WAYSIDE ENERGY STORAGE STUDY
Volume II - Detailed Description of Analysis

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FINAL REPORT

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The United States Government does not endorse products or manufacturers. Trade or manufacturer's names appear herein solely because they are considered essential to the object of this report.
Volume II 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: Atchison, 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.

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:

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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

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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.
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°C = \left( °F - 32 \right) \times \frac{5}{9}
SECTION 1

INTRODUCTION

The initial intent of this Wayside Energy Storage Study was to establish the feasibility and to quantify the benefits of recuperating braking energy from freight operations. (Such energy—the annual equivalent of many million barrels of oil—is presently wasted in the daily operation of freight trains on long downgrades or during stopping); however, it was recognized at the outset that the study should concentrate on determining the best sites for deployment of wayside energy storage systems (WESS's). Therefore, criteria were established regarding grade characteristics such as elevation change, traffic density, track configuration, and length of grade. These criteria allowed a quick screening of data gathered on grades throughout the United States. The WESS study began with a series of visits to operating railroads and the Federal Railroad Administration (FRA) to obtain the needed data on actual grades.

PROGRAM OUTLINE

The WESS study was conducted by AiResearch and the program subcontractor, Rechtel, Inc.; it consisted of performing the 11 work items specified in the Statement of Work in the contract. The specific work items completed during this program are summarized below:

Item 1, Locations--Survey the route system of U.S. railroads to identify and classify potential locations for application of wayside flywheel energy storage. The contractor shall acquire all pertinent data that is currently available, including parameters of grade, length of grade, traffic density, train speeds, train consists, and fuel consumption data. In accumulating the aforementioned data, the contractor, and/or its subcontractor, shall not conduct any survey involving more than nine (9) railroads, or other elements of the general public by questionnaire, telephone call, personal visit, or other means.

Item 2, Systems--Derive concepts of complete systems for the applications identified by the survey (including equipment in the locomotives and at flywheel stations) for both electrified and diesel-electric railroads. System concepts for flywheel stations may also include other energy storage concepts operating in conjunction with the flywheel. Realistic operational scenarios shall be defined by the contractor. The benefits to be derived from each of the concepts, based upon the adopted scenario, shall be identified in terms of technical risks and/or deficiencies, and potential benefits. The study shall determine where a need exists for a wayside-to-train communications link to alert the ascending train of the available energy, or to inform the wayside station of train weight, length, and other pertinent data. This system study shall determine the most cost-effective design concepts along with the operational procedure to be used. The contractor shall establish limits on parameters such as train length and grade for a particular system configuration.
Item 3, Calculations--Perform calculations of power and energy requirements for proposed systems at candidate locations, and compare with fuel consumption data for existing operations. An existing train performance simulation, modified as required to model wayside storage, may be used to evaluate the performance of each system concept considered. This computer simulation model shall be capable of taking into account various operating parameters including, but not limited to, the following:

(a) Varying the rated horsepower of locomotive
(b) Varying the size of the train
(c) Varying the train schedule
(d) Topographic conditions

The simulation model may have value beyond the scope of this study. It may be employed by a railroad for a particular application to determine the proper system configuration and to measure potential benefits.

Item 4, Locomotives--Determine modifications required for diesel-electric locomotives to deliver and receive energy from the propulsion system. Consider both the direct transfer at propulsion system dc voltage level, and the onboard conversion to a different voltage level to match the ratings of the wayside collector system.

Item 5, Wayside--Derive concepts of wayside, third-rail, and/or catenary equipment to deliver and receive energy from the locomotives. Systems to be considered are to include those using the running rails as one electrical side, as well as bipolar systems consisting of two catenary wires or two opposite-side third rails. Consider the impact on existing signaling systems using the rails as one electrical side.

Item 6, Stations--Derive concepts for the flywheel stations, including alternative types of motor/generator flywheel sets, flywheel designs, number of sets for reliable service, use of standard machinery, vacuum systems, and duty cycle. Other energy storage concepts involving the flywheel also shall be considered, including batteries. The study also should consider automatic alterations to the flywheel system configuration based on approaching train data, including parameters such as weight and length.

Item 7, Controls--Determine methods for regulating the flow and storage of energy for various train configurations such as: one track with one train on the descending grade, no train ascending; ditto with ascending train; two tracks with all combinations of ascending and descending trains.
Item 8, Energy Supplement--Analyze use of utility energy to precharge the flywheels, or to supplement the flywheel energy for ascending trains. Return of energy to the utility will be taken into consideration, as will the use of flywheel sets integrated with gas turbines or other auxiliary power sources for peak-shaving at wayside substations.

Item 9, Electrified Railroads--In the design concepts of flywheel systems, consider the problem of coupling single-phase buses to substation buses. Consideration should be given to the use of flywheel sets at electrical points common to several substations, and also to the use of flywheel sets integrated with gas turbines or other auxiliary power sources for peak-shaving at wayside substations.

Item 10, Engineering Economics--Provide an engineering economy study to determine the economic viability that results from installation of a track-side flywheel energy storage system at the crucial points identified by this study. All major cost and savings increments should be considered, including those related to energy, fleet size, locomotive maintenance, and capital investment in wayside equipment and locomotive modifications. Credit should be included for equipment that would be retired, presuming it can be redeployed elsewhere in the system. Traffic density should be based upon actual schedules, and traffic growth should be based upon Department of Commerce projections. The analysis should be conducted for both diesel-electric and all-electric operation. Cost parameters to which the analysis is highly sensitive should be identified and their effect should be demonstrated by a sensitivity study.

Item 11, Development Program--Based on the results of the study covered by the preceding tasks, preliminary estimates shall be provided for a suitable follow-on program. This program shall contain recommendations concerning selected concepts, equipment requirements, test/demonstration programs, suitable test locations, and R&D requirements.

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

PROGRAM METHODOLOGY

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

Black Mesa and Lake Powell

Conrail
Figure 1-1. Wayside Energy Storage Study Methodology
Duluth, Missabe, and Iron Range
Southern
Southern Pacific
Union Pacific

In addition, detailed track and operational data were provided by FRA for 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 these activities are shown in Figure 1-1. 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 1-1, development plans were formulated (item 11); this task was followed by various program review and documentation activities (items 12 through 15).

TRAIN PERFORMANCE CALCULATOR

After the study was under way, a task was added to the WESS program by AirResearch 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 AirResearch and Bechtel TPC programs do not have this capability, nor does the TSC program. Therefore, AirResearch decided to generate a new TPC with the required capability of simultaneously calculating the energy requirements in a complete railroad division. The new AirResearch 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.

As a demonstration of its versatility, the new TPC has been used to calculate the complete energy profile for a full day of operation on the Pittsburgh-Harrisburg section of Conrail, based on actual dispatcher's records. This unique TPC has been developed 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 later in this volume.
FORMAT OF FINAL REPORT

The sheer volume of material generated during the 1-year Wayside Energy Storage Study has necessitated publishing this report in three volumes. Volume 1 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 the present volume. 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 which were described in detail in Section 1:

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 were then 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, and, 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
- Deep discharge cycle life
- Energy density
- Power density
- Initial cost
- Maintenance cost
The use of these criteria in the analysis resulted in the identification and consideration of the energy storage techniques described below. Comparative data for the major characteristics of these energy storage systems are shown in Table 2-1.

**Batteries**

The energy density of the battery often is higher than that of the flywheel; however, the battery is clearly inferior to the flywheel in power density (charge or discharge rate capability). This low battery power density often sizes the battery. For example, for a 5 Mw-hr battery with an energy density of 14 w-hr/lb, the power density would be expected to be the lower value of 10 w/lb as shown in Table 2-2. Then the battery weight based on energy density would be 180 tons, while the weight based on power density would be 250 tons. The latter weight would then be required for the WESS application.

The deep discharge cycle life of the flywheel is its most important attribute since in WESS service the energy storage system could see as many as 40 charge-discharge cycles per day. The projected life of the flywheel at this level of service would be 55 years while that of the battery would be only 38 days.

The cost differential shown in Table 2-1 between the battery and flywheel is of negligible concern when the comparable useful lives are considered. In addition, the battery would require a high level of maintenance (changeout, watering, equalizing, etc.) compared to the flywheel, which is compatible with long, unattended operation.

The round trip efficiency of the battery (i.e., useful discharge energy divided by charge energy) is very low (60 percent) compared with that of the flywheel (i.e., useful spin-down energy divided by spin-up energy), except for very long charge-discharge cycles.

The flywheel clearly offers by far the better combination of characteristics for the WESS application as shown in Table 2-1. Consideration was also 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 economic deep discharge cycle lives are not expected to exceed 2500.

**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 (although it is recognized that costs of these schemes are very much dependent on the terrain encountered). For the typical 10-Mw scheme developed later in the study, a cost of $700/kw could be expected, assuming that there were no abnormal difficulties associated with construction. Such installations make use of reversible turbine sets which, when pumping, have an efficiency of

*References are listed in Section 9.*
### TABLE 2-1
ALTERNATIVE STORAGE CONCEPTS

<table>
<thead>
<tr>
<th>Storage Concept</th>
<th>Round Trip Efficiency, percent</th>
<th>Installed, $/kwhr</th>
<th>Cycle Life</th>
<th>Service Life</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery</td>
<td>60</td>
<td>70</td>
<td>1000</td>
<td>2 Months</td>
</tr>
<tr>
<td>Pumped hydroelectric</td>
<td>76</td>
<td>1000</td>
<td>10^6</td>
<td>30 Years</td>
</tr>
<tr>
<td>Regeneration to utility</td>
<td>92</td>
<td>120</td>
<td>10^6</td>
<td>30 Years</td>
</tr>
<tr>
<td>Compressed air</td>
<td>37</td>
<td>N/A</td>
<td>10^6</td>
<td>30 Years</td>
</tr>
<tr>
<td>Flywheel</td>
<td>91.2</td>
<td>270</td>
<td>10^6</td>
<td>30 Years</td>
</tr>
</tbody>
</table>

*Site-dependent

### TABLE 2-2
ENERGY STORAGE SYSTEM COMPARISON
(Based on existing technology applied to full-size systems)

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Present Batteries</th>
<th>Flywheels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy density, W-hr/lb</td>
<td>8 to 14</td>
<td>3 to 12</td>
</tr>
<tr>
<td>Power density, W/lb</td>
<td>10 to 30</td>
<td>100 to 200</td>
</tr>
<tr>
<td>Deep discharge, W/lb</td>
<td>500 to 1500</td>
<td>10^6</td>
</tr>
<tr>
<td>Cost, $/kwhr</td>
<td>100</td>
<td>270</td>
</tr>
<tr>
<td>Round trip efficiency</td>
<td>60 percent</td>
<td>91.2 percent</td>
</tr>
</tbody>
</table>

85 to 90 percent, and when acting as a turbine, have an efficiency of 90 to 95 percent. Therefore, the round trip efficiency of the pumped hydroelectric system is typically 75 percent compared with 91.2 percent for the flywheel.

Regeneration to the Utility

This technique is technically attractive, having the high round trip efficiency of 92 percent; however, economically it suffers from the disadvantage of not getting a full credit for the energy returned (usually only 60 percent for a railroad-type operation), and there would be no credit for the demand portion of the utility change (which normally accounts for 50 percent of the utility...
Therefore, the value of the energy saved is significantly lower than for the flywheel configured system, amounting to approximately one-third of the original cost.

**Compressed Air Storage**

This storage system is based on gas turbine technology and consists of gas turbines compressing air in large underground storage caverns. During regeneration, the generators, running as motors, would "recharge" the air-storage caverns.

During discharge periods, the high-pressure air from underground storage caverns is released to spin the plant's turbine generators and provide the required energy to the railroad.

Potentially suitable air-storage sites include underground salt formations, depleted oil and gas wells, and played-out mines.

It is expected that this novel approach to energy storage will be of increased importance in the coming years; however, in the immediate future it is not considered suitable for WESS because of its low round trip efficiency and the improbability of finding a conveniently sized underground cavern near a WESS candidate grade.

**Flywheels**

The flywheel is probably the oldest energy storage technique known to man. The most common application is on the reciprocating engine where energy is stored between each power stroke of a piston to provide a near-constant output of torque from the crankshaft. The larger the flywheel, the less the variation in torque output. In the WESS application, the flywheel has most of the advantages of direct regeneration to the utility (including a high round trip efficiency of 91.2 percent) with the advantage of receiving full credit for regenerated energy. The life of the system is in excess of $10^6$ deep discharge cycles, and the energy and power densities are at least competitive with those of the battery.

Large-flywheel technology is expected to make a significant advance during 1978 with the commissioning of the Tokomak flywheels, which are described in detail later in this report. Therefore the WESS flywheel will be within the state of the art.

As a result of this analysis, summarized in Table 2-1, 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.

**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 used 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 energy transmission are described in the following paragraphs.

Low-Voltage Dc Third Rail

The common 600- to 1000-vdc third-rail system that is used for rapid transit systems as well as for operating electric switching locomotives in electrified freight yards was the first candidate considered. In this system, power is transmitted to and from the third rail by collector shoes on each locomotive. Thus, when descending the grade, the locomotive traction motors would act as dc generators supplying power to the third rail for transmission to the wayside. At the flywheel station a converter would be used to condition this power to a suitable form to drive an electric machine that would be connected to the flywheel. The power from the descending train would thus be used to spin up the flywheel. The discharge of the flywheel to deliver power to a subsequent train climbing the grade would be the reverse of the charging sequence.

From the locomotive standpoint, the low-voltage system appears attractive since only minimal modifications would be required to an existing diesel-electric locomotive. This point is important since about 99 percent of the U.S. freight operations are accomplished by diesel-electric locomotives. There are presently only four electrified freight lines in the U.S.; these are: Conrail on the Northeast Corridor from New Haven into Washington and Harrisburg, Black Mesa and Lake Powell Railroad in northern Arizona, Muskingum Railroad in southeastern Ohio, and Texas Utility Company Railroad in Texas.

A calculation was then made of the third-rail requirements for electrification of a typical WESS grade. For this analysis it was assumed that a typical WESS site consisted of an elevation change of 1500 ft with an average grade of 1.0 percent. The length of this grade is then 23.6 miles with a wayside flywheel station assumed to be at the midpoint. A typical freight consist operating at the grade would have three 3000-hp diesel-electric locomotives (equivalent to the General Motors Electro-Motive Division (EMD) Model SD40).
If the locomotives were used to provide their full braking capability of 4000 rail hp (the higher braking capability is fully explained later in this section), this would result in the delivery of 3560 hp to the third rail from each locomotive due to the generation efficiency. The total train power into the third rail of 10,680 hp at 600 vdc would result in a current level of 13,300 amp. The transmission of this current from the extremities of the typical grade to the flywheel station with a 25-percent voltage drop would result in a two-way voltage drop of 12.7 v per mile. The third-rail resistance based on an equivalent resistance return path can then be calculated as follows:

$$\text{Third-Rail Resistance} = \frac{\text{Voltage Drop}}{\text{Current}}$$

or,

$$\text{Third-Rail Resistance} = \frac{6.35 \text{ v}}{13,300 \text{ amp}} = 0.48 \text{ ohm}$$

The required conductor size based on the use of soft annealed cooper is the equivalent of 539 AWG 4/0 conductors, which would have a cross section of 89.6 sq in. (a square conductor 9.5 in. on a side), which would have a weight of 911 tons per mile. Clearly, such a third-rail conductor is impractical (particularly since an equivalent return rail would be required because the running rail resistance is far too high to be a suitable return).

**High-Voltage Dc Catenary**

The second transmission system considered was a high-voltage dc system possibly similar to the 3-kv catenary used by the Milwaukee Road in Montana and Washington until 1974 (ref 2). This application made use of special high-voltage dc locomotives with frequent catenary feed points. The Milwaukee Road system was regenerative back to the catenary providing for the use of braking energy by other trains operating over the electrified sections.

The application of a high-voltage dc catenary system to WESS would require modification of both the present diesel-electric and electric locomotives (which operate at high ac voltages) to be compatible with dc operation. In the more important case of the diesel-electric locomotive, the conversion from high-voltage dc to low-voltage dc (and vice versa) requires a dc-to-dc voltage transformation that must be accomplished by a relatively expensive solid-state power conditioning unit. Unfortunately dc cannot be transformed in voltage as simply as ac power with a transformer. The dc-to-dc converter required for propulsion would consist of an inverter that changes the high-voltage dc to high-voltage ac power, which can be simply transformed to low-voltage ac. The resulting ac power would then be rectified and supplied to the locomotive traction motors. During braking operations, the low-voltage converter must act as a dc-to-ac inverter whose output is stepped up to be rectified for connection to the catenary.

The complexity of the converter required in which both high- and low-voltage sections must act as either an inverter or a rectifier was found to be prohibitive from a cost standpoint for serious consideration in the WESS study.
Current railroading practice has tended to draw away from high-voltage dc catenary systems in favor of high-voltage ac systems largely because of the complexity and cost of the bilateral converter.

**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. The findings were that the LIM has very low round-trip efficiency compared with catenary systems (32 percent compared with 96 percent for a catenary system--both based on the distribution system). In addition, the initial cost of installing the LIM stator magnetic structure between the running rails for a distance of 23 miles on a typical grade was found to be excessive (at least twenty times the cost of providing a catenary).

The combination of low efficiency and high cost, which is characteristic of the type of LIM required for the WESS application, resulted in dropping this concept from considerations at an early stage of the study.

**High-Voltage Ac Catenary**

The current practice on electrified U.S. railroads is to use a high-voltage ac catenary for electrification. Recently the preferred voltage is 25 kv, 60 Hz on older, congested routes with tighter clearances like the Northeast Corridor (this is the new electrification that will replace the present 11-kv, 25-Hz voltage and is also being proposed for the extension from Harrisburg to Pittsburgh). The electrification of Western railroads has generally been directed toward the use of 50 kv, 60 Hz as is the case with the Black Mesa and Lake Powell Railroad.

The WESS concept configured with a high-voltage ac catenary is readily compatible with the use of present electric locomotives provided these units are modified to provide regeneration back to the catenary. This modification involves the conversion of the semi-controlled rectifiers in the locomotive to fully controlled rectifiers, which can be accomplished by replacing the silicon diodes in the lower arms of the present bridges with thyristors, as shown in the schematic of Figure 2-1, and making the necessary changes in the control circuitry. The fully controlled rectifiers then would act as line commutated inverters during braking, coupling energy to the catenary. This arrangement is similar to that which has been used on the four regenerative electric locomotives built by ASEA, one of which is currently operating in Rumania. The same modification could be applied to either new or existing General Electric Model E60 electric locomotives.

Regenerative locomotives are currently in widespread use in Switzerland and the Soviet Union. Presently 52 of the order of 89 Brown Boveri Company (BBC) Model RE 6/6 electric locomotives are in service on the Swiss National Railways, providing regenerative braking for freight operations (refs 3,4). The extent of Soviet deployment of regenerative locomotives is not known since no published information is available.
Figure 2-1. Regenerative Electric Locomotive Schematic
The regenerative electric locomotive could be directly used with WESS on presently electrified railroads. These locomotives could also be used as helpers to operate freight consists over grades with local electrification. The implications of this latter mode of operation will be discussed later in this section of the report.

The important question of making the present diesel-electric locomotive compatible with the high-voltage ac catenary was then addressed. The first approach studied was the use of slugs that would be added to the consist at its originating yard. These slugs would be fitted with a pantograph to pick up power from the high-voltage ac catenary at the grades. This power would be stepped down in voltage by a transformer and then rectified by a two-section phase delay rectifier to provide a controlled dc voltage as shown in the schematic of Figure 2-2. This controlled dc voltage would then be connected to the traction motors of the diesel locomotives in the consist and also to a set of traction motors on the slug. The freight train would operate under diesel power up to the WESS grades, at which point the diesel engines would be unloaded and run at a sufficient speed to provide auxiliary power, and the slug would be used to provide the power to all the traction motors in the consist to operate the train regeneratively over the grade. In the sections of the route between WESS grades, the slug could use power from the diesel locomotives to operate its traction motors, thereby increasing the low-speed tractive effort of the train, reducing the adhesion requirement, and possibly reducing the required diesel locomotive consist.

The idea of using slugs as helpers located only at the grades was rejected because of the difficulty of breaking the locomotive consist to place the slug between locomotives at one end of the grade, and to remove it at the other end.

The concept of using slugs was ultimately abandoned largely because of the difficulties foreseen in coupling the required high currents from the slug to the locomotives. The peak current requirement of an EMD model SD40 locomotive is 1000 amp per traction motor or 6000 amp per locomotive. Thus, if a slug were located in the middle of a consist of four locomotives it would be necessary to couple 12,000 amp through the adjacent locomotive couplings and 6000 amp through the remote locomotive couplings. The conductor size required for the connection of the slug to the diesel-electric locomotives is equivalent to 20 AWG 4/0 conductors that have a total cross-sectional area of 3.32 in.². This requires two 2.0-in.-dia copper cables to be installed on all the locomotives that would be used on the WESS grade. This requirement along with the minor modifications in locomotive controls to provide for operation on the WESS grade with power supplied from the slug does not appear impossible to provide; however, the connection of the slug to the other locomotives in the consist does pose a formidable obstacle, since these connections must be capable of being made automatically as part of the coupler (the use of manual connections for this purpose has been found to be operationally unacceptable to the railroads contacted). An investigation was made into the development of an automatic connector with the necessary capability since nothing even remotely similar is presently available. The results have shown that such a development
Figure 2-2. WECC Slug Schematic

- Protection and isolation equipment not shown

Power to other locomotives

Lightning arrestor

Grounding switch

Catenary

Pantograph

Primary overload vacuum circuit breaker

Main transformer

Auxiliaries

Smoothing choke

Pantograph bounce protection

Slugs to traction motors

Smoothed current 0.0
would necessarily be expensive and without a guarantee of success. The reason is that the contact resistance that must be initially achieved and then maintained under all operating conditions is so low as to be virtually unattainable. For example, a contact resistance at either connection of only one milliohm (which is the resistance of one foot of AWG 10 wire) would result in a local power dissipation at that point of 144 kw. It was on the basis of the difficulty of making these power connections that the slug concept was dropped.

The second locomotive concept that was investigated for compatibility with the high-voltage ac catenary was the dual-mode locomotive. This is a modified diesel-electric locomotive that can be operated either conventionally with the diesel engine or as a regenerative electric locomotive deriving its power from the catenary. The modifications that are described in detail later in this section consist of the addition of a pantograph, transformer, power converter, and traction motor choke. Also, the traction motors are to be rewound for separate field excitation, and the controls are to be altered.

The results of the dual-mode locomotive study showed the feasibility of this concept. The detailed findings of this investigation, which are described later, revealed that the dual-mode locomotive could meet all the requirements for WESS while providing compatibility with operation on a high-voltage ac catenary.

The WESS concept then could be deployed with regenerative electric locomotives on electrified railroads or helpers on electrified grades and as an alternative with dual-mode locomotives operating over routes where only selected grades are electrified for energy recuperation.

Thus, the first conclusion reached in the systems study (Item 2) was that the optimum system for transmission of energy from trains to the wayside is by a high-voltage ac catenary. The voltages recommended are 25 kv for railroads where clearances are limited and 50 kv for more wide-open railroads like those of the Western U.S.

The overhead line equipment was designed and costed by Bechtel. The system is designed for 70 mph with 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 Figures 2-3 and 2-4.

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

A study of the cost of electrification showed that the cost in 1977 dollars could vary as shown in Table 2-3 (ref 5).
Figure 2-3. Typical Overhead Line Equipment

Figure 2-4. Proposed Catenary Support
TABLE 2-3
RANGE OF ELECTRIFICATION COST FROM REFERENCE 5

<table>
<thead>
<tr>
<th>Estimate</th>
<th>Electrification Cost, 1977 Dollars</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Single Track</td>
</tr>
<tr>
<td>Low estimate</td>
<td>$125,000</td>
</tr>
<tr>
<td>High estimate</td>
<td>$350,000</td>
</tr>
</tbody>
</table>

The costs quoted in Table 2-3 do not include the cost of the conventional utility tie-in associated with railroad electrification. Before it was decided whether a utility tie-in was necessary, the energy supplement study (Item 8) addressed the question of the optimum source of additional energy required to move the ascending train up the hill. Clearly some form of energy supplement is necessary since the energy regenerated by the descending train is subjected to the system inefficiencies (discussed later in this section). Therefore, AiResearch considered four sources of energy supplement:

- Locomotive diesel engine (for the dual-mode locomotive)
- Gas turbine generating unit
- Diesel generator unit
- Utility tie-in

Since the prime object of the WESS program is to save oil, those sources of energy supplement directly dependent on oil products were not favored in principle; however, the economic case for each of the three latter alternatives was investigated, and the results are shown in Table 2-4.

The saving in energy cost of the utility system is compared with the diesel system and has a net present value of $0.8 million, based on the 30-year project life. The clear conclusion reached was that the utility tie-in represented the most economic and energy-efficient source of energy supplement; however, there may be isolated locations where the cost of provision of a utility tie-in exceeds the average value used in Table 2-4 by such a margin that the diesel engine alternative should be considered.

The costs of electrification used in this study (including the utility tie-in, catenary, signalling, and substation) are shown in Table 2-5.

Comparison of Tables 2-3 and 2-5 shows that the electrification costs used in this study are conservative, and this is reflected later in the study when the return on investment for electrification schemes is seen to be lower than figures normally quoted.
**TABLE 2-4**

**EVALUATION OF ENERGY SUPPLEMENT OPTIONS**

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Utility</th>
<th>Diesel</th>
<th>Gas Turbine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat rate/fuel consumption</td>
<td>9500 Btu/kwhr</td>
<td>0.36 lb/bhp hr*</td>
<td>0.42 lb/bhp hr*</td>
</tr>
<tr>
<td>Energy efficiency at generator output terminals</td>
<td>36 percent</td>
<td>32.3 percent*</td>
<td>29.2 percent*</td>
</tr>
<tr>
<td>Energy efficiency at railroad metering point</td>
<td>34 percent</td>
<td>31.6 percent</td>
<td>28 percent</td>
</tr>
<tr>
<td>Daily energy requirement</td>
<td>96 Mwhr</td>
<td>96 Mwhr</td>
<td>96 Mwhr</td>
</tr>
<tr>
<td>Power source capacity</td>
<td>400 Mw</td>
<td>4 Mw</td>
<td>4 Mw</td>
</tr>
<tr>
<td>Fuel</td>
<td>Various</td>
<td>DF2</td>
<td>DF2</td>
</tr>
<tr>
<td>Supply availability</td>
<td>100 percent</td>
<td>95 percent†</td>
<td>98 percent†</td>
</tr>
<tr>
<td>Initial cost</td>
<td>$1,250,000**</td>
<td>$800,000</td>
<td>$1,600,000</td>
</tr>
<tr>
<td>Daily cost</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy cost</td>
<td>$1920</td>
<td>$3034</td>
<td>$3427</td>
</tr>
<tr>
<td>Power cost</td>
<td>$ 838</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Total supply cost</td>
<td>$2758</td>
<td>$3034</td>
<td>$3427</td>
</tr>
</tbody>
</table>

*At rated output
**Based on average cost of tie-ins identified in this study.

**TABLE 2-5**

**ELECTRIFICATION COSTS DERIVED BY BECHTEL FOR THIS STUDY**

<table>
<thead>
<tr>
<th>Electrification Cost/Route Mile, 1977 Dollars</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Track</td>
</tr>
<tr>
<td>238,000</td>
</tr>
<tr>
<td>Two Tracks</td>
</tr>
<tr>
<td>400,000</td>
</tr>
<tr>
<td>Four Tracks</td>
</tr>
<tr>
<td>500,000</td>
</tr>
</tbody>
</table>

2-14
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 or 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 route of Conrail, which is a candidate for 25-kv 60-Hz electrification. All large western railroads (like Union Pacific, Southern Pacific, Santa Fe, Burlington Northern, and Denver and Rio Grande Western) are examples of railroads that will probably continue to be operated by diesel-electric locomotives.

Locomotive Equipment

After a high-voltage ac catenary system is chosen, the locomotive equipment becomes fully defined, and the major elements are:

- Pantograph
- Transformer
- Fully controlled thyristor converter
- Smoothing choke
- Traction motors

A complete description of this equipment is given later in this report.

Flywheel Station Configuration

The choice of interface between the high-voltage ac distribution system and the flywheel is not exclusively defined by the distribution system choice. There are two basic choices for the flywheel machine:

- Dc flywheel machine
- Ac flywheel machine

Initially, a large dc machine was considered for this application, since such a machine places minimal constraints on the converter and is easy to start up. A dc machine in the 10-Mw power range, however, would necessarily operate at a much lower speed than the highly stressed flywheel, which would require reducing gears to be used between flywheel and motor. These gears reduce system efficiency and increase the maintenance requirements of the system. In addition, the dc machine imposes the requirement for brush maintenance. Also, the dc machine with its gearbox would be much larger and heavier than a comparable capacity ac machine and on this basis would adversely influence wayside station cost.
The use of an ac synchronous machine for WESS was found attractive since present commercial designs are available that are suitable for the application. These machines can be provided in brushless configurations and can operate at flywheel speeds, which results in minimal maintenance requirements. The converter required to operate the ac machine is relatively complicated, since it must accept a single-phase, constant-voltage, fixed-frequency input and must deliver polyphase, variable-voltage, variable-frequency power to the flywheel machine. Such a converter, however, is well within the present state of the art. On the basis of these considerations, AiResearch recommends the use of an ac synchronous flywheel machine to operate the flywheel.

The final decisions to be made in the energy transmission system reflect assurance of the compatibility of WESS with the utility and standard railroad electrification. The basic utility requirement concerns the phase unbalance due to the single-phase load demanded by the railroad. Generally phase unbalance is defined as:

\[ \frac{\text{Peak single phase load}}{\text{Utility short circuit capacity}} \times 100 \]

Where utility supplies are found to not be strong enough to meet this requirement, there are two courses of action open: either a second feeder or a solid-state converter can be used as described later.

Usually an electrified railroad makes use of more than one phase and therefore, by definition, the flywheel converter must have the capability of accepting more than one phase as input before reconfiguration to variable-frequency, three-phase output to the flywheel machine. The optional schemes available are shown diagrammatically in Figures 2-5 to 2-11.

Figure 2-5 shows a system that is not compatible with normal railroad electrification, since it involves the use of a variable-frequency catenary, the frequency being determined by the flywheel speed. This system was disregarded due to the difficulties in providing electrical equipment suitable for the frequency operating range. In particular the locomotive transformer would require sizing for the lower frequency, which would impose unnecessary restraints when it is considered that this system does not reduce the hardware requirements when compared to the systems considered below.

The system shown in Figure 2-6 is compatible with standard mainline electrification. The catenary has the same phase either side of the neutral section and therefore direct regeneration from one locomotive to another is possible without involving the flywheel converter. This system is compatible with the Black Mesa and Lake Powell Railroad system. The system shown in Figure 2-7 is identical to that of Figure 2-6 except that a converter is used to ensure full balance of the railroad load at the 3-phase utility tie-in.

Figure 2-8 shows the typical railroad electrification using more than one phase with unbalance at the utility. The regenerating locomotive returns energy to the flywheel converter, where it is either phase shifted and returned to a receptive locomotive or reconfigured to 3-phase variable frequency and supplied to the flywheel machine. Figure 2-9 shows the same system with the addition of a utility balance converter.
Figure 2-5. WESS High-Voltage Ac Regeneration System Option 1: Variable-Frequency Catenary
Figure 2-6.  NESS High-Voltage Ac Regeneration System Option 2: Constant-Frequency, 1-Phase Catenary (Unbalance at Utility)
Figure 2-7. WESS High-Voltage Ac Regeneration System Option 3: Constant-Frequency, 2-Phase Catenary (Unbalance at Utility)
Figure 2-8. WESS High-Voltage Ac Regeneration System Option 4: Constant-Frequency, 1-Phase Catenary (Balance at Utility)
Figure 2-9. WESS High-Voltage Ac Regeneration System Option 5: Constant-Frequency, 2-Phase Catenary (Balance at Utility)
Figure 2-10. WESS High-Voltage Ac Regeneration System Option 6: Constant-Frequency, 1-Phase Catenary (Balance at Utility)
Figure 2-11. WESS High-Voltage Ac Regeneration System Option 7: Constant-Frequency, 2-Phase Catenary (Balance at Utility)
The converter logic for the above schemes requires subcyclic decision-making; that is, at each instant in time the converter must be able to decide whether energy should be returned to the catenary, the flywheel machine, or the utility. This represents an expensive addition to the converter and, to minimize costs, a method of avoiding the subcyclic decision process was considered.

The systems avoiding subcyclic decisions for one- and two-phase catenaries are shown in Figures 2-10 and 2-11. Essentially the flywheel machine is allowed to absorb the energy of each half-cycle so that, if conditions change during the half-cycle, the converter is not required to redirect the energy during that period. Therefore subcyclic decisions are not required. To achieve this, however, an additional converter is required for the normal railroad two-phase catenary, and therefore the cost of converter equipment is higher than for the subcyclic decision converter.

Therefore, the basic decision was to use the system shown in Figure 2-7. The transformer coupling the utility to WESS is a three-phase to two-phase connection designed by Gibbs & Hill (Figure 2-12) that has been demonstrated in service at the Cos Cob substation of the Northeast Corridor. This transformer connection has been shown to be superior in operation to the familiar Scott-connected tee arrangement commonly used for three-phase to two-phase transformation.

SYSTEM EFFICIENCY

A critical characteristic of the WESS system is its efficiency. After the optimum system shown in Figure 2-7 was defined, the overall system efficiency was determined as described below.

The system comprises three discrete subsystems:

- Locomotive
- Distribution
- Flywheel station

Each subsystem may be considered separately.

Locomotive

The mechanical energy available at the wheel of a braking locomotive passes first through the traction motor assembly (comprising gears and a traction motor), where electrical and mechanical losses result in an energy loss that is speed- and load-dependent. Figure 2-13 shows the efficiency curve for the D77 traction motor as published by EMD. It can be seen that typically the efficiency of the motor assembly is 90 percent.
Figure 2-12. Gibbs and Hill Three-Phase/Two-Phase Transformer Connection
Figure 2-13. D77 Traction Motor Characteristics for 3000-hp SD40 Locomotive
The energy, now in electrical form, passes from the traction motor to the converter, where a forward voltage drop of 1.5 V per device occurs. This results in a converter efficiency of 98 percent. Losses in the locomotive transformer during step-up in voltage to 25 or 50 kv are load dependent but may be assumed typically to result in an efficiency of 96 percent. Therefore, the overall efficiency of the locomotive regeneration system is 84.6 percent. Similarly 84.6 percent of the energy derived from the pantograph during propulsion is delivered to the locomotive wheels as useful energy.

**Distribution System**

From the locomotive pantograph to the flywheel station energy losses are dependent on load and distance from the feeder point. Typically an efficiency of 96 percent is reasonable.

**Flywheel Station System**

Electrical energy from the distribution system received at the flywheel station is reconfigured from 25-/50-kv, single-phase, 60-Hz supply to 25-/50-kv, three phase, variable-frequency (flywheel speed dependent) supply. The losses in the converter are load dependent. Losses in the flywheel machine are load and speed dependent. On a typical duty cycle the efficiency at the flywheel converter and machine is estimated to be 96 percent.

The losses in the flywheel (bearing and air friction, ancillaries, etc.) amount to 1.5 percent per hr at full speed and 0.5 at half speed. Therefore the efficiency used in this study (99 percent) represents a conservative estimate.

The system efficiency diagram is shown in Figure 2-14. Consideration of the overall system shows system efficiency at 60 percent. That is, 60 percent of the energy available at the wheel of the descending train is available for reuse at the wheel of a subsequent ascending train.

The typical figures for efficiency derived here were not used in the detailed calculations made later in the study.

**OPERATIONAL CONSTRAINTS**

During the study AirResearch had many discussions with railroads, from which a number of operational constraints appeared. These constraints are addressed below.

**Adhesion**

A great deal of research has been undertaken by various organizations around the world in an attempt to understand railroad adhesion and its characteristics. The deployment of WESS demands that, whichever option is adopted, a fully controlled thyristor bridge circuit is used to control the traction motors. This enables the question of the assumed adhesion level to be re-examined and designs to be optimized.

The advent of the thyristor has enabled traction engineers to assume tractive effort/axle load ratios that would not have been considered a few years before. A steep tractive effort/speed curve was an advantage when an axle slipped. If the curve was steep enough, spontaneous recovery of adhesion resulted.
Figure 2-14. WESS Storage System Efficiency
The use of thyristors (either in the main power circuit or in field control, or both) facilitates individual motor control, which eliminates the difficulty in ensuring equal distribution of current values between sets of motors. Then when slipping does occur, the action taken is limited only to the motor affected and does not entail a general reduction of current in the other motors with consequent loss of tractive effort.

To operate at the practical limit of adhesion it must be possible to vary the firing angle of the thyristors rapidly and frequently. Unlike mechanical systems involving moving contacts, variation of the firing angle involves no wear and does not in any way affect the life of the thyristor. This fact has fundamental implications as regards the ideal system of regulation for making optimum use of existing adhesion.

With individual supply to the motors, no constraints are encountered other than those related to the difference in wheel diameter permitted by the user railroad. This is not a major problem since, with the thyristor, each motor can be operated at the limit of adhesion.

The thyristor, with good slip correction and current regulation, makes it possible to dispense with all the ingenious mechanical and electrical devices designed to offset weight transfer (which is a product of the tractive effort and coupler height and can never be eliminated altogether). Once speed builds up, it should be realized that axle loads vary quite appreciably anyway. Consequently, all the devices intended to improve weight distribution under quasi-static conditions have little real effect during conditions of normal running. The benefit of individual axle control, as applied to a typical U.S. locomotive, is analyzed later in this report.

It is generally stated that the adhesion of an electric locomotive is greater than that of a diesel; this is incorrect. If the electric transmission were to be treated similarly in the two types of locomotive, the same results would be obtained in terms of the use of adhesion. In any case it must not be said that a type of locomotive has "an adhesion of X percent." No locomotive can "produce" adhesion: all that can and should be expected is that the locomotive makes optimum use of the adhesion existing between wheel and rail. If there is six percent adhesion available between rail and wheel, no locomotive can extract more.

The only way to raise the adhesion coefficient in particularly unfavorable conditions is by putting down sand, or perhaps cleaning the rail with a chemical. Sanding is very efficient, and can be combined with the anti-slip function. The extremely sophisticated automatic devices now available are able to decide for themselves when to introduce foreign matter, whether sand or something else.

It is considered, therefore that, in view of the foregoing an adhesion level of 22 percent may be assumed for separately excited, thyristor-controlled motors, using creep prediction techniques for both dual-mode (electric/diesel) and electric locomotives.
Head-End Brake Limitation

Because the dynamic brake concentrates the braking force and braking power at the head end of the train, there are practical limits concerning the amount of braking that can be achieved with the dynamic brake alone. The ideal situation for WESS is to have the locomotive units do all the braking; however, the division of the braking work done by the cars and the locomotive units equipped with regenerative brake is important in order to obtain the best train operation in any particular situation. In practical terms, it has been found that from 200,000 to 240,000 lb of retarding force concentrated at the locomotives is the most that should be used when going through turnouts, into and out of passing tracks, and on sharp curves (ref 6). A large consist of modern diesel engine units has the capability of producing considerably more than 240,000 lb of retarding force with the dynamic brake. Caution must be exercised in the amount of dynamic brake that is to be used not only for grade braking operations, but also for assisting the slowdowns and stops.

The limit as to the number of axles and motors in dynamic braking for reliably safe operation depends upon:

(a) Type of equipment. Units with pin type couplers and no alignment control features must have bolster stops applied to allow operation in consists with units capable of high dynamic braking effort. The bolster stops limit bolster-to-truck-frame lateral clearance to 1/2 in. on each side, thereby limiting lateral rail forces when units are subjected to buff loads.

(b) Particular track profile conditions.

(c) Engineer's skill.

(d) The practical limit for dynamic brake is often stated as "no more than 24 motorized axles may be operated in dynamic brake from the lead locomotive of the consist".

Calculations of power and energy regenerated during braking must take into account this limitation. When necessary the required brake force could be achieved by adding helper locomotives part way down the train or using the air brake to supplement the dynamic brake.

It is proposed that the brake force developed by any group of locomotives modified for WESS operation will be automatically limited to 240,000 lb to enable braking effort to be developed by a remote group of locomotives as required. In the calculation of power and energy for this study, the head-end braking force was limited to 210,000 lb.

Axle Load Limitation

While it is recognized that axle loads should be kept to a minimum to reduce track and truck maintenance, it has been considered reasonable to assume the current maximum axle loads when calculating usable tractive effort. The maximum static axle load assumed for performance calculations was 68,300 lbf.
Dedicated Locomotives

Railroad operations depend on flexibility: the ability to be able to send any locomotive anywhere at any time. It is recognized that most railroads prefer to keep certain locomotives operating within specific divisions but these are not necessarily dedicated locomotives since they have the ability to go anywhere at any time as required. Therefore, any scenario developed for WESS that requires modifications to existing locomotives or the introduction of new locomotives, with neither able to operate outside a small specific route, would probably have difficulty in gaining acceptance by the railroads. The key to the problem is probably found in the size of the route to which locomotives must be restricted in relation to the amount of through traffic.

As a general rule it has been assumed in this study that a diesel-locomotive fleet may, under normal conditions, be restricted to operate between two nominated classification yards. When a service disruption occurs the dedicated fleet may be used anywhere on the system, and standard locomotives are able to use the routes where WESS is deployed (without, of course, the benefit of WESS).

Electric locomotives, of course, are constrained to operate in electrified areas only.

Examples of routes that are assumed to accept dedicated fleets are:

- Harrisburg-Pittsburgh
- Los Angeles-Salt Lake City
- Salt Lake City-Omaha
- Los Angeles-Belen
- Colton-El Paso
- Sacramento-Ogden

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. Communications are handled by microwave data link and/or open-wire overhead lines where relatively long distances are encountered. 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 for electrification. The electromagnetic and electrostatic fields developed by a catenary system can, and usually do, induce currents and voltages in signaling and communications systems closely associated with railroad operations that are adverse to operations. The source and effects must be considered and appropriate action taken to keep these effects within tolerable limits.

2-31
The electrification analysis undertaken by Bechtel included consideration of the modification of the existing signalling systems on the specific routes in question. The AT&SF and UP routes are presently signalled with dc track circuits and therefore require replacing with 100-Hz or 92-2/3-Hz circuits to achieve compatibility with electrification at 60 Hz. The track circuit lengths will be reduced to about 1 mile, which is about the maximum length for satisfactory operation of track circuits under electrified sections, to keep the induced voltage to acceptable levels.

Electrification

It has been established (ref 7) that most of the grades suitable for WESS are on routes that are considered possible candidates for future electrification (Figure 2-15 shows those major U.S. routes). This is hardly surprising since both WESS and electrification require a high traffic flow to be cost effective. This reinforces the case for constraining the WESS system to be compatible with the mainline electrification systems proposed for use in the U.S. and other interested countries.

All of the major railroads contacted have performed electrification studies on routes that were later identified as WESS routes (that is, routes with many WESS candidate grades). The economics of such a major capital investment, however, have not yet been shown to be attractive enough to justify the funding level required. As will later be demonstrated, the inclusion of WESS in an electrification program significantly enhances the economics of railroad electrification.

Operating Scenarios

Within the total system design, three operating scenarios have been identified. It is essential that the interface between the new and existing systems result in the minimum disturbance to either system. The operating scenarios are:

(a) Dual-Mode Locomotive—Under normal operations the routes under consideration are assumed to be operated by dual-mode locomotives, which are 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.
BASE NETWORK

ROUTES WITH SUITABLE CHARACTERISTICS
FOR ELECTRIFIED OPERATIONS

HIGHEST DENSITY ROUTES
(GENERALLY >40 MGTW/M-YR)

OTHER HIGH DENSITY ROUTES

Figure 2.15. Proposed National Electrified Network
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 railroads to gain electric operation experience before committing themselves to very large investments.

(b) Electric Helper--When ascending/descending a WESS grade, the motive power comprises diesel locomotives with the addition of up to two electric locomotives. The latter are designed for high tractive effort and limited-speed, high-power, 50/25-kvac, 60-Hz operation. 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 to take account of travelling time to and from the possibly remote location of the WESS grade.

(c) 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), if such a system is provided (see below).

The three scenarios described above are summarized in Table 2-6. 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 will also be clear that the true cost of adoption cannot be considered on a grade-by-grade basis since locomotive fleet sizes depend on traffic flows between classification yards.

Operational Procedure

The scenarios defined in Table 2-6 may, as far as operational procedure is concerned, be divided into the two types as described below.

1. Through Working of Motive Power

This applies to scenarios 1 and 3. In all cases there is no action required by the engineer on arrival at the WESS site. Where necessary the pantograph will be automatically raised using track magnets. When voltage has been established at the transformer secondary, the control equipment will cut off the power from the diesel engine and reduce the engine to a speed at which it is able to supply auxiliary loads. The traction and auxiliary power will be supplied from the transformer. This state will continue until the flywheel is fully charged,
### TABLE 2-6

**SUMMARY OF WESS SCENARIOS**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Whole Route Electrified</th>
<th>New Vehicles Required</th>
<th>New/Modified Vehicles Usable on Other Routes</th>
<th>Additional Operating Labor Required</th>
<th>Diesel Locomotives Saved</th>
<th>Special Stops Required</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Dual-Mode</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>2 Electric Helper</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>3 Electric Railroad</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

at which time power will be supplied from the utility. As a regenerating locomotive enters the section, direct energy transfer may take place. On arrival at the end of the WESS-equipped section, the pantograph will be automatically lowered in a sequence initiated by a track magnet and diesel power will be restored.

In the case of the electrified railroad, the engineer will follow normal rules and methods of operation and will have no visible indication of whether the train is regenerating to the flywheel, to another train, or to the utility; and similarly he will have no indication of the source of the power. It is proposed that a light should be provided to indicate to the engineer when rheostatic brake is in operation.

2. **Change of Motive Power at a Grade**

This applies only to scenario 2. Consider a typical single-track layout:

![Diagram](image)

The track would be electrified from A to B, including the sidings, which are those sidings nearest to the extremities of the grade. The train with the electric locomotive leading departs from A and the electric locomotive performs its duty as an interface with the distribution system. On arrival at the signal at B the train halts, and the electric locomotive is uncoupled and draws forward onto the siding where it either couples immediately to a waiting train or waits for an A-bound train to arrive. It is expected that a crew of two would be permanently occupying the electric locomotive. The train from A is now cleared to carry on its journey. When the A-bound train arrives, the
electric locomotive is coupled and then departs, and on arrival at A the uncoupling procedure is repeated. To handle two consecutive trains in the same direction, a storage siding is required to store the spare electric locomotive. The principle of operation for a double-track line is the same.

On routes where a number of grades exist but which are so far apart that the track in between has not been electrified, the procedure adopted would be as follows.

The train departs A as above but at the approach to the end of the electrified section, the pantograph is automatically lowered by track magnets and the diesel engines take over completely, supplying the train power requirements. On arrival at the next electrified section of track, the pantograph is automatically raised, and the electric locomotive again interfaces with the distribution system.

At the final electrified section the electric locomotive uncouples as described above.

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 only be used to optimize peak shaving. The benefit of WESSCOM would then be the difference between a best guess at the required average demand and the computer-predicted average demand.

A utility tie-in is not essential to the railroad/WESS operation in scenarios 1 and 2. The cost of provision of such a tie-in was considered against the anticipated benefits in the study. In cases where it is decided against having the utility tie-in, it is imperative that the flywheel is 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, but the resulting loss in power and delay before diesel power was available would be unacceptable. 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.

Such a system is commercially available from the Reliance Electric Company based on the Automate 31ML Programmable Controller. A flow diagram for the system is shown in Figure 2-16.
Figure 2-16. WESSCOM Flow Diagram
The microprocessor, located at each flywheel station will be programmed to accept the following inputs:

- Estimated train arrival time (ETA)
- Train weight
- Train direction
- Train identification code

Time of arrival would initially be inputted by the dispatcher, but to provide for unforeseen delays en route, provision will be made in the system for automatic and manual update of the arrival time at subsequent WESS stations as each station is encountered. Train weight, direction, and identification code would be entered by the dispatcher at the commencement of the journey.

With the above inputs the microprocessor will be able to compute the optimum demand from the utility tie-in to ensure that the flywheel is at the necessary speed for energy to be provided to an ascending train without incurring an unnecessarily high demand peak. If the flywheel is predicted to be at too high a speed to accept all the energy available from a descending train, then one of two actions will be taken. If the utility is receptive, energy could be returned to the utility (even if no credit is received). The second option is to accept that the locomotive resistor brake and/or air brake will be required for at least part of the descent.

The first option is preferred but is dependent on utility receptivity. If the utility is not receptive, a signal will be transmitted to the regenerating locomotives as the flywheel approaches full speed. This will enable the engineer to reduce electrical braking and apply (or increase) air braking.

Wayside flywheel assembly fault indication will be provided as an output from the microprocessor and will include the following:

- Vibration—Accelerometers will be used to sense vibration levels and give a warning of impending failure.
- Oil Characteristics—Oil pressure and temperature.
- Oil Pump Status—Main or back-up pump running.
- Vacuum—Within specified limits.

Based on the actual time the train leaves the WESS site, the revised estimated time of arrival at the next site will be calculated based on the train weight (since the microprocessor has been programmed with the route data) and transmitted to the succeeding WESS stations. The cost of this system would be $6000 per site and approximately $20,000 for the initial programming.

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.

For the diesel-electric railroad that is converted to dual-mode, probably the greatest impact will be in the provision of maintenance facilities, although this will be minimal. There are three impact areas surrounding the maintenance function:

- **Retraining**—As with the introduction of any new equipment, maintenance personnel will require training in fault-finding techniques and general maintenance requirements.

- **Spares holding**—Due to the reduction in fleet size (described later in this report), the level of diesel spares will be reduced but this will be offset by the spare equipment required for the electric traction mode.

- **Maintenance Equipment**—Existing lifting equipment will be suitable for the electric traction equipment. A transformer oil test facility, however, will be required at each major maintenance facility.

A common practice nowadays is the running through of locomotives from one railroad to another. The concept of the dual-mode locomotive or a newly electrified railroad would reduce the financial incentive to continue this procedure. Therefore, additional work will be required at the classification yards at the extremities of the WESS and/or fully electrified route to change motive power that previously would have worked through to the train's final destination.

**MOTIVE POWER**

In this study all calculations and design studies have assumed only continuous ratings. Advantage is not taken of short-term ratings that could distort the findings of the study.

**Dual-Mode Locomotives**

The system concept of a high-voltage ac catenary was shown to be highly compatible with a dual-mode locomotive. The background, description, and cost of modification of an existing diesel-electric locomotive to a dual-mode configuration is described in this section. The locomotives selected for the modification that will be described are the General Motors Electro-Motive Division (EMD) models SD40 or SD40-2, which are the present workhorses of U.S. freight railroad operations. These modifications have been reviewed with the technical staff of EMD. Similar modifications can be made with other locomotives such as the GE model C-30.

The concept of dual-mode traction equipment is not new since the problem of interfacing electrified and non-electrified railroads has existed since the first electric railway started operation. Normally the problem is one of economic viability, and the operator is forced to accept the operating restrictions of dedicated motive power units. Advancing technology has enabled higher
power/weight and power/volume ratios to be developed that have resulted in
the increased viability of the dual-mode locomotive and multiple unit.

Usually it is accepted that when on the "secondary mode," operation will
be at a reduced performance. This will not be the case for the converted
diesel locomotives. It is intended to operate up to the known limit of the
traction motors when on electric (secondary) mode, rather than be limited by
the prime mover as is the case for the diesel (primary) mode.

The dual-mode locomotive design is such that the motive power will be
derived from either the diesel engine or the catenary, never both together,
thus avoiding causing distress to the alternator by the introduction of
harmonics.

To establish which existing diesel locomotives should be considered for
modification it was first necessary to determine the population of road
locomotives in the U.S. This is shown in Table 2-7.

It can be seen that by far the most popular road locomotive is the SD40
(and SD40-2, which does not differ significantly as far as this study is
concerned from the basic model). Therefore the major effort in this study
was concentrated on the SD40 locomotive, although cursory checks of the
DD-40-X, SD45, and SD38 showed that those locomotives were also candidates
for the modification.

1. Modification Principles

The basic principle of this modification is to use the existing equip­
ment, modified as necessary, and to provide the minimum of new equipment
compatible with satisfactory operation.

To commence the feasibility study it was first necessary to determine
the equipment required to achieve the secondary mode. A simplified schematic
is shown in Figure 2-17. Current is taken from the catenary via the panto­
graph through a high-voltage circuit breaker incorporating a grounding switch
to a transformer (protected by a lightning arrester). The low-voltage output
from the transformer is conditioned in a thyristor converter (phase delay
rectifier) to give irregular pulses of variable-voltage dc. A smoothing
choke is required to reduce the ripple to a level acceptable to the traction
motors.

Therefore the equipment to be accommodated on the existing locomotive
comprises:

• Roof equipment
  Pantograph
  Circuit breaker
  Grounding switch
  Lightning arrester
<table>
<thead>
<tr>
<th>Railroad</th>
<th>DD-40-X</th>
<th>SD45</th>
<th>SD40 &amp; SD40-2</th>
<th>EMD 2500-to 3000-hp Range</th>
<th>Other Locomotives</th>
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</thead>
<tbody>
<tr>
<td>Atchison, Topeka, &amp; Santa Fe</td>
<td>-</td>
<td>254</td>
<td>48</td>
<td>188</td>
<td>87</td>
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<tr>
<td>Burlington Northern</td>
<td>-</td>
<td>220</td>
<td>147</td>
<td>45</td>
<td>319</td>
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<td>-</td>
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<td>79</td>
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<tr>
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<td>53</td>
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<td>-</td>
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<td>34</td>
<td>132</td>
</tr>
<tr>
<td>Western Pacific</td>
<td>-</td>
<td>-</td>
<td>43</td>
<td>19</td>
<td>20</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>47</td>
<td>1340</td>
<td>2169</td>
<td>1150</td>
<td>2174</td>
</tr>
</tbody>
</table>
Before equipment sizes could be determined, it was necessary to establish the performance required from the locomotive. Currently the SD40 locomotive is limited in the power it can produce by its prime mover, the diesel engine, to 2600 rail horsepower. The tractive effort of the SD40 is limited by its traction motor (under the conditions considered), which has a continuous rating of 1050 amp. The power available for traction (that is the rail horsepower) is derived from Figure 2-18 as follows:

<table>
<thead>
<tr>
<th>Component</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine output</td>
<td>3100</td>
</tr>
<tr>
<td>Auxiliaries</td>
<td>40</td>
</tr>
<tr>
<td>Alternator loss (4 percent)</td>
<td>122</td>
</tr>
</tbody>
</table>

2. Locomotive Performance

Figure 2-17. Secondary Mode Simplified Schematic
Rectifier loss (2 percent) 59 hp
Traction motor assembly loss (10 percent) 288 hp
Power available to rail 2590 rail horsepower (rhp)

The published rating of the EMD D77 traction motor (the motor used in all the EMD road locomotives) is approximately 720 shp (input), giving a total traction motor power capability of 4000 rhp. For this study it was considered appropriate to take advantage of the surplus traction motor capability and rate the locomotive in the secondary mode at 4000 rhp.

The D77 traction motor, having been modified to improve heat dissipation by fitting aluminum conductors, has a continuous current rating of 1050 amp. From Figure 2-13 it will be seen that the tractive effort available at that current is 13,780 lb. Therefore the secondary mode characteristic is defined and is shown in Figure 2-19, where it is compared with the existing or primary mode performance.

3. Secondary Mode Equipment

After the desired power rating was established, the next task was to establish whether the equipment could be located satisfactorily on the locomotive.

a. Roof Equipment

It is proposed that the roof equipment consisting of a pantograph mounted on standoff insulators, vacuum circuit breaker, grounding switch, lightning arrestor, and high-tension cable through bushing will be mounted on an extended cab roof. A typical layout of roof equipment for an electric locomotive is shown in Figure 2-20. The cab roof will need to be strengthened to afford protection to the crew in the event of a mishap involving the forcing down of the pantograph toward the cab area.

b. Body Equipment

There are two potential space envelopes available in the SD40 locomotive in which the body-mounted equipment (transformer, thyristor converter, and smoothing choke) may be mounted. Those spaces are in the short front hood (Figure 2-21) and the compressor compartment (Figure 2-22).

To avoid dilution of the main effort of the study by making detailed design studies of the various required components, a survey of equipment ratings and physical sizes was conducted. The following information sources were used:

(a) General Electric E42C—Currently being delivered to the Taiwan Railway Administration (TRA)
(b) General Motors JM4C—Locomotive designed but never built
(c) GE Traction 87101—Thyristor locomotive built in 1974 for British Rail
IITAKE TEMPERATURE - 60°F
BIOMETER PRESSURE - 29.4" HG.
FUEL SPECIFIC GRAVITY - 0.879
API GRAVITY - 29.5°
LOWER HEATING VALUE - 133.000 BTU/GAL.
FUEL WEIGHT - 7.318 LBS. PER GAL.

Figure 2-18. Performance of 16-645E3 Engine on SD40-2 Diesel Locomotive (Ref 4)

Figure 2-19. Proposed Locomotive Characteristics for WESS Dual-Mode Locomotive, Based on Continuous Ratings
Figure 2-20. Electric Locomotive Roof Equipment

Figure 2-21. SD40 Short Hood Compartment
Figure 2-22. SD40 Compressor Compartment
Transformer sizes are shown in Table 2-8.

<table>
<thead>
<tr>
<th></th>
<th>General Electric 42C</th>
<th>General Motors JM4C</th>
<th>GEC Traction 87101</th>
<th>GEC Traction (TRA-BB)</th>
<th>BR Class 88</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power rating</td>
<td>4000 rhp</td>
<td>4000 rhp</td>
<td>6561 rhp</td>
<td>3000 rhp</td>
<td>5550 rhp</td>
</tr>
<tr>
<td>Input voltage</td>
<td>25 kv</td>
<td>25 kv</td>
<td>25 kv</td>
<td>25 kv</td>
<td>25 kv</td>
</tr>
<tr>
<td>Catenary frequency</td>
<td>60 Hz</td>
<td>50 Hz</td>
<td>50 Hz</td>
<td>60 Hz</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Height</td>
<td>58 in.</td>
<td>54 in.</td>
<td>75 in.</td>
<td>64 in.</td>
<td>43 in.</td>
</tr>
<tr>
<td>Width</td>
<td>48 in.</td>
<td>48 in.</td>
<td>43 in.</td>
<td>36 in.</td>
<td>60 in.</td>
</tr>
<tr>
<td>Length</td>
<td>64 in.</td>
<td>108 in.</td>
<td>75 in.</td>
<td>56 in.</td>
<td>74 in.</td>
</tr>
<tr>
<td>Volume</td>
<td>116 cu ft</td>
<td>195 cu ft</td>
<td>140 cu ft</td>
<td>75 cu ft</td>
<td>110 cu ft</td>
</tr>
<tr>
<td>No. of secondaries</td>
<td>6 + 2</td>
<td>6 + 2</td>
<td>4 + 2</td>
<td>4 + 2</td>
<td>4 + 2</td>
</tr>
</tbody>
</table>

The number of secondaries in Table 2-8 refers to the number of traction and auxiliary windings. Therefore 6 + 2 refers to 6 traction secondaries and 2 auxiliary secondaries.

The space available in the short hood section is 54 (H) by 48 (L) by 72 in. (W). The data gathered showed that this space would not be sufficient; however, it is possible to extend the length of the short hood an additional 12 in. to accommodate the transformer without causing an obstruction (see Figure 2-23).

The inspection of Table 2-8 was made against the background that certain fundamental relations exist between the kva ratings of transformers and their physical size and performance; for example, larger transformers are inherently more efficient than smaller units. To simplify the problem of deriving the relations, the following assumptions were made:

- Constant physical proportions
- Constant current density in the copper
- Constant flux density in the iron
Figure 2-23. Short Hood of SU40 Locomotive

Figure 2-24. Size and Performance Relations to Rating of Transformers
Because in practical designs these factors are only approximately constant over a limited range, actual transformers follow these relations only approximately. Where the difference in kva rating is not too great, the relations are sufficiently accurate for estimating purposes. These relationships are shown graphically in Figure 2-24. Furthermore the transformer decreases in volume approximately in proportion to the frequencies at which it is designed to operate, within the 50- to 60-Hz variation under consideration.

Consideration of Table 2-8 and Figure 2-24 led to the conclusion that the dual-mode locomotive transformer could be housed in a volume 54 (H) by 60 (L) by 60 in. (W) giving a total volume of 112 cu ft. This conclusion was reinforced when, as described later in this section, the decision was made to have two secondary traction windings and one secondary auxiliary winding on the transformer.

The thyristor converter size was based on the General Electric E60C locomotive, since this is the only locomotive for which size information was readily available. The E60C converter has a total volume of 56 (H) by 12 (W) by 48 in. (L) to give 12.5 cu ft. AiResearch determined that in the compressor compartment of the SD40 a space 48 (H) by 72 (W) by 46 in. (L) (giving a volume of 24 cu ft) was available.

The sizes of smoothing chokes currently in use are given in Table 2-9.

<table>
<thead>
<tr>
<th>TABLE 2-9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical Smoothing Choke Sizes</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>General Electric E42C</th>
<th>General Motors JM4C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power rating</td>
<td>400 hp</td>
<td>4000 hp</td>
</tr>
<tr>
<td>Input voltage</td>
<td>25 kv</td>
<td>25 kv</td>
</tr>
<tr>
<td>Catenary frequency</td>
<td>60 Hz</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Height</td>
<td>32 in.</td>
<td>34 in.</td>
</tr>
<tr>
<td>Width</td>
<td>32 in.</td>
<td>48 in.</td>
</tr>
<tr>
<td>Length</td>
<td>102 in.</td>
<td>108 in.</td>
</tr>
<tr>
<td>Volume</td>
<td>60 cu ft</td>
<td>102 cu ft</td>
</tr>
</tbody>
</table>

AiResearch determined that in the compressor compartment of the SD40, a space 48 (H) by 72 (W) by 46 in. (L) (giving a volume of 92 cu ft) was available.
It should be remembered when comparing sizes of equipment for a given power rating that the generous width of the U.S. gage does not normally impose serious constraints on equipment size, and therefore it is probable that equipment sizes may be reduced further from those given for the dual-mode locomotive following a concerted design effort.

4. Power Circuit

A simplified power schematic was shown in Figure 2-17. The dual-mode locomotive has a full regenerative capability in the secondary mode, which necessitates the use of a fully controlled thyristor converter bridge (see Figure 2-1), whereas a nonregenerative thyristor-controlled locomotive requires a half-controlled bridge. The usual fully controlled bridge configuration suffers from the distinct disadvantage of having to operate at a very poor power factor due to the fact that there is no freewheeling path to ensure device commutation. The AiResearch circuit overcomes this inherent disadvantage by continuously gating thyristors T3, T4, T7, and T8 of Figure 2-17 when operating in the propulsion mode and therefore providing the necessary freewheeling path.

The simple transformer/converter arrangement chosen enables the volume occupied by those components to be minimized. Full control of each individual axle is maintained by the use of separately excited traction motors.

In the braking mode, it is essential to have a continuous path for the braking current; however, the pantograph does not maintain continuous contact with the catenary. Pantograph bounce occurs even at the relatively low speeds under consideration (maximum 70 mph). It is also necessary to have an instantaneously available alternate path for the braking current in the event of the wayside flywheel reaching maximum speed and no longer being receptive. These requirements are achieved by use of the stabilizing resistor circuit shown in the schematic of Figure 2-17. In the event of pantograph bounce or nonreceptivity, thyristor T9 is gated and energy is dissipated in the existing dynamic brake resistor. Since the traction motors are separately excited, field control eliminates the need for the extended range dynamic brake feature. During pantograph bounce, the T9 thyristor may be gated for up to an hour. This blending feature is an extension of the Garrett chopper circuit (see Figure 2-25) technology developed and proved for use on transit cars.

5. Traction Motors

Because all motors are controlled by a single thyristor converter, this configuration does not provide the flexibility desirable in the event of a fault developing or wheel spin unless a separately excited motor configuration is adopted. The decision to adopt the separately excited motor configuration was a tradeoff based on the need to minimize the transformer size. While separately excited motors have advantages over the series field machine, there are serious risk areas that must be addressed and accommodated in the circuit design and analysis.

The series field machine is inherently self-protecting in the event of a flashover. The field provides inductance in the faulty motor leg to limit the rate of rise of current while the protection equipment is operating. The
The series field machine is the simplest machine configuration available, relying on the applied voltage to overcome the armature back emf and supply current that is used to provide magnetic flux and torque. There are two mechanisms by which the field strength can deviate from the designed value for a given armature current:

(a) Field winding shorted

(b) Field weakening fault (contactor welded)

For the separately excited machine, it is still possible to have the field winding short as in the case of the series machine but the possibility of the field control malfunctioning is increased by sheer component count of the power supplies required to control the fields.
A decision as to whether to use separately excited or series field machines can only be made following an in-depth analysis of the dual mode locomotive.

6. Weight Transfer Compensation

If individual axle control is provided, this will enable the tractive effort applied at each axle to be matched to the dynamic axle load. Typical weight transfer characteristics of a C-C locomotive are shown in Figure 2-26.

![Diagram of locomotive](image)

Figure 2-26. Typical Weight Transfer Characteristics of a C-C Locomotive

Currently all railroads contacted (with the exception of Conrail) dispatch their locomotives on the basis of 20-percent adhesion (see para. 4, "Railroad Dispatching Policy", at the end of this section). The adhesion value used is defined as:

\[
\text{Effective } \mu_{\text{max}} = \frac{T}{0.86 \frac{W}{6}}
\]

where \(\mu_{\text{max}}\) = coefficient of friction at lightest axle.
Therefore, without increasing the maximum effective adhesion level, the tractive effort for the dual mode locomotive becomes

\[ \sum_{\text{axle } 1} \left( \frac{T}{0.86 \text{ W}} \right) \times \text{dynamic axle load} \]

\[ \sum_{\text{axle } 6} \left( \frac{T}{0.86 \text{ W}} \right) \left[ \frac{0.92 \text{ W}}{6} + \frac{0.94 \text{ W}}{6} + \frac{1.14 \text{ W}}{6} + \frac{0.86 \text{ W}}{6} + \frac{1.06 \text{ W}}{6} + \frac{1.08 \text{ W}}{6} \right] \]

\[ = \frac{6T}{0.86} = 6.977T \]

Therefore, increase in available tractive effort per locomotive:

\[ = 6.977T - 6T \]

\[ = 0.977T \]

Therefore, for the SD40 based dual-mode locomotive with separately excited motors, the tractive effort available for the same adhesion level may be increased by 16 percent compared with the standard locomotive.

7. Locomotive Reliability

The circuit configuration used for the electric mode is not that which would normally be chosen for a road locomotive, since if a fault occurs on the converter, power will be lost to all motors. Normal practice is to provide at least two independent power circuits so that in the event of a fault a minimum of 50 percent power is maintained; however, since in the event of an electric mode failure the diesel engine is available to provide power (albeit reduced), this tradeoff against equipment size is considered satisfactory.

8. Dual-Mode Conversion Cost

A statement of work has been prepared for the modification of the SD40 and SD40-2 locomotives to dual mode, and is attached as Appendix A. Based on this statement of work a cost estimate has been prepared and is attached as Appendix B. This shows that the total cost for a railroad to carry out the modification would be $211,000.

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 2-27. The
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. This results in an estimated cost of $1,071,000 for a 5100-rhp 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 cost of modifying new E60 locomotives as described above was reviewed with the GE Locomotive Department. 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.
No change is proposed to the locomotive performance in the propulsion or resistor braking modes. The proposed regenerative braking characteristic is shown in Figure 2-28, where the limitation on the existing braking effort imposed by the resistor grids is removed.

**Locomotive Fleet Size**

Before the benefit of a reduction in fleet size could be quantified, it was first necessary to establish the size of the existing locomotive fleet required to operate a particular route with a known traffic level. Initially an attempt was made to get the information from the cooperating railroads, but it was found that the determination of this information would take more resources than the railroads were able to commit. Therefore to establish fleet size it was necessary to resort to statistical data. The Federal Railroad Administration provided the following statistics for locomotive use in U.S. (ref 5):

<table>
<thead>
<tr>
<th>Type of Locomotive</th>
<th>Min.</th>
<th>Max.</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric locomotives/1,000 MGTM*/year</td>
<td>1.94</td>
<td>4.22</td>
<td>3.6</td>
</tr>
<tr>
<td>Diesel locomotives/1,000 MGTM/year</td>
<td>2.80</td>
<td>9.90</td>
<td>6.8</td>
</tr>
</tbody>
</table>

The routes to be considered later in this report are representative of the most efficient railroad operations in the U.S. and, therefore, it would be expected that the locomotive utilization would be above the average; that is, in the case of the diesel locomotive where, for the U.S. on the average, 680 locomotives are required to move 10^5 MGTM/year, the more efficient routes probably require only 400 to 450 locomotives for the same freight movement. Since the basis for this projection could not be quantified, however, the average locomotive use figures of 6.8 (diesel) and 3.6 (electric) have been used in this study, thereby presenting a conservative approach to the economics study.

After the fleet size for the existing railroad was established, it was possible to determine the number of locomotives required for the modified railroad.

1. **Dual-Mode Locomotive Railroad**

Consider a typical 4600 trailing ton train required to travel at 60 mph on level track with diesel power and to negotiate a 2.2 percent grade at 20 mph under electric power. This will be compared with a conventional SD40 performing the same duty using only diesel power. Since the SD40 is ballasted to the maximum permissible axle load (total locomotive weight 205 ton) it is assumed that the dual-mode version weighs the same as the standard locomotive.

From Figure 2-29 it can be seen that it requires three locomotives to achieve 60 mph on level track.

To ascend a 2.7 percent grade at 20 mph requires either six SD40 locomotives as shown in Figure 2-30 or four dual-mode locomotives as shown in Figure 2-30.

*MGT: millions of gross ton miles

2-55
Figure 2-28. Proposed E60C Regenerative Brake Characteristic
Figure 2-29. Number of SD40 Locomotives Required to Achieve Speed on Level Track.
Figure 2-30. Number of SD40 Locomotives Required to Climb a Grade at 20 mph
Thus, the benefit of using a dual-mode locomotive is considerable. It must be recognized that a utility tie-in is necessary to take advantage of this saving since if the electrical capability could not be guaranteed, the diesel capability would still be required.

2. Electric Helper Railroad

The number of locomotives saved in the case of the electric locomotive hauling the diesel locomotives and consist up the grade is reduced since the electric locomotive has to haul the dead weight of the diesel locomotives (as the diesels do not contribute to the train tractive effort, thus saving the maximum amount of diesel fuel).

3. Electric Railroad

The introduction of WESS to the electric railroad does not impact the fleet size.

4. Railroad Dispatching Policy

The savings in locomotives referred to above in the dual-mode and electric helper cases are directly dependent on the railroad dispatching policy. In the example, it was assumed that the consist was required to achieve a speed of 20 mph on the ruling grade and 60 mph on level track. When the criteria had been established for determining the number of locomotives required for a given train, some of the cooperating railroads supplied the information shown in Table 2-10.

<table>
<thead>
<tr>
<th>Railroad</th>
<th>Drag</th>
<th>Medium-Speed Service</th>
<th>High-Speed Service</th>
<th>Adhesion Level, percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>AT&amp;SF</td>
<td>12.5</td>
<td>17.5</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Conrail</td>
<td>11</td>
<td>11</td>
<td>20</td>
<td>18</td>
</tr>
<tr>
<td>Southern</td>
<td>11</td>
<td>20</td>
<td>25</td>
<td>20</td>
</tr>
<tr>
<td>Union Pacific</td>
<td>15</td>
<td>20</td>
<td>25</td>
<td>20</td>
</tr>
</tbody>
</table>

The saving in locomotives was computed for each railroad based on their dispatching policy. The crucial factor is the tractive effort available at the minimum speed required on the ruling grades.

2-59
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 speed required on level track. Therefore, there is a minimum number of grades that may be electrified on each route and still allow the full locomotive saving to be legitimately claimed. This point is reached where, in the diesel mode, the number of locomotives required to negotiate the remaining nonelectrified ruling grade is less than or equal to the number of locomotives required on level track.

A similar argument applies to the electric helper scenarios.

For the purpose of this study it was assumed that for the dual-mode locomotive scenario, the locomotive fleet could be reduced by the ratio of tractive efforts available in the primary and secondary modes at the minimum speed required for a medium-speed train to ascend the ruling grade. For example, in the case of AT&SF where the minimum speed on the ruling grade for a medium-speed train is 17.5 mph (from Table 2-10), the tractive effort in the primary mode at 17.5 mph is 45,000 lb and in the secondary mode is 83,000 lb. Therefore the fleet may be reduced in size from N locomotives to 0.54 N. Since the value of N used in the study is conservative, the remaining locomotives requiring modification will also be conservative; however, since railroads can and do take advantage of short-term ratings of electrical equipment, the full credit in terms of locomotives saved is not allowed in the study. This adds yet another conservative element to the study.
SECTION 3
WESS APPLICATION TO INDIVIDUAL GRADES

LOCATION STUDY (ITEM 1)

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. 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 3-1) 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.

Consider the general case where a train of weight $W$ ton is descending a grade of length $L$ miles with a change in elevation of $h$ feet. It is assumed for this preliminary calculation only that the train arrives at the grade at the descent speed $v$ mph/hr, which is taken to be constant. Neglecting the effect of curvature (which is generally of second-order importance) and aerodynamic drag (which is negligible at the typical ascent and descent speeds being considered), train resistance may be expressed as a constant $W r$, where $r$ is the specific rolling resistance in lb/ton.

The above may be represented diagrammatically, as shown in Figure 3-2.
Figure 3-1. Location Study Methodology
Then, change in potential energy = \( Wh \) ft-lb  
\[ = 3.77 \times 10^{-7} \text{ kwhr} \]

Energy consumed by train resistance = \( WrL \) ft-lb  
\[ = 9.94 \times 10^{-7} \text{ kwhr} \]

Energy available at the wheel of the descending train  
\[ = \text{change in potential energy} - \text{energy consumed by train resistance} \]
\[ = (3.77 \times 10^{-7} \text{ Wh} - 9.94 \times 10^{-7} \text{ WrL}) \text{ kwhr} \]
\[ = 3.77 \text{ W}(h - 2.64rL)10^{-7} \text{ kwhr} \]

Assuming that the train resistance has the constant value of 3.8 lb/ton,

Energy saving at the wheel of the descending train = 3.77 \( W(h - 10L)10^{-7} \)

From Figure 3-3, it will be seen that the overall round trip efficiency of the WESS system is 60 percent. Therefore, energy saving at the wheel of the ascending train  
\[ = 0.60 \times 3.77 \text{ W}(h - 10L)10^{-7} \text{ kwhr} \]
\[ = 2.22 \text{ W}(h - 10L)10^{-7} \text{ kwhr} \]

Annual energy saving = (energy saved/ascending train) x number of trains/year  
\[ = 2.22 \text{ W}(h - 10L)10^{-7} \times \frac{T}{G} \text{ kwhr} \]
Figure 3-3. WESS Efficiency with High-Voltage AC Catenary

* OVERALL ROUND TRIP EFFICIENCY 60%
where \( T \) = annual traffic density in the direction under consideration (gross trailing tons) 

\( G \) = average gross trailing ton/train

Assuming an energy content/gal of diesel fuel at 52 hphr (38.8 kwhr) and from Figure 3-4, a diesel locomotive efficiency of 25.2 percent

\[
\text{Energy saving} = \frac{2.22 \text{WT}}{0.252 \times 38.8 \frac{\text{G}}{\text{h}}} (h-10L)10^{-7} \text{ gal of fuel}
\]

Assuming a 30-year life and discounting at 10 percent, the net present value (NPV) of this annual saving

\[
\text{NPV} = (\text{discount factor} \times \text{fuel cost/gallon} \times \text{energy saving}) \text{ dollars}
\]

\[
= 9.427 \times 0.38 \times 0.227 \frac{\text{WT}}{\text{G}} (h-10L)10^{-7} \text{ dollars}
\]

The initial investment required to realize the annual saving consists of the following three major elements:

Electrification--The cost of electrification is approximately proportional to the track length (L miles) and number of tracks \( n \). An electrification cost of $0.15 million was assumed at this stage of the study. More accurate figures were used in the engineering economics analysis later in the study.

Slugs--For the purpose of this preliminary analysis, it was assumed that the cost of motive power modifications and provision of slugs would be offset by the savings in locomotives previously referenced in Section 2 of this volume.

Flywheel--The flywheel was initially estimated to cost $0.33 million/\( \text{Mwhr} \), a more detailed analysis not being available at this stage.

Initial Investment (IIN) is then

\[
IIN = 0.15 n L + 1.0 \times nL + 2.22 \text{ WT} (h-10L)10^{-7} \times 0.330 \frac{1}{10} \frac{n}{\eta} \frac{10^{-5}}{10^{-5}}
\]

where \( \eta \) = system efficiency from wheel to flywheel = 0.77 from Figure 3-3.

\[
\therefore IIN = \$ \left[ \frac{0.15 nL + 0.951 W(h-10L)10^{-10}}{2} \right] M
\]
Although it was derived in a crude manner, having made many assumptions that at the time could not be validated, there now existed a simple method of assessing the relative merit of the grades being considered. AiResearch took the view for this initial approach that if the NPV of the annual savings at least equalled the initial investment, then the grade was worth investigating further. This was particularly true since it was known that the motive power costs were overestimated.

\[
\text{NPV} = 11N
\]

\[
0.813 \frac{WT}{L} (h - 10L) 10^{-13} = 0.15 nL + 0.951 W (h - 10L) 10^{-10}
\]

Assuming an average train size of 4600 gross trailing tons with an associated train weight of 5010 tons and dividing both sides of the above equation by L, we have

\[
0.813 \times 5010 \times 2000 \times T \left( \frac{h}{L} - 10 \right) 10^{-13} = 0.15n + 0.951 \times 5010 \times 2000 \left( \frac{h}{L} - 10 \right) 10^{-10}
\]

\[
1764 T(52.8p - 10) 10^{-13} = 0.15n + 0.953 (52.8p - 10) \times 10^{-3}
\]
where $p$ = grade in percent, e.g., 1.4

$T = 0.15n + 0.953 \left( \frac{52.8p - 10}{10^{-13}} \right)$ for economic viability at the preliminary stage

Then the solution to this equation shows typically the traffic density required for viable WESS installations on various track configurations and grade combinations. The solutions are shown in the curve of Figure 3-5.

Figure 3-5. Relationship Between Traffic Density and Grade for Initial WESS Candidacy

Clearly, a finite amount of energy must be recovered to make the system viable and to place practical constraints on this theoretical approach. Initially, AIResearch regarded 600 kwhr as the minimum amount of energy that should be available at the wheel of the ascending train for deployment of a WESS. Therefore, from equation 1:

Energy saved = $2.22 \text{ Wh} (h - 10L) 10^{-7} = 600$ kwhr

$\therefore 2.22 \text{ Wh} \left( \frac{L - 10}{52.8p} \right) 10^{-7} = 600$
If \( W = 5010 \) ton as before

\[
2.22 \times 5010 \times 2000 \times h \frac{(1 - 10^{-10})^{10^{-7}}}{52.8p} = 600
\]

\[
\therefore h = \frac{270}{(1 - 10^{-10})^{52.8p}}
\]

for realistic energy savings at this preliminary stage.

where \( h = \) elevation change (ft)

\( p = \) grade (percent)

The solution to this equation is shown in the curve of Figure 3-6.

![Figure 3-6. Relationship Between Elevation Change and Grade for Minimum Specified Energy Saving](image)

The simplified approaches used above were solely for the purpose of identification of individual grades and were not used in the study for any other purpose. Calculations of energy savings were made using the AIResearch TPC, specially developed for the purpose, which treats all the variables in a technically correct manner.
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 $20 \times 10^6$ ton 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 following six railroads were approached by TSC:

- Southern Pacific Transportation Company (SP)
- Union Pacific Railroad (UP)
- Southern Railway (SR)
- Consolidated Rail Corporation (Conrail)
- Atchison, Topeka, and Santa Fe Railway Company (AT&SF)
- Burlington Northern (BN)

In their responses, 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 index number (GIN) from initial information on traffic density and grades. The 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 data collected for the prime candidate grades are shown in Appendix C. For each grade, a location map identifies the grade in relation to the nearest state or international borders. The grade data are shown on a separate sheet and include:
- Track profile (distance and elevation)
- Track configuration
- Annual traffic level (tonnage includes locomotives and was escalated from 1976 data—SP data 1977)
- Speed limits

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 3-7) 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.

Information was also obtained from the Denver & Rio Grande Western Railroad, 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
- D&RGW - 2 grades
- BM&LP - 2 grades

The data collected for these further prime candidate grades are included in Appendix C. 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 10 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 \( h \).
Figure 3-7. Routes Covered by Location Study

KEY

ROUTES COVERED BY LOCATION STUDY

ROUTES NOT COVERED BY LOCATION STUDY
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 3-1. It will be seen that the most attractive trades identified by this method were between Cheyenne and Laramie on the UP mainline, and between Harrisburg and Pittsburgh on the Conrail line.

The two grades on BMLP could not be evaluated in this manner since it is already electrified; also, the low cost of energy to that railroad further distorts the ranking; however, subjectively it appeared that with the combination of large elevation change and electrification already existing, these grades must be extremely attractive.

Identification of WESS Routes

The 34 prime candidate grades were displayed on a map of U.S. railroads, Figure 3-8, 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)
- Pocatello-Council Bluffs (UP)
- Pocatello-Portland (UP)
- Sacramento-Ogden (SP)
- Sacramento-Portland (SP)
- Los Angeles-El Paso (SP)
- Denver-Salt Lake City (D&RGW)
### TABLE 3-1
**WESS PRIME CANDIDATE GRADES**

<table>
<thead>
<tr>
<th>Grade Index No.</th>
<th>Railroad</th>
<th>Identification</th>
<th>Ranking Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>035</td>
<td>Union Pacific</td>
<td>Baker - Weatherby</td>
<td>32.4</td>
</tr>
<tr>
<td>036</td>
<td>Union Pacific</td>
<td>Union Junction - Powder River</td>
<td>69.7</td>
</tr>
<tr>
<td>037</td>
<td>Union Pacific</td>
<td>La Grande - Duncan</td>
<td>32.88</td>
</tr>
<tr>
<td>056</td>
<td>Union Pacific</td>
<td>Cheyenne - Laramie</td>
<td>112.75</td>
</tr>
<tr>
<td>061</td>
<td>Union Pacific</td>
<td>Echo - Wahsatch</td>
<td>57.5</td>
</tr>
<tr>
<td>063</td>
<td>Union Pacific</td>
<td>Orr - Milepost 40</td>
<td>43.0</td>
</tr>
<tr>
<td>088</td>
<td>Union Pacific</td>
<td>Elgin - Crestline</td>
<td>27.8</td>
</tr>
<tr>
<td>089</td>
<td>Union Pacific</td>
<td>Borax - Las Vegas</td>
<td>27.12</td>
</tr>
<tr>
<td>090</td>
<td>Union Pacific</td>
<td>Kelso - Nipton</td>
<td>27.46</td>
</tr>
<tr>
<td>121</td>
<td>Southern</td>
<td>Breswell Mountain</td>
<td>37.4</td>
</tr>
<tr>
<td>145</td>
<td>CNW</td>
<td>Duluth</td>
<td>23.3</td>
</tr>
<tr>
<td>175</td>
<td>Southern Pacific</td>
<td>Cascades (South)</td>
<td>41.2</td>
</tr>
<tr>
<td>176</td>
<td>Southern Pacific</td>
<td>Cascades (North)</td>
<td>39.7</td>
</tr>
<tr>
<td>183</td>
<td>Southern Pacific</td>
<td>Sierras (Roseville - Sparks)</td>
<td>41.6</td>
</tr>
<tr>
<td>195</td>
<td>Southern Pacific</td>
<td>Cotton - Indio</td>
<td>56.0</td>
</tr>
<tr>
<td>202</td>
<td>Denver &amp; Rio Grande Western</td>
<td>Helper - Springville</td>
<td>34.1</td>
</tr>
<tr>
<td>205</td>
<td>Denver &amp; Rio Grande Western</td>
<td>Denver - Granby</td>
<td>30.6</td>
</tr>
<tr>
<td>220</td>
<td>Burlington Northern</td>
<td>Wenatchee - Skykomish</td>
<td>*</td>
</tr>
<tr>
<td>222</td>
<td>Burlington Northern</td>
<td>Easton - Auburn</td>
<td>*</td>
</tr>
<tr>
<td>227</td>
<td>Burlington Northern</td>
<td>Garrison - Missoula</td>
<td>*</td>
</tr>
<tr>
<td>227</td>
<td>Burlington Northern</td>
<td>De Smet - Dixon</td>
<td>*</td>
</tr>
<tr>
<td>230</td>
<td>Consolidated Rail Corp.</td>
<td>Harrisburg - Pittsburgh</td>
<td>10.8</td>
</tr>
<tr>
<td>240</td>
<td>Atchison Topeka &amp; Santa Fe</td>
<td>San Bernardino - Victorville</td>
<td>69.5</td>
</tr>
<tr>
<td>242</td>
<td>Atchison Topeka &amp; Santa Fe</td>
<td>Needles - Goffs</td>
<td>50.7</td>
</tr>
<tr>
<td>243</td>
<td>Atchison Topeka &amp; Santa Fe</td>
<td>Flagstaff - Canyon Diablo</td>
<td>50.3</td>
</tr>
<tr>
<td>244</td>
<td>Atchison Topeka &amp; Santa Fe</td>
<td>Bellemont - Flagstaff</td>
<td>50.2</td>
</tr>
<tr>
<td>246</td>
<td>Atchison Topeka &amp; Santa Fe</td>
<td>Eagle Nest - Williams Junction</td>
<td>55.8</td>
</tr>
<tr>
<td>247</td>
<td>Atchison Topeka &amp; Santa Fe</td>
<td>Hackberry - Pica</td>
<td>56.1</td>
</tr>
<tr>
<td>248</td>
<td>Atchison Topeka &amp; Santa Fe</td>
<td>Topock - Kingman</td>
<td>56.3</td>
</tr>
<tr>
<td>251</td>
<td>Atchison Topeka &amp; Santa Fe</td>
<td>Gallup - Belen</td>
<td>54.3</td>
</tr>
<tr>
<td>252</td>
<td>Atchison Topeka &amp; Santa Fe</td>
<td>Belen - Silo</td>
<td>29.1</td>
</tr>
<tr>
<td>255</td>
<td>Atchison Topeka &amp; Santa Fe</td>
<td>Vaughn - Fort Sumner</td>
<td>56.9</td>
</tr>
<tr>
<td>261(a)</td>
<td>Black Mesa &amp; Lake Powell</td>
<td>Page - Milepost 31</td>
<td></td>
</tr>
<tr>
<td>261(b)</td>
<td>Black Mesa &amp; Lake Powell</td>
<td>Milepost 44 - Kayenta</td>
<td></td>
</tr>
</tbody>
</table>

*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 3-8. WESS and the National Electrified Network
The routes operated by railroads who had indicated they did not wish to be involved in the study were deleted and four representative routes then were chosen for detailed analysis. The routes chosen were:

- **Los Angeles - Belen**—This route is part of the major Santa Fe artery between Chicago and Los Angeles and currently has a traffic density of approximately $50 \times 10^6$ GTT/year. The traffic is virtually all operated as high-speed manifest with typically a 2.6 hp/ton power/weight ratio. This route is classified in this report as a high-speed, high-traffic route.

- **Los Angeles - Salt Lake City**—Although this route is not associated with the high traffic routes of Union Pacific it is UP's only link between the Pacific Northwest, the Great Plains, and Los Angeles. It currently has a traffic density of approximately $39 \times 10^6$ GTT/year. The traffic consists of a mixture of high-speed manifest (4 hp/ton), medium speed (2.5 hp/ton), and drag (1.2 hp/ton).

- **Harrisburg - Pittsburgh**—This route is Conrail's major link to the East Coast from the heavy industry of Pennsylvania and currently has a traffic density of approximately $112 \times 10^6$ GTT/year. A large proportion of the traffic consists of heavy coal and ore unit trains.

- **Black Mesa and Lake Powell**—This coal-hauling railroad is electrified at 50 kv, 60 Hz and has a total traffic density of $21.2 \times 10^6$ GTT/year. Trains are made up of three E60C locomotives hauling 70 coal cars of 120-ton capacity.

The AiResearch train performance calculator (TPC) for this analysis used the route characteristics (grade, mileposts, curvature, speed restriction) available from track charts supplied by TSC. The output from the program was the identification of all sections of potential regeneration, a task impossible to undertake manually before the systems analysis had produced realistic operating scenarios. A detailed description is contained in Section 5 of this report.

The end result was the identification of many more candidate grades on the four representative routes, as shown in Table 3-2.

On the basis of this information, AiResearch recommended to TSC that the original intention to consider individual grades should be disregarded in favor of consideration of complete routes between major classification yards, thus enabling all costs and system design to be considered on a total system basis. TSC concurred with this request.
Figure 3-9. WESS Routes

- WESS Routes Analyzed
- Other Potential WESS Routes Identified in Study
- Other Routes Considered in Study
TABLE 3-2

NUMBER OF ADDITIONAL CANDIDATE SITES DERIVED FROM USE OF TPC

<table>
<thead>
<tr>
<th>Route</th>
<th>Primary Candidate Grades</th>
<th>Total Grades identified by TPC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Los Angeles-Belen</td>
<td>6</td>
<td>18</td>
</tr>
<tr>
<td>Los Angeles-Salt Lake City</td>
<td>4</td>
<td>10</td>
</tr>
<tr>
<td>Harrisburg-Pittsburgh</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Page-Kayenta</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

Location Study Output

As a result of the location study, AiResearch has identified 34 prime candidate grades and ten routes with WESS potential; however, AiResearch does not claim that the location study was 100 percent complete as far as identification of all major grades was concerned, because the contract statement of work limited the contacts to not more than nine railroads. Other prime contact candidate grades and WESS routes no doubt exist on other railroads, but these remain unidentified by this analysis; however, this location study encompassed as many railroads as possible that had high traffic densities and that were located in mountainous terrain.

The preliminary calculations identified the range of flywheel sizes and power rating required to be compatible with the WESS system. Table 3-3 shows the flywheel size for the 10 most attractive grades. This range of sizes was later confirmed by the TPC.

FLYWHEEL STATION STUDY (ITEM 6)

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, 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 3-3.
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 electric machine that couples energy into and out of the flywheel. Required power was found to vary from 4 to 11.6 Mw 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>
<thead>
<tr>
<th>Grade Index No.</th>
<th>Railroad</th>
<th>Energy Storage from Single Train, Mwhr</th>
<th>Flywheel Capacity, Mwhr</th>
</tr>
</thead>
<tbody>
<tr>
<td>056</td>
<td>UP</td>
<td>4.9</td>
<td>9.8</td>
</tr>
<tr>
<td>175</td>
<td>SP</td>
<td>10.5</td>
<td>21.0</td>
</tr>
<tr>
<td>195</td>
<td>SP</td>
<td>6.4</td>
<td>12.8</td>
</tr>
<tr>
<td>206</td>
<td>DRGW</td>
<td>9.6</td>
<td>19.2</td>
</tr>
<tr>
<td>230</td>
<td>Conrail</td>
<td>3.0</td>
<td>6.0</td>
</tr>
<tr>
<td>240</td>
<td>ATSF/UP</td>
<td>6.9</td>
<td>13.8</td>
</tr>
<tr>
<td>242</td>
<td>ATSF</td>
<td>5.3</td>
<td>10.6</td>
</tr>
<tr>
<td>248</td>
<td>ATSF</td>
<td>2.7</td>
<td>5.4</td>
</tr>
<tr>
<td>261(a)</td>
<td>EM &amp; LP</td>
<td>8.3</td>
<td>16.6</td>
</tr>
<tr>
<td>(b)</td>
<td>EM &amp; LP</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Large Flywheels

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 3-4.

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 w-hr per pound. Both the General Atomic and Tokamak flywheels described in Table 3-4 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 3-4, 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 many WESS applications.

Because the catapult flywheel design requires expensive forgings, a simpler design, better suited to the WESS application, was developed.

Flywheel Design

The flywheel for the WESS should have the following characteristics based on the sizing considerations given above:

- Usable energy storage (to 50 percent speed) 5.5 Mwhr
- Total energy storage (100 percent speed) 7.33 Mwhr
- Power level 10 Mw

<table>
<thead>
<tr>
<th>Description</th>
<th>Flywheel Capacity, Mwhr</th>
<th>Power Rating, Mw</th>
<th>Rotor Weight, ton</th>
<th>Rotor Speed, rpm</th>
<th>Rotor Diameter, ft</th>
</tr>
</thead>
<tbody>
<tr>
<td>Navy Catapult</td>
<td>0.113</td>
<td>70</td>
<td>5.5</td>
<td>6000</td>
<td>7</td>
</tr>
<tr>
<td>General Atomic</td>
<td>0.444</td>
<td>260</td>
<td>200</td>
<td>400</td>
<td>20</td>
</tr>
<tr>
<td>Tokamak</td>
<td>1.25</td>
<td>475</td>
<td>500</td>
<td>375</td>
<td>22</td>
</tr>
</tbody>
</table>
Operating life with minimum maintenance: 30 years

Vertical installation

Minimum cost

Design speed (100 percent): 1800 to 3600 rpm

Low parasitic losses

Three basic designs were considered in the study, as follows:

- All-steel flywheel constructed of axial discs with a peripheral speed of 1440 fps.
- A composite (fiberglass/epoxy) flywheel comprised of several concentric annular cylinders mounted upon an aluminum-spoked hub.
- A hybrid design, which would contain a steel flywheel core surrounded by a multilayer composite cylinder.

The composite flywheel rings are made using two different filaments in order to use available materials to the greatest advantage:

(a) The inner rings, up to a rim speed of 2100 fps, are made using S-glass.

(b) These rings are overlaid with rings made using Kevlar filaments to a diameter that will produce a rim speed of 2500 fps. The inside/outside diameter ratio of the combination is 0.8.

The hybrid flywheel shows no real advantage over the all-steel flywheel. This is primarily because of the following three constraints arbitrarily imposed on this design as analyzed:

- The rim speed of the steel portion was reduced from 1440 to 1300 fps to allow for poorer shape factor of the discs in order to provide for "spokes" to support the composite overlay.
- The composite inner diameter is only 2 percent greater than the steel disc OD. This configuration reduces the length and weight of the spokes.
- The ID/OD ratio of the composite cylinder is 0.8.

It is probable that with adjustment of the constraints during a complete design analysis, a more advantageous hybrid design would evolve.

Each of these designs was considered in both the 1800-rpm and the 3600-rpm versions; therefore, a total of six configurations was considered in the
design study. These are summarized in Table 3-5. Additional data on the composite flywheels are shown in Table 3-6. The relative sizes of the three 1800-rpm flywheels and three 3600-rpm flywheels are illustrated in Figure 3-10.

It immediately becomes apparent from Tables 3-5 and 3-6 that there are significant advantages in cost and power loss when a composite flywheel is used; however, the composite design entails greater technical risk and a more complex installation (greater vacuum requirement). The hybrid design offers a more compact rotor than the pure composite, and has the additional advantage of accommodating magnetic levitation to reduce the hydrostatic bearing size and losses.

A second comparison of interest is the magnitude of power loss between the 1800-rpm and the 3600-rpm machines. The weight of the flywheel, for any configuration, is the same regardless of operating speed. Since the principal power loss in the flywheel system is the hydrostatic bearing and the bearing power loss is directly proportional to speed, the slower flywheel has only about half the loss of the faster one.

Flywheel Manufacture

The flywheels analyzed in the study are large structures with high rotating speeds. Any basic design—steel, composite, or hybrid—will involve special manufacturing techniques and additional facilities. Fabrication of a steel flywheel, however, involves less technical risk than the other designs. Fabrication of a composite (or hybrid) flywheel involves development of several manufacturing techniques currently being developed for much smaller units.

Steel Flywheel Fabrication

In this study, the use of steel discs in flywheels up to 15.25 ft in diameter is considered. Several steel companies were consulted and the largest material that can be supplied currently in high-grade SAE 4340 steel is 180 in. wide by 4 in. thick. The largest disc that can be heat-treated to the desired properties is 13.5 ft in diameter. The approximate maximum thickness that can be hardened uniformly is 3 in. The material given prime consideration for the steel flywheel design was Lukens Steel Company Electroslag Remelt Processed SAE 4340 steel.

With the above dimensions as limitations, a seventh flywheel type (no. 7 in Table 3-5) was defined. In this flywheel, the rotational speed is adjusted to produce 1440 ft/sec tip speed at 100 percent rpm with a 13.5-ft-dia. disc. Thus, the no. 7 design is optimized to avoid compromises in energy density due to the existing material and heat-treating limitations.

Composite Flywheel Fabrication

The composite flywheel will be fabricated by assembling a number of axial composite rim sections to form a flywheel cylinder of the required length. Each rim section would be made up of a series of annular rings one upon the other. Each one of these rings is wound and cured before the next ring is applied. This method, which is currently being used to manufacture small flywheels (up to 4-ft diameter), would be extrapolated to make the WESS flywheel.
Figure 3-10. Flywheel Options

3-22
### TABLE 3-5

**SUMMARY OF FLYWHEEL CONFIGURATIONS**

<table>
<thead>
<tr>
<th>Material</th>
<th>Type</th>
<th>Steel</th>
<th>1800 rpm</th>
<th>Hybrid</th>
<th>Steel</th>
<th>3600 rpm</th>
<th>Hybrid</th>
<th>Steel</th>
<th>2037 rpm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
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<tr>
<td>Diameter, ft</td>
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<tr>
<td>Steel 0D</td>
<td></td>
<td>15.28</td>
<td>19.52</td>
<td>13.79</td>
<td>7.64</td>
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<td>Composite 0D</td>
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<td>26.53</td>
<td>14.07</td>
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<td>34.84</td>
<td>56.62</td>
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<td>133.5</td>
<td>84.4</td>
<td>133.5</td>
<td>84.4</td>
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<tr>
<td>Total</td>
<td></td>
<td>604.4</td>
<td>133.5</td>
<td>601.2</td>
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<td>601.2</td>
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<tr>
<td>Tip Speed ft/sec</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td>1440</td>
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<td>1440</td>
<td>-</td>
<td>1300</td>
<td>1440</td>
<td></td>
</tr>
<tr>
<td>S-glass</td>
<td></td>
<td>2300</td>
<td>1657</td>
<td>2300</td>
<td>1657</td>
<td>2300</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Kevlar</td>
<td></td>
<td>2500</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Material Cost, $</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steel at 0.60/lb</td>
<td>824,368</td>
<td>704,486</td>
<td>824,368</td>
<td>-</td>
<td>824,368</td>
<td>704,486</td>
<td>824,368</td>
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<tr>
<td>S-Glass at $1.90/lb</td>
<td>-</td>
<td>380,000</td>
<td>320,749</td>
<td>380,000</td>
<td>320,749</td>
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<tr>
<td>Kevlar at $4.80/lb</td>
<td>-</td>
<td>321,600</td>
<td>-</td>
<td>321,600</td>
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<td>Total</td>
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<td>704,486</td>
<td>824,368</td>
<td>704,486</td>
<td>824,368</td>
<td>704,486</td>
<td>824,368</td>
<td></td>
</tr>
<tr>
<td>Vacuum requirement, micron</td>
<td></td>
<td>1000</td>
<td>1</td>
<td>1000</td>
<td>1</td>
<td>1000</td>
<td>1000</td>
<td>-</td>
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<tr>
<td>Loss at 100-percent speed, kw</td>
<td></td>
<td>120</td>
<td>27</td>
<td>120</td>
<td>240</td>
<td>54</td>
<td>240</td>
<td>136</td>
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<tr>
<td>Polar moment ft-sec²</td>
<td></td>
<td>1,095,345</td>
<td>273,836</td>
<td>855,203</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<td></td>
</tr>
</tbody>
</table>

*Composite wheels made of Kevlar and S-glass. See Table 3-6.*
TABLE 3-6
SUMMARY OF COMPOSITE CYLINDERS

<table>
<thead>
<tr>
<th>Type (see Table 3-5)</th>
<th>2</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed, rpm</td>
<td>1800</td>
<td>3600</td>
</tr>
<tr>
<td>Material</td>
<td>Kevlar</td>
<td>S-Glass</td>
</tr>
<tr>
<td></td>
<td>2500</td>
<td>2300</td>
</tr>
<tr>
<td>Tip speed, ft/sec</td>
<td>26.53</td>
<td>13.26</td>
</tr>
<tr>
<td></td>
<td>24.40</td>
<td>12.20</td>
</tr>
<tr>
<td>Outside diameter, ft</td>
<td>12.20</td>
<td>9.75</td>
</tr>
<tr>
<td>Inside diameter, ft</td>
<td>26.53</td>
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<td></td>
<td>24.40</td>
<td>12.20</td>
</tr>
<tr>
<td>Length, ft</td>
<td>67,000</td>
<td>133.5</td>
</tr>
<tr>
<td>Weight, lb</td>
<td>200,000</td>
<td>267,000</td>
</tr>
<tr>
<td></td>
<td>34.84</td>
<td>133.5</td>
</tr>
<tr>
<td>Total weight, lb</td>
<td>267,000</td>
<td>267,000</td>
</tr>
<tr>
<td>Total weight, tons</td>
<td>133.5</td>
<td>133.5</td>
</tr>
<tr>
<td>Material cost</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kevlar at $4.80/lb</td>
<td>$321,600</td>
<td>$321,600</td>
</tr>
<tr>
<td>S-Glass at $1.90/lb</td>
<td>$380,000</td>
<td>$380,000</td>
</tr>
<tr>
<td>Total:</td>
<td>$701,600</td>
<td>$701,600</td>
</tr>
</tbody>
</table>

A flywheel of the size required for the WESS application would require the construction of a winding facility that would include these items of special equipment:

- A rack to hold the creels of revolving material and the devices to apply the proper tension to the roving as it leaves the creel. Probably four creels per winding machine would be used.
- An evacuated wet-out box to apply the epoxy resin to the rovings.
- A power-driven spindle, either vertical or horizontal, upon which to mount the winding mandrel.
- Several winding mandrels upon which the layer after layer of composite material would be wound.
A curing oven into which the mandrels would be placed after each layer is made to cure the matrix.

Handling equipment (a mandrel and flywheel section might weigh five tons).

Inspection equipment.

Raw materials handling and storage.

Flywheel rim-to-hub assembly fixture.

Probably three or four parallel sets of some of this equipment would be installed in a facility in order to reduce the total manufacturing time.

Winding a flywheel of this size could take considerable time. Typically, a section might be made of 12 to 14 layers (concentric rings). Each layer would have 192 wraps. Winding four rovings at a time, it takes 10 revolutions to axially wind 1 in. A 6-in.-wide ring would take 60 revolutions of the mandrel. One concentric ring would require 11,520 (60 x 192) revolutions of the mandrel. At 8 rpm, which appears to be a practical roving feed speed for this size rim, this process would take 24 hr. A complete flywheel (17 sections of 14 layers each) would require 238 24-hr days for winding only if a single winding machine were available. In addition, there are other operations that must be performed as each layer is wound (gelling, curing, cleaning, inspection, and possible repair). Because this flywheel is considerably larger than those manufactured previously, some time would have to be devoted to developing manufacturing techniques.

Preferred Flywheel Design

After giving consideration to the availability of materials and fabrication technology, it appears that the steel flywheel is the most practical for development and deployment for at least the next 10 years. The potential of composite or hybrid flywheels is fully expected to be realized prior to the year 2000. Therefore, this decision must be reassessed periodically to assure that the optimum flywheel type will go into ultimate production for widespread application of the WESS concept.

The flywheel design considered to be optimal for the demonstration phase of the program is the steel flywheel of design no. 7 shown in Table 3-5. As pointed out above, this flywheel is designed in view of the realities of presently available materials, material cost, and limitations in heat-treating facilities. This flywheel will be made by flame-cutting unpierced 13.7-sq ft, 3-in.-thick blanks of the Luken Electroslag Remelt Processed 4340 steel. This stock is currently available in mill run quantities at approximately 60 cents per pound. These blanks will be Blanchard-ground on both faces and cut to 13.5-ft-dia discs, which will be jig-drilled for twenty-four 6-in. holes around the outer periphery. The finished discs will be heat treated to a minimum yield strength of 200,000 psi. The top and bottom discs will be forgings, which include suitable hubs on the specially shaped end discs. Consideration in final design will also be given to electron-beam or inertia welding of the hubs on the end discs. The complete 5.5-Mwhr steel flywheel will then comprise 67 center discs and two end discs.
The flywheel rotor will be assembled in situ at the WESS grade, as is the practice with large hydroelectric generators. The lower hub will be lowered into the lower bearing and then the center discs will be stacked on the lower disc. When the upper disk has been placed on the stack, 24 through-bolts will be used to hold the rotor assembly together. These bolts will be placed in tension, either by inserting and tightening heated bolts or by local tensioning of each bolt.

The 10-Mw electrical machine used to spin the flywheel and to extract energy from the rotor then will be installed. This conventional polyphase synchronous machine is essentially a standard 1800-rpm design that will be modified, if necessary, to permit operation up to 2037-rpm flywheel speed. The flywheel will be dynamically balanced by spin-up, using the flywheel machine with weights added to the rotor ends to effect balance.

The leading characteristics of this optimum steel flywheel are summarized in Table 3-7. The housing around the flywheel will be sufficient to support the bearings and to provide the capability for supporting a vacuum. The entire flywheel in its housing will be located in a waterproof concrete pit below grade level at the WESS site.

<table>
<thead>
<tr>
<th>TABLE 3-7</th>
<th>CHARACTERISTICS OF OPTIMUM STEEL FLYWHEEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total capacity</td>
<td>7.33 Mwhr</td>
</tr>
<tr>
<td>Usable capacity (2 to 1 speed range)</td>
<td>5.5 Mwhr</td>
</tr>
<tr>
<td>Maximum speed</td>
<td>2037 rpm</td>
</tr>
<tr>
<td>Diameter</td>
<td>13.5 ft</td>
</tr>
<tr>
<td>Length</td>
<td>17.28 ft</td>
</tr>
<tr>
<td>Weight</td>
<td>604.4 tons</td>
</tr>
<tr>
<td>Peripheral speed</td>
<td>1440 ft/sec</td>
</tr>
<tr>
<td>Vacuum requirements</td>
<td>10 torr</td>
</tr>
<tr>
<td>Loss at 100 percent speed</td>
<td>136 hp</td>
</tr>
<tr>
<td>Loss at 50 percent speed</td>
<td>48 hp</td>
</tr>
<tr>
<td>Moment of inertia</td>
<td>855,800 lb-ft-sec²</td>
</tr>
<tr>
<td>Spin-down time (100 to 50 percent speed)</td>
<td>87 hr</td>
</tr>
</tbody>
</table>

3-26
Flywheel Housing Evacuation

The area immediately surrounding the rotating flywheel must be evacuated for two reasons:

(a) To reduce windage losses

(b) To reduce aerodynamic heating

If a steel flywheel is used, the first reason, windage losses, predominates. If the housing is evacuated sufficiently to reduce the windage to a reasonable value, aerodynamic heating will be low enough to be no problem. Also, the vacuum requirements are not very severe, and an absolute pressure of 10 torr (or even higher) will reduce windage to a negligible value. This pressure is compatible with the oils that might normally be used in the bearing system. Furthermore, the steel flywheel is not very sensitive to an increase in housing pressure, and can, in fact, be made to survive a sudden loss of vacuum without damage.

On the other hand, the composite flywheel requires a much higher vacuum because of the higher tip speed and the sensitivity of the epoxy binder to temperature. A composite flywheel will require an absolute pressure environment in the neighborhood of 1 to 10 microns (1000 microns = one torr), and any significant increase in pressure could almost immediately result in damage to the surface of the flywheel. The high temperature resulting from windage makes the surface vulnerable because of the low specific heat and the low thermal conductivity of the laminate. Therefore, much more complicated evacuation system would be required. Some considerations of this system would be:

(a) Better sealed housing (including shaft seal)

(b) Great vacuum pump capability

(c) Better controls to sense pressure and changes in pressure that might indicate an impending problem

(d) Any oils that are exposed to the low pressure must have corresponding low vapor pressure at the expected operating temperature

(e) Special provisions for rapidly slowing down the flywheel in the event of loss of vacuum

The requirements for the hybrid type of flywheel would be the same as those for the composite flywheel.

For either type of installation, commercially available vacuum pumps would be used. If the housings were manufactured with reasonable care, the principal source of leakage would be the shaft seal. Therefore the pump basically is designed to accommodate the shaft seal leakage. A 1-hp unit (15 cfm displacement) should be sufficient for a steel flywheel installation, but a somewhat
larger unit (possibly 5 hp and 80 cfm capacity) might be required for a composite flywheel. The evacuation system could be a demand type so that power would be consumed only as required to maintain the desired condition. In any event, the pump power requirement for the steel wheel is very small, compared with the hydrostatic bearing power requirements. Also, with a composite flywheel, vacuum pump power should be no more than 5 percent of total installation power requirements. Therefore, the choice of the steel flywheel minimizes the vacuum requirements considered.

**Flywheel Bearings**

The flywheel for the WESS is installed with a vertical rotational axis. At least one bearing would have to support the weight of the flywheel as an axial load. Design objective is to have a very long service life. Conventional rolling element bearings (ball or roller bearings) would be ideal from a frictional point of view, but the lifetime of rolling element bearings is limited under heavy load. Therefore, other longer-life types were investigated for the bearing to support the weight of the flywheel.

Rolling element bearings were still considered for two locations in the flywheel:

1. The upper shaft bearing that would be relatively lightly loaded, functioning only to keep the rotor vertical.
2. An emergency bearing to receive the weight of the flywheel rotor in the event of a failure of the main thrust bearing. A rolling element bearing is well-suited to this type of service because it can withstand high overloads for a short period of time.

**Fluid Film Bearings**

Two main types of fluid film bearings exist: self-acting and externally pressurized (hydrostatic). For large loads and high speeds they have the advantage over rolling element bearings of potentially infinite life; this is due to lack of contact between the rotating and stationary elements, and operation at much lower stress levels. The self-acting type is not load-supporting on the oil film alone until the design operating speed is nearly reached. This leads to problems in startup and shutdown. On the other hand, the hydrostatic type is supported from standstill on the pressurized oil cavity. This type of bearing was selected to support the flywheel in the WESS application.

**Magnetic Suspension**

Magnetic suspension could be used to support the weight of the flywheel; or, at least, to partially support the weight and lessen the load on the other thrust bearing. To be effective, a magnetically supported flywheel should be short and have a rather large diameter in order to present sufficient axially exposed surface area per unit of weight. This configuration is not compatible with the high rotative speeds desired in this application. Also, application of magnetic levitation to an object the size of this flywheel would be very experimental and is not recommended to be included in the present design.
Selected Design

The selected design for the flywheel bearings is shown in Figure 3-11. The flywheel is supported principally by means of a spherically radiused hydrostatic bearing as shown in Figure 3-12. This hydrostatic bearing has four pockets through which oil at high pressure is fed to the bearing. The pressure-projected area product is sufficient to support the entire weight of the rotor. The spherical shape tends to maintain the axis of the rotor coincident with the axis of the bearing.

Before operation, the weight of the rotor is supported by the rolling element thrust bearing (item A of Figure 3-12). The weight of the rotor depresses the unpressurized bearing, B, which is supported by several weak springs, S. At this time there is a gap, D, between the bearing shoe B, and the stator, C. At startup, oil under pressure is supplied to the cavity, E, under the bearing shoe. This oil is communicated to the four pockets in the bearing shoe and the resulting force lifts the rotor and supports it on a thin film of oil leaking from the bearing pockets to the edge of the shoe. At the same time the entire bearing shoe is lifted by the pressure in the lower cavity, closing the gap, D, and lifting the rotor clear of thrust bearing, A. Thus the entire rotor assembly is then supported by the hydrostatic bearing only. The support of the hydrostatic bearing is not a function of rotor speed so the rotor is supported from standstill to maximum speed.

If the hydraulic system fails, the hydrostatic bearing would collapse, but the rotor would again be supported by the rolling element thrust bearing, A. This bearing would be sufficient to support the rotor until it is slowed to a standstill.

A hydrostatic bearing has two principal sources of power consumption: (1) the power required to pump the pressurized oil to the bearing; and (2) the power consumed in shearing the oil at the shaft/shoe interface. These relationships are considered in the bearing detail design to optimize the various factors and bring the power consumption to a minimum. The approximate size of the bearing for the proposed flywheel system is shown in Figure 3-12.

The upper end of the flywheel shaft is supported in the radial direction by means of a roller bearing as shown in Figure 3-13. This bearing is resiliently mounted and loaded so it will have an extremely long life. The outer race of the bearing is elliptical to maintain positive contact between the rollers and the race ways. This bearing is cooled by oil flowing under the inner race, and lubricated by a minute amount of oil that is allowed to flow through the bearing.

Flywheel Shaft Seal

Some sort of air seal must be provided to separate the flywheel cavity from the surrounding ambient air. If a steel flywheel is used the flywheel cavity pressure needs to be reduced to approximately 1 to 10 torr; but if a composite flywheel had been used the pressure would have been less than 10 microns. This lower pressure puts a much more severe requirement on the shaft seal.
Figure 3-11. Flywheel Lower Bearing Arrangement

Figure 3-12. Hydrostatic Thrust Bearing
Face seals have been used effectively on smaller and higher-speed flywheel applications, but the service life is limited as to that desired for the WESS flywheel. Special care in seal design and installation might permit the use of a face seal, especially if the design permitted easy replacement after possibly 20,000 hours of operation. At the present time this type of seal probably is the best option with other designs, discussed below, being investigated for possible application when proven feasible.

Ferro-Fluid Seal

This type of seal has been suggested for a number of similar applications, but no high-speed long-duration applications are known. The principle of operation, as shown in Figure 3-14, involves a fluid into which there is a colloidal (100 angstroms) suspension of magnetic particles that are retained in the seal area by means of permanent magnets in the housing. While this arrangement will provide an excellent near-zero friction seal for low-speed shafts, the combination of problems incurred by viscous heating and centrifugal forces associated with a high surface speed (3000 fpm) shaft make this application an advance in the state of the art.

Slinger Seal

Another type of seal that may work in this application is the slinger seal, as shown in Figure 3-15. In this seal, a slug of oil is held in an
Figure 3-14. Ferro-Fluid Seal

Figure 3-15. Slinger Seal Assembly
annular groove in the housing by the centrifugal force on the oil slug. The rotating oil slinger, which puts the oil into this groove, also acts as a dam whose outer periphery is submerged in the oil pool. In this design, a number of criteria must be simultaneously satisfied if proper sealing is to be obtained; any upset could lead to sudden and catastrophic pressurization of the flywheel cavity in the case of a composite or hybrid rotor. Also, this design requires that the shaft be rotating at some speed before the seal can be initially formed. In order to retain the pressure differential across the seal, an equivalent head must be developed by the fluid column across the seal.

**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 operating speed range (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. It weighs 150,000 lb.

Because the flywheel machine is typical of small utility generators, cost estimates for the 7.5-Mw capacity were obtained from the large machinery department at General Electric Corporation (GE) 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 was also used in the economic analysis.

A general outline of the machine is shown in Figure 3-16 (as supplied by GE), and is a commercially available, small-size utility generator.

**Flywheel Converter**

The static power converter (Figure 3-17), which connects the flywheel machine to the railroad electrification system, converts 2-phase, high-voltage 60-Hz power to variable-frequency, 3-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. This capability is used only infrequently, for flywheel startups after inspection or after an unscheduled shutdown.

The decision regarding operating voltage involves a detailed design study to trade off the cost of transformers against the cost of devices. For this study, the cost of $30 per kw is based on using sufficient series bridges to accommodate 50 kv without using transformers.

The configuration used allows direct phase-to-phase regeneration without the need to pass through the flywheel. The addition of a bridge for phase C would allow balanced 3-phase regeneration to the utility. This third bridge also could be used to accommodate situations where the railroad uses all three phases for the catenaries (as may be the case on the Harrisburg-Pittsburgh route).
Figure 3-16. Mechanical Outline of Flywheel Machine
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 3-18. 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 3-19. The overall WESS site, the building, adjacent electrification, equipment, and access to the site are shown in Figure 3-20.

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

Flywheel Cost

The cost of the flywheel has been analyzed in detail and the results are shown in Appendix D. Most of the cost is attributable to the flywheel material, and an accurate assessment of this cost element is clearly essential. A cost of $0.60/lb for mill run quantities of SAE 4340 steel was supplied by Luker Steel. (For two flywheel discs only, the cost would be $0.65 per lb). This firm price for the major cost item ensures the acceptability of the AiResearch estimate.
Figure 3-18. Flywheel Housing
Figure 3-19. Flywheel and Converter Buildings
Figure 3-20. YESS Site Plan
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, brake system, and wheel maintenance, and possibly 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.

The comparison of savings to costs has been performed by using the 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

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. (Year zero is 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 economic techniques to be employed in this study were agreed upon by TSC and FRA at an early stage, when an attempt was made to assess the viability of the WESS concept using the techniques with which industry and government are most familiar. These techniques are described below.

Office of Management and Budget Circular A-94

This is a net present worth or net present value technique and, as the name implies, is concerned with assessing the value of monies spent or saved in future years in terms of today's money value; however, this is not a technique for dealing with inflation. OMB A-94 allows relative inflation to be taken into account. Inflation factors are shown in Table 4-1.

A crucial discussion to be presented is the rate at which future monies should be discounted. OMB A-94 dictates that 10 percent be used because this represents an estimate of the average rate of return on private investment, before taxes and after inflation; however, railroads typically realize only a 5 to 6 percent rate of return and therefore the applicability of the OMB A-94 guidelines to WESS is questionable. For this reason the results derived from this technique were not used as the baseline case.
TABLE 4-1

SUMMARY OF INFLATION RATES

<table>
<thead>
<tr>
<th>Analysis Technique</th>
<th>Diesel Fuel</th>
<th>Electricity</th>
<th>Maintenance</th>
<th>General Price Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>OMB A-94</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>4R Act</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Sensitivity 1</td>
<td>8</td>
<td>7</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>Sensitivity 2</td>
<td>10</td>
<td>7</td>
<td>8</td>
<td>6</td>
</tr>
</tbody>
</table>

Railroad Revitalization and Regulatory Reform (4R) Act-1976

The purpose of the 4R Act was to provide financial assistance for the U.S. railroads to enable them to invest in essential new projects (such as track maintenance, track reconfiguration, etc.). It was considered prudent to assess the benefit of WESS using the guidelines of the 4R Act even though WESS would probably not qualify for 4R assistance as the Act is currently structured.

Because the 4R Act guidelines make no allowance for general or relative inflation, AiResearch feels that the results do not reflect the real world. Therefore, the results from this technique were not used as the baseline case.

Sensitivity Analyses I and II

These analyses were recommended by AiResearch as being a real-world case, taking inflation into account and producing an output based on current dollars. Like the 4R Act, they employ ROI techniques, the only difference being the recognition of inflation. The inflation factors for the two analyses are shown in Table 4-1.

Sensitivity I was used as the baseline case for the economic analyses because this is considered to be the most realistic scenario.

INFLATION

In a study such as this, when the year of decision is 1990 and the hardware is designed for a 30-year economic life, the choice of inflation factor is a crucial decision. Many different components make up the total costs and annual savings; historically, each of these components has increased in cost at different rates relative to general price level (GPL).

General Price Level

When the inflation factors were formulated in September 1977, the GPL was rising at 6 percent per year. This figure has been used in the study, although at the date of this report, the GPL is rising at 10 percent per year.
Diesel Fuel

The diesel fuel inflation is difficult to predict since, more than any other item, it is subjected to international political pressure. Reference 9 suggests that diesel fuel will probably escalate at between 2 and 4 percent above the GPL over the next 25 years, and Figure 4-1 is based on a 2-percent differential inflation rate. Therefore, 2 percent above GPL is considered to be the most realistic estimate for fuel inflation.

Electrical Energy

Because electrical energy may be derived from various sources (oil, gas, coal, nuclear, and--in the future--solar and geothermal), it is less sensitive to the variation in relative price of any one lb-base fuel. Reference 9 suggests that electrical energy will inflate at 1 percent per year for the next 25 years; this agrees with the predictions of Figure 4-1.

Maintenance

Department of Commerce (Bureau of Labor) projections of increased costs in manufacturing and nonmanufacturing industry have historically shown an increase in maintenance costs of 2 percent above GPL. This level of increase has been assumed to continue for the life of the WESS.

ECONOMIC ANALYSIS METHODOLOGY

Economic Scenario

Four economic scenarios have been developed, based on the three operating scenarios described in section 2 of this report. They are:

Dual-Mode Locomotive--All motive power normally operating on this route is converted to the dual-mode concept, and credit is taken for the reduction in fleet size that results from the increased tractive effort of these locomotives. Electrification is available only at grades.

Electric Helper--Regenerative electric locomotives are stationed at the grades and a saving in diesel locomotives is claimed due to the easing of the gradient duty imposed on the diesel locomotives. Electrification is available only at grades.

Electrified Railroad--Where the railroad is already electrified, the only costs to WESS are for the installation of the flywheel station and modification of electric locomotives.

Concurrent Electrification and WESS--The diesel railroad is converted to electric operation and all the associated changes are considered with the cost of the WESS stations.
Figure 4-1. Comparison of Cost Projections, Railroad Diesel Fuel and Electric Energy (Ref 7)
Economic Computer Program

To accommodate the large amount of data in the economic analysis, AiResearch generated a computer program, for which a simplified flow chart is shown in Figure 4-2. The program listing is contained in Appendix E. It has been written for the Univac 1100 computer.

1. Description of Program

Main program: WESS - calls subroutines INPUT and DETAIL

Subroutines:

1. INPUT  Reads input data from cards
2. DETAIL Main subroutine: Organizes data for site rankings, calls subroutines for economic analysis; calls subroutines TREE, G1990D, SUM90, NPVNAS and REPORT.
3. TREE Sorts subroutine, aids in site rankings.
5. SUM90 Sums 1990 dollars—initial investment and annual costs.
6. NPVNAS Calculates net present values, net annual savings. Calls subroutine RONINV.
7. RONINV This subroutine determines the return on investment. Calls subroutine ITRAT.
8. ITRAT Auxiliary subroutine that aids in the iterative solution for return on investment.
9. REPORT Prints final report, called by subroutine DETAIL.
10. RLKDAT Fortran block data element that contains initial values for most variables used in the program.

The program size is approximately 15,000 decimal words.

2. Description of Input Data

Input data can be stored in the block data subroutine and also input via four namelists in subroutine INPUT. Any data input always override data stored in the program.

Fortran namelists can be used to input any necessary data or titles for the WESS program. The names of these four namelists are: ONE, TWO, INVEST, and ANNUAL. Tables 4-2 through 4-5 define the variables in each namelist.
Figure 4-2. Simplified Flow Chart
TABLE 4-2

INPUT VARIABLES IN NAMELIST ONE

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><strong>IROUTE</strong> - Points to ROUTE analyzed; can have a value of 1, 2, 3 or 4 (1)**</td>
</tr>
<tr>
<td>2</td>
<td><strong>ISEN</strong> - ScENario; can have a value of 1, 2, 3 or 4 (1) Points to scenario used.</td>
</tr>
<tr>
<td>3</td>
<td><strong>IANANO</strong> - ANALysis Number; four characters can be input which identify the analysis number. (A4 format)</td>
</tr>
<tr>
<td>4</td>
<td><strong>NOSITT</strong> - Maximum number of sites per route (1)</td>
</tr>
<tr>
<td>5</td>
<td><strong>KSTART</strong> - Minimum number of sites to be analyzed. Note: NOFIX ≤ KSTART ≤ NOSITT (1)</td>
</tr>
<tr>
<td>6</td>
<td><strong>RMILES</strong> - Route MILES (1)</td>
</tr>
</tbody>
</table>
| 7 | **TDENEB** - Traffic DENSity East Bound (millions of tons), (R)**
| 8 | **TDENWB** - Traffic DENSity West Bound (millions of tons), (R) |
| 9 | **GTTONS** - Gross Trailing TONS (1) |
| 10 | **NOLOC** - Number Of LOcomotives (1) |
| 11 | **LOCTYP** - LOcomotive TYPE (4A6 format) |
| 12 | **LOCUSE** - LOcomotive USEage (R) |
| 13 | **LOCFM1** - LOcomotive Fleet Mileage (R) |
| 14 | **SCENIO** - SCENARIO description title - (6A6, A4 format) |
| 15 | **FLYCOS** - FLYwheel COST (R) |
| 16 | **IRNAME** - Route Title - up to 24 characters can be used to describe route. (4A6 format) |
| 17 | **IRROAD** - Railroad Title - up to 10 characters. (A6, A4 format). |
| 18 | **IPR** - Debug print flag - IPR = 0 gives no debug print & IPR = 3 gives maximum debug print (1). |
| 19 | **NOFIX** - Number Of sites to be FIXED (1). |
| 20 | **FIX** - Site numbers to be FIXED (always to be included in economic analysis). Up to 10 sites can be fixed (1). |

** (1) indicates integer (no decimal point).

** (R) indicates real number (decimal point).

4-7
TABLE 4-3

INPUT VARIABLES IN NAMELIST TWO:

1. ISITES - Array which contains numbers which identify each SITE
2. MILEPF - MILEPosts, From-array, (l)
3. MILEPT - MILEPosts, To-array, (l)
4. ESAVEP - Energy SAVED at railroad Metering Point. Units of KWH for scenario #3; otherwise the units are in gallons (R).
5. REGPL - REGeneration Power Level, MW (R)
6. FLYSC - FLYwheel Storage Capacity, MWH (R)
7. STABLD - STAtion BuLDing (constant), flywheel station costs ($M) (R)
8. ELEHEL - ELEctric HELpers (l)
9. EHCREW - Electric Helper CREWs (l)

TABLE 4-4

INPUT VARIABLES IN NAMELIST INVESt:

1. NEWLOC - Number of NEW LOcomotives required. (l)
2. COSNEW - COST ($M) for each NEW locomotive (R)
3. MODLOC - MODified LOcomotives Required (l)
4. COSMOD - COST ($M) for each MODified locomotive. (R)
5. LOCTRA - Number of LOcomotives TRAnsferred. (l)
6. COSTRA - COS ($M) for each locomotive TRAnsferred (R)
7. ROUTEE - ROUTE Electrification $M. (R)
8. COSEND - Route END of program COST $M. (R)
9. SITELE - SITE Electrification $M. (R)
10. ELECHI - Cost of ELECTric Helpers per site, $M. (R)

* All input variables for namelist TWO represent arrays which require a value for each site.

** Dollars in Millions.

*** The variables input thru Namelist INVESt are all for initial investment.
<table>
<thead>
<tr>
<th>No.</th>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>CILMCS</td>
<td>Change in Locomotive Maintenance Costs (route dependent), $ per mile. (R)</td>
</tr>
<tr>
<td>2.</td>
<td>TCILMC</td>
<td>Total Change in Locomotive Maintenance Costs for route, $M. (R)</td>
</tr>
<tr>
<td>3.</td>
<td>EMATPM</td>
<td>Route Electrification Maintenance, $M per mile. (R)</td>
</tr>
<tr>
<td>4.</td>
<td>TEMTPM</td>
<td>Total Route Electrification Maintenance, $M. (R)</td>
</tr>
<tr>
<td>5.</td>
<td>DFSMPG</td>
<td>Diesel Fuel Saving (train movement &amp; route dependent) $ Per Gal. (R)</td>
</tr>
<tr>
<td>6.</td>
<td>TDFSTM</td>
<td>Total route Diesel Fuel Saving (Train Movement) $M. (R)</td>
</tr>
<tr>
<td>7.</td>
<td>DFSIPG</td>
<td>Diesel Fuel Saving (train idling &amp; route dependent) $ Per Gal. (R)</td>
</tr>
<tr>
<td>8.</td>
<td>TDFSTI</td>
<td>Total route Diesel Fuel Saving (Train Idling) $M. (R)</td>
</tr>
<tr>
<td>9.</td>
<td>SAVLRP</td>
<td>Savings in Locomotive Replacement, $ per locomotive, route dependent. (R)</td>
</tr>
<tr>
<td>10.</td>
<td>TSAVLR</td>
<td>Total Savings in Locomotive Replacement, route dependent, $M. (R)</td>
</tr>
<tr>
<td>11.</td>
<td>ELEENE</td>
<td>Electrical Energy, route dependent, $M. (R)</td>
</tr>
<tr>
<td>12.</td>
<td>ADDLAB</td>
<td>Additional Labor, route dependent. $M. (R)</td>
</tr>
<tr>
<td>13.</td>
<td>NYRCON</td>
<td>Number of Years Considered after Jan 1, 1990, YRS. (1)</td>
</tr>
<tr>
<td>14.</td>
<td>DISCON</td>
<td>Discount rate, fraction. (R)</td>
</tr>
<tr>
<td>15.</td>
<td>EHELPM</td>
<td>Electric Helper Maintenance per site, $M. (R)</td>
</tr>
<tr>
<td>16.</td>
<td>ADLABR</td>
<td>Additional Labor per site, $M. (R)</td>
</tr>
<tr>
<td>17.</td>
<td>RPEAKD</td>
<td>Site Reduction in PEAK Demand, $M. (R)</td>
</tr>
<tr>
<td>18.</td>
<td>EMAINT</td>
<td>Electrification Maintenance per site, $M. (R)</td>
</tr>
</tbody>
</table>

* Data for ANNUAL cost & credits.
ECONOMIC VARIABLES

It can be seen from the above that the costs and credits for the system application have been considered as those that are route-dependent and those that are site-dependent.

Route-Dependent Costs and Credits

(a) New Electric Locomotives--Dependent on the traffic flows between classification yards and applies only to economic scenario 4.

(b) Modified Locomotives Required--As in item (a), dependent on traffic flow between classification yards.

(c) Locomotives Transferred--Reflects reduction in locomotive fleet size owing to introduction of WESS locomotives. Each transferred locomotive is assumed to be worth half the new cost.

(d) Route Electrification--Considered only in scenario 4, when whole route electrification is applied.

(e) Saving in Locomotive Replacement--Based on not having to replace as many locomotives each year due to the reduction in fleet size.

(f) Change in Locomotive Maintenance Costs--Dependent on change in number or type of locomotive considered.

(g) Electrification Maintenance--Only applicable in scenario 4, where new electrification is installed throughout.

(h) Electrical Energy--Only applicable in scenario 4, where diesel oil consumption is replaced by electrical energy considered over the entire route.

(i) Diesel Fuel Saving (Train Movement)--Only applicable to scenario 4, as in item (h) above.

(j) Diesel Fuel Saving (Train Idling)--Applies when the number of diesel locomotives in the fleet is reduced and unnecessary idling is eliminated.

(k) Additional Labor--Charges WESS with the additional labor required at classification yards for changing motive power, which would normally run through.

Site Dependent Costs and Credits

(a) Flywheel Station--Includes building, flywheel, flywheel machine, and flywheel converter.

(b) Site Electrification--includes catenary signaling, utility tie-in, and substation.
(c) Electric Helpers--Dependent on traffic flow and grade length and applies only to scenario 2.

(d) Electric Helper Maintenance--Estimated at $0.35/mile and applies only to scenario 2.

(e) Additional Labor--Includes manpower for the electric helpers.

(f) Energy Saving at the Railroad Metering Point--Calculated from TPC and assigned the appropriate monetary value.

(g) Reduction in Peak Demand--The flywheels have been sized to accommodate a reduction in peak demand of 6 Mw at each location. This savings applies only to scenarios 3 and 4.

(h) Electrification Maintenance--Where electrification is available only at the site (scenarios 1 and 2), then electrification maintenance is site-dependent.

Sensitivity Analysis

The use of the computer enabled AiResearch to carry out a sensitivity analysis on the following cost elements, which were identified as being of particular interest in the study:

- Flywheel cost ±50 percent
- Dual-mode locomotive cost ±50 percent
- Energy saving ±25 percent, -50 percent

ECONOMIC ANALYSIS STRUCTURE

Before using the economics program it is necessary to determine the ruling grades so that when claiming a reduction in locomotives, the remaining locomotives are able to negotiate the route at the required speed or journey time.

Having inputted all the variables listed, the program will then analyze all the grade information and output the results of each economic analysis technique for a diminishing number of grades. The selection procedure is based on the combination of grades that will give the next best (or worst) ROI so that the ROI shown represents the best possible combination of grades for those grades identified on that route.

The output from the computer program is contained in Volume 3. A detailed description of the sensitivity analysis applied to each route is contained in section 5 of the present volume.

CALCULATION OF ECONOMIC DATA

Motive Power Related Data

Consider a route of length "L" miles carrying a total traffic of T MGTT/year, operating with locomotives that achieved a utilization of n locomotives/10^9
GTTM/year. Therefore, the number of locomotives (N) required to operate the route is given by

\[ N = n \text{TXL} \times 10^{-5} \]

As previously discussed, the value of \( n \) is dependent on the locomotive type under consideration and the dispatching policy of the railroad. Having established the existing fleet size, it is possible then to determine the reduction in fleet size due to either the dual-mode, electric helper, or electrified railroad scenarios, and this gives the number of locomotives to be transferred and modified.

The determination of the reduction in the diesel fleet allows the maintenance and idling fuel saving to be calculated. Knowing the ton miles/year for the route and the average train size, it is possible to determine the total locomotive miles for each scenario and the change from the existing condition. Locomotive maintenance costs have been obtained from reference 5.

It is well known that diesel locomotives spend long periods idling due to many operational considerations such as battery condition, climate, etc. Reference 8 provided information to formulate Table 4-6, which shows that a typical SD40 locomotive spends 12 hr per day idling. If the locomotive fleet is reduced, then so is the total amount of fuel consumed during idling. AiResearch judged that of the 12 hr spent idling, 8 hr of this could be termed unnecessary (i.e., not while the locomotive is on the road). Therefore, if the fleet is reduced in size, the saving due to elimination of idling would be conservatively calculated as:

\[ \text{Locomotives saved} \times 5.5 \text{ gal/hr} \times 8 \text{ hr/day} \times 310 \text{ day/yr} \]

**TABLE 4-6**

**EXAMPLE OF A TYPICAL DAILY EMD SD40 DIESEL LOCOMOTIVE UNIT OPERATION**

<table>
<thead>
<tr>
<th>Throttle Position</th>
<th>Delivered Horsepower</th>
<th>Operation, hrs</th>
<th>Fuel Rate, gal/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>3100</td>
<td>3.6</td>
<td>168</td>
</tr>
<tr>
<td>7</td>
<td>2550</td>
<td>1.0</td>
<td>146</td>
</tr>
<tr>
<td>6</td>
<td>2000</td>
<td>1.0</td>
<td>108</td>
</tr>
<tr>
<td>5</td>
<td>1450</td>
<td>1.0</td>
<td>79</td>
</tr>
<tr>
<td>4</td>
<td>950</td>
<td>1.0</td>
<td>57</td>
</tr>
<tr>
<td>3</td>
<td>500</td>
<td>1.0</td>
<td>41</td>
</tr>
<tr>
<td>2</td>
<td>200</td>
<td>1.0</td>
<td>25</td>
</tr>
<tr>
<td>1</td>
<td>58</td>
<td>1.2</td>
<td>7.5</td>
</tr>
<tr>
<td>Idle</td>
<td></td>
<td>12.0</td>
<td>5.5</td>
</tr>
<tr>
<td>Dynamic Brake</td>
<td></td>
<td>1.2</td>
<td>25</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>-</strong></td>
<td><strong>24.0</strong></td>
<td><strong>-</strong></td>
</tr>
</tbody>
</table>
The diesel fuel saving due to train movement is derived directly from the AiResearch TPC and is applicable only in scenario 4.

To determine the number of electric helpers (and hence crews) required, it is necessary to know the average number of helpers per train (N), the journey time over the grade (T hours), and the total number of trains over the grade per hour (X). Then the number of helpers becomes the next highest integer multiple of N given by the product of NTX.

The electric helper maintenance is dependent on the annual milage and was assumed to be $0.35/mile, this being based on the AiResearch judgment that the electric helper, because of its usually remote location, would cost more to maintain than the $0.30/mile for a standard electric locomotive (ref 5).

The cost of the electric helper locomotive, including an allowance of 10 percent for centrally held spare locomotives, was based on $191/rph (ref. 5) giving a locomotive cost of $1.43 million.

The use of run-through agreements, allowing the locomotives of one railroad to carry on to the ultimate train destination on other railroad tracks, is increasing. Therefore, in this study, where running through is a normal practice, it has been assumed the 20 percent of the trains must have out-of-course motive power changes, and this has been factored into the economic analysis by allowing 2 man-hours for each change of motive power.

Flywheel-Related Data

The cost of the flywheel, flywheel machine, flywheel converter, and flywheel building have been derived in Section 3. Knowing the energy and power levels, the cost of all flywheel-related items is calculable.

Electrification-Related Costs

As already discussed, initial costs of railroad electrification have been determined by Bechtel, Inc. on a per-route mile basis. Maintenance costs were derived from reference 5 on a per-route mile basis. Therefore, knowing the length of the site or route under consideration, the all-electrification costs are available.
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.

TRAIN PERFORMANCE CALCULATOR

The train performance calculator (TPC) developed by AiResearch for the analysis of WESS is a digital computer program that simulates the operation of multiple trains over a railroad route. The TPC contains the characteristics of the locomotives and rolling stock as internal program parameters. The route and schedule data are input to the program. The program computes speed, time, distance, acceleration, locomotive input power, efficiency, power factor, apparent power, and energy input from the pantograph. It also computes tractive effort during motoring and braking from the propulsion and friction braking systems. It performs analysis of specific energy consumption in watt-hours per ton-mile for each train and accumulates the power and energy required for all trains operating over specific sections of the route to define substation power versus time and energy requirements. Simulation of up to 100 trains over a 24-hr period of operation can be performed by the program. The program outputs the time history of a selected train over the route and a listing of 5-min power demands for each subdivision of the route (up to 10 subdivisions); it also lists the 5-min power demands over the total route for an entire 24-hr period. Total energy requirements for each division and the total route also are output for the 24-hr period.

Complete details of the program, including a program listing, program nomenclature, key algorithms, and input data requirements are presented in Appendix F.

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 x 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 10). 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 5-1 for the entire route.

TABLE 5-1

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

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Annual Energy Savings at 1990 Traffic Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dual mode</td>
<td>27.82 Mgal</td>
</tr>
<tr>
<td>Electric helper</td>
<td>25.04 Mgal</td>
</tr>
<tr>
<td>Electrified railroad</td>
<td>291,000 Mwhr</td>
</tr>
</tbody>
</table>

The results of the sensitivity analyses are discussed below.

Dual-Mode Locomotive Scenario

The AT&SF dispatching policy requires that medium-sized trains attain a minimum speed on the ruling grade of 17.5 mph. To be conservative, it has been assumed that the dual-mode locomotive utilization will be 4.44 locomotives per $10^9$ GTM/year, compared with 6.8 locomotives per $10^9$ GTM/year for the existing diesel fleet.

Therefore, 395 diesel locomotives will be required in 1990 on this route, compared with 258 dual-mode locomotives. This results in a saving of 137 diesel locomotives that may be transferred to other duties. Assuming that locomotives are replaced on a 15-year cycle, the reduction in fleet size by 137 locomotives results in an annual saving of 9 replacement locomotives.

Other savings resulting from the reduction in fleet size are calculated in Section 4 and are tabulated in Volume 3.

1. Baseline (Analysis 1/1)

In this baseline analysis, the following assumptions were made:

- Flywheel, $0.270$ million/Mwhr stored
- Dual-mode conversion, $0.211$ million
- Energy saving, as calculated by TPC
Figure 5-1 shows the results of the baseline analysis and it can be seen that the ROI increases as the number of locomotives decreases. This is because the major savings are achieved by the route-dependent rather than the site-dependent factors. The decision as to how many grades would be equipped with WESS depends on:

(a) Funding level available

(b) Whether other projects exist that show a better ROI. That is, there may not be a project which can show an ROI greater than that for seven locations, in which case seven locations would be equipped.

2. Flywheel Cost Sensitivity (Analysis 1/2)

In this analysis, flywheel costs ranging +50 percent from the baseline are assumed; the results of the study are shown in Figure 5-2. The ROI is not significantly affected by the change in flywheel cost because the major portion of the system costs is route-dependent and constant.

3. Dual-Mode Locomotive Cost Sensitivity (Analysis 1/3)

In this analysis, it is assumed that costs of the dual-mode locomotive range +50 percent from the baseline analysis, as shown in Figure 5-3. The 50 percent increase in locomotive cost results in a 15 percent change in ROI. This is the most sensitive variable.
Figure 5-2. Los Angeles to Belen Dual-Mode Locomotive Sensitivity Analysis: Flywheel Cost

Figure 5-3. Los Angeles to Belen Dual-Mode Locomotive Sensitivity Analysis: Dual-Mode Locomotive Cost
4. Energy Saving Sensitivity (Analysis 1/4)

In this analysis, it is assumed that energy saving levels are ±25 percent and -50 percent of the baseline analysis. The purpose of this analysis is to test the sensitivity of the results to differences in railroad policy and driving techniques as far as the use of electric braking is concerned. The results are shown in Figure 5-4 and it may be seen that the results are not very sensitive to the level of energy saving assumed because most cost and credit elements are route-dependent.

5. Dual-Mode Locomotive Only (Analysis 1/5)

The purpose of this analysis is to define the benefit of the WESS when applied to a dual-mode railroad. The results are shown in Figure 5-5, from which it can be seen that the addition of WESS to a project to convert a railroad to dual-mode operation would result in an increase in the ROI of 12.5 percent.

Electric Helper Scenario

The same locomotive fleet economies calculated from the dual-mode locomotive scenario apply to this scenario. The increase in journey time resulting from this method of operation has not been quantified due to lack of information from the railroad.

1. Baseline (Analysis 2/1)

In this baseline analysis, the following assumptions are made:

- Flywheel cost, $0.270 million/Mwhr stored
- Energy saving, as calculated by TPC

Figure 5-6 shows the results of the baseline analysis and it can be seen that, as in the case of the dual-mode locomotive, the ROI increases as the number of locations decreases. The logic of the dual-mode locomotive scenario also applies to this scenario. The relatively low ROI (15 percent maximum) and the inept operations procedure involved make it doubtful whether this scenario would be considered past this study. Examination of Figure 5-6 shows that the ROI steadily decreases until a negative value is reached. These values have not been plotted because the computer program was not equipped to deal with negative ROI's and the results may be erroneous.

2. Flywheel Cost Sensitivity (Analysis 2/2)

For this analysis, it was assumed that flywheel costs varied ±50 percent from the baseline. As shown in Figure 5-7, the ROI is not significantly affected by the change in flywheel cost because most of the flywheel costs are route-dependent and constant.
Figure 5-4. Los Angeles to Belen Dual-Mode Locomotive Sensitivity Analysis: Energy Saving

Figure 5-5. Los Angeles to Belen Dual-Mode Locomotive Only
Figure 5-6. Los Angeles to Belen Electric Helper: Baseline Case

Figure 5-7. Los Angeles to Belen Electric Helper
Sensitivity Analysis: Flywheel Cost
3. Energy Saving Sensitivity (Analysis 2/3)

Here energy savings ranging +25 percent and -50 percent from the baseline analysis were assumed. From Figure 5-8, it may be seen that the results are not unduly affected by the variation in flywheel cost.

4. Electric Helper Only (Analysis 2/4)

The purpose of this analysis is to define the benefit of WESS when applied to a railroad that makes extensive use of electric helpers. It will be seen from Figure 5-9 that for the case of ruling grades only, the addition of WESS to a project to implement the use of electric helpers at the ruling grades increases the ROI by 11 percent. The effect is much greater when considering less attractive grades.

Electrified Railroad Scenario

Assuming no change in the AT&SF dispatching policy and the average locomotive utilization of 3.6 locomotives per 10^9 TM/year, 209 electric locomotives will be required to operate this route in 1990. Also, because they are assumed to exist, these locomotives will require modification to a regenerative system. Because the base performance at the locomotive remains unaltered, there is no reduction in the fleet size.

![Figure 5-8](image-url)

Figure 5-8. Los Angeles to Belen Electric Helper Sensitivity Analysis: Energy Saving
1. Baseline (Analysis 3/1)

In the baseline analysis, the following is assumed:

- Flywheel cost, $0.270 million/Mwhr stored
- Energy saving, as calculated by TPC

Figure 5-10 shows the results of the baseline analysis and it can be seen that as the number of locations increases, so does the ROI until a maximum value would have been reached if more grades had been included. (AIResearch did not consider grades that gave an energy saving of less than 450 kwhr). This maximum ROI, estimated to be 23.5 percent, occurs when the weighting of the site-dependent costs and savings is the same as the weighting of the route-dependent costs in the ROI calculation. It is because the site-dependent costs and savings predominate for the lower number of locations that the ROI increases, whereas in the two scenarios previously considered, route-dependent elements predominated throughout.

2. Flywheel Cost Sensitivity (Analysis 3/2)

In this analysis, flywheel costs ranging ±50 percent from the baseline were assumed. As shown in Figure 5-11, the ROI is not significantly affected by the increased cost of the flywheel, although it will be seen that the optimum ROI is achieved due to the increased site-dependent cost.
Figure 5-10. Los Angeles to Belen Electrified Railroad: Baseline Case

Figure 5-11. Los Angeles to Belen Electrified Railroad
Sensitivity Analysis: Flywheel Cost
3. Energy Saving Sensitivity (Analysis 3/3)

Here, it was assumed that energy savings were +25 percent and -50 percent of the baseline analysis. As shown in Figure 5-12, the effect on the ROI was insignificant.

Concurrent Electrification and WESS

As for the electrified railroad scenario, it is assumed that the AT&SF dispatching policy is unaltered by the changeover from diesel to electric operation. This means that in 1990, some 395 diesel locomotives in use on this route may be transferred and replaced by 209 electric locomotives. Each year, the replacement of 26 diesel locomotives will be saved.

Other savings resulting from the change in locomotive type (idling fuel and maintenance) are tabulated in Volume 3.

1. Baseline (Analysis 4/1)

In this baseline analysis the following is assumed:

- Flywheel, $0.270 million/Mwhr stored
- Energy saving, as calculated by TPC

![Figure 5-12. Los Angeles to Belen Electrified Railroad Sensitivity Analysis: Energy Savings](5-11)
Figure 5-13 shows the large initial investment required when considering electrification and WESS. The ROI increases as the number of locations increases until a maximum ROI is reached at more than 18 grades. This is because the site-dependent savings are larger when compared with the site-dependent costs since electrification is route-dependent in this scenario. (See Volume 3.) The low ROIs determined for this scenario are put into perspective in the discussion of the "electrification only" case, para 4 below.

2. Flywheel Cost Sensitivity (Analysis 4/2)

In this analysis, flywheel costs of ±50 percent from the baseline were assumed. The results are shown in Figure 5-14, from which it can be seen that the flywheel cost does not unduly affect the ROI for WESS deployment.

3. Energy Saving Sensitivity (Analysis 4/3)

Here, energy savings of ±25 percent and -50 percent from the baseline were assumed. As shown in Figure 5-15, the maximum effect is to reduce the ROI for 18 locations by 7 percent, which is insignificant.

4. Electrification Only (Analysis 4/4)

The purpose of this analysis is to test the benefit of incorporating WESS at the same time as an electrification scheme is implemented. It may be seen from Figure 5-16 that the ROI can be increased by up to 22 percent if...
Figure 5-14. Los Angeles to Belen Concurrent Electrification and WESS Sensitivity Analysis: Flywheel Cost

Figure 5-15. Los Angeles to Belen Concurrent Electrification and WESS Sensitivity Analysis: Energy Saving
WESS is added to the electrification scheme. It is known that typically, the railroad's own studies (but not necessarily for AT&SF on this route) generally show an ROI for electrification of 15 to 17 percent. The low value calculated in this economic study represents an extremely conservative approach and the assumption of worst-case conditions throughout.

Summary of WESS Application on AT&SF

The above analysis shows that WESS, when applied to a diesel railroad between Los Angeles and Belen using dual-mode locomotives, is economically attractive. The electric helper scenario is not economically attractive and would probably not be acceptable from the operational standpoint.

If the route were already electrified, WESS could be installed on at least 18 grades with an attractive ROI.

Should AT&SF decide to electrify this route, then the application of WESS would significantly enhance the economic justification for that electrification.

The only variable to which the results are particularly sensitive is the cost of the dual-mode locomotive. For this reason a detailed analysis was carried out to determine this cost (see Section 2 of this report).

Figure 5-16. Los Angeles to Belen, Electrification Only
The Los Angeles-Salt Lake City route of UP is characterized as a mixed traffic route that operates at power/ratios of up to 5 hp/GT and that currently has a total traffic level of some $39 \times 10^6$ GTT/year. The route negotiates the Southern California mountains during its 782 route miles, which 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 10). Zero growth has been assumed beyond 1990. The results of the power and energy calculations are shown in Table 5-2 for the entire route.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Annual Energy Saving at 1990 Traffic Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dual mode</td>
<td>22.04 Mgal</td>
</tr>
<tr>
<td>Electric helper</td>
<td>19.84 Mgal</td>
</tr>
<tr>
<td>Electrified railroad</td>
<td>237,000 Mwhr</td>
</tr>
</tbody>
</table>

The results of the sensitivity analyses are discussed below.

Dual-Mode Locomotive Scenario

The UP dispatching policy requires that medium-sized trains attain a minimum speed on the ruling grade of 17.5 mph. To be conservative, it has been assumed that the dual-mode locomotive utilization will be 4.44 locomotives per $10^9$ GTM/year, compared with 6.8 locomotives per $10^9$ GTM/year for the existing diesel fleet.

Therefore, 266 diesel locomotives will be required in 1990 on this route, compared with 174 dual-mode locomotives. This results in a saving of 92 diesel locomotives that may be transferred to other duties. Assuming that locomotives are replaced on a 15-year cycle, the reduction in fleet size by 92 locomotives results in an annual saving of 6 replacement locomotives.

Other savings resulting from the reduction in fleet size are calculated in Section 4 and are tabulated in Volume 3.

1. Baseline (Analysis 1/1)

In this baseline analysis, the following assumptions were made:

- Flywheel, $0.270$ million/Mwhr stored
Dual-mode conversion, $0.211 million

- Energy saving, as calculated by TPC

Figure 5-17 shows the results of the baseline analysis and it can be seen that the ROI increases as the number of locomotives decreases. This is because the major savings are achieved by the route-dependent rather than the site-dependent factors. The decision as to how many grades would be equipped with WESS depends on:

(a) Funding level available

(b) Whether other projects exist that show a better ROI. That is, there may not be a project that can show an ROI greater than that for seven locations, in which case seven locations would be equipped.

2. Flywheel Cost Sensitivity (Analysis 1/2)

In this analysis, flywheel costs ranging ±50 percent from the baseline are assumed; the results of the study are shown in Figure 5-18. The ROI is not significantly affected by the change in flywheel cost because the major portion of the system costs are route-dependent and constant.

Figure 5-17. Los Angeles to Salt Lake City Dual-Mode Locomotive: Baseline Case
Figure 5-18. Los Angeles to Salt Lake City Dual-Mode Locomotive Sensitivity Analysis: Flywheel Cost

Figure 5-19. Los Angeles to Salt Lake City Dual-Mode Locomotive Sensitivity Analysis: Dual-Mode Locomotive Cost
3. Dual-Mode Locomotive Cost Sensitivity (Analysis 1/3)

In this analysis, it is assumed that costs of the dual-mode locomotive range ±50 percent from the baseline analysis, as shown in Figure 5-19. The 50 percent increase in locomotive cost results in a 10 percent change in ROI. This is the most sensitive variable.

4. Energy-Saving Sensitivity (Analysis 1/4)

Here, it is assumed that energy-saving levels are ~25 percent and ~50 percent of the baseline analysis. The purpose of this analysis is to test the sensitivity of the results to differences in railroad policy and driving techniques as far as the use of electric braking is concerned. The results are shown in Figure 5-20 and it may be seen that the results are not very sensitive to the level of energy saving assumed because most cost and credit elements are route-dependent.

5. Dual-Mode Locomotive Only (Analysis 1/5)

The purpose of this analysis is to define the benefit of the WESS when applied to a dual-mode railroad. The results are shown in Figure 5-21, from which it can be seen that the addition of WESS to a project to convert a railroad to dual-mode operation would result in an increase in the ROI of 21.5 percent.

Electric Helper Scenario

The same locomotive fleet economies calculated from the dual-mode locomotive scenario apply to this scenario. The increase in journey time resulting from this method of operation has not been quantified due to lack of information from the railroad.

1. Baseline (Analysis 2/1)

In this baseline analysis, the following assumptions are made:

- Flywheel cost, $0.270 million/Mwhr stored
- Energy saving, as calculated by TPC

Figure 5-22 shows the results of the baseline analysis and it can be seen that, as in the case of the dual-mode locomotive, the ROI increases as the number of locations decreases. The logic of the dual-mode locomotive scenario also applies to this scenario. The relatively low ROI (5 percent maximum) and the inept operations procedure involved make it doubtful whether this scenario would be considered past this study. Examination of Figure 5-22 shows that the ROI quickly decreases until a negative value is reached. These values have not been plotted because the computer program was not equipped to deal with negative ROI's and the results may be erroneous.
Figure 5-20. Los Angeles to Salt Lake City Dual-Mode Locomotive Sensitivity Analysis: Energy Saving

Figure 5-21. Los Angeles to Salt Lake City, Dual-Mode Locomotive Only
Figure 5-22. Los Angeles to Salt Lake City Electric Helper: Baseline Case

2. **Flywheel Cost Sensitivity (Analysis 2/2)**

For this analysis, it was assumed that flywheel costs varied ±50 percent from the baseline. As shown in Figure 5-23, the ROI is not significantly affected by the change in flywheel cost because most of the flywheel costs are route-dependent and constant.

3. **Energy Saving Sensitivity (Analysis 2/3)**

Here energy savings ranging ±25 percent and -50 percent from the baseline analysis were assumed. From Figure 5-24, it may be seen that the results are not unduly affected by the variation in energy saving at the low ROI's considered in this case.

4. **Electric Helper Only (Analysis 2/4)**

The purpose of this analysis is to define the benefit of WESS when applied to a railroad that makes extensive use of electric helpers. It will be seen from the analysis in Volume 3 that the electric helper scenario alone cannot achieve a positive ROI on the UP route, thus confirming the undesirability of this scenario.
Figure 5-23. Los Angeles to Salt Lake City Electric Helper Sensitivity Analysis: Flywheel Cost

Figure 5-24. Los Angeles to Salt Lake City Electric Helper Sensitivity Analysis: Energy Saving
Electrified Railroad Scenario

Assuming no change in the UP dispatching policy and the average locomotive utilization of 3.6 locomotives per 10^9 TM/year, 141 electric locomotives will be required to operate this route in 1990. Also, because they are assumed to exist, these locomotives will require modification to a regenerative system. Because the base performance at the locomotive remains unaltered, there is no reduction in the fleet size.

1. Baseline (Analysis 3/1)

In the baseline analysis, the following is assumed:

- Flywheel cost, $0.270 million/Mwhr stored
- Energy saving, as calculated by TPC

Figure 5-25 shows the results of the baseline analysis and it can be seen that as the number of locations increases, so does the ROI until a maximum value is reached at nine grades. This maximum ROI (23.33 percent) occurs when the weighting of the site-dependent costs and savings is the same as the weighting of the route-dependent costs in the ROI calculation. It is because the site-dependent costs and savings predominate for the lower number of locations that the ROI increases, whereas in the two scenarios previously considered, route-dependent elements predominated throughout.

2. Flywheel Cost Sensitivity (Analysis 3/2)

In this analysis, flywheel costs ranging +50 percent from the baseline were assumed, as shown in Figure 5-26. The maximum deviation in ROI due to increased cost of the flywheel is less than 10 percent.

3. Energy Saving Sensitivity (Analysis 3/3)

Here, it was assumed that energy savings were +25 percent and -50 percent of the baseline analysis. As shown in Figure 5-27, the effect on the ROI was not significant.

Concurrent Electrification and WESS

As for the electrified railroad scenario, it is assumed that the UP dispatching policy is unaltered by the changeover from diesel to electric operation. This means that in 1990, some 266 diesel locomotives in use on this route may be transferred and replaced by 141 electric locomotives. Each year, the replacement of 8 diesel locomotives will be saved.

Other savings resulting from the change in locomotive type (idling fuel and maintenance) are tabulated in Volume 3.
Figure 5-25. Los Angeles to Salt Lake City Electrified Railroad: Baseline Case

Figure 5-26. Los Angeles to Salt Lake City Electrified Sensitivity Analysis: Flywheel Cost
1. Baseline (Analysis 4/1)

In this baseline analysis the following is assumed:

- Flywheel, $0.270 million/MWhr stored
- Energy saving, as calculated by TPC

Figure 5-28 shows the relatively large initial investment required when considering electrification and WESS. The ROI increases as the number of locations increases until a maximum ROI is reached at more than 10 grades. This is because the site-dependent savings are larger when compared with the site-dependent costs since electrification is route-dependent in this scenario (see Volume 3). The low ROI's determined for this scenario are put into perspective in the discussion of the "electrification only" case, para. 4. below.

2. Flywheel Cost Sensitivity (Analysis 4/2)

In this analysis, flywheel costs of ±50 percent from the baseline were assumed. The results are shown in Figure 5-29, from which it can be seen that the flywheel cost does not significantly affect the ROI for WESS deployment.
Figure 5-28. Los Angeles to Salt Lake City Concurrent Electrification and WESS: Baseline Case (4/1)

Figure 5-29. Los Angeles to Salt Lake City Concurrent Electrification and WESS Sensitivity Analysis: Flywheel Cost
3. Energy Saving Sensitivity (Analysis 4/3)

Here, energy savings of +25 percent and -50 percent from the baseline were assumed. As shown in Figure 5-30, the maximum effect is to reduce the ROI for 10 locations by 6 percent, which is insignificant.

4. Electrification Only (Analysis 4/4)

The purpose of this analysis is to test the benefit of incorporating WESS at the same time as an electrification scheme is implemented. It may be seen from Figure 5-31 that the ROI can be increased by up to 16 percent if WESS is added to the electrification scheme. It is known that typically the railroad's own studies (but not necessarily for UP on this route) generally show an ROI for electrification of 15 to 17 percent. The low value calculated in this economic study represents an extremely conservative approach and the assumption of worst-case conditions throughout.

Summary of WESS Application on UP

The above analysis shows the WESS, when applied to a diesel railroad between Los Angeles and Salt Lake City using dual-mode locomotives, is economically attractive. The electric helper scenario is not economically attractive and would probably not be acceptable from the operational standpoint.

If the route were already electrified, WESS could be installed on at least 10 grades with an attractive ROI.

Should UP decide to electrify this route, then the application of WESS would significantly enhance the economic case for that electrification.

The only variable to which the results are particularly sensitive is the cost of the dual-mode locomotive. For this reason a detailed analysis was carried out to determine this cost as shown in Section 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 10) and therefore zero growth has been assumed. The results of the power and energy calculations are shown in Table 5-3.
Figure 5-30. Los Angeles to Salt Lake City Concurrent Electrification and WESS Sensitivity Analysis: Energy Saving

Figure 5-31. Los Angeles to Salt Lake City: Electrification Only
The results of the sensitivity analyses are discussed below.

### Dual-Mode Locomotive Scenario

The Conrail dispatching policy requires that medium-sized trains attain a minimum speed on the ruling grade of 11 mph. To be conservative, it has been assumed that the dual-mode locomotive utilization will be 5.1 locomotives per $10^9$ GTM/year, compared with 6.8 locomotives per $10^9$ GTM/year for the existing diesel fleet.

Even assuming zero traffic growth, 190 diesel locomotives will be required in 1990 on this route, compared with 142 dual-mode locomotives. This results in a saving of 48 diesel locomotives that may be transferred to other duties. Assuming that locomotives are replaced on a 15-year cycle, the reduction in fleet size by 48 locomotives results in an annual saving of 3 replacement locomotives.

Other savings resulting from the reduction in fleet size are calculated in Section 4 and are tabulated in Volume 3.

1. **Baseline (Analysis 1/1)**

In this baseline analysis, the following assumptions were made:

- Flywheel, $0.270$ million/Mwhr stored
- Dual-mode conversion, $0.211$ million
- Energy saving, as calculated by TPC

Figure 5-32 shows the results of the baseline analysis and it can be seen that the ROI increases as the number of locomotives decreases. This is because the major savings are achieved by the route-dependent rather than the site-dependent factors. The decision as to how many grades would be equipped with WESS depends on:

(a) Funding level available
(b) Whether other projects exist that show a better ROI. That is, there may not be a project that can show an ROI greater than that for three locations, in which case three locations would be equipped.

2. **Flywheel Cost Sensitivity (Analysis 1/2)**

In this analysis, flywheel costs ranging ±50 percent from the baseline are assumed; the results of the study are shown in Figure 5-33. The ROI is not significantly affected by the change in flywheel cost because the major portion of the system costs is route-dependent and constant.

3. **Dual-Mode Locomotive Cost Sensitivity (Analysis 1/3)**

In this analysis, it is assumed that costs of the dual-mode locomotive range ±50 percent from the baseline analysis, as shown in Figure 5-34. The 50 percent increase in locomotive cost results in a 20 percent change in ROI. This is the most sensitive variable.

4. **Energy-Saving Sensitivity (Analysis 1/4)**

In this analysis, it is assumed that energy-saving levels are ±25 percent and -50 percent of the baseline analysis. The purpose of this analysis is to test the sensitivity of the results to differences in railroad policy and driving techniques as far as the use of electric braking is concerned. The results
Figure 5-33. Harrisburg to Pittsburgh Dual-Mode Locomotive Sensitivity Analysis: Flywheel Cost

Figure 5-34. Harrisburg to Pittsburgh Dual-Mode Locomotive Sensitivity Analysis: Dual-Mode Locomotive Cost
are shown in Figure 5-35 and it may be seen that the results are not very sensitive to the level of energy saving assumed because most cost and credit elements are route-dependent.

5. Dual-Mode Locomotive Only (Analysis 1/5)

The purpose of this analysis is to define the benefit of the WESS when applied to a dual-mode railroad. The results are shown in Figure 5-36, from which it can be seen that the addition of WESS to a project to convert a railroad to dual-mode operation would result in an increase in the ROI of 19 percent.

Electric Helper Scenario

The same locomotive fleet economics calculated from the dual-mode locomotive scenario apply to this scenario. The increase in journey time resulting from this method of operation has not been quantified due to lack of information from the railroad.

1. Baseline (Analysis 2/1)

In this baseline analysis, the following assumptions are made:

- Flywheel cost, $0.270 million/Mwhr stored
- Energy saving, as calculated by TPC

The analysis results given in Volume 3 show that this scenario has a positive ROI for site 1 only—an ROI of 2.06 percent. Therefore, the sensitivity analyses are plotted for site 1 only by depicting ROI and initial investment against the percentage of change in the variable under consideration. This confirms the undesirability of this scenario, but does not have any relevance to the existing diesel helper operation on this route.

2. Flywheel Cost Sensitivity (Analysis 2/2)

For this analysis, it was assumed that flywheel costs varied +50 percent from the baseline. As shown in Figure 5-37, the ROI is not significantly affected by the change in flywheel cost because most of the flywheel costs are route-dependent and constant.

3. Energy Saving Sensitivity (Analysis 2/3)

Here energy savings ranging +25 percent and -50 percent from the baseline analysis were assumed. From Figure 5-38, it may be seen that the energy savings do have an effect on this already very low ROI.

4. Electric Helper Only (Analysis 2/4)

The purpose of this analysis is to define the benefit of WESS when applied to a railroad that makes extensive use of electric helpers. The unattractive results of this scenario are confirmed by the results of analysis 2/4 in Volume 3, where it can be seen that the electric helper alone cannot achieve a positive ROI.
Figure 5-35. Harrisburg to Pittsburgh Dual-Mode Locomotive
Sensitivity Analysis: Energy Saving

Figure 5-36. Harrisburg to Pittsburgh, Dual-Mode Locomotive Only
Figure 5-37. Harrisburg to Pittsburgh Electric Helper Sensitivity Analysis: Flywheel Cost

Figure 5-38. Harrisburg to Pittsburgh Electric Helper Sensitivity Analysis: Energy Saving
Electrified Railroad Scenario

Assuming no change in the Conrail dispatching policy and the average locomotive utilization of 3.6 locomotives per 10^9 TM/year, 100 electric locomotives will be required to operate this route in 1990. Also, because they are assumed to exist, these locomotives will require modification to a regenerative system. Because the base performance at the locomotive remains unaltered, there is no reduction in the fleet size.

1. Baseline (Analysis 3/1)

In the baseline analysis, the following is assumed:

- Flywheel cost, $0.270 million/Mwhr stored
- Energy saving, as calculated by TPC

Figure 5-39 shows the results of the baseline analysis and it can be seen that as the number of locations increases, so does the ROI.

2. Flywheel Cost Sensitivity (Analysis 3/2)

In this analysis, flywheel costs ranging ±50 percent from the baseline were assumed. As shown in Figure 5-40, the ROI is not significantly affected by the increased cost of the flywheel.

3. Energy Saving Sensitivity (Analysis 3/3)

Here, it was assumed that energy savings were ±25 percent and -50 percent of the baseline analysis. As shown in Figure 5-41, the effect on the ROI was only significant for the extreme case of saving only 50 percent of the calculated energy.

Concurrent Electrification and WESS

As for the electrified railroad scenario, it is assumed that the Conrail dispatching policy is unaltered by the changeover from diesel to electric operation. This means that in 1990, some 188 diesel locomotives in use on this route may be transferred and replaced by 100 electric locomotives. Each year, the replacement of 6 diesel locomotives will be saved.

Other savings resulting from the change in locomotive type (idling fuel and maintenance) are tabulated in Volume 3.

1. Baseline (Analysis 4/1)

In this baseline analysis the following is assumed:

- Flywheel, $0.270 million/Mwhr stored
- Energy saving, as calculated by TPC
Figure 5-39. Harrisburg to Pittsburgh Electrified Railroad, Baseline Case (3/1)

Figure 5-40. Harrisburg to Pittsburgh Electrified Railroad Sensitivity Analysis: Flywheel Cost
Figure 5-41. Harrisburg to Pittsburgh Electrified Railroad Sensitivity Analysis: Energy Saving

Figure 5-42 shows the large initial investment required when considering electrification and WESS. The ROI increases slightly as the number of locations increases until a maximum ROI is reached at more than 18 grades. The low ROI's determined for this scenario are put into perspective in the discussion of the "electrification only" case, para 4 below.

2. Flywheel Cost Sensitivity (Analysis 4/2)

In this analysis, flywheel costs of ±50 percent from the baseline were assumed. The results are shown in Figure 5-43, from which it can be seen that the flywheel cost does not unduly affect the ROI for WESS deployment.

3. Energy Saving Sensitivity (Analysis 4/3)

Here, energy savings of ±25 percent and -50 percent from the baseline were assumed. As shown in Figure 5-44, the maximum effect is to reduce the ROI for 18 locations by 4 percent, which is insignificant.

4. Electrification Only (Analysis 4/4)

The purpose of this analysis is to test the benefit of incorporating WESS at the same time as an electrification scheme is implemented. It may be seen from Figure 5-45 that the ROI can be increased by up to 10 percent if WESS is added to the electrification scheme. It is known that typically, the railroad's own studies (but not necessarily for Conrail on this route) generally
Figure 5-42. Harrisburg to Pittsburgh Concurrent Electrification and WESS: Baseline Case (4/1)

Figure 5-43. Harrisburg to Pittsburgh Concurrent Electrification and WESS Sensitivity Analysis: Flywheel Cost
Figure 5-44. Harrisburg to Pittsburgh Concurrent Electrification and WESS Sensitivity Analysis: Energy Saving

Figure 5-45. Harrisburg to Pittsburgh Concurrent Electrification and WESS Sensitivity Analysis: Electrification Only
show an ROI for electrification of 15 to 17 percent. The low value calculated in this economic study represents an extremely conservative approach and the assumption of worst-case conditions throughout.

Summary of WESS Application on Conrail

The above analysis shows the WESS, when applied to a diesel railroad between Harrisburg and Pittsburg using dual-mode locomotives, is economically attractive. The electric helper scenario is not economically attractive and would probably not be acceptable from the operational standpoint.

If the route were already electrified, WESS could be installed on at least 18 grades with an attractive ROI.

Should Conrail decide to electrify this route, then the application of WESS would significantly enhance the economic case for that electrification.

The only variable to which the results are particularly sensitive is the cost of the dual-mode locomotive. For this reason a detailed analysis was carried out to determine this cost as shown in Section 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 main line U.S. railroad system. The railroad currently has a traffic level of $18.2 \times 10^6$ 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 5-4 for the entire route, which is treated as one grade for the purpose of the calculations.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Annual Energy Saving</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric railroad</td>
<td>12,000 Mwhr</td>
</tr>
</tbody>
</table>

The results of the sensitivity analyses are discussed below.

Timetable Variations (Analysis 3/1)

Because the energy charge is extremely low, the major saving from the deployment of WESS on this railroad is attributable to the reduction in demand charges the railroad must pay to the Navajo-Tribal Utility Authority (NTUA). The peak 1-hr demand in any 1-hr period sets the demand rate for the next
12 mos and is charged at $5.09/kw/mo. Therefore, this analysis tests methods of inherently reducing the demand charge by operating a larger number of smaller trains rather than the few large trains which are operated at this time. Figure 5-46 shows the existing timetable used in analysis 3/1A; Figures 5-47 and 5-48 show the proposed timetables used for analyses 3/1B and 3/1C, respectively. Discussions with BM&LP did not identify any objections to these timetable changes, provided that the additional labor required was included in the economic analysis.

From Volume 3, it can be seen that the resulting ROI's are:

- Current timetable (3/1A), 10.12 percent
- 25-hr timetable (3/1B), 17.26 percent
- 24-hr timetable (3/1C), 12.82 percent

For this study, analysis 3/1R was taken as the baseline case in the subsequent sensitivity analyses.

**Flywheel Cost Sensitivity (Analysis 3/2)**

In this analysis, flywheel costs of +50 percent from the baseline are assumed. The results are shown in Figure 5-49. Since the flywheel cost is the major cost item, it can be seen that the increase in flywheel cost reduces the ROI by 17 percent.

**Energy Saving (Analysis 3/3)**

In this analysis energy saving levels +25 percent and -50 percent of the baseline analysis are used. The purpose of this analysis is to test the sensitivity of the results to differences in driving techniques, as far as the use of the electric brake is concerned. From the results shown in Figure 5-50, the ROI is insensitive to the energy savings because the value of the energy savings is low, compared with the value of the demand savings.

**Summary of WESS Operation on BM&LP**

The above analysis shows that the application of WESS to the already-electrified BM&LP railroad is economically attractive, provided that changes are made to the operating timetable. The only variable to which the results are particularly sensitive is the flywheel cost. For this reason, a detailed analysis was carried out to determine this cost, as shown in Section 3 of this report.
Figure 5-46. Existing BM&LP Timetable

Figure 5-47. Proposed 24-hr Cycle Timetable on BM&LP
Figure 5-48. Proposed 24-hr Cycle Timetable on BM&LP

Figure 5-49. BM&LP Electrified Railroad Sensitivity Analysis: Flywheel Cost
Figure 5-50. BM&LP Electrified Railroad Sensitivity Analysis: Energy Saving
The results of the Wayside Energy Storage Study have shown the operational feasibility and economic advantages of the wayside energy storage system (WESS). This concept may be employed on either fully electrified railroads or on present diesel routes by electrifying grades and using dual-mode locomotives. On this basis, a development program that will lead to the ultimate widespread deployment of WESS has been formulated. The overall program is structured to initially address the areas of technical risk identified for the WESS concept. Once these risks have been satisfactorily controlled, the program follows a logical process of design, fabrication, testing, and demonstration of the WESS concept.

The three major areas of risk identified in the study are the following:

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

The development program will continue to address these risks until their complete resolution makes this no longer necessary. The first phase of the three-phase development program comprises design studies; these are followed by detailed design of the complete WESS system in suitable form for a Phase I demonstration at the Pueblo Transportation Test Center. The third phase of the program will entail full-scale deployment of a WESS system on an operating railroad like Black Mesa and Lake Powell. The proposed schedule for the development program is shown in Figure 6-1.

PHASE I, DESIGN AND DEVELOPMENT

This program will start with a series of design studies to establish that the three risk areas can be controlled throughout the entire program. These studies will be followed by the detailed design of all the elements of the WESS system required for demonstration of both dual-mode locomotive and electrified railroad operations at a test site—probably Pueblo. The result of the Phase I program will be a complete set of drawings prepared for fabrication and modification of equipment needed for a small-scale demonstration of the system.

The details of the proposed Phase I design and development program are presented below in the form of a series of task descriptions.

Dual-Mode Locomotive Design Study

The primary objective of the dual-mode design study is the determination of the practicality of modifying both new and existing diesel locomotives to the dual-mode configuration. As part of this study, the operation of the regenerative power converter to be used on the dual-mode locomotive along with its controls should be verified. The contractor will provide the necessary material, labor, facilities, and services to perform the following tasks:
DESIGN AND DEVELOPMENT.

EXPERIMENTAL PHASE

PROTOTYPE PHASE

YEARS FROM GO-AHEAD

Figure 6-1. WESS Development Program Schedule
1. **Task 1, Data Acquisition**

Gather necessary diesel locomotive data required for dual-mode modification design from locomotive manufacturers, FRA, and operating railroads.

2. **Task 2, Dual-Mode Modification Preparation Study**

Determine the extent of preparations (removing or moving existing equipment) which must be accomplished to both a new and a typical used EMD SD40 locomotive to permit modification to a dual-mode configuration. Where it is found necessary to move existing equipment, the contractor will show that adequate space for relocation exists on the locomotive.

3. **Task 3, Component Specifications**

Prepare a set of specifications suitable for procurement or modification of the complete set of components required to modify a diesel locomotive to a dual-mode configuration. The required components as a minimum will include the following:

- Pantograph
- Lightning arrester
- Vacuum/circuit breaker
- Grounding switch
- Main transformer
- High-tension cable
- Power converter
- Smoothing choke
- Traction motor (modification to separate excitation)
- Traction motor field supply
- Supply changeover switch
- Oil/air heat exchanger

4. **Task 4, Control Modifications**

Define control requirements for regenerative electric operation in sufficient detail to permit necessary redesign of existing locomotive controls for diesel locomotives.
5. **Task 5, Locomotive Structural Modifications**

Prepare a set of drawings that define modifications to the locomotive structure required to accommodate the installation of the new dual-mode locomotive components.

6. **Task 6, Installation Layouts**

Prepare a set of layout drawings that define the installation of the components that constitute the dual-mode locomotive modification. These drawings will include all necessary details on piping and ducting required for the installation.

7. **Task 7, Electrical Interconnection Drawings**

Prepare a complete set of electrical interconnection drawings sufficient for the installation of the dual-mode modification into a diesel locomotive.

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**Regenerative Electric Locomotive Design Study**

This study will be conducted to establish the practicality of modifying both new and existing electric locomotives to a full regenerative-electric configuration. The study will include the verification of the locomotive and its controls for regenerative operation. The contractor will provide the necessary material, labor, facilities, and services to perform the following tasks:

1. **Task 1, Data Acquisition**

   Gather necessary electric locomotive data required for the regenerative modification design from locomotive manufacturers, FRA, and operating railroads.

2. **Task 2, Modification Preparation Study**

   Determine the extent of preparations (removing or moving existing equipment) required to permit modification to a regenerative configuration for both a new and a typical used GE E60 locomotive. Where it is found necessary to move existing equipment, the contractor will show that adequate space for relocation exists on the locomotive.

3. **Task 3, Component Specifications**

   Prepare a set of specifications suitable for procurement or modification of the complete set of components required to modify an electric locomotive to a regenerative configuration. The required modifications as a minimum will include the following:

   - Converter modifications
   - Control modifications
4. Task 4, Electrical Interconnection Drawings

Prepare a complete set of electrical interconnection drawings sufficient for the installation of the regenerative modification into an electric locomotive.

Wayside Station Design Study

This study will be conducted to establish the complete feasibility of the wayside flywheel station including all of its components and the tie-in to an electric utility and the railroad electrification. The contractor will provide the necessary material, labor, facilities, and services to perform the following tasks:

1. Task 1, Flywheel Study

Review candidate flywheel configurations suitable for full-scale WESS application. Select the most logical configuration and conduct finite-element stress analyses to verify flywheel integrity and cycle life.

2. Task 2, Flywheel Ancillary Study

Conduct design studies at the following flywheel ancillaries and accessories:

- Hydrostatic bearing (bottom)
- Roller bearing (top)
- Seals
- Evacuation system
- Housing

3. Task 3, Installation Study

Determine the most economical and practical way to install the flywheel at a typical WESS station.

4. Task 4, Flywheel Machine Specification

Prepare a specification suitable for procurement of the flywheel machine.

5. Task 5, Converter Study

Review candidate power converter configurations suitable for the wayside flywheel station. Select the optimum converter configuration and prepare a complete specification suitable for procurement.
6. Task 6, Interface Study

Establish the suitability of electrification interfaces between the flywheel and electric utility, and between the flywheel and railroad.

Scale Model Flywheel Demonstration

The objective of this demonstration is to verify the design of the steel axial disc type of flywheel proposed for WESS by actually building and testing a scale model flywheel. The contractor will provide the necessary material, labor, facilities, and services to perform the following tasks:

1. Task 1, Flywheel Design

Design a 7.33-kwhr steel axial-disc flywheel rotor that operates at the same stress levels and energy density as a full-size WESS flywheel.

2. Task 2, Flywheel Fabrication

Fabricate the scale model flywheel rotor using similar techniques as proposed for large WESS flywheel.

3. Task 3, Flywheel Testing

Conduct a program of spin tests on the scale model flywheel rotor suitable to verify the power density, energy density, and cycle life predictions for the design.

4. Task 4, Test Data Analysis

Verify the suitability of the scale model flywheel design for the full-size WESS flywheel by analysis of the test data.

Dual-Mode Locomotive Detail Design

The objective of this task is to completely define the modification of either a new or typical used SD40 locomotive from its original diesel arrangement to a dual-mode configuration, making it suitable for operation either as a diesel locomotive or as a regenerative electric locomotive. The resulting drawing package will be suitable for the actual modification of locomotives that will take place during the Phase II program.

Regenerative Electric Locomotive Detail Design

In this task, the contractor will fully define the modifications to a new or existing GE E60 electric locomotive necessary to provide a full regenerative braking capability. The resulting drawing package will be suitable for the actual modification of locomotives, which will take place during the Phase II program.
Wayside Station Detail Design

The objective of this task is to fully define a flywheel wayside station that would be suitable for a WESS demonstration at Pueblo, adjacent to the high-voltage ac catenary electrified rail section. The drawing package will be suitable for the actual construction of the wayside station at Pueblo and will describe the design of a usable 1-Mwhr flywheel. All ancillaries and all equipment required for interface with the electric utility and the electrified railroad will be included.

The approximate cost of the entire Phase I Design and Development Program is $3 million (1977 dollars).

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 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 (1977 dollars).

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 (1977 dollars).

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 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. railroads 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 travelled 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 providing peak demand-shaving.

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.

7-1
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:

   **Large Flywheel**—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.

   **Dual-Mode Locomotive**—Although no problems are foreseen, the modification of an existing locomotive like the EMD Model SD-40 to a dual-mode configuration has not been previously accomplished.

   **Regenerative Electric Locomotive Operation**—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:

   **Dual-Mode Locomotive Design Study**—Confirm the physical and electrical feasibility of modifying an EMD Model SD-40 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).

   **Scale Model Flywheel**—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 flywheel 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 like Black Mesa and Lake Powell and the North East Corridor (NEC), or on routes that may be electrified such as the Conrail Pittsburgh to Harrisburg run.

4. A seminar on the latest WESS program results should be held to inform operating railroads on 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 1) 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


8-1/8-2
APPENDIX A
WAYSIDE STORAGE STUDY DUAL-MODE LOCOMOTIVE
STATEMENT OF WORK

INTRODUCTION

The dual-mode locomotive for use in conjunction with WESS is to be based on the conversion of the SD40 locomotive (and its derivative, the SD40-2) since this locomotive is the most commonly used in freight service on U.S. railroads.

A general arrangement of the locomotive is shown in Figure A-1 and a simplified schematic is shown in Figure A-2.

PREPARATORY WORK

The following preparatory work is required before the installation of new equipment.

Ballast

Where possible, the locomotives selected for this modification will comprise the light underframe model with little or no ballast to be removed; however, as necessary, for heavy frame locomotives, ballast may need to be removed in order to meet axle load limitations. The weight of the transformer is estimated at eight tons and the converter and choke at two tons.

Sandboxes

The sandboxes at each end of the locomotive are to be repositioned on the guard rail (similar to the DD-40-X locomotive). The associated sand delivery pipes to each truck and pneumatic connections are to be rerouted and extended as necessary to be compatible with the repositioned sandboxes.

Electrical Connection Box

The electrical connection box, mounted inside the short hood, is to be repositioned so that access is available from outside the locomotive. Attention to adequate sealing against rain, snow, sand, etc. is imperative.

Short Hood

The short hood is to be removed and extended in length by approximately 12 in. The top section is to be removable to facilitate transformer removal and replacement.

Alternately, the transformer tank may form part of the front hood assembly, thus reducing the cooling requirement on the oil/air heat exchanger.
1 PANTOGRAPH
2 TRANSFORMER
3 CONVERTER
4 CHOKE

Figure A-1. Layout of Equipment

Figure A-2. Secondary Mode Schematic
Cab Roof

The cab roof requires strengthening to provide adequate support for the roof equipment (pantograph, circuit breaker, etc.) and to afford protection for the crew in the event of a mishap involving damage to the pantograph. Reposition warning horns below roof line.

MAJOR ELECTRICAL EQUIPMENT

The following equipment will be supplied to the railroad for installation on the locomotive:

a. Roof equipment
b. HT cable
c. Transformer
d. Converter
e. Smoothing choke
f. Modified traction motors
g. Supply changeover switches
h. Traction motor field power supplies
i. Oil/air heat exchanger
j. Automatic power control equipment

ROOF EQUIPMENT

Install pantograph mounting feet insulators, roof through bushing and lightning arrester(s). Install pantograph and pneumatic air pipe to pantograph air system. Install vacuum circuit breaker.

HIGH TENSION (HT) CABLE

Install HT cable from roof through bushing in protective channel through cab area, under cab floor, and into transformer compartment.

MAIN TRANSFORMER

Install transformer mounting feet and mount transformer. Connect HT cable. Run four secondary cables in conduit or ducting from transformer to compressor compartment of locomotive. Cables to be rated at 3000 amps continuous. Transformer cooling oil pipes to be run to oil/air heat exchanger located in dynamic brake resistor cooling air stream or in traction motor cooling air duct. Rework front hood assembly as necessary.
COMPRESSOR COMPARTMENT

Install mountings for thyristor converter and choke and mount the equipment.

Provide cable connection between converter output and smoothing choke, rated at 6000 amp continuous.

Run cables from choke and output of converter to supply changeover switch located in electrical cabinet.

Run cables to dynamic brake grid compartment from stabilizing resistor thyristors and smoothing choke.

DYNAMIC BRAKE GRID COMPARTMENT

Install transformer oil/air heat exchanger above/below resistor grids and connect stabilizing resistor cables to existing dynamic brake grids. An alternative position for the heat exchanger is in the traction motor cooling air duct.

TRUCKS

Remove traction motors for reworking to separately excited traction motors. Refit after modification.

Weld automatic power control (APC) receiver mounting bracket to truck frame and mount APC receiver. Provide interface control wiring between APC receiver and pantograph control circuit.

WORK ASSOCIATED WITH SEPARATE EXCITATION OF TRACTION MOTORS

Run cables from alternator output terminals to traction motor field supply converter.

Install field control units in electrical cabinet and provide control wire interfaces with traction motor current monitoring devices (CMD) (to be installed in each motor leg), existing wheel slip/slide protection, converter logic, and dynamic brake demand.

CONTROL FUNCTIONS

Install supply changeover switch in electrical cabinet.

Provide cable to transmit throttle position from TH module to converter in compressor compartment.

Install pantograph control equipment.
Miscellaneous control system modifications are required to reduce engine speed to 700 rpm under power demand and inhibit dynamic brake when the pantograph is raised.

COMPLETED LOCOMOTIVE

Weigh locomotive to establish each wheel load and ballast as necessary.
TABLE B-1
MAN-HOUR COSTS

<table>
<thead>
<tr>
<th>Cost Item</th>
<th>Cost, Man-hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preparatory work</td>
<td></td>
</tr>
<tr>
<td>Remove ballast (where necessary)</td>
<td>80</td>
</tr>
<tr>
<td>Reposition sandboxes</td>
<td>32</td>
</tr>
<tr>
<td>Electrical connector box</td>
<td>48</td>
</tr>
<tr>
<td>Short hood</td>
<td>64</td>
</tr>
<tr>
<td>Strengthen cab roof</td>
<td>16</td>
</tr>
<tr>
<td>Reposition warning horns (if necessary)</td>
<td>8</td>
</tr>
<tr>
<td>Roof equipment</td>
<td></td>
</tr>
<tr>
<td>Install roof insulators</td>
<td>16</td>
</tr>
<tr>
<td>Install pantograph</td>
<td>8</td>
</tr>
<tr>
<td>Install vacuum circuit breaker</td>
<td>8</td>
</tr>
<tr>
<td>Manufacture and install roof busbars</td>
<td>24</td>
</tr>
<tr>
<td>Connect air supplies and control wires</td>
<td>8</td>
</tr>
<tr>
<td>High-tension cable</td>
<td></td>
</tr>
<tr>
<td>Installation and provision of channel</td>
<td>48</td>
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<tr>
<td>Main transformer</td>
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</tr>
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<td>Manufacture and install mountings</td>
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<td>Install transformer</td>
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<td>Connect cables to transformer</td>
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<td>Install cooling oil pipes</td>
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<tr>
<td>Rework front hood</td>
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<tr>
<td>Compressor compartment</td>
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<tr>
<td>Converter and choke mountings</td>
<td>24</td>
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<td>Install converter and choke</td>
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</tr>
<tr>
<td>Cable runs</td>
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<tr>
<td>Cost Item</td>
<td>Cost, Man-hr</td>
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<tr>
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<td>--------------</td>
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<tr>
<td>Dynamic brake grid compartment</td>
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<td>Install heat exchanger</td>
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<td>Connect cables</td>
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<tr>
<td>Connect oil pipes</td>
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</tr>
<tr>
<td>Trucks</td>
<td></td>
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<tr>
<td>Lift locomotive and remove trucks</td>
<td>20</td>
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<tr>
<td>Remove and replace traction motors</td>
<td>24</td>
</tr>
<tr>
<td>Automatic Power Control (APC) bracket</td>
<td>4</td>
</tr>
<tr>
<td>Mount APC equipment and control wiring</td>
<td>6</td>
</tr>
<tr>
<td>Retruck locomotive</td>
<td>24</td>
</tr>
<tr>
<td>Separately excited traction motors</td>
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<tr>
<td>Cables to power supplies from alternator</td>
<td>24</td>
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<tr>
<td>Install field control units</td>
<td>48</td>
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<tr>
<td>Install current monitoring device in each motor leg</td>
<td>24</td>
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<tr>
<td>Control modifications</td>
<td>60</td>
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<td>Control functions</td>
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<td>Cable from TH module to converter</td>
<td>4</td>
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<tr>
<td>Pantograph control equipment</td>
<td>24</td>
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<td>Miscellaneous control modifications</td>
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<td>Completed locomotive</td>
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<td>Weigh locomotive</td>
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<td>Short hood</td>
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<tr>
<td>Strengthen cab roof</td>
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<td>Vacuum circuit breaker</td>
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<td>Insulators</td>
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<td>Lightning arrester</td>
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<td>Main transformer</td>
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<td>High-tension cable</td>
<td>500</td>
</tr>
<tr>
<td>Converter</td>
<td>60,000</td>
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<tr>
<td>Smoothing choke</td>
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<tr>
<td>Traction motor modification</td>
<td>18,000</td>
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<tr>
<td>Traction motor field supplies</td>
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<tr>
<td>Supply changeover switches</td>
<td>8,000</td>
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<tr>
<td>Oil/air heat exchanger</td>
<td>5,000</td>
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<tr>
<td>Automatic power control equipment</td>
<td>2,000</td>
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<tr>
<td>Roof equipment</td>
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<td>Protective trunking</td>
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<td>Main transformer</td>
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<td>Mounting pads</td>
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<td>Conduit/ducting</td>
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<td>Cooling pipes</td>
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</tr>
<tr>
<td>-----------------------------------</td>
<td>---------</td>
</tr>
<tr>
<td>Compressor compartment</td>
<td></td>
</tr>
<tr>
<td>Mounting pads</td>
<td>300</td>
</tr>
<tr>
<td>Dynamic brake grid compartment</td>
<td></td>
</tr>
<tr>
<td>Oil/air heat exchanger mounting</td>
<td>100</td>
</tr>
<tr>
<td>Trucks</td>
<td></td>
</tr>
<tr>
<td>APC mounting bracket</td>
<td>100</td>
</tr>
<tr>
<td>Complete locomotive</td>
<td></td>
</tr>
<tr>
<td>Ballast (if required)</td>
<td>3,000</td>
</tr>
<tr>
<td>Cable cost (estimated)</td>
<td>10,000</td>
</tr>
<tr>
<td>TOTAL MATERIAL COST</td>
<td>$187,820</td>
</tr>
<tr>
<td>MODIFICATION COST</td>
<td>$211,492</td>
</tr>
</tbody>
</table>
GRADE IDENTIFICATION NUMBER 035

WASHINGTON

PORTLAND

BAKER

PLEASANT VALLEY

WEATHERBY

OREGON

IDAHO

POCATELLO

GRADE IDENTIFICATION NUMBER 035

UNION PACIFIC RAILROAD

OREGON DIVISION

TRAFFIC DENSITY

EASTBOUND $19.2 \times 10^6$ TON/YEAR

WESTBOUND $14.1 \times 10^6$ TON/YEAR

MILE POSTS

ELEVATION FEET (000)

340 360 380

350 360 370

1 2 3 4 5

Baker 341.30M.

Quintz 342.71FL.

Fording 351.52M.

Pleasant Valley 356.20M.

Durkee 366.79M.

Weatherby 377.40M.

360 380
GRADE IDENTIFICATION NUMBER 036

WASHINGTON

PORTLAND

OREGON

UNION JCT

LAGRANDE

POWDER

BAKER

IDAHO

POCATELLO

UNION PACIFIC RAILROAD
OREGON DIVISION

TRAFFIC DENSITY

EASTBOUND 19.2x10^6
TON/YEAR

WESTBOUND 14.1x10^6
TON/YEAR

C-2
GRADE IDENTIFICATION NUMBER 037

WASHINGTON

PORTLAND

MEACHAM

KAMELA

HILGARD

LA GRANDE

ENTERPRISE

OREGON

POCATELLO

IDaho

GRADE IDENTIFICATION NUMBER 037

UNION PACIFIC RAILROAD
OREGON DIVISION

TRAFFIC DENSITY
EASTBOUND 19.2x10^6 TON/YEAR
WESTBOUND 14.1x10^6 TON/YEAR
GRADE IDENTIFICATION NUMBER 056

[Diagram showing the geographic locations and mile posts of Laramie, Hermosa, Dale, Sherman, and Cheyenne with elevation and traffic density details.]

UNION PACIFIC RAILROAD
WYOMING DIVISION MAINLINE

TRAFFIC DENSITY
EASTBOUND $77 \times 10^6$ TON/Year
WESTBOUND $37 \times 10^6$ TON/Year

MILE POSTS
0 10 20 30 40 50 60 70

ELEVATION FEET (000)
0 6 7 8
GRADE IDENTIFICATION NUMBER 063

GRADE IDENTIFICATION NUMBER 063

UNION PACIFIC RAILROAD
IDAHO DIVISION — MAINLINE

TRAFFIC DENSITY
IN EACH DIRECTION
22.5x10^6 TON/YEAR
GRADE IDENTIFICATION NUMBER 088

UNION PACIFIC RAILROAD
UTAH DIVISION MAINLINE

TRAFFIC DENSITY
EASTBOUND 10.6x10^6 TON/YEAR
WESTBOUND 17.9x10^6 TON/YEAR
GRADE IDENTIFICATION NUMBER 089

UNION PACIFIC RAILROAD
CALIFORNIA/UTAH DIVISION
MAIN LINE

TRAFFIC DENSITY
EASTBOUND 14.9x10^6 TON/YEAR
WESTBOUND 13x10^6 TON/YEAR
GRADE IDENTIFICATION NUMBER 145

DULUTH MISSABE AND IRON RANGE

GRADE IDENTIFICATION NUMBER 145

DULUTH MISSABE AND IRON RANGE

MISSABE DIVISION

TRAFFIC DENSITY
25.7 x 10^6 TON/YEAR DOWNHILL
5.9 x 10^6 TON/YEAR UPHILL

C-11
GRADE IDENTIFICATION NUMBER 175 AND 176

GRADE IDENTIFICATION NUMBER 175

SOUTHERN PACIFIC RAILROAD
CASCADES II

TRAFFIC DENSITY
EASTBOUND $18.42 \times 10^6$ TON/YEAR
WESTBOUND $21.52 \times 10^6$ TON/YEAR

GRADE IDENTIFICATION NUMBER 176

SOUTHERN PACIFIC RAILROAD
CASCADES I

TRAFFIC DENSITY
EASTBOUND $16.02 \times 10^6$ TON/YEAR
WESTBOUND $19.02 \times 10^6$ TON/YEAR
GRADE IDENTIFICATION NUMBER 195

SOUTHERN PACIFIC RAILROAD
BEAUMONT HILL

TRAFFIC DENSITY
EAST BOUND $21.53 \times 10^6$ TON/YEAR
WESTBOUND $26.10 \times 10^6$ TON/YEAR
GRADE IDENTIFICATION NUMBERS 202, 206

GRADE IDENTIFICATION NUMBER 202

GRADE IDENTIFICATION NUMBER 206
GRADE IDENTIFICATION NUMBER 226

SPEED DATA NOT SUPPLIED

BURLINGTON NORTHERN
GARRISON — MISSOULA
TRAFFIC DENSITY
LESS THAN
20x10^6 TON/YEAR

GRADE IDENTIFICATION NUMBER 227

BURLINGTON NORTHERN
DE SMET — DIXON
TRAFFIC DENSITY
LESS THAN
20x10^6 TON/YEAR
GRADE IDENTIFICATION NUMBER 230

PENNSYLVANIA

PITTSBURGH
PITCAIRN
JOHNSTOWN
GALLITZIN
ALTOONA
HARRISBURG
PHILADELPHIA

SPEED DATA NOT SUPPLIED

CONSOLIDATED RAIL CORPORATION

HARRISBURG — PITTSBURGH
TRAFFIC DENSITY
56.8 x 10^6 TON/YEAR
IN EACH DIRECTION

C-18
GRADE IDENTIFICATION NUMBER 240

CALIFORNIA

SALT LAKE CITY

NEVADA

SPEED LIMITS SET BY AT&SF (NOT MADE AVAILABLE)

ATCHISON TOPEKA & SANTA FE UNION PACIFIC RAILROAD (LINES JOINTLY OPERATED)

CAJON PASS

TOTAL TRAFFIC DENSITY

30.1 x 10^6 TON/YEAR EASTBOUND

41 x 10^6 TON/YEAR WESTBOUND

C-19
GRADE IDENTIFICATION NUMBERS
242, 243, 244, 246, 247, 248

GRADE IDENTIFICATION NUMBER 242

ATCHISON TOPEKA & SANTA FE
NEEDLES — GOFFS

TRAFFIC DENSITY
EASTBOUND 26x10^6 TON/YEAR
WESTBOUND 32x10^6 TON/YEAR

MILEPOSTS
610 600 590 580 570

Elevation (feet)
0 1000 2000 3000

Track Design Mile/Hour
70 60 50 40 30 20 10 0

NEEDLES 978 ML. 423 FT
GOFFS 808 ML. 2980 FT
GRADE IDENTIFICATION NUMBER 243

ATCHISON TOPEKA & SANTA FE
FLAGSTAFF — CANYON DIABLO

TRAFFIC DENSITY
EASTBOUND 28x10^6 TON/YEAR
WESTBOUND 34x10^6 TON/YEAR

GRADE IDENTIFICATION NUMBER 244

ATCHISON TOPEKA & SANTA FE
BELLEMONTE — FLAGSTAFF

TRAFFIC DENSITY
EASTBOUND 28x10^6 TON/YEAR
WESTBOUND 34x10^6 TON/YEAR
GRADE IDENTIFICATION NUMBER 246

EAGLE NEST — WILLIAMS JUNCTION
TRAFFIC DENSITY
EASTBOUND 26x10^6 TON/YEAR
WESTBOUND 32x10^6 TON/YEAR

GRADE IDENTIFICATION NUMBER 247

HACKBERRY — PICA
TRAFFIC DENSITY
EASTBOUND 26x10^6 TON/YEAR
WESTBOUND 32x10^6 TON/YEAR

GRADE IDENTIFICATION NUMBER 248

TOPOCK — KINGMAN
TRAFFIC DENSITY
EASTBOUND 26x10^6 TON/YEAR
WESTBOUND 32x10^6 TON/YEAR
GRADE IDENTIFICATION NUMBER 252

Traffic Density

Eastbound: 26x10^6 TON/YEAR
Westbound: 33x10^6 TON/YEAR

GRADE IDENTIFICATION NUMBER 255

Traffic Density

Eastbound: 26x10^6 TON/YEAR
Westbound: 33x10^6 TON/YEAR
GRADE IDENTIFICATION
NUMBER 261

LOADED

EMPTY

TRACK DESIGN
SPEED LIMITS

BLACK MESA AND
LAKE POWELL
RAILROAD (ARIZONA)
TRAFFIC DENSITY
IN — 44,000
GTT/DAY
OUT — 9840
GTT/DAY
APPENDIX D

WESS FLYWHEEL COST ANALYSIS

ASSUMPTIONS

The following are assumed in this WESS flywheel cost analysis:

- **Flywheel capacity**: 7,333 MWhr
- **Rotor material**: Lukens Electro Slag Remelt 4340 Steel
- **Rotor weight**: 604.4 tons
- **Rotor diameter**: 13.5 ft
- **Rotor length**: 17.28 ft
- **Rotor material cost**: $0.60/lb
- **Material scrap value**: $0.15/lb

**ROTOR MATERIAL COST**

Based on through hardenability of 3 in.,

\[
\text{No. of rotor plates} = \frac{17.28}{0.25} = 69
\]

because the top and bottom plates are forgings. Also allow 0.25 in. for machining top and bottom plate surfaces; also allow 1 in. on the radius. Then,

\[
\text{Material weight} = (13.667)^2(12)^2(3.5)(0.283)(67) = 1,785,000 \text{ lb}
\]

\[
\text{Material cost} = (1,785,000)(0.6) = $1,071,000
\]

Actual material required = \((13.5)^2(12)^2(3)(0.283)(67)\pi/4 = 1,172,472 \text{ lb}

\[
\text{Scrap value} = (0.15)(612,528) = $91,872
\]

Total material cost = $979,121

**TOP AND BOTTOM FORGING MATERIAL COST**

\[
\text{Useful weight} = \frac{2.12}{69.12} (604.4)(2000) = 37,075 \text{ lb}
\]
But, assume that twice useful material is required for forging:

Material weight = 74,151 lb
Scrap weight = 37,075 lb

Material cost = (74,151)(0.6) - (37,075)(0.15) = $38,929

ROTOR PLATE PREPARATION COST

Labor hours for rotor plate preparation are as follows:

<table>
<thead>
<tr>
<th>Process</th>
<th>Labor Hr/Plate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flame cut to 13.67 ft diameter</td>
<td>4</td>
</tr>
<tr>
<td>Mill both sides to reach 3.1 in. thickness</td>
<td>8</td>
</tr>
<tr>
<td>Blanchard grind both sides 0.050 in.</td>
<td>16</td>
</tr>
<tr>
<td>Bore twenty-four 6-in. holes</td>
<td>12</td>
</tr>
<tr>
<td>Finish machine diameter to 13.5 ft</td>
<td>16</td>
</tr>
<tr>
<td>Heat treat</td>
<td>8</td>
</tr>
<tr>
<td>Inspection</td>
<td>6</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>70 hr</strong></td>
</tr>
</tbody>
</table>

Assume labor cost at $22/hr. Then,

Plate preparation cost = (67)(70)(22) = $103,180

TOP AND BOTTOM FORGING PREPARATION COST

Labor hours for top and bottom forging preparation are as follows:

<table>
<thead>
<tr>
<th>Process</th>
<th>Labor Hr/Plate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating and handling</td>
<td>24</td>
</tr>
<tr>
<td>Rough forging</td>
<td>80</td>
</tr>
<tr>
<td>Final forging</td>
<td>40</td>
</tr>
<tr>
<td>Bore twenty-four 6-in. holes</td>
<td>24</td>
</tr>
<tr>
<td>Final machining</td>
<td>160</td>
</tr>
<tr>
<td>Heat treat</td>
<td>12</td>
</tr>
<tr>
<td>Inspection</td>
<td>24</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>374 hr</strong></td>
</tr>
</tbody>
</table>

Total forging preparation cost = (2)(374)(22) = $16,456

THROUGH-BOLT COST

Assume machining from 6.5-in. rod.

Material weight = (24)(20)(12)(6.5)²(.283)π/4 = 54,091 lb.
Material cost (4340 steel) = (54,091)(0.6) = $32,455

Cost to fabricate:

<table>
<thead>
<tr>
<th>Process</th>
<th>Labor Hr/Bolt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turn to diameter</td>
<td>16</td>
</tr>
<tr>
<td>Cut threads (both ends)</td>
<td>16</td>
</tr>
<tr>
<td>Heat treat</td>
<td>4</td>
</tr>
<tr>
<td>Inspection</td>
<td>4</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>40 hr</strong></td>
</tr>
</tbody>
</table>

Total fabrication cost = (24)(40)(22) = $21,120

Through-bolt cost totals:

| Material | $32,455 |
| Fabrication | 21,120 |
| Nuts (48) | 7,200  |
| **Total Cost** | **$60,775** |

HOUSING MATERIAL COST

Housing material cost analysis is based on a 2-in.-thick conformal housing with reinforced top and bottom fabricated from 1020 grade steel (cost $0.20/lb). Housing height is 20 feet with an inside diameter of 13.7 ft.

Weight of cylinder = (14,033$^2$ - 13.7$^2$)(12)$^2$($\pi$)(12)(.283) = 71,012 lb

Weight of top and bottom = (2)(14.033$^2$)(12)$^2$($\pi$)(.283) = 32,100 lb

Total material cost = (0.2)(103,112) = $20,622

HOUSING FABRICATION COST

Labor hours for housing fabrication are as follows:

<table>
<thead>
<tr>
<th>Process</th>
<th>Labor Hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roll cylinder</td>
<td>160</td>
</tr>
<tr>
<td>Weld cylinder</td>
<td>80</td>
</tr>
<tr>
<td>Machine cylinder ends</td>
<td>80</td>
</tr>
<tr>
<td>Flame cut top and bottom</td>
<td>16</td>
</tr>
<tr>
<td>Reinforce top and bottom</td>
<td>80</td>
</tr>
<tr>
<td>Machine top and bottom</td>
<td>240</td>
</tr>
<tr>
<td>Inspection</td>
<td>64</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>720 hr</strong></td>
</tr>
</tbody>
</table>

Housing fabrication cost = (720)(22) = $15,840
TOP AND BOTTOM BEARING AND SEAL ASSEMBLY COST

Labor hours for top and bottom bearing and seal assembly are as follows:

<table>
<thead>
<tr>
<th>Process</th>
<th>Labor Hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machine top assembly</td>
<td>960</td>
</tr>
<tr>
<td>Machine bottom assembly</td>
<td>1200</td>
</tr>
<tr>
<td>Inspection</td>
<td>216</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>2376 hr</strong></td>
</tr>
</tbody>
</table>

Total fabrication cost = (2376)(22) = $52,272

Material including seals and bearings = $10,000

Total bearing and seal assembly cost = $62,272

ANCILLARIES AND ASSEMBLY MATERIAL COST

The cost for ancillaries and assembly material is:

2 High-pressure lube pumps $4000
2 Low-pressure lube pumps 1000
2 Vacuum pumps 3000
2 Heat exchanger systems 2000
2 Sumps 800
1 Air compressor 500
1 Air reservoir and controls 1500
6 Hydraulic jacks 6000
1 Set misc. assembly material 20000

Total Ancillary Cost $38,000

FLYWHEEL SHIPMENT COST

Assuming a rail shipment of 2500 miles, the quotation for flywheel shipment from ATSF and Conrail is $49,776.
FLYWHEEL ASSEMBLY AND TEST COST

Labor hours for flywheel assembly and test are as follows:

<table>
<thead>
<tr>
<th>Process</th>
<th>Labor Hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Install bottom housing and bearing</td>
<td>480</td>
</tr>
<tr>
<td>Stack flywheel discs</td>
<td>690</td>
</tr>
<tr>
<td>Assemble housing and top support</td>
<td>720</td>
</tr>
<tr>
<td>Install ancillaries</td>
<td>640</td>
</tr>
<tr>
<td>Install flywheel machine</td>
<td>480</td>
</tr>
<tr>
<td>Test rotating system</td>
<td>240</td>
</tr>
<tr>
<td>Disassemble and balance rotor</td>
<td>480</td>
</tr>
<tr>
<td>Reassemble</td>
<td>240</td>
</tr>
<tr>
<td>Conduct system tests</td>
<td>960</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>4930 hr</strong></td>
</tr>
</tbody>
</table>

Flywheel assembly and test cost = (4930)(22) = $108,460

COST SUMMARY

The preceding costs can be summarized as follows:

<table>
<thead>
<tr>
<th>Element</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor material</td>
<td>$1,071,000</td>
</tr>
<tr>
<td>Top and bottom forging material</td>
<td>38,929</td>
</tr>
<tr>
<td>Rotor plate preparation</td>
<td>103,180</td>
</tr>
<tr>
<td>Top and bottom forging preparation</td>
<td>16,456</td>
</tr>
<tr>
<td>Through-bolt</td>
<td>60,775</td>
</tr>
<tr>
<td>Housing material</td>
<td>20,622</td>
</tr>
<tr>
<td>Housing fabrication</td>
<td>15,840</td>
</tr>
<tr>
<td>Top and bottom bearing and seal assemblies</td>
<td>62,272</td>
</tr>
<tr>
<td>Ancillaries and assembly material</td>
<td>38,800</td>
</tr>
<tr>
<td>Flywheel shipment</td>
<td>49,776</td>
</tr>
<tr>
<td>Flywheel assembly and test</td>
<td>108,460</td>
</tr>
<tr>
<td><strong>Total Cost</strong></td>
<td><strong>$1,586,110</strong></td>
</tr>
</tbody>
</table>

Then,

Cost/Kwhr = $216.29

Assume general and administrative cost plus profit of 25 percent.

Final Cost/Kwhr of flywheel = $270
MAIN PROGRAM

STORAGE USED: CODE(1) 0000551 DATA(10) 000144 BLANK COMMON(2) 003321

COMMON BLOCKS:

0003 AAAAA 001230
0004 HHRRR 000070
0005 EEEEEE 000135

EXTERNAL REFERENCES (BLOCK NAME):

0006 MINTBC
0007 INPUT
0010 DETAIL
0011 MINTAS
0012 XERAS
0013 XSTOP

STORAGE ASSIGNMENT (BLOCK TYPE + RELATIVE LOCATION NAME):

0001 000026 IUL 0001 000465 13AG 0002 002727 AVIAB
0002 003128 PLLPP 0005 002723 BENFC
0002 001347 CQENG 0006 002777 COENG
0002 001476 DFSPP 0007 001476 DFSPP
0002 003137 STEPL 0008 002633 ELECP
0002 002633 ELECP 0009 014500 EMAFP
0002 001168 FSPPL 0009 001168 FSPPL
0002 001236 FLVPL 0010 001236 FLVPL
0000 000000 1 0011 002744 IFLAG
0003 001228 FPF 0012 002333 FPF
0002 002628 SHAM 0012 002628 SHAM
0002 000036 ROSTTB 0013 002390 ROSEP
0003 001472 YNCP 0013 001472 YNCP
0003 001474 WUI 0013 001474 WUI
0002 002741 XFFX 0014 002741 XFFX
0002 002741 XFFX 0015 002741 XFFX
0002 000026 STAHL 0015 000026 STAHL
0002 003060 TOSF 0015 003060 TOSF
0002 001541 TTP 0016 001541 TTP
0002 002774 TOTO8 0016 002774 TOTO8
0002 002717 TSAPL 0017 002717 TSAPL
0001 000070 ZMAGC 0017 000070 ZMAGC
00121  40  CALL 11:TTHU(14+30+19)
00122  50  \$134016,1110=13
00123  60  \$134016,1110=13
00124  70  \$134016,1110=13
00125  80  \$135476,11113=135
00126  90  \$135476,11113=135
00127  100  10  CONTINUE
00128  110  F(K,E)=
00129  120  CALL  INPUT
00130  130  HOSITE=HOSITE(1)WRITE
00131  140  NO 12  HOSITE
00132  150  HOSITE(11114)=HOSITE
00133  160  CALL  DFT
00134  170  GO  TO  10
00135  180  END

END OF COMPILETION  NO DIAGNOSTICS.
### Block Data

**Storage Used:** Code(1) 000001 Data(0) 000001 Blank Common(2) 083321

**Common Blocks:**

<table>
<thead>
<tr>
<th>Segment</th>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0003</td>
<td>AAAAAA</td>
<td>001230</td>
</tr>
<tr>
<td>0004</td>
<td>BBRRRR</td>
<td>000070</td>
</tr>
<tr>
<td>0005</td>
<td>VEEFEE</td>
<td>000135</td>
</tr>
</tbody>
</table>

**Storage Assignment (Block, Type, Relative Location, Name):**

<table>
<thead>
<tr>
<th>Block No.</th>
<th>Block Type</th>
<th>Relative Location</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>0002</td>
<td>H</td>
<td>002727</td>
<td>AUDLAB</td>
</tr>
<tr>
<td>0005</td>
<td>H</td>
<td>000001</td>
<td>AUDLAB</td>
</tr>
<tr>
<td>0007</td>
<td>H</td>
<td>001123</td>
<td>COSHUL</td>
</tr>
<tr>
<td>0009</td>
<td>H</td>
<td>000703</td>
<td>DISCON</td>
</tr>
<tr>
<td>0012</td>
<td>H</td>
<td>003111</td>
<td>ELECH9</td>
</tr>
<tr>
<td>0014</td>
<td>H</td>
<td>003203</td>
<td>EMAT9</td>
</tr>
<tr>
<td>0016</td>
<td>I</td>
<td>000001</td>
<td>FREE</td>
</tr>
<tr>
<td>0018</td>
<td>I</td>
<td>001140</td>
<td>FLY9S</td>
</tr>
<tr>
<td>0020</td>
<td>I</td>
<td>000004</td>
<td>IIIII</td>
</tr>
<tr>
<td>0022</td>
<td>I</td>
<td>000005</td>
<td>I-NAME</td>
</tr>
<tr>
<td>0024</td>
<td>I</td>
<td>000049</td>
<td>ISUN</td>
</tr>
<tr>
<td>0026</td>
<td>H</td>
<td>000100</td>
<td>LOC0SE</td>
</tr>
<tr>
<td>0028</td>
<td>H</td>
<td>000006</td>
<td>MUD1Y</td>
</tr>
<tr>
<td>0030</td>
<td>H</td>
<td>000002</td>
<td>NAS</td>
</tr>
<tr>
<td>0032</td>
<td>H</td>
<td>000102</td>
<td>R0EPL</td>
</tr>
<tr>
<td>0034</td>
<td>H</td>
<td>002776</td>
<td>ROUT9</td>
</tr>
<tr>
<td>0036</td>
<td>H</td>
<td>002735</td>
<td>R0JAR</td>
</tr>
<tr>
<td>0038</td>
<td>H</td>
<td>002713</td>
<td>SAVL9</td>
</tr>
<tr>
<td>0040</td>
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**Common Data:**

- Include Common/List
- DREG
- REAL
- LOGICAL
- INTEGRAL
- INTEGER
- COMMON
- INCLUDE

**Variables:**

- X1, X2, X3, X4, X5, X6, X7, X8, X9
- Y1, Y2, Y3, Y4, Y5, Y6, Y7, Y8, Y9

---

Note: The text contains FORTRAN coding statements and data structure definitions, typical for a computer program.
DATA IRH,

DATA IRH,

DATA IRH,

DATA IRH,

DATA IRH,

DATA IRH,

DATA IRH,

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Note: The rates used for annual costs (after 1993) are approximate and subject to change.
END OF COMPILATION: NO DIAGNOSTICS.
00125 14*
00126 15*
00127 16*
00128 17*
00130 18*
00131 19*
00132 20*
00133 21*
00134 22*
00135 23*
00136 24*
00137 25*
00138 26*
00140 27*
00141 28*
00142 29*
00144 30*
00146 31*
00147 32*
00150 33*
00151 34*
00152 35*
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00154 37*
00155 38*
00156 39*
00157 40*
00158 41*
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00160 43*
00164 44*
00165 45*
00166 46*
00167 47*
00168 48*
00169 49*
00170 50*
00171 51*
00172 52*
00173 53*
00174 54*
00175 55*
00176 56*
00177 57*
00178 58*
00179 59*

END OF COMPI#LATION: NO DIAGNOSTICS.

00180
00181
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00243
DO 100 I=1,N
I=NSUR(I)
FILYSC(I) = FLYSC(I,ROUTE) = FLYCOST(I)
FLYMA(I) = RECP(I,ROUTE) + 0.06
FLYCV(I) = RECP(I,ROUTE) + 0.03
TCOSFS(I) = FLYSC(I) + FLYMA(I) + FLYCV(I) + STABL(I,ROUTE)
100 CONTINUE
CALL MSK(FLYMA(I),TCOSFS(I))
C Detail = CALC INITIAL INVESTMENT
TRENEW(I,ROUTE) = TCDLOC(I,ROUTE) = COSW(I,ROUTE)
TCOMEW(I,ROUTE) = COSW(I,ROUTE) = COSTH(I,ROUTE)
TOTTTRA(I,ROUTE) = TOTTTRA(I,ROUTE) = COSTH(I,ROUTE)
DO 200 II=1,NOSITE
I=NSUR(I)
TSITEC(I) = SITE(I,ROUTE) + TCOSFS(I)
200 CONTINUE
C C * ANNUAL COSTS & CREDITS (1977 $)
C * ROUTE DEPENDENT
C * DETAIL = SITE RANKING *
C * SUM ANNUAL COSTS & CREDITS ROUTE DEPENDENT,
C ZUMACCZTSAVR(ROUTE) = TCDLOC(ROUTE) + TECDFW(ROUTE) +
C 1 ELENE(I,ROUTE) + TDSTM(I,ROUTE) + TDSTI(I,ROUTE) +
C 30ZUMACCZTSAVR(I)
C * SUM INITIAL INVEST. COSTS ROUTE DEPENDENT,
C ZUMINVW = TOTWE(I,ROUTE) + TOTDA(I,ROUTE) + TOTTTRA(I,ROUTE) + TOTTTRA(I,ROUTE) +
C 32ZUMINVW = ZUMINVW + ZUMINVW
C DO 300 II=1,NOSITE
C 340 CONTINUE
C 350 I=NSUR(I)
C 360 C * CALC NET ANNUAL SITE SAVINGS MILLIONS OF DOLLARS ( SODAVA(I) )
C 370 C ESRUPI(I,ROUTE) = ESRVPI(I,ROUTE) = 0.02/12*10000*TDENEW(I,ROUTE)
C 380 C 1 GTONS(I,ROUTE) = 1000000.
C 390 CONSTG(I) = 0.1
C 400 IF (ILSCN3) = CONSTG(I)
C 410 IF (ISFMTD) = CONSTG(I)
C 420 IF (TRENED) = CONSTG(I)
C 430 ESUTE(I,ROUTE) = ESRVPI(I,ROUTE) = TRENED(I,ROUTE) +
C 440 SODAVA(I) = SODAVA(I)
C 450 IF (TRAF(I,ROUTE) = TDENNINE(I,ROUTE) + TDENNINE(I,ROUTE) +
C 460 I=1,ROUTE)
C 470 C * CALC INITIAL SITE DEPENDENT COSTS $ = SODCS1(I)
C 480 C SODOCS(I) = TCOFS(I) + SODAVA(I)
C 490 C 1 GTONS(I,ROUTE) = 1.333
C 500 C 1 GTONS(I,ROUTE) = 1.333
C 510 240 IF (SODCS(I) = 0.01) = SODCS(I)
C 520 WRITE (6,240) SODCS(I)
C 530 SIGN = 1.0
C 540 IF (SODCS(I) = 0.01) = SIGN
C 550 IF (SODCS(I) = 0.01) = SIGN
C 560 240 CONTINUE
C 570 HECFC(I) = SODAVA(I) + SODCS(I)
C 580 HECFC(I) = SODAVA(I) + SODCS(I)
C 590 300 CONTINUE
C 600 C * SORT SITE RANKINGS
C 610 DO 314 II = 1,NOSITE
C 620 NSUR1(I) = NSUR(I)
C 630 NSUR1(I) = NSUR1(I)
C 640 I=1,NOSITE
C 650 314 CONTINUE
C 660 CALL THEBRENBEN (NOSITE)
0230 64  DO 316 I=1,NOSITE
0233 65  316 ISUM(I)=RANK(I)
0235 70  CALL TREE(ISUB(1),RANK(1))
0236 71  [IFLAG=1]
0237 72  CALL REPORT
0240 73  DO 319 I=1,NOSITE
0243 74  ISU8(I)=RANK(I)
0244 75  NSUB3(I)=NSUB(I)
0245 76  319 CONTINUE
0245 77  C  ** NEW RANK TECHNIQUE ** MAY 1978 PER L. COOK
0247 78  C  LOAD FIXED SITES INTO NSUB3(I)
0251 80  DO 333 I=1,NOSITE
0254 81  NSUB3(I)=FIX(I)
0254 83  C  ** LOAD SURFEL SITES (EXCLUDING FIXED OF COURSE) INTO REMAINING
0254 88  C  ** NSUB3(I) ALWAYS CELLS UP TO NSITE CELLS,.
0255 88  K=K+1
0257 88  DO 341 I=1,NOSITE
0262 88  E=K+1
0266 88  IF (NSUB3(I).EQ.FIX(K)) GO TO 342
0267 89  CONTINUE
0271 90  KSUKK=K
0272 90  NSUB3(KK)=SUB(I)
0273 91  341 CONTINUE
0275 92  343 CONTINUE
0276 93  AAANN=ZLMAAC
0277 94  BBBNEN=ZUMNV
0280 96  NOSTEM=NOFX
0301 96  350 CONTINUE
0302 97  NOSTEM(NOSTEM+1)
0303 98  IF (NOSTEM.EQ.NOSITE) GO TO 370
0305 99  DO 360 II=NOSTEM,NOSITE
0310 100  I=NSUB3(I)
0311 101  CURS=AAAAN+SDSAV(I)
0312 102  CURS=DBBEN+SDCSI(I)
0313 103  XDEM=CURSD
0314 104  IF (ABS(XDEM).LT.14) XDEM=1.4
0316 105  BENZ(I)=CURSN
0317 106  RHSN2(I)=RHSN2(I)
0320 107  360 CONTINUE
0322 108  NOUN=NOSTEM+1
0323 109  DD 362 J=1,NUM
0326 110  J=NOSTEM+1
0327 111  I=NSUB3(J)
0330 112  ROUM(J)=RBNZ2(I)
0331 113  NSUB(J)=J
0333 114  CALL TREE(ROUM,NSUB3,NOSITE)
0333 115  C  ** RELOAD NSUB3 & RBNZ2(I)
0334 116  DO 364 J=1,NOSITE
0337 117  J=NOSTEM+1
0339 119  NSUB3(J)=I
0341 120  RBNZ(I)=RDUM(J)
0343 121  364 CONTINUE
0345 122  AAAAN=AAAAN+SDSAV(NSUB3(NOSTEM))
0346 123  BBBNEN=BBBREN+SDCOSI(NSUB3(NOSTEM))
0347 124  DD 32A J=1,NOSITE
0350 125  370 CONTINUE
0351 126  DD 380 I=1,NOSITE
0354 127  NSUB3(I)=NSUB3(I)
00356 128* IFLAG=2
00357 129* CALL G1990D
00358 130* DO 320 I=KSTART,NOSITE
00359 131* NOSUSE=NOSITE+KSTART-I
00360 132* IIII=I+1=KSTART
00361 133* CALL SUM90
00362 134* SUMIV9=IIIIV90
00363 135* CALL NPVNAS
00364 136* CONTINUE
00365 137* CALL REPORT
00366 138* RETURN
00367 139* END

0 DIAGNOSTICS
CPU13,253 CTPI,096 SUPS110,670
SUBROUTINE TREE ENTRY POINT 00172

EXTERNAL REFERENCES (BLOCK, NAME)

STORAGE ASSIGNMENT (BLOCK, TYPE, RELATIVE LOCATION, NAME)

DIMENSION L(N), LSUB(N)

IF (N.LE.1) RETURN

I = N/2

IF (I.GT.1) GO TO 40

NFLAG = 1

K = 1

L = LSUB(K)

IF (NFLAG.EQ.0) GO TO 20

END OF COMPILATION NO DIAGNOSTICS.
SUBROUTINE G19900 ENTRY POINT 002001

STORAGE USED: CODE(1) 0002151 DATA(0) 0001261 BLANK COMMON(2) 003321

COMMON BLOCKS:
0003 - AAAAA 001320
0004 - BBBB 000070
0005 - CEEE 000135

EXTERNAL REFERENCES (BLOCK, NAME)
0006 - XPRR
0007 - NWLS
0010 - NERR33

STORAGE ASSIGNMENT (BLOCK, TYPE, RELATIVE LOCATION, NAME)

001 - 000051 132G
002 - R 003161 ADBL A
003 - R 001347 COSENG
004 - R 001526 DFSHPG
005 - R 003137 EHELP9
006 - R 003363 EHELP
007 - R 001765 ESRHWP
008 - R 002043 FLWCPV
009 - R 000202 0900DL
010 - R 000000 IRNAME
011 - R 000048 ISUB
012 - R 001100 LOCUSE
013 - R 002047 MODPL
014 - R 000062 NA5
015 - R 000554 NLOC
016 - R 002776 ROUTE9
017 - R 002776 ROUTE9
018 - R 002776 ROUTE9
019 - R 002776 ROUTE9
020 - R 002776 ROUTE9
021 - R 002776 ROUTE9
022 - R 002776 ROUTE9
023 - R 002776 ROUTE9
024 - R 002776 ROUTE9
025 - R 002776 ROUTE9
026 - R 002776 ROUTE9
027 - R 003664 SIIV9
028 - R 001353 SITELE
029 - R 003333 TOLMC
030 - R 000444 TOLMC
031 - R 001521 TEMPL9
032 - R 000273 TOTL9
033 - R 001469 TSEC

FOR 3E=05/15/79-1312154 (05)
PARAMETER NP1=4+NP2*16+NP3*16+NP4*1
NP5=50

LOGICAL LSCEN1,LSCEN2,LSCEN3,LSCEN4

REAL LOGUSE,LGCREW,FLX

REAL NPV,NAS

INTEGER SCEN1*0MILES,ATTONS,HELMET,EHCREW,FIX

C * * * BLANK COMMON

COMMON

1 IRNAME(NP1), IRRAD(AxNP1), RMILES(NP1), NOSITI(NP1),
2 TEMPL(NP1), TGENE(BP1), QTIONS(NP1), NOLOC(NP1),
3 LOC(NP1), LK1(NP1), LOCUSE(NP2), LGCREW(NP2), FLXW(NP1)
4 FLYNAV(NP3), FLYCSV(NP3), STABLO(NP3), TCOSF9(NP3),
5 TSITES(NP3), MILEF(NP3), NPL(NP3), NPLV(NP3), EFECH(NP3),
6 FLXS(NP1), SCLEN(TNP1), JANANS, JROUTE,
7 ILUSE(NP1), LOCLOC(NP1), LOCRA(NP1), COSNEE(NP1),
8 TCOSF(NP1), TCOSF9(NP1), TCOSF9(NP1), TOTTRA(NP1),
9 ROUTE(NP1), COSEND(NP1), SITEL(NP3), NPL1, TSITEC(NP3),
A CILMCS(NP1), CTICLM(NP1),
B EMAPM(NP1),
C TEMPL(NP1), DFSIPG(NP1), DFTSTM(NP1), DFSIPG(NP1),
D NP5=50
E IRNAME(NP1), IRRAD(AxNP1), RMILES(NP1), NOSITI(NP1),
F NPL(NP3), NPLV(NP3), EFECH(NP3),
G FLYNAV(NP3), FLYCSV(NP3), STABLO(NP3), TCOSF9(NP3),
H INC1, INC2, INC3, INC4, INC5, INC6, INC7, INC8, INC9, INC10,
I INC11, INC12, INC13, INC14, INC15, INC16, INC17, INC18,
J INC19, INC20, INC21, INC22, INC23, INC24, INC25, INC26,
K INC27, INC28, INC29, INC30, INC31, INC32, INC33, INC34,
L INC35, INC36, INC37, INC38, INC39, INC40, INC41, INC42,
M INC43, INC44, INC45, INC46, INC47, INC48, INC49, INC50,
N INC51, INC52, INC53, INC54, INC55, INC56, INC57, INC58,
O INC59, INC60, INC61, INC62, INC63, INC64, INC65, INC66,
P INC67, INC68, INC69, INC70, INC71, INC72, INC73, INC74,
Q INC75, INC76, INC77, INC78, INC79, INC80, INC81, INC82,
R INC83, INC84, INC85, INC86, INC87, INC88, INC89, INC90,
S INC91, INC92, INC93, INC94, INC95, INC96, INC97, INC98,
T INC99, INC100, INC101, INC102, INC103, INC104, INC105,
U INC106, INC107, INC108, INC109, INC110, INC111, INC112,
V INC113, INC114, INC115, INC116, INC117, INC118, INC119,
W INC120, INC121, INC122, INC123, INC124, INC125, INC126,
X INC127, INC128, INC129, INC130, INC131, INC132, INC133,
Y INC134, INC135, INC136, INC137, INC138, INC139, INC140,
Z INC141, INC142, INC143, INC144, INC145, INC146, INC147,
A INC148, INC149, INC150, INC151, INC152, INC153, INC154,
B INC155, INC156, INC157, INC158, INC159, INC160, INC161,
C INC162, INC163, INC164, INC165, INC166, INC167, INC168,
D INC169, INC170, INC171, INC172, INC173, INC174, INC175,
E INC176, INC177, INC178, INC179, INC180, INC181, INC182,
F INC183, INC184, INC185, INC186, INC187, INC188, INC189,
G INC190, INC191, INC192, INC193, INC194, INC195, INC196,
H INC197, INC198, INC199, INC200, INC201, INC202, INC203,
I INC204, INC205, INC206, INC207, INC208, INC209, INC210,
J INC211, INC212, INC213, INC214, INC215, INC216, INC217,
K INC218, INC219, INC220, INC221, INC222, INC223, INC224,
L INC225, INC226, INC227, INC228, INC229, INC230, INC231,
M INC232, INC233, INC234, INC235, INC236, INC237, INC238,
N INC239, INC240, INC241, INC242, INC243, INC244, INC245,
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P INC253, INC254, INC255, INC256, INC257, INC258, INC259,
Q INC260, INC261, INC262, INC263, INC264, INC265, INC266,
R INC267, INC268, INC269, INC270, INC271, INC272, INC273,
S INC274, INC275, INC276, INC277, INC278, INC279, INC280,
T INC281, INC282, INC283, INC284, INC285, INC286, INC287,
U INC288, INC289, INC290, INC291, INC292, INC293, INC294,
V INC295, INC296, INC297, INC298, INC299, INC300, INC301,
W INC302, INC303, INC304, INC305, INC306, INC307, INC308,
00103  40  CUM1  PROC
00104  40  PARAMETER NP1=4,NP2=6,NP3=18,NP4=1,NP5=50
00105  40  LOGICAL LSCE1,LSCE2,LSCE3,LSCE4
00106  40  REAL LOCUSE,LOCFM1
00107  40  REAL NPV,NAS
00108  40  INTEGER SCAL"5,SCAL6,SCAL7,SCAL8,SCAL9
00109  40  COMMON
00110  40  COMMON
00111  40  COMMON  X,/*,I,IT,II,/*I,/*,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**,*,**
LISTING: NO DIAGNOSTICS.

END OF COMPIILATION.
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<th>CODE(1)</th>
<th>DATA(1)</th>
<th>BLANK COMMON(2)</th>
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**COMMON BLOCKS:**
- AAAAA 001230
- BBBHH 000070
- EEEEL 000135

**EXTERNAL REFERENCES**
- F0N1
- XPR
- APR
- WORK
- NEHRS

**STORAGE ASSIGNMENT**

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**OTHER**
- AAAAA 001230
- BBBHH 000070
- EEEEL 000135

**INTERNAL REFERENCES**
- NAME | BLOCK | TYPE | RELATIVE LOCATION | NAME |
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</table>

**OTHER**
- AAAAA 001230
- BBBHH 000070
- EEEEL 000135
SUBROUTINE NPVNAS
THIS SUBR CALCULATES NET PRESENT VALUE AND NET ANNUAL SAVINGS.

C = * NPV() NET PRESENT VALUE
C = * NPVI() NET PRESENT VALUE

C = * NAS(I,J) NET ANNUAL SAVINGS
C = * NYR = J ANALYSIS MODE
C = * NS = J NUMBER OF YEARS CONSIDERED AFTER 1990
C = * TSCON = DISCOUNT RATE OF TEN PERCENT
C = * XIR(I,J) = OVER INFLATIONARY RATE FOR ELEMENT I,J AT J POINTS
C = * TO TYPE OF STUDY (TO BE EXPLAINED)
C = * GET NET PRESENT VALUE FOR 1990
C = * INCLUDE COM1LIST

PARAMETER NP1, NP2, NP3, NP4, NP5 = 0

LOGICAL LSCEI, LSCEN, LSCEN, LSCEN
REAL LOCUSE, LOCPH
REAL NPVNAS

INTEGER SCENI, SCEN2, SCEN3, SCEN4
COMMON/AAAAAA/NPV(NP4), NASCIOO, NP1, NYRCON, DISCON, XIR(12,4)
COMMON/BBBBBB/MDUKP3)
COMMON/CCEEE/NP3)
COMMON/DDDEEE/NP4, ADLOA8(NP3)
COMMON/FFFFF/NP3), ADLOA8(NP3)
COMMON/GGGGG/NP3), ADLOA8(NP3)

PARAMETER NPla4, NP2 = 16, NP3a18, NP4 = 1, NP5 = 50
REAL
SUBR CALCULATES NET PRESENT VALUE AND NET SAVING

C * BLANK COMMON
COMMON

1 NAMEI(A, NP1, I, RPDA1, J, RPDA2, J, RPDA3, J, NPSITI(NP1), NPSITJ(NP2), NPSITK(NP3), NPSITL(NP4), NPSITM(NP5))
2 TENERI(NP1), TENCRI(NP2), TENCRI(NP3), TENCRI(NP4), TENCRI(NP5)
3 LOCPI(NP1), LOCPI(NP2), LOCPI(NP3), LOCPI(NP4), LOCPI(NP5)
4 FLYWMA(NP3), FLYWMA(NP3), FLYWMA(NP3), FLYWMA(NP3), FLYWMA(NP3)
5 STAHLLL(NP3, NP4), STAHLLL(NP3, NP4), STAHLLL(NP3, NP4), STAHLLL(NP3, NP4)
6 NFPLP(NP3, NP4), NFPLP(NP3, NP4), NFPLP(NP3, NP4), NFPLP(NP3, NP4)
7 MFPLP(NP3, NP4), MFPLP(NP3, NP4), MFPLP(NP3, NP4), MFPLP(NP3, NP4)
8 MDFPLP(NP3, NP4), MDFPLP(NP3, NP4), MDFPLP(NP3, NP4), MDFPLP(NP3, NP4)
9 ROUTE(NP1), ROUTE(NP1), ROUTE(NP1), ROUTE(NP1)
CILMC(NP1), CILMC(NP1), CILMC(NP1), CILMC(NP1)
EMTPH(NP1), EMTPH(NP1), EMTPH(NP1), EMTPH(NP1)
TENIP90000, TENIP90000, TENIP90000, TENIP90000
THIS DEPENDENT ($1)

0 D EFLPM(NP3), EFLPM(NP3), EFLPM(NP3), EFLPM(NP3)
1 EFLPM(NP3), EFLPM(NP3), EFLPM(NP3), EFLPM(NP3)
2 EFLPM(NP3), EFLPM(NP3), EFLPM(NP3), EFLPM(NP3)
3 EFLPM(NP3), EFLPM(NP3), EFLPM(NP3), EFLPM(NP3)
4 EFLPM(NP3), EFLPM(NP3), EFLPM(NP3), EFLPM(NP3)
5 EFLPM(NP3), EFLPM(NP3), EFLPM(NP3), EFLPM(NP3)
6 EFLPM(NP3), EFLPM(NP3), EFLPM(NP3), EFLPM(NP3)
7 EFLPM(NP3), EFLPM(NP3), EFLPM(NP3), EFLPM(NP3)

FLYWHEEL COST
FLYWHEE
FLYCO
COMMON

G NOUSE, ELEHEE(NP1, NP3), ELEHEE(NP1, NP3), ELEHEE(NP1, NP3), ELEHEE(NP1, NP3)
H SAVLPR(NP1), SAVLPR(NP1), SAVLPR(NP1), SAVLPR(NP1)
M SAVLPR(NP1), SAVLPR(NP1), SAVLPR(NP1), SAVLPR(NP1)

COMMON

R1356, R1356, R1356, R1356, R1356
1LSCEI, LSCEN, LSCEN, LSCEN, LSCEN
INITIAL INVESTMENTS 1990 DOLLARS
COMMON

1 TOTNE9, TOTNE9, TOTNE9, TOTNE9, TOTNE9
2 TOTNE9, TOTNE9, TOTNE9, TOTNE9, TOTNE9
3 TOTNE9, TOTNE9, TOTNE9, TOTNE9, TOTNE9
4 TOTNE9, TOTNE9, TOTNE9, TOTNE9, TOTNE9
5 TOTNE9, TOTNE9, TOTNE9, TOTNE9, TOTNE9
6 TOTNE9, TOTNE9, TOTNE9, TOTNE9, TOTNE9
7 TOTNE9, TOTNE9, TOTNE9, TOTNE9, TOTNE9
8 TOTNE9, TOTNE9, TOTNE9, TOTNE9, TOTNE9

1 ANNUAL COST AND CREDITS 1990 DOLLARS.

1 TOTNE9, TOTNE9, TOTNE9, TOTNE9, TOTNE9
2 TOTNE9, TOTNE9, TOTNE9, TOTNE9, TOTNE9
3 TOTNE9, TOTNE9, TOTNE9, TOTNE9, TOTNE9
4 TOTNE9, TOTNE9, TOTNE9, TOTNE9, TOTNE9
5 TOTNE9, TOTNE9, TOTNE9, TOTNE9, TOTNE9
6 TOTNE9, TOTNE9, TOTNE9, TOTNE9, TOTNE9
7 TOTNE9, TOTNE9, TOTNE9, TOTNE9, TOTNE9
8 TOTNE9, TOTNE9, TOTNE9, TOTNE9, TOTNE9

1 DIMENSION RELA1(11), SACC90, S1IV90, FNPD, NASRRETINV, NPV

0.000000
C * * CHECK FOLLOWING STATEMENT OUT * * $6?????

NAS(I,J)+SAC90

IF(I.NE.J)NAS(I,J)=AS(I+1)+S1IV90

NPV(I) =SAC90/(1.0+DISCON)**0.5+S1IV90

DO 50 I=2,NYRCON

X(I)=

X1=X(I)-0.5

50 CONTINUE

C * * GET NET ANNUAL SAVINGS

NAS(I,J)=0

DO 48 K=1,12

NPV(I,J)=NAS(I,J) + SACPS9(K)*(1.+XIR(K,J))**XII

48 CONTINUE

C * * CALC NET PRESENT VALUE

NPV(I) =NPV(I-1) + NAS(I+1)/(1.+DISCON)**XI

DO 50 CONTINUE

NPV(NYRCON) =NPV(NYRCON) + COSEN9/(1.+DISCON)**NYRCON

FNPV(NYRCON) =NPV(NYRCON)

DO 100 J=2,4

100 CONTINUE

IF(I.NE.NYRCON)NAS(I,J)=NAS(I,J)-COSEN9/(1.+DISCON)**NYRCON

CONTINUE

J(I,J)=0

X(I)=X(I)-0.5

DO 70 1=1,12

70 CONTINUE

IF(1.EQ.NYRCON)NAS(I,J)=COSEN9/(1.+DISCON)**NYRCON

CALL RONINV(NAS(J,J)+S1IV90,ROI(J,J),1PR)

RETURN

END
FORTRAN RONINV
ATHENA EXTENDED FORTRAN 241-05 (14 APR 77)

COMPILATION DONE ON 15 MAY 78 AT 13143116

*SUBROUTINE RONINV ENTRY POINT 00522 SEG 000102

STORAGE USED (BLOCK, NAME, LENGTH)

0001 CODE 000567
0000 CONST TEMP 000236
0002 SIMPLE VAR 000222
0004 ARRAYS 001004
0005 NSBLNK 000000

EXTERNAL REFERENCES

0006 ITAT
0007 NDUS
0010 NIO15
0011 NIO25
0012 NEAPS
0013 NSTOPS
0014 NERLO

STORAGE ASSIGNMENT FOR VARIABLES (BLOCK, TYPE, RELATIVE LOCATION, NAME)

0002 R 000013 CONVG 0002 R 000010 CONVG 0004 R 000000 DCF 0002 R 000015 DCFACT 0002 R 000001 DCFRES
0002 R 000005 DUMSUM 0002 R 000011 FHAX 0002 R 000003 I 0004 R 000002 IT
0002 I 000000 ITLIM 0002 I 000012 J 0002 I 000002 KOUNT 0002 R 000020 PRO 0002 R 000005 ROISS
0002 R 000007 ROIRES 0002 R 000017 ROISAV 0002 R 000021 ROITEM 0002 R 000004 RANAND 0023 R 000014 XP
0004 R 00007A XX 0004 R 00007B YY 0001 000081 10L 0001 000061 10L 0001 000112 1631
0001 000026 1711 0000 000035 12F 0001 000153 12L 0001 000161 13L 0001 000041 13D6 0001 000112 1601
0001 000122 169G 0001 000131 10L1 0001 000153 1731 0001 000063 175L 0001 000065 158L 0001 000065 180L
0000 000135 18F 0001 000003 2F 0001 000170 2049 0001 000213 218G 0001 000224 2211 0001 000224 2211
0001 000343 265I 0001 000315 26L 0001 000313 2561 0001 000323 2581 0001 000330 2591 0001 000330 2591
0001 000343 2581 0001 000360 2671 0001 000137 27L 0001 000370 271I 0001 000416 274I 0001 000416 274I
0000 000027 8F 0001 000047 2041 0001 000433 3071 0001 000455 3201 0001 000474 3360 0001 000474 3360
0000 000005 A 0001 000155 47L 0001 000331 50L 0002 000007 9IF 0000 000044 6F 0000 000044 6F
0001 000243 7L 0001 000033 8L 0000 000076 9F 0000 000120 9997F 0000 000134 9998F
0001 000456 9999L

00100 1 0 C * CASHFLOW ANALYSIS * ROI PROGRAM * CARL HEINZ * GARRETT CORP.
00101 2 0 SUBROUTINE RONINV(CASHFLOW,NYR,ROI,STVRIOV1PR)
00101 3 0 MID YEAR DISCOUNTING
00101 4 0
00101 5 0
00101 6 0
00101 7 0
00101 8 0
00101 9 0
00101 10 0
00101 11 0
00101 12 0
00101 13 0
00101 14 0
00101 15 0
00101 16 0
00101 17 0
00101 18 0
CONTROL CARD

COG DCFDES.O.O DEFOES SET BY USER ARGUMENT

READ 5(11,END=9999)NYR,ROI,GSS,CONVG

SPECIAL EXPERIMENTAL GUESS ROUTINE FOR ROI FOR WESS PROGRAM.

DO 10 CONTINUE

CONTINUE TOLERANCE:..G17.6

READ IN

CO1

I OT:1

THI

ALLOW FOR MIN YEAR DISCOUNTING.
SUBROUTINE ITRAT ENTRY POINT 000121

STORAGE USED: CODE(1) 0001451 DATA(0) 0000651 BLANK COMMON(2) 000000

EXTERNAL REFERENCES (BLOCK NAME)

0003 NWDS
0004 NIO2S
0005 NERRA5
0006 NERRAS

STORAGE ASSIGNMENT (BLOCK, TYPE, RELATIVE LOCATION, NAME)

END OF COMPILATION NO DIAGNOSTICS.
C * * 1/YEAR 1

C * * 2ND PAGE

WRITE(6,15) DATETIME, PAGE

WRITE(6,1) WRITE(6,1)

WRITE(6,100) WRITE(6,100)

WRITE(6,110) WRITE(6,110)

WRITE(6,120) WRITE(6,120)

WRITE(6,130) WRITE(6,130)

WRITE(6,140) WRITE(6,140)

WRITE(6,150) WRITE(6,150)

WRITE(6,160) WRITE(6,160)

WRITE(6,170) WRITE(6,170)

WRITE(6,180) WRITE(6,180)

WRITE(6,190) WRITE(6,190)

WRITE(6,200) WRITE(6,200)

WRITE(6,210) WRITE(6,210)

WRITE(6,220) WRITE(6,220)

WRITE(6,230) WRITE(6,230)

WRITE(6,240) WRITE(6,240)

WRITE(6,250) WRITE(6,250)

WRITE(6,260) WRITE(6,260)

WRITE(6,270) WRITE(6,270)

WRITE(6,280) WRITE(6,280)

WRITE(6,290) WRITE(6,290)

WRITE(6,300) WRITE(6,300)

WRITE(6,310) WRITE(6,310)

WRITE(6,320) WRITE(6,320)

WRITE(6,330) WRITE(6,330)

WRITE(6,340) WRITE(6,340)

WRITE(6,350) WRITE(6,350)

WRITE(6,360) WRITE(6,360)

WRITE(6,370) WRITE(6,370)

WRITE(6,380) WRITE(6,380)

WRITE(6,390) WRITE(6,390)

WRITE(6,400) WRITE(6,400)

WRITE(6,410) WRITE(6,410)

WRITE(6,420) WRITE(6,420)

WRITE(6,430) WRITE(6,430)

WRITE(6,440) WRITE(6,440)

WRITE(6,450) WRITE(6,450)

WRITE(6,460) WRITE(6,460)

WRITE(6,470) WRITE(6,470)

WRITE(6,480) WRITE(6,480)

WRITE(6,490) WRITE(6,490)

WRITE(6,500) WRITE(6,500)

WRITE(6,510) WRITE(6,510)

WRITE(6,520) WRITE(6,520)

WRITE(6,530) WRITE(6,530)

WRITE(6,540) WRITE(6,540)

WRITE(6,550) WRITE(6,550)

WRITE(6,560) WRITE(6,560)

WRITE(6,570) WRITE(6,570)

WRITE(6,580) WRITE(6,580)

WRITE(6,590) WRITE(6,590)

WRITE(6,600) WRITE(6,600)

WRITE(6,610) WRITE(6,610)

WRITE(6,620) WRITE(6,620)

WRITE(6,630) WRITE(6,630)

WRITE(6,640) WRITE(6,640)

WRITE(6,650) WRITE(6,650)

WRITE(6,660) WRITE(6,660)

WRITE(6,670) WRITE(6,670)

WRITE(6,680) WRITE(6,680)

WRITE(6,690) WRITE(6,690)

WRITE(6,700) WRITE(6,700)

WRITE(6,710) WRITE(6,710)

WRITE(6,720) WRITE(6,720)

WRITE(6,730) WRITE(6,730)

WRITE(6,740) WRITE(6,740)

WRITE(6,750) WRITE(6,750)

WRITE(6,760) WRITE(6,760)

WRITE(6,770) WRITE(6,770)

WRITE(6,780) WRITE(6,780)

WRITE(6,790) WRITE(6,790)

WRITE(6,800) WRITE(6,800)

WRITE(6,810) WRITE(6,810)

WRITE(6,820) WRITE(6,820)

WRITE(6,830) WRITE(6,830)

WRITE(6,840) WRITE(6,840)

WRITE(6,850) WRITE(6,850)

WRITE(6,860) WRITE(6,860)

WRITE(6,870) WRITE(6,870)

WRITE(6,880) WRITE(6,880)

WRITE(6,890) WRITE(6,890)

WRITE(6,900) WRITE(6,900)

WRITE(6,910) WRITE(6,910)

WRITE(6,920) WRITE(6,920)

WRITE(6,930) WRITE(6,930)

WRITE(6,940) WRITE(6,940)

WRITE(6,950) WRITE(6,950)

WRITE(6,960) WRITE(6,960)

WRITE(6,970) WRITE(6,970)

WRITE(6,980) WRITE(6,980)

WRITE(6,990) WRITE(6,990)
00537 119* WRITE(6,15)DATETIME,IPAGE
00544 119* WRITE(6,4)       
00547 120* WRITE(6,202)
00552 121* FORMAT(193*,INITIAL INVESTMENT (1977 SM)*/)
00555 122* WRITE(6,204)
00566 123* FORMAT(100*ROUTE DEPENDENT *)
00566 124* C IF (LSCENJ1,OR (LSCENJ2))
00557 125* WRITE(6,206) NEWLOC,ROUTE, COSNEW1ROUTE1, TOTNEW1ROUTE1
00565 126* FORMAT(100*NEW ELECTRIC LOCOMOTIVES REQUIRED * T165,F11,3)
00565 127* C IF (LSCENJ1,OR (LSCENJ2))
00565 128* WRITE(6,208) MODLOC1ROUTE1, COSMOD1ROUTE1, TOTMOD1ROUTE1
00574 130* FORMAT(100*MODIFIED LOCOMOTIVES REQUIRED*,T51,F11,3)
00574 131* C IF (LSCENJ1,OR (LSCENJ2))
00574 132* WRITE(6,210) LOCTRA1ROUTE1, COSTRA1ROUTE1, TOTTRA1ROUTE1
00603 134* FORMAT(100*LOCOMOTIVES TRANSFERRED1 T51,F11,3)
00603 135* C IF (LSCENJ1,OR (LSCENJ2))
00604 136* WRITE(6,4)
00604 137* C IF (LSCENJ1,OR (LSCENJ2))
00607 138* WRITE(6,212) ROUTE1ROUTE1
00613 139* FORMAT(T15*, ROUTE ELECTRIFICATION*,T73,F11,3)
00614 140* WRITE(6,41)
00617 141* FORMAT(T15*, END OF PROGRAM COST*,T73,F11,3)
00623 142* C * SITE DEPENDENT
00626 143* WRITE(6,220)
00627 144* FORMAT(100*SITE DEPENDENT *)
00630 146* WRITE(6,222)
00633 147* FORMAT(T15*,SITE*,T25,FLYWHEEL*,T421SITE*,T58, ELECTRIC*
00633 148* 1,T25*,TOTAL*/)
00633 149* 1,T25*,STATION*,T38*, ELECTRIFICATION*,T58,HELPERS*,T78,
00633 150* 2,SITE COST*)
00634 151* DC 240 111*NOSITE
00637 152* TSNUR1SITE
00640 153* WRITE(6,430)SITESIROUTE1TOSIFS(1) SITELE1ROUTE1)
00640 154* 1 ELECT1ROUTE1TSE1ROUTE1)
00650 155* CONTINUE
00652 156* FORMAT(T14*,I4, T25,F6,3, T40,F8,3, T56,F6,3, T76,F8,3)
00655 157* I PAGE=IPAGE*
00656 158* WRITE(6,15)DATETIME,IPAGE
00661 159* WRITE(6,4)
00664 160* WRITE(6,250)
00667 161* FORMAT(T73*,ANNUAL COSTS AND CREDITS (1977 SM)*)
00670 162* WRITE(6,2)
00673 163* WRITE(6,204)
00676 164* WRITE(6,2)
00701 165* WRITE(6,256)SAULP1ROUTE1,TSULP1ROUTE1
00706 166* FORMAT(T73*,SAVING IN LOCOMOTIVE REPLACEMENT*,T65*F6,3)
00706 167* 1,T4*,T63,F11,1,T65,10,3)
00707 168* WRITE(6,41)
00712 169* WRITE(6,260) CILMCS1ROUTE1, TCILMCS1ROUTE1
00717 170* WRITE(6,41)
00722 171* WRITE(6,264) EMATPM1ROUTE1, TEMATPM1ROUTE1
00727 172* WRITE(6,41)
00732 173* WRITE(6,255)ELECE1ROUTE1)
00736 174* FORMAT(T73*,ELECTRICAL ENERGY*,T63,F11,1,T67,F8,3)
00737 175* WRITE(6,41)
00742 176* WRITE(6,266) DFSMPG1ROUTE1, TDFSTM1ROUTE1
00747 177* WRITE(6,41)
00757 174+ WRITE(6,229) DATA(SITE1!1ROUTE), T9ST1111ROUTE)
00756 174+ WRITE(6,229) ADOLANTHRATE)
00746 181+ 268 FORMAT(T10,ADDITIONAL LAROH, T6311,1671F8.3)
00747 182+ WRITE(6,229) ADOLANTHRATE)
00746 183+ C 268 FORMAT(T10,CHANGE IN LOROHIVE MAINT. COSTS, T46, T7.3)
00748 184+ WRITE(6,229) ADOLANTHRATE)
00746 185+ 112/MILE ( Arb. 3, 3.3)
00748 186+ WRITE(6,229) ADOLANTHRATE)
00746 186+ 268 FORMAT(T10, ELECTRIFICATION MAINTENANCE, T61, T7.3)
00748 187+ WRITE(6,229) ADOLANTHRATE)
00746 188+ 268 FORMAT(T10, DIESEL FUEL SAVING (TRAIN MOVEMENT), T69, T7.3)
00748 189+ WRITE(6,229) ADOLANTHRATE)
00746 190+ 1Y/GAL ( Arb. 3, 3.3)
00748 191+ WRITE(6,229) ADOLANTHRATE)
00746 191+ 268 FORMAT(T10, DIESEL FUEL SAVING (IDLING), T69, T7.3)
00748 192+ WRITE(6,229) ADOLANTHRATE)
00746 192+ WRITE(6,229) ADOLANTHRATE)
00757 193+ WRITE(6,229) DATA(SITE1!1ROUTE), T9ST1111ROUTE)
00756 194+ WRITE(6,229) ADOLANTHRATE)
00757 195+ WRITE(6,229) DATA(SITE1!1ROUTE), T9ST1111ROUTE)
00756 196+ WRITE(6,229) ADOLANTHRATE)
00757 197+ WRITE(6,229) DATA(SITE1!1ROUTE), T9ST1111ROUTE)
00756 198+ WRITE(6,229) ADOLANTHRATE)
00757 199+ WRITE(6,229) DATA(SITE1!1ROUTE), T9ST1111ROUTE)
00756 200+ WRITE(6,229) ADOLANTHRATE)
00757 201+ WRITE(6,229) DATA(SITE1!1ROUTE), T9ST1111ROUTE)
00756 202+ WRITE(6,229) ADOLANTHRATE)
00757 203+ WRITE(6,229) DATA(SITE1!1ROUTE), T9ST1111ROUTE)
00756 204+ WRITE(6,229) ADOLANTHRATE)
00757 205+ WRITE(6,229) DATA(SITE1!1ROUTE), T9ST1111ROUTE)
00756 206+ WRITE(6,229) ADOLANTHRATE)
00757 207+ WRITE(6,229) DATA(SITE1!1ROUTE), T9ST1111ROUTE)
00756 208+ WRITE(6,229) ADOLANTHRATE)
00757 209+ WRITE(6,229) DATA(SITE1!1ROUTE), T9ST1111ROUTE)
00756 210+ WRITE(6,229) ADOLANTHRATE)
00757 211+ WRITE(6,229) DATA(SITE1!1ROUTE), T9ST1111ROUTE)
00756 212+ WRITE(6,229) ADOLANTHRATE)
00757 213+ WRITE(6,229) DATA(SITE1!1ROUTE), T9ST1111ROUTE)
00756 214+ WRITE(6,229) ADOLANTHRATE)
00757 215+ WRITE(6,229) DATA(SITE1!1ROUTE), T9ST1111ROUTE)
00756 216+ WRITE(6,229) ADOLANTHRATE)
00757 217+ WRITE(6,229) DATA(SITE1!1ROUTE), T9ST1111ROUTE)
00756 218+ WRITE(6,229) ADOLANTHRATE)
00757 219+ WRITE(6,229) DATA(SITE1!1ROUTE), T9ST1111ROUTE)
00756 220+ WRITE(6,229) ADOLANTHRATE)
00757 221+ WRITE(6,229) DATA(SITE1!1ROUTE), T9ST1111ROUTE)
00756 222+ WRITE(6,229) ADOLANTHRATE)
00757 223+ WRITE(6,229) DATA(SITE1!1ROUTE), T9ST1111ROUTE)
00756 224+ WRITE(6,229) ADOLANTHRATE)
00757 225+ WRITE(6,229) DATA(SITE1!1ROUTE), T9ST1111ROUTE)
00756 226+ WRITE(6,229) ADOLANTHRATE)
00757 227+ WRITE(6,229) DATA(SITE1!1ROUTE), T9ST1111ROUTE)
00756 228+ WRITE(6,229) ADOLANTHRATE)
00757 229+ WRITE(6,229) DATA(SITE1!1ROUTE), T9ST1111ROUTE)
00756 230+ WRITE(6,229) ADOLANTHRATE)
00757 231+ WRITE(6,229) DATA(SITE1!1ROUTE), T9ST1111ROUTE)
00756 232+ WRITE(6,229) ADOLANTHRATE)
00757 233+ WRITE(6,229) DATA(SITE1!1ROUTE), T9ST1111ROUTE)
00756 234+ WRITE(6,229) ADOLANTHRATE)
00757 235+ WRITE(6,229) DATA(SITE1!1ROUTE), T9ST1111ROUTE)
00756 236+ WRITE(6,229) ADOLANTHRATE)
00757 237+ WRITE(6,229) DATA(SITE1!1ROUTE), T9ST1111ROUTE)
00756 238+ WRITE(6,229) ADOLANTHRATE)
01142 238 1SENSITIVITY 2/ T15*4ESS SITES*T66f($MILLIONS)1/
01142 239 2 T66fNPVfT70fINIT. COSTfT2fINTERNAL RATEf T99;
01142 240 3 INTERNAL RATEfT118fINTERNAL RATEfT70f(19905)fT84fOF RETURN
01142 241 5 T84fOF RETURN 8fT118 fOF RETURN 8f/
01143 242 DD 395 I KSTART*NOSITE
01146 243 KKNOSITE*KSTART-I
01150 244 WRITE(6,376) NSUB(J)+J*1,1K
01157 246 376 FORMAT(3X,1013) 246
01160 247 KKK=KKK-I
01161 248 WRITE(6,377)(ACOM(JJ),JJ-1,KKK)
01170 249 377 FORMAT(I8,3X,18IL) 249 378
01171 250 WRITE(6,370) FN1V(J),ROPER(J),ROPER(J)
01171 251 1 ROPER(J)
01201 252 378 FORMAT(I8,3X,18IL) 379
01202 253 CONTINUE
01204 254 IDUM=1
01206 255 410 IF(FLAG,NE,3)GO TO 510
01207 256 IDUM=1
01210 257 510 CONTINUE
01211 258 RETURN
01212 259 END

0 DIAGNOSTICS
CPUI7,778 CPU1,196 SUPS18,778
APPENDIX F

TRAIN PERFORMANCE CALCULATOR

INTRODUCTION AND SUMMARY

This appendix summarizes features of the AiResearch train performance calculator (TPC) program. A detailed definition of route data and schedule data requirements is included, together with a program listing and program nomenclature. This program was developed to support train performance calculations (TPC's) required by the WESS study performed for FRA. A summary of program features is shown in Table F-1.

TABLE F-1

TPC FEATURES

<table>
<thead>
<tr>
<th>Program Feature</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Principal emphasis</td>
<td>Power demand and energy required from the wayside for multitrain operation of long-haul freight trains</td>
</tr>
<tr>
<td>Remote run on line</td>
<td>No</td>
</tr>
<tr>
<td>Batch run</td>
<td>Yes</td>
</tr>
<tr>
<td>Input media</td>
<td>Disc file or cards</td>
</tr>
<tr>
<td>Output medium</td>
<td>Line printer</td>
</tr>
<tr>
<td>Computer size required</td>
<td>Medium</td>
</tr>
<tr>
<td>Computer now in disc</td>
<td>Univac 1100</td>
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<tr>
<td>Language</td>
<td>ANSI Fortran</td>
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<tr>
<td>Modifications required for interchange</td>
<td>None</td>
</tr>
<tr>
<td>Data</td>
<td></td>
</tr>
<tr>
<td>Access mode</td>
<td>Sequential</td>
</tr>
<tr>
<td>Form</td>
<td>Point</td>
</tr>
<tr>
<td>Organized</td>
<td>Separate route of schedule data</td>
</tr>
<tr>
<td>Ease of use</td>
<td>Good</td>
</tr>
<tr>
<td>Economy</td>
<td>Good</td>
</tr>
<tr>
<td>User's manual</td>
<td>None available</td>
</tr>
</tbody>
</table>

F-1
TPC General Description

The TPC developed by AiResearch for the analysis of WESS is a computer program that simulates the operation of many trains over a railroad route. The TPC contains characteristics of the locomotives and rolling stock as internal program parameters; route and schedule data are input to the program. The program computes speed, time, distance, acceleration, locomotive input power, efficiency, power factor, apparent power, and energy input from the pantograph. It also computes tractive effort during motoring and braking from both the propulsion system and the friction braking system. To define substation power versus time and energy requirements, it analyzes specific energy consumption in watt-hours per ton-mile for each train and accumulates the power and energy requirements for all trains operating over specific sections of the route. Simulation of up to 100 trains over a 24-hr period of operation can be performed. Outputs include the time history of a selected train over the route and a listing of 5-min power demands for each subdivision of the route (up to 10 subdivisions). It also outputs the total route 5-min power demand for an entire 24-hr period. Total energy requirements for each division and the total route also are output for the 24-hr period.

The basic route data inputs required in a route file for each route are listed below. Detailed information on route data requirements and input format is provided later in this appendix under the paragraph, "Track Data Requirements".

- Curvature, deg
- Grade, percent
- Civil speed limit, mph
- Elevation, ft

The basic schedule information required in a schedule file for each train is listed below. Detailed information on schedule data requirements and input format is provided later under "Train Schedule Requirements".

- Train identification
- Direction of travel
- Trailing tons
- Start time
- Location of intermediate stop
- Intermediate stop dwell
- Start location
- Number of locomotives (minimum)
Complete listings of the program and program nomenclature are presented at the end of this appendix.

The program is based on the calculation of train resistance from the modified Davis formulas and the use of representative propulsion system efficiency and power factor characteristics based on E60C locomotive data, as shown in the algorithms of Figures F-1 and F-2, respectively. In these algorithms, efficiency and power factors are assumed to be a function of speed only. Speed is defined as \( V \), efficiency as \( \eta \), and power factor as \( \varphi \).

The tractive effort and propulsion power calculation logic for blended friction and regenerative braking, coast, or motoring is shown in Figure F-3.

The program simulates operation of the train in accordance with speed limits by means of an algorithm that represents a dead-band type of speed control with rate of change of acceleration or deceleration and anticipation of stopping distances. This logic is shown in Figure F-4.

**TPC USES**

The TPC is useful in performing any of the following tasks:

(a) Determining the power and energy demand that results from operation of multiple trains over a route in accordance with a definite schedule and trailing ton distribution between trains.

(b) Determining the effect of motive power on the performance of a train over a route.

(c) Evaluating the effect of track relocation, grade changes, curve changes, speed restrictions, and other route changes on performance, schedule, motive power requirements, and energy consumption.

(d) Evaluating the effect of schedule changes, train size, and motive power assignment on power demand and energy requirements.

The TPC provides a valuable, simple, and time-saving method for simulating train performance as well as changes in route characteristics or schedule factors.

**TPC AVAILABILITY**

The AiResearch TPC is available immediately. It includes a complete program listing, program nomenclature, track data requirements, and schedule data requirements; these are enclosed at the end of this appendix. This program contains no proprietary information. It is available to any interested user.

**GENERAL-PURPOSE TPC**

The AiResearch TPC is designed primarily as a tool for analyzing of long-haul freight service, with emphasis on energy and power demand requirements of multitrain operations. It also can be employed for intercity rail passenger service.
Figure F-1. TPC, Propulsion System Efficiency Algorithm

\[ \eta = \frac{0.9649}{V + 4.278} \]

\[ \eta = \frac{0.9592}{V + 6.378} \]

\[ \eta = \frac{0.9364}{V + 8.5207} \]

Figure F-2. TPC, Propulsion System Power Factor Algorithm

\[ \text{PF} = \frac{1.307}{V + 6.933} \]

\[ \text{PF} = \frac{1.123}{V + 9.595} \]

\[ \text{PF} = \frac{1.0925}{V + 14.180} \]
Figure F-3. TPC, Tractive Effort and Propulsion Power
Figure F-4. TPC, Speed Control Logic
The TPC is not suited to the analysis of multistop rail rapid transit operations. Although it includes only electric locomotive motive power, it could be modified for other propulsion types.

MACHINE CONSIDERATIONS

Batch-Processing and Time-Sharing

The AirResearch TPC is well-suited to running under batch control because no user interaction is required during program execution. Basic locomotive and trailing car characteristics are included in the program. Route and schedule data inputs are developed prior to the run.

Input/Output

The program is designed as a self-contained main program that receives input from the route and schedule files. These files may be input from a card reader or tape files. It is designed to output data on a line printer.

Machine Size

The TPC is used on a medium-size engineering computer, a Univac 1100, in a time-sharing mode with other batch jobs. It requires no excessive storage or time to calculate typical runs.

Cost of Use

The TPC is a simple program that analyzes complete routes such as Harrisburg to Pittsburgh or Los Angeles to Salt Lake City at moderate costs per run.

Programming Language

The TPC is written in ANSI Fortran and should therefore be compatible with most computer installations.

Interchangeability

Selection of ANSI FORTRAN ensures that the program is almost completely interchangeable with any computer system without any major problem.

User Considerations

The TPC is easy to use on any computer installation. It requires only simple program changes to accommodate changes in motive power and the development of route and schedule data. Track data and schedule data requirements are defined in the ensuing paragraphs of this appendix. Track data are read in a sequential mode as present in the route data file. The entire route data file is read at one time and is processed prior to execution of a run. Schedule data are processed in a similar manner. Route data are entered in point form, e.g., by milepost location. Curvature, speed limit, and grade data are entered at the point to define the characteristics over the interval to the next point of change. Grade data may be alternately entered as elevation data in point form.
All route data are combined on one record in a common file. Schedule data are maintained in a separate file. No problem has been experienced in the use of this approach.

TRACK DATA REQUIREMENTS

Figure F-5 shows the format of a route data input card. The route data card contains the milepost location, degree of curvature, grade, civil speed, and elevation data that define the route profile. Location inputs may be increasing, decreasing, or mixed. Whenever a change occurs in the milepost reference, the equivalent location in terms of the new reference must be specified on the route data input card that identifies the location of the change in milepost reference. The equivalent location is specified in field 7 of the route card. The following card may then utilize the new reference for milepost locations. Up to 1000 route data input cards may be included in the route data file. A route data input card is required only for each location where changes in route data occur.

Grade data may be input directly as the grade to the next grade change location where the grade is expressed as a percent of grade. An alternate method of inputting grade data is to input elevation data at each grade change location with the elevation data expressed in feet. In the absence of elevation input data, the program defaults to the input grade data. If elevation data and grade data are both omitted, the program defaults to zero grade.

The route data are input to the program and are stored in a route matrix \( RT(1000,9) \). The relationship between the route matrix elements \( RT(i,j) \) and the route data input cards is as follows:

**Milepost Location**--the milepost location in card field 1, card columns (cc) 1-10, is the identification of the location for a change in any one or more input route parameters. It is expressed in miles with an \( F10.3 \) format. It may start at any number within this format and be monotone, increasing or decreasing in the "forward" direction of travel. The reference milestone may change. Whenever the reference milestone changes, the equivalent milestone based on the new reference must be defined in field (7) at the last data point by using the old reference. For the next data point, mileposts based on the new reference should be used. The milepost location is stored in \( RT(i,1) \).

**Curvature**--The curvature of a section that starts at the milepost defined by field (1) is shown in field (2), cc 11-20, in degrees deflection per 100 feet of chord (the customary railroad engineering unit) using an \( F10.3 \) format. The curvature is stored in \( RT(i,2) \).

**Grade**--The grade for a section of the route that starts at the milepost defined by field (1) is shown in field (3), cc 21-30, with the grade expressed in percent using an \( F10.3 \) format. The grade is stored in \( RT(i,3) \).
<table>
<thead>
<tr>
<th>MILEPOST LOCATION, MI</th>
<th>CURVATURE, DEG</th>
<th>GRADE, PERCENT</th>
<th>CIVIL SPEED LIMIT, MPH</th>
<th>ELEVATION, FT</th>
<th>EQUVALENT MILEPOST PER NEW REFERENCE, MI</th>
</tr>
</thead>
<tbody>
<tr>
<td>269,000</td>
<td>1.000</td>
<td>60.000</td>
<td>(1)</td>
<td>(2)</td>
<td>RT(1.1)</td>
</tr>
<tr>
<td></td>
<td>1,000</td>
<td>100.000</td>
<td>(3)</td>
<td>(4)</td>
<td>RT(1.2)</td>
</tr>
<tr>
<td></td>
<td>60,000</td>
<td></td>
<td>(5)</td>
<td>(6)</td>
<td>RT(1.3)</td>
</tr>
<tr>
<td></td>
<td>110,000</td>
<td></td>
<td></td>
<td></td>
<td>RT(1.4)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Figure F-5: Route Data Input Card Format*
Civil Speed Limit--The civil speed limit for a section that starts at the milepost defined by field (1) is shown in field (4), cc 31-40; the speed limit is expressed in miles per hour using an F10.3 format. The civil speed is stored in RT (1, 4).

Elevation--The elevation at the location milepost defined by field (1) is shown in field (5), cc 41-50. Elevation is expressed in feet above a reference elevation by using F10.3 format. The elevation data are stored in RT (1, 5). The same common reference elevation must be used for all inputs. Elevation data may be positive or negative.

Unused Field--Field (6) is not used for input. This field (cc 51-60) should remain blank.

Milepost Reference Change--If the milestone reference is to change, the milepost location defined in field (1) must be expressed as an equivalent milepost, based on the new reference in field (7). The milepost locations are expressed in miles using an F10.3 format. The new equivalent milepost location is stored in the route matrix as RT (1, 7).

Unused Field--Field (8) is not used for input. This field (cc 71-70) should remain blank.

Stored Route Data

Stored route data must be contained in a deck or file with the individual milepost cards in the "Forward" route direction sequence. A negative number (-.001) is required in card columns 31-40, field (4), of the last milepost-card to stop the train at the end of the route.

The end of the file is identified by a card immediately following the last milepost card. This end of file card must contain 9999 in card columns 1-10, field (1), of the route deck.

1. Reverse Direction

Route data are required only for the forward direction of a route. Train operation may be simulated for forward or reverse route directions by input of the appropriate code in the train schedule data. The program automatically computes the proper reverse route matrix from the forward route input data.

2. Data Entry

The route data must be entered only when a change occurs in any one or more parameters. If no change is required in a given parameter, the field must be left blank or the parameter may be repeated. To distinguish a zero parameter as a new or different value, a zero must be entered as .001. If a true zero is entered, the program will assume no change from the previous value of the parameter at the last milepost data card having a non-zero value.
Train Schedule Requirements

Figure F-6 shows the format of a train schedule data input card. One card is required for each train. A train may travel between two points with one intermediate stop. It may start at any time during the day and may start at any location. Any dwell up to 24 hr may be specified for the intermediate stop. If a train is required to stop at more than one intermediate point along the route, a separate schedule card is required to start the train at the first intermediate stop at a specified time, continue to the second intermediate stop, dwell, and then proceed to the end of the route. The second section of the route requires reidentification of the train. The dwell at the first intermediate stop must be greater than 24 hr to prevent continuation of that train.

The schedule data input card contains the train identification, direction of travel code, trailing tons, start time, intermediate stop location, and number of locomotives. In the absence of any start location input, the train will start at the appropriate terminal, as determined by the input direction of travel code. The program is capable of reading 100 schedule cards. The last schedule card must be followed by a card having a negative one in card columns 9-10 to indicate the end of the schedule deck.

The train identification (up to eight alphanumeric digits) is stored as a train identification vector ID (I). The remaining schedule input data are stored as a schedule matrix SCH (I, J). The same train index (I) is common to both elements to identify the train schedule parameters for a given train.

The schedule input card is divided into 15 fields, as shown in Figure F-6. Each field is as defined below:

Train Identification--Any alphanumeric identification containing up to 8 characters may be used for train identification. The train identification is contained in field (1), cc 1-8 of the schedule card in A8 format. The program stores train identification data as ID (N).

Direction of Travel Code--The direction of travel is selected by a code. If the direction of travel is in the "forward" direction of the route (direction of the route deck sequence) the code is "0". If a "reverse" direction is desired, the direction code "1" is entered in field (2), cc 9-11 of the schedule card in F3.0 format. The program defaults to the "forward" direction if no entry is made in field (2). The program stores direction of travel in the first column of the schedule matrix SCH (I,1).

Trailing Tons--The number of trailing tons is entered in field 3, cc 12-30, in F19.6 format. The program defaults to the number of locomotives only when this field is blank. The program stores the trailing tons in the second column of the schedule matrix.

Start Time--The schedule departure time for the train is entered in fields (4), cc 31-32, and (6) cc 34-35. Field (4) contains the hours and field (6) contains the minutes. Field (5), cc 33, provides
**Figure F-6. Schedule Data Card**

<table>
<thead>
<tr>
<th>LA-BEL</th>
<th>0</th>
<th>4600.</th>
<th>08:29</th>
<th>( )</th>
<th>( )</th>
<th>( )</th>
<th>( )</th>
<th>( )</th>
<th>( )</th>
<th>( )</th>
<th>( )</th>
<th>( )</th>
<th>( )</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>ID(N)</td>
<td>SCH(N,1)</td>
<td>SCH(N,2)</td>
<td>SCH(N,3)</td>
<td>SCH(N,4)</td>
<td>SCH(N,5)</td>
<td>SCH(N,6)</td>
<td>SCH(N,7)</td>
<td>SCH(N,8)</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A8</td>
<td>F3.0</td>
<td>F19.6</td>
<td>F2.0</td>
<td>F2.0</td>
<td>5X</td>
<td>F10.6</td>
<td>F2.0</td>
<td>F2.0</td>
<td>5X</td>
<td>F10.6</td>
<td>F1.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>8</td>
<td>11</td>
<td>30</td>
<td>32</td>
<td>33</td>
<td>35</td>
<td>40</td>
<td>50</td>
<td>52</td>
<td>53</td>
<td>55</td>
<td>60</td>
<td>70</td>
<td>71</td>
</tr>
</tbody>
</table>

**Legend:**
- **LA-BEL:** Label
- **ID(N):** Identification Number
- **A8:** Additional Code
- **SCH:** Schedule
- **START TIME, HR:** Start Time, Hour
- **START TIME, MIN:** Start Time, Minute
- **MILEPOST FOR INTERMEDIATE STOP:** Milepost for Intermediate Stop
- **INTERMEDIATE STOP DWELL, HR:** Intermediate Stop Dwell, Hour
- **INTERMEDIATE STOP DWELL, MIN:** Intermediate Stop Dwell, Minute
- **MINIMUM NUMBER OF LOCOMOTIVES:** Minimum Number of Locomotives

**Notes:**
- Unused fields are indicated.
- Additional codes and specific times are provided for scheduling.

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**Figure F-6 continues below...**
space for a colon to facilitate card reading, and is ignored by the program. The program stores the start time hours in the third column of the Schedule Matrix SCH (N, 3) and the minutes in the fourth column SCH (N, 4). The format of the data is F2.0. In the absence of start time input the program defaults to departure at 0000 hours.

Unused Field--Field (7) is unused.

Intermediate Stop Milepost--Field 8, cc 41-50, defines the location of the intermediate stop, if any. This location must be expressed in terms of the common reference milepost location, as shown in column 8 of the route matrix listing. If this field is not punched, no intermediate stop is made. The format of this field is F10.6. The location is stored in column five of the schedule matrix SCH (N,5).

Intermediate Stop Dwell--The dwell for an intermediate stop is entered in field (9), cc 51-52, and field (11), cc 54-55. Field (9) contains the dwell hours and field (11) contains the dwell minutes. Field (1), cc 53, provides space for a colon to facilitate card reading, and is ignored by the program. The program stores the dwell time hours in the sixth column of the schedule matrix (SCH (N,6); minutes are stored in the seventh column SCH (N,7). The format of the data is F2.0. In the absence of dwell time data input the program defaults to zero dwell. Dwell is ignored if the intermediate stop data is zero.

Unused Field--Field (12) is unused.

Start Location--Start locations, other than those at the terminals, must be specified by entry of the start location milepost. This is done by using a common reference milepost, as shown in column 8 of the route matrix output listing. The milepost location is entered into field (13), cc 61-70, in F10.6 format. The program stores the start location in column 8 of the schedule matrix SCH (N,8). In the absence of input in field (13), the program starts at the terminals, as determined by the direction code input in field (2).

Minimum Number of Locomotives--The program selects the number of locomotives needed for operation over the maximum grades for the specified trailing tons and performance. If a number of locomotives are specified in field (14), cc 71, the number of locomotives will be no less than that specified in this field. The format of this field is F1.0. The program stores the minimum number of locomotives required in the ninth column of the schedule matrix.

Unused Field--Field (15) is unused.

Data Entry

Schedule data must be entered in start time sequence.
The following printout defines the TPC program.
C TPC
C TRAIN PERFORMANCE SIMULATION
C NEGATIVE 1 IN CC10 INDICATED END OF SCH DECK
C LAST CARD IN DATA DECK MUST CONTAIN 9999. IN CC 1-10
C NEGATIVE SPEED LIMIT IN CC 40-50 INITIATES STOP AT LOC IN CC 1-10
C REAL KVA, H
C DOUBLE PRECISION I0
C DIMENSION SCH(1000,9), ID(100)
C DIMENSION RT(1000,9), RT1(1000,9)
C DIMENSION RRT(1000,8), RRT(1000,8)
C DIRECTION CODE 0= OUT 1= IN
C CONSTANTS
C HEG=1
C NSEL=1
C NS=10
C GEE=21.927
C TAU1=1.
C TIMX=300.
C AJERK=2.
C THM=1.
C THM=1.
C TG=1.
C TG=1.
C CONTINUE
C VXT=25.
C VX=30.
C MAX=5
C THAILING CARS
C AFC=98.
C NAC=4
C TONC=85.
C TONC=85.
C INPUT SCHEDULE DATA
C DC 5 I=1,100
REAL(5,501) ID(1) *(SCH(I,J),J=1,9)
IF(SCH(I,1).LT.0.) GO TO 6
5 CONTINUE
STOP
6 WRITE(6,502)
NID=I-1
WRITE(6,503) (ID(I),(SCH(I,J),J=1,9),I=1,NID)
C INPUT ROUTE DATA
DO 10 I=1,1000
READ(5,101) RT(I,1),RT(I,2),RT(I,3),RT(I,4),RT(I,5),RT(I,6),RT(I,7)
10 IF(RT(I,1).GT.999.) GO TO 12
11 CONTINUE
STOP
12 NR=I-1
RT(I,8)=RT(I,1)
56 DIF1=ABS(RT(2,1)-RT(1,1))
57 DO 14 I=2,NR
58 J=I+1
59 K=I-1
60 DIF=ABS(RT(J,1)-RT(I,1))
61 IF(RT(I,7).NE.0.) DIF=ABS(RT(J,1)-RT(I,7))
62 RT(I,8)=RT(K,8)+DIF1
63 DIF=DIF1
64 IF(RT(I-1,5).EQ.0.) GO TO 14
65 IF(RT(I,5).EQ.0.) GO TO 14
66 RT(I-1,3)=(RT(I,5)-RT(I-1,5))/(52.6*(RT(I,8)-RT(I-1,8)))
67 IF(RT(I-1,3).EQ.0.) RT(I-1,3)=0.001
68 CONTINUE
69 DO 20 I=2,NR
70 IF(RT(I,2).NE.0.) GO TO 16
71 RT(I,2)=RT(I-1,2)
72 IF(RT(I,3).NE.0.) GO TO 18
73 RT(I,3)=RT(I-1,3)
74 IF(RT(I,4).NE.0.) GO TO 20
75 RT(I,4)=RT(I-1,4)
76 CONTINUE
77 DO 21 I=1,NR
78 DO 21 J=1,8
79 RTF(I,J)=RT(I,J)
80 CONTINUE
DO 22 I=1,NR
RTF(I,7)=RTF(I,8)
22 CONTINUE
PI1(NR+1)=RT(I,1)
RT1(NR+2)=0.
RT1(NR+3)=0.
RT1(NR+4)=0.
RT1(NR+5)=RT1(I,5)
RT1(NR+6)=RT1(I,6)
DO 23 I=2,NR
K=IP+1=1
RT1(K+1)=RT(I,1)
RT1(K+2)=RT(I-1,2)
RT1(K+3)=RT(I-1,3)
RT1(K+4)=RT(I-1,4)
RT1(K+5)=RT(I-1,5)
RT1(K+6)=RT(I,8)
23 CONTINUE
DO 24 I=1,NR
DO 25 J=1,NR
RT1(I,J)=RT1(I,J)
24 CONTINUE
DO 25 I=1,NR
RTF(I,7)=RTF(I,8)
25 CONTINUE
DO 24 I=1,NR
IF P=INT(SCH(N+1))
NL=SCH(N+1)
TL=SCH(N+1)
KC=TL/TNL
C Initialization
IFLAG=0
VMW1=0,
TIME=0.
TX=0.
ACC=0.
ACC1=0.
V=0.
V1=0.
AJERK = AJERK
TN = 0,
VP = 0,
EV = 0,
ER = 0,
ISR = 1
EV1 = 0,
CLOCK = 0
THETA = 36000 * SCH(N,3) + 60 * SCH(N,4)
IF (IROUTE, EQ, 1) GO TO 27
DO 26 I = 1, NR
DO 26 J = 1, S
RT(I, J) = RTF(I, J)
26 CONTINUE
GO TO 29
DO 28 I = 1, NR
DO 28 J = 1, S
RT(I, J) = RT(I, J)
28 CONTINUE
IF (SCH(N, 5), NE, 0) GO TO 30
GO TO 335
TEST = SCH(N, 5)
CONST = RT(1, 8)
DO 32 I = 1, NR
IF (RT(I, 8), EQ, TEST) GO TO 33
32 CONTINUE
WRITE (6, 515) IO(N)
GO TO 254
RT(1, 4) = -0.001
33 IRET = 1
335 TAU = TAU1
TIMEX = TIMX
DO 39 I = 1, NR
NX = NL
34 WT = NX * WLI + NC * WTC
AMASS = (MFPA * NL * NC * WTC) / GEE
TIM = AJERK * AMASS / TAU
35 TG = WRT(I, 3) / 100.
36 TRLX = NX * (1.3 * 0.3 * VXT) * TONL * 29 * ONAL * 0.024 * AFL * VAXT * 0.082
37 TRCX = UC0 * (1.3 * 0.45 * VXT) * TONC * 29 * ONAC + 0.005 * AFC * VAXT * 0.082
38 TCX = 0.086 * CTT / 2000.
161 TDX=TRLX+TCX+TX+TG  
162 TLX=NXoTEMAX  
163 IF(TLX.GT.TDX) GO TO 36  
164 NX=NX+1  
165 GO TO 34  
166 36 RT(I+1)=NX  
167 RT(I+6)=RT(I+4)  
168 THL=NXO(10.3+03+RT(I+6))OTNL+290NAL+0.0024AF+RT(I+6)+2  
169 TC=08RCOUT/2000+  
170 TD=TR+TC+TG  
171 TDYN=8EMAX+NX  
172 IF(RT(I+6).GT.VXB) TDYN=NXoBEMAXoVXB/RT(I+6)  
173 IF(TD.LT.TDYN) GO TO 38  
174 GO TO 39  
175 38 IF(RT(I+6).LT.VXB) GO TO 39  
176 RT(I+6)=RT(I+6)-5  
177 GO TO 37  
178 39 CONTINUE  
180 C OUTPUT TRAIN ID  
181 IF(N.NE.NSEL) GO TO 40  
182 WRITE(6,057) ID(N)  
183 C OUTPUT ROUTE HEADER  
184 WRITE(6,201)  
185 C OUTPUT UNIT HEADER  
186 WRITE(6,202)  
187 C OUTPUT ROUTE DATA  
188 WRITE(6,203) ((RT(I,J),J=1,9),I=1,NR)  
189 40 IF((ROUTE.EQ.1) GO TO 42  
190 DO 41 I=1,NR  
191 RT(I+1)=RT(I+8)  
192 41 CONTINUE  
193 GO TO 44  
194 42 DO 43 I=1,NR  
195 RT(I+1)=CONST-RT(I+8)  
196 43 CONTINUE  
197 C OUTPUT TRAIN ID  
198 C OUTPUT TIME HISTORY HEADER & UNITS  
199 44 IF(N.NE.NSEL) GO TO 45  
200 IF(REGN.EQ.0) WRITE(6,512) ID(N)
IF (IREG = 1) WRITE (6, 513) ID(N)
WRITE (6, 204)
WRITE (6, 205)

45 I = 1
S = RT (I, 1)
IF (SCH(N, H) .NE. 0) S = SCH(N, H)
IF (SCH(N, H) .NE. 0 .AND. IROUTE .EQ. 1) S = CONST .SCH(N, H)
RC = RT (I, 2)
G = RT (I, 3)
VCART (I, 4)
NX = RT (I, 9)
SPACE = (ABS (RT(I, 1) - RT(I, 1))) / NS
C
CONTINUE LINK

46 J = I + 1
IF (S .GT. RT(J, 1)) GO TO 50
GO TO 90
I = I + 1
NX = RT (I, 9)
ISR = 1
IF (RT(J, 2) .EQ. 0) GO TO 60
RC = RT (J, 2)
60 IF (RT (J, 3) .EQ. 0) GO TO 70
G = RT (J, 3)
70 IF (RT (J, 6) .EQ. 0) GO TO 80
VCART (J, 6)
80 IF (S .GE. RT (J + 1)) GO TO 46
IN = I + 1
DO 110 II = IN, NR
IF (RT(I, 6) .NE. 0) GO TO 100
GO TO 110
ST = RT (II, 1)
VCN = RT (II, 6)
100 IF (VCN .LT. VC) GO TO 120
CONTINUE
110 CONTINUE
120 ST = RT (II, 1)
VCN = RT (II, 6)
130 ISTOP = 1
VCN = 0,
ST = ST
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<th>Code</th>
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<tbody>
<tr>
<td>240</td>
<td>C DRAKE CALCULATIONS, GRADE</td>
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<tr>
<td>241</td>
<td>140 TGRA=160/100.</td>
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<tr>
<td>242</td>
<td>C LOCOMOTIVE DRAKE</td>
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<tr>
<td>243</td>
<td>TRL=NXO(1.3+03PV)<em>TONL</em>29.0<em>0AFL</em>0024<em>AFL</em>00V)</td>
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<tr>
<td>244</td>
<td>C CAM DRAKE</td>
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<tr>
<td>245</td>
<td>TRC=NCO(1.3+045PV)<em>TONC</em>29.0<em>0AC</em>0005<em>AFC</em>00V)</td>
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<td>246</td>
<td>C CURVE DRAKE</td>
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<td>247</td>
<td>TCR=PCOME/200.</td>
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<td>248</td>
<td>C TOTAL TRAIN DRAKE</td>
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<tr>
<td>249</td>
<td>TDT=THL+TC+TG</td>
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<tr>
<td>250</td>
<td>C PROPULSION EFFICIENCY</td>
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<tr>
<td>251</td>
<td>ETA=104V</td>
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<tr>
<td>252</td>
<td>IF(V GT 5.0 ETA=95649O/V/(v+4.27b)</td>
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<tr>
<td>253</td>
<td>IF(V GT 13.0 ETA=95920V/(v+6.378)</td>
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</tr>
<tr>
<td>254</td>
<td>IF(V GT 32.0 ETA=93640V/(v+8.5207)</td>
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<tr>
<td>255</td>
<td>C POWER FACTOR</td>
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<tr>
<td>256</td>
<td>PF=.3+.049O</td>
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<tr>
<td>257</td>
<td>IF(V GT 5.0 PF=1.3076O/(v+6.993)</td>
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<tr>
<td>258</td>
<td>IF(V GT 13.0 PF=1.1239O/(v+9.595)</td>
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<tr>
<td>259</td>
<td>IF(V GT 32.0 PF=1.0925O/(v+14.499)</td>
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<td>260</td>
<td>C ELECTRICAL BRAKING EFFORT AT PRESENT SPEED</td>
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<tr>
<td>261</td>
<td>TDTN=EMAX0N</td>
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<tr>
<td>262</td>
<td>IF(V GT 3.0 TDTN=NX0EMAX0VX0/V</td>
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<tr>
<td>263</td>
<td>T6=TD+TDYN</td>
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<tr>
<td>264</td>
<td>C SWITCH TO CONTINUE BRAKING IF ISH IS ZERO</td>
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<tr>
<td>265</td>
<td>IF(ISH=0.0 GO TO 160</td>
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<td>266</td>
<td>C BRAKING EFFORT AT NEXT CIVIL SPEED</td>
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<tr>
<td>267</td>
<td>TDTN=NXO(1.3+03PV)<em>TONL</em>29.0<em>0AFL</em>0024<em>AFL</em>00V</td>
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<td>268</td>
<td>TCRN=NCO(1.3+045PV)<em>TONC</em>29.0<em>0AC</em>0005<em>AFC</em>00V)</td>
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<td>269</td>
<td>TDYN=TRLN+TPCN+TC+TG</td>
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<tr>
<td>270</td>
<td>TUNN=EMAX0N</td>
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<tr>
<td>271</td>
<td>IF(VCN GT 3.0 TUNN=NX0EMAX0VX0/VCN</td>
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<tr>
<td>272</td>
<td>TTHN=TUN+TDYN</td>
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<tr>
<td>273</td>
<td>C AVERAGE BRAKING EFFORT (APPROXIMATE) &amp; DECL RATE</td>
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<td>274</td>
<td>TBRAB=(TR+TBN)/2.</td>
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<tr>
<td>275</td>
<td>DECL=TBRAB/AMASS</td>
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<tr>
<td>276</td>
<td>C SLOWING DOWN DISTANCE &amp; TRANSITION POINT</td>
<td></td>
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<tr>
<td>277</td>
<td>X=10(V+VOL)/(v-VOL)/DECL/720O</td>
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<tr>
<td>278</td>
<td>STAT=ST+X</td>
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<tr>
<td>279</td>
<td>IF(S GT STAT) GO TO 150</td>
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</tbody>
</table>
GO TO 160

150 ISR=0

202 VC=VCN

203 IF (V.YGT.1.05*VC) GO TO 180

204 IF (V.YGT.VC) GO TO 170

205 TN=TN+1NI

206 GO TO 190

207 C SPEED IN DEADBAND

208 170 TN=TN-TNI

209 IF (TN.LT.0.) TN=0.

210 GO TO 190

211 C SPEED ABOVE DEADBAND

212 180 TN=TN-TNI

213 C TRACTIVE EFFORT AND PROPULSION LIMITING

214 190 IF (TN.LT.-AMASS*DECMAX) TN=-AMASS*DECMAX

215 TP=TN+1NI

216 IF (TP) 200, 220, 210

217 C BRAKING

218 200 TPT=-AMASS*EMAX

219 IF (V.YGT.VXB) TPT=-AMASS*EMAX*VXB/V

220 IF (TP.LT.-TPT) GO TO 302

221 EB=TP

222 FB=0.

223 GO TO 228

224 302 EB=TPT

225 FB=TP=EB

226 TP=EB*EP/375

227 TP=TM*ETA9.746

228 GO TO 230

229 C MOTORING

230 210 TPT=AMASS*EMAX

231 IF (V.YGT.VXT) TPT=-AMASS*EMAX*VXT/V

232 IF (TP.LT.TPT) TP=TPT

233 C COASTING

234 220 EB=0.

235 FB=0.

236 PP=TP*VP*.746/(375*ETA)

237 IF (IREG>0.0) AND. (PP.LT.0.) PP=0.

238 RF=SQR(1.-PF*PF)
C VEHICLE INPUT POWER
VP=PP+PAUX*NX
C VEHICLE INPUT KVA
KVA=SQRTP(VP*VP+PO*PO)
C VEHICLE DYNAMICS
TN=TP-TU
ACC=IN/AMASS
ABAR=(ACC+ACC1)/2.
ACC1=ACC
V=V+AHAR*TAU
VRAR=(V+V1)/2.
V1=V
S=S+VBAR*TAU/3600.
C VEHICLE ENERGY
PBAR=(VP+VP1)/2.
VP1=VP
IF (PBAR*LT.0.) GO TO 931
ER=ER+PBAR*TAU/3600.
EV=(PBAR*TAU/3600.)**.96**4.99*EV
GO TO 932
931 ER=ER+PBAR*TAU/3600.
932 EV=(PBAR*TAU/3600.)**.96**4.99*EV
TONM1=1T1*(S-RT(1+1))/200.
SP=1000.*EV/TONMI
VM=VP/1000.
VMVA=KVA/1000.
TPP=TP/1000.
FBB=FB/1000.
C UPDATE TIME
THETA=THETA+TAU
IF (VM<LT.0.) GO TO 234
IF (IFLAG.EQ.1) GO TO 232
GO TO 238
232 REMP=ER**.96**.96**.99**.96
VM=1=0.
TAX=1
IFLAG=0
GO TO 238
234 IF (IFLAG.EQ.1) GO TO 236
ER=0.
IFLAG=1
IAX=1
TAX=0

236 RMAX=AMAX1(-VMW,VMW)
VMW1=RMAX

238 TXX=TXX+TAU
IF(TXX.GF.60.) IAX=1
IF(TXX.GF.60.) TXX=0
IF(Nht.NE.NSEL) IAX=0
IF(IAX.EQ.1) WRITE(6,206)THETAX,ACC,V,STA,VMK,ETA,PF,VMVA,EV,TPP
1+FBSP+CGVC+RMAX+REMP
IF(IAX.EQ.1) IAX=0
TIM=TIM+TAU
IF(TIM.GE.TMAX) IWC=1
IF(TIM.GE.TMAX) TIM=0
IF(ROUTE.EQ.0) STA=S
IF(ROUTE.EQ.1) STA=CONST-S
IF(ISTOP.EQ.1) GO TO 240
IF(VLT.0.) V=0.
GO TO 46

240 IF(SG.EQ.STT) GO TO 250.
IF(VLT.0.) GO TO 250
GO TO 46

250 S=STT
V=0.

255 O=ELL=3600.*SCH(N,6)+60.*SCH(N,7)
IF(SCH(N,5).EQ.0.) GO TO 254
IF(O.EQ.0.) GO TO 254

702 IF(CLOCK.EQ.O.) GO TO 252
CLOCK=CLOCK+TAU
GO TO 46

C END OF O=ELL

252 CLOCK=0.
I=IRET
ISR=1
SCH(N,6)=99.
IF(Nht.NE.NSEL) IAX=1
VC=IF(TF(IRET,4))
IF(ROUTE.EQ.1) VC=MTK(IRET+4)
SCH(N,5)=0.
ISTOP=0
GO TO 4b
CONTINUE
10 FORMAT(7F10.3)
201 FORMAT(1H0,7I1H MILES POST CURVATURE GRADE CIVIL SPEED ELEVATION 2
TRADE SPEED LOCATION NUM LOCOS)
202 FORMAT(1H0,7I1H MILES DEGREES % MPH FEET
1 MPM MILES)
203 FORMAT(1H0,7I1H ACC SPEED DIST VEH EFF PF MVA F-LIMIT
1 IF FE SPECIFIC PWR CURVE GRADE SPEED LT Fw H=MP)
205 FORMAT(1H0,7I1H MSEC MPH SI MPH MI NW PL PU MVA KMPH
1 KLR KLR WHRATON=M1 DEG % MPH NW KMPH)
206 FORMAT(2F7.0,F5.2,F5.1,F6.1,F6.2,F5.3,F5.3,F6.2,F8.0,F7.0,F7.0
1F10.2,F6.2,F6.2,F6.0,F6.0)
501 FORMAT(4F3.0,F19.6,F2.0,1X,F2.0,6.5,F10.6,F2.0,0,1X,F4.0,5.5,F1.0,6
1F1.0)
502 FORMAT(1H0,75HTRAIN ID ROUTE DIR TRL TONS START STOP HM
10WELL START HM NO LOCOS)
503 FORMAT(1H0,7I1H 0,F7.0,F10.0,F7.0,1H0,F3.0,F14.2,F6.3,1H0,F3.0,F10.0,2
13.0)
506 FORMAT(12F10.2)
507 FORMAT(1H0,9H TRAIN ID; AB)
508 FORMAT(1H0,9H TRAIN ID; AB)
509 FORMAT(1H0,59H SYSTEM ENERGY INCLUDING TRANSMISSION LOSS; 1;E
1.0)
510 FORMAT(1H0,10X,10HAVE LOAD: F10.2,3X,11HDISCH CAP: F10.2,3X,12H
1CHANGE CAP: F10.2)
511 FORMAT(1H0,1X,4H TIME; 44AX,16SUBSTATION POWER; 44AX,11MITAL POWER)
512 FORMAT(1H0,39H NON REGENERATIVE PERFORMANCE TRAIN ID; AB)
513 FORMAT(1H0,39H,5N,42X,17H REGENERATIVE PERFORMANCE TRAIN ID; AB)
514 FORMAT(1H0,45X,17H SUBSTATION ENERGY)
515 FORMAT(1H0,17H STOP FOR TRAIN; AB,10H NOT FOUND)
STOP
END
The following printout defines the program nomenclature.
NOMENCLATURE:

FORTRAN SYMBOL DESCRIPTION UNITS
ABAH AVERAGE ACCELERATION MPH/SEC
ACC ACCELERATION MPH/SEC
ACC1 OLD ACCELERATION MPH/SEC
AFC FRONTAL AREA OF CAR SQ FT
AFL FRONTAL AREA OF LOCOMOTIVE SQ FT
AJERK JERK RATE MPH/S/S
AJERKR RATED JERK RATE MPH/S/S
AMASS EFFECTIVE TRAIN MASS G LHS
HEMAX MAXIMUM BRAKING EFFORT PER LOCU LHS
CLC Location of train at start SEC
DECL DECELERATION MPH/SEC
DECMAV MAXIMUM DECELERATION LIMIT MPH/SEC
DIF ABSOLUTE DISTANCE TO NEXT ROUTE MATRIX LOCATION MI
DIF1 ABSOLUTE DISTANCE FROM LAST ROUTE MATRIX LOCATION MI
DWAELL DWELL TIME AT INTERMEDIATE STOP (INPUT AS HR/MIN) SEC
EH ELECTRICAL BRAKING EFFORT LHS
EH REGENERATED ENERGY AT PANIGRAPH PU
ETA PROPULSION SYSTEM EFFICIENCY KWHRS
EV NET VEHICLE ENERGY CONSUMPTION KWHRS
EV1 ENERGY INPUT TO VEHICLE-OLD KWHRS
FH MECHANICAL (FRICTION) BRAKING EFFORT LBS
FHB MECHANICAL (FRICTION) BRAKING EFFORT KILO-LBS
G GRADE
GEE ACCELERATION DUE TO GRAVITY (21.927) MPH/SEC
I INDEX
ID TRAIN INDEX
IFLAG CONTROL FOR COMPUTATION OF FLYWHEEL CAPACITY
II INDEX
IN NUMBER OF ROUTE DATA CARDS
INREG REGENERATION CODE 1=REG, 0=NON-REG
INDX INDEX FOR INTERMEDIATE STOP IN ROUTE MATRIX
ROUTE ROUTE CODE 0=WESTBOUND, 1=EASTBOUND
ISH SPEED REDUCTION CODE
ISTOP STOPPING CODE
IW C WRITE COMMAND
IXX TIME HISTORY OUTPUT CODE 1=OUTPUT, 0=NON-OUTPUT
J INDEX
K INDEX
KVA VEHICLE INPUT APPARENT POWER KVA
MF LOCOMOTIVE MASS FACTOR
N TRAIN SCHEDULE INDEX
NAC NUMBER OF AXLES ON CARS
NAL NUMBER OF AXLES ON LOCOMOTIVES
NC NUMBER OF CARS IN TRAIN
NTO NUMBER OF TRAINS IN SCHEDULE
NL NUMBER OF LOCOMOTIVES IN TRAIN
NH NUMBER OF CARS IN ROUTE DATA
NS NUMBER OF FEED POINTS
NSEL TRAIN SELECTED FOR OUTPUT (ID NUMBER)
<table>
<thead>
<tr>
<th>Symbol</th>
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<tr>
<td>PAUX</td>
<td>LOCOMOTIVE AUXILIARY POWER</td>
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<td>MAXIMUM TRACTIVE EFFORT</td>
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<td>LOCATION OF INTERMEDIATE STOP (START BASE)</td>
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<td>TRACTION HORSEPOWER AT WHEELS</td>
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<td>OUTPUT HOURS TIME</td>
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<tr>
<td>TRCN</td>
<td>CAR DRAG AT NEXT LOWER SPEED LIMIT</td>
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<tr>
<td>XT</td>
<td>SPEED REDUCTION DISTANCE</td>
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APPENDIX G

REPORT OF NEW TECHNOLOGY

No "subject inventions" resulted from the Wayside Energy Storage Study. However, an improvement over present equipment was developed in concept which could have a significant impact on U.S. railroad operations. This is the dual-mode locomotive which is described on pp 20-25 of Volume 1 and pp 2-39 through 2-53 of Volume 2 of this report. This locomotive is a modification of a standard diesel-electric locomotive to which a pantograph, transformer, converter, and smoothing inductor are added. The resulting dual-mode locomotive can then operate either as a conventional diesel-electric locomotive or as an electric locomotive powered from an overhead catenary. Such locomotives can then provide the benefits of both diesel-electric and electric locomotives without the drawbacks of either. For example, the dual-mode locomotive can operate on electrified lines with the energy efficiency, long life, and reduced maintenance of an electric locomotive but when required, can operate with full performance on non-electrified lines as a diesel-electric locomotive. The application of dual-mode locomotives to railroad routes with local electrification on ruling grades can result in annual returns on investment up to 27% based on reductions in required locomotive consist, energy savings, and reduced maintenance.

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