PB81-191314

FRA/ORD-80/82.I

DUAL-MODE LOCOMOTIVE SYSTEMS ENGINEERING

VOLUME 1
SUMMARY

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FEBRUARY 1981

FINAL REPORT

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Springfield, Virginia 22161

Prepared for

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL RAILROAD ADMINISTRATION
WASHINGTON, DC 20590

Technical Report Documentation Page

1. Report No. FRA/ORD-80/82.I	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle DUAL-MODE LOCOMOTIVE SYSTEMS ENGINEERINGS VOLUME I: Summary		5. Report Date February 1981 6. Performing Organization Code
7. Author(s) L. M. Cook, L. J. Lawson		8. Performing Organization Report No. 80-17253-1
9. Performing Organization Name and Address AiResearch Manufacturing Company of California A Division of The Garrett Corporation 2525 W. 190th Street Torrance, CA 90509		10. Work Unit No. (TRAIS) 11. Contract or Grant No. DTFR53-80-C00010
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Railroad Administration Office of Research and Development Washington, DC 20590		13. Type of Report and Period Covered Final Report December 1979 through November 1980 14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

This report, Volume I, provides a summary of the systems engineering study undertaken as Phase I of a proposed five-phase program. The intent of the overall program is the development, in-service demonstration, and ultimate deployment of dual-mode locomotives. This study has confirmed the technical viability of the dual-mode locomotive (DML) based on a modified model SD40-2, which can operate from either a high voltage catenary electrified at 60 Hz or from an onboard diesel engine. The DML is available in both 50- and 25-kv versions and can have a regenerative electric brake capability if required. The weight of a 50-kv, regenerative DML (the heaviest option) is under 398,000 lb, with normal options included. The space requirements for the electric components are compatible with installation on existing locomotive platforms without interfering with the diesel power equipment.

The cost of the conversion of an SD40-2 to the DML configuration at locomotive rebuild is up to $414,097. This conversion will make possible an initial electrification project that will result in a return on investment that is superior to conventional electrification for a fraction of the initial cost. A record of the Industry Review held in Chicago on October 16, 1980, presenting the results of this study, is contained in the Appendix.

This report comprises two volumes as follows: Volume I - Summary and Volume II - Detailed Description and Analysis.

17. Key Words Locomotives, railroads, electrification, regenerative braking, dual-mode locomotives, electric locomotives		18. Distribution Statement Document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 94	22. Price

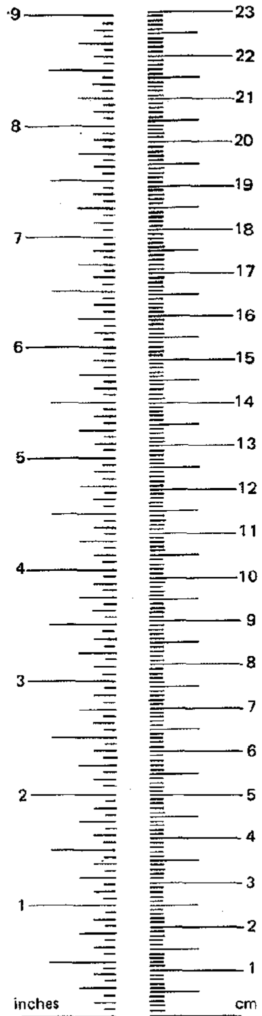
Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

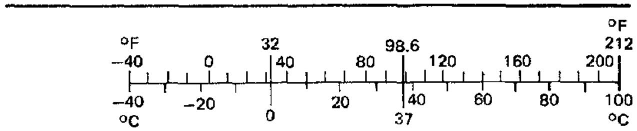
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2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

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



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	36	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



PREFACE

This final report summarizes the results of the dual-mode locomotive (DML) systems engineering study. It is submitted to the Federal Railroad Administration (FRA) by the AiResearch Manufacturing Company of California, a division of the Garrett Corporation, in accordance with U.S. Department of Transportation (DOT) Contract No. DTFR53-80-C-00010. This final report comprises two volumes:

Volume No.	Title
I	Summary
II	Detailed Description of Analysis

This DML study represents the joint efforts of Garrett; GEC Traction (U.K.) Ltd., who assisted in the determination of component sizes; and Morrison-Knudsen, who conducted an equipment installation analysis.

The continued assistance and guidance of the FRA Contracting Officer's Technical Representative, Mr. John Koper, Program Manager, Energy/Environment, and several members of the FRA, Transportation Systems Center (TSC), and Department of Energy (co-sponsor) staffs were invaluable to the success of the program.

The interest and support for the DML concept given by Mr. Peter Eggleton, Director General, Transport Canada Research and Development Centre, and his staff have contributed to the likelihood of DML deployment throughout North America.

Major contributions were made by the Association of American Railroads and by many individual U.S. railroads, who provided comprehensive information that was used to establish and maintain the necessary data base. Many of these railroads also acted as sounding boards in the formulation and review of the DML concept. Their comments and suggestions have been incorporated into the final recommendations of this report, with the result that the concept favored for preprototype construction and for ultimate fleet deployment is representative of equipment that railroads would consider for future procurement. The following railroads have given substantial assistance or have expressed interest in the DML concept to Garrett during the study:

Amtrak
Atchison, Topeka, and Santa Fe
Burlington Northern
Chessie
Chicago and North Western
Chicago Milwaukee St. Paul and Pacific
Consolidated Rail Corporation
Denver and Rio Grand Western
Duluth Missabe and Iron Range
Louisville and Nashville
Missouri Pacific
Norfolk and Western
Seaboard Coast Line
Soo
Southern
Southern Pacific
Union Pacific

In addition, many equipment suppliers were helpful in defining the equipment that would be required to achieve the locomotive modification and in the review of the proposed modification. The suppliers contributing to the study were:

Dow Corning
Faiveley
General Electric Industrial Sales Division
General Motors (Electro-Motive Division)
Ingersoll Rand
Kim Hotstart
Matra Electric Inc.
Power Energy Industry
Ringsdorf
Southern California Edison
Vapor Corporation
Western Compressor Service (Sullair)

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SECTION 1

INTRODUCTION

BACKGROUND

The dual-mode locomotive (DML) concept was first identified during a wayside energy storage study conducted by Garrett (see Reference 1*). Garrett was subsequently awarded a contract for a DML systems engineering study (Phase 1 of a five phase program). The study, which considered economic issues when evaluating DML deployment versus conventional electrification, confirms the technical feasibility of the DML concept. Results are summarized in this document. Rather than a competitor to conventional electrification, the DML provides a cost-effective transition (approximately over the next 20 years) from state-of-the-technology to development of more energy-efficient electrification systems.

The major advantages of the DML for a railroad considering electrification are:

(a) The initial electrification scheme need only require catenary on the ruling grades, and the purchase of new locomotives is avoided. These factors can reduce the initial investment to 20 percent of that required for a normal electrification project.

(b) The return on investment (ROI) for DML deployment is usually higher than for conventional electrification.

(c) Locomotive flexibility is maintained.

(d) Loading/unloading facilities need not be electrified.

(e) Power changes at the end of an electrified section are not mandatory.

(f) Passing siding need not be electrified.

PROGRAM OBJECTIVES AND SCOPE

The DML Systems Engineering Study was structured to provide the basis for the proposed Phase II design activity. The study was based entirely on the use of state-of-the-art equipment and established, well-proven design parameters known to be applicable to the heavy freight railroads of the United States.

The overall objectives addressed in the study were to:

(a) Confirm technical feasibility of the DML concept

(b) Assess the economic impact of DML deployment

(c) Inform the railroad industry of the DML concept

(d) Formulate proposals for eventual demonstration of the concept

To meet these objectives, a statement of work for this Garrett study was developed. Major contributors (subcontractors) were GEC Traction and Morrison-Knudsen. The work scope comprised the following:

Establish Technical and Economic Requirement (Task 1)--Review the work previously published for the the DML concept (References 1 and 2) and update this information to include the most recent operating methods of major railroads. Also, analyze locomotive population in order to recommend the locomotive model to be used as a demonstrator unit.

Establish Baseline Concept (Task 2)—Determine design requirements for the DML to be used as a baseline. baseline.

*References are listed in Section 6.

Preliminary Design Definition (Task 3)--Produce outline of equipment required for the achievement of the baseline concept.

System Performance (Task 4)--Establish the requirements of the infrastructure and the locomotive, and identify the impact of one on the other.

Develop Preliminary Equipment Performance Specifications (Task 5)--Identify standard and purpose-designed equipment, and develop performance specifications for this equipment.

Develop Preliminary Cost Estimate (Task 6)--Produce a cost estimate for the DML using the results of the preceding five tasks as a basis. Reassess the economic benefits of DML deployment.

PROGRAM METHODOLOGY

The methodology followed by Garrett, GEC Traction, and Morrison-Knudson is shown in Figure 1. Throughout the study, many railroads provided specific assistance by attending quarterly review meetings and providing followup information. These railroads were:

Amtrak
Burlington Northern
Conrail
Missouri Pacific
Southern Pacific
Union Pacific

As part of the Task 6 effort, costs associated with DML deployment were reviewed using the system engineering data as a basis. Pertinent economic data from a recently completed electrification feasibility study prepared for Conrail by Gibbs & Hill (Reference 3) were also incorporated in the cost analysis.

TRAIN PERFORMANCE CALCULATOR (TPC)

The journey times and energy calculations required for this study were performed using the Garrett TPC, which was originally developed for a previous FRA program (Reference 1). Since that program, the TPC has been further augmented to accurately model the operation of a DML, including automatic changeover. The TPC has been validated as follows: energy accuracy is within 7 percent, and time accuracy is within 2 percent.

FORMAT OF THE FINAL REPORT

Due to the large volume of material generated during this 8-1/2 month study, this report is published in two volumes. In this volume, the work performed during the study is summarized and the selected locomotive configuration is described. Volume II contains detailed backup data and descriptions of options that were considered.

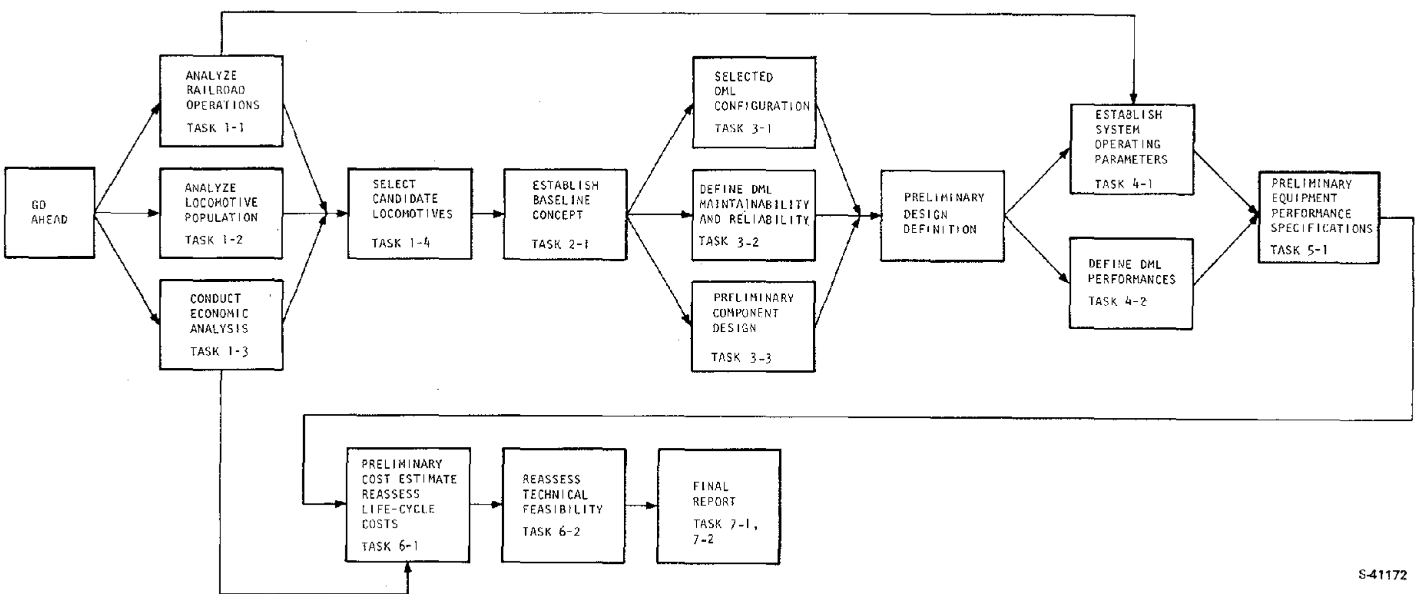

Figure 1. DML System Engineering Study Methodology

SECTION 2

DUAL-MODE LOCOMOTIVE CONCEPT

INTRODUCTION

In this section, the fundamental parameters of the selected DML configuration are described and available options are identified

BASE LOCOMOTIVE

The population of U.S. road locomotives, which are owned by 14 major railroads, is summarized in Table 1. Approximately one-half of the nation's locomotives are included. By far the most common locomotive is the SD40-2, and therefore the retrofit design has been initially based on that locomotive. Other locomotives which could be considered are the SD-45 and GP38-2.

LOCOMOTIVE OPTIONS

The DML design has been constrained to be available in both 50- and 25-kv, 60-Hz versions and to offer the option of regenerative braking to improve energy efficiency. It is anticipated that electrification in the West will be at 50 kv, due to the absence of clearance difficulties, whereas in the East the relatively close centers of population and attendant bridges, etc. will make 25 kv more economical. Due to the large size and weight of a transformer constructed for 25-Hz operation, this frequency was not considered in Detail. Therefore, the DML is suitable for operation on the Northeast Corridor only after completion of the Northeast Corridor Improvement Program.

TABLE 1

LOCOMOTIVE POPULATION SUMMARY

Model	Number	Age, yr	Percent of Total
SD35	349	14.0	2.9
SD40	797	11.7	6.6
SD40-2	2,529	4.8	21.0
SD45	1,155	11.8	9.6
SD45-2	359	7.0	3.0
GP30	800	17.5	6.6
GP35	943	14.4	7.8
GP38	682	10.8	5.7
GP38-2	1,108	5.4	9.2
GP40	874	11.8	7.2
GP40-2	456	4.0	3.8
U30C	524	7.3	4.3
U30-7	478	1.5	4.0
U33C	316	9.5	2.6
U23B	371	8.7	3.1
B23-7	326	1.3	2.7
TOTAL	12,067	8.9	100.1

NOTES: 1. Based on survey of 14 railroads
2. Only models with more than 300 in sample included in this table

The DML will be offered with regenerative braking, if this is requested by the railroad. The impact of the decision to use regenerative braking is the increased weight of the equipment and increased cost. This must be traded off against savings in energy, which are likely to be small--particularly during the early stages of DML deployment.

A number of minor options are available to the railroad. These include:

- The engine is allowed to idle during the electric mode of operation (the standard is to shut down the engine).
- Changeover from one mode to the other is manual (the standard is automatic changeover).
- Increased capacity of fuel tank to 3500 gal (the standard is 3000 gal).
- Improved wheelslip equipment in diesel mode (the standard is current/voltage balance).

The DML control scheme has been designed to be compatible with the existing trainline functions, and therefore a DML is able to M-U with unmodified diesel locomotive.

PRINCIPLES OF OPERATION

The operating principles of the DML are shown in the system schematic, Figure 2. The existing diesel mode of operation remains unchanged. The principle of the electric mode of operation is to provide an alternate, parallel power source for the traction motors that utilizes the existing power switching equipment (reversers, contactors, etc.) without modification.

In the electric mode, electrical power at high voltage (50 or 25 kv) and industrial frequency (60 Hz) is taken from the contact wire of the catenary system by means of a pantograph. Local fault protection and isolation are provided by a vacuum circuit breaker, lightning arrestor, and grounding switch.

The primary of the main transformer is connected to the high-voltage supply and is grounded to the running rail through axle-end ground brushes. The transformer reduces the voltage and supplies the main converter with low voltage ac. The function of the converter is to supply controlled variable-voltage dc to the traction motors; this is achieved using thyristors. To ensure that the output from the converter is acceptable to the traction motors, a smoothing inductor is provided in the positive leg.

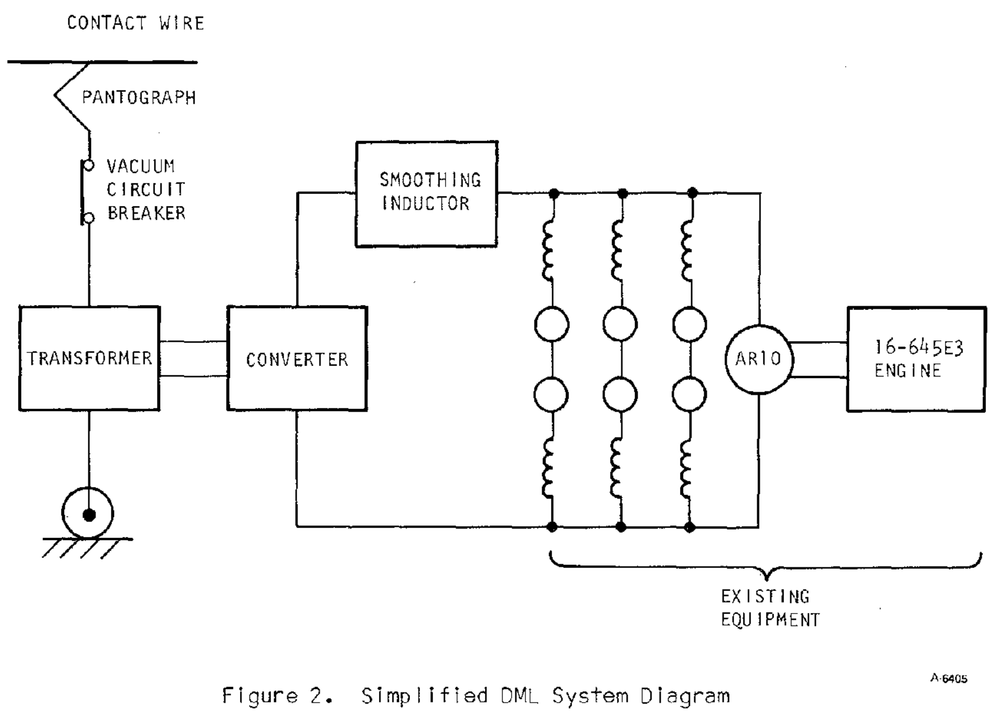

Figure 2. Simplified DML System Diagram

LOCATION OF EQUIPMENT

Diagrams of equipment location are shown in Figures 3 and 4 for the 50- and 25-kv versions, respectively. The only major differences between the two versions are the roof equipment insulation distances and the size of the main transformer.

The cab and electrical cabinet have been moved forward 6 ft to accommodate the pantograph, vacuum circuit breaker, lightning arrestor, and transformer primary bushing. The additional equipment does not exceed the clearance restrictions of AAR Plate C, dated March 1, 1968.

The displaced primary air filter is to be discarded and replaced by a lighter polypropylene filter (used in other locomotive applications) and located in the side of the carbody beneath the vacuum circuit breaker. The oil cooler for the transformer will be located in the primary airflow, thus avoiding the need for a separate oil cooler blower.

The existing equipment blower will be retained with a modified drive system, which includes the replacement of the auxiliary generator by an auxiliary alternator/equipment blower motor and magnetic clutch. The system is described in detail later in this section of the report.

To allow the engine to slow idle or be shut down during electric mode operation, the engine-driven compressor is replaced by a constant-speed, electrically driven compressor to be described later in this section of the report. Physical location of the compressor is essentially unchanged, therefore avoiding extensive piping modifications.

At the rear of the locomotive, the long hood has been lengthened as far as possible to accommodate the main converter unit and the smoothing inductor. The oil cooler for the main converter assembly is located adjacent to the existing radiator assembly. The sandbox has been raised to allow the smoothing inductor to be placed on the locomotive platform.

At the front of the locomotive, the shortened front hood contains the sandbox, radio equipment, toilet, water cooler, etc. The cab has been constrained to conform to AAR clean cab requirements.

The fuel tank, centrally located for maintenance of balance as fuel is consumed, has a capacity of 3000 gal. The motor-alternator is located in the space made available at the rear end. The remaining space at the front of the locomotive could be used for an increased fuel tank size, but this would result in a varying imbalance between trucks as fuel is consumed.

The existing traction motors, assumed to be D77's, are retained without modification. Minor modifications are required to the trucks to fit axle-end ground brushes and safety ground straps.

Locomotive equipment weights for the 50-kv DML are summarized in Table 2.

LOCOMOTIVE PERFORMANCE

The locomotive performance characteristics in the diesel mode are unchanged--continuous tractive effort below 11 mph being limited by the continuous current rating of the traction motor and above 11 mph by the engine output power. Overall fuel consumption in the diesel mode will be the same as for an unmodified locomotive, the less efficient auxiliary system being compensated for by the use of smaller, constant-speed machines (to be described later in this section of the report). Performance of the SD40-2 based locomotive in the electric mode is described below.

Tractive Effort

The power rating in the electric mode is determined by the rating of the D77 traction motor. As currently used in the SD40-2, the D77 has a rating of 356 kw (input), whereas in the GP40-2 the rating is 536 kw (input). Therefore, in the SD40-2 application, the six traction motors are able to accept 1080 kw above that available from the onboard power unit. This results in power ratings at the rail of 2600 rhp* (unchanged) for the diesel mode and 3880 rhp for the electric mode.

To minimize the size and cost of the main transformer and converter unit, the series-parallel transition is retained for electric mode operation. The output characteristic required of the power converter is given in Figure 5, which shows that the maximum current requirement is established immediately after transition at 5000 amp. To minimize the transformer size, the current after transition is to be limited to 4000 amp continuous (5000 amp one-hour). This has only a minor impact on locomotive performance, but has a major impact on transformer size and cost. The resulting tractive effort-speed curves are shown in Figure 6.

*rhp = rail horsepower

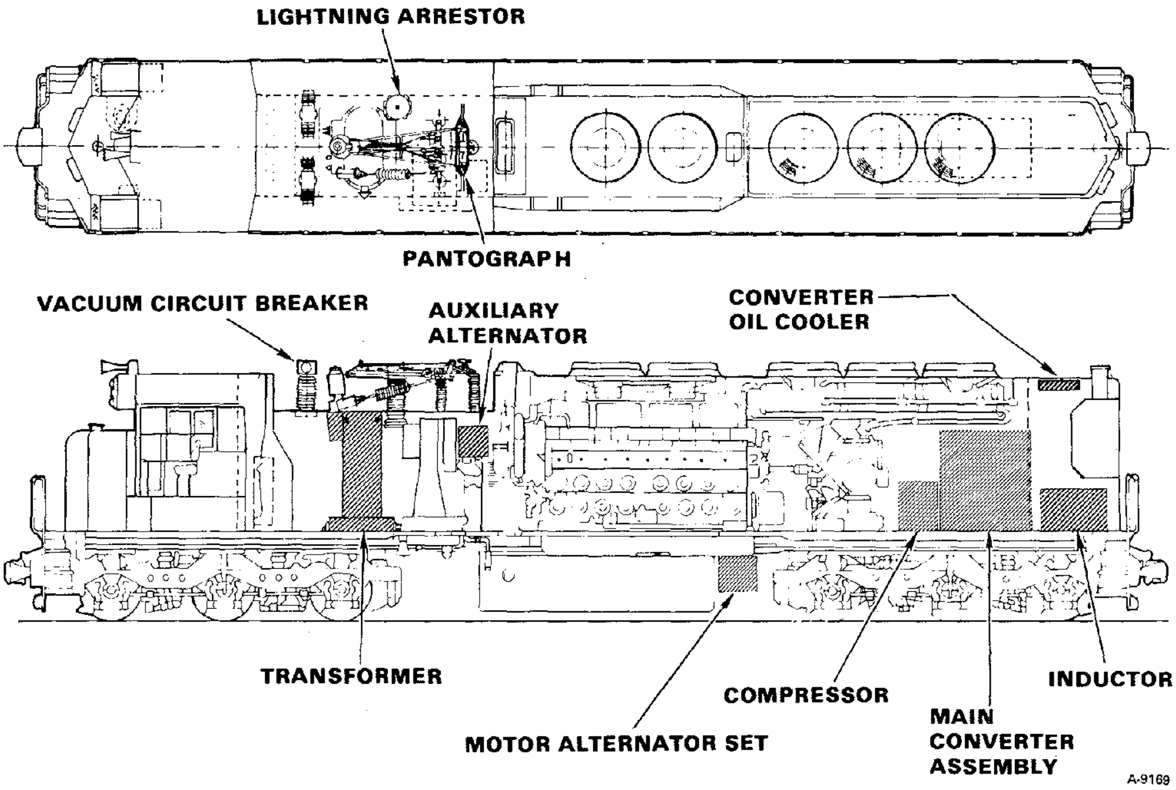

Figure 3. 50-kv DML, Equipment Layout

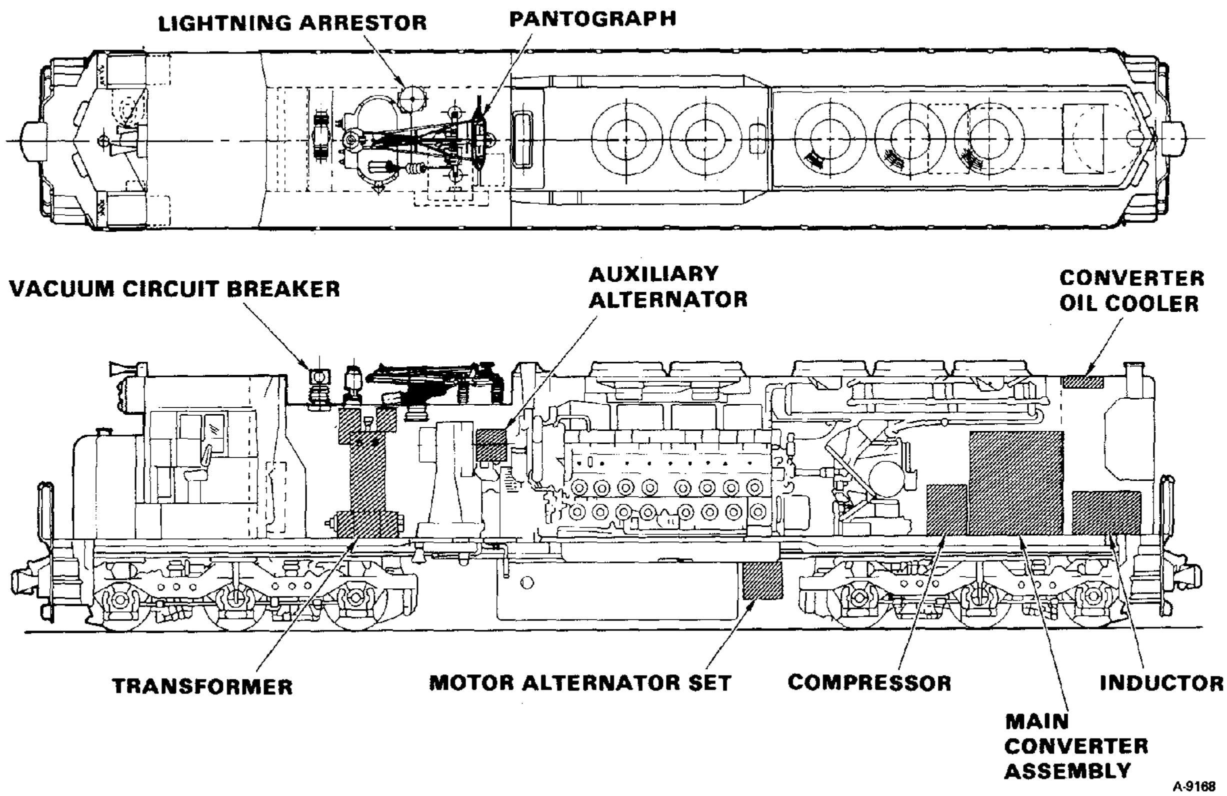

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Figure 4. 25-kv DML, Equipment Layout

TABLE 2

SCHEDULE OF EQUIPMENT FOR 50-kv VERSION

Item	Quantity	Location	Weight, lb
Pantograph	1	Low roof	264
Vacuum circuit breaker	1	Low roof	815
Grounding switch	1	Low roof	50
Lightning arrestor	1	Low roof	144
Roof insulators	3	Low roof	315
Main transformer	1	Carbody, beneath low roof	15,650
Main converter assembly	1	Carbody, rear of locomotive	4,300*/4,100
Smoothing inductor	1	Carbody, rear of locomotive	2,500
+ Cold weather protection	1	Carbody, free end of engine	400
Motor-alternator set	1	Underframe, between trucks	4,000
Compressor	1	Carbody, in place of existing compressor	790
Control relays	16	Electrical cabinet	25
* Power contactors	5	Electrical cabinet	50
Axle-end ground brushes	3	Truck	30
Axle speed probes	6	Gear case	10
+ Rack actuator	1	Engine	5
+ Low water reset solenoid	1	Engine	5
APC receiver	2	Truck	150
Power cable	–	Various	500 (power and control cable together)
Control cable	–	Various	
Auxiliary alternator	1	In place of AG10	2,000
Auxiliary transformer/rectifier	1	Air brake compartment	235
Auxiliary drive clutch	1	Auxiliary alternator shaft	30
+ Operator control switches	1	Cab	1
Operator indicators	2	Cab	1
* Field shunting thyristors	6	Electrical cabinet	200
Air pressure switch	1	Low roof section	2
* Dynamic brake blower assembly	2	Dynamic brack hatch	1,400
Stand-off insulators	10	Truck/underframe	20
Safety ground straps	4	Truck/underframe	8
Oil cooler - transformer	1	Carbody, beneath low roof	200
Oil cooler - converter	1	Carbody, rear of locomotive	200
Primary air filter	1	Carbody, beneath low roof	200

* Regenerative option only

+ Engine shutdown in electric mode option only

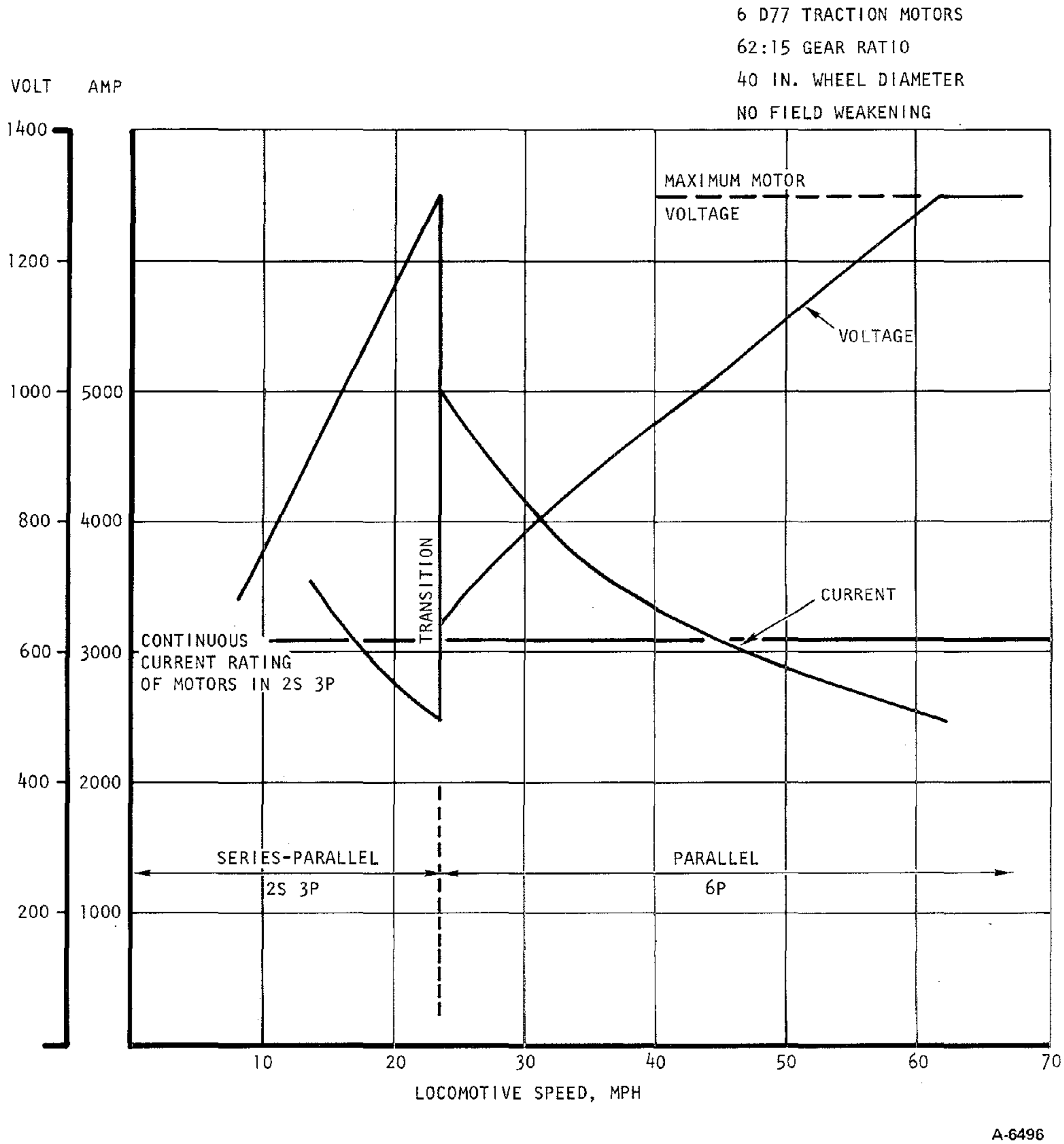

Figure 5. Output Characteristics of DML Converter

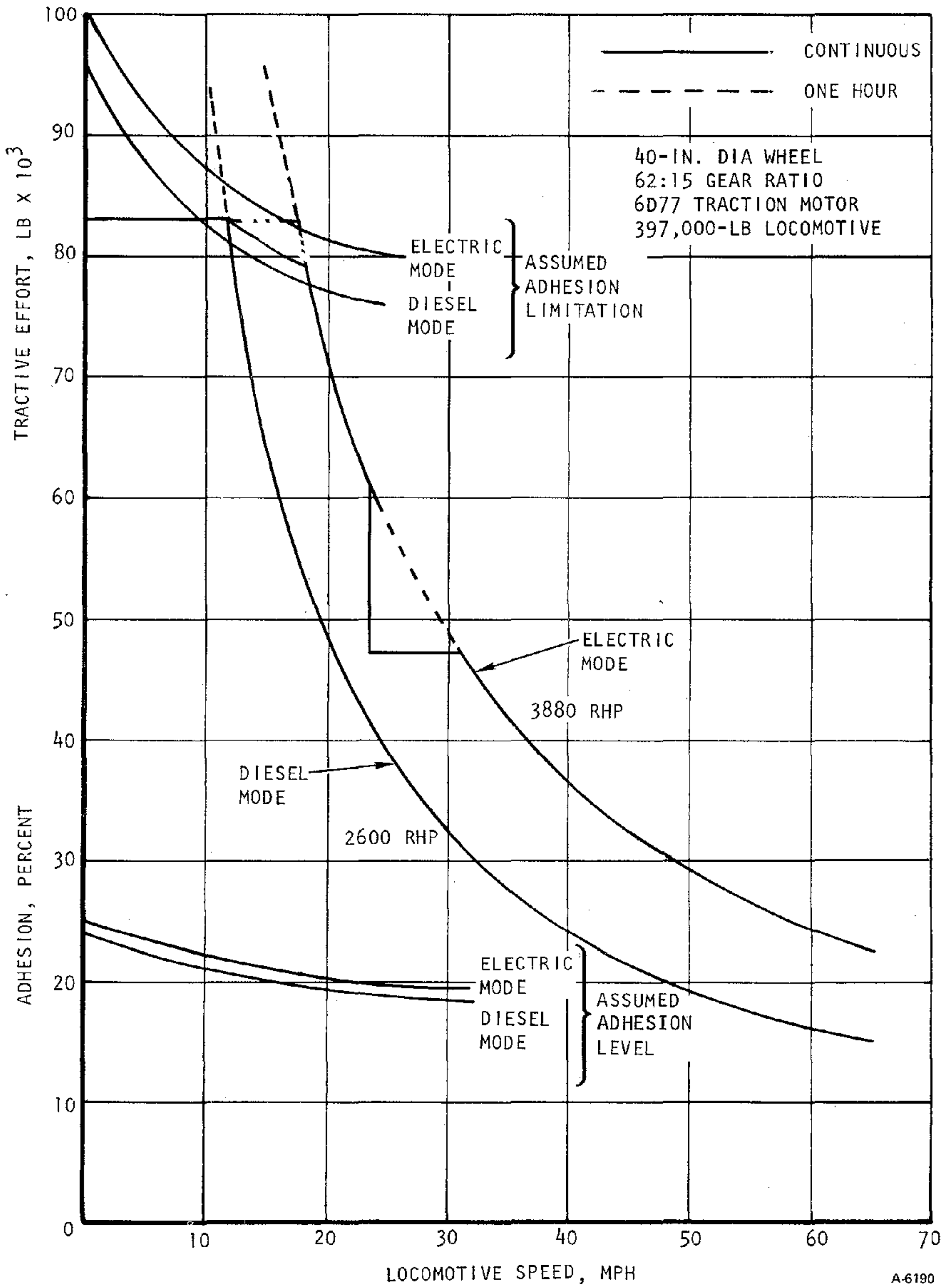

Figure 6. Tractive Effort-Speed Characteristics for SD40-2 Based DML

Power Factor

One of the disadvantages associated with using thyristor control is the relativey poor power factor compared with tapchanger control. The main converter assembly contains a bank of capacitors for power factor correction to compensate for this. The variation of power factor with speed, with and without the power factor correction capacitors, is shown in Figure 7.

Interference

The electrical interference generated by the DML has been predicted using the psophometric weighting approach. The variation of psophometric current with speed is shown in Figure 8.

AUXILIARIES

Since the diesel engine will be, at best, idling and more likely shut down during electric operation, it is necessary to provide for auxiliary supplies that are independent of the diesel engine and, in the interest of economy, suitable for operation in the diesel and electric modes. Such a scheme is shown in Figure 9.

In the diesel mode, the auxiliary drive clutch is engaged and the engine shaft drives the equipment blower and, via a belt drive, the auxiliary alternator. Three-phase, constant-voltage output from the alternator is rectified by the auxiliary rectifier located in the main converter assembly and supplied to the motor of the motor-alternator (MA) set. Three-phase, constantvoltage, constant-frequency output from the alternator is used to drive the compressor and the battery charger.

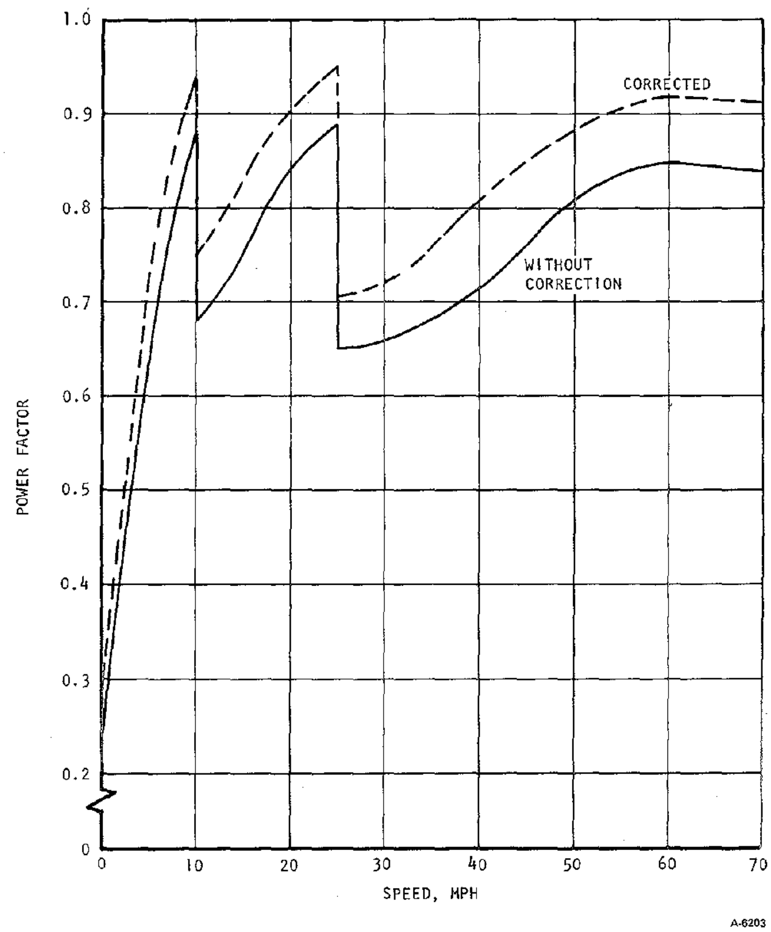

Figure 7. DML Power Factor

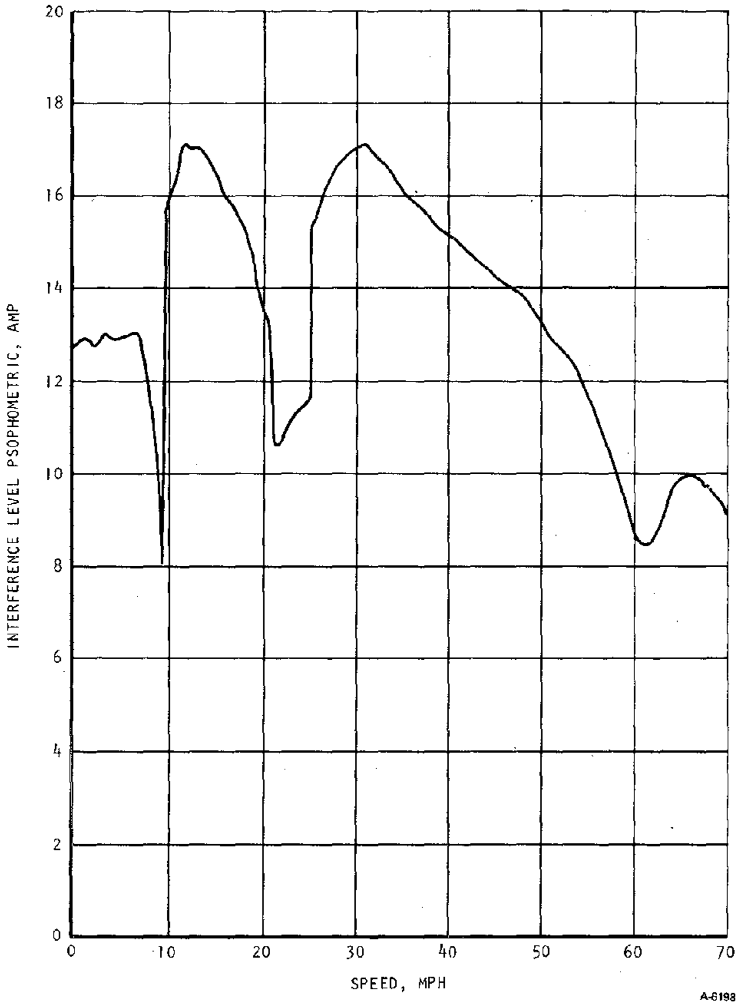

Figure 8. Variation of Psophometric Current with Speed

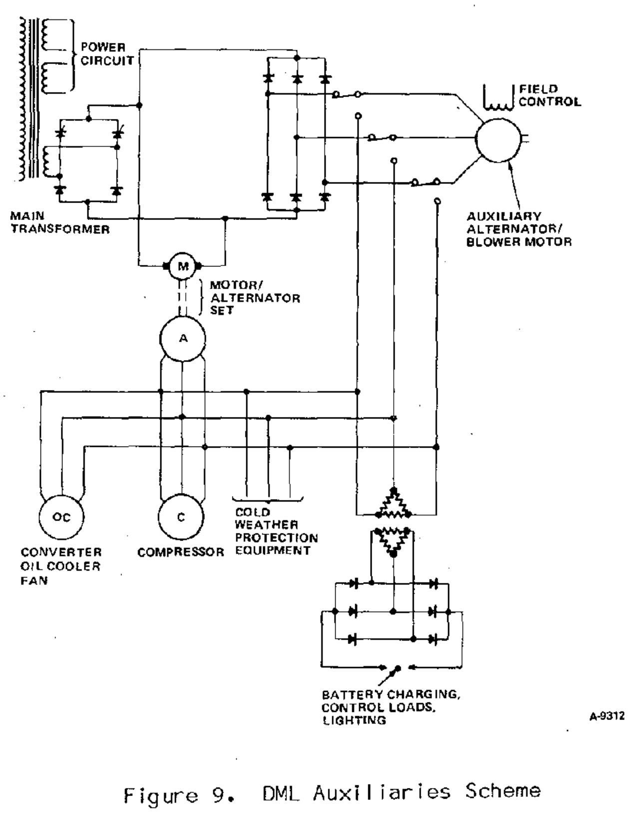

Figure 9. DML Auxiliaries Scheme

In the electric mode, the auxiliary winding of the transformer supplies a phase delay rectifier located in the main converter assembly. The phase delay rectifier is used to compensate for fluctuations in catenary voltage and maintain a constant voltage at the dc link supplying the MA set. The alternator of the MA set is then used to supply not only the compressor and battery charger (as before), but also the equipment blower (the auxiliary drive clutch is disconnected) and the converter oil cooler blower.

EQUIPMENT DESCRIPTION

The major items of equipment required to achieve the DML modification are described below. Where possible, standard components are used to minimize costs. No attempt has been made to dual-source or optimize the equipment for cost, location, or delivery schedules, since the work to date has concentrated on establishing the feasibility of the concept.

Pantograph

Two pantograph types have been considered in this study and both represent the most widely accepted and proven pantograph designs available. The pantographs, manufactured by Faiveley and GEC Traction, are shown in Figures 10 and 11, respectively.

Both pantographs have copper braid shunting to minimize the current carried by bearings located at joints, and weight has been minimized to improve the dynamic response of the pantograph head to irregularities in the contact wire.

At high speed, the current collection characteristics of the GEC Traction pantograph are superior to the Faiveley due to the symmetrical design resulting in aerodynamic forces being the same in both directions. This is not a significant factor in the DML design since the maximum speed of the locomotive is to be 65 mph. The requirements of the DML--low weight, minimum length--favor the use of the Faiveley pantograph and the installation analysis was based on that pantograph.

As an option, a minor modification to the pantograph could be accomplished to provide an automatic pantograph-down facility in the event of the collector head becoming damaged. This feature prevents excessive damage to the overhead installation and can be provided for nominal cost.

Vacuum Circuit Breaker

The vacuum circuit breaker (VCB) is used to provide on-board fault protection and isolation for maintenance purposes. A VCB is preferred to an air blast breaker since the latter requires much more maintenance and is noisier in operation.

The VCB recommended for use on the DML is the GEC model available in both 25- and 50-kv versions, as shown in Figures 12 and 13, respectively. The 25-kv breaker has two vacuum interrupters in series, operated by two opposed pistons that move apart when air is admitted, compressing springs and allowing the contacts to close.

Lightning Arrestor

A lightning arrestor is required to provide protection against line voltage transients that may be caused by lightning or station switching, and basically consists of a series arrangement of spark gaps and nonlinear resistors. In the event of a voltage surge, the spark gap flashes over and puts a ground fault on the system for the duration of the surge. The power-follow current that will flow through the arrestor is limited by the series nonlinear resistors to a value that can be cleared by the gaps. The series resistors must withstand both the passage of the surge energy to ground and the subsequent reapplication of the full system voltage for the remainder of the half-cycle in which the surge occured. The arrestor gaps then clear just before zero voltage.

A typical lightning arrestor is shown in Figure 14.

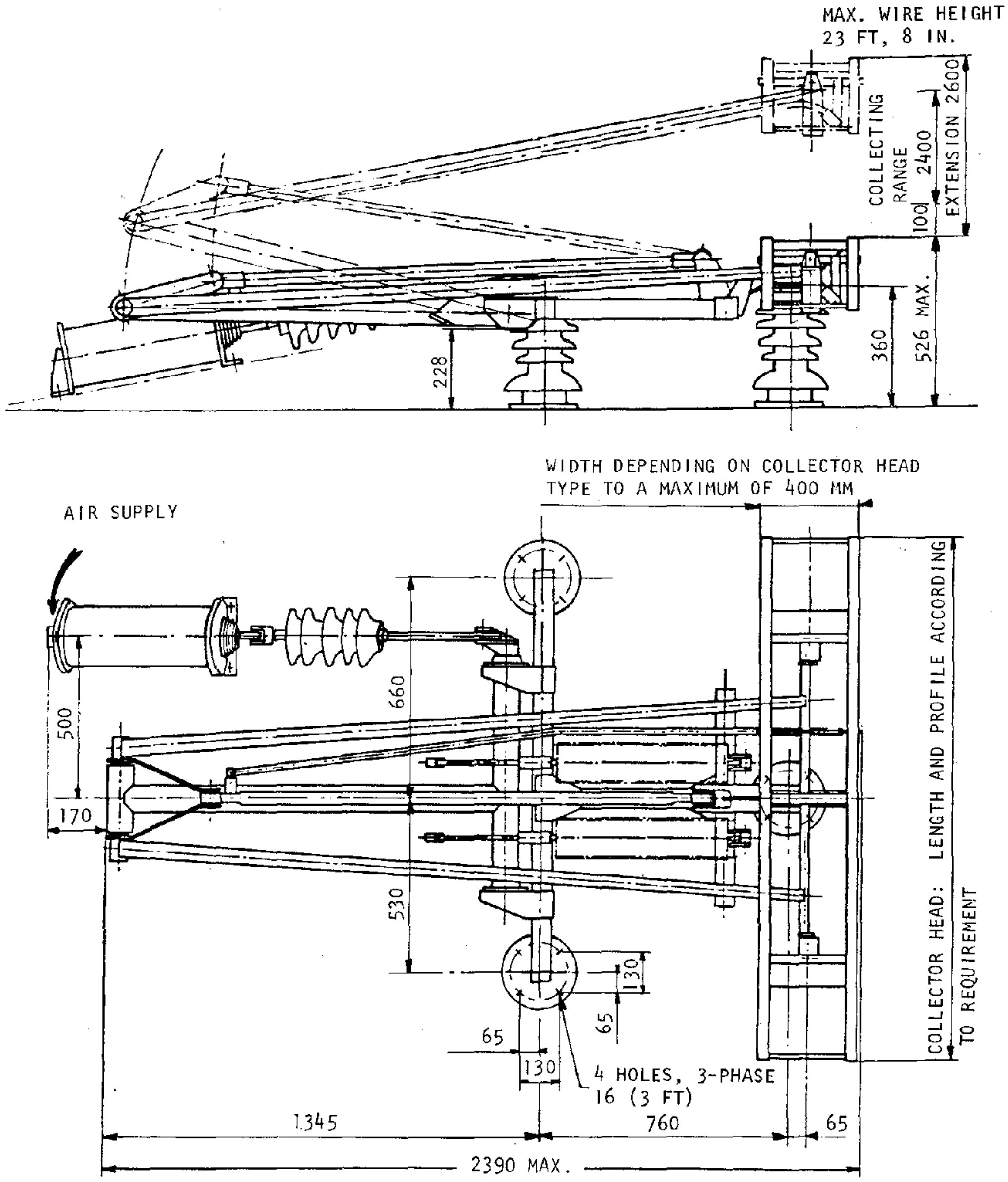

Figure 10. Faiveley Pantograph

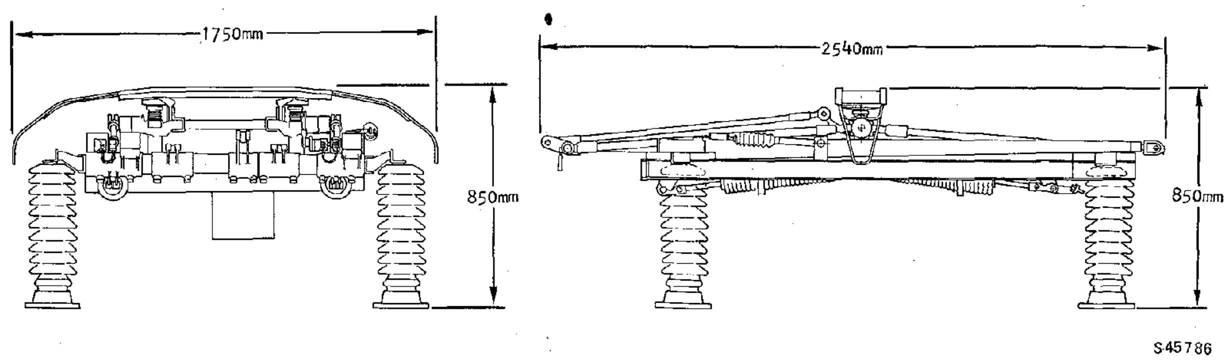

Figure 11. GEC Traction Pantograph

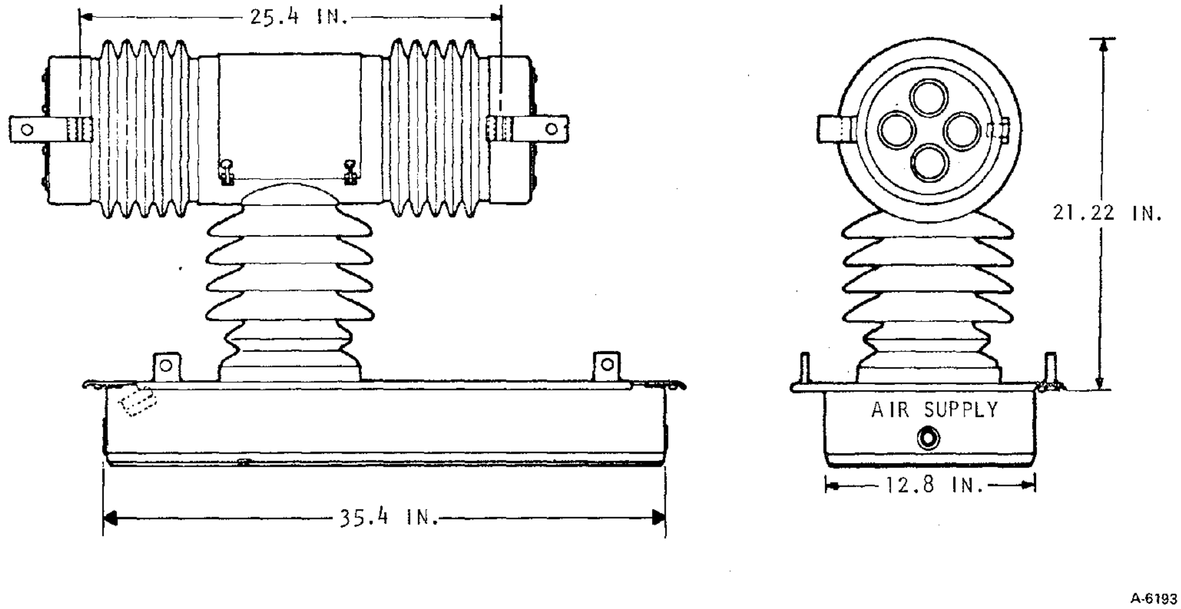

Figure 12. 25-kv Vacuum Circuit Breaker

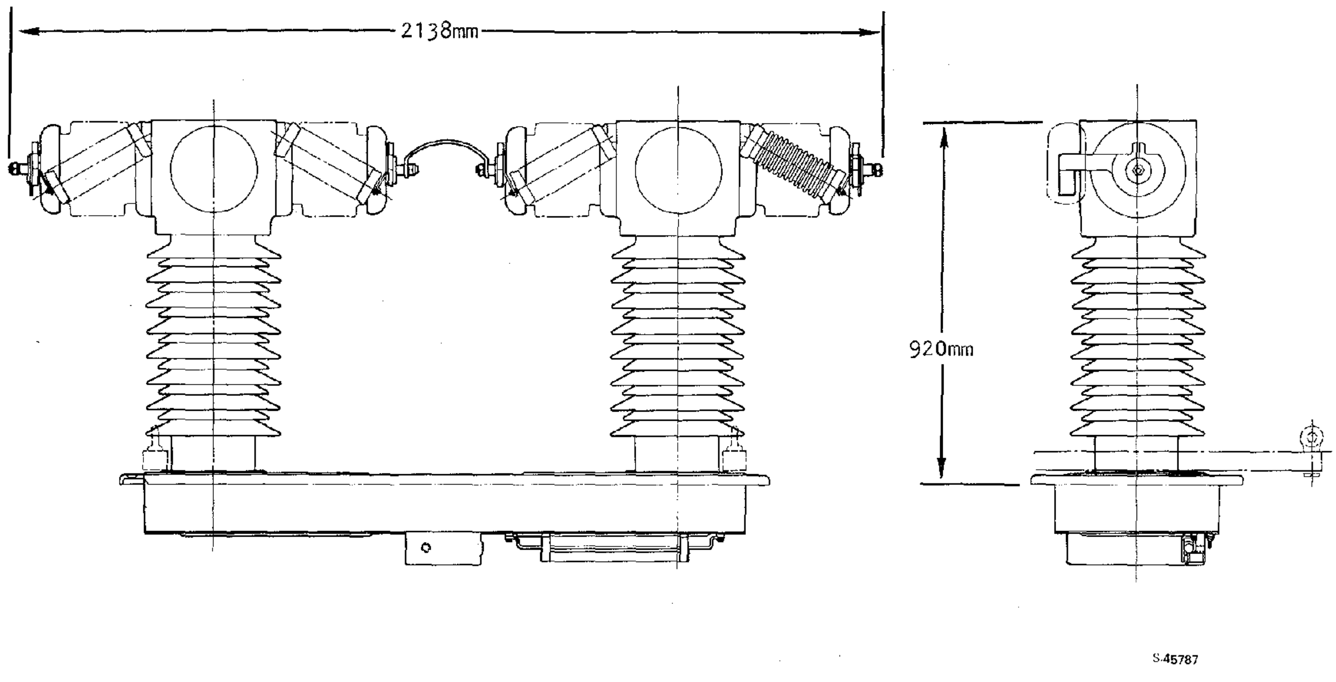

Figure 13. 50-kv Vacuum Circuit Breaker

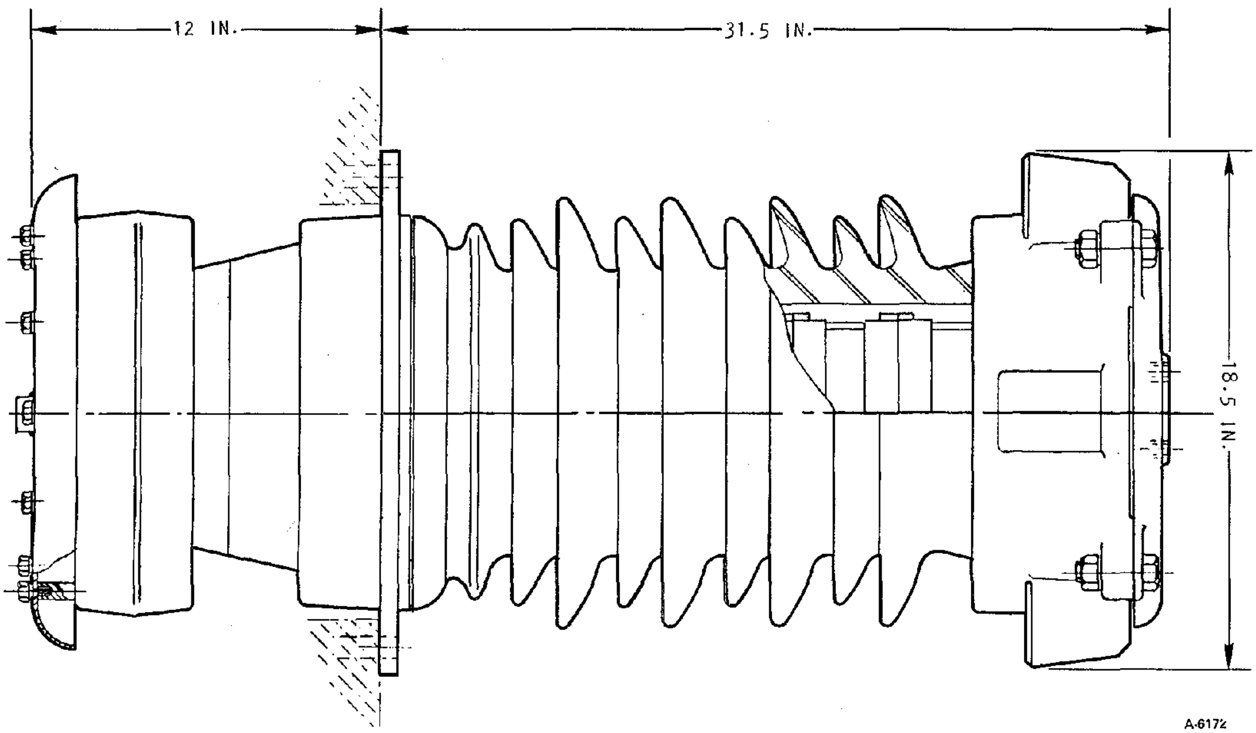

Figure 14. Typical Lightning Arrestor

Main Transformer

The main transformer represents the most difficult of the electric mode components to accommodate within the anticipated stringent volume and weight constraints. For this reason, European technology has been utilized and, in particular, the technology that has been developed for the construction of transformers for locomotives on British Rail (BR) and South African Railways. It was previously established by discussion with two North American electric locomotive suppliers that the construction of a transformer to meet the volume and weight restraints imposed by the DML was beyond the North American state of the art, and this was confirmed by one manufacturer at the DML second quarterly review.

With the reason for the advanced state of the art in traction transformer design established, it is necessary to determine whether direct technology transfer is feasible, or whether modifications are necessary to suit the arduous conditions encountered in North America. The basic questions are: (1) method of rating, (2) strength of construction, and (3) method of cooling.

It has been reported that the DML transformer has been rated to continuously supply the six EMD or GE traction motors at their total continuous rating plus the required auxiliary loads. The mechanical design of the transformer is compatible with vibration levels in excess of 5 g, which are beyond that encountered even in heavy North American practice.

The method of cooling the transformer has become a crucial question recently following the ban on polychlorinated biphenyls (PCB's). The accepted transformer coolant had been askerel, but the ban on PCB's has necessitated the use of other nontoxic coolants. Some countries use mineral oil but its extreme flammability makes it generally unacceptable in North America. Conrail recently undertook an investigation of the feasibility of replacing askerel with silicone fluid, an inert liquid, which, although more flammable than askerel, is not as flammable as mineral oil and is generally gaining acceptance for traction transformers throughout the world. Conrail found that using silicone fluid resulted in the need to derate the transformer (originally designed for cooling with askerel) by 30 percent. This has been recognized in the transformer design proposed for the DML and particular attention has been paid to coolant flow patterns. These design techniques have already been proven in railroad service.

The primary and secondary windings are constructed of paper-wrapped copper conductors, formed on bakelized paper cylinders, with the cylinders mounted on the core legs and held in position by axial wedges running the full length of the winding. Detailed attention to the mechanical integrity of the windings ensures that the windings can withstand the mechanical forces associated with a short circuit.

The magnetic core is built up of low-loss, cold-rolled, grain-oriented silicon steel laminations that are fully annealed after punching. The leg/yoke joints are mitered to give optimum magnetic performance. Ultimate mechanical strength is provided by core bolts, limited in number so that they do not impair the magnetic performance achieved by the mitered joints and high-grade steel. Extra rigidity of the core clamping framework is obtained by bonding together the outer packets of the core with epoxy resin. The resultant design provides a robust, rigid core with low loss and magnetizing current, even at maximum input voltage.

The high-voltage connection is mounted on top of the transformer tank so that the actual connection is to the shedded bushing protruding through the roof. Low-voltage connections are tinned copper cast in a resin molding. Outlines of the 25- and 50-kv transformers are shown in Figures 15 and 16.

Main Converter Assembly

The main converter assembly contains the following subassemblies:

(a) Phase delay rectifier

(b) Electronic control unit (ECU)

(c) Power factor correction capacitors

(d) Single-phase auxiliary rectifier

(e) Three-phase auxiliary rectifier

(f) Field power supply

The main converter processes and controls the ac power from the main transformer to provide dc power for the traction motors. The converter basically consists of an input power factor correction filter assembly, input fuse assembly, eight thyristor subassemblies, electronic control unit (ECU) assembly, and oil cooling system for the thyristor subassemblies. The converter is housed within a 60 in. by 50 in. by 71 in. steel enclosure and weighs approximately 4300/4100 lb for the regenerative/non-regenerative options.

Electrical connections within and between the various power assemblies, as well as external power connections, are via tin-plated aluminum bus bars. The bus bars are designed to limit their temperature rise to 30°C over 40°C ambient temperature conditions. Connections between the ECU and the internal power or external interface circuits are via electrical connectors using standard copper insulated wire or cable.

1. Phase Delay Rectifier

The thyristors form two identical bridges, each consisting of four thyristor subassemblies that are electrically connected in series. Each thyristor subassembly contains two electrically paralleled thyristors, resulting in a total of 16 thyristors being used for power conversion. Each thyristor is mounted between two oil-cooled heat sinks whereby the maximum thyristor junction temperature is limited to 212°F based on an oil flow of 6 gpm at 145°F. In addition, each thyristor subassembly contains two suppression networks for voltage transient protection, two inductors for current stress control, and two gating networks for turning on or firing the thyristors. The thyristor subassembly networks, inductors, and thyristor heat sinks are mounted on an insulated panel for ease of manufacture and maintenance.

The dc current and voltage output characteristics are shown in Figure 5, from which it can be seen that the maximum current requirement is determined immediately after transition. To minimize the main transformer rating, it will be assumed that the 5000-amp requirement is for no more than one hour at a time. The phase delay rectifier has to be designed for 5000 amp continuous.

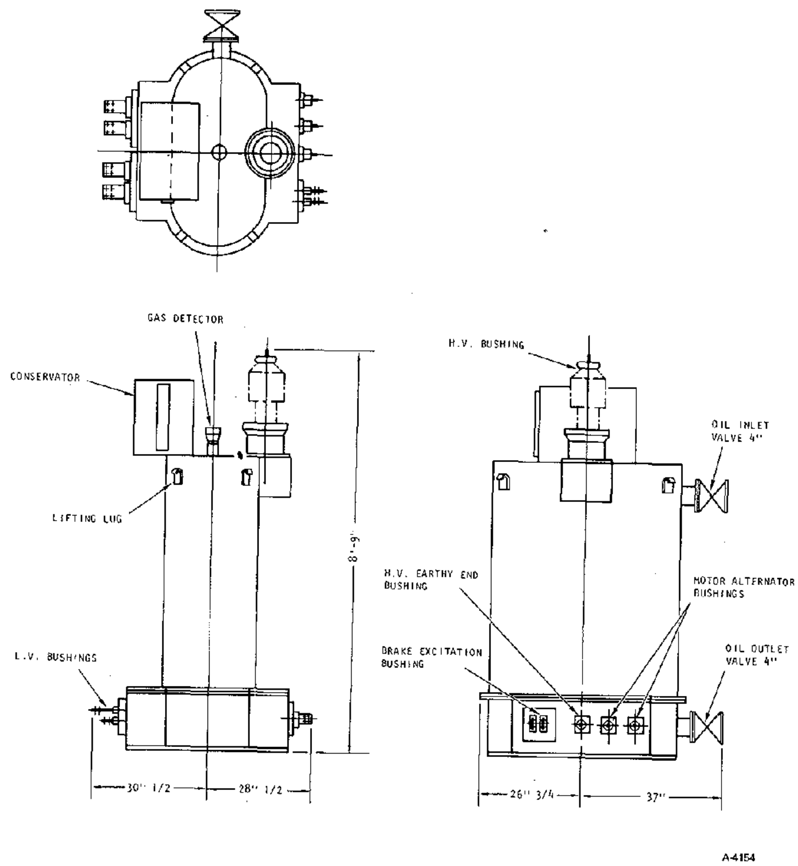

Figure 15. 25-kv Transformer

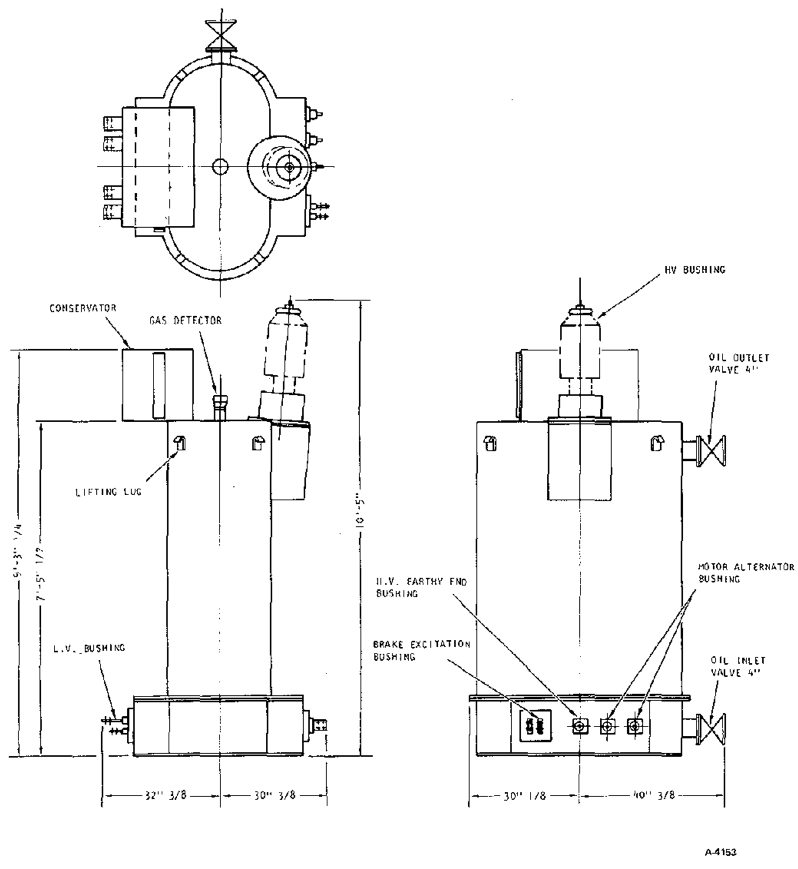

Figure 16. 50-kv Transformer

2. Electronic Control Unit

The ECU consists of 7 printed wire assembly (PWA) cards, control relays, and interface wiring/connectors, all contained within an aluminum chassis. The PWA cards and control relays are plug-in units. The chassis wiring is based on established wire wrap techniques currently used in all Garrett transit vehicle applications. The ECU is mounted independent of the power assemblies to provide minimum electrical interference levels and to allow servicing of the ECU via an external access door of the converter enclosure.

Also mounted within the main converter assembly are the auxiliary rectifiers, which utilize the same oil cooling\circuit as the main converter. For the regenerative converter, the field power supply is also included.

3. Capacitor Bank

The power factor correction assembly consists of 12 capacitors, each with a series fuse for protection purposes. Six capacitor/fuse combinations are connected in parallel across each set of the main transformer input bus bars.

The fuse assembly is integral with the bus bar arrangement, with each fuse accessible for inspection or replacement without further disassembly. Each fuse is equipped with an indicator for inspection purposes.

4. Auxiliary Rectifiers

There are two auxiliary recitifiers contained within the main converter assemblies, a half-controlled single-phase rectifier for the electric mode, and a fixed three phase rectifier for the diesel mode. The required ratings are shown in Table 3. The diodes and thyristors are oil cooled using the same oil circuit as the main phase delay rectifier.

TABLE 3

DML AUXILIARY LOADS

Electric Mode, kw	Load	Diesel Mode, kw
30	Compressor (loaded)	30
2	Oil cooler blower motor	-
91	Motor blowers (maximum)	-
24	Engine heating	-
20	Battery charging, etc.	20
167	Total (peak)	50

5. Field Power Supply

The regenerative option requires a field power supply (FPS) semiconverter fed from an auxiliary winding of the main transformer. FPS responds to control signals from the four voltage control trainlines during braking to give the required level of braking effort. Output characteristics of FPS are:

Output current (maximum)	1000 amp
Output voltage (normal)	40 v
Output voltage (forcing)	60 v

Compressor

An electrically driven compressor is required to supply compressed air in the electric mode, whether or not the diesel engine is allowed to idle, since the compressor delivery at engine slow idle speed would be inadequate for train needs. The adoption of an electrically driven compressor could also have a favorable impact on the overall operation of the locomotive, eliminating, for example, the operation of the engine at high speed (notch 5) in order to pump up a train since the electrically driven compressor would be a constant speed machine.

The standard compressor on the SD40-2 has a displacement of 254 cfm at 900 rpm, which results in approximately 180 cfm delivered when operating at 140 lbf/sq in. Therefore, a constant speed machine would require a delivery somewhat less than that of the existing compressor. Since the maximum engine speed permitted by EMD for pump-up operations is that equivalent to notch 5 (645 rpm), it is considered that the electrically driven compressor delivery should be 135 cfm or more.

Two basic options are available for the compressor, reciprocating or screw. The reciprocating compressor has been the traditional compressor used on locomotives for many years and has been well developed. It does suffer from a number of disadvantages, however, such as significant maintenance requirements and noisy operation. The screw compressor offers much less maintenance and has seen many applications at duty cycles similar to that required by the DML.

A suitable compressor is available from the Sullair Corporation, which is 48 by 29 by 36 in. and weighs 790 lb. The compressor is driven by a 40-hp, three-phase, 460-v machine, and has a delivery of 140 cfm at 140 psi.

Cold Weather Protection Equipment

In order to provide the railroads with the option of shutting down the diesel engine during electric mode operation, it is necessary to ensure that the engine and associated systems are not damaged during cold weather operation. A system has been identified that provides the protection required and is available from Kim Hotstart Manufacturing Company, Spokane, Washington (see Figure 17).

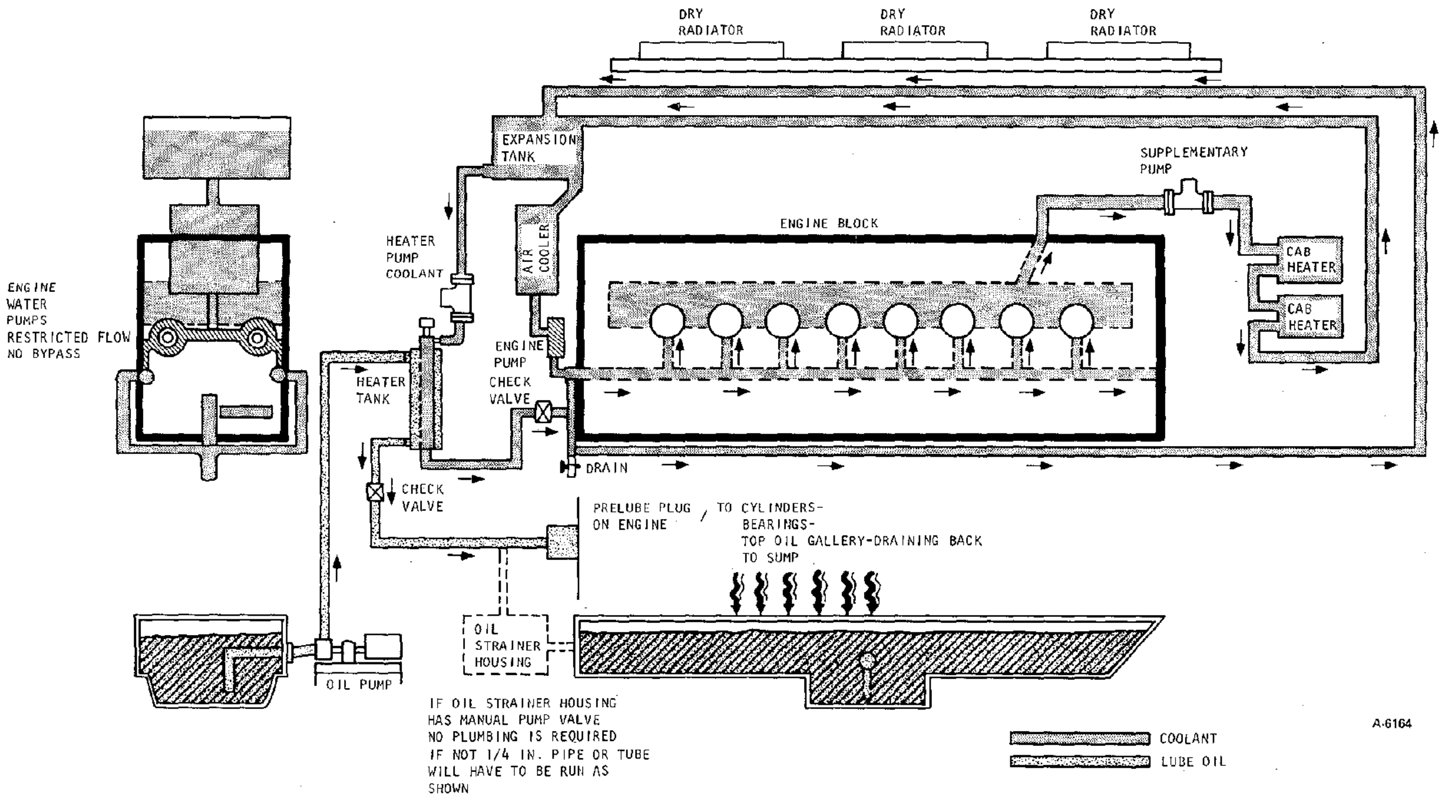

Figure 17. Typical Kim Hotstart Two-Fluid System

The system, as presently available, can handle any two of three fluids--lube oil, coolant, or diesel fuel. To provide low temperature protection for all three fluids, the system requires merely an additional heating chamber, pump, and control gear. A two-fluid system is shown in Figure 17, and the palletized equipment is shown in Figure 18. In support of this study, Kim Hotstart have prepared outline designs for the three fluid system.

The system requires a standard 60-Hz, three-phase supply that is usually available at locations where locomotives are normally stored. In the case of the DML, the three-phase, 60-Hz supply is available from the motor alternator set.

Cab Controls

For the engineer, the method of controlling a DML will be almost the same as for a conventional diesel locomotive. Power/tractive effort in the electric mode is controlled from the same throttle handle used to control the diesel mode performance. Simlarly, braking in both modes is controlled using the existing control handle. The only visible difference to the engineer is a set of lights that indicate the status of the locomotives in the consist and the mode of operation selected.

MAINTENANCE

The addition of the electric mode equipment to the base locomotive may increase the locomotive maintenance cost. The proposed initial maintenance schedule for the DML electric mode equipment is shown in Table 4. The analysis to date has not identified any areas of significant impact on the diesel made maintenance.

Clearly, the total maintenance costs are dependent on the locomotive duty cycle, and could in fact be significantly less than the diesel locomotive costs if most of the operation is in the electric mode.

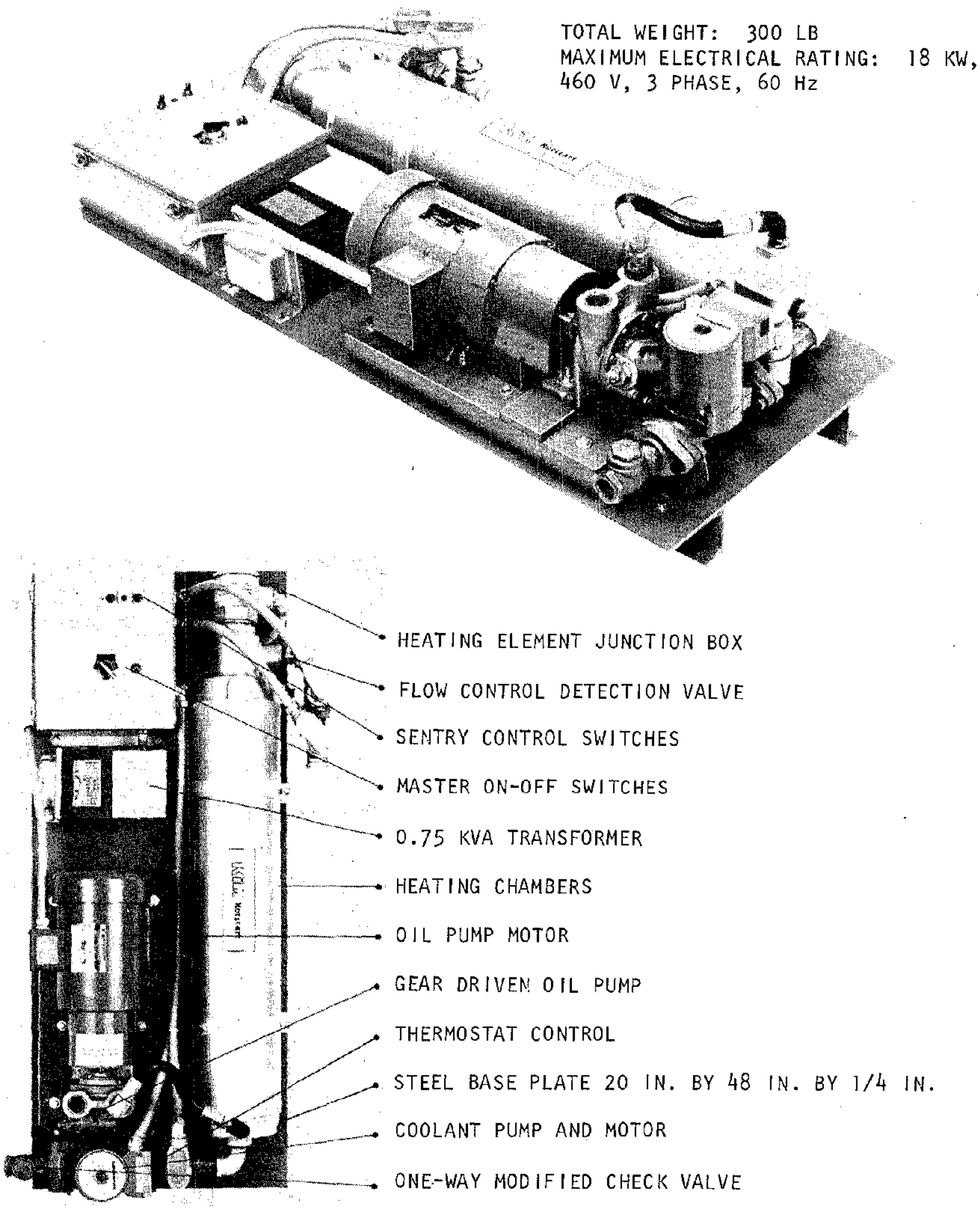

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Figure 18. Kim Hotstart Equipment (Two Fluid)

TABLE 4

DML MAINTENANCE SCHEDULE

Item	Manhours	Frequency	Annual Manhours*
Roof Equipment			
Clean insulators	0.5	30 days	5
Inspect pantograph	0.5	30 days	5
Change pantograph carbons	2.0	annual	2
Clean ground switch	0.5	30 days	5
Inspect VCB	0.2	30 days	2
Main transformer			
Clean cooler matrix	1.0	30 days	10
Main converter assembly			
Clean cooler matrix	1.0	30 days	10
Inductor	-	-	
Motor alternator set			
Inspect brushes and holders	0.5	30 days	5
Change brushes	1.0	annual	1.0
Compressor			
Clean air filter	0.5	annual	0.5
Check oil level	0.2	30 days	2
Axle-end ground brushes			
Check	2.0	30 days	20
Change	3.0	annual	3.0
Miscellaneous Operations	5.0	30 days	50
		TOTAL	120.5

*300 days/year

SECTION 3

ECONOMIC ISSUES

To be attractive for the railroads, the deployment of the DML must show some financial advantages over the deployment of conventional electrification. To assess the economic case, a life-cycle cost analysis was performed.

SCHEDULE OF COSTS

A schedule of costs (in 1980 dollars) is contained in Table 5. Of particular interest to this report is the DML conversion cost, a breakdown of which is shown in Table 6. A 10-percent variation due to options is possible, but the DML cost shown is for the most expensive option (50 kv, regenerative). The labor hours were estimated on the basis of the modification being carried out at the same time as a locomotive rebuild.

ECONOMIC ANALYSIS

The economic analysis of the DML applied gradually to sections of increasing length of the Conrail Harrisburg-Pittsburgh and Union Pacific Los Angeles-Salt Lake City routes is shown in Tables 7 and 8. Also shown in these tables is the comparative cost and ROI for conventional electrification.

TABLE 5

SCHEDULE OF DML DEPLOYMENT COSTS (1980 DOLLARS)

Item	Cost	Source
Locomotives		
Initial		
DML conversion	$367,014 to 414,097	This study
SD40-2 locomotive	$ 791,000	Transportation Systems Center (Reference 4)
E60C locomotive	$1,540,000	Transportation Systems Center (Reference 4)
Maintenance		
DML	$1.37/mile	This study
Diesel	$1.33/mile	Transportation Systems Center (Reference 4)
Electric	$0.65/mile	Transportation Systems Center (Reference 4)
Electrification		
Design, management, etc.	$30,000/trackmile	Conrail/G&H Study (Reference 3)
Initial, including substations and signalling		
Single track	$473,000/route mile	Transportation Systems Center
Two track	$780,000/route mile	Transportation Systems (Reference 4)
Three track	$1,059,000/route mile	This study
Four track	$1,100,000/route mile	This study
Maintenance	$4,400/route mile/yr	Transportation System Center (Reference 4)
Energy		
Diesel fuel (average)	$1.00/gal	This study
Electricity, including demand charges	$0.042/kwh	Conrail/G&H Study (Reference 3)

TABLE 6

BREAKDOWN OF DML EQUIPMENT COST FOR 50-KV, REGENERATIVE

Item	Supplier	Cost, 1980 dollars
Pantograph	Faiveley	5,000
Vacuum circuit breaker	GEC Traction	18,973
Lightning arrestor	GEC Traction	3,021
Roof insulators	Faiveley	Included in pantograph
Main transformer	GEC Traction	122,660
Main converter assembly	Garrett	85,480
Smoothing inductor	PEI	5,000
Cold weather protection	Kim Hotstart	3,975
M-A set	Westinghouse	15,000
Compressor	Westco	10,988
Power contactors	EMD	5,000
Auxiliary alternator	GE	8,000
Auxiliary transformer/rectifier	GE	3,000
Dynamic brake blower	EMD	3,000
Oil coolers	Dunham Bush	7,200
Miscellaneous	Various	21,800
Labor	Railroad	96,000

TABLE 7

ECONOMIC ANALYSIS OF APPLICATION OF DML's
HARRISBURG-PITTSBURGH BASELINE CASE
1980 DOLLARS (MILLIONS)

Cost Element	Extent of Electrification (Mileposts)				Normal Electrification
	237-259	222-271	167-337	Whole Route	
Initial					
Management	2.64	5.88	16.86	50	50
Catenary, etc.	22.72	50.6	178.4	261	261
Locomotives	63.5	58.3	49.2	45.5	154
Locomotives transferred	(6.7)	(12.3)	(22.15)	(26.1)	(75)
Net total	82.16	102.48	222.31	330.4	390
Annual					
Diesel fuel saving	(10.22)	(18.3)	(42.5)	(60.8)	(62.4)
Electrical energy	3.65	6.2	15.2	20.2	21
Locomotive maintenance	(3.04)	(6.06)	(12.03)	(13.66)	(17.4)
Catenary maintenance	0.10	0.22	0.75	1.1	1.1
Savings in locomotive replacement	(0.9)	(1.63)	2.95)	(3.48)	(10.0)
Net savings	10.41	19.51	41.53	56.64	67.7
ROI, percent	12.7	19.1	18.7	17.1	17.35

TABLE 8

ECONOMIC ANALYSIS OF APPLICATION OF DML's
LOS ANGELES-SALT LAKE CITY BASELINE CASE
1980 DOLLARS (MILLIONS)

Cost Element	Extent of Electrification (Mileposts)					Normal Electrification
	68-107 211-254	48-17 68-107 209-281 668-703	7-51 68-111 183-352 417-450 498-532 652-759	7-51 66-137 182-766	Whole route	
Initial						
Management	3.63	6.48	14.16	23.1	29	29
Catenary, etc.	50.7	95.7	216.1	352.4	396.6	446
Locomotives	55.1	51.4	48.6	46.6	46.2	117
Locomotives transferred	(13.4)	(17.0)	(19.8)	(21.8)	(22.1)	(67)
Net total	96.03	136.58	259.06	400.3	449.7	525
Annual						
Diesel fuel saving	(21.52)	(32.6)	(54.97)	(75.89)	(81.2)	(81.4)
Electrical energy	4.67	8.87	15.5	22.56	24.53	24.5
Locomotive maintenance	(12.23)	(15.79)	(20.4)	(22.5)	(22.7)	29.5
Catenary maintenance	0.36	0.78	1.88	3.08	3.4	3.5
Saving in locomotive replacement	(1.79)	(2.26)	(2.64)	(2.9)	(2.95)	(9.0)
Net savings	30.51	41.0	60.63	75.65	78.92	91.9
ROI	31.7	30.0	23.4	18.9	17.5	17.5

SECTION 4

FUTURE PLANS

Based on the determination of the technical feasibility and economic attractiveness of the DML concept, a suggestion for future work was generated within the scope of the overall FRA program plan. A future program, which is described below and shown in Figure 19, uses the results from this Phase I program as a base.

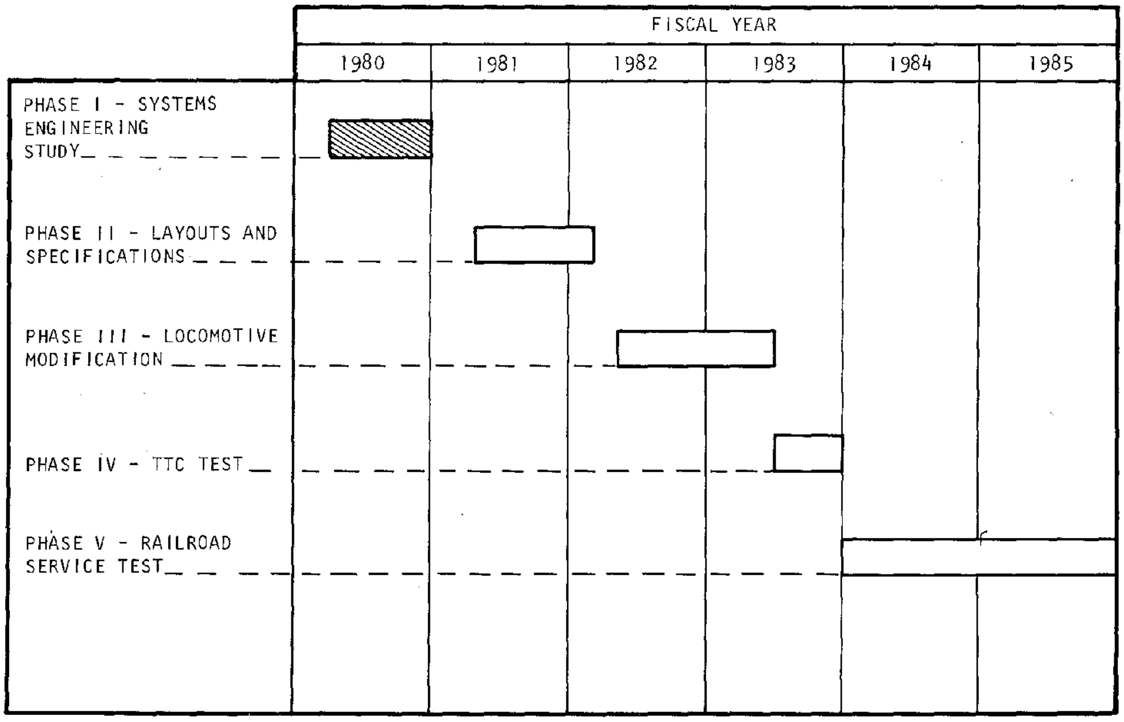


Figure 19. Proposed DML Program

PHASE II, LAYOUTS AND SPECIFICATIONS

The purpose of Phase II is to produce: (1) sufficient layout drawings and specifications to permit modification of an SD40-2 locomotive without the costly process of detail design, and (2) a final cost estimate. The specific tasks are as follows:

Layout Drawings (Task 1)--Using the general arrangement drawings available for all DML components, the following installation drawings will be made showing the new and relocated components, and identifying the methods of mounting and interfacing:

a. Roof equipment

b. Transformer compartment

c. Compressor, converter, inductor compartment

d. Converter oil cooler installation

e. Motor-alternator (MA) set installation

f. Auxiliary alternator drive system

g. Rear hood extension

h. 3,000-gal fuel tank

i. Relocation of cab

Final Component Design (Task 2)--Produce final designs of nonstandard components and prepare assembly drawings.

Final Specifications (Task 3)--Using the output available from the Phase I systems engineering study, final specifications for all equipment required to produce a DML will be produced. Where standard components are to be used without modification, these components should be identified by drawing and/or part number.

Cost Estimate (Task 4)--Using the output from Tasks 1 and 2, prepare a firm cost estimate for the modification material and labor hours required to modify locomotives to the DML configuration. The estimate should be based on the assumption that the work is completed at a locomotive 5- to 7-yr overhaul interval, when most equipment has been removed from the locomotive. The cost estimate should be supported by quotations and work breakdowns as appropriate, assuming quantities of 5, 50, and 150 are to be ordered.

Modification Package (Task 5)--Prepare a package of specifications and drawings suitable for use in accomplishing the modification of an SD40-2 to the DML configuration.

PHASE III, LOCOMOTIVE MODIFICATION

The output from this phase will be a preprototype DML, based on the use of an SD40-2 locomotive, suitable for testing at Pueblo and operation in normal revenue service. The specific tasks associated with this phase are as follows:

Specifications/Design Review (Task 1)--Review the specifications and designs generated in Phase II to ensure compatibility with DML concept at current status. Identify (and justify) changes, if any, considered to be necessary.

Material Procurement (Task 2)--Place orders for all long-lead items at the earliest possible time to ensure locomotive delivery on schedule. Order other material as it becomes finalized.

Installation Design (Task 3)--Review the component installation data and ensure compatibility with the installation design completed in Phase II. Update installation design if necessary.

Locomotive Modification (Task 4)--Modify one locomotive to the DML configuration resulting from Task 1. All installation work should be to normal railroad standards and of a permanent nature so that the locomotive is suitable for revenue service on a cooperating railroad.

Locomotive Test (Task 5)--Test all aspects of diesel mode operation on the modified locomotive, including a test run hauling a consist of freight cars and multiple-unit (M-U) operation with unmodified locomotives. All electric mode control circuits should be tested for correct operation.

Locomotive Delivery (Task 6)--Following the completion of Task 6, deliver the DML to the Transportation Test Center (TTC) Pueblo, Colorado.

PHASE IV, LOCOMOTIVE TESTING

The output from this phase will be a preprototype locomotive suitable for revenue service testing by a cooperating railroad. This phase will consist of the following tasks:

Locomotive Inspection (Task 1)--Check out locomotive following delivery to assess any transit damage and rectify as necessary.

Instrumentation (Task 2)--Provide sufficient instrumentation to test both diesel and electric mode operation. Parameters to be measured should be agreed to with FRA, and Phase V railroads (if known).

Diesel Mode Testing (Task 3)--Confirm satisfactory operation in diesel mode, as determined under Task 6 of Phase III.

Electric Mode Testing (Task 4)--Check out operation at normal operating voltage of catenary (either 25 or 50 kv depending on chosen configuration). Testing should include hauling a consist of freight cars and M-U operation with the DML in electric mode coupled to an unmodified diesel locomotive.

Simulated Service (Task 5)--Provide support to TTC during the simulated service testing, which will include checkout of the automatic changeover equipment, as specified in Phase II.

PHASE V, REVENUE SERVICE

The purpose of this phase is to evaluate the service performance and reliability of a DML, and includes:

Locomotive Delivery (Task 1)--Deliver the DML to the cooperating railroad (to be nominated by FRA) and carry out post-delivery inspection, including operation of locomotive in both electric and diesel modes. A source of 50- or 25-kv power will be provided to the contractor.

Locomotive Testing (Task 2)--Provide test-support personnel and DML peculiar equipment support for the DML program to ensure satisfactory locomotive operation. Operator and maintenance personnel training will be provided.

Final Report (Task 3)--Prepare a final report that gives details of the DML modification, testing, service history; spare parts listing; and recommendations for modification for later locomotives. The report should summarize the relevant data available from Phase II, III, and IV reports.

PROGRAM OPTIMIZATION

The program outlined above has been based on the FRA plan. Following the completion of this study, it may be considered desirable to reduce the period of the overall program to provide a proven DML within the minimum period of time. It is estimated that, given the right conditions, a DML could be made available for test within 18 months from the go-ahead being given. This would involve completely restructuring the program to provide for the minimum of delay between program milestones.

SECTION 5

CONCLUSIONS AND RECOMMENDATIONS

The completion of the DML Systems Engineering Study has resulted in the definition of the DML concept, a determination of the DML cost, and an analysis of the economic benefits of the DML as it may be deployed on the nation's railroads as a first step toward full electrification of the major routes. In addition, a program plan has been outlined for the demonstration of a preprototype locomotive using an SD40-2 locomotive. The specific conclusions and recommendations of this eight-month study, which resulted from the detailed work described in Vol. 2, are described in the following text.

CONCLUSIONS

The conclusions reached in this study are as follows:

(a) The DML concept has been shown to be technically viable. The equipment layout has been determined to meet with the approval of major U.S. railroads.

(b) The cost of a DML conversion can vary from \$367,014 to \$414,097, depending on the options, and this results in the provision of approximately 1,280 additional rhp at \$287/rhp to \$323/rhp, compared to \$304/rhp for the basic SD40-2 locomotive. A typical nonregenerative, electric locomotive cost would be \$302/rhp.

(c) The DML can be deployed on U.S. railroads with ROI's comparable to 50 that for normal electrification. The initial investment required for the deployment of the DML's is typically one-fifth that of normal electrification when only the ruling grades are electrified.

(d) The DML can be made available in the following options:

  (1) 50- or 25-kv catenary voltage

  (2) Regenerative or nonregenerative braking

  (3) Automatic or manual mode changeover

  (4) Engine idle or shutdown during electric operation

  (5) Ballasting to 70,000 lb axle load

(e) The DML provides a partial solution to the most commonly cited barrier to railroad electrification--the huge initial investment normally required--and allows the electrification process to proceed at a slower rate than would normally be possible. The DML is seen as a 20-yr transitional locomotive until normal electrification is established.

(f) The DML provides many intangible benefits to a railroad contemplating electrification that have not been quantified in this study. The more important of these benefits are the following:

  (1) The DML can start a journey off-wire and then operate over the electrified section and complete the trip off-wire. Such operations are expected to be relatively common for many unit trains traveling from mines to utilization or tran-shipping points.

  (2) The DML can provide continuity of railroad operations during electric power outages and in the case of a downed catenary.

  (3) The DML could M-U with electric locomotives on a contemplated electrified railroad in either mode.

  (4) The DML can offer training opportunities to railroad personnel unfamiliar with electric operations.

  (5) The DML will use a majority of existing, well-proven components already in the logistics system.

(g) The DML can provide substantial advantages to the transportation sector by helping to reduce dependence on petroleum fuel and by minimizing the environmental impacts of railroad operations.

RECOMMENDATIONS

The following recommendations are made:

(a) The Phase II program described in Section 4 of this report should be promptly initiated. This program offers a minimum cost method of preparing for a DML preprototype.

(b) Initiate a design study to determine the feasibility of a 4-axle DML since many railroads would prefer a 4-axle locomotive.

(c) The impact of the DML concept on contemplated railroad electrification programs should be considered and factored into the engineering and economic studies.

(d) The Memorandum of Understanding existing between FRA and Transport Canada should be used to transmit DML technology and information between future DML programs in the two countries.

(e) A series of briefings on the DML concept to the senior management of the U.S. railroads that are prime candidates for electrification should be provided.

(f) Initiate a study to assess the applicability of the DML concept to passenger operations.

(g) Briefings on the impact of the DML should be provided to representatives of the Department of Energy, the Department of Commerce, and the Environmental Protection Agency in areas that fall within their cognizance.

SECTION 6

REFERENCES

1. Lawson, L. J. and L. M. Cook, Wayside Energy Storage Study Final Report, AiResearch Manufacturing Company of California, under contract to DOT-TSC, June 1978, Report No. FRA/ORD-78/78.

2. Cook L. M., and L. J. Lawson, Application of Wayside Energy Storage System Concepts to Canadian Railways, Final Report, Garrett Manufacturing, Ltd. under contract to Transport Canada, February 1980.

3. "Electrification Feasibility Study," Gibbs & Hill, Inc., Volume II, 1980.

4. Spenny, C. H., "An Update of the Costs and Benefits of Railroad Electrification," Project Memorandum of Transportation Systems Center under agreement with DOT-FRA.

5. Cook, L. M., et al., Flywheel Energy Storage Switcher Final Report, AiResearch Manufacturing Company of California, under contract to DOT-FRA, April 1979, Report No. FRA/ORD-79/20.

APPENDIX

DUAL-MODE LOCOMOTIVE
INDUSTRY REVIEW
OCTOBER 16, 1980

APPENDIX

DUAL MODE LOCOMOTIVE INDUSTRY REVIEW

The results of the Systems Engineering Study for the dual mode locomotive were presented to the railroad industry on October 16, 1980 in Chicago. The purpose of this meeting was to review the concept with the industry to ensure that the approach and assumptions were compatible with day-to-day railroad operation.

MEETING ATTENDEES:

The following people were in attendance:

Name	Title	Company
John D. O'Neill	Assistant Vice President, Motive Power	Chicago & North Western
Henry Liban	Assistant Manager, Electrical Engineering	Conrail
Walt Carrington	Staff Assistant, Finance	Santa Fe
Tim Jorgensen	Assistant to Director of Business Research	Santa Fe Industries
Dale H. Propp	Assistant Chief Mechanical Officer	Burlington Northern
Michael L. Wall	Superintendent, Motive Power	Missouri Pacific
Wayne G. Town	Chief Industrial Engineer	Elgin, Joliet & Eastern
R. K. Wildu	Superintendent, Motive Power	Elgin, Joliet & Eastern
Glen Fisher	Vice President and General Manager (Consulting)	Canadian Pacific
T. C. Gilbert	Manager, Locomotive Design Engineering	Southern Railway
D. W. Mayberry	Manager, Mechanical & Electrical Locomotives	Norfolk & Western
R. J. Thelen	Director Technical Committees	Association of American Railroads
Conan P. Furber	Manager, Environmental & Special Studies Division	Association of American Railroads
Hal Henderson	Electrification Product Planning	General Electric
Eric M. Sjokrist	Manager, Advanced Engineering	Electro-Motive Division (GM)
H. E. Quinn	Project Manager, Electric Locomotives	Electro-Motive Division (GM)
Peter Eggleton	Executive Director, Research & Development	Transport Canada
Steve Ditmeyer	Associate Administrator for Research and Development	Federal Railroad Administration
A. J. Bang	Chief, Freight Service Division, Research and Development	Federal Railroad Administration
John Koper	Energy Research Manager	Federal Railroad Administration
M. S. Kellman	Transportation Industry Analyst	Federal Railroad Administration
John Harrison	Project Engineer, NECIP	Bechtel
E. G. Schwarm	Manager, Electric Power Systems	Arthur D. Little
J. F. Pearce	Manager, Special Projects	Morrison-Knudsen
R. J. Dixon	Sales Manager	Alco Power
Michael Rachlin	Vice President, Government Relations	Garrett
Ken Blakely	Government Relations Representative	Garrett
Ralph Wortmann	Public Relations Manager	Garrett
R. C. Hess	Sales Engineer, Ground Transportation	Garrett
Jim Lawson	DML Program Manager	Garrett
Len Cook	DML Program Engineer	Garrett

MEETING FORMAT

The meeting was opened by Mr. Steve Ditmeyer, who reviewed the position of the DML program in relation to the overall FRA electrification program and assured the audience that the various programs were being coordinated within FRA. Mr. Arne Bang then presented an overview of the FRA Office of Freight Systems energy research activities, as shown in the briefing charts (pages A-8 through A-12) of the Dual Mode Locomotive Systems Engineering Industry Review. All of the briefing charts are included at the end of this Appendix.

The Garrett presentation started with Mr. Mike Rachlin, who reviewed Garrett's ground transportation history and introduced representatives of the DML team--Mr. Jim Pearce from Morrison Knudsen, and Mr. Bob Dixon representing GEC Traction.

The Garrett technical presentation was made by Mr. Jim Lawson and Mr. Len Cook. Discussion was invited as the presentation proceeded rather than holding a discussion session at the end of the presentation. The briefing charts used for the technical presentation are shown on pages A-13 through A-51

DISCUSSION

To clarify the discussions of this review meeting, comments have been grouped together by subject and do not represent a chronological record of the discussion. The major questioner is identified in parentheses after the paragraph title.

Short Hood (Mr. Quinn)

The feasibility of accommodating all of the necessary equipment in the shortened hood was questioned. Subsequent to the meeting, a layout of equipment was prepared and is contained in Figure A-1.

FURTHER ACTION: NONE

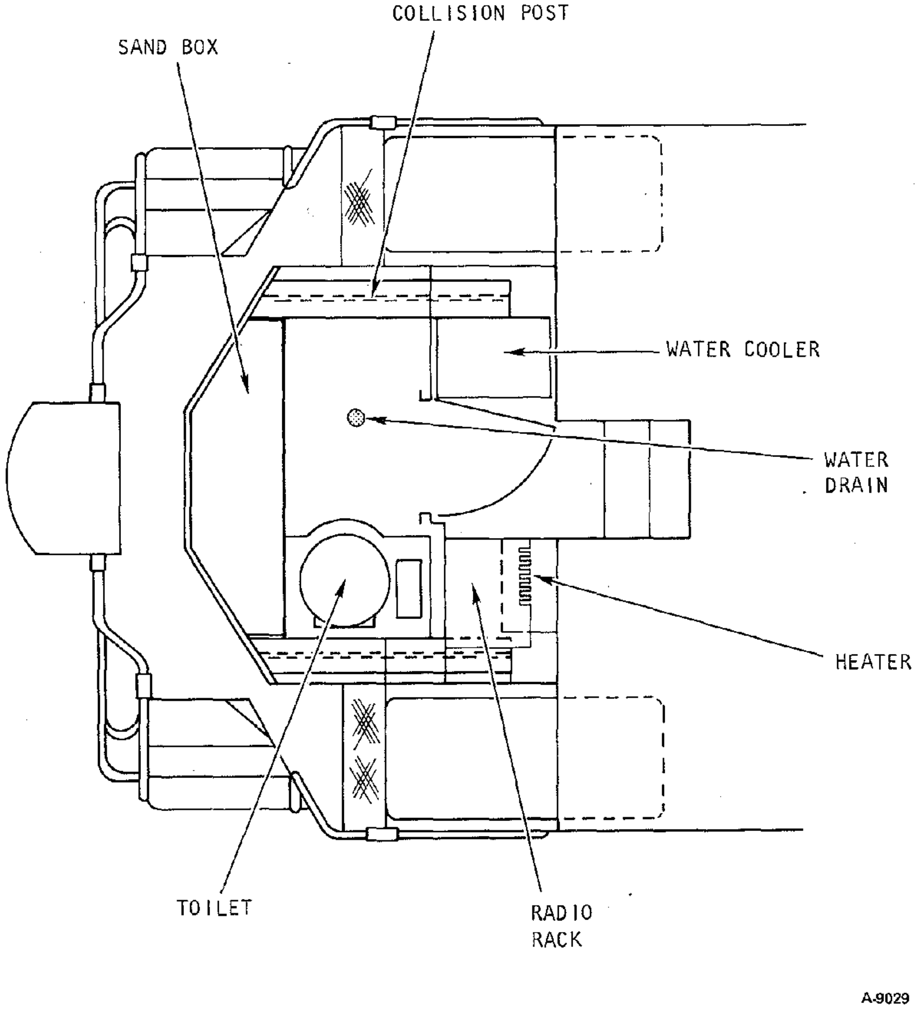


Figure A-1. DML Short Hood Arrangement

Auxiliaries (Mr. Quinn)

An inquiry was made concerning the power rating of the equipment blower motor. The machine is rated for 91 kw as a motor, and for 50 kw as an alternator.

FURTHER ACTION: NONE

Roof Equipment (Mr. Quinn)

The pantograph shown by Garrett for the DML is based on the recommendations of Faiveley. The model is LV2600. It was felt that the weight quoted on the chart of page A-25 was too low. This has since been confirmed by Garrett to be the correct weight.

FURTHER ACTION: NONE

Traction Motors (Messrs. Quinn and Gilbert)

The performance of the D77 in the 11 to 20 mph speed range was seriously questioned. It was stated that due to core losses, 1050 amps per motor could not be maintained to 17 mph, as shown on the chart of page A-33. This matter has been further investigated since the meeting with the following results. The problem, in fact, is one of eddy current losses and not core losses. Previous work carried out by Garrett for FRA (Reference 5) has developed the relationship between armature eddy current density and motor speed as:

$$D = 4699 \left[1 + \left(0.421 \times \frac{N}{1000}\right)\right] \text{ amp/sq in.}$$

where D = current density (amp/sq in.)
N = motor speed (rpm)

With class H insulation, the maximum value of D that can be tolerated for continuous operation is 5000 amp/sq in., which corresponds to a motor speed of 390 rpm. This speed, with fully worn wheels, gives a speed of 10.4 mph using the 62:15 gear ratio.

A 1-hr rating current density figure is 5 percent above the continuous, i.e. 5250 amp/sq in., which occurs at 527 rpm or 14 mph with fully worn wheels. With this new data factored into the traction motor model, the DML tractive effort characteristic becomes as shown in Figure A-2, and as subsequently revised in the main body of the report.

The major reason for the relatively high susceptibility to eddy currents is the method of construction of the armature coils that are welded together at the ends, thus forming a short circuit. It is understood that this method of construction, which is adequate for normal D77 operations, has not been used on the D87 model developed for EMD-50 series locomotives, and therefore the D87 has significantly lower susceptibility to eddy currents and could be operated at 1050 amps up to 17.5 mph.

The impact of this change in performance was analyzed on the Union Pacific route used in the study, and no significant difference was noted since the minimum continuous speed on that line is above 20 mph.

FURTHER ACTION: Modify converter ECU problem statement to include 1-hr restriction.

Transformer (Messrs. Liban, O'Neill, and Sjokvist)

It was the opinion of the railroads that the DML should have a 25- and 50-kv capability to permit the degree of through running currently enjoyed. Conrail also felt that a 12.5/25 kv, 25/60-Hz capability was required. All of these facilities can be provided at the penalty of increased size, weight, and cost. For the preprototype, it is considered desirable to keep the locomotive as simple as possible and to keep to a single voltage capability.

FURTHER ACTION: NONE

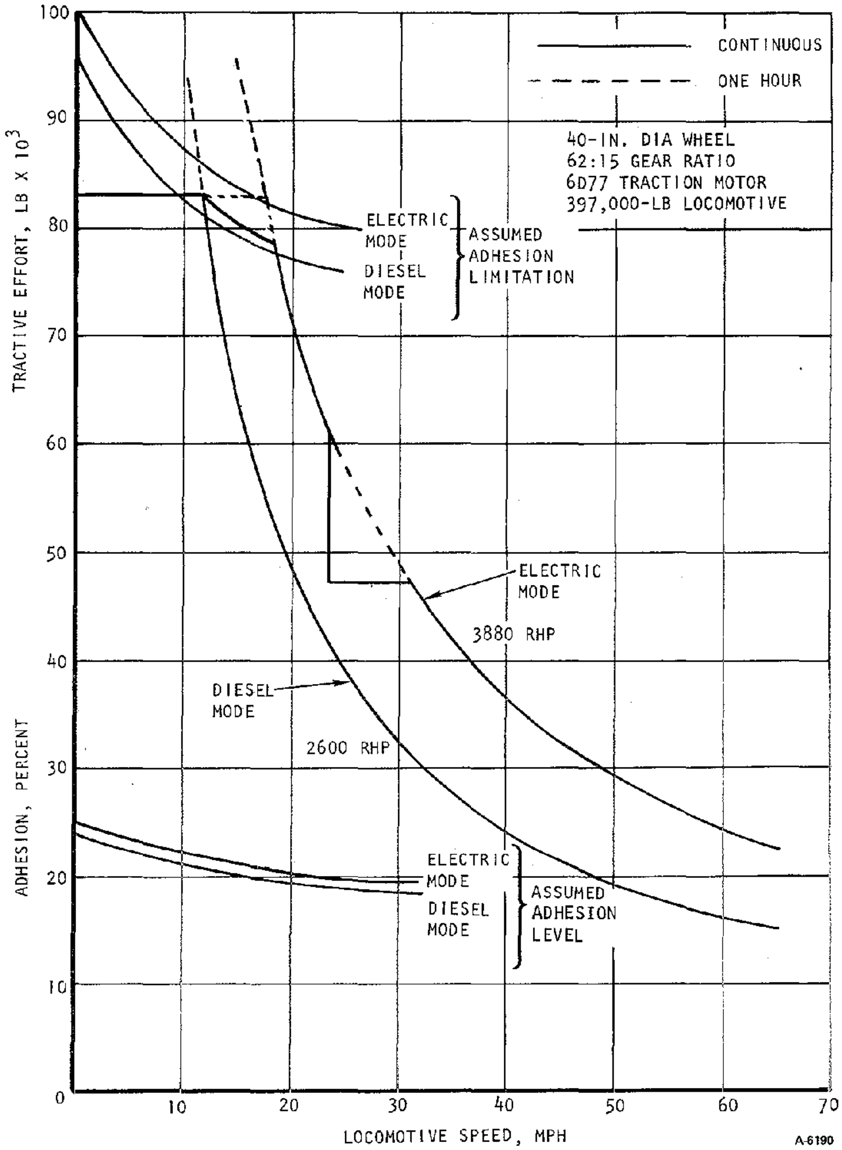


Figure A-2. Revised DML Tractive Effort Characteristic

Converter/Cabling (Mr. Quinn)

It was suggested that the cabling required for the modification would be a nightmare. Garrett indicated that the modification cost included the complete replacement of all control and power cables, and therefore route optimization would be possible.

The converter is rated for 5,000 amps (1670 amps per leg starting current), which was suggested to be insufficient. Subsequent to the meeting, it was confirmed by EMD to be more than adequate.

FURTHER ACTION: NONE

Smoothing Inductor (Messrs. Quinn and Liban)

Questions were raised concerning the method of cooling, percentage traction motor ripple assumed, typical losses, and the feasibility of connecting copper cable lugs to the aluminum coil. In reply, it was stated that the inductor is oil immersed with natural cooling from the tank to the ambient surrounding. The inductor had been sized to give a 5 percent ripple when taking into account the effect of the series traction motor field. The losses at continuously rated current are 74 kw. The standard method of attaching copper and aluminum is to use a plating technique such as silver or, more commonly, cadmium.

FURTHER ACTION: NONE

Control System (Messrs. Gilbert and Quinn)

The location of the electronic control unit (ECU) for electric mode operation and the method of wheel slip protection were both questioned. The chart on page A-29 shows that the ECU is located between the two phase delay rectifier panels in the main converter assembly. The method of wheelslip protection has not yet been finalized. Options available include current/voltage balance detection and axle speed measurement.

FURTHER ACTION: Investigate wheel slip protection further in next phase.

Trucks (Mr. Quinn)

It was stated that axle-end ground brushes cannot be used on the HTC truck with Hyatt bearings and the center-axle end-float precluded the use of a brush on that axle with any bearing type. The axle-end brush arrangement proposed for this application has been designed and is manufactured by M-K with successful application to the FL9 locomotive. The brush arrangement is suitable for use with a Hyatt bearing, provided the bearing unit has the end-of-axle drive box fitted. It is intended to fit the axle-end brushes only to the two outer axles since the center axle must accommodate the shock absorber mounting bracket.

FURTHER ACTION: NONE

Adhesion (Mr. Sjokvist)

The reason for the improved adhesion level was questioned since the source of power (catenary or diesel-engine) did not inherently affect the assumable adhesion level. The major reason for the higher adhesion level in the electric mode is the reduction in weight variation due to the smaller fuel tank. In addition, other benefits accrue from the faster response of the converter (in the electric mode) compared with the alternator (in the diesel mode) once a slip has been detected. Since all-axle control and conventional slip detection methods are being used, it is not possible to assume the high adhesion levels normally associated with electric locomotives.

FURTHER ACTION: NONE

Electromagnetic Compatibility (Messrs. Quinn and Sjokvist)

The psophometric current levels shown on page A-35 were considered to be high and the locomotive would be classified as "noisy". Examples of other railroad specifications were quoted as being between 2 and 8 amps maximum. This has been investigated and it has been determined that the 2-amp level is specified for lower power locomotives operating on 16-2/3 Hz. The most recent South African Railways (SAR) 50-kv specification required a maximum of 7 amps for 50 Hz with full advance on the thyristor bridges. This compares with the DML prediction of approximately 9 amps with full advance. Taking into account the higher power level of the DML and the 60-Hz operation, the DML is compatible with the latest SAR specification.

Psophometric current is only a problem on railroads that use line side telephones or have telephone company transmission lines using the railroad right-of-way. Radio communication (in the MHz band) is not affected.

FURTHER ACTION: NONE

Maintenance (Messrs. Liban, Sjokvist, and Gilbert)

The DML maintenance schedule was based on a 30-day cycle, whereas the railroads prefer 90 days. It was pointed out that since some of the equipment proposed for use on the DML had not been used in North America, it was considered prudent to work with a conservative maintenance cycle. It is fully expected that a 90-day maintenance cycle will be readily achieved following service experience.

It was considered that the electric locomotive to diesel locomotive maintenance cost ratio was unrealistic since it did not take into account changing out PCB's and high wheel-wear rates. Clearly since the modern transformer does not use PCB's, it is not necessary to take this into account and there is no reason why wheel wear on an electric locomotive should differ from that on a diesel locomotive.

When calculating the maintenance costs attributable to the DML for a given duty cycle, it was assumed that engine maintenance was proportional to fuel consumption above an amount required for fixed plant. This is covered in Vol. 2, Section 7 of this report.

FURTHER ACTION: NONE

Fuel Consumption (Mr. Gilbert)

An inquiry was made regarding the assumed equivalence of electrical energy to diesel fuel. It was pointed out that this method of calculating electrical energy consumption is technically unacceptable and provides only a poor estimate of electrical energy consumption on a subsequently electrified railroad. The major factor is the fact that the method of operating an electrified railroad is completely different to that of a diesel railroad. Furthermore, the comparison between diesel and electric fuel consumptions is site specific as shown below.

The fuel/energy consumptions used in this study were calculated using the Garrett TPC, as described in Vol. 2, Section 2. The diesel/electrical energy equivalence resulting from the TPC calculations on the two study routes are shown in Table A-1.

TABLE A-1

ENERGY EQUIVALENCE

Route	Energy Equivalent of DF2, kwh/gal	
	EB	WB
Harrisburg-Pittsburgh	10.58	10.94
Los Angeles-Salt Lake City	10.03	9.17

The figure apparently used by the Southern Railway was 12 kwh/gal of DF2.

FURTHER ACTION: NONE

Locomotive Weight (Messrs. Quinn, Sjokvist, and O'Neill)

EMD supplied the data shown in Table A-2, which gives a breakdown of the locomotive weight and location of ballast for four recent locomotive orders. Consideration of these data confirm that the DML concept is viable on a wide range of SD40-2 models, including the heavy underframe models ordered by Burlington Northern and Missouri Pacific. Without taking into account the displaced equipment (smaller fuel tank, compressor, etc.), the weight of the ballast in some cases exceeds the weight of the new equipment to be installed.

TABLE A-2

ANALYSIS OF SD40-2 WEIGHT

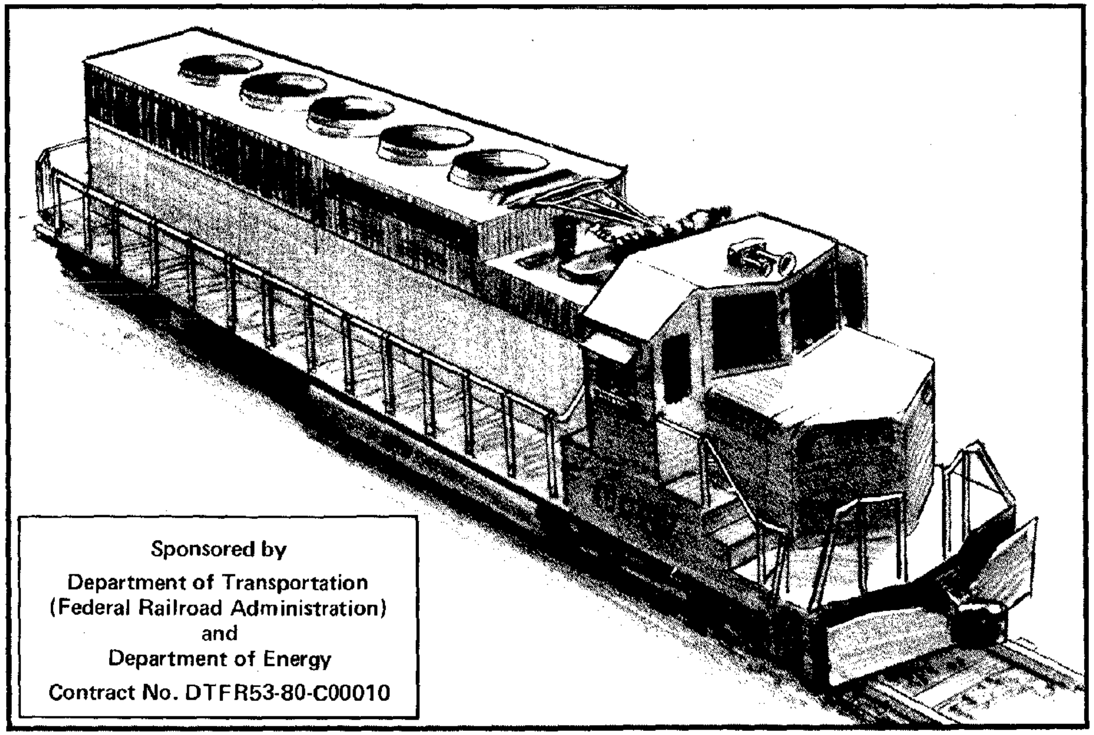
	786256-B.N.	786193-Conrail	796311-Mopac	796297-U.P.
Units, No.	92	42	20	110
Weight, lb	416,000 +4,000 -5,000	389,500 ±5,000	414,000 ±5,000	390,000 ±5,000
Underframe	Heavy	Standard	Heavy	Standard
Cab ballast, lb	6,430	5,455	7,240	4,450
Hood ballast, lb	7,265	7,265	7,670	6,455
Center ballast, lb	21,155	13,622	14,827	11,960
Unit nos.	8090-8181	6483-6524	6054-6073	3659-3768
Date shipped	7/80	7/79	4/80	1/80

NOTE: Data supplied by EMD on October 16, 1980.

FURTHER ACTION: NONE

DUAL MODE LOCOMOTIVE SYSTEMS ENGINEERING INDUSTRY REVIEW

OCTOBER 16, 1980



Sponsored by
Department of Transportation
(Federal Railroad Administration)
and
Department of Energy
Contract No. DTFR53-80-C00010

SPA 6468-1

OFFICE OF FREIGHT SYSTEMS
OFFICE OF RESEARCH AND DEVELOPMENT

ENERGY PROGRAM THRUST

- ☐ ENERGY AUDIT
- ☐ ALTERNATIVE FUELS
- ☐ FUEL EFFICIENT TRAIN OPERATIONS
- ☐ DUAL-MODE LOCOMOTIVE

SPA 6468-42

DUAL-MODE LOCOMOTIVE

BACKGROUND

- ☐ ENERGY CONSERVATION (PETROLEUM) PROGRAM
- ☐ WAYSIDE ENERGY STORAGE STUDY
- ☐ DUAL-MODE LOCOMOTIVE SPIN-OFF
- ☐ PROJECT MANAGEMENT MASTER PLAN
- ☐ PHASE I – SYSTEMS ENGINEERING – DML

SPA 6468-43

DUAL-MODE LOCOMOTIVE

POTENTIAL SCENARIOS

- ☐ DML ROLE ALONE (RULING GRADES)
- ☐ CONTRIBUTOR TO ELECTRIFICATION (INCREMENTAL)
- ☐ FORERUNNER OF OPTIMUM POWER MIX

SPA 6468-44

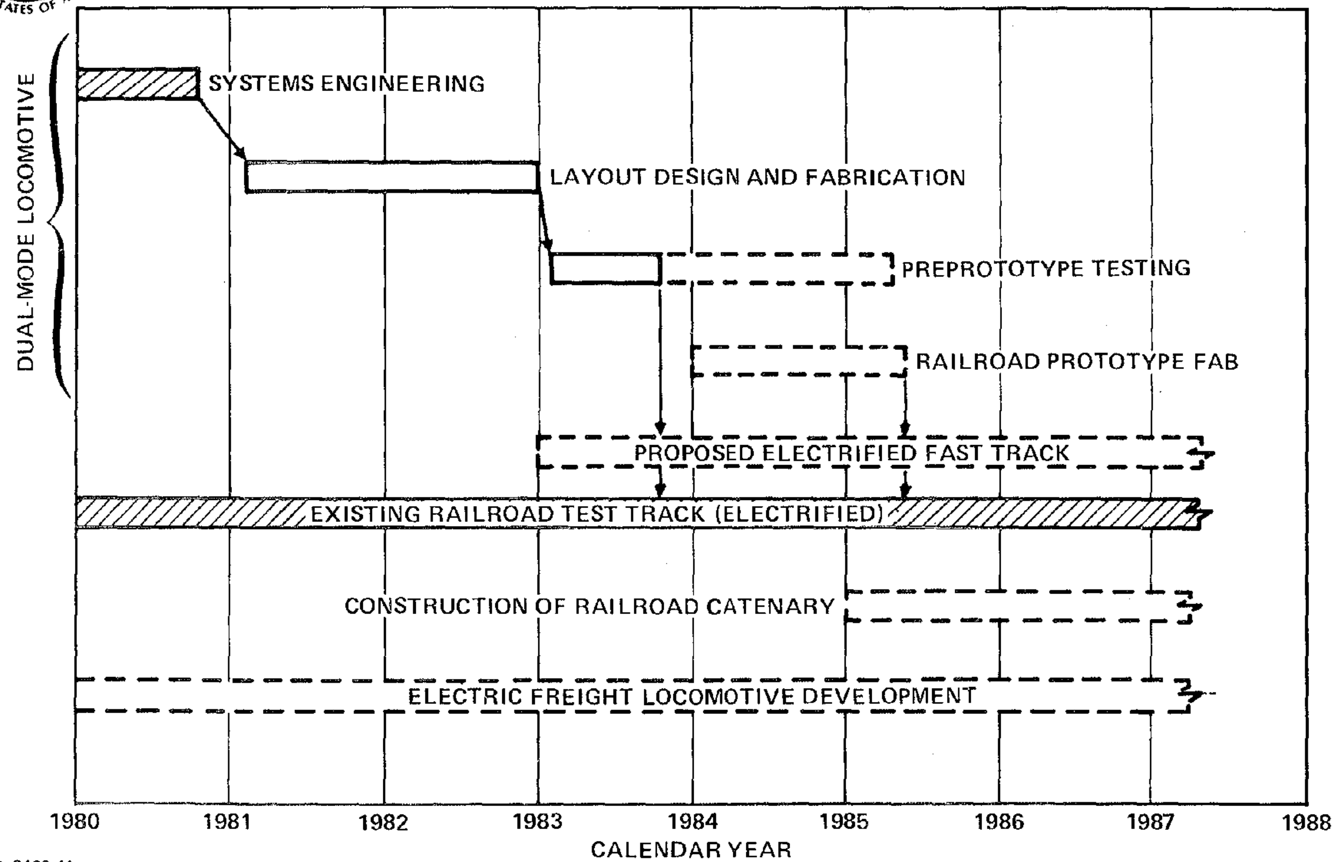
DUAL-MODE LOCOMOTIVE

LEVELS OF RAILROAD PARTICIPATION

- ☐ MONITORING (PASSIVE)
- ☐ TECHNICAL REVIEW (ACTIVE)
- ☐ COOPERATIVE RESEARCH (DIRECT)
- ☐ GO IT ALONE (NONE)

SPA 6468-45

POSSIBLE TIME SCENARIO



SPA 6468-41

PROGRAM RATIONALE

- ☐ DEVELOP A MEANS OF REDUCING THE LARGE INITIAL INVESTMENT ASSOCIATED WITH CONVENTIONAL RAIL ROAD ELECTRIFICATION WHILE MAINTAINING THE RETURN ON INVESTMENT
- ☐ RETAIN THE OPERATING FLEXIBILITY OF THE DIESEL LOCOMOTIVE DURING CHANGEOVER PERIOD FROM DIESEL TO ELECTRIC OPERATION
- ☐ MINIMIZE INTRODUCTION OF NEW TECHNOLOGY ASSOCIATED WITH ELECTRIFICATION

PROGRAM OBJECTIVES

- ☐ CONFIRM THE TECHNICAL FEASIBILITY OF THE DUAL-MODE LOCOMOTIVE CONCEPT
  - VOLUME OF EQUIPMENT
  - WEIGHT OF EQUIPMENT
  - MAINTENANCE ACCESS
- ☐ ASSESS THE ECONOMIC BENEFITS OF DUAL-MODE LOCOMOTIVE DEPLOYMENT
  - MINIMIZED INITIAL INVESTMENT
  - ACCEPTABLE RETURN ON INVESTMENT

SPA 6468-3

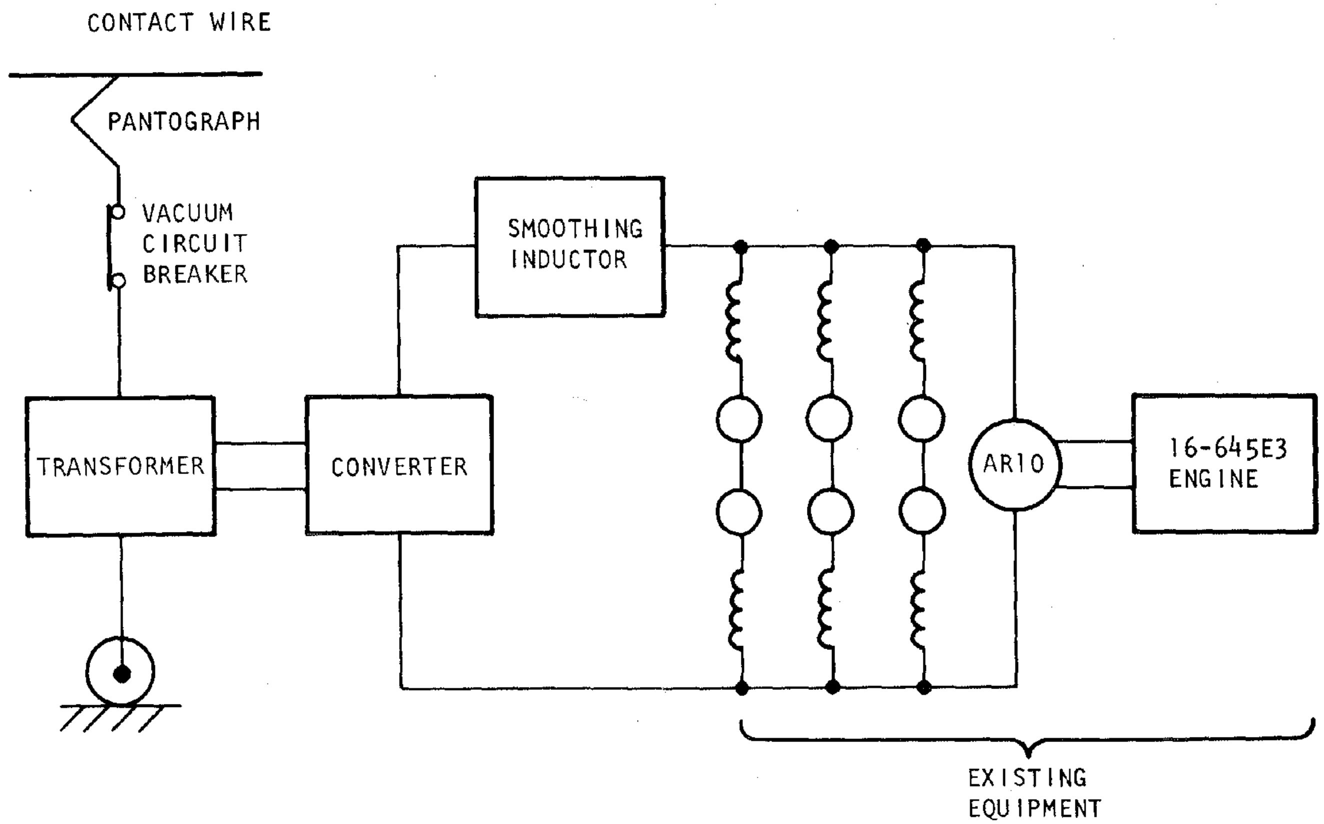
GARRETT

DUAL-MODE LOCOMOTIVE CONCEPT

- ☐ A LOCOMOTIVE CAPABLE OF OPERATION FROM EITHER A DIESEL ENGINE OR CATENARY
- ☐ CAN BE APPLIED TO A NEW OR REBUILT LOCOMOTIVE

SPA 6468-4

OPERATING PRINCIPLE



SPA 6468-6

LOCOMOTIVE POPULATION

DATA SUPPLIED BY THE FOLLOWING RAILROADS

- ATCHISON TOPEKA AND SANTA FE
- BURLINGTON NORTHERN
- CHICAGO AND NORTH WESTERN
- CHICAGO MILWAUKEE ST. PAUL AND PACIFIC
- CONRAIL
- DULUTH MISSABE AND IRON RANGE
- LOUISVILLE AND NASHVILLE
- MISSOURI PACIFIC
- NORFOLK AND WESTERN
- SEABOARD COAST LINE
- SOUTHERN
- SOUTHERN PACIFIC
- UNION PACIFIC

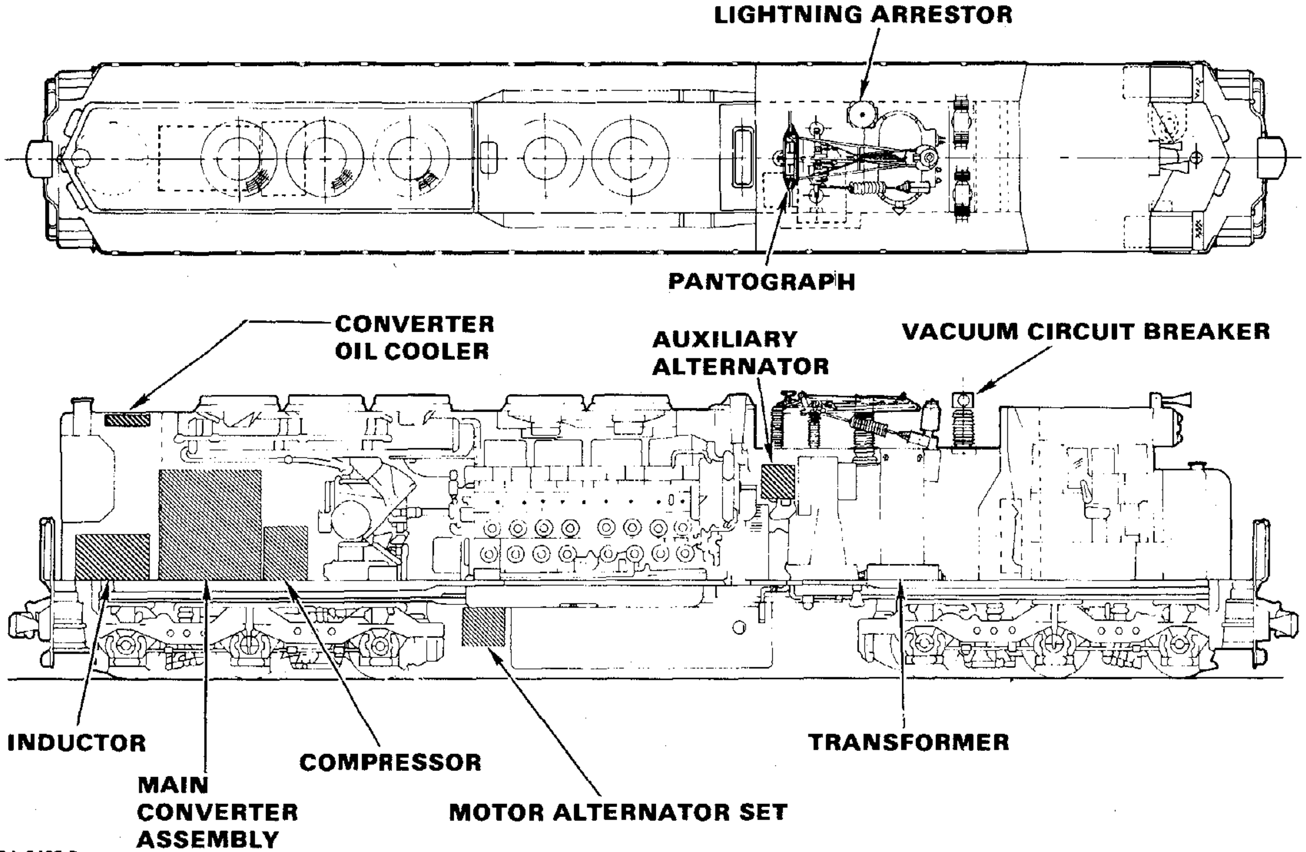
GARRETT

LOCOMOTIVE POPULATION

MODEL	NUMBER	AVERAGE AGE	PERCENT OF TOTAL
SD35	349	14.0	2.9
SD40	797	11.7	6.6
SD40-2	2,529	4.8	21.0
SD45	1,155	11.8	9.6
SD45-2	359	7.0	3.0
GP30	800	17.5	6.6
GP35	943	14.4	7.8
GP38	682	10.8	5.7
GP38-2	1,108	5.4	9.2
GP40	874	11.8	7.2
GP40-2	456	4.0	3.8
U30C	524	7.3	4.3
U30-7	478	1.5	4.0
U33C	316	9.5	2.6
U23B	371	8.7	3.1
B23-7	326	1.3	2.7
TOTAL	12,067	8.9	100.1

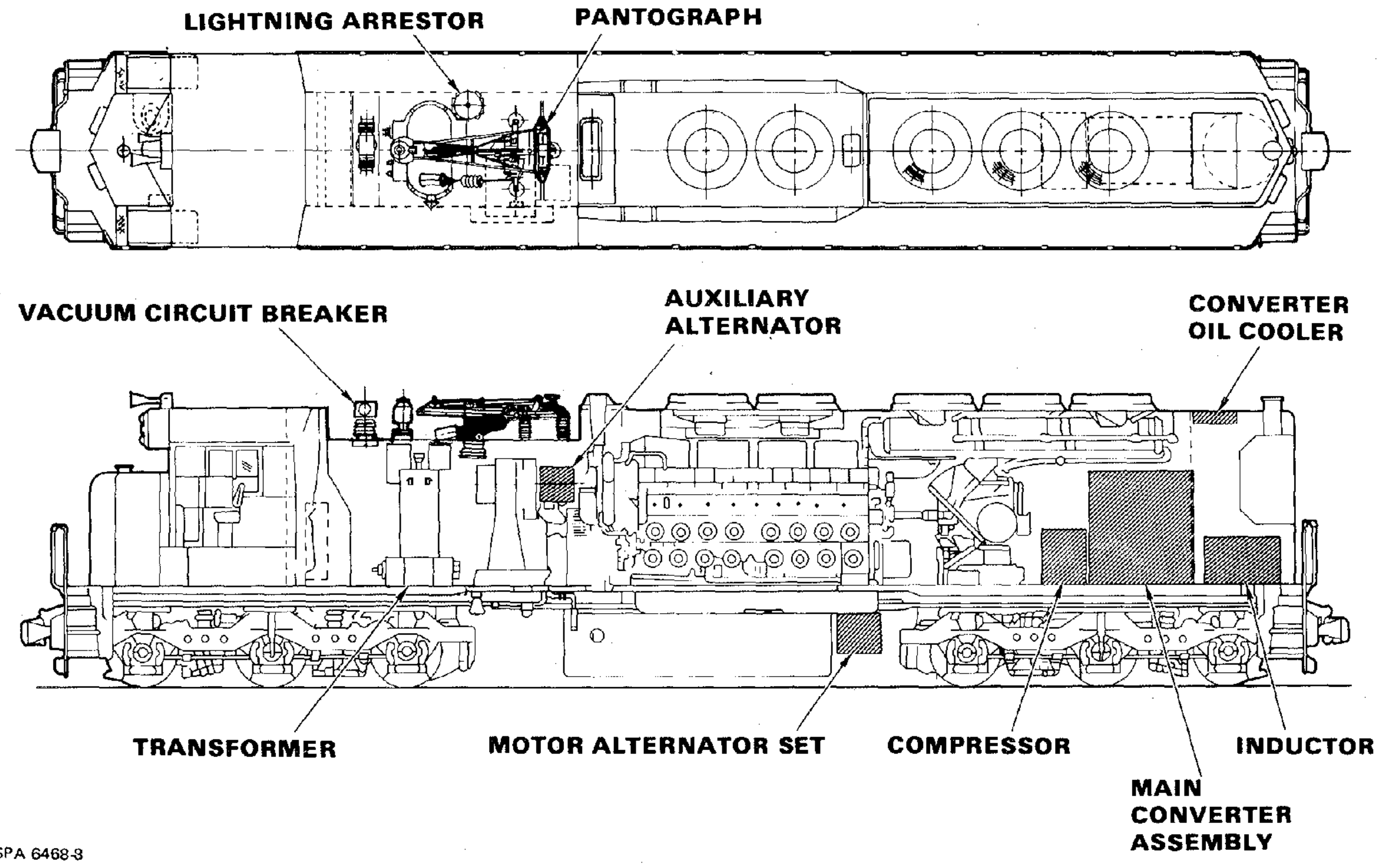
SPA 6468-5-1

50 KV DML ARRANGEMENT



SPA 6468-7

25 KV DML ARRANGEMENT



SPA 6468-3

SCHEDULE OF MAJOR EQUIPMENT (50 KV)

ITEM	QUANTITY	LOCATION	WEIGHT, LB
PANTOGRAPH	1	LOW ROOF	264
VACUUM CIRCUIT BREAKER	1	LOW ROOF	815
GROUNDING SWITCH	1	LOW ROOF	50
LIGHTNING ARRESTOR	1	LOW ROOF	144
ROOF INSULATORS	3	LOW ROOF	315
MAIN TRANSFORMER	1	CARBODY, BENEATH LOW ROOF	15,650
MAIN CONVERTER ASSEMBLY	1	CARBODY, REAR OF LOCOMOTIVE	4,300*/4,100
SMOOTHING INDUCTOR	1	CARBODY, REAR OF LOCOMOTIVE	2,500
+COLD WEATHER PROTECTION	1	CARBODY, FREE END OF ENGINE	400
MOTOR-ALTERNATOR SET	1	UNDERFRAME, BETWEEN TRUCKS	4,000
COMPRESSOR	1	CARBODY, IN PLACE OF EXISTING COMPRESSOR	790
POWER CABLE	–	VARIOUS	500
CONTROL CABLE	–	VARIOUS	
AUXILIARY ALTERNATOR	1	IN PLACE OF AG10	2,000
AUXILIARY TRANSFORMER/RECTIFIER	1	AIR BRAKE COMPARTMENT	235
AUXILIARY DRIVE CLUTCH	1	AUXILIARY ALTERNATOR SHAFT	30
PRIMARY AIR FILTER	1	CARBODY, BENEATH LOW ROOF	200

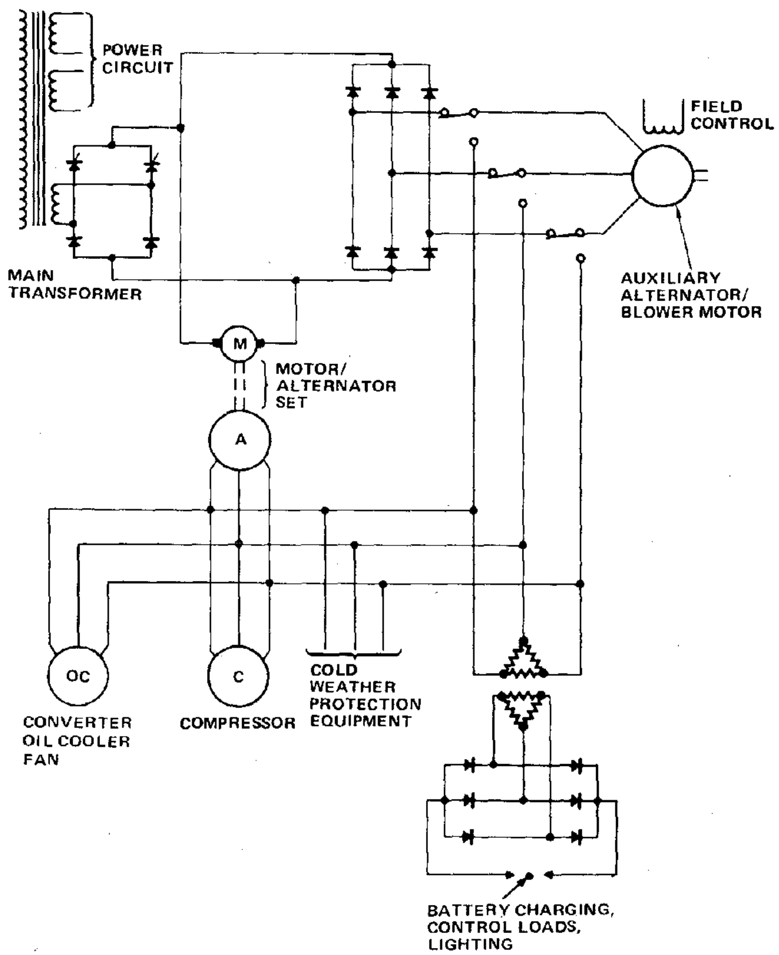
SPA 6468-9

SUMMARY OF WEIGHTS AND BALANCE

OPTION	BOLSTER LOAD, LB			COMPLETE LOCOMOTIVE LB
	FRONT	REAR	DIFFERENCE	
50 KV REGENERATIVE	143,752	139,654	4,098	397,806
50 KV NONREGENERATIVE	143,760	139,445	4,315	397,605
25 KV REGENERATIVE	140,674	138,985	1,689	394,059
25 KV NONREGENERATIVE	140,492	138,996	1,526	393,888

SPA 6468-10

DML AUXILIARIES SCHEME



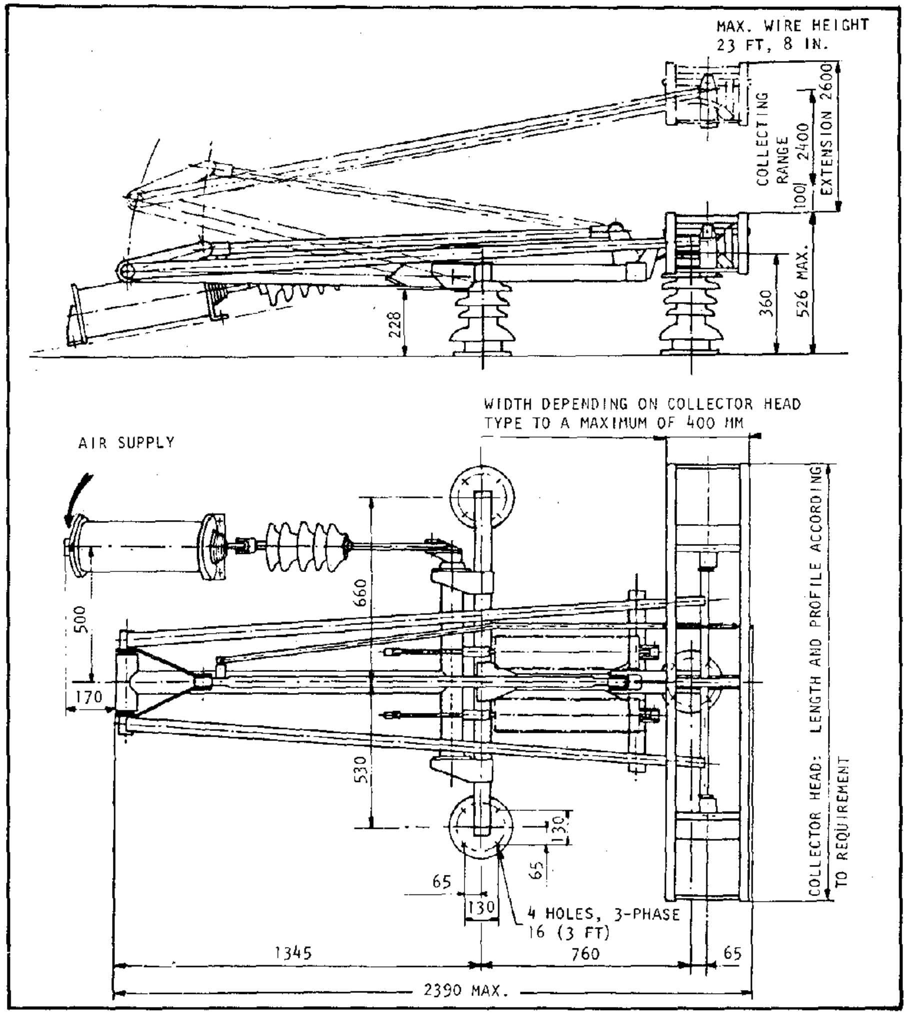
SPA 6468-11

GARRETT

EQUIPMENT DESCRIPTION

SPA 6468-12

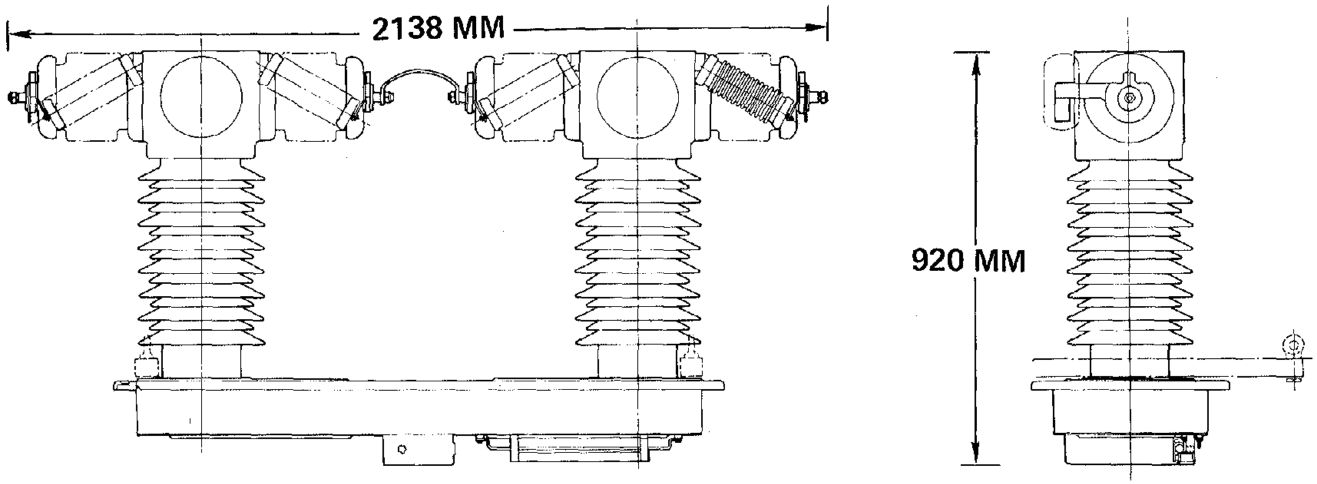
PANTOGRAPH



- MANUFACTURED BY: FAIVELEY
- WEIGHT: 264 LB

SPA 6468-13

50 KV VACUUM CIRCUIT BREAKER

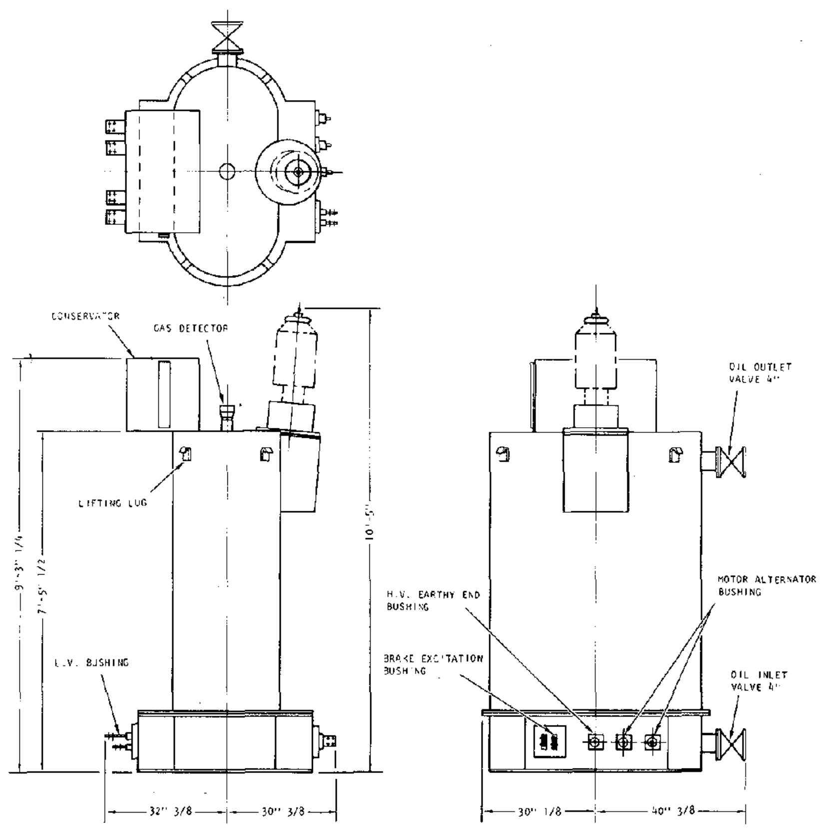


- MANUFACTURED BY: GEC TRACTION
- WEIGHT: 815 LB

NOTE: 25 KV VACUUM CIRCUIT BREAKER IS ONE HALF OF ITEM SHOWN AND WEIGHS **262 LB**

SPA 6468-14

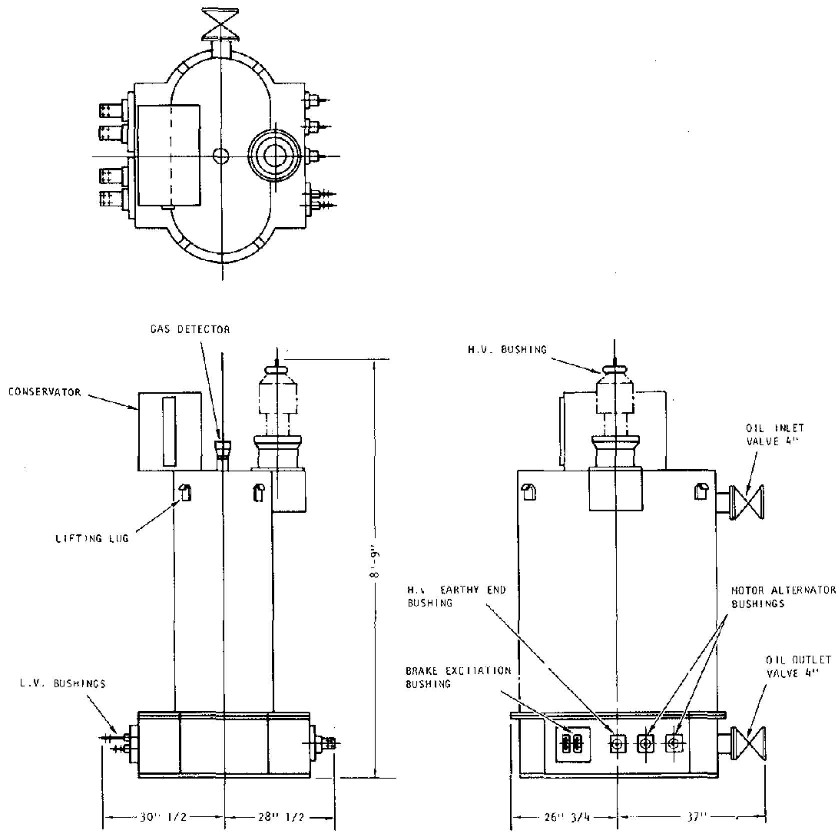
MAIN TRANSFORMER—50 KV



- MANUFACTURED BY: GEC TRACTION
- WEIGHT: 15,650 LB
- COOLED BY: SILICONE OIL

SPA 6468-16

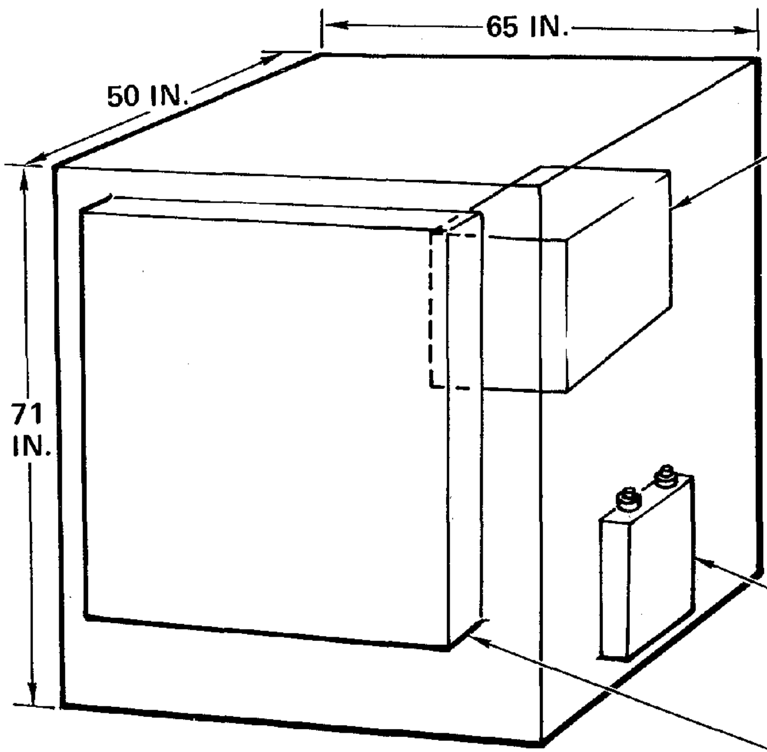
MAIN TRANSFORMER—25 KV



SPA 6468-15

- MANUFACTURED BY: GEC TRACTION
- WEIGHT: 12,563 LB
- COOLED BY: SILICONE OIL

MAIN CONVERTER ASSEMBLY

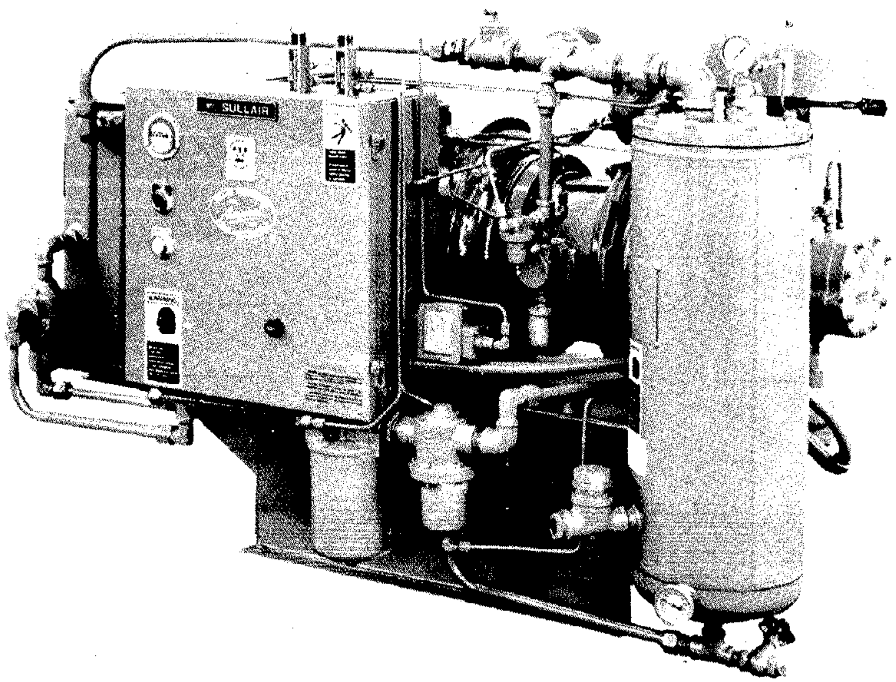


WEIGHT:

- 4300 LB REGENERATIVE
- 4100 LB NONREGENERATIVE

SPA 6468-17

COMPRESSOR

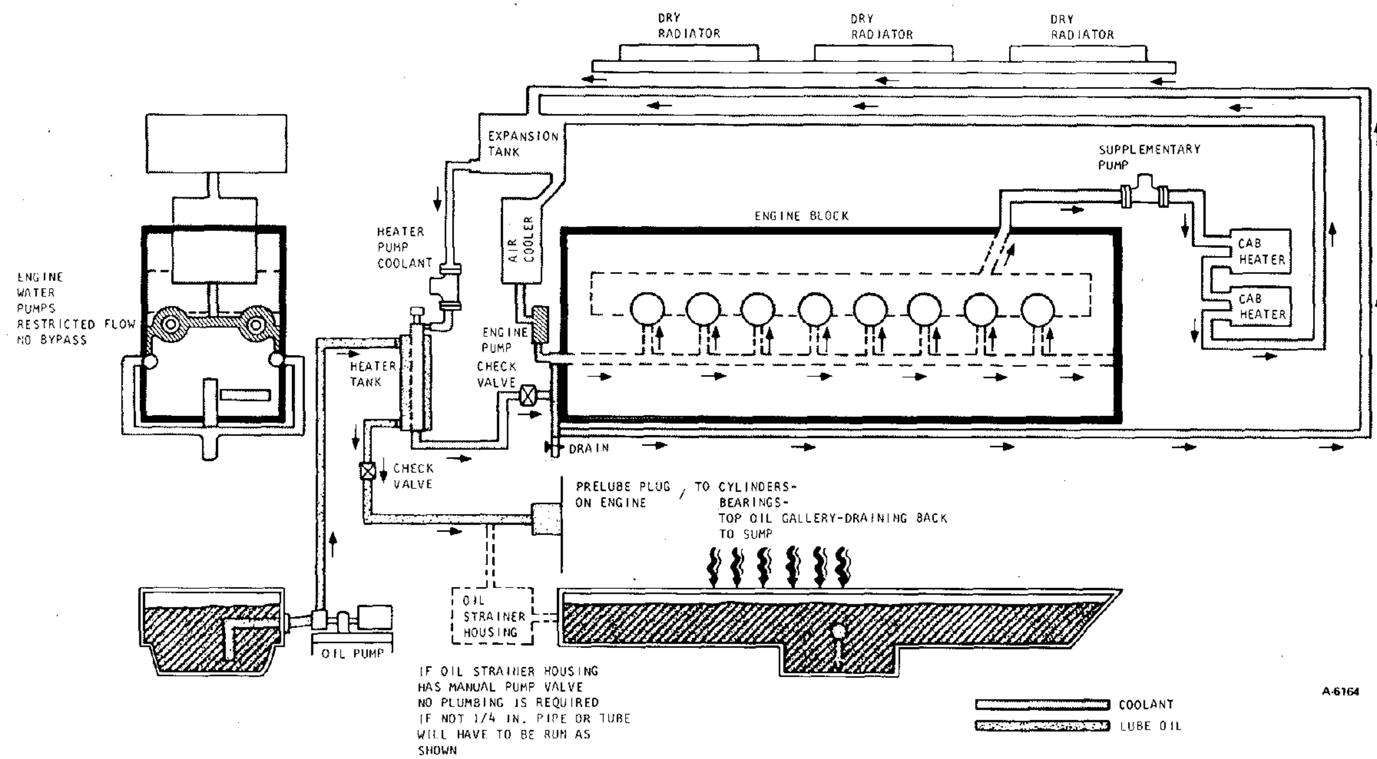


- MANUFACTURED BY:
  SULLAIR
- 10 YEAR WARRANTY
- 140 SCFM AT 140 PSI

SPA 6468-18 A

COLD WEATHER PROTECTION

TYPICAL SYSTEM



SPA 6468-19

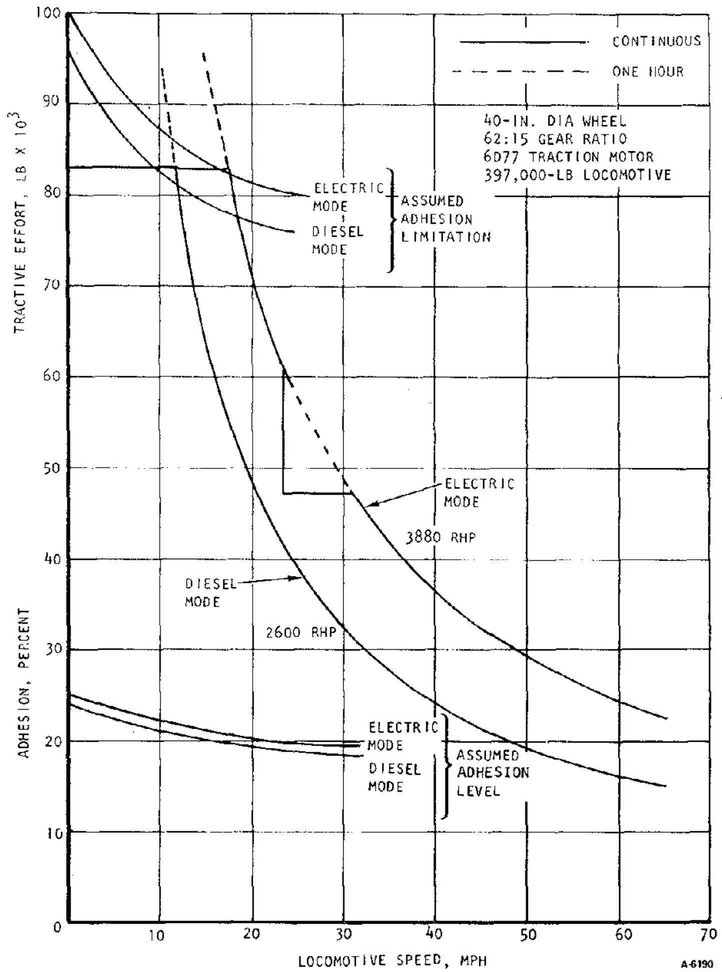
• MANUFACTURED BY: KIM HOTSTART

PERFORMANCE

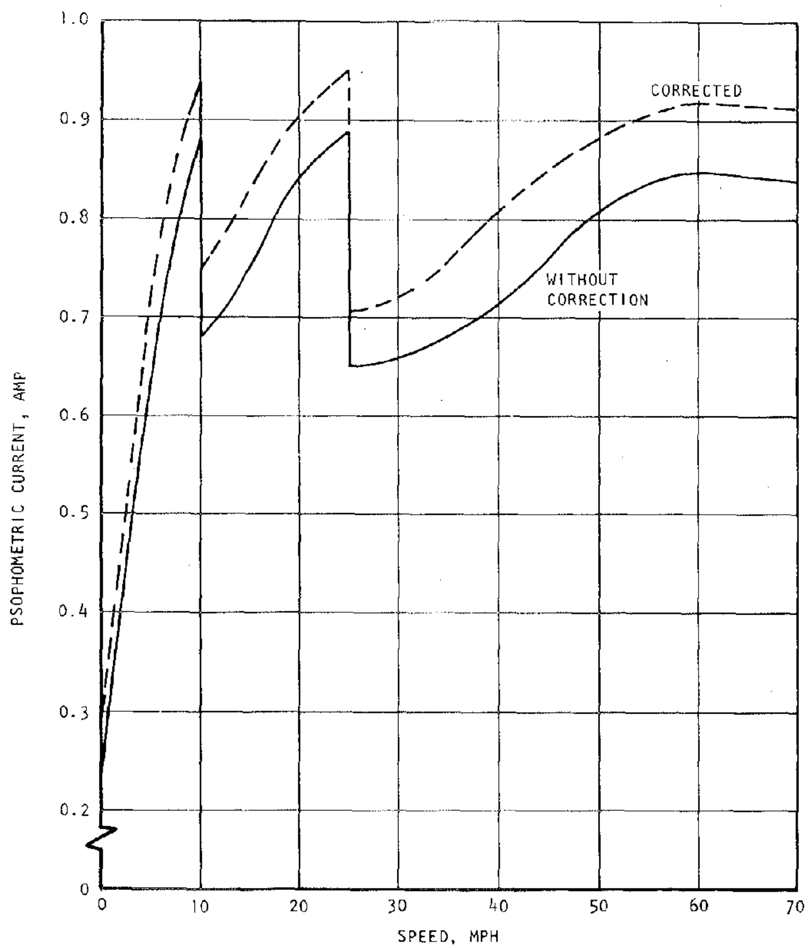
SPA 6468-20

GARRETT

DML TRACTIVE EFFORT



DML POWER FACTOR



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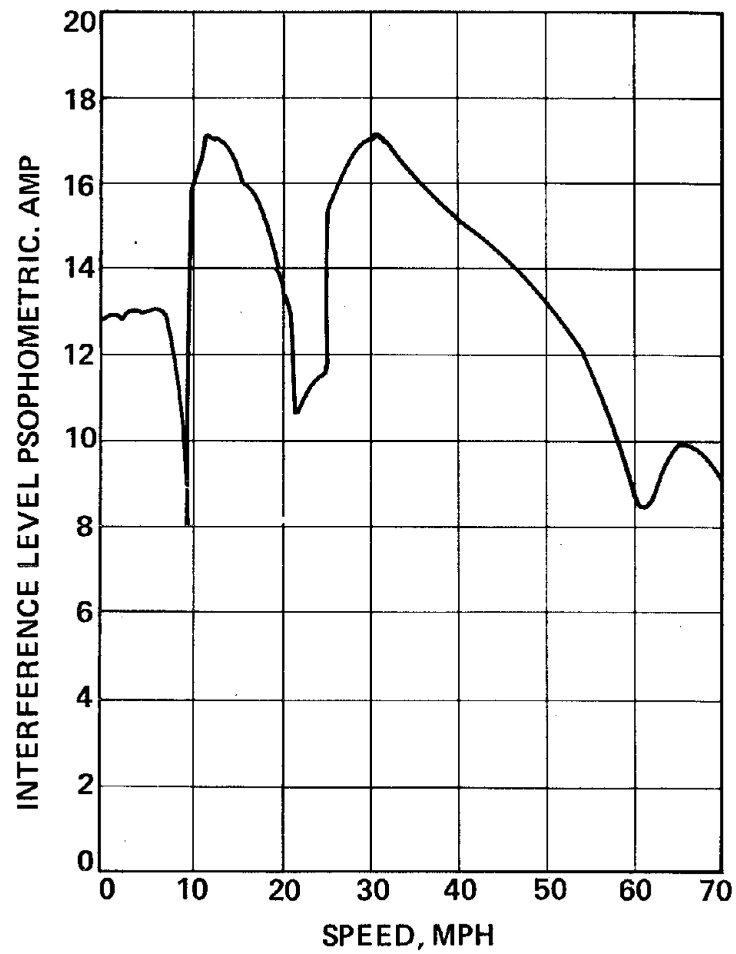
DML ELECTROMAGNETIC COMPATIBILITY

TELEPHONE INTERFERENCE



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ECONOMIC ANALYSIS

SPA 6468-25

DML MAINTENANCE SCHEDULE

ITEM	MANHOURS	FREQUENCY	ANNUAL MANHOURS*
ROOF EQUIPMENT			
• CLEAN INSULATORS	0.5	30 DAYS	5
• INSPECT PANTOGRAPH	0.5	30 DAYS	5
• CHANGE PANTOGRAPH CARBONS	2.0	ANNUAL	2
• CLEAN GROUND SWITCH	0.5	30 DAYS	5
• INSPECT VCB	0.2	30 DAYS	2
MAIN TRANSFORMER			
• CLEAN COOLER MATRIX	1.0	30 DAYS	10
MAIN CONVERTER ASSEMBLY			
• CLEAN COOLER MATRIX	1.0	30 DAYS	10
INDUCTOR	–	–	
MOTOR ALTERNATOR SET			
• INSPECT BRUSHES AND HOLDERS	0.5	30 DAYS	5
• CHANGE BRUSHES	1.0	ANNUAL	1.0
COMPRESSOR			
• CLEAN AIR FILTER	0.5	ANNUAL	0.5
• CHECK OIL LEVEL	0.2	30 DAYS	2
AXLE-END GROUND BRUSHES			
• CHECK	2.0	30 DAYS	20
• CHANGE	3.0	ANNUAL	3.0
MISCELLANEOUS OPERATIONS	5.0	30 DAYS	50
		TOTAL	120.5

*300 DAYS/YEAR

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DML EQUIPMENT COST BREAKDOWN

ITEM	SUPPLIER	COST, 1980 DOLLARS
PANTOGRAPH	FAIVELEY	5,000
VACUUM CIRCUIT BREAKER	GEC TRACTION	18,973
LIGHTING ARRESTOR	GEC TRACTION	3,021
ROOF INSULATORS	FAIVELEY	INCLUDED IN PANTOGRAPH
MAIN TRANSFORMER	GEC TRACTION	122,660
MAIN CONVERTER ASSEMBLY	GARRETT	85,480
SMOOTHING INDUCTOR	PEI	5,000
COLD WEATHER PROTECTION	KIM HOTSTART	3,975
M-A SET	WESTINGHOUSE	15,000
COMPRESSOR	WESTCO	10,988
POWER CONTACTORS	EMD	5,000
AUXILIARY ALTERNATOR	GE	8,000
AUXILIARY TRANSFORMER/RECTIFIER	GE	3,000
DYNAMIC BRAKE BLOWER	EMD	3,000
OIL COOLERS	DUNHAM-BUSH	7,200

SPA 6468-27

DML LABOR COST BREAKDOWN

MODIFICATION	MISCELLANEOUS MATERIALS, DOLLARS	LABOR, HR
REMOVE CAB, SHORT NOSE, AND ELECTRICAL CABINET INCLUDING AIRBRAKE, BATTERIES, BALLAST, ETC.	0	500
REPACKAGE SHORT NOSE/CAB AND ACCESSORIES AND FILTER COMPARTMENT IN NEW INSTALLATION	2,000	1,400
INSTALL TRANSFORMER	500	100
INSTALL NEW PRIMARY AIR FILTERS AND OIL COOLER	100	200
INSTALL VACUUM CKBR/LIGHTNING ARRESTOR, PANTOGRAPH, AND COPPER BUSES	1,500	500
REMOVE EXISTING AUXILIARY GENERATOR AND BLOWER AND INSTALL NEW AUXILIARY GENERATOR/ ALTERNATOR FOR DRIVING ACCESSORIES	500	100
REBUILD CARBODY IN CLEAN AIR COMPARTMENT AREA	500	400
REMOVE, MODIFY, AND REINSTALL FUEL TANK OF REDUCED VOLUME	50	200
INSTALL MOTOR ALTERNATOR SET IN PREFABRICATED SUPPORT STRUCTURE	100	50
REMOVE LONG HOOD, EXISTING COMPRESSOR, AND REINSTALL ELECTRICALLY DRIVEN COMPRESSOR	300	100
INSTALL MAIN CONVERTER ASSEMBLY	200	100
INSTALL INDUCTOR (SMOOTHING CHOKE)	200	100
MODIFY LONG HOOD STRUCTURE, RAISE SAND BOX, AND INSTALL THE CONVERTER OIL COOLER	2,000	400
INSTALL NEW TRACTION MOTOR CABLING AND ALL NEW HIGH AND LOW VOLTAGE WIRING	} 12,000	935
INSTALL ADDITIONAL 16 EA. 1325/24 CABLING FROM HV CABINET TO CONVERTER AND FROM INDUCTOR TO HV CABINET. 4(+) AND 4(–) EACH WAY		100
INSTALL KIM HOTSTART	200	70
INSTALL RELAY PANELS IN HV CABINET AREA	100	50
AXLE END GROUND BRUSHES (3 EA.)	850	225
SPEED PROBE MOUNTED IN TRACTION MOTOR GEAR CASE FOR COUNTING BULLGEAR TEETH. (6 EA.)	– 0 –	100
INSTALL MAGNETIC RACK ACTIVATOR	50	60
LOW WATER RESET MODIFICATION	50	60
INSTALL SLOW SPEED CRANKING	400	50
DYNAMIC BRAKE MODIFICATION (REGENERATIVE ONLY)	200	200
TOTAL	21,800	6,000

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SCHEDULE OF DML DEPLOYMENT COSTS

ITEM	COST	SOURCE
LOCOMOTIVES		
• INITIAL		
SD40-2 BASED DML	$367,014 TO 414,097	THIS STUDY
SD40-2 LOCOMOTIVE	$791,000	TRANSPORTATION SYSTEMS CENTER
E60C LOCOMOTIVE	$1,540,000	TRANSPORTATION SYSTEMS CENTER
• MAINTENANCE		
DML	$1.37/MILE	THIS STUDY
DIESEL	$1.33/MILE	TRANSPORTATION SYSTEMS CENTER
ELECTRIC	$0.65/MILE	TRANSPORTATION SYSTEMS CENTER
ELECTRIFICATION		
• DESIGN, MANAGEMENT, ETC.	$30,000/TRACKMILE	CONRAIL/G&H STUDY
• INITIAL, INCLUDING SUB-STATIONS AND SIGNALLING		
SINGLE TRACK	$473,000/ROUTE MILE	TRANSPORTATION SYSTEMS CENTER
TWO TRACK	$780,000/ROUTE MILE	TRANSPORTATION SYSTEMS CENTER
THREE TRACK	$1,059,000/ROUTE MILE	THIS STUDY
FOUR TRACK	$1,100,000/ROUTE MILE	THIS STUDY
• MAINTENANCE	$4,400/ROUTE MILE	TRANSPORTATION SYSTEM CENTER
ENERGY		
• DIESEL FUEL (AVERAGE)	$1.00/GAL	THIS STUDY
• ELECTRICITY, INCLUDING DEMAND	$0.042/kwh	CONRAIL/G&H STUDY

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SITE SPECIFIC ANALYSIS

SPA 6468-30

APPLICATION OF DML TO HARRISBURG-PITTSBURGH

COST ELEMENT	EXTENT OF ELECTRIFICATION				CONVENTIONAL ELECTRIFICATION
	237-259	222-271	167-337	FULL ELECTRIFICATION	
INITIAL					
MANAGEMENT	2.64	5.88	16.86	50	50
CATENARY, ETC.	22.72	50.6	178.4	261	261
LOCOMOTIVES	63.5	58.3	49.2	45.5	154
LOCOMOTIVES TRANSFERRED	(6.7)	(12.3)	(22.15)	(26.1)	(75)
NET TOTAL	82.16	102.48	222.31	330.4	390
ANNUAL					
DIESEL FUEL SAVING	(10.22)	(18.3)	(42.5)	(60.8)	(62.4)
ELECTRICAL ENERGY	3.65	6.2	15.2	20.2	21
LOCOMOTIVE MAINTENANCE	(3.04)	(6.06)	(12.03)	(13.66)	(17.4)
CATENARY MAINTENANCE	0.10	0.22	0.75	1.1	1.1
SAVINGS IN LOCOMOTIVE REPLACEMENT	(0.9)	(1.63)	(2.95)	(3.48)	(10.0)
NET SAVINGS	10.41	19.51	41.53	56.64	67.7
ROI, PERCENT	12.7	19.1	18.7	17.1	17.35

SPA 6468-31

APPLICATION OF DML TO LOS ANGELES-SALT LAKE CITY

COST ELEMENT	EXTENT OF ELECTRIFICATION					CONVENTIONAL ELECTRIFICATION
	68-107 211-254	48-17 68-107 209-281 668-703	7-51 68-111 417-450 498-532 652-759	7-51 66-137 182-766	WHOLE ROUTE	
INITIAL						
MANAGEMENT	3.63	6.48	14.16	23.1	29	29
CATENARY, ETC.	50.7	95.7	216.1	352.4	396.6	446
LOCOMOTIVES	55.1	51.4	48.6	46.6	46.2	117
LOCOMOTIVES TRANSFERRED	(13.4)	(17.0)	(19.8)	(21.8)	(22.1)	(67)
NET TOTAL	96.03	136.58	259.06	400.3	449.7	525
ANNUAL						
DIESEL FUEL SAVING	(21.52)	(32.6)	(54.97)	(75.89)	(81.2)	(81.4)
ELECTRICAL ENERGY	4.67	8.87	15.5	22.56	24.53	24.5
LOCOMOTIVE MAINTENANCE	(12.23)	(15.79)	(20.4)	(22.5)	(22.7)	(20.7)
CATENARY MAINTENANCE	0.36	0.78	1.88	3.08	3.4	3.5
SAVING IN LOCOMOTIVE REPLACEMENT	(1.79)	(2.26)	(2.64)	(2.9)	(2.95)	(9.0)
NET SAVINGS	30.51	41.0	60.63	75.65	78.92	83.1
ROI	31.7	30.0	23.4	18.9	17.5	15.8

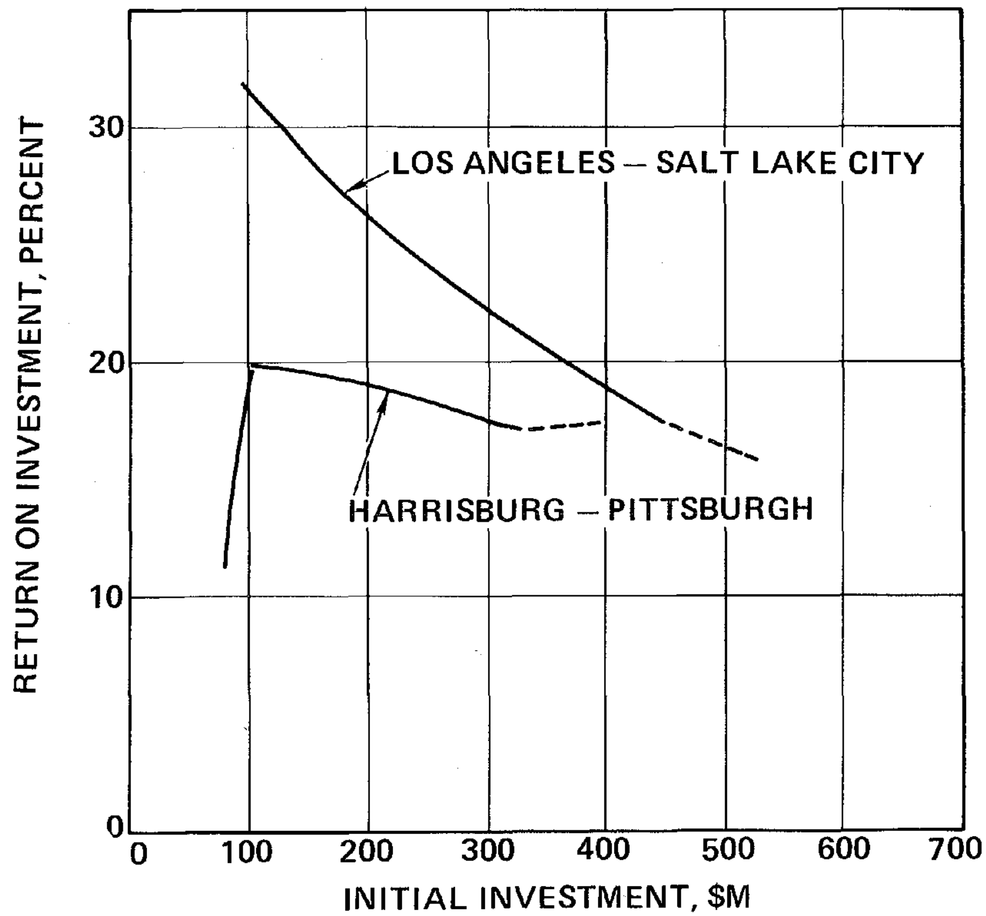
SPA 6468-32

SENSITIVITY ANALYSIS SUMMARY

SENSITIVITY		TYPICAL VARIATION IN ROI	
		WHOLE ROUTE DML, PERCENT	CONVENTIONAL ELECTRIFICATION, PERCENT
ELECTRIFICATION	+50 PERCENT	-30.0	-26.0
LOCOMOTIVE COSTS	+50 PERCENT	-11.8	-26.0
DIESEL FUEL	+4 PERCENT PER YR	+81.3	+62.9
ELECTRICAL ENERGY	+4 PERCENT PER YR	-15.5	-12.4
TRAFFIC GROWTH	-2 PERCENT PER YR	-24.5	-19.5
TRAFFIC GROWTH	+2 PERCENT PER YR	+26.3	+21.7
LOCOMOTIVE UTILIZATION	-20 PERCENT	-0.3	-3.0
LOCOMOTIVE UTILIZATION	+20 PERCENT	+0.4	+3.0
LOCOMOTIVE LIFE	20 YR	-2.2	-4.5

SPA 6468-33

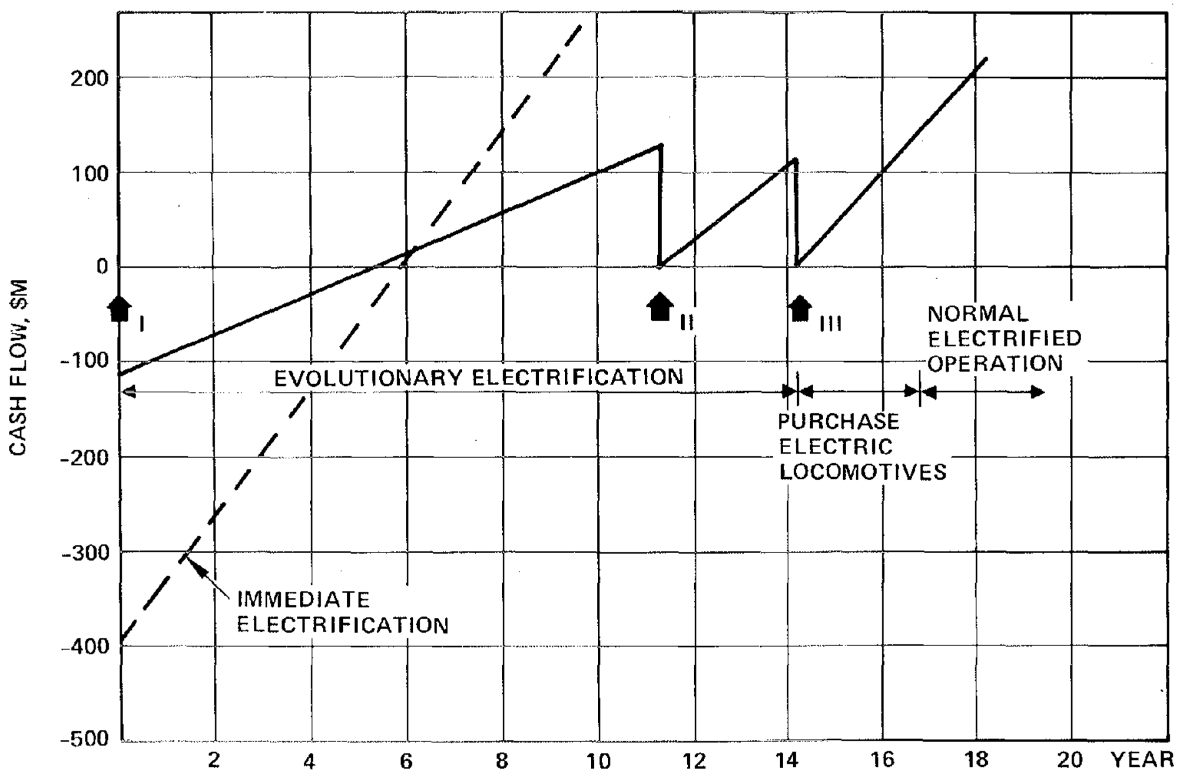
SUMMARY OF ECONOMIC ANALYSIS



SPA 6468-34

EVOLUTIONARY ELECTRIFICATION

HARRISBURG-PITTSBURGH



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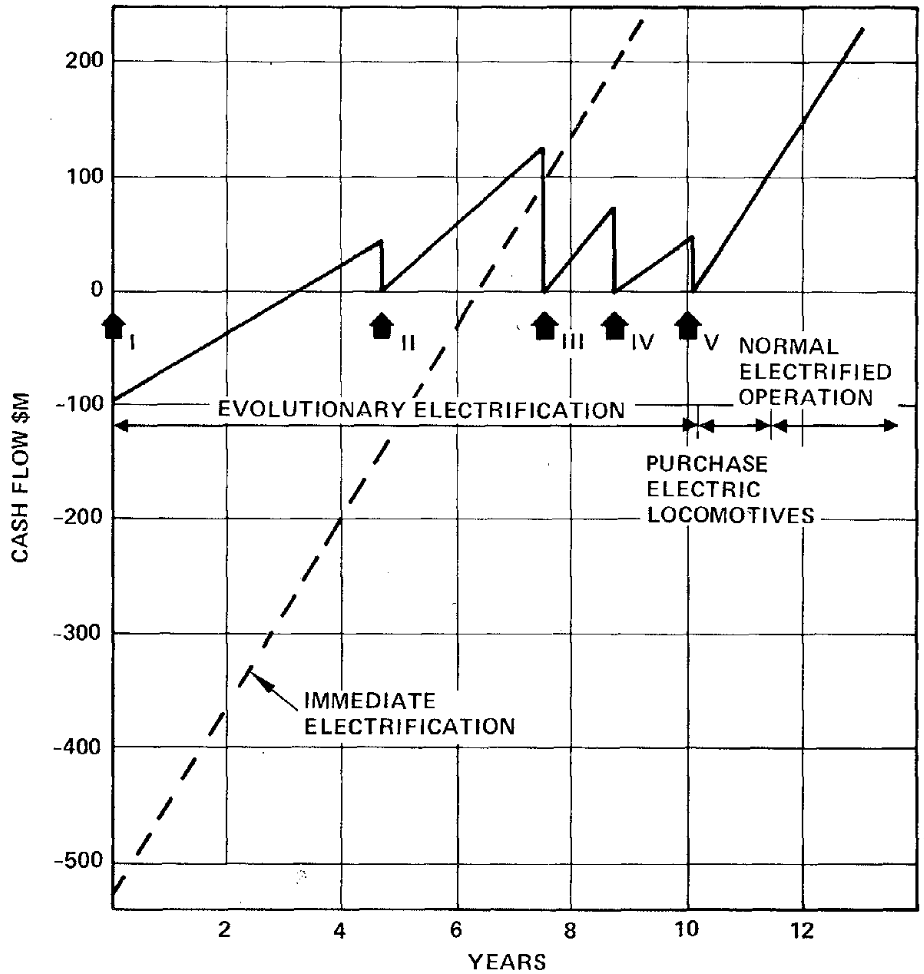
EVOLUTIONARY ELECTRIFICATION
LOS ANGELES TO SALT LAKE CITY



SPA 6468-35

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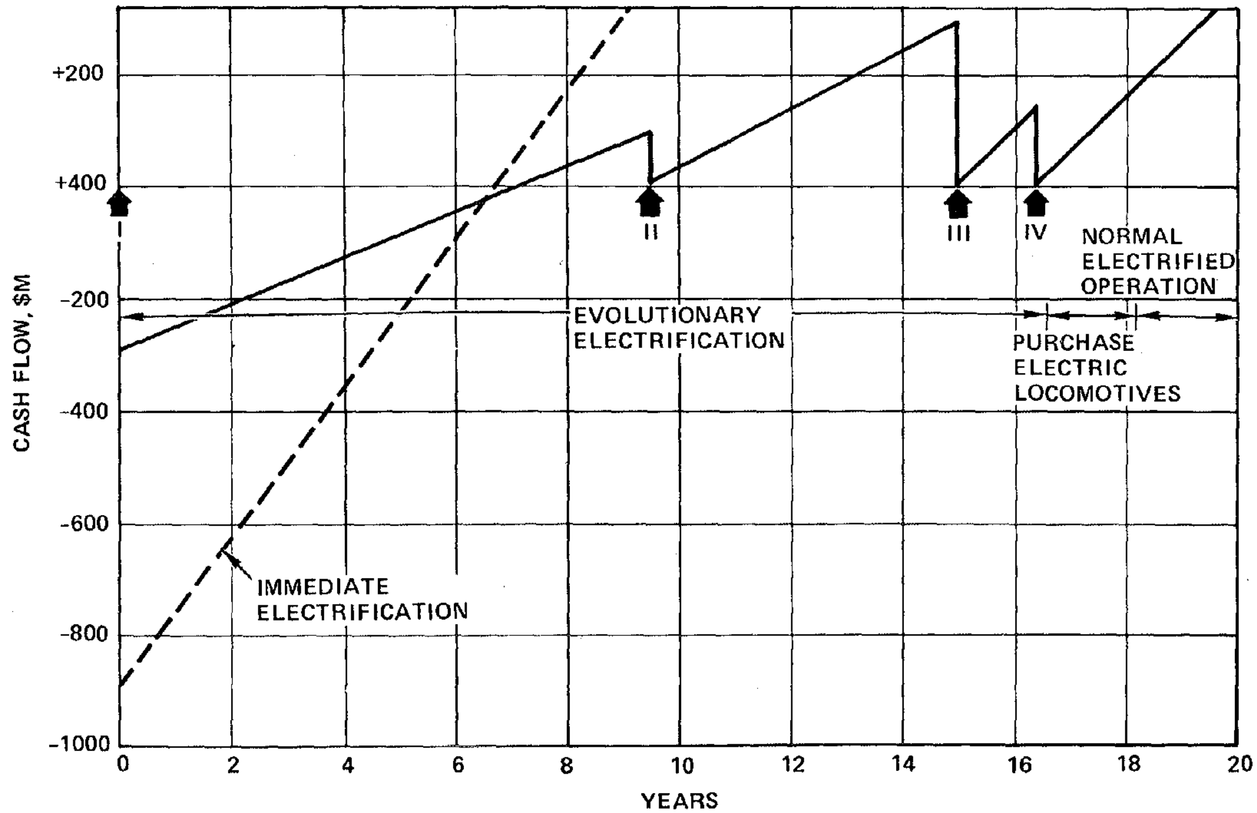
EVOLUTIONARY ELECTRIFICATION

BELEN TO LOS ANGELES



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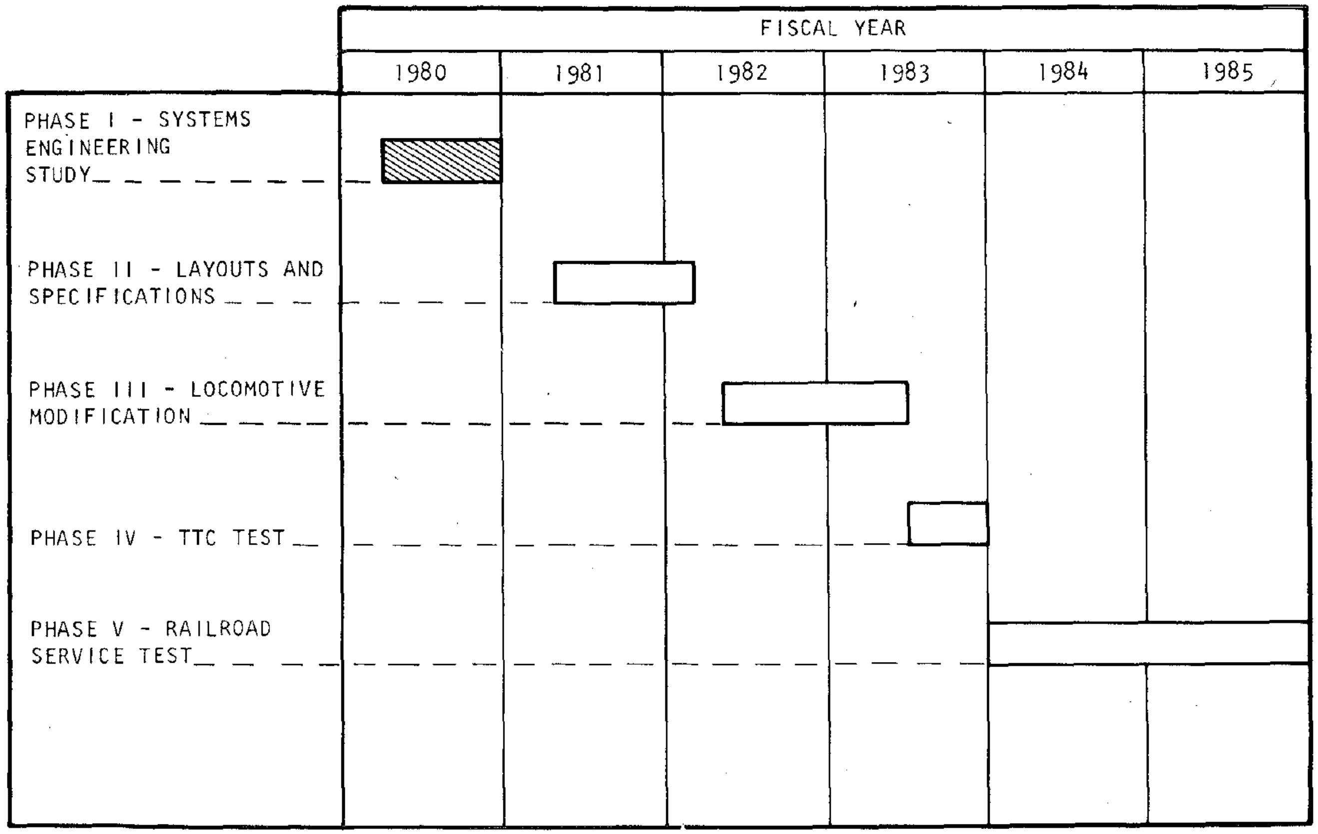
SUGGESTED DML DEVELOPMENT PLANS



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CONCLUSIONS

- ☐ DML CONCEPT IS TECHNICALLY FEASIBLE
- ☐ DML COST RANGES FROM $367,000 TO $414,000
- ☐ DML DEPLOYMENT REQUIRES ONE FIFTH OF INITIAL INVESTMENT OF CONVENTIONAL ELECTRIFICATION BUT ENHANCES THE RETURN ON INVESTMENT
- ☐ DML OPTIONS INCLUDE:
  - 50 OR 25 KV CATENARY
  - REGENERATIVE OR NONREGENERATIVE BRAKING
  - AUTOMATIC OR MANUAL CHANGEOVER
  - ENGINE IDLE OR SHUTDOWN DURING ELECTRIC OPERATION
  - BALLASTING TO 70,000 LB AXLE LOAD

DML IS THE MEANS OF ELECTRIFYING THE NATION'S RAILROADS WITHIN THE PRESENT FUNDING CONSTRAINTS

SPA 6468-38

RECOMMENDATIONS

- ☐ PHASE II PROGRAM SHOULD BE PROMPTLY INITIATED
- ☐ CONSIDERATION SHOULD BE GIVEN TO A FOUR AXLE DML
- ☐ DML DEPLOYMENT SHOULD BE FACTORED INTO FUTURE ELECTRIFICATION STUDIES

SPA 6468-39

* U.S.G.P.O. 725-613/1302-1156