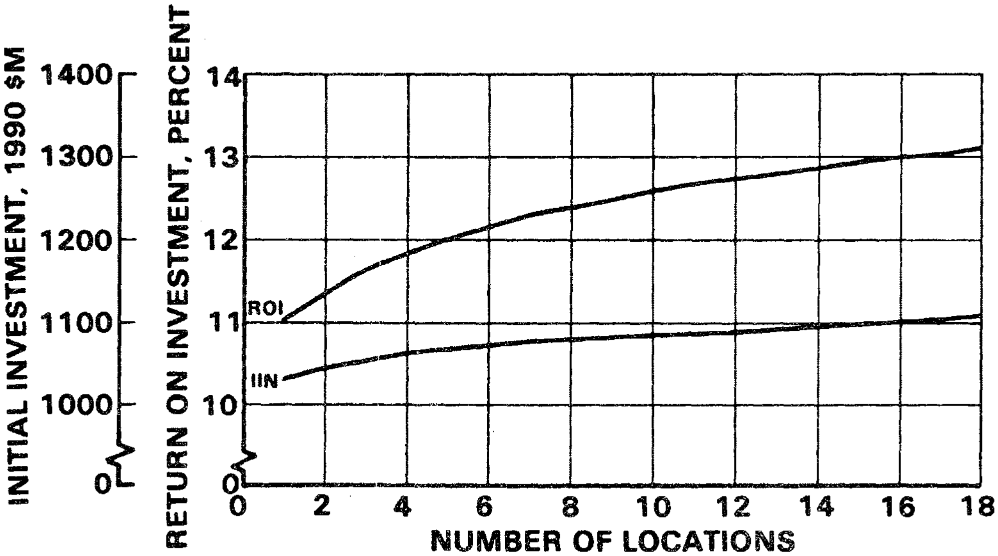

Figure 26. Los Angeles-Belen Concurrent Electrification and WESS, Baseline Case

In the baseline dual-mode analysis (Figure 23), it can be seen that as the number of locations equipped with WESS decreases, so the initial investment decreases and the ROI increases. This is because for each case (i.e., consideration of a number of grades) the least attractive grade is dropped from the previous analysis. This process continues until only the ruling grades remain. These grades were fixed into the analysis because the ruling grades must be equipped with WESS in order to legitimately claim the locomotive savings (as referred to earlier in Section 2 of this report).

The baseline analysis of the electric helper scenario (Figure 24) has a similar shape to the dual-mode locomotive, although the initial investment is higher and the ROI falls sharply from the ruling grades case and goes negative, inferring that the annual costs are greater than annual savings. Clearly, this is not an attractive scenario.

The scenarios for the electric railroad (i.e., already electrified) and concurrent electrification and WESS--in which the cost of electrification is considered--do not have the ruling grade limitation of the dual-mode and electric helper scenarios imposed on them. This is because savings in locomotive fleet size are not claimed. The electrified railroad baseline analysis (Figure 25) shows that as the number of locations considered decreases, so the initial investment decreases. In this case, an optimum return on investment is reached where the annual savings are optimized in relation to the initial cost. This aspect is more fully discussed in Volume 2.

In the concurrent electrification and WESS baseline analysis (Figure 26), it will be seen that the effect of WESS on the total initial investment is minimal, increasing as the number of locations increases. The return on investment increases until, as in the electrified railroad analysis, a maximum value is reached.

It is essential to point out that the locations may change for each separate analysis. Thus, for the condition "number of locations equals 2", the locations could be sites 5 and 6 or sites 3 and 4. This is because for each set of conditions, the computer program assesses the optimum ROI for each combination of grades and route dependent costs.

The results of the sensitivity analyses are to be found in Volume 2 of this report.

UNION PACIFIC RAILROAD

The Los Angeles-Salt Lake City route of UP is characterized as a mixed traffic route operating at power/weight ratios of up to 5 hp/GT, currently having a total traffic level of some 39 x 10^6 GTT/year. The route negotiates the Southern California mountains during its 782 route miles that are predominantly single track. Ten potential WESS sites have been identified on this route.

Traffic is expected to increase at an average annual rate of 2 percent until at least 1990 (ref 6). Zero growth has been assumed beyond 1990. The results of the power and energy calculations are shown in Table 11 for the entire route.

TABLE 11

ANNUAL ENERGY SAVING FOR LOS ANGELES-
SALT LAKE CITY ON 10 WESS SITES

Scenario	Annual Energy Saving at 1990 Traffic Levels
Dual-mode	22.04 Mgal
Electric helper	19.84 Mgal
Electrified railroad	237,000 Mwhr

The baseline case economic analyses, using the best available data for each scenario, are given in Figures 27 through 30; they show the benefit of installing the WESS system at a varying number of locations, starting with all sites, and successively leaving out the least attractive site until only the ruling grades (where appropriate) remain. The shape of the curves is explained in the discussion of AT&SF sites at the beginning of this section. The results of the sensitivity analysis are to be found in Volume 2 of this report.

CONSOLIDATED RAIL CORPORATION

The Harrisburg-Pittsburgh route of CR is widely cited as a candidate for electrification in the near future. It is characterized as a slow-speed route consisting of coal and ore unit trains as well as other mixed traffic, and currently has a traffic level of 112 x 10^6 GTT/year. The route negotiates the Allegheny Mountains during its 245 route miles that typically accommodate three or four tracks. Three potential WESS sites have been identified on this route. Traffic is not expected to increase during the period under question (ref. 6) and therefore zero growth has been assumed. The results of the power and energy calculations are shown in Table 12.

TABLE 12

ANNUAL ENERGY SAVING FOR HARRISBURG-PITTSBURGH ON THREE WESS SITES

Scenario	Annual Energy Saving at Zero Traffic Growth
Dual-mode	6.5 Mgal
Electric helper	5.86 Mgal
Electrified railroad	66,400 Mwhr

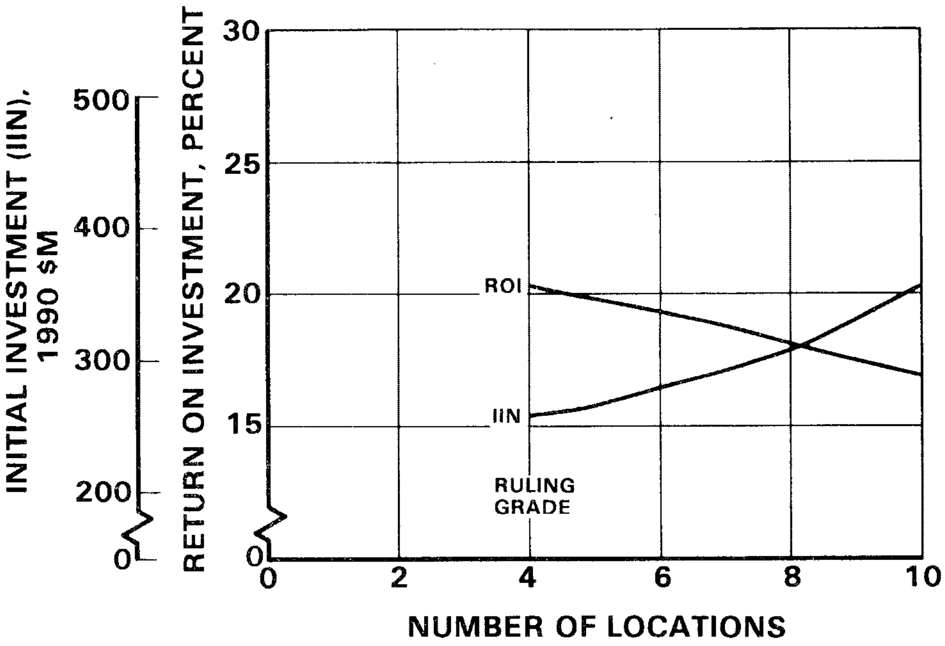

Figure 27. Los Angeles-Salt Lake City Dual-Mode Locomotive, Baseline Case

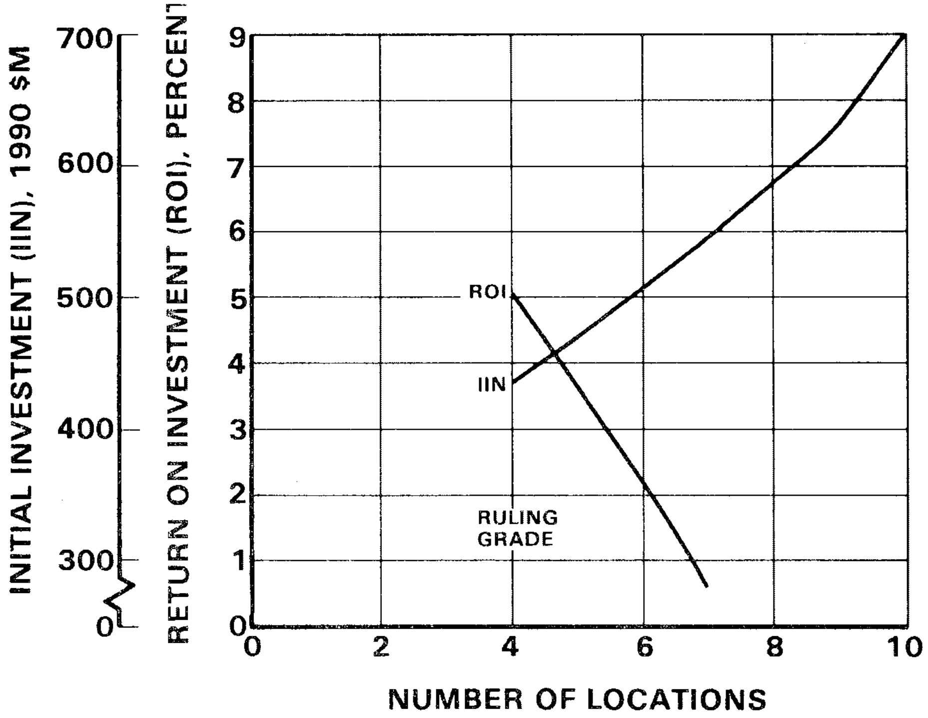

Figure 28. Los Angeles-Salt Lake City Electric Helper, Baseline Case

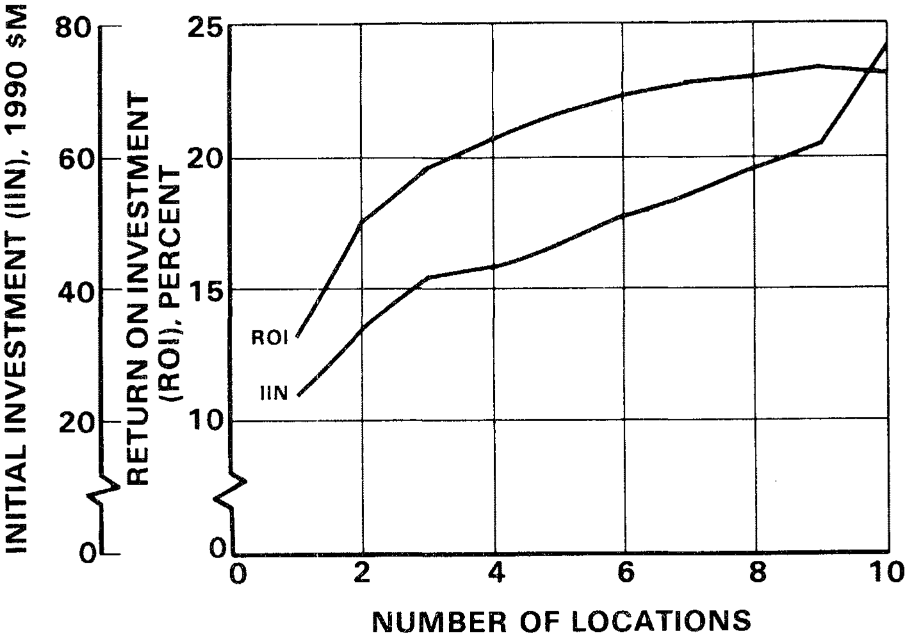

Figure 29. Los Angeles-Salt Lake City Electrified Railroad, Baseline Case

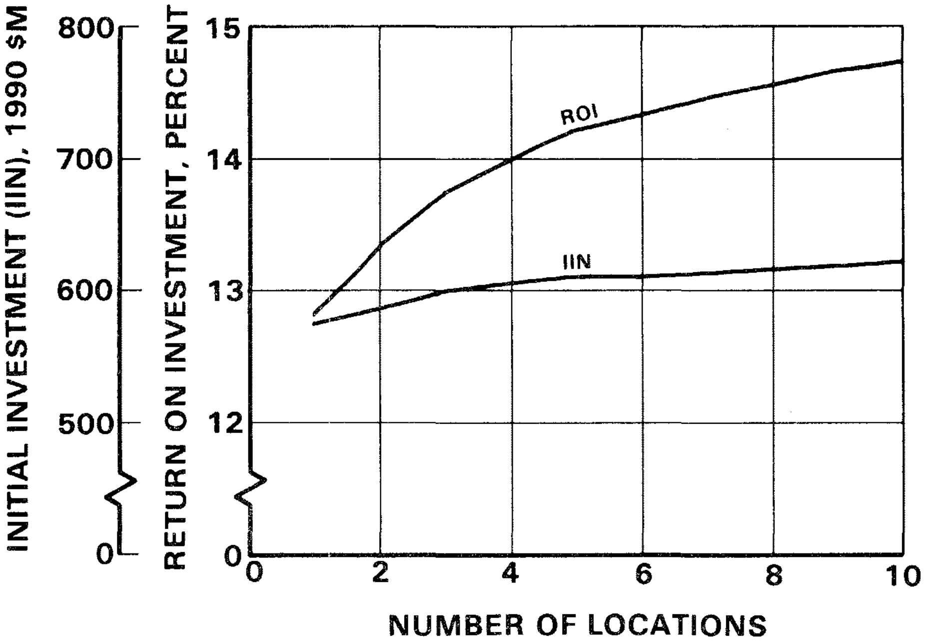

Figure 30. Los Angeles-Salt Lake City Concurrent Electrification and WESS, Baseline Case

The baseline case economic analyses, using the best available data, are given in Figures 31 through 33 (except for the electric helper scenario) and show the benefit of installing the WESS system at a varying number of locations, starting with all sites, and successively leaving out the least attractive site until only the ruling grade (where applicable) remains. The shape of the curves is explained above in the discussion of AT&SF sites.

The ROI for the electric helper scenario is negative for more than one location and cannot be represented graphically. For one grade the ROI is 2.4 percent. This low ROI in no way reflects on the current diesel helper operation on this route. The results of the sensitivity analysis are to be found in Volume 2 of this report.

BLACK MESA AND LAKE POWELL

The Black Mesa and Lake Powell (BM&LP) railroad is electrified at 50 kv, 60 Hz and was constructed for the sole purpose of delivering coal from the Kayenta Mine to the Navajo Generating Station. It has no rail connection to the mainline U.S. railroad system. The railroad currently has a traffic level of 21×10^6 GTT/year and this is not expected to change unless a fourth generating unit is added at the power station. During its 78 miles of single track, the railroad descends from the mine before rising to climb the Black Mesa; it then descends into the Colorado Valley near Page, Arizona.

The results of the power and energy calculations are shown in Table 13 for the entire route, which is treated as one grade for the purpose of the calculations.

TABLE 13

ANNUAL ENERGY SAVING FOR THE BLACK MESA AND LAKE POWELL ROUTE

Scenario	Annual Energy Saving
Electric railroad	12,000 Mwhr

The baseline case economic analysis (involving a restructuring of the timetable) shows a return on investment of 17.26 percent. The relatively low ROI is due to the extremely low cost of energy to the railroad. The results of the sensitivity analyses are to be found in Volume 2 of this report.

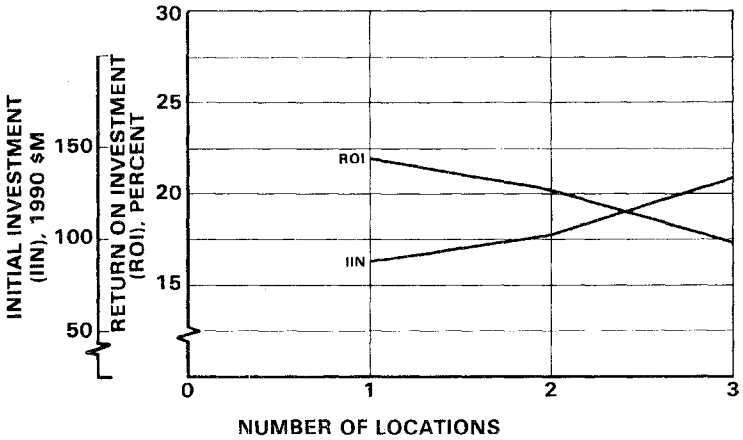

Figure 31. Harrisburg-Pittsburgh Dual-Mode Locomotive, Baseline Case

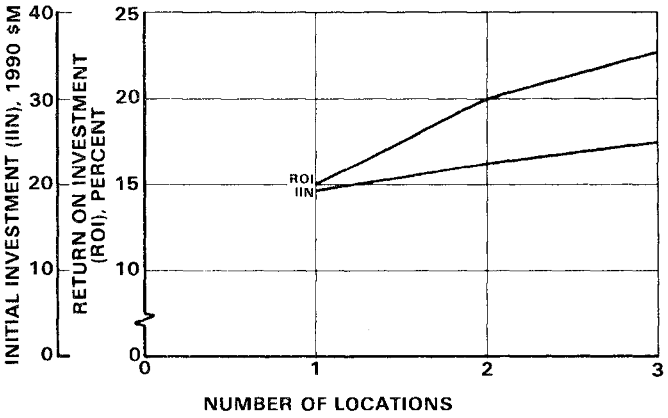

Figure 32. Harrisburg-Pittsburgh Electrified Railroad, Baseline Case

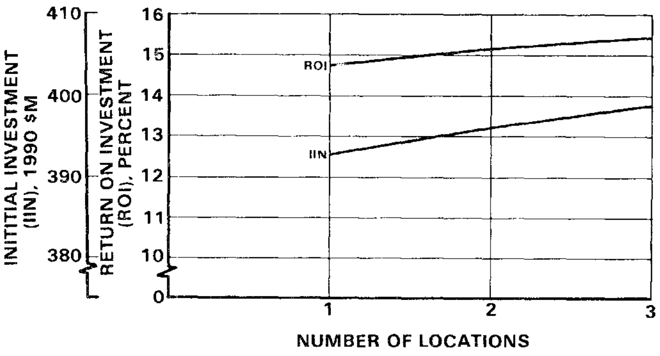

Figure 33. Harrisburg-Pittsburgh Concurrent Electrification and WESS, Baseline Case

SECTION 6

DEVELOPMENT PROGRAM PLANS

A major conclusion to be drawn from the Wayside Energy Storage Study is that wayside flywheel storage of energy from a descending train for subsequent reuse by an ascending consist is technically and operationally feasible as well as economically attractive. Three major areas of risk have been identified as follows:

- Large flywheel
- Dual-mode locomotive
- Regenerative electric locomotive operation.

Any subsequent development program (item 11) must therefore address these three risk areas. A number of options are available and are discussed in detail in Volume 2; however, AiResearch recommends that the following development program (timescales shown in Figure 34) be implemented immediately.

PHASE I, DESIGN AND DEVELOPMENT

Phase I would comprise three major tasks:

Dual-Mode Locomotive--Initially, carry out a design study that will result in equipment specifications. This task would be followed by detailed equipment design.

Electric Locomotive--Design and develop a fully controlled thyristor converter and modified control system that is suitable for modern electric locomotives and compatible with the WESS concept.

Flywheel Station--Initially, carry out a design study that will result in material and ancillary equipment specifications that will be used as a basis for the subsequent detailed design of the flywheel system.

The estimated cost of Phase I is $3 million.

PHASE II, EXPERIMENTAL INSTALLATION

In this phase, a 1-Mwhr flywheel would be installed at the Pueblo Transportation Test Center. It would be linked to the 14-mile Railroad Test Track, which is currently being electrified at 12.5/25/50 kv, 60 Hz. Included in this experimental phase would be the purchase of an electric locomotive that would be modified to be fully regenerative.

To investigate the dual-mode locomotive, it is proposed to borrow from cooperating railroads five locomotives, which would then be modified in accordance with the dual-mode concept. After initial proving trials and system

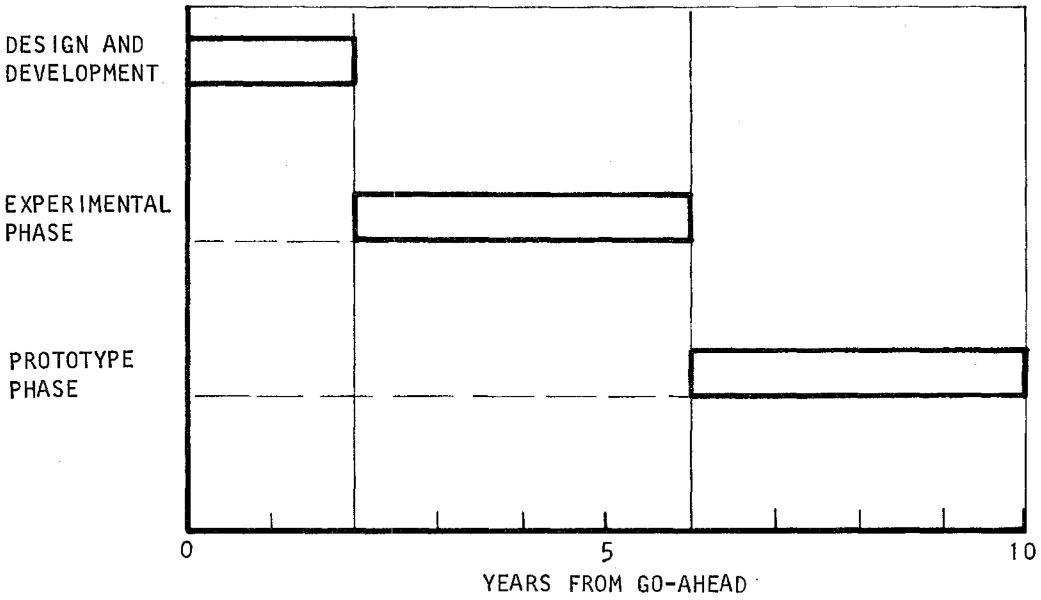

Figure 34. Phases of Recommended Development Program

integration testing at Pueblo, these locomotives would be placed into service on an electrified railroad to accumulate a minimum of 1 million locomotive miles.

The estimated cost of Phase II is $12 million.

PHASE III, PROTOTYPE INSTALLATION

This phase consists of a full demonstration program on an operating railroad. To minimize the cost of such a program, it would be advantageous if the program were to be carried out on an electrified railroad that is also a WESS candidate. At this moment, the only railroad meeting such criteria is Black Mesa and Lake Powell; however, within the timescale under consideration, it is possible that some major electrification will have taken place that would allow alternate sites to be considered.

The estimated cost of Phase III is $6.9 million.

At the conclusion of Phase III, when all the major risk areas have been evaluated, sufficient information will be available to enable railroads to decide whether WESS operationally and economically fits into their long-term planning.

SECTION 7

CONCLUSIONS AND RECOMMENDATIONS

The completion of the Wayside Energy Storage Study (WESS) has resulted in the quantification of the costs involved and the benefits derived from the concept of recuperating braking energy from freight trains on long downgrades with storage in a wayside flywheel. On this basis, the deployment of WESS on actual routes of U.S. railraods has been found economically attractive. In addition, the technical feasibility of the concept has been determined and a set of plans has been generated to verify the operational suitability of WESS. The specific conclusions and recommendations of this 1-year WESS study are given below.

CONCLUSIONS

1. Thirty-four prime candidate sites for WESS were identified. These sites are located on the most heavily traveled U.S. railroads that operate over mountain ranges. In addition, it is estimated that another 40 to 50 potential WESS sites exist in the U.S.

2. Ten railroad routes between major classification yards have been found to be viable candidates for local WESS installations on their grades. The installation programs could take place gradually, continuing until all worthwhile grades are converted.

3. WESS is highly compatible with presently electrified railroads and can effect substantial economies by shaving the peak demand.

4. The WESS concept enhances the economics of railroad electrification and permits evolutionary electrification of complete routes.

5. The most practical system scenario for diesel railroads is the use of dual-mode locomotives on WESS routes; this would provide regenerative electric operation on grades and conventional diesel operation between grades.

6. The preferred electrification system for use with WESS is a high-voltage ac catenary system for the transmitting power between the wayside flywheel station and the dual-mode locomotives.

7. The application of WESS to actual railroad grades can reduce energy consumption by as much as 23 percent, depending on grade characteristics and locomotive operating techniques.

8. The flywheel technology required for WESS can be based on the state of the art for steel flywheels. (Units of similar size are currently being fabricated). Future improvements in composite flywheel fabrication techniques should reduce costs and make larger-capacity flywheels possible.

9. The use of dual-mode locomotives operating over WESS grades permits a reduction in the number of locomotives required for the same performance on most railroad routes.

10. A presently available control system can optimize WESS operations by use of train dispatching information, flywheel status, and electric utility demand constraints.

11. In providing make-up power for the WESS sites, an electric utility was found to be superior to auxiliary diesel or gas turbine power generating sets.

12. The study identified three areas of potential technical risk that should be addressed in the subsequent development program at a cost of $22 M. The areas of risk are:

> <u>Large Flywheel</u>--Although steel flywheels in the weight range of the WESS unit have been built and high energy density flywheels in smaller capacities have been built, the combination has not been demonstrated to date.
>
> <u>Dual-Mode Locomotive</u>--Although no problems are foreseen, the modification of an existing locomotive such as the EMD Model SD40 to a dual-mode configuration has not been previously accomplished.
>
> <u>Regenerative Electric Locomotive Operation</u>--With the exception of a few European locomotives, no extensive service demonstration has been conducted with fully regenerative electric locomotives.

13. Use of large flywheels for user level peak-shaving and optimization of cogeneration schemes has applications beyond WESS.

RECOMMENDATIONS

1. The Phase I design and development program should be promptly initiated. As a first stage of this program, it is suggested that two design studies be started immediately to directly address the three potential technical risk areas. These design studies and their objectives are as follows:

> <u>Dual-Mode Locomotive Design Study</u>--Confirm the physical and electrical feasibility of modifying an EMD Model SD40 locomotive to a dual-mode configuration. In addition, determine the electrical characteristics of the regenerative converter and the alterations required on the locomotive control circuitry. (The last two objectives also can be used to reduce the technical risk associated with the regenerative electric locomotive operation).
>
> <u>Scale Model Flywheel</u>--Design, build, and test a 7.33-kwhr flywheel (0.1 percent of WESS flywheel energy) to verify the design of the axially stacked, bolted, flat, unpierced, disk flyhweel proposed for actual WESS demonstrations.

2. Extend the application study of WESS to include Canadian railroads in light of the Memorandum of Understanding between DOT and Transport Canada. Three Canadian railroads appear to have attractive combinations of traffic and grades--Canadian Pacific, Quebec and North Shore Labrador, and Port Cartier.

3. The peak-shaving potentials of WESS should be evaluated on actual candidate electrified railroads such as Black Mesa and Lake Powell and the North East Corridor (NEC), or on routes that may be electrified such as the Conrail Harrisburg to Pittsburgh run.

4. A seminar on the latest WESS program results should be held to inform operating railroads of the concept.

5. The results of the WESS program should be coordinated with cognizant representatives of the Department of Energy to facilitate technology transfer from WESS to other energy conservation programs such as:

- Peak-shaving at user level (similar to NEC)
- Optimization of cogeneration schemes (similar to WESS)

6. Extend the Location Study (Item I) beyond the contract limitation of nine railroads to identify more potential WESS locations. Additional railroads that could be considered include the Milwaukee Road, Western Pacific, Baltimore & Ohio, Chessie, Norfolk & Western, as well as the Canadian railroads.

7. Conduct a nationwide study of WESS application to the National Electrification Network for routes over 40 million gross trailing tons per year. This study would extend the WESS analysis to cover about 10,000 miles of electrified railroad.

SECTION 8

REFERENCES

1. Yao, N.P., "Advanced Secondary Batteries for Electric Vehicle Propulsion," Proceedings of 1978 Advanced Transit Association International Conference, April 1978.

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3. The Air Brake Association, Management of Train Operation and Train Handling, Chicago, 1972.

4. Federal Railroad Administration, An Evaluation of the Costs and Benefits of Railroad Electrification, Draft Report, Washington D.C., Undated.

5. Schwarm, E.G., Energy Costs for Railroad Electrification. Final Report prepared by A.D. Little, Inc., under contract to DOT-TSC, May 1977.

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Pocatello-Council Bluffs (UP)

Pocatello-Portland (UP)

Sacramento-Ogden (SP)

Sacramento-Portland (SP)

Los Angeles-El Paso (SP)

Denver-Salt Lake City (D&RGW)

Harrisburg-Pittsburgh (Conrail)

Page-Kayenta (BM&LP)

These routes are shown in Figure 15.

Four representative routes then were chosen for detailed analysis:

Los Angeles-Belen	High speed, high traffic
Los Angeles-Salt Lake City	Medium speed, medium traffic
Harrisburg-Pittsburgh	Low speed, high traffic
Page-Kayenta	Electrified

For this analysis, the AiResearch train performance calculator (TPC) used the route characteristics (grade, mileposts, curvature, speed restrictions) available from track charts supplied by TSC. The output from the program was the identification of all sections of potential regeneration, a task that was impossible to undertake manually before the systems analysis had produced realistic operating scenarios. The end result was the identification of many more grades on the four representative routes worthy of consideration as WESS candidates. For example, on the Los Angeles-Belen route where six prime candidate grades were originally identified, 18 grades were identified by the completion of the study.

On the basis of this information, it was decided that complete routes between major classification yards should be considered.

Location Study Output

As a result of the location study, AiResearch has identified 34 prime candidate grades and ten routes with WESS potential; however, the location study was not 100 percent complete as far as identification of all major grades was concerned. Prime candidate grades and WESS routes no doubt exist on other railroads, but these remain unidentified by this analysis; however, as many high-traffic-density, mountainous-terrain-located railroads as possible were covered in this location study.

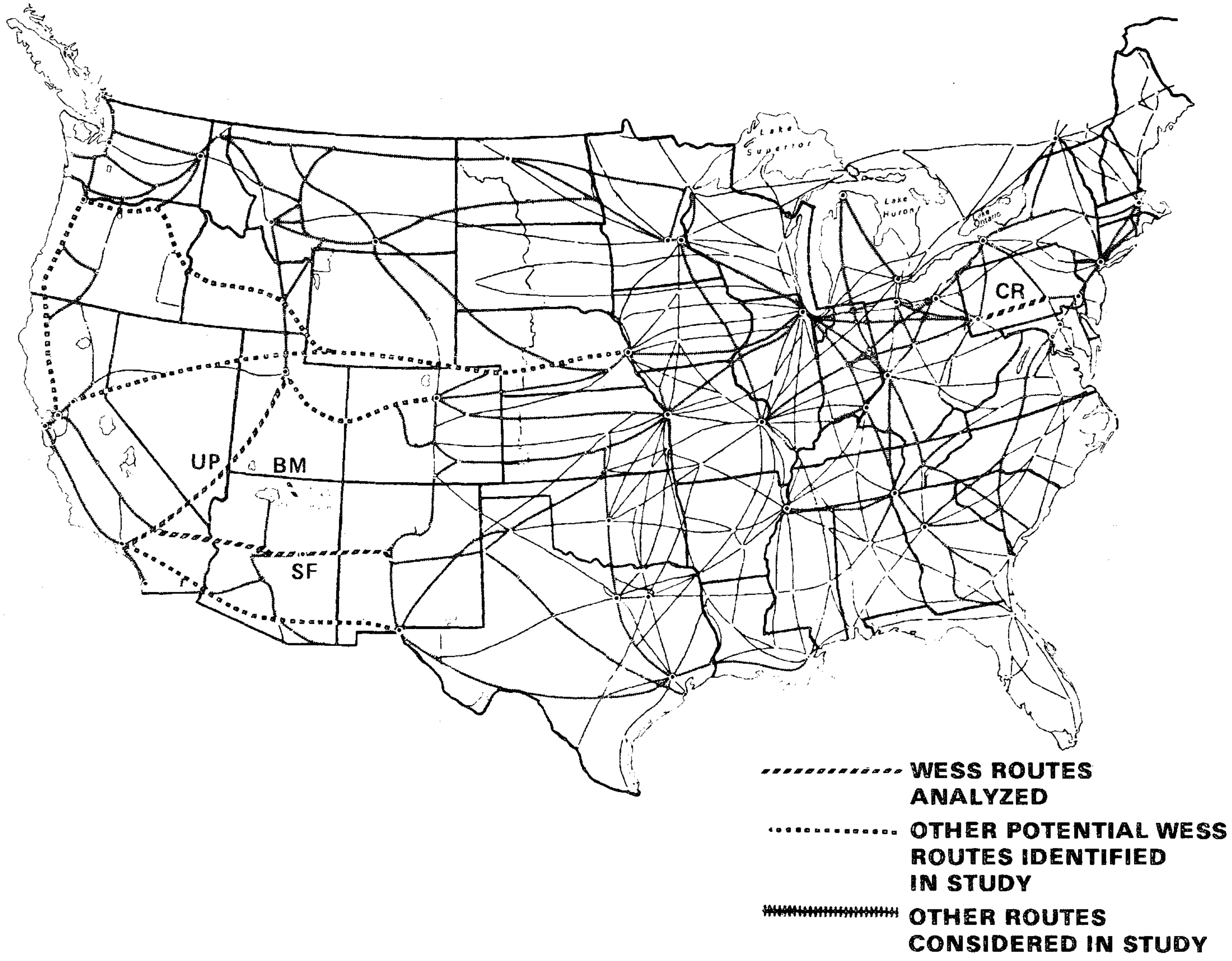

Figure 15. WESS Routes