

**ROLL DYNAMICS UNIT
DYNAMOMETER EVALUATION TEST
USING A GP40-2 LOCOMOTIVE**

MARCH 1984



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16. Abstract <p>This report describes evaluative testing of the Roll Dynamics Unit (RDU) at the Transportation Test Center near Pueblo, Colorado. Previous uses of the RDU had been limited to short braking tests, truck stability tests and the transient absorption of power from a transit car. The Dynamometer tests were initiated to demonstrate the viability of the RDU as a dynamometer in testing diesel-electric locomotive tractive performance and brake system safety for extended periods.</p> <p>A GP40-2 locomotive owned by the Burlington Northern Railroad was used to conduct the test. Matters of greatest interest were tractive power, wheel slip/slide, power flow (both motoring and generating), effect on site and utility electric power, dynamic braking, and friction braking. Typical train operating conditions such as breakaway, acceleration, coasting, braking and pulling a grade were simulated. All important parameters were measured and recorded as data. The RDU proved itself safe and viable for the uses suggested, as the measured parameters all agreed well with theoretical values.</p>					
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LIST OF ACRONYMS AND SHORT NAMES

AAR	Association of American Railroads
BN	Burlington Northern
BSI	Boeing Services International
DAS	Data Acquisition System
DOT	Department of Transportation, U.S.
EMD	Electromotive Division
FRA	Federal Railroad Administration
GM	General Motors
LATSA	Lateral Actuator Thrust Structure Assembly
PCR	Power Control Room
RDU	Roll Dynamics Unit
RDUSS	RDU Support Structure
RDL	Rail Dynamics Laboratory
RMU	Roll Module Unit
TTC	Transportation Test Center
TOS	Train Operation Simulator
VTU	Vibration Test Unit

ABBREVIATIONS AND SYMBOLS

METRIC EQUIVALENTS

A	Amperes	
a.c.	Alternating Current	
dB	Decibel	
d.c.	Direct Current	
I	Current (in formulae)	
emf	Electromotive Force	
E_{arm}	Armature Voltage	
$^{\circ}F$	Degrees Fahrenheit ($^{\circ}F-32) \frac{5}{9} = ^{\circ}C$	
F	Force	
ft	Foot, Feet	= 30.48 centimeters
ft lbs	Foot Pounds	
h, hr	Hour(s)	
hp	Horsepower	
Hz	Hertz	
I_f	Field Current	
", in	Inch	= 2.54 millimeters
kip	Kilopound	
lb	Pound	= .45359 Kilograms
mph	Miles Per Hour	
MVA	Megavolt Amps	
MW	Megawatts	
#	Number	
psi	Pounds Per Square Inch	
rpm	Revolutions Per Minute	
rps	Revolutions Per Second	
%	Percent	
S	Speed (in formulae)	
V	Volts	
VAR	Voltampere Reactive (reactive power)	
W	Weight (in formulae)	

EXECUTIVE SUMMARY

Previous uses of the Roll Dynamics Unit (RDU) in the dynamometer mode had been limited to the transient absorption of power from a transit car and included limited braking tests. A study was initiated to determine the feasibility of testing a locomotive on the RDU in the power mode using the full regeneration capability of the RDU electrical control system to produce sustained power for site use. Following the study, a demonstration test was proposed to the Federal Railroad Administration (FRA). This test was designed to examine the extent to which the RDU could be used to conduct full scale power absorption and braking tests. The objectives of the demonstration test were as follows:

- To demonstrate that the RDU would provide an energy-efficient method of testing the tractive performance of a diesel-electric locomotive.
- To determine that the RDU can be used effectively for brake system safety evaluation.
- To determine the additional modifications required to operate the RDU as a dynamometer for extended periods.

The test program, which was funded jointly by the FRA and the Association of American Railroads (AAR), involved the reconfiguration of the RDU to fit a GP40-2 locomotive, provided by the Burlington Northern Railroad. The subsequent tests encompassed steady state and transient traction power absorption, wet and dry friction and dynamic brake testing, controlled condition wheel slip/slide initiation, and system failure mode simulation.

Since the main objective of the test was to demonstrate the capability of the RDU as a dynamometer and not to evaluate the locomotive, the instrumentation was kept simple and relied mainly on the built-in instrumentation of the RDU system. No pretest calibrations were performed except for the strain gauge equipped longitudinal restraint system, which was subjected to a simple two point calibration. It was recognized that the data obtained would be no better than 2% accurate.

During the reconfiguration of the RDU and subsequent installation of the locomotive on the rollers, the opportunity was taken to evaluate the tolerances and procedures supplied by the original contractors. Simplification of these procedures and the relaxation of some of the tolerances resulted in time savings of more than 50% in future reconfigurations over previous methods. It should be noted that the installation of the gearboxes in the drive trains for this test, together with the two largest flywheels, constituted the most extensive reconfiguration that could be performed.

The first test sequence was designed to establish the RDU drive train losses and effective inertia of the four drive trains. Standard 'coast down' and constant speed powering procedures were used, first without the locomotive to establish baseline values for the free drive trains, then with the locomotive to establish the traction motor and wheelset losses and rotational inertia. The effective average flywheel inertia of 164,139 lbs agreed well with

the theoretical value of 163,592 lbs, the added inertia resulting from the other rotational components (gearboxes, rollers, etc.) not included in the calculation. The drive train losses amounted to 62 hp per axle at 62.5 mph with an additional 18 hp per axle attributed to the traction motor, gearing, and wheel-set losses.

The second test sequence was designed to examine the performance of the RDU as a power absorbing dynamometer by measuring the power characteristics of the locomotive. Two test methods were employed. The first method, which was designed to measure the characteristics above the RDU 10-minute overload power limiting line, called for the locomotive to be run at constant throttle settings working against the RDU in the constant speed mode. This method only covered the full throttle range at the higher speeds. A second test method was established in which the locomotive was set up to accelerate the drive trains against a negative torque with the RDU in the constant torque control mode (representing the acceleration of a consist on a grade). This enabled the lower speed, high throttle notch, characteristics to be measured. While these tests were being performed, the quality of generated a.c. power was measured.

The power absorption tests were successful in every way. First, realistic locomotive characteristics were produced which agreed well with the data presented by the manufacturer. Second, the quality of the a.c. power produced by the RDU was acceptable for site use. Approximately 60% of the notch 8 power produced by the locomotive was converted to site power. While the power factor of the regenerated power is relatively low, no significant cost penalty should result from short term testing.

The third test sequence was designed to examine the ability of the RDU to function as a full scale brake dynamometer. Tests were conducted on the locomotive's friction and dynamic brake systems. Friction braking was simulated for both wet and dry conditions, while dynamic braking was simulated as dry only, and, again, two test methods were employed. The first was the dynamometer version of the stopping distance test; the second was a constant speed braking effort test. Very little comparative braking data was available for the locomotive friction brake characteristics. However, when compared with the manufacturer's dynamic brake characteristics, the dynamic brake data was in good agreement. The wet braking data showed little difference from the dry data, probably because of the type and duration of the water spray used. The braking test sequence showed that, with modification to procedures, realistic and repeatable brake tests can be performed on the RDU.

Wheel slip and wheel slide could be produced on the RDU as indicated by the wheel slip light in the locomotive cab. However, the wheel slip/slide test sequence did not produce any useful data, since no additional instrumentation was used. One useful by-product of this test was an approximate assessment of the adhesion levels which could be obtained on the rollers. The maximum dry roller adhesion (without sanding) was 18%. With the application of water to the wheel/roller interface this could be reduced to 12%.

The final test sequence was designed to demonstrate the fail-safe nature of the RDU-locomotive system in the event of the most common failure modes. The failure modes investigated were:

- the failure of the locomotive engine.
- a simulated site power outage.

Under all circumstances tested the test system was brought to a stop without any danger to equipment or personnel.

The major conclusions drawn from these tests were:

- The RDU could function as a full scale, energy-efficient, dynamometer for both power and braking tests.
- The quality of the power generated by the RDU is acceptable for site use.

Based on this test program, it was recommended that:

- The use of the 42-inch rather than 60-inch diameter rollers be considered to improve system efficiency if sufficient work can be foreseen to justify the cost of the final machining process for the 42-inch units presently in stock.
- The possibility of using the RDU control system to accept power directly from the locomotive traction motor leads should be investigated. This would provide an energy efficient method of testing locomotive power units and provide the TTC with a 1.5 MW emergency power generating capability.

1.0 INTRODUCTION

1.1 BACKGROUND

The Rail Dynamics Laboratory (RDL) at the Transportation Test Center (TTC) contains two major pieces of equipment: the Vibration Test Unit (VTU) and the Roll Dynamics Unit (RDU). The VTU is a whole vehicle shaker system and was not used during this test. The RDU is a full scale roller rig designed to support a rail vehicle on its wheels and allow it to "roll" at speeds up to 140 mph.

There are two main modes of operation. First, the wheelsets may be driven by the RDU drive trains to permit the study of truck and wheelset stability (roller rig mode). Alternatively, the RDU can be used to absorb energy from the drive axles of a powered vehicle or to store energy to be dissipated in the braking system of both powered and unpowered vehicles (dynamometer mode).

The first use of the Roll Dynamics Unit (RDU) in a dynamometer mode was to test the transient power absorption mode using a powered transit car during 1981.(1)* In this test, transit car energy was used to accelerate the RDU inertia modules adjusted to represent the longitudinal car inertia. No attempt was made to regenerate the transit car power from its mechanical form back to electricity and inject it into the TTC site bus. However, during this test, the RDU was frequently brought to a standstill by means of regenerative power, using the "Regen Stop" Control.

A brief study confirmed that the RDU electronic controllers were equipped for motoring forward and reverse directions and for regeneration (or inverter action) from both directions. Preliminary checkout tests of a.c. power from the 4160 V (supply) busbars confirmed regeneration power flowing into the bus bars from the RDU.

In order to determine the characteristics of the RDU as a dynamometer, a test was proposed to demonstrate that the RDU could provide a continuous load to a locomotive. Such a test would enable test designers to gain first hand experience in powered locomotive testing and to determine what RDU modifications were required to make the RDU an almost ideal locomotive dynamometer test facility. This report pertains to such a test.

Additional tests involving brake system evaluation and RDU/locomotive failure mode evaluation were also conducted during this test program.

A GP40-2 locomotive was used as the power source for this testing which was performed during February and March 1983.

1.2 OBJECTIVES

The major objectives of this test program were:

1. To demonstrate that the RDU would provide an energy-efficient method of testing the tractive performance of a diesel electric locomotive in simu-

* References are listed on page 75

lated full-scale operation. That is, a sizeable portion of the developed power at the equivalent rail interface would be converted to electric power and returned to the TTC system within the constraints of the utility contract.

2. To determine that the RDU can be used effectively for locomotive brake system evaluation, including the simulation of environmental degradation of braking performance.
3. To determine whether all the failure mode control circuitry and the mechanical interlocks, which are inherent in the RDU systems, work under critical test conditions to ensure safety of the RDU, test vehicle, and personnel.
4. To determine the additional modifications required to operate the RDU as a dynamometer for longer term, over-the-road simulations to support safety and energy related research projects.

1.3 TEST DESCRIPTION

The test program involved running the RDU in both torque and speed control modes under steady state, acceleration, and braking conditions. In order to accomplish the overall objectives, a number of miscellaneous tasks were performed. These were as follows:

1. Test the mechanical behavior of the RDU drive system for unusual forces or vibrations, which may excite one of the shafting resonance frequencies.
2. Ascertain the safe range of possible regenerative electric power, that the RDU could deliver.
3. Qualify the regenerated power in terms of its power factor and waveform and ascertain possible penalty costs from the load utility.
4. Determine the functionality of the RDL building air handling and cooling systems to ensure a safe working environment in the test area.
5. Characterize the RDU drive train assemblies with and without the locomotive and obtain the rotating mass inertia.

The information obtained from the above performance checks was used to support subsequent testing - friction and windage losses, RDU as a dynamometer, braking, wheel slip/slide, and failure modes.

2.0 TEST PROGRAM

2.1 ROLL DYNAMICS UNIT

2.1.1 The Mechanical System

The RDU is equipped with four roller assemblies which are designed to accommodate four wheelsets of a wheeled vehicle. When a powered vehicle such as a locomotive is mounted on the RDU, the unit can be used in the motoring mode (roller rig) or the power absorbing mode (dynamometer). At each roller assembly the test vehicle wheelset rests on top of a pair of hardened steel rollers mounted on a steel shaft. The present rollers are 60 inches in diameter with a rim profile designed to simulate a standard railhead profile on a standard 1 in 40 tie plate. An alternative set of 42-inch diameter rollers is available in rough machined form. The specifications of the RDU physical capabilities are as given in Table 2-1.

Each roller assembly is coupled to a drive train through the Lateral Actuator Thrust Structure Assembly (LATSA), designed to absorb any lateral thrust forces (i.e., forces along the drive train axis) and prevent them from being transmitted to the drive train. A photo of the RDU system is shown as Figure 2-1.

A drive train consists of an optional gearbox (ratio 2302:805 \approx 2.86), up to three inertia units (flywheels), and the main motor/generator. The gearbox is designed to increase the motor speed for a given roller speed by the gearbox ratio and to increase the effective inertia of the flywheels, as seen by the rollers, by the square of the gearbox ratio. There are three sizes of flywheels available to be incorporated in the drive train; three are used without the gearbox, but only two are used with the gearbox. The largest flywheel unit,

TABLE 2-1. RDU PHYSICAL CAPABILITIES.

Vehicle Length (max)	108.0 ft (32.92 m)
Vehicle Width (max)	12.0 ft (3.66 m)
Vehicle Weight (max)	400,000 lbs (181,437 kg)
Axle Load (max)	100,000 lbs (43,360 kg)
Truck Center Distance	
(min)	20.0 ft (6.10 m)
(max)	80.0 ft (24.38 m)
Truck Axle Spacing	
(min)	54.0 in (1.75 m)
(max)	110.0 in (2.79 m)
Gauge	
(min)	56.5 in (1.44 m)
(max)	66.0 in (1.68 m)
Powered Axles	Four (600 hp)

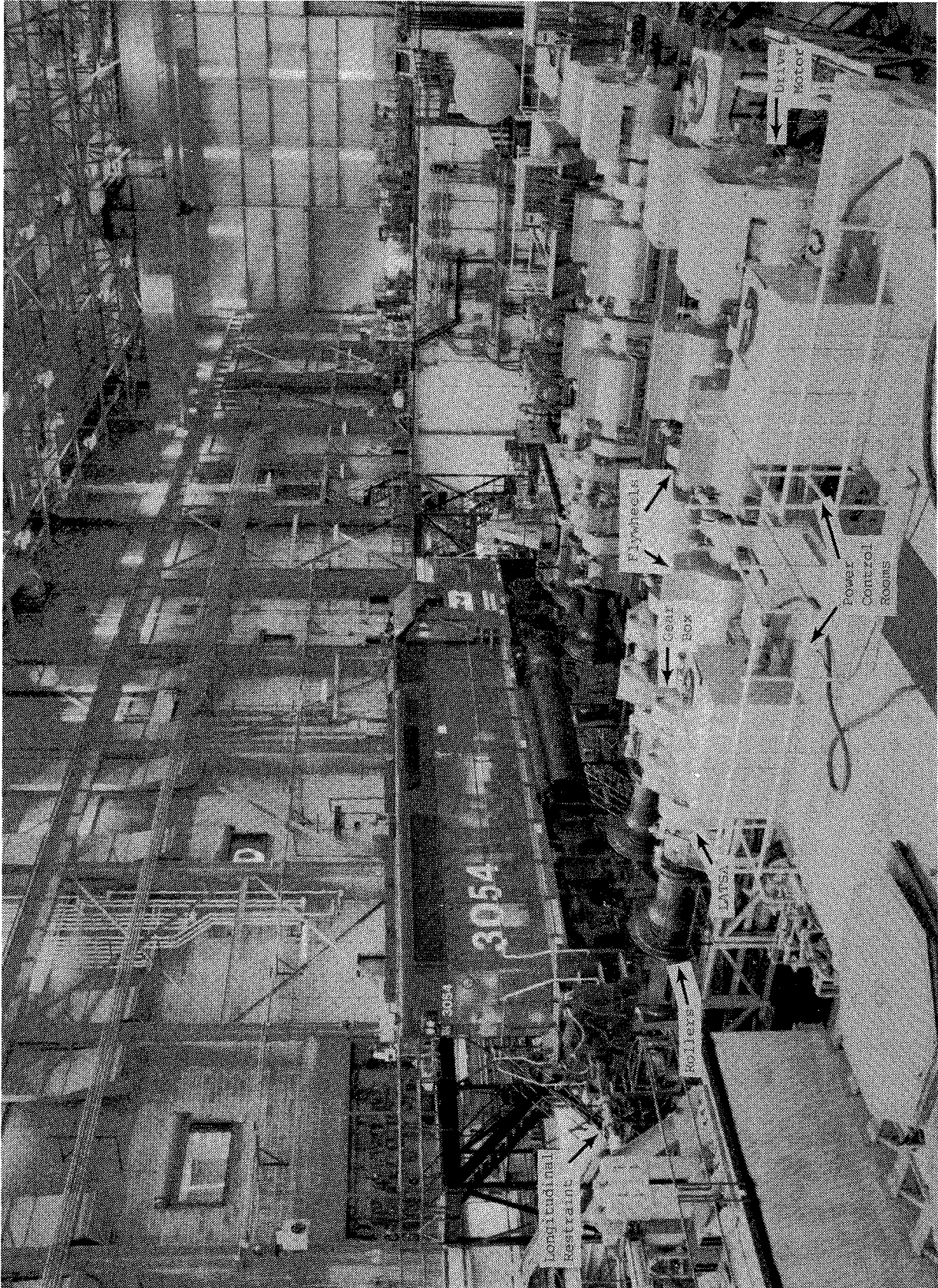


FIGURE 2-1. ACTUAL LAYOUT OF THE RDU.

designated #3, represents a longitudinal inertia of 10,000 lbs when used with to the 60-inch rollers without gearbox. The #2 unit represents 5000 lbs, and the #1 unit represents 2500 lbs. The present test configuration employs 60-inch rollers, gearbox, and two #3 inertia units, representing a total longitudinal inertia, per axle, of 163,592 lbs.

2.1.2 The Main Drive Motor/Generator

The main motor is a d.c. motor rated at 600 hp and is designed to drive the RDU system in the roller rig mode. The motor characteristic is in two distinct parts. Up to the base speed of 1000 rpm, the motor torque is constant, controlled by a constant field current and a varying applied armature voltage to produce an armature current of 960 amperes. The output power is, therefore, proportional to speed up to 1000 rpm. For example, at 200 rpm, the maximum continuous power output of each unit is:

$$\frac{200}{1000} \times 600 = 120 \text{ hp}$$

For the above base speed and up to the maximum rated speed of 2300 rpm, the motor characteristic is constant horsepower limited. In this speed range the armature voltage is kept constant at 500 V and the field current reduced to increase the motor speed, again at a constant armature current of 960 A.

In the dynamometer mode, the motor works as a generator with substantially the same characteristic, absorbing power and returning current to the electrical supply through the power conversion electronics, or "Silcomatic" as it is called by the manufacturers. The gearbox in the drive train enhances the capability of the unit as a dynamometer in that it reduces the base speed of the motor from 1000 rpm to a roller speed of 350 rpm, which is equivalent to a locomotive road speed of 62.5 mph. Use of the 42-inch rollers would further reduce the effective road speed to 43.7 mph at the motor base speed.

2.1.3 The Silcomatic Controller

Silcomatic is the General Electric trade name for its heavy duty thyristor controllers. These are typically used with large motors in steel rolling mills, or as sources of variable d.c. power for process motors.

When the RDU is driving the test vehicle, the Silcomatic controls convert 3-phase alternating current at 4160 V to 500 V direct current. At low motor speeds, rated armature current is easily achieved with low armature voltage. As speed increases, a higher voltage is required until the full rated 500 V is achieved. The Silcomatic accomplishes this smoothly, increasing voltage by changing the angle of firing of the thyristors from 90 degrees retard to 0 degrees (full-on). When full-on, the thyristors act as diodes and rectify the full-wave of 60 Hz current.

In the dynamometer mode, the power flow is reversed from motoring, so the Silcomatic adjusts the thyristor firing angle from 90 degrees retard (no power) to a maximum of 150 degrees retard (full inverting power). The control is smooth and reliable. In this mode, the Silcomatic inverts the d.c. output of the generator (motor) to line voltage and waveform so that the net locomotive power appears on the TTC site 4160 V utility supply.

2.1.4 The RDL Exhaust and Cooling Systems

The RDL building is equipped with ceiling exhaust fans to remove the heat and fumes from the diesel electric locomotives. It is also equipped with three chiller units with cooling towers to supply ample quantities of chilled water. The chilled water supply is used to cool air which, in turn, cools the transformers and the Silcomatic thyristor module heat sinks in the Power Control Rooms (PCR's). Cold air from the roof-mounted air conditioning system is blown by pit blowers in the direction of the locomotive.

2.1.5 RDU Control Modes

The RDU control mode is selected for each test:

1. Speed Control - A reference speed signal is exactly matched by a signal proportional to the actual measured motor speed.
2. Torque Control - A reference torque signal is compared to a signal from the torquemeter and the motor output is controlled to produce the desired torque.
3. Computer Control - A reference torque signal calculated by the computer is compared to a signal from the torquemeter by adjusting motor voltage. A reference speed signal from the computer can also be used for speed control. These systems have not been completely installed and remain inoperative.

Selection of the required mode is by means of a three-position switch on the Operator control panel. Auxiliary relays short the two unselected mode signals to ground. In the speed mode, the torque is not controlled, and in the torque mode, speed must be closely monitored to prevent an overspeed condition.

The control system essentially monitors the selected input mode signal and then adjusts the armature voltage and current or the field current to achieve the desired motor speed and torque. Contained within the control are limits for the input signals to prevent overdriving of equipment. There are also ramp circuits which smoothly ramp the signals from their present value to the new value over preselected time periods.

To control a compound d.c. motor with separate field excitation, only three control conditions are available:

1. Armature Voltage - Rated voltage is 500 V. E arm. is proportional to field current (If) and speed (S rpm):

$$E \text{ arm} = k_1 (I_f)(S) \text{ where } k_1 \text{ is a constant.}$$

2. Armature Current - Rated current is 960 A. Armature current varies as a result of the voltage difference between the applied terminal voltage and the self-generated voltage (back-emf), which is proportional to field current and speed. Control is achieved below base speed by varying the applied voltage.

3. Field Current - Rated current is up to 16.0 A. Field current is varied to produce the required torque and to produce speeds above 1000 rpm (to 2300 rpm). A separate solid state exciter produces the field current from one control signal.

Since this test did not exceed RDU motor speeds of 1000 rpm, the field current was constant. Also, since armature current varies due to armature voltage and back-emf, control was accomplished by varying only the armature voltage.

2.2 GP40-2 LOCOMOTIVE CHARACTERISTICS

The GP40-2 is a General Motors (GM) built 3000 hp diesel-electric general purpose locomotive. The four Electromotive Division (EMD) direct current, series wound, forced ventilated, axle hung motors, (Model #D77), are powered from an alternator-generator set. The main generator, Model AR-10, is a.c. with rectified output for delivery to traction motors and is rated at 1200 V nominal and 4000 A direct current rating. It is ventilated by a blower. The auxiliary alternator, D14, is an EMD, 200 V, 3-phase, 16-pole alternator, built integral with the main generator, to supply a.c. power for engine cooling fan induction motors, main generator excitation, and inertial separator exhaust fan. The engine is a GM 16-cylinder, 2-cycle diesel model 16-645E3. The traction motor has a gear ratio of 62:15 and the locomotive has 40-inch diameter wheels.

Figure 2-2 shows the power curves for a GM GP40-2 locomotive geared for 65 mph operation superimposed on the characteristics of the RDU. The curves for the locomotive were obtained by combining the speed and torque performance curves for each notch position. As can be seen, the locomotive power available at low speeds increases rapidly with speed, and then flattens out over a substantial portion of the speed range.

The ideal RDU characteristic would be one which enveloped the locomotive power curve, but to have the capability to absorb all the locomotive power at low speeds would require a motor several times as large as the one installed. The RDU as a power converter is shown in Figure 2-2 for (1) the 60-inch diameter rollers with the gearbox installed and (2) the 42-inch diameter rollers and the gearbox. Note the improvement in the matching of the characteristics of the RDU with the 42-inch rollers, as well as the levelling off of the power at the RDU continuous rating of 2400 hp. The 10-minute overload rating of 125% and the 3-minute rating of 150% for the 60-inch diameter roller are also presented. Thus, for short-term testing, the RDU can handle the power from notch #8 above the speed of 45 mph. Special acceleration tests were developed to encompass the entire range of GP40-2 characteristics.

2.3 INSTRUMENTATION

This test had relatively few special instrumentation requirements as the RDU is extensively instrumented as a functional unit. It senses, displays, alarms, and automatically shuts down when conditions exceed preset limits. Also, the power flow within the RDU is already well covered by the standard instrumentation, and, so, only limited additional instrumentation was required. This section deals in detail with the instrumentation.

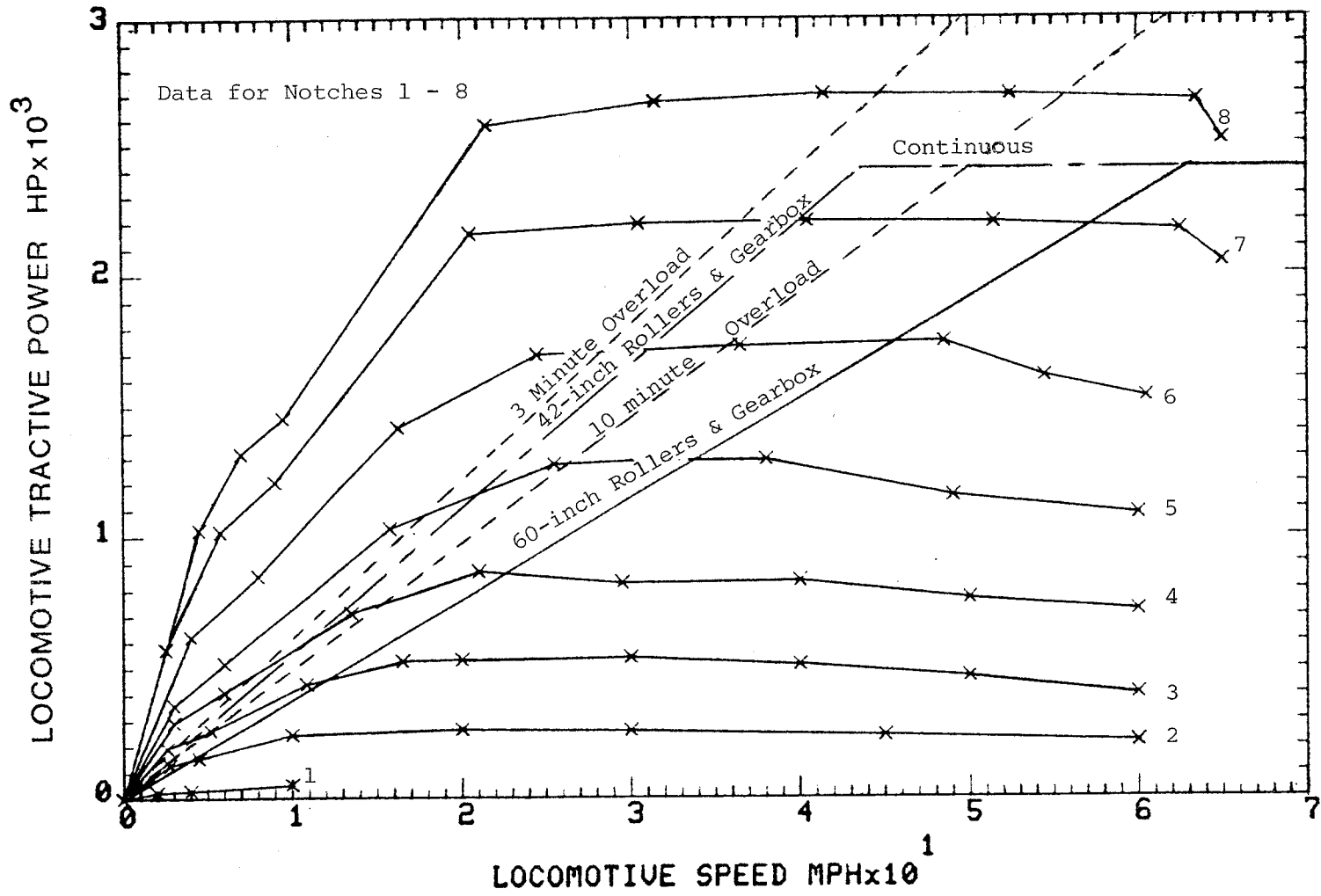


FIGURE 2-2. GP40-2 LOCOMOTIVE AND RDU POWER CHARACTERISTICS.

2.3.1 Locomotive Air Temperature

Five air temperatures were sensed and a display obtained on graph paper in the locomotive cab to indicate ambient and discharge air temperatures. These were required since the locomotive normally relies on its forward velocity to augment the air flow to cool the engine and electrical components, and the still air intake conditions within the RDL could have caused engine overheating.

2.3.2 Torque and Speed

The RDU has one torquemeter per drive train, located between the motor output shaft and the inertia modules. These torquemeter outputs are also patched to the control room where the digital recording equipment is located.

Each drive train also has two speed tachometers, one on the outboard motor shaft and one in the LATSA unit. Both are digital pulse generators whose output is changed to an analog voltage for control purposes and is suitable for instrumentation purposes. The speed signal from the motor shaft is available at the patch panel in the control room for recording purposes.

The torques and speeds from the outboard motor shaft for all four drive trains were recorded digitally in foot pounds and miles per hour for most of the testing. Manual readings of torque and rpm were also taken whenever necessary.

2.3.3 D.C. Motor Voltage and Current

Each motor armature voltage and current are displayed on meters in the operator's panel in the RDU power control rooms (PCR's) and the RDL control room. The 600/0/600 V and the 2000/0/2000 A meters were manually read and tabulated for all tests as required. The voltages and currents for all four of the motors are accessible on the patch panel, but the scale factors were not evaluated, and, so, no digital recordings were attempted.

2.3.4 Quality of Regenerated Power

An oscilloscope and spectrum analyzer were connected across resistors inserted into the 10 MVA site transformer secondary current transformers to record current waveforms. A voltage was also recorded from potential transformers across the site bus. These were recorded to study the influence of the RDU in the regenerated mode upon other TTC loads, especially the large computers. Since these computers contain well isolated power supplies, no disturbance was noted.

The worst current and voltage waveforms occurred at locomotive notch 8, at 50 mph, when all harmonics of 60 Hz to 1000 Hz were very evident except the 6th and 12th harmonics. See Section 3-4 for pictures and spectrum analysis. No disturbance was noticed by the utility so the 10 MVA transformer and the 115 kV transmission line evidently diminished these harmonics to satisfactory levels. Therefore, it was concluded that the quality of regenerated power was acceptable. This area will be further investigated during future testing to determine methods for achieving improved waveforms and site power factor when regenerating power from the RDU.

2.3.5 A.C. Power to Main Busbar

The RDU is supplied from the 4160 volt busbars through two feeder air circuit breakers and metering systems. Each metering system consists of a watt-hour meter and a watt transducer to obtain a cumulative record of energy and instantaneous reading of power flow.

Since this was the first time the RDU had been used as a dynamometer there was interest in verifying and recording that the power flow did actually reverse from a load to a generator as the locomotive produced more power. Depending upon set speed, the watt-hour meter slowed down, then stopped, and then reversed about locomotive notch 2 or 3. Also, the watt transducer output voltage did decrease and went negative in synchronism with the watt-hour meter. At no electric power flow in the feeder lines the locomotive is actually supplying the losses of the RDU by regeneration through the Silcomatic and back through the RDU auxiliary systems.

2.3.6 TTC Site Power and Power Factor

The electric utilities watt-hour and volt-ampere hour reactive meters in the Department of Transportation (DOT) switchyard were monitored during the loading test to determine the magnitude of the power taken, to ensure there was always a positive site power load, and to determine site power factor.

2.3.7 A.C. Power for RDL Auxiliaries

The RDL motor control center (in the switchyard) is equipped with a watt-hour meter that measures the energy consumed by the RDL cooling system, that is, the cooling chiller and its tower exhaust fans and pumps. The power was recorded manually to calculate net regenerative power.

2.3.8 Drawbar Force

The longitudinal position of the test vehicle on top of the rollers is maintained by means of restraining rods attached to the vehicle couplers and anchored to two 200-ton reaction masses outboard of the roller assemblies at each end of the vehicle. The restraining rods are tensioned to approximately 50 kips by means of hydraulic cylinders. The vehicle is centered on the rollers and the rods are locked in place. The tension in the rods is checked at the start of each test day to ensure that the mechanical locking arrangement has not released overnight.

The restraining rods which are normally used in tension at each end of the locomotive were equipped with strain gauges to measure longitudinal forces. The outputs of these strain gauges were displayed on meters in the RDU control console in units of pounds. The rods were calibrated using only a two point calibration, but served well the purpose of demonstrating the technique of measuring tractive effort. The drawbar forces at each end were manually recorded when necessary. This method was an update from the previous concept of inserting load cells in the coupler/draft area of the locomotive. The previous method was time consuming in setting up and did not give reliable results as it was very hard to maintain a perfectly perpendicular load on the load cells. As the locomotive powered the RDU, one longitudinal restraint reading increased and the opposite end unit decreased a small amount, showing the net drawbar effort being exerted by the locomotive.

During the entire course of the test program, data was gathered in digital format using the RDL Data Acquisition System (DAS). Only the four motor/generator torques and speeds were available during the tests, and, so, acquisition was limited to eight channels. The outputs of the volt, ampere, and kilowatt hour meters were not available to record digitally. Future tests should have appropriate recording capabilities to provide a means of collecting accurate data. Future development should also include making available the d.c. current and voltage requirements for digital recording. However, the a.c. power data should not be required as test data since this information is only normally of interest in the event of site electrical interference problems. Manual recording of data for this test was carried out and proved quite adequate in meeting the objectives of a demonstration type test program. Digital data was low pass filtered at 1 Hz and sampled at rates of 2 samples/second and 32 samples/second as per individual test requirements.

The data on digital magnetic tapes was processed on a PDP 11/60 and analyzed as required. Time histories and X-Y plots were obtained for analysis purposes.

3.0 CONDUCT OF TESTS, ANALYSES, AND RESULTS

3.1 TEST SETUP

One of the major objectives of this test program was to develop recommendations for more accurate and practical testing methods. A special concern has been that large numbers of manhours are normally spent to reconfigure the RDU to accommodate different test vehicles. For this test there were major methodological strides made in reconfiguration of the RDU and lifting and setup of the locomotive, which will result in significant manhour savings in the future. This will, of course, have the effect of reducing future test costs. A detailed description of the procedures follows.

The reconfiguration procedures, per the RDU manufacturers, consisted of adjusting the axle spacing, truck center-to-center spacing, and PCR positioning, all within close tolerances.

The truck center-to-center distance and the axle spacing dimensions both had a tolerance specification of 0.015 inch. As a result of engineering analysis by the test personnel, the respective tolerances were changed to 0.25 inch and 0.125 inch. The original tolerances required the vehicle to be removed from the trucks, the axles forced together and then apart, with measurements being taken at both extremes. The measured extremes were then averaged to obtain the desired accuracy of 0.015 inch. To obtain the original truck center spacing tolerance, the vehicle was measured from king pin to king pin. With the new larger tolerances, the dimensions provided on the vehicle manufacturer's drawings were all that was required. A savings of approximately 200 manhours was achieved by relaxing the tolerances with no resultant problems observed during subsequent testing.

Originally, removal of all the 60-inch rollers was required in order to allow access to the two center bolts on the Roll Module Unit (RMU). These bolts were designed to hold the RMU to the mainframe of the support structure and had to be loosened to allow movement of the RMU for a new axle spacing. The original bolts were removed and not reinstalled. Instead, a bracket and a new bolt were installed at this location thus eliminating the need to remove the 60-inch rollers each time a reconfiguration took place. This modification resulted in savings of approximately 250 manhours.

Translation of the RDU Support Structure (RDUSS) previously involved inflating air bearings under the structure and manually cranking two small winches until the new position on the laboratory floor was reached. Then the RDUSS was leveled to a tolerance of 0.030 inch using hydraulic jacks before it was secured to the ground. An alternative method was adopted during the present locomotive demonstration test in which two 1-inch cables, one at each end of the RDUSS, were connected and passed through a pulley mounted to the floor T-slots and up to a 100-ton crane. The air bearings were inflated and the crane hook raised to translate the RDUSS to its desired new location as predefined by blocks in the T-slot, to within 0.5 inch. This was a satisfactory tolerance in view of the new 0.25 inch truck tolerance center-to-center distance. This procedure reduced the manhours involved from 250 to 80 hours.

The PCR's were designed to be translated by air bearings. This method was found to be time consuming. The air bearings were removed, and one of the 100-ton overhead cranes was used to move the PCR's, shortening the time by approximately 50 percent.

As a further time saving for future tests the PCR's and Lube Modules (the modules which provide the lubricating oil supply for the drive train hydrostatic bearings) were placed 3 feet short of their normal location when translating for the present GP40-2 locomotive. This provided the benefit of not having to reconfigure the PCR's, their cables, and the drive train lube module in the event of testing a General Electric locomotive, which is 3 feet longer than the GM-GP40-2.

Lifting of the locomotive and positioning it on top of the rollers was achieved by purchasing a 2-inch diameter, endless sling system, approved by the railroad industry and designed specifically for this model of locomotive. Previous practice had required that the test vehicle be set on hydraulic jacks at the end of a testing day. This was deemed necessary in order not to load the roller bearings, located on the shaft of the 60-inch rollers, for long periods of time. Consultation with the manufacturer of the roller bearings revealed that the vehicle weight on the bearings was unlikely to cause damage over a period of several days. Now the vehicle is left sitting on the RDU rollers overnight or when not under test for a few days--a safer means of storage which eliminates the time otherwise required to jack the vehicle up and down. Two photographs of the locomotive, one showing the lifting operation and the other showing the vehicle installed on the RDU, are presented as Figure 3-1, views (a) and (b).

Finally, a means of fueling the locomotive was devised which did not require the transfer of fuel from a tank truck within the building, a potential fire hazard. Existing hydraulic piping along the south wall of the RDU pit to the outside southeast corner of the building was used to fuel the locomotive. Permanent connections were made to the locomotive to prevent fuel spillage within the building. Since the hydraulic piping in question is no longer used for hydraulic supplies, it can be retained as a permanent fuel line which will conform to existing TTC and State fire codes.

3.2 FRICION AND WINDAGE TESTS

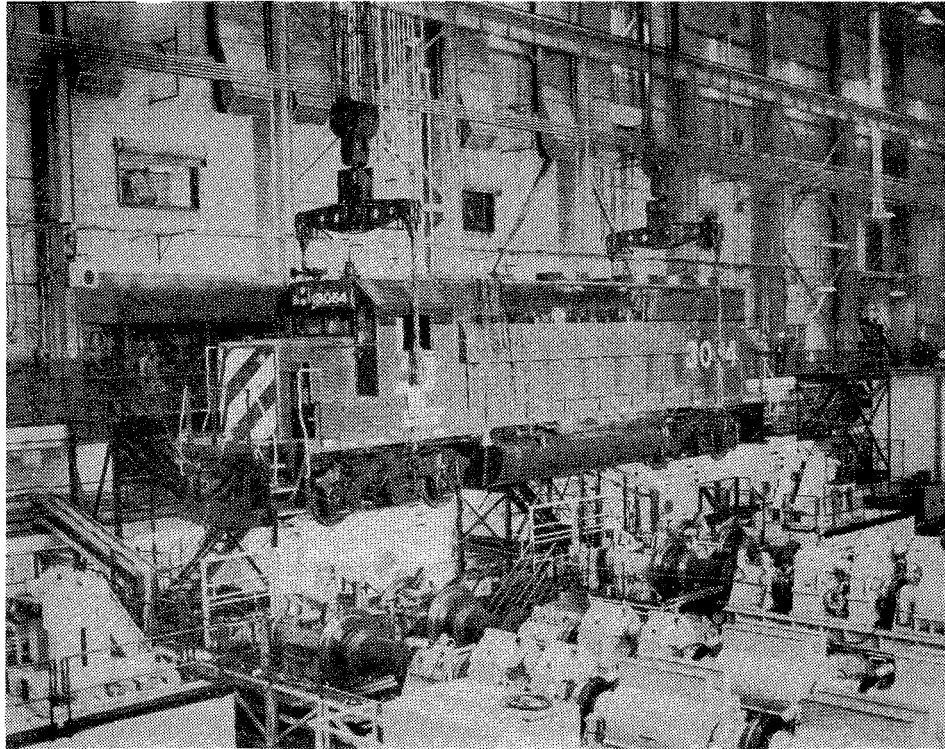
3.2.1 Objective

The first set of runs was designed to determine the friction and windage losses of the RDU at all operable speeds specified in the test program.

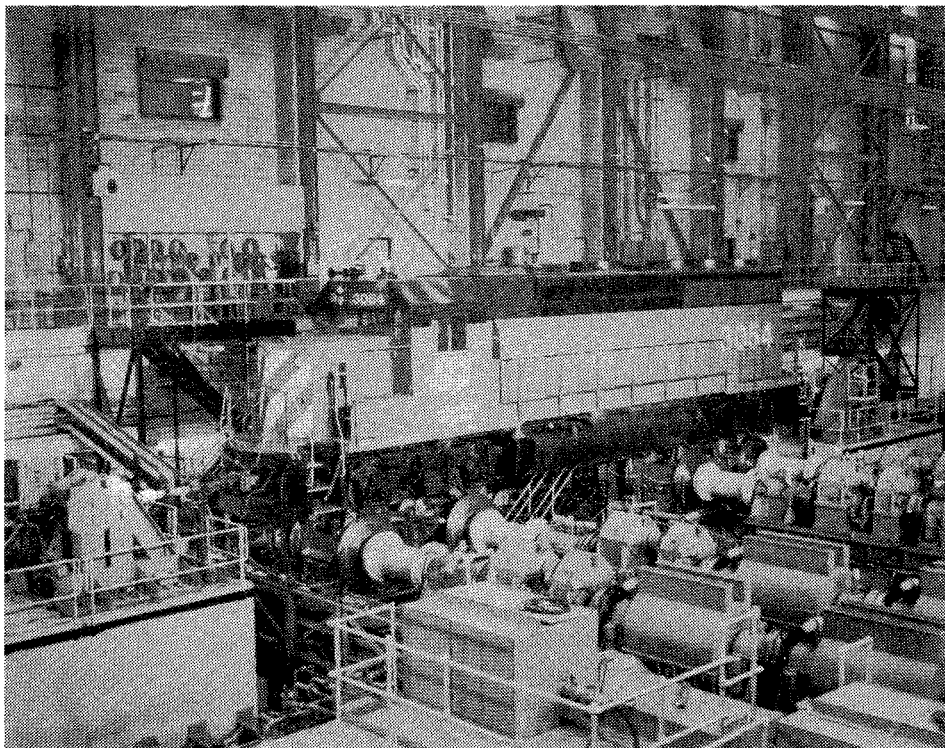
Each RDU drive train motor was run up to a 1000 rpm (RMU rotational speed of 350 rpm), at which speed all power sources were removed from the rotating equipment. This was achieved by switching to "coast stop" from the speed control mode.

3.2.2 Test Conduct

Digital data for speed and time were recorded, and the speed was also manually read from the control room motor rpm meters until the system came to a near stop (≈ 10 rpm). The results were used to produce the total frictional



(a) LOCOMOTIVE LIFTING ARRANGEMENT



(b) FINAL INSTALLATION

FIGURE 3-1. LOCOMOTIVE INSTALLATION ON RDU.

losses of the RDU drive trains. The test was repeated after the locomotive was installed to determine the losses due to its rotating mass inertia.

Resistance in coast or torque resistive motion at the rollers during coasting of the drive trains can be mathematically represented as:

$$T = I\dot{\omega} \quad \text{Equation (1)}$$

where: T = Torque in ft lbs
 I = mass inertia in ft lb-sec²
 $\dot{\omega}$ = Rate of change of rotational speed

here:

$$\dot{\omega} = 2\pi (\text{revolutions per sec/sec}) = 2\pi \left(\frac{\text{rps}}{\text{s}}\right) \quad \text{Equation (2)}$$

The plot of speed versus time from the coast test can be differentiated to obtain $\dot{\omega}$.

Since the losses are to be subtracted from the locomotive tractive power calculations they were calculated in horsepower units.

$$\text{Horsepower (hp)} = 0.00019 TS \quad \text{Equation (3)}$$

where: T is Torque in ft lbs
 S is speed in rpm

Horsepower can be converted to Kilowatts by multiplying by 0.746.

As is evident, one must know the mass inertia of the drive trains in order to calculate the torque. A simple test was performed to obtain the individual inertia values with and without the locomotive installed on the RDU.

The mass inertia was obtained from a separate test as follows: The time to accelerate the drive trains from 100 rpm to 600 rpm (motor speed) under a constant torque of approximately 2000 ft lbs was noted. The torques required to maintain a speed of 600 rpm and 100 rpm were also obtained. These torques were obtained by keeping the RDU in the torque control mode and adjusting the torque with the thumb dial switches until a speed of 600 or 100 rpm could be maintained steadily. The following mathematical relationship was used to calculate I .

$$I = (T_c - T_f)(t_1) \times \frac{1}{2\pi N}$$

where: I = Inertia in ft lb-sec² at roller side of the drive train
 t_1 = Time in seconds required to accelerate from 100 rpm to 600 rpm
 T_c = Constant torque \cong 5720 ft lbs on roller side
 T_f = Torque to maintain a speed of 600 rpm on roller side
 N = Δ revolutions per second of rollers

The gearbox between the rollers and the motor/generator reduces the roller speed by the gear ratio of 2.86.

3.2.3 Test Results And Analysis

The calculated mass inertia of the four drive trains with and without the locomotive when referenced to the roller side are given in Table 3-1.

TABLE 3-1. CALCULATED MASS INERTIA OF DRIVE TRAINS.

Drive Train	MASS INERTIA (ft lb-sec ²)			
	#1	#2	#3	#4
Without Locomotive	32,157 (165,673 lbs)	32,061 (165,181 lbs)	32,058 (165,167 lbs)	31,159 (160,536 lbs)
With Locomotive	32,400 (166,924 lbs)	32,745 (168,703 lbs)	33,016 (170,099 lbs)	32,386 (177,854 lbs)

The equivalent weight (W) in lbs, which is included in Table 3-1, is calculated from the inertias as follows:

$$I = Mr^2 = \frac{Wr^2}{g}$$

$$\text{Therefore: } W = \frac{Ig}{r^2}$$

Where: I = inertia in ft lb-sec²
 g = gravitational acceleration ft/sec²
 r = roller radius in ft

The values obtained for the inertia of the RDU drive trains compare very well with the theoretical value of 163,592 lbs, mentioned in Section 2, for the test configuration of two #3 flywheels and gearbox with the 60" roller, except for drive train #4, which shows a lower value. The excess inertia in the cases of drive trains #1, #2 and #3 is due to other modules like the LATSA, etc, which are not considered in the value of 163,592 lbs.

The horsepower at roller required to overcome the friction and windage due to rotation of the drive trains, with and without the locomotive installed on the RDU, is plotted with respect to locomotive or roller speed in mph in Figures 3-2 and 3-3. Figure 3-2 shows all four drive trains with and without the locomotive and Figure 3-3 shows the total of all four with and without the locomotive installed.

The total horsepower loss in the drive trains was a maximum of approximately 320 hp and 250 hp with and without the locomotive installed respectively for a speed of 62.5 mph. The maximum scatter between the individual drive train horsepower losses was about 8-10 hp. Overall, the test values showed that the drive train losses were consistent with each other, indicating that the lubrication levels were adequate and that the gearboxes were in good condition. The data also demonstrated that the drive train losses would not dominate the locomotive power output and result in negligible energy recovery.

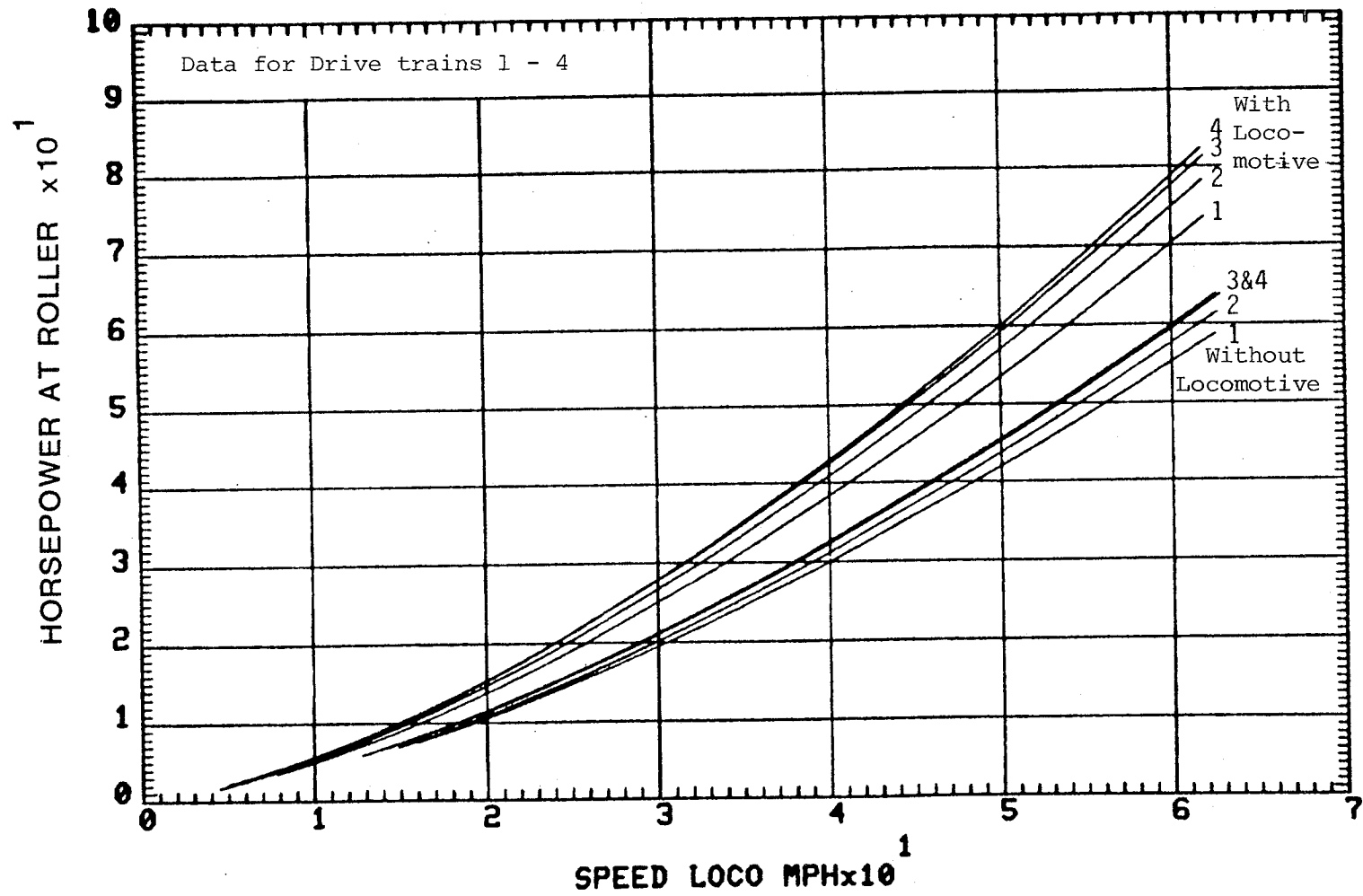


FIGURE 3-2. DRIVE TRAIN RESISTANCE IN COAST, WITH AND WITHOUT LOCOMOTIVE.

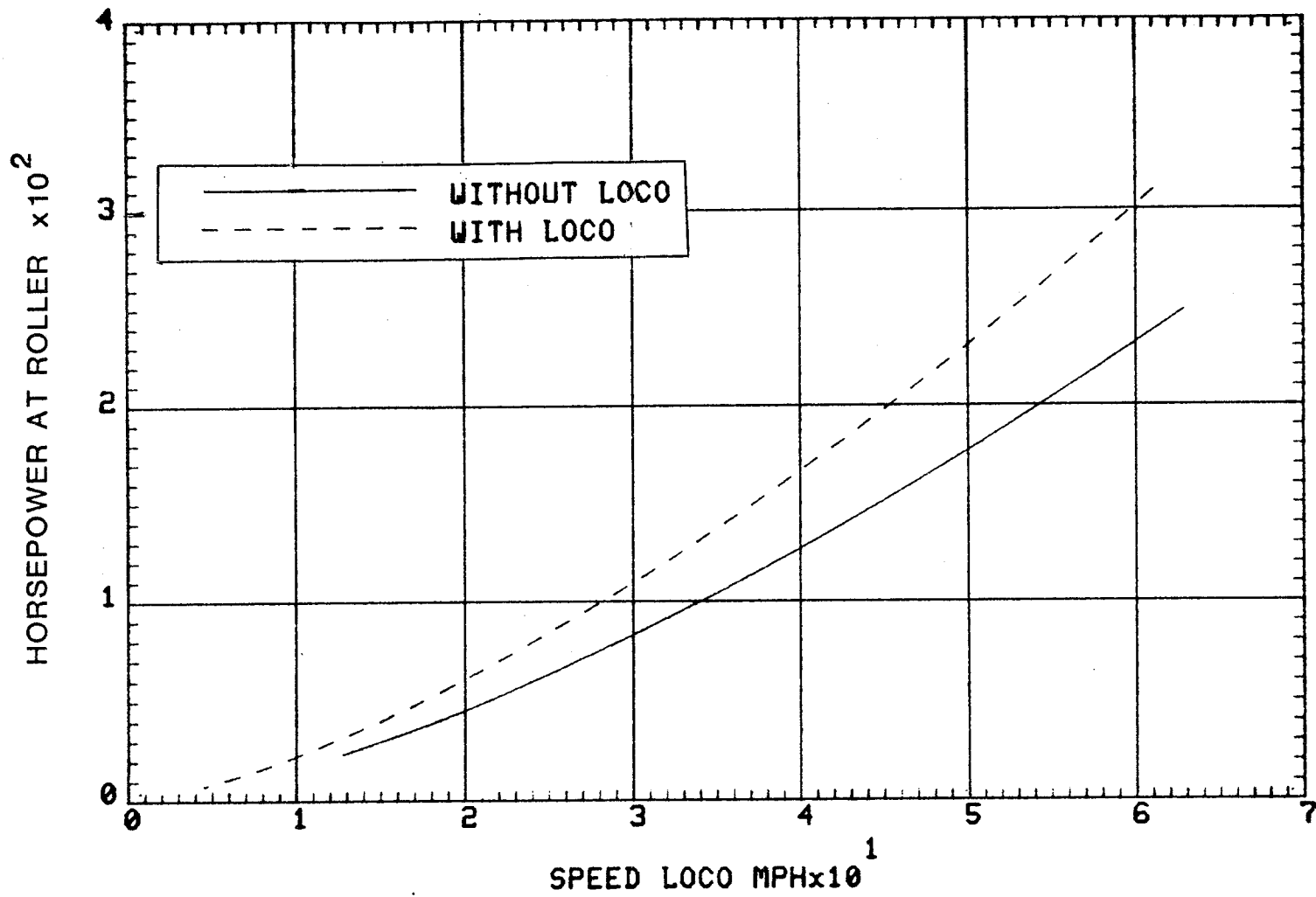


FIGURE 3-3. TOTAL RESISTANCE IN COAST, WITH AND WITHOUT LOCOMOTIVE.

3.3 RDU AS A DYNAMOMETER - TRACTIVE POWER CHARACTERIZATION

3.3.1 Objective

The objective of this test series was to demonstrate the viability of the RDU as an energy efficient dynamometer for testing the short and long term tractive performance of diesel-electric locomotives, in simulated full scale operation.

One set of test results was used to deduce the capability of obtaining the tractive power of the GP40-2 locomotive. A similar set of test results was used to quantify and qualify the RDU generated power into the TTC site bus. The two aspects being equally important for future testing on the RDU, each has been addressed in separate sections. This section pertains to the tractive power data obtained during testing of the GP40-2. Section 3.4 deals with the regenerated power from the RDU when operated as a dynamometer.

3.3.2 Test Conduct

There were two different methods envisaged to obtain data for two different sections of the locomotive tractive power curves with respect to locomotive speed.

The first approach was to drive the RDU in the speed control mode with the locomotive throttle in various notches. This was done at speeds between 10 mph and 65 mph. The testing was conducted in the following steps:

- a. The RDL cooling and exhaust systems were started and checked for full operation.
- b. The locomotive was started and prepared to take load. The throttle was placed in "idle".
- c. The RDU was set in the speed control mode.
- d. 10 mph (158 motor rpm) was dialed up in the RDU master speed control thumb switches.
- e. The Silcomatic main contactors were manually placed in the "on" (closed) position. The RDU modules accelerated to the 10 mph speed. The locomotive wheels and motors also accelerated, simulating the locomotive coasting at 10 mph.
- f. Data was acquired at this steady state. Speed, torque, voltages and currents, both d.c. and a.c., and the drawbar forces were taken manually. Also, a reading of the total power input to the Silcomatics was obtained.
- g. The locomotive throttle was advanced to notch "1", and data was acquired after holding steady at notch "1".
- h. The throttle positions were successively advanced to higher notches and data acquired at each steady state condition. This process was continued until an RDU armature current limit was observed on the operator's panel in the control room. This value is close to a 125% overload limit for the RDU

in the regeneration mode. The locomotive throttle was advanced with caution to avoid any wheelslip.

- i. After acquiring data at the highest notch possible at 10 mph, the RDU and locomotive were brought to zero speed and the locomotive left in "idle".
- j. Steps c. thru i. were repeated successively for RDU speeds of 20, 30, 40, 50, 60 and 65 mph.

As previously mentioned, the locomotive power available at low speeds increases rapidly with speed, and then flattens out over a substantial portion of the speed range. This particular test method only gave data which allowed calculations of the tractive power over the flat portion of the characteristic at the different notch settings.

The second test method was devised to obtain the rapid change in tractive power at low speeds, increasing with speed. The concept behind this test method was to make the locomotive work against a constant negative torque provided by the RDU when in the Torque Control mode. The testing steps were:

- a. The locomotive, RDU, and RDU auxiliaries were prepared to take load, and the locomotive was placed in "idle".
- b. The RDU was set in the Torque Control mode. A torque of 0.0 ft lbs was dialed in at the thumb switches in the control room.
- c. The friction airbrakes were set on the locomotive at a pressure of approximately 20-30 psi.
- d. A negative torque of 1500 ft lbs was dialed in at the RDU control thumb switches. The brakes of the locomotive resisted any rotation in the opposing direction due to this torque.
- e. The locomotive throttle was shifted to notch "2", and the locomotive brakes released.
- f. Digital data acquisition was started prior to release of the brakes and continued until there was no apparent increase in the RDU motor rpm readouts in the control room. This was assumed to be balance speed where the locomotive and the RDU powers matched.
- g. The locomotive and RDU were brought back to a static state, and steps b. thru f. were repeated for notch positions "3", "4", and "6".
- h. Steps b. thru f. were repeated with a negative torque of 3000 ft lbs for notch positions of "3" thru "8".

3.3.3 Test Results and Analysis

Calculations of the tractive power of the locomotive from the test method, for which the RDU was in the speed control mode, were made using the following equations:

1. Longitudinal Restraint Readings (Manual Recordings)

Drawbar Power is:

$$\text{Horsepower (hp)} = \Delta(\text{East and West Restraint drawbar force readings}) \times (\text{mph}) \frac{1.46}{550} \text{ Equation (4)}$$

- where:
- o difference in drawbar force is in pounds
 - o 1.46 constant: mph to ft per sec conversion
 - o 550 constant: ft lb/sec to horsepower conversion

2. RDU Motor Torque and Speed Readings (Digital and Manual Recordings).

Since the RDU motor torques and speeds were known, the hp was directly calculated using Equation (3) in Section 3.2., i.e., horsepower = 0.00019 TS. Note should be made that the locomotive tractive power being calculated was at the wheel/roller interface, which is on the other side of the gearbox, with respect to the RDU motor. The torque is increased and the speed is decreased by the gear ratio in going from the motor to the roller end of the drive train. But since the horsepower is a multiplication of the torque and speed, the gear ratio cancels out.

3. RDU Motor Voltage and Current Readings (Manual Recordings).

The horsepower is calculated directly as:

$$\text{hp} = \frac{VI}{746} \text{ Equation (5)}$$

- where: V = Voltage in volts
I = Current in amperes

and 746 is the conversion factor to horsepower from watts.
(1 hp = 746 watts).

The second method which involved using the RDU in the Torque Control mode used the digitally recorded RDU motor speed to calculate the locomotive tractive power in horsepower. The speed signal was digitally differentiated using a mid-point derivative differentiation software technique. This gave the \dot{w} term in the equation:

$$\text{Torque} = I\dot{w} \text{ which is Equation (1) in Section 3.2.}$$

Proper units were maintained and inertia values from previous test results, as conducted during the Friction and Windage tests, were used to obtain the torques. Then Equation (3) was used to calculate horsepower.

Figures 3-4, 3-5 and 3-6 are tractive power curves with respect to speed for the locomotive calculated from the test values of the drawbar force, RDU motor torque and speed and RDU motor voltage and current respectively. The drawbar force readings are not very accurate due to the fact that the longitudinal restraints have only a two point (high-low kip) calibration curve. The d.c. voltage and current values will have errors in them due to motor/generator efficiency fluctuations involved. The torque and speed from the RDU motor is at

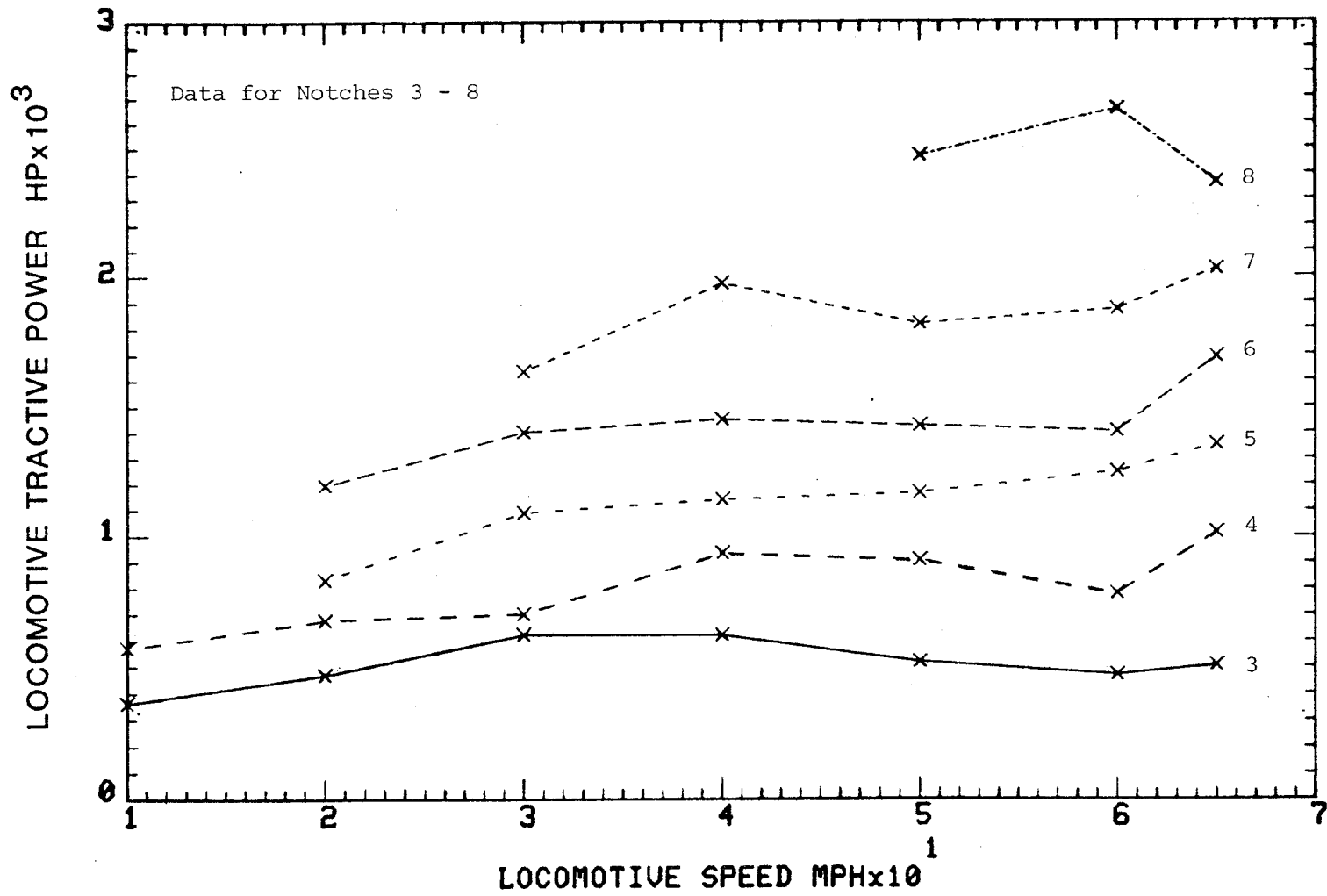


FIGURE 3-4. TRACTIVE POWER CALCULATED FROM THE DRAWBAR FORCE.

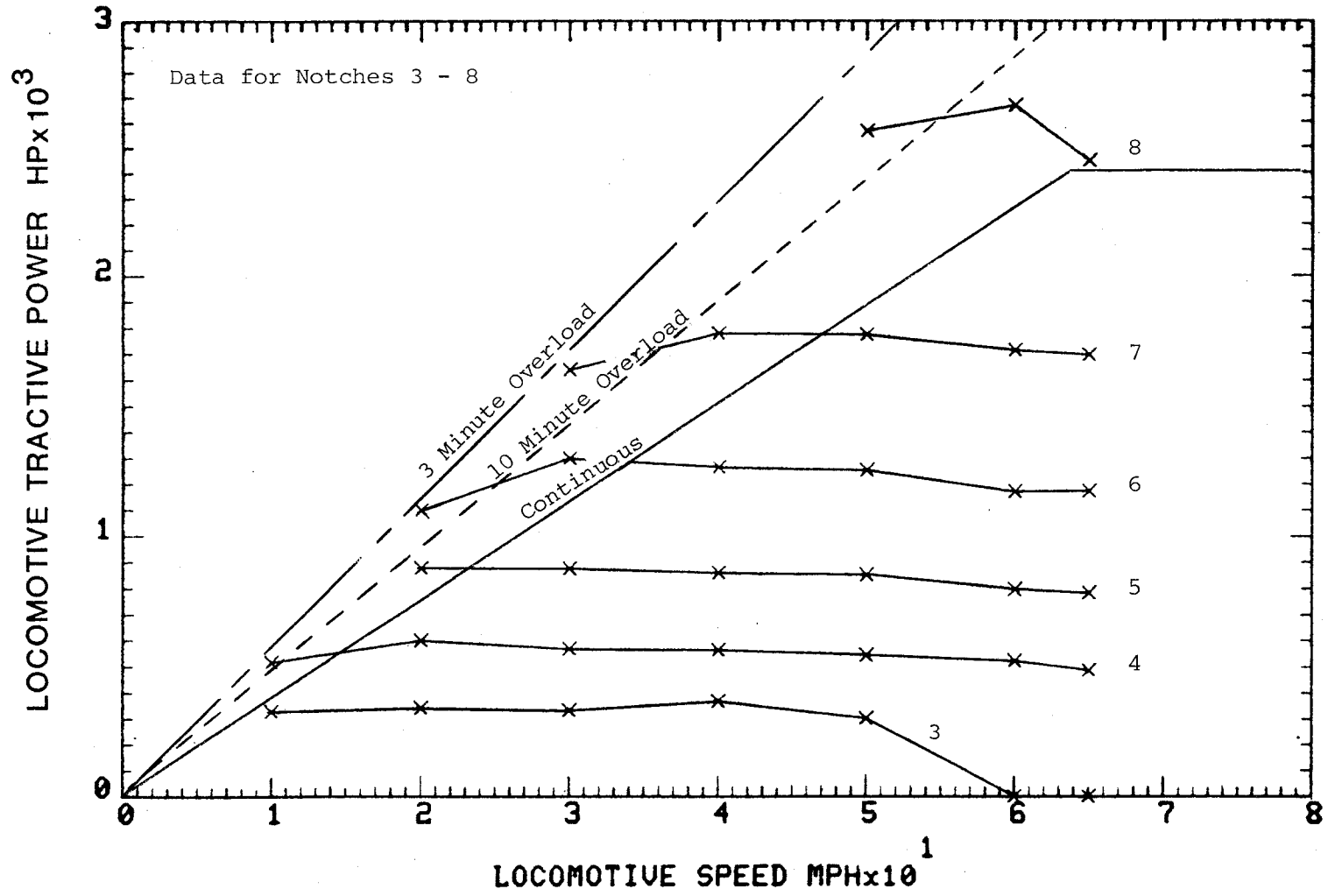


FIGURE 3-5. TRACTIVE POWER CALCULATED FROM TORQUE AND SPEED READOUTS.

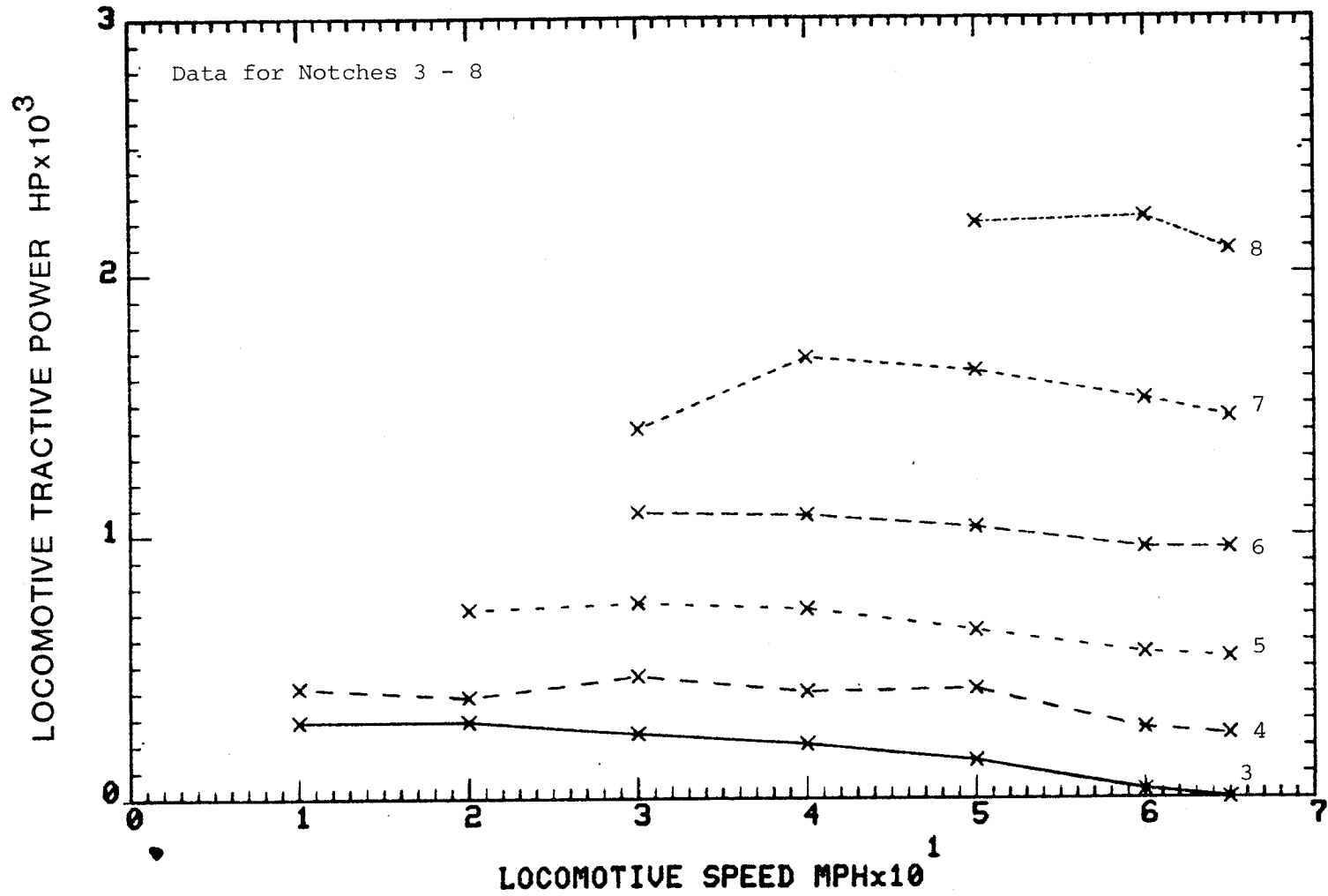


FIGURE 3-6. TRACTIVE POWER CALCULATED FROM D.C. VOLT AND AMP READOUTS.

present the most accurate measurement. The losses incurred in friction and windage are thus taken into account for the tractive curve obtained using the torque and speed readings (Figure 3-5).

Figure 3-7 shows the tractive power curves of the GP40-2 locomotive obtained using the specification values and the test values as in Figure 3-5. It is evident that at the higher notches, except notch "8", the test curves are lower than the specifications claim. The reason for this disagreement could be improper notch settings (governor settings) before testing the locomotive. Since this test program focused on the ability to perform similar tests and not on evaluating locomotive performance, the data seemed quite sufficient. Further investigation could be pursued in the future to ascertain the facts in detail.

Figure 3-8 is the tractive power curve obtained from the test data pertaining to the second method, when the RDU was in the Torque Control mode. The locomotive was accelerating against a constant torque of 3000 ft lbs. As can be seen, the initial rapidly changing tractive power portion of the curve was easily calculated. The curves were extended by hand for the constant portions of the curves through the speed range of the locomotive. Figure 3-8 is for notch numbers "4", "5", "6", "7" and "8". Figure 3-9 is a similar plot for notches "2", "3", "4" and "6" and a constant RDU torque of 1500 ft lbs.

It is evident from these results that the RDU performed very well in meeting the objectives of the test program. A very accurate and verifiable dynamometer system will be available for future testing once calibration improvements are made to the RDU system meter outputs for the longitudinal restraint rods, torquemeters, and d.c. motor voltage and current.

3.4 RDU AS A DYNAMOMETER - POWER FLOW IN THE RDU

3.4.1 General Description of RDU Power Flow

Site electric power at 4160 V, 3-phase is supplied by the RDL Substation (Blue Barn) to each Power Control Room where it passes through the various transformers and protective devices before it is rectified by the Silcomatic controllers to energize the RDU motors as shown in Figure 3-10. In the present test configuration, PCR's #1 and #2 control power to and from the front truck of the locomotive (East End), while PCR's #3 and #4 do likewise for the rear truck (West End). The RDU control systems are interlocked so that the roll module cannot operate unless the auxiliary systems are operational. Power for the auxiliaries is taken from the PCR's and must be accounted for in tracing the power from the locomotive to the TTC site busbars.

During the regeneration mode, the locomotive supplies power for the auxiliaries of the RDU by transferring mechanical power through the roll and inertia units, converting it to electrical power by means of the d.c. motor (acting as a generator). The Silcomatic controller operates in the inverter mode, and finally the main transformer transfers power to the 4160 V PCR feeder. Power for the auxiliaries is taken from the PCR feeder by means of stepdown transformers which reduce the 4160 V to 480 V for the larger pumps and blowers and to 115 V for control, lighting and power. At the electrical balance point, when feeder power flow is zero, the total auxiliary load is supplied by the locomotive; at that time the locomotive traction load is the auxiliary load divided by the

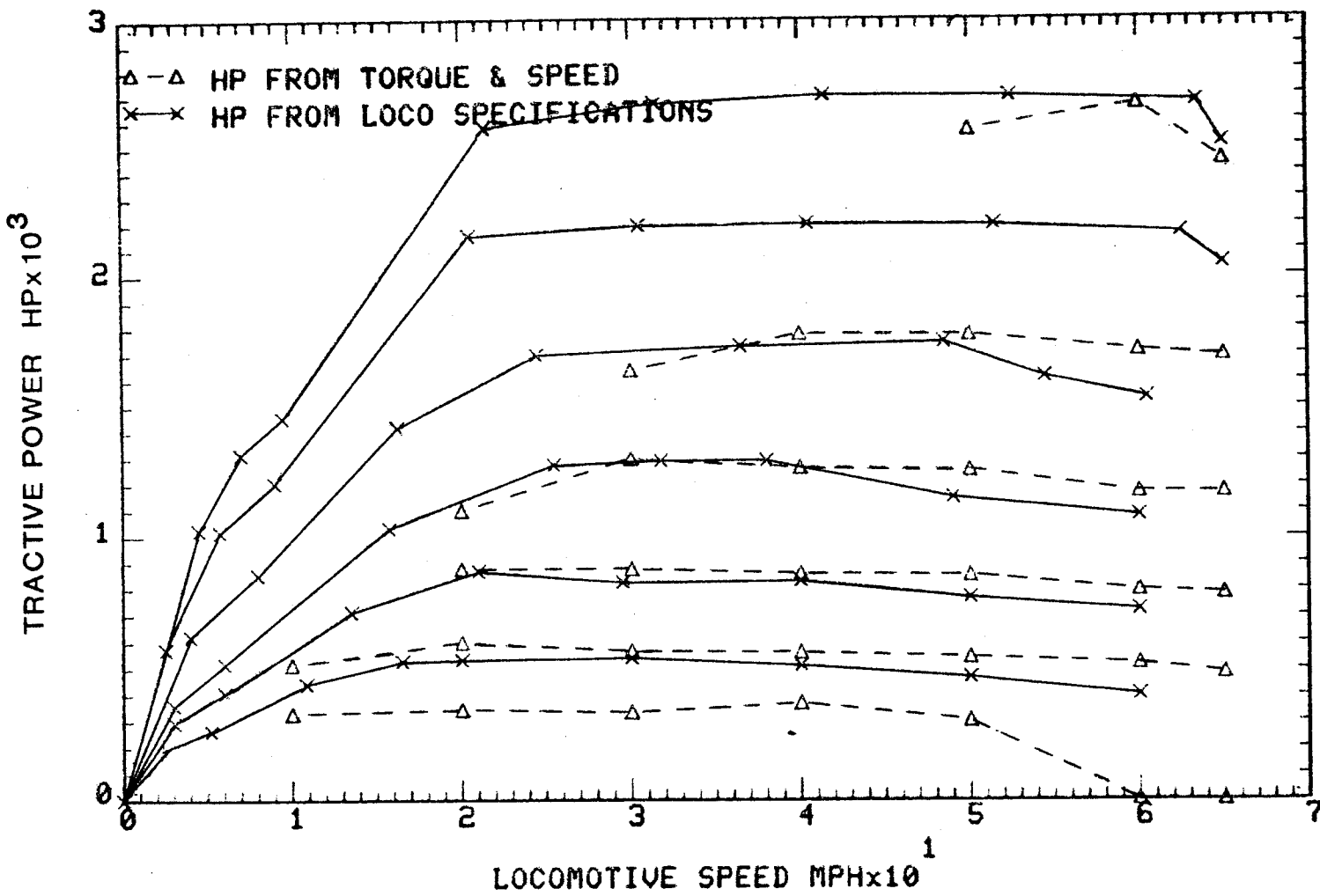


FIGURE 3-7. LOCOMOTIVE HP FROM TEST DATA AND SPECIFICATIONS.

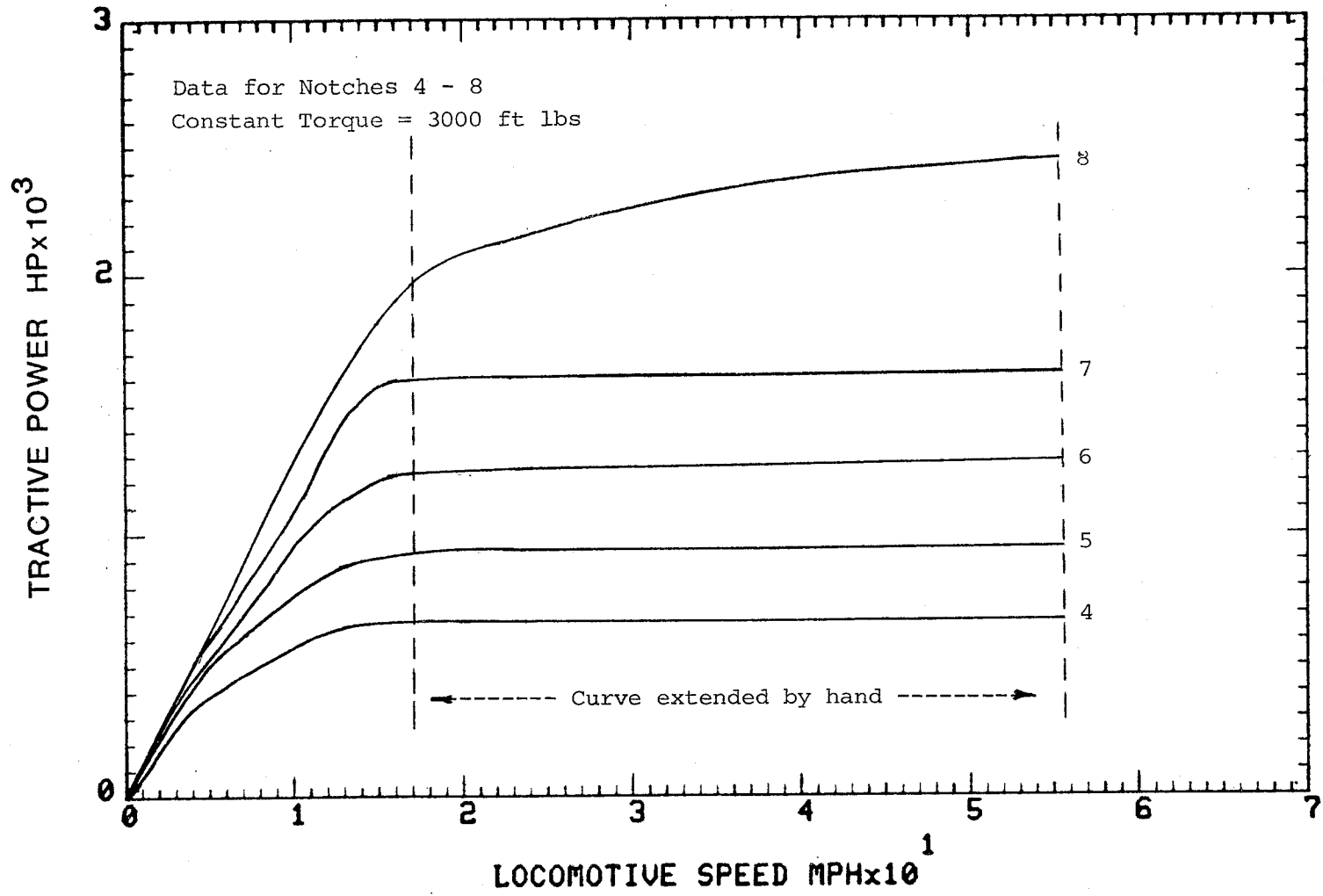


FIGURE 3-8. TRACTIVE POWER HP CALCULATED FROM SPEED IN CONSTANT TORQUE MODE.

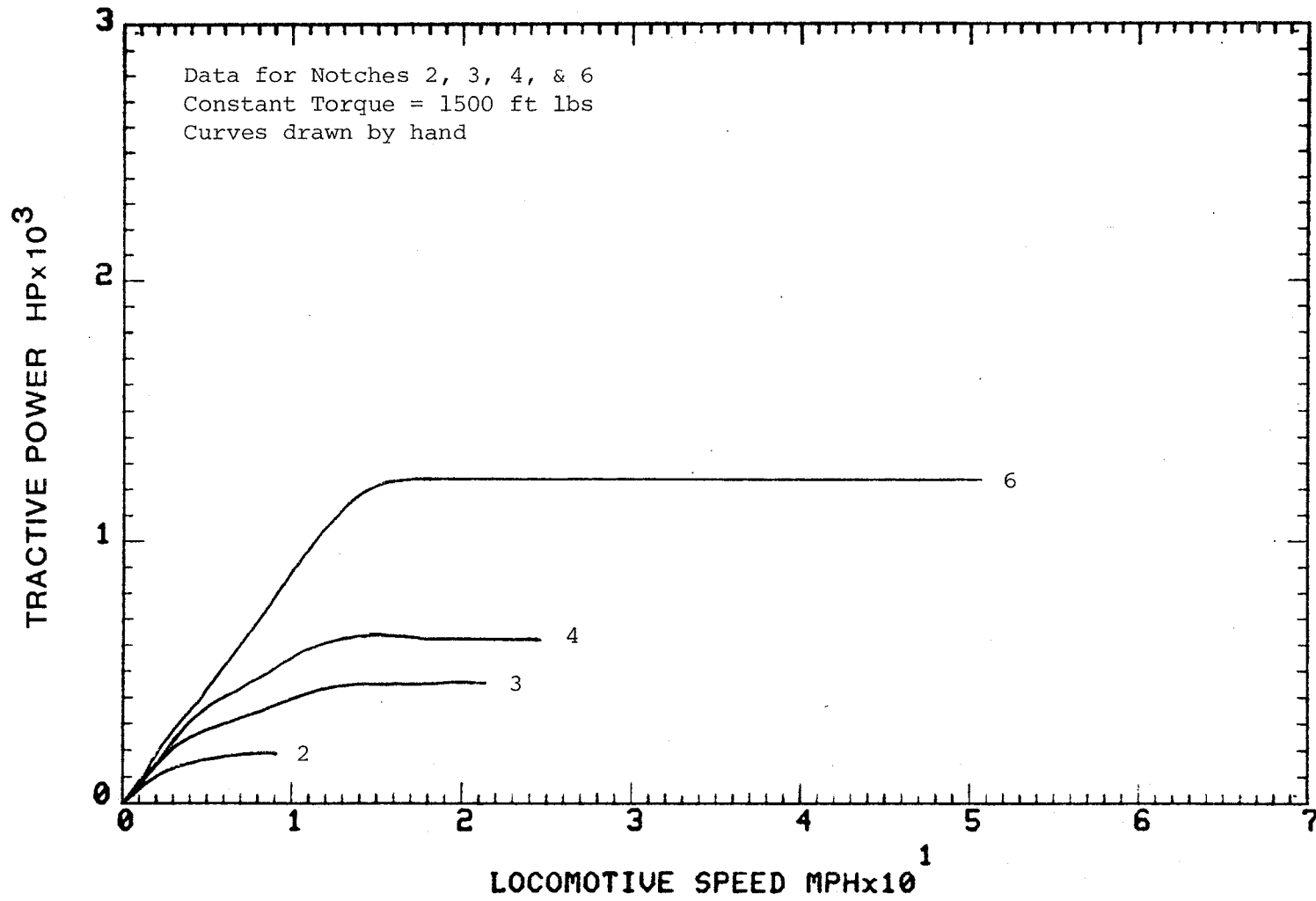


FIGURE 3-9. TRACTIVE POWER HP CALCULATED FROM SPEED IN CONSTANT TORQUE MODE.

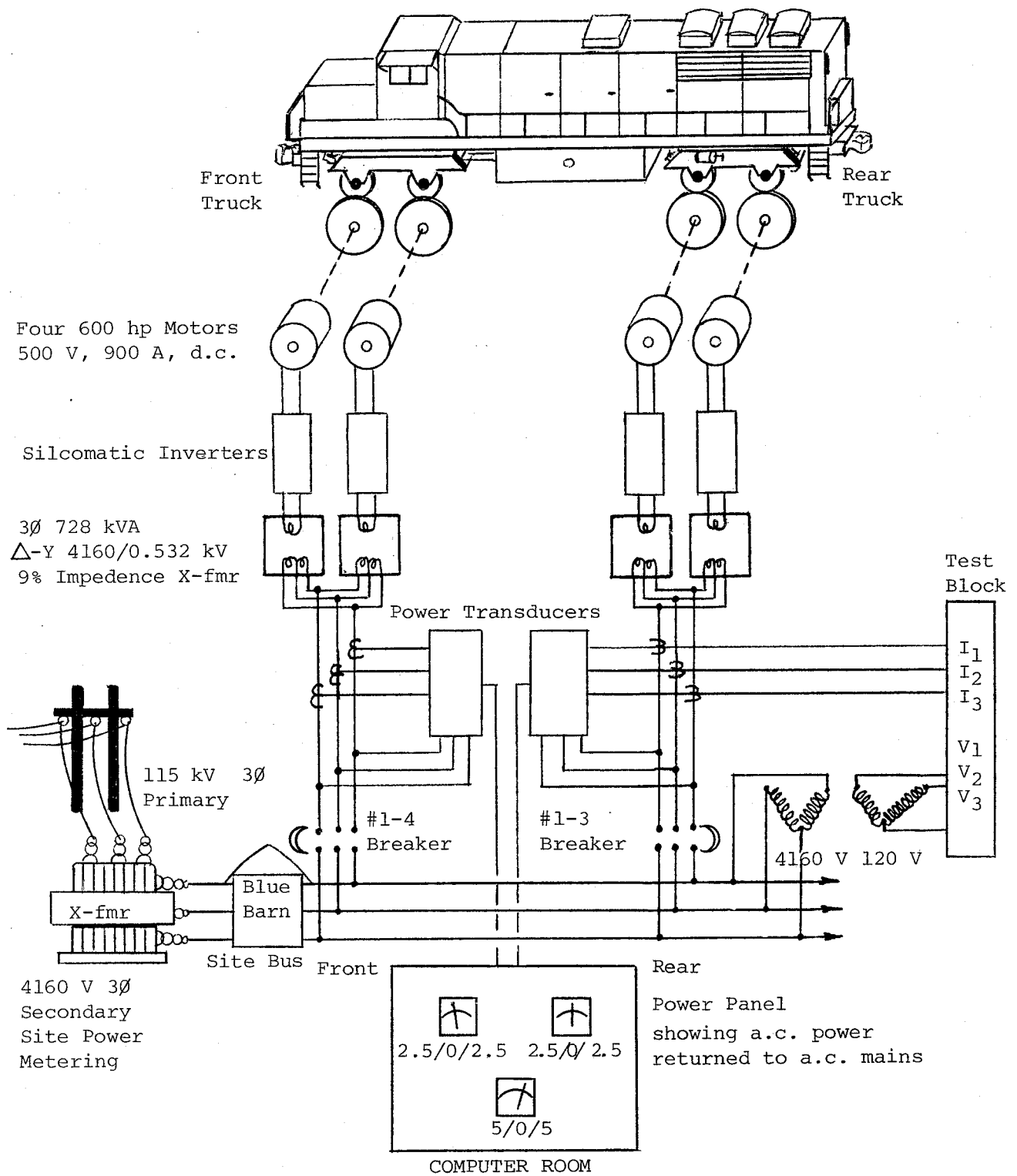


FIGURE 3-10. POWER SYSTEM SCHEMATIC.

efficiency ratio of the RDU mechanical drive and electrical conversion system. The locomotive tractive power is defined as the power absorbed by the RDU rollers from the locomotive wheels.

Figure 3-11 shows the flow of power in the dynamometer mode and indicates the location of power flow sensors. Data on the roller friction and windage losses was obtained from coast down tests with and without the locomotive (see paragraph 3.2). Auxiliary power for the four Power Control Rooms was measured at 113 kW. This data was taken on the incoming feeder watt transducer prior to RDU startup. It should be noted that the auxiliary power is not measured by the RDL Substation instrumentation when the RDU is in the regeneration mode.

3.4.2 Power Measurement Locations

- a. Power at Drawbar. As the locomotive wheels turn the RDU rollers, they exert a drawbar force on the longitudinal restraint rods that secure the locomotive longitudinal position on top of the roller assemblies. The longitudinal restraints are equipped with strain gauges to measure the drawbar force but for this test were monitored on a low resolution meter (see paragraph 2.3.8). Thus, the drawbar force could not be considered to be an accurate measurement. The power at the drawbar was calculated from the drawbar force and the equivalent locomotive road speed. For the purpose of this analysis, all power is expressed in kilowatts.
- b. Power at Torquemeter. The torquemeters are located directly at the d.c. motor output shafting, so in the regeneration mode they measure generator input torque. Each torquemeter has its own digital readout in pounds feet and an analog electrical output for computer logging. The data was manually recorded for the power generation test. The d.c. generator input power was calculated from the motor/generator torques and speeds.
- c. Power Output of Generators. The d.c. generator armature currents and voltages are indicated on wide scale instruments and were manually recorded for this test. Motor field currents are supplied as part of the auxiliary power and are, therefore, not taken into account in the d.c. generator process. The generator power is calculated from the products of the armature current and voltage.
- d. A.C. Power by Watthour Meters. Feeders #1-3 and #1-4 in the Blue Barn are equipped with watthour meters. The original purpose of these devices was to measure energy flowing to the RDU Silcomatic controllers. During this test, the power flow was reversed so these meters rotated in reverse direction, subtracting kilowatt hours of energy from their registers. Watthour meters can be used to measure power flow by timing the rotation of the disc for one revolution. The meter gearing is simply used to integrate the number of revolutions for the month by totalizing. For the purpose of this test the total a.c. power was measured by timing the rotation of the two watthour disks.
- e. A.C. Power by Watt Transducer. A watt transducer is connected in series with each watthour meter in Feeders #1-3 and #1-4 in the Blue Barn. A watt transducer is a solid state device using two Hall Effect transducers that effectively multiply the instantaneous a.c. voltage and instantaneous a.c.

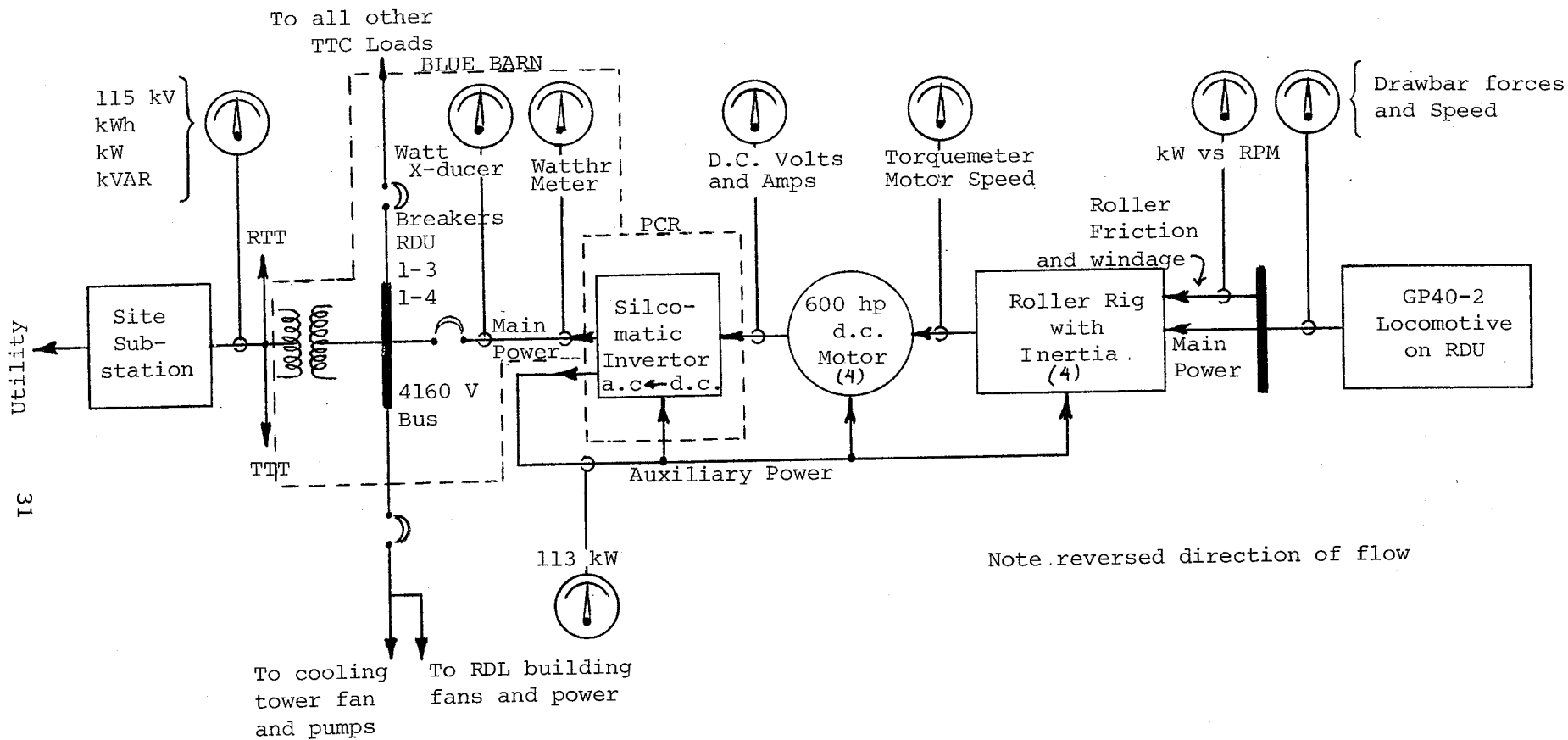


FIGURE 3-11. POWER FLOW IN DYNAMOMETER MODE (CONSTANT SPEED).

current to produce a d.c. voltage proportional in power flow. Output voltage thus changes from positive to negative as the RDU changes from the motoring mode to the generating mode. The two outputs of the watt transducers can be summed by connecting their outputs in series. The power was measured directly by reading the transducer output voltage and multiplying by a scaling factor.

- f. A.C. Power by Site Load Decrease. Since the power from the RDU flows back into the TTC site bus, it reduces the power flowing to the TTC from the utility company's power line. This reduction was measured by taking the disk timing before and during each test. The site load was assumed to be constant during this time interval, an assumption made possible by temporarily halting other major electrical power consuming tests on site while the measurements were being made. Other minor site loads varied, but the net site power from the utility agreed quite closely with the RDU output.

The site power is metered by conventional watthour meters and is therefore susceptible to the same errors as the watthour meters on the RDU feeders as discussed in paragraph 3.4.3.

3.4.3 Correction of Watthour Meter for RDU Waveshapes

A comparison of the two a.c. power metering systems in the Blue Barn is presented in Figure 3-12. Each data point indicates a power measured simultaneously by the two systems during early test runs. The question naturally arises as to which is correct. While the probable answer is that both systems are subject to errors, the watt transducer is technically more accurate and its data correlates better with the other data from the torquemeter and d.c. motor. Therefore, it was used for the measurement of a.c. power.

The problem of a.c. power measurement inaccuracies was discussed with Westinghouse Applications Engineers, since both devices were manufactured by that company. They advised that special instrumentation is required whenever voltages and currents are noticeably distorted, especially at low power factor (a large phase angle exists between the two signals). Both conditions exist with the Silcomatic output power. Watthour meters are extremely accurate with time and over 1000:1 range in current loads, but their design requires good sinusoidal waveshapes and good power factor. Due to their principle of operation, watt transducers are fundamentally better suited to measure the "noisy" Silcomatic output power. If required for testing, the power measurement problem will be studied to improve the measurement accuracy of the distorted, low power factor currents and voltages from the Silcomatic. It should be noted that, due to the filtering effect of the site distribution system, the watthour meters at the site substation were not subject to the same errors.

3.4.4 Errors in Reading the Test Data

During the power generation test, the RDU was operated in the Speed Mode of control where the same reference signal was sent to each of the four controllers. The speed control loop is a very tight servo system in which small speed variations can result in large corrective power flows for short intervals. This leads to difficulty in resolving the readings on the analog and digital meters. Many of the manual readings were visual averages of the meter display which should be considered in the interpretation of the following data tabulations.

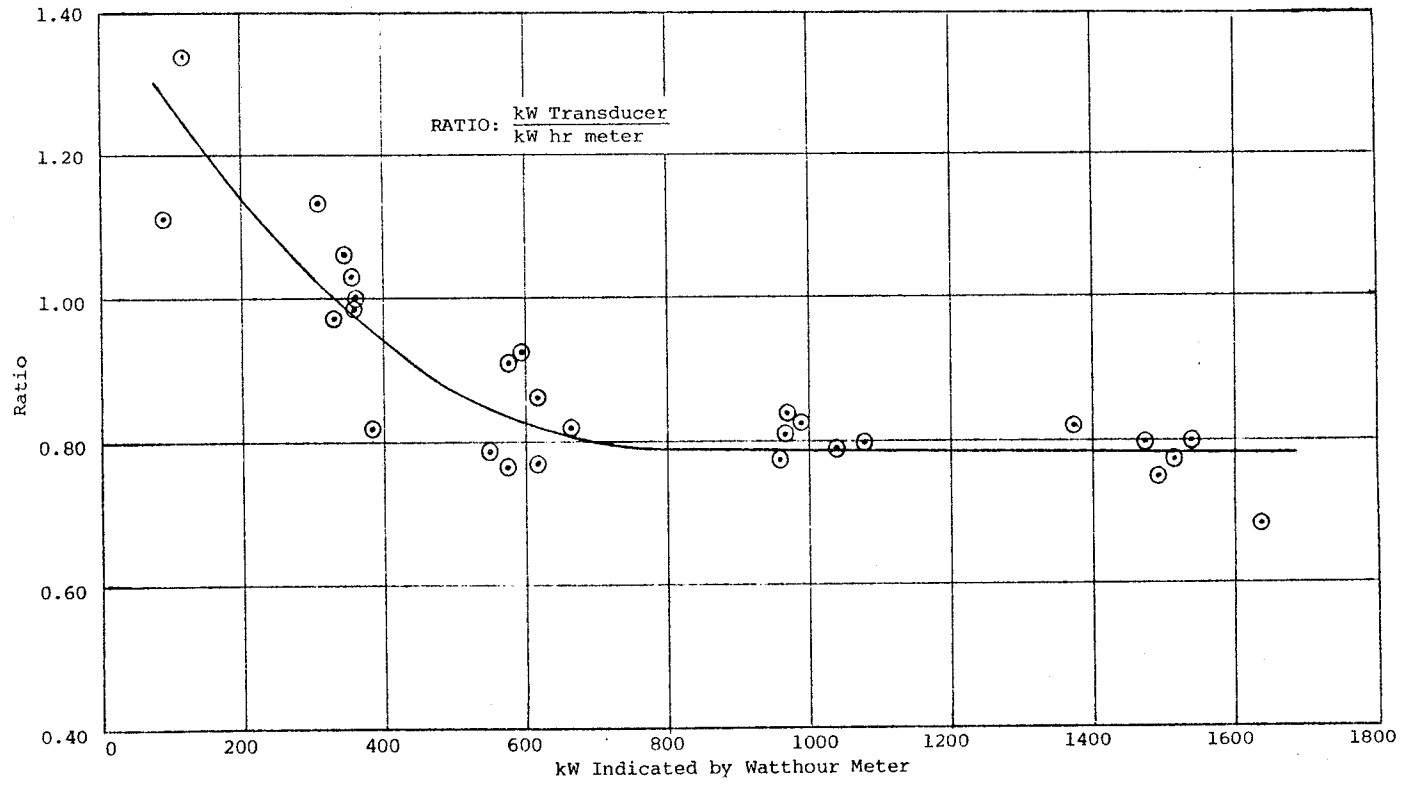


FIGURE 3-12. COMPARISON OF TRANSDUCERS AT SILCOMATIC OUTPUT.
(REGENERATION MODE: RDU TO A.C. BUS.)

3.4.5 RDU Power Flow Test Results

The power flow data for five typical characterization tests are listed in Table 3-2 for which complete test data was taken. The same data is presented in the form of performance ratios in Table 3-3 with the torquemeter power readings as reference. It should be noted that the torquemeter and motor speed readouts were considered to be the system's prime instrumentation. Due to uncertainties in the drawbar force measurements, the tractive power at the locomotive wheels was calculated by adding the drive train losses to the torquemeter power data. The actual drawbar force readings were used as a data check only.

The columns in Table 3-2 are as described below.

- Column 1 is the calculated tractive power derived from the difference in the two drawbar forces and speed. This data is used for comparison purposes only.
- Column 2 details the friction and windage losses of the roller rig obtained from Figure 3-3, Section 3.2 for the equivalent locomotive speed.
- Column 3 is the calculated tractive power obtained by adding friction and windage losses (Column 2) to the torquemeter power (Column 4).
- Column 4 is the power transmitted by the torquemeters to the motors, calculated from the torquemeter and speed readings. This data is considered to be the prime measurement of dynamometer power.
- Column 5 is the product of the four generator voltages and currents.
- Column 6 is the calculated power returned to the 4160 V feeders by the RDU as measured by the watt transducers.
- Column 7 is the estimated service power to the RDU derived from average measurements taken during standstill. The RDU lubrication and cooling loads (113 kW) are derived from the PCR 4160 V busbar and are, therefore, not included in the watt transducer measurements. The building cooling and exhaust removal fan power (75 kW) is derived from a separate 4160 V busbar in the "Blue Barn" and is therefore metered by the watt transducer in the regeneration mode.
- Column 8 is the calculated Silcomatic power output derived from Column 6 plus the 113 kW auxiliary power tapped off directly before being metered. These data are used to calculate Silcomatic efficiency in Table 3-3.
- Column 9 is the RDU system power output that is fed back into the 4160 V busbar and the TTC site loads. It is derived by subtracting the 75 kW building load from the power in Column 6.
- Column 10 is the observed decrease in power flow from the electric utility to the TTC during each test.

TABLE 3-2. POWER FLOWS.

COLUMN	1	2	3	4	5	6	7	8	9	10
LOCOMOTIVE DATA	DRAWBAR	LOSSES	CALC	TORQUEMETER	D.C. MOTOR	A.C. WATT	ESTIMATED	SILCOMATIC	RDU SYSTEM	SITE kW
SPEED	THROTTLE	POWER	F&W	TRACTIVE POWER	OUTPUT	OUTPUT	SERVICE POWER	OUTPUT	OUTPUT	DECREASE
MPH	NUMBER	kW	kW	kW	kW	kW	AUX FANS (kW) & BLOWERS (kW)	kW	kW	kW
50	8	2061	168	1962	1794	1618	113 75	1339	1151	1046
60	7	1562	227	1324	1097	1052	113 75	877	689	821
60	8	2344	227	1975	1748	1662	113 75	1348	1160	1127
65	7	1763	254	1463	1209	1180	113 75	953	765	903
65	8	2468	254	1840	1586	1536	113 75	1247	1059	1020

RDU CHARACTERIZATION TEST RESULTS
 TEST DATE: 3/1/83

TABLE 3-3. PERFORMANCE RATIOS.

COLUMN	1		2		3		4		5		
LOCOMOTIVE DATA		TORQUE POWER		D.C. OUTPUT		CORRECTED kWh		SILCOMATIC		RDU OUTPUT	
SPEED	THROTTLE	TRACTIVE POWER		TORQUE OUT		WATT OUT		D.C. OUT		DRAWBAR INPUT	
MPH	NUMBER	RATIO		RATIO		RATIO		RATIO		EFFICIENCY	
50	8	0.914		0.902		0.975		0.827		58.7%	
60	7	0.829		0.959		0.966		0.834		52.0%	
60	8	0.885		0.951		0.968		0.811		58.7%	
65	7	0.826		0.976		0.973		0.808		52.3%	
65	8	0.862		0.968		0.960		0.812		57.6%	

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RDU CHARACTERIZATION TEST RESULTS
 TEST DATE: 3/1/83

Figure 3-13 is a graphical presentation of Table 3-2, corresponding to the power flow diagram, Figure 3-11. The data in Table 3-3 is the efficiency of the regeneration process as measured by the instrumented system. The data is defined as follows:

- Column 1 is the efficiency ratio of the mechanical drive train, reflecting the friction and windage losses (obtained from Table 3.2, Column 4/Column 3).
- Column 2 is the efficiency of the d.c. motor as a generator excluding field losses which are included in the auxiliary power (see Figure 3-11) (obtained from Table 3.2, Column 5/Column 4).
- Column 3 is the power measured by the watthour meter, corrected by the curve Figure 3-12, divided by power measured by the watt transducer. This data is not a measure of system efficiency, but is a measure of agreement of the two measurement systems. The watt transducer was used as the prime a.c. measurement system.
- Column 4 is the efficiency of the Silcomatic operating as an inverter (obtained from Table 3-2, Column 8/Column 5).
- Column 5 is the calculated overall efficiency of the RDU in the regeneration mode at the higher notch settings of the locomotive expressed in terms of the power returned to the site utility as a ratio of the locomotive tractive power (obtained from Table 3.2, Column 9/Column 3).

The overall efficiency of the regeneration process at the higher locomotive notch positions is in excess of 50% and demonstrates that the RDU can perform as an energy efficient test facility for locomotive testing. Some of the data relative to the individual stages of the conversion process is suspect. The measured Silcomatic converter efficiency of 81% appears to be low since the inherent efficiency of a thyristor rectifier system normally exceeds 90%. This observation is supported by the lack of heat dissipation in the thyristor cooling system, where excessive Silcomatic losses would appear as heat. It is probable that the cause of the measurement error is in the a.c. transducer system which would also adversely affect the overall efficiency data. Since the measurement of the a.c. power output is not vital to the basic operation of the RDU as a dynamometer, further development of an accurate a.c. measurement system is probably not justified.

3.4.6 Line Power Flow for Locomotive Speed and Notch Positions

Line power flow for various locomotive speeds and notch positions is an important characteristic since the previous tests detailed only the upper range of continuous dynamometer performance. Figures 3-14 and 3-15 show line power flow from idle to notch 8 over the range of acceptable RDU performance. Note that the locomotive does not regenerate into the line power until notch 3 is reached. Up to this point the locomotive is furnishing some of the RDU roller rig losses reducing the line power flow into the RDU with each advance of the throttle. Above notch 3 the locomotive power supplies all the losses and the power flow reverses so that the locomotive decreases the site electrical load.

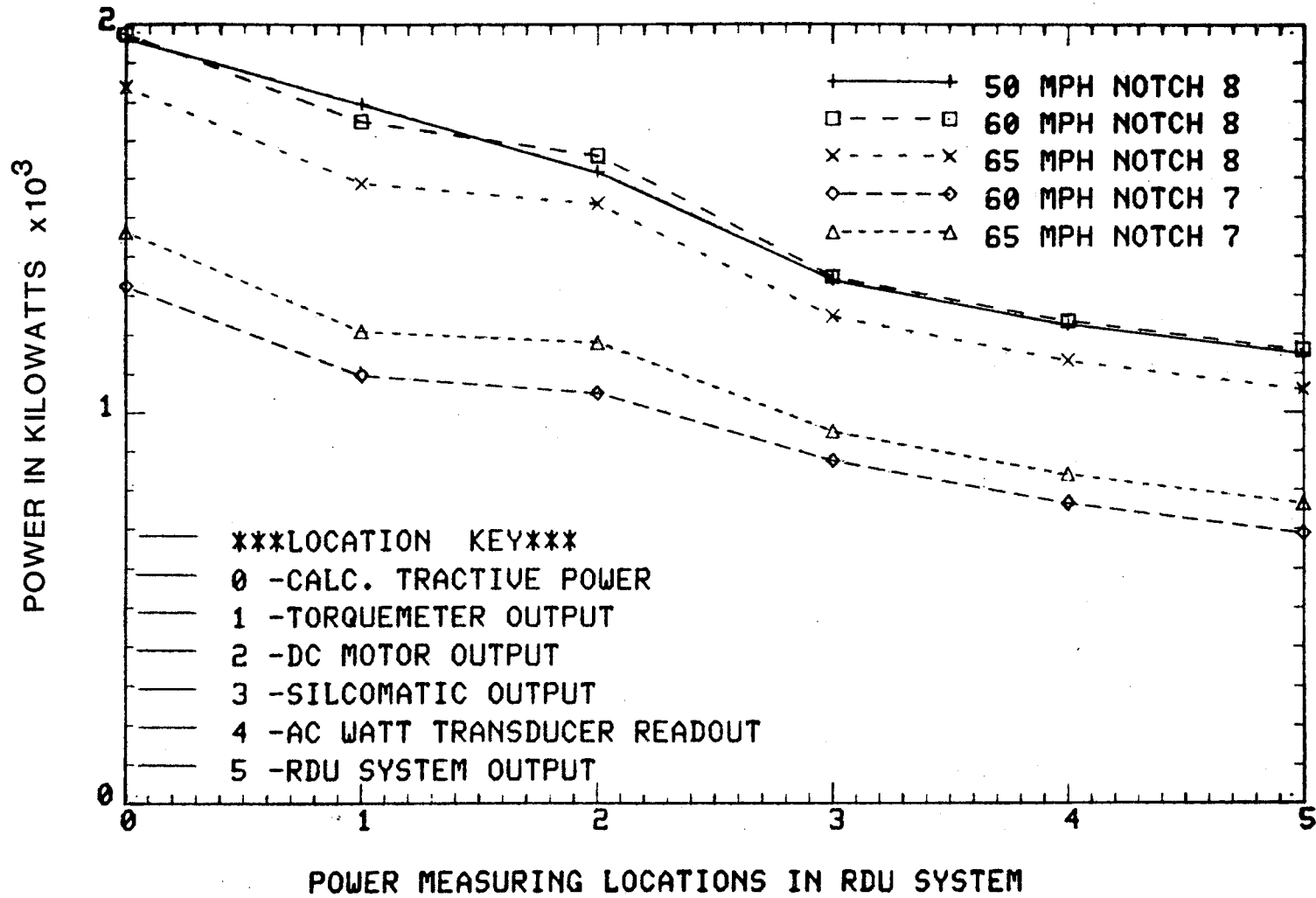


FIGURE 3-13. RDU POWER FLOW.

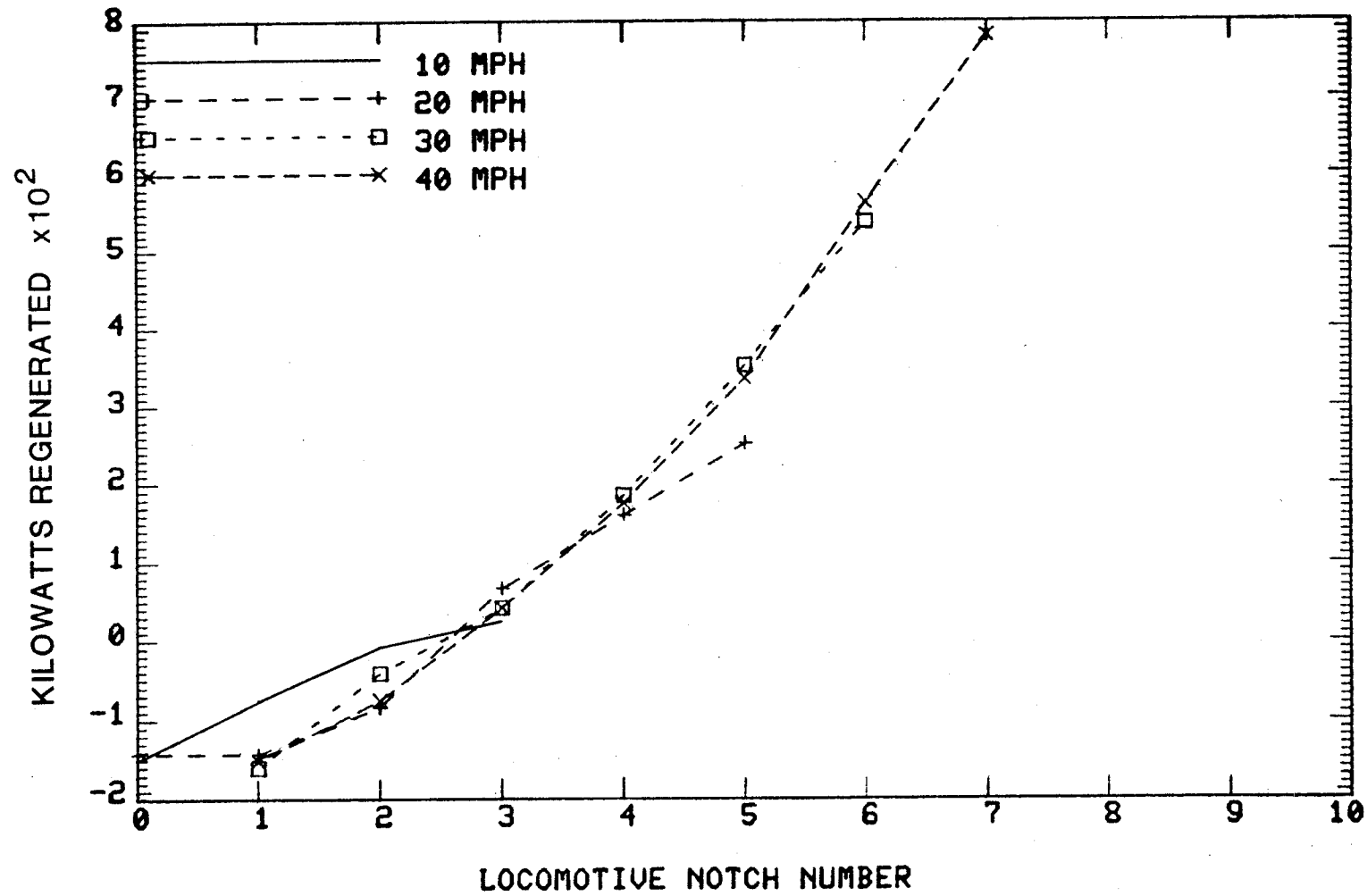


FIGURE 3-14. NET LOCOMOTIVE POWER OUTPUT MEASURED AT THE 4160 V BUSBAR (LOWER SPEEDS).

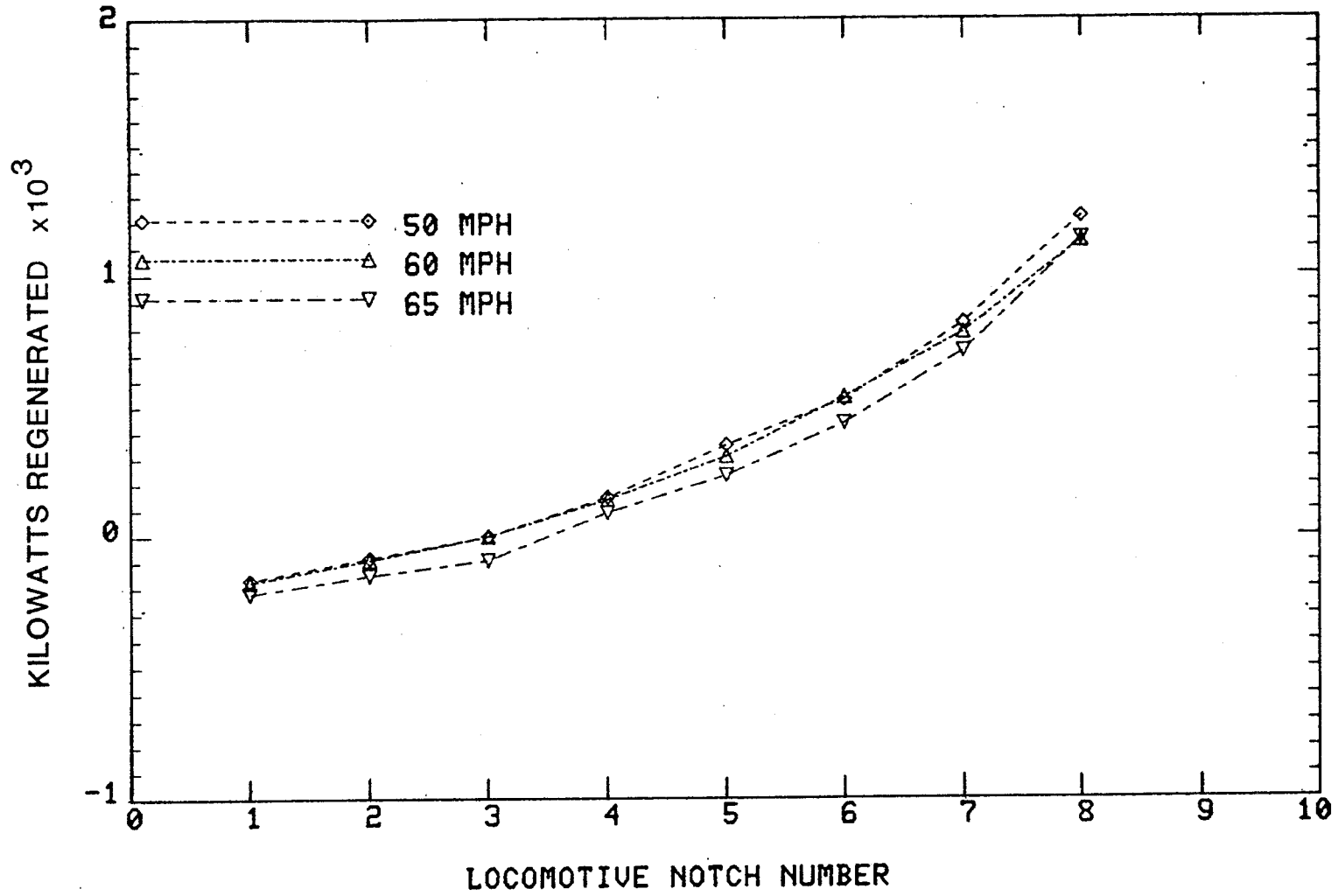


FIGURE 3-15. NET LOCOMOTIVE POWER OUTPUT MEASURED AT THE 4160 V BUSBAR (HIGHER SPEEDS).

The data presented in Figures 3-14 and 3-15 is limited by the ability of the RDU to accept power at low speeds, since the motor power rating below 1000 rpm is proportional to speed.

Table 3-4 lists the test data for power flow, feeder current and RDU feeder power factor. Negative power factor indicates motoring; positive indicates generation. When regeneration merely supplies the losses, the feeder power is zero so power factor changes sign. Obviously, the RDU-locomotive system has a much smoother power factor characteristic than the data listed in the table, and the true power factor probably does not exceed 70% at the maximum regeneration power level. Most of the RDU dynamometer operation is at poor power factors. This was confirmed by noting the increase in TTC site Volt Ampere Reactive (VAR) meter disc rotation during the March 1, 1983 detail power flow test. However, due to the algorithm used by the utility company to calculate the power factor (see equation below), the poor power factor caused by the RDU is insignificant unless multi-shift operation were to take place and the locomotive were to be operated at high notch settings for extended periods.

$$\text{Monthly Power Factor} = \frac{\text{Monthly kW hrs}}{\sqrt{(\text{Monthly kW hrs})^2 + (\text{Monthly kVAR-hrs})^2}}$$

3.4.7 Quality Of Electric Power Generated

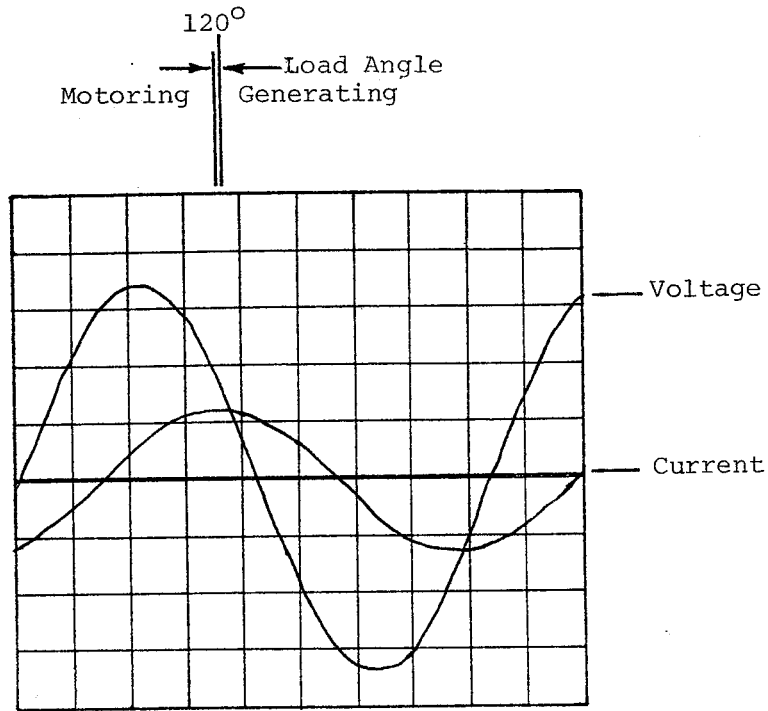
Another major objective of the RDU dynamometer test was to determine the impact of the regenerated electric power on other TTC electric users and on the source electric utility. By reference to earlier utility contracts, the new electric utility billing schedule, adopted October 1982, allows the TTC to generate electricity and return it to the utility power line. However, the watt-hour meter used for billing has a detent mechanism so designed that any power generated in excess of site demand will flow to the utility free of charge--such generation will not decrement the meter register. Although the intent of testing is not to generate site power, per se, the return power agreement does provide the TTC with a dumping ground for any power over our usage. This is valuable on second shift testing when the RDU could easily generate more than the site power usage.

The TTC site power has to meet several criteria relative to the quality of power used, or generated. The site electric power is supplied with a conventional penalty factor clause which decreases the site demand cost for good power factor above 85% and penalizes the demand cost for less than 85% power factor. Thus, the basic commutation process of inverters requiring a source of 90° current to the voltage is a penalty on the costs of testing on the RDU. This problem can be alleviated by the use of phase correction capacitors, but for these tests no attempt was made to improve the already high site power factor by adding capacitors due to the short duration of the tests. For extended RDU testing, the cost penalty could be significant and the use of capacitors may be appropriate.

Another concern relative to the quality of the generated power is the harmonic content of the current and voltage waveshapes. To monitor the site power, oscilloscope waveform pictures were taken at various loads, and a spectrum analyzer was used to measure the component of voltage or current at each frequency up to 1 kHz (16th harmonic = 960 Hz). Figures 3-16a through 3-16g are a series of seven photographs of waveforms and their corresponding spectrum

TABLE 3-4. LOCO TESTS ON RDU FEB 22, 1983 (GP40-2)

LOCO NOTCH #	SPEED	A.C. LINE kW	A.C. LINE AMPS	A.C. LINE POWER FACTOR
0	0	-50	30	-23%
0	10	-151	36	-58%
1	10	-76	48	-22%
2	10	-8	84	-1%
3	10	+25	162	+2%
0	20	-143	48	-41%
1	20	-143	48	-41%
2	20	-84	60	-19%
3	20	+67	102	+9%
4	20	+160	156	+14%
5	20	+252	168	+21%
1	30	-160	30	-74%
2	30	-42	30	-19%
3	30	+42	72	+8%
4	30	+185	102	+25%
5	30	+353	180	+27%
6	30	+538	210	+35%
1	40	-151	36	-58%
2	40	-76	24	-44%
3	40	+42	36	+16%
4	40	+176	72	+34%
5	40	+336	108	+43%
6	40	+563	156	+50%
7	40	+781	216	+50%
1	50	-168	30	-78%
2	50	-84	24	-48%
3	50	0	24	0
4	50	+151	48	+44%
5	50	+353	84	+58%
6	50	+529	114	+64%
7	50	+823	162	+70%
8	50	+1218	240	+70%
0	60	-176	-	-
1	60	-176	48	-51%
2	60	-92	36	-36%
3	60	0	30	0
4	60	+142	36	+55%
5	60	+310	60	72%
6	60	+538	96	78%
7	60	+787	132	83%
8	60	+1126	156	95%
1	65	-221	48	-63%
2	65	-151	30	-70%
3	65	-92	30	-42%
4	65	+92	30	+42%
5	65	+235	54	+60%
6	65	+437	86	+71%
7	65	+714	150	+66%
8	65	+1134	192	+82%



SPEED: 0
 THROTTLE: Idle
 POWER: Motoring, 100 kW

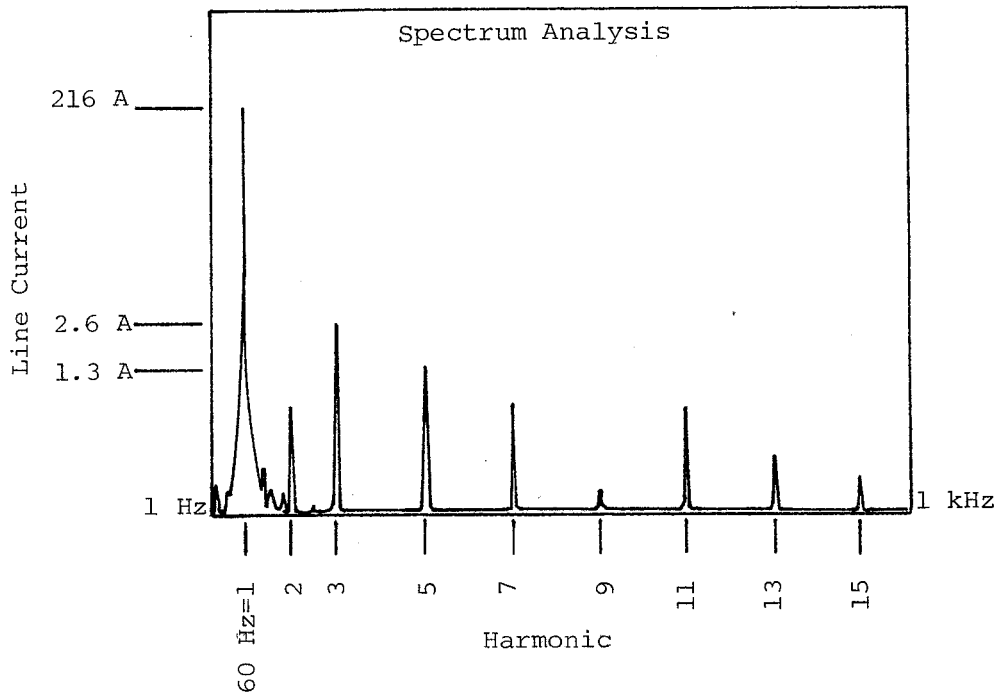
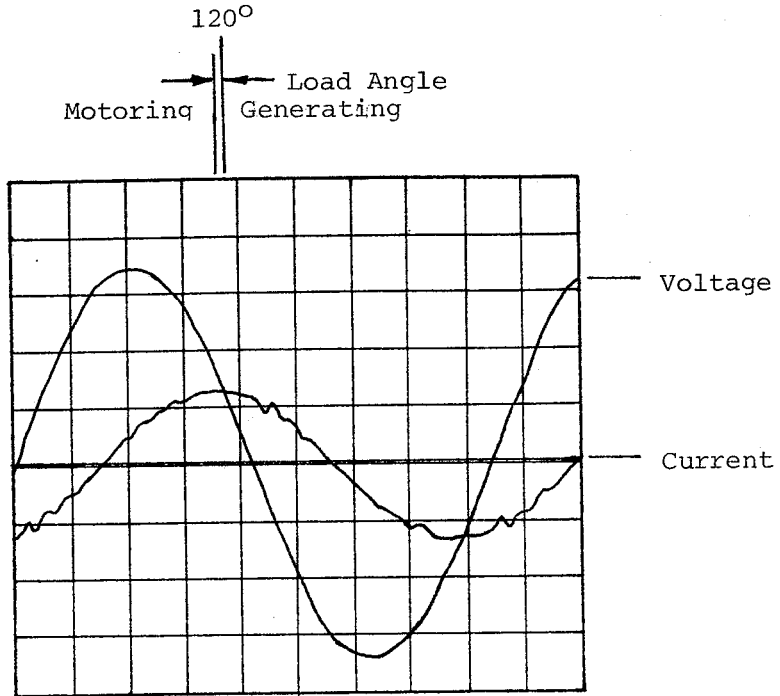


FIGURE 3-16a. EFFECT ON CORE AREA LOAD, (RDU AUXILIARIES ONLY).



SPEED: 60 mph
 THROTTLE: Idle
 POWER: Motoring, 244 kW

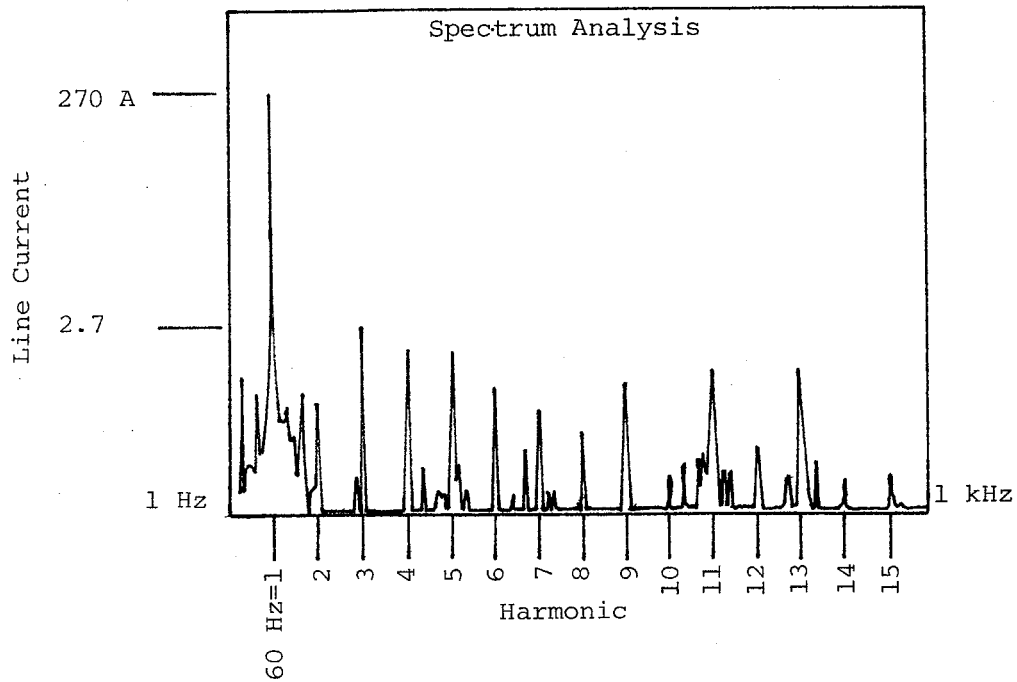
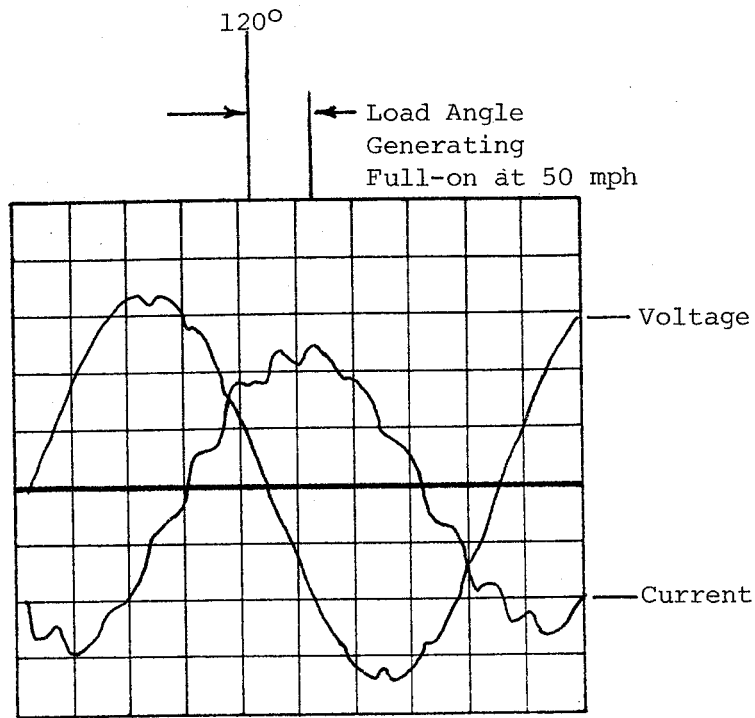


FIGURE 3-16b. EFFECT ON CORE AREA LOAD, (60 MPH, IDLE).



SPEED: 50 mph
 THROTTLE: Notch 8
 POWER: Generating, 1226 kW

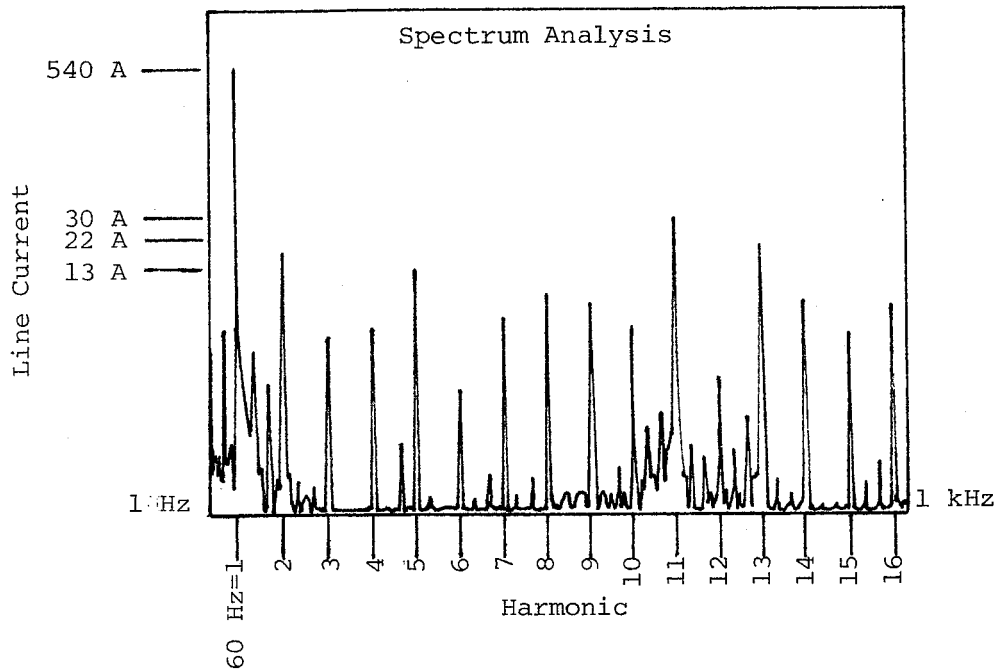
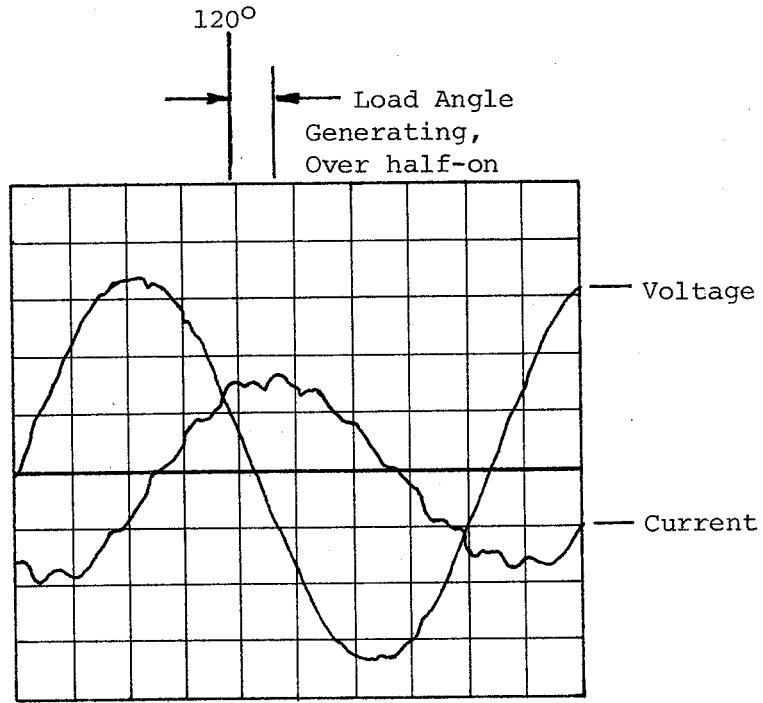


FIGURE 3-16c. EFFECT ON CORE AREA LOAD, (50 MPH, NOTCH #8).



SPEED: 60 mph
 THROTTLE: Notch 7
 POWER: Generating at 764 kW

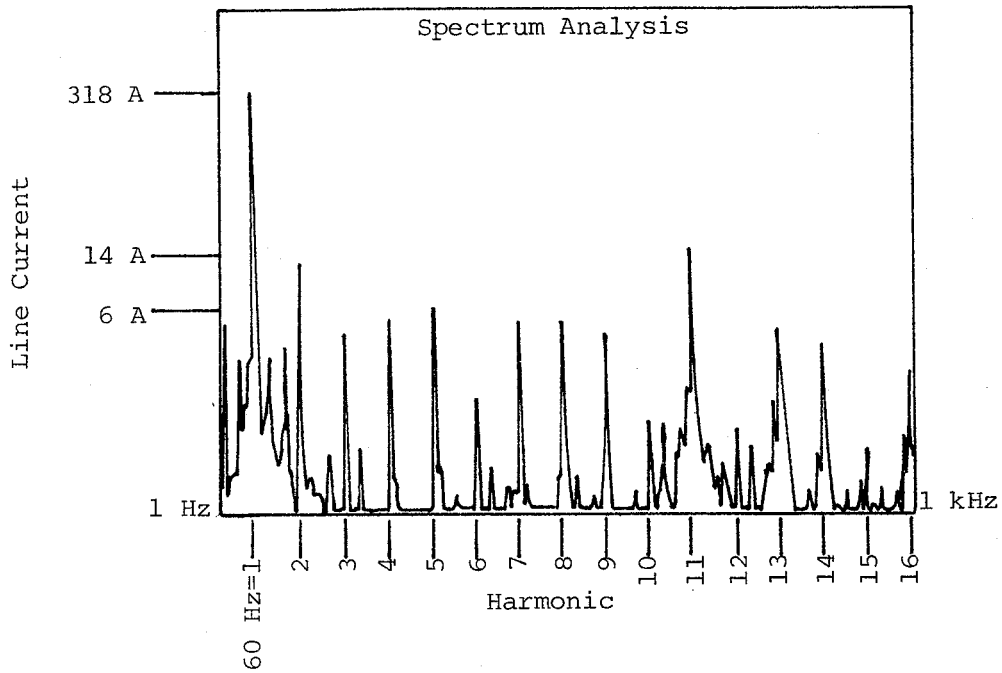
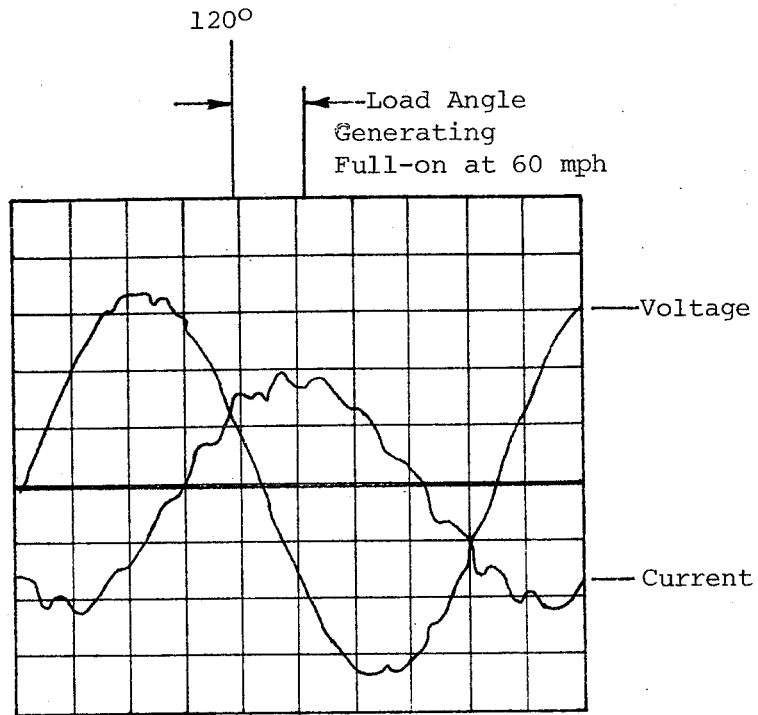


FIGURE 3-16d. EFFECT ON CORE AREA LOAD, (60 MPH, NOTCH #7).



SPEED: 60 mph
 THROTTLE: Notch 8
 POWER: Generating at 1235 kW

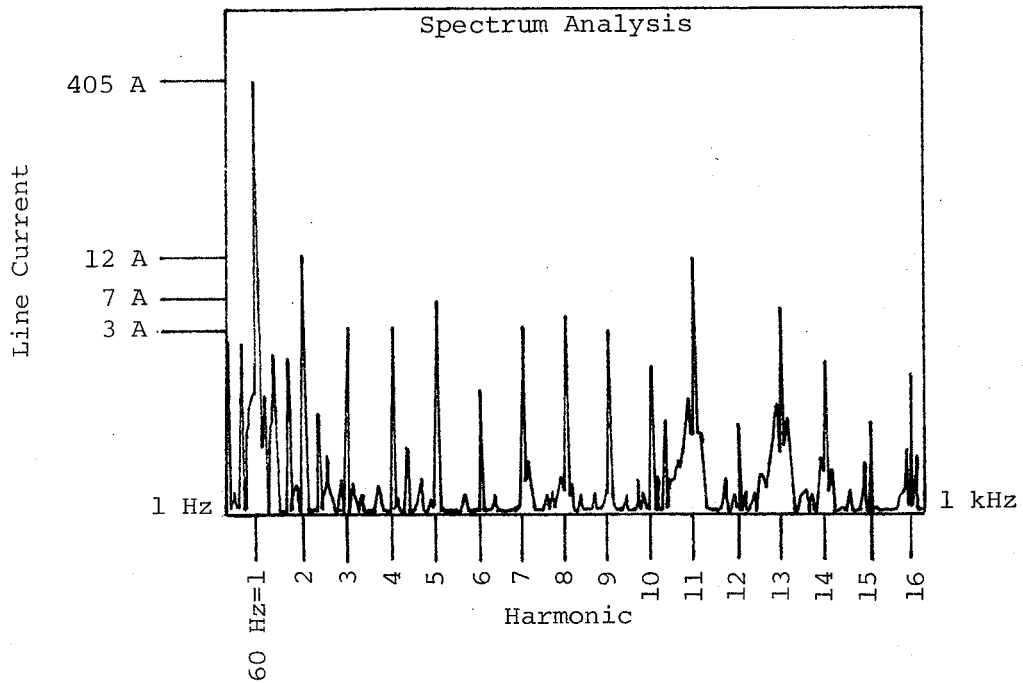
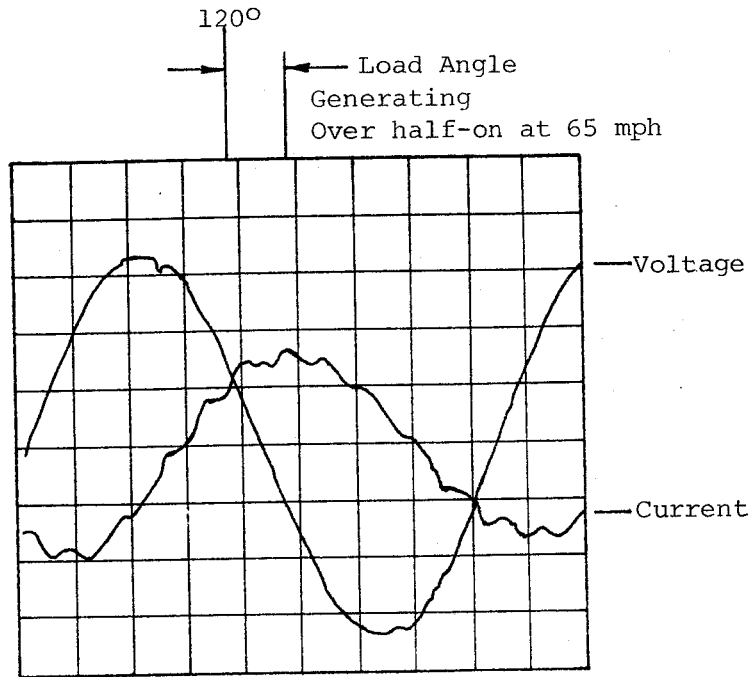


FIGURE 3-16e. EFFECT ON CORE AREA LOAD, (60 MPH, NOTCH #8).



SPEED: 65 mph
 THROTTLE: Notch 7
 POWER: Generating at 840 kW

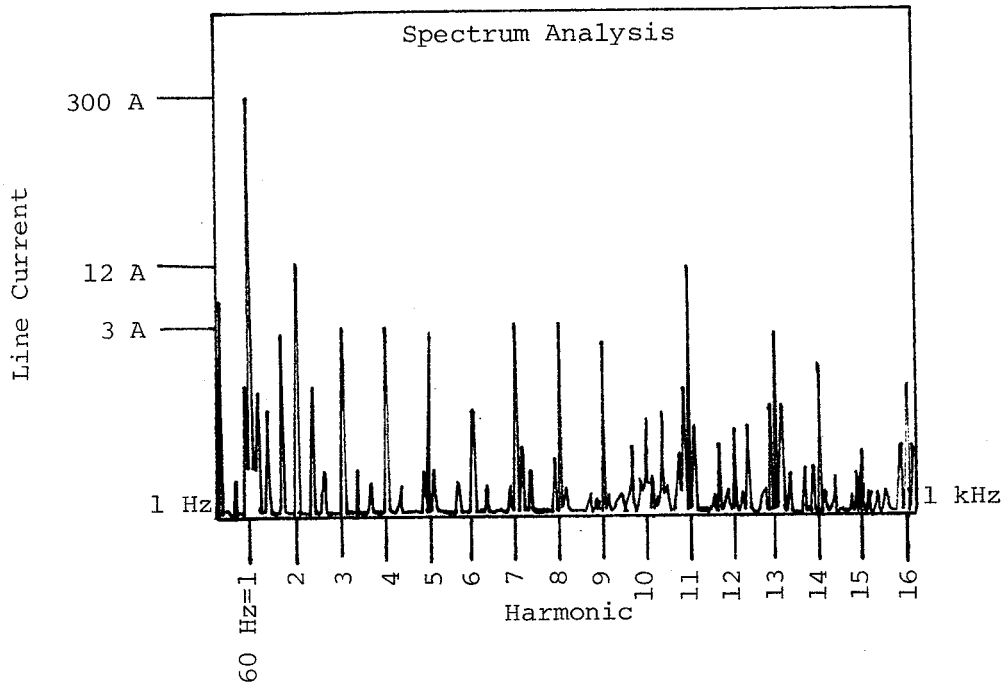
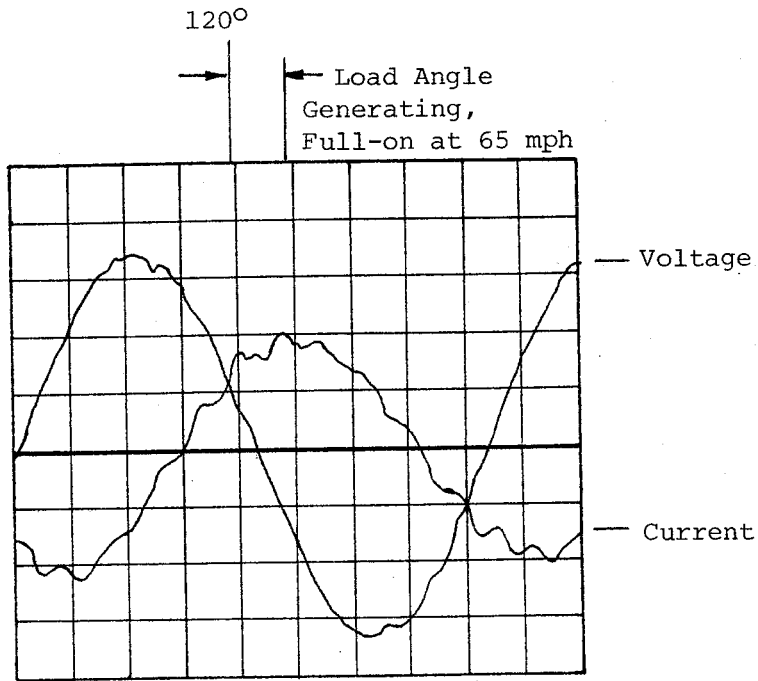


FIGURE 3-16f. EFFECT ON CORE AREA LOAD, (65 MPH, NOTCH #7).



SPEED: 65 mph
 THROTTLE: Notch 8
 POWER: Generating at 1134 kW

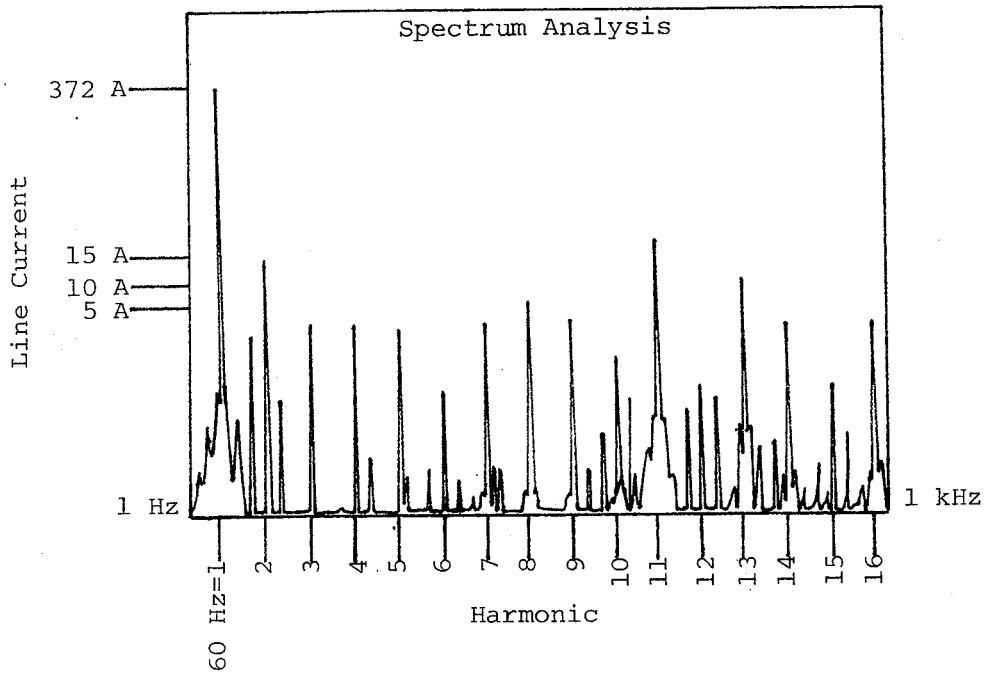


FIGURE 3-16g. EFFECT ON CORE AREA LOAD, (65 MPH, NOTCH #8).

analyses. The shifting of the current waveform relative to the voltage is identified to show the automatic action of the Silcomatic in power control. Since the voltage waveform is a phase-to-phase voltage, the power factor angle is not clearly evident, but as more power is transferred back into the system the phase angle is shown to increase. For this test the voltage and current were monitored on the 115 kV/4160 V 10MW transformer secondary winding to the 4160 V bus and not one of the RDU feeders.

The spectrum analyzer display is graduated in 10 decibels per horizontal line. Decibel displays are commonly used for such measurements, as they are logarithmic in nature allowing a very large dynamic range to be displayed. Approximate magnitudes of the current are listed to show that even relatively small current harmonics can effect the visible shape of the waveform, highlighting the effect.

To date, there have been no interference problems reported at the TTC or by the utility company resulting from the RDU operation. However, the installation of the new Digital Equipment Company VAX 11/780 computer system on the Operations Building 480 V, 3-phase power supply without a motor-alternator isolator will be closely monitored. A double shielded transformer will provide line to secondary spike attenuation, but the shield will have no effect on current spikes in the primary current source.

3.5 BRAKING TESTS

3.5.1 Objective

The purpose of these tests was to develop methods to safely evaluate the friction and dynamic braking systems of locomotives with the use of the RDU. These tests were to produce data which would be comparable to theoretical values and could be compared with other test data, if available.

3.5.2 Test Conduct

The tests performed followed two distinct methods of obtaining the same data. Test Method #1 consisted of acquiring speed decay data from different initial speeds while the RDU was in the coast mode and the locomotive was braking. The speed-time plot was differentiated to obtain the rate of change of speed, and the braking resistance data was calculated by using the following mathematical expression:

Brake resistance at the roller/wheel interface (lbs)

$$= I_R (2\pi \frac{\text{rps}}{\text{sec}}) \frac{1}{r}$$

where: I_R = Inertia - rollerside in ft lb-sec²

rps = revolutions per second

r = radius of the rollers in feet

Test Method #2 consisted of making the locomotive brakes work against the RDU drive trains which were set in the speed control mode at various pre-sel-

ected speeds. This was analogous to a locomotive putting out a brake resistance while going down a grade at a constant speed. The brake resistance in these tests was calculated from the RDU torquemeter recordings. Torque is force times lever arm (radius of rollers in feet), and, so, the braking force in pounds was calculated after converting the RDU motor torque to roller torque by multiplying by the gear ratio of 2.86.

Friction as well as dynamic braking test runs were performed, and a wet condition friction braking sequence was also carried out using both test methods for all cases.

The friction braking runs were conducted following these steps:

Method #1:

- a. The locomotive brakes were released.
- b. The RDU drive trains were run up to a speed of 10 mph and the RDU controls set in the coast mode.
- c. The locomotive air brakes were applied at $\frac{1}{4}$ service (15 psi) until the rollers came to a stop.
- d. Speed data was recorded digitally.
- e. Brake shoe temperatures were recorded and not permitted to rise above 600° F.
- f. Steps a. through e. were repeated for $\frac{1}{2}$ service (30 psi).
- g. Steps a. through f. were repeated for a speed of 20 mph.
- h. Water sprays were applied at the wheel/roller interface and steps a. through f. were repeated.

Method #2:

- a. The locomotive brakes were released.
- b. The RDU was set up in the speed control mode at 10 mph.
- c. The locomotive air brakes were applied at $\frac{1}{4}$ service.
- d. RDU drive train torques and speeds were recorded digitally at each steady condition of braking.
- e. Steps a. through d. were repeated for $\frac{1}{2}$ service brakes at speeds of 20 and 30 mph.
- f. Steps a. through d. were repeated for speeds of 20, 30 and 35 mph.
- g. Steps a. through f. were repeated with the water spray.

The dynamic brake test runs were conducted in a similar fashion, except that the dynamic range settings were: Range 2, 4 and 6, at speeds of 40 and 65 mph for Method #1 and Range 4 and 6, at speeds of 20, 30, 40, 50, 60 and 65 mph for Method #2. No water spray condition was conducted in the dynamic braking mode.

3.5.3 Test Results and Analysis

Figures 3-17 and 3-18 are plots of brake resistance in pounds with respect to locomotive speed in mph for $\frac{1}{4}$ (15 psi) and $\frac{1}{2}$ (30 psi) service friction air brake test runs from initial speeds of 10 and 20 mph respectively. Figures 3-19 and 3-20 are similar plots for the wet condition when the water spraying was present. All these plots from 3-17 to 3-20 represent test Method #1. The speed decay plot versus time was differentiated using a mid-point derivative technique and multiplied by the appropriate inertia term and other constants to obtain resistance in pounds.

Figure 3-21 is a plot which shows stopping distance for the four friction braking test runs in the dry condition. In this case the speed decay plot versus time was integrated using the trapezoidal technique, and total distance in feet was obtained.

Figure 3-22 is a similar plot for the wet (water spray) condition tests.

Figure 3-23 is a plot of brake resistance at the roller/wheel interface in pounds with respect to locomotive speed in mph. This data was obtained from the test runs using Method #2. Each data point was obtained from a steady state condition run at a given speed and friction service braking. The torque recordings were converted to force in pounds by appropriate manipulation, using the gear ratio and roller radius.

Figure 3-24, again, plots brake resistance in pounds with respect to locomotive speed, but is from the dynamic brake test runs. Ranges 2, 4 and 6 brake resistances are plotted for initial speeds of 40 and 65 mph. This data is from Method #1 test runs.

Figure 3-25 is a plot of braking resistance calculated from theoretical data made available from the AAR Train Operation Simulator (TOS) computer program.(2) Discrete values of resistances in pounds at discrete speeds in mph are plotted for Ranges 2, 4 and 6 of dynamic braking of a GP40-2 locomotive.

Figure 3-26 is a plot of resistance with respect to locomotive speed obtained from the Method #2 test runs using dynamic braking. Each point was obtained while a steady state condition of speed and range setting existed. Speeds of 20, 30, 40, 60 and 65 mph are plotted versus brake resistance in pounds for Range 4 and speeds of 20, 30, 40, 50, 60 and 65 mph for Range 6 dynamic brake settings.

Figure 3-27 is a plot of braking effort (pounds) with respect to speed in (mph) from the Locomotive Service Manual published by the EMD branch of GM.(3)

The friction braking runs produced data which are very consistent with theoretical values, calculated from actual mechanical lever ratio measurements of this particular brake rigging on the GP40-2 locomotive. A brief description of the calculations from the brake rigging measurements is presented.

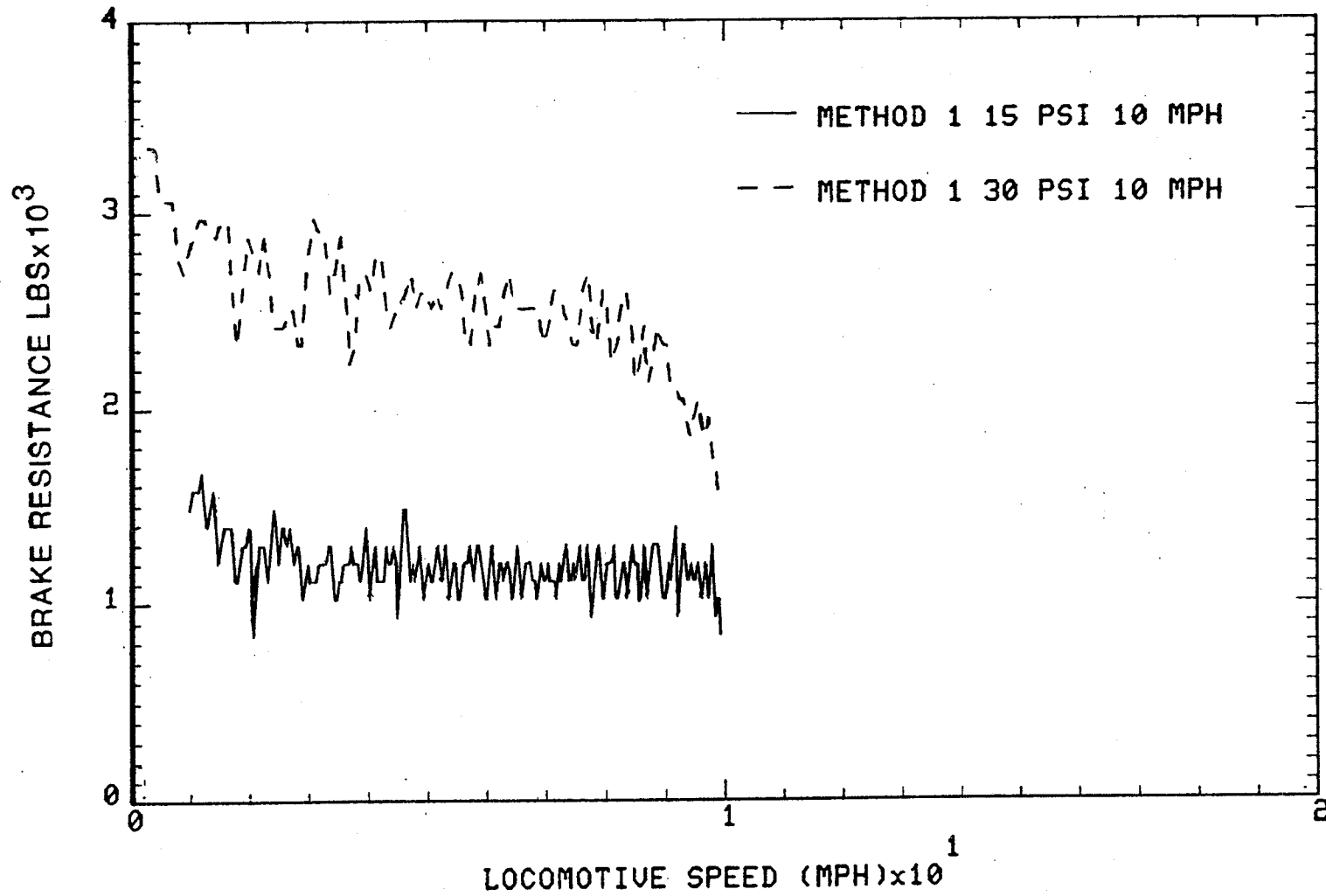


FIGURE 3-17. FRICTION BRAKING RESISTANCE IN POUNDS FROM SPEED MEASUREMENTS.

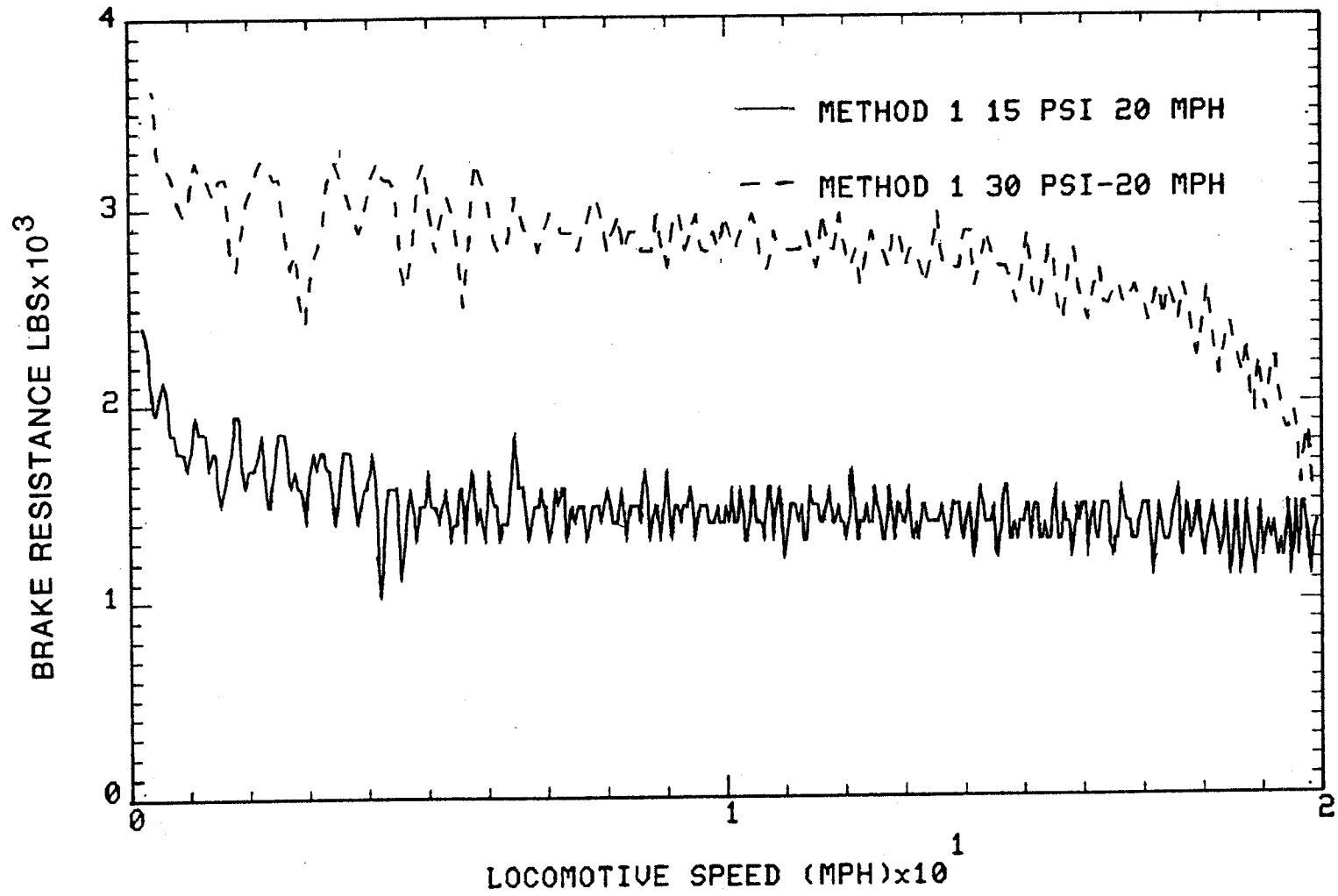


FIGURE 3-18. FRICTION BRAKING RESISTANCE IN POUNDS FROM SPEED MEASUREMENTS.

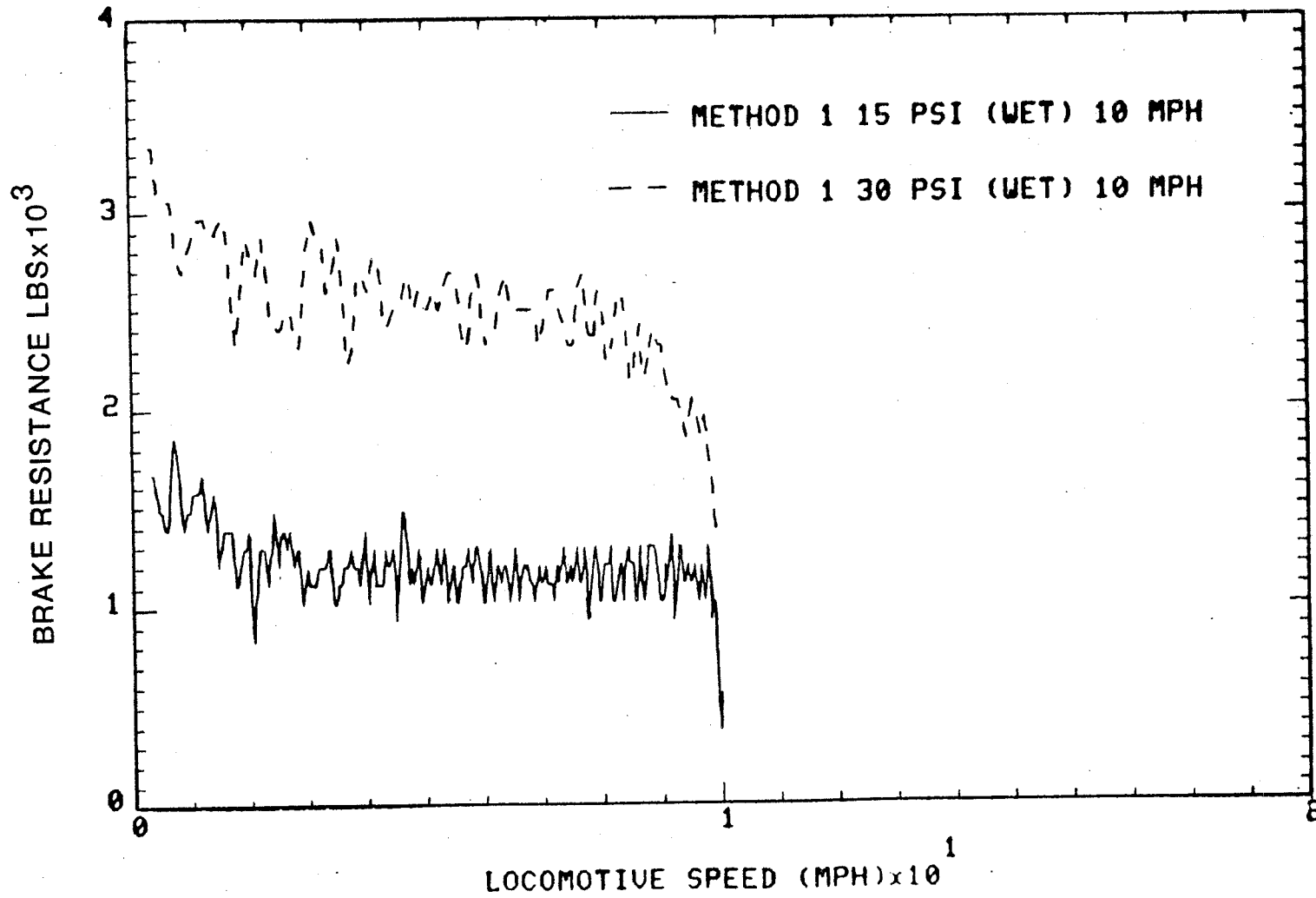


FIGURE 3-19. FRICTION BRAKING RESISTANCE IN POUNDS FROM SPEED MEASUREMENTS.

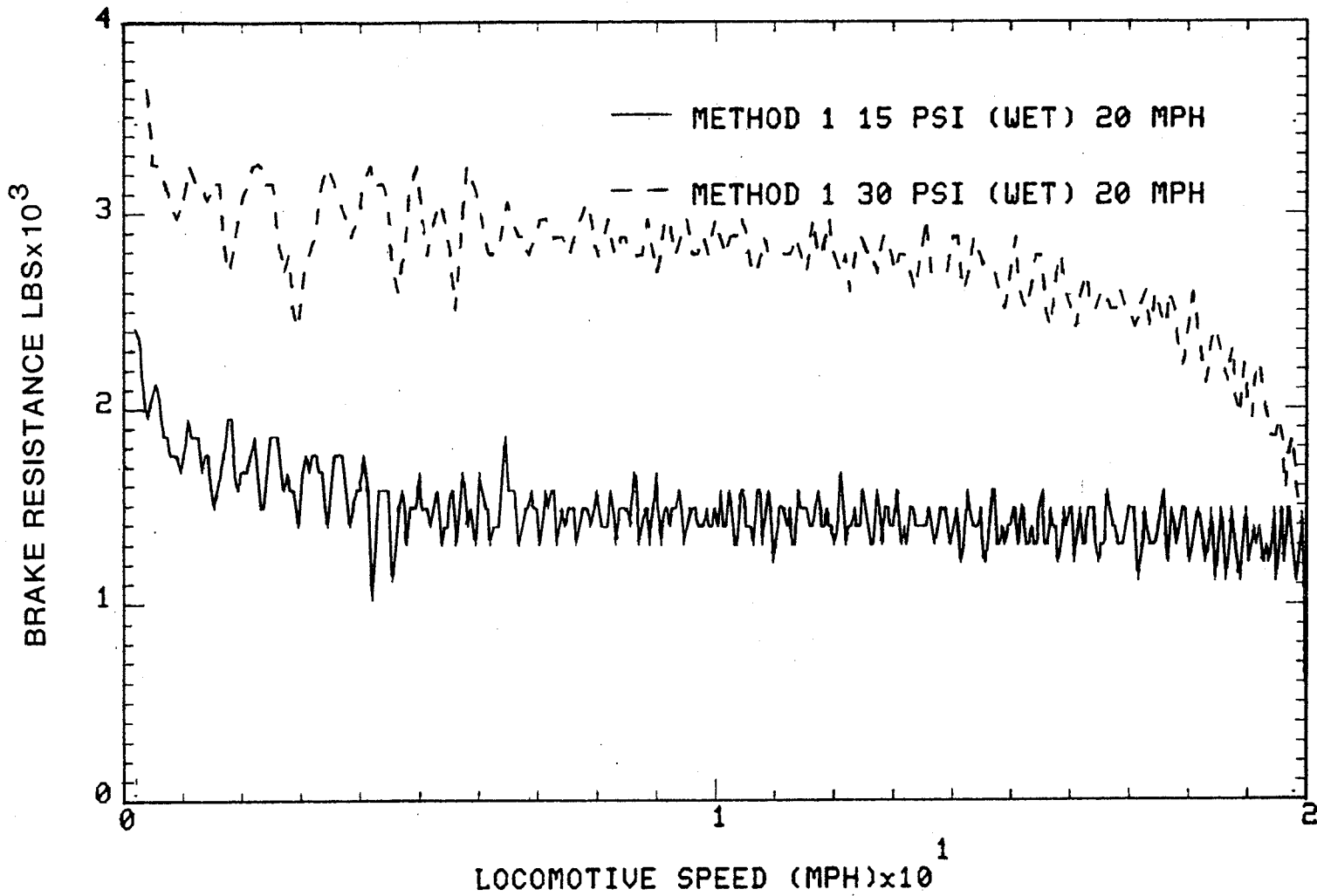


FIGURE 3-20. FRICTION BRAKING RESISTANCE IN POUNDS FROM SPEED MEASUREMENTS.

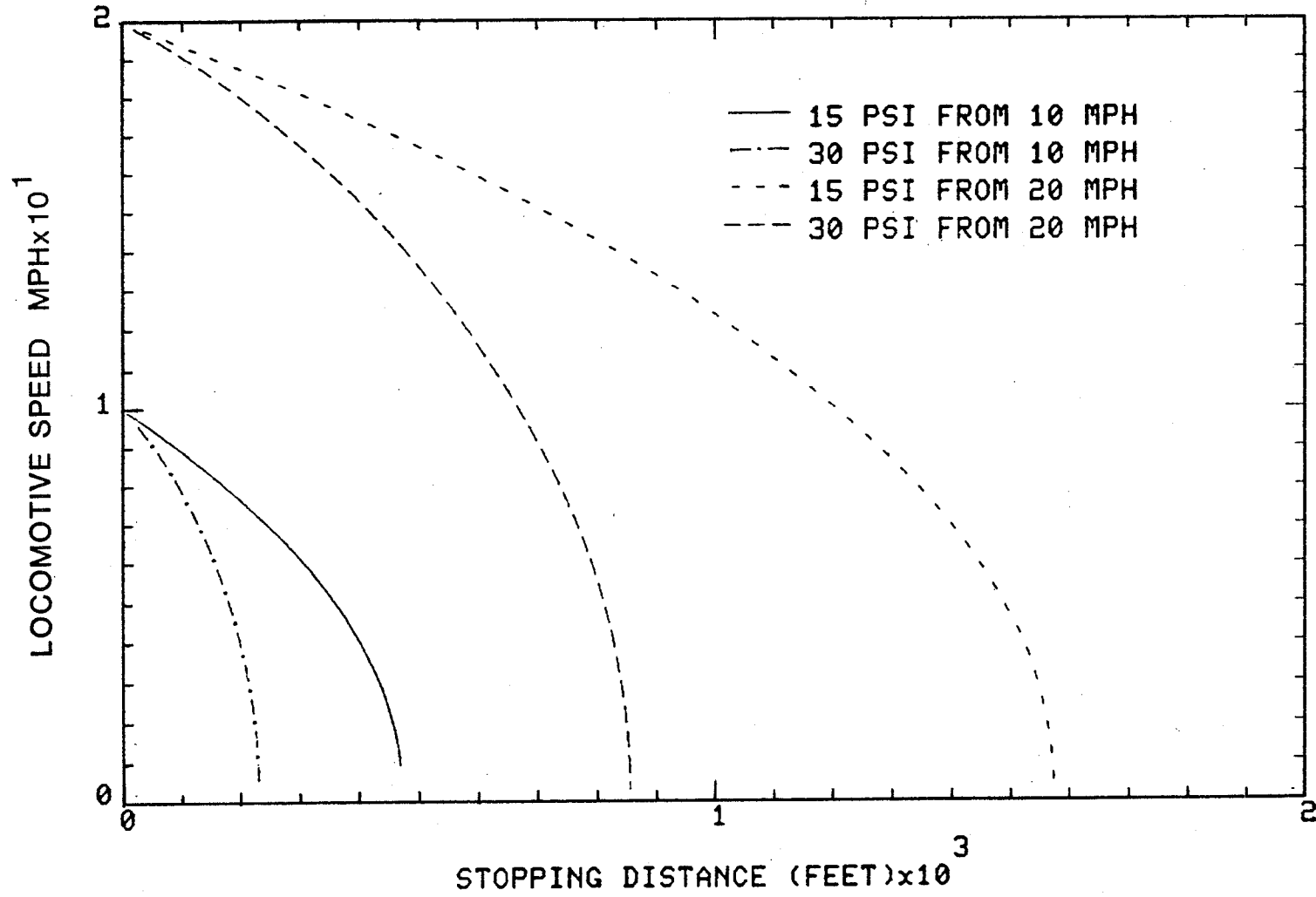


FIGURE 3-21. DRY FRICTION BRAKE SPEED/DISTANCE CURVES.

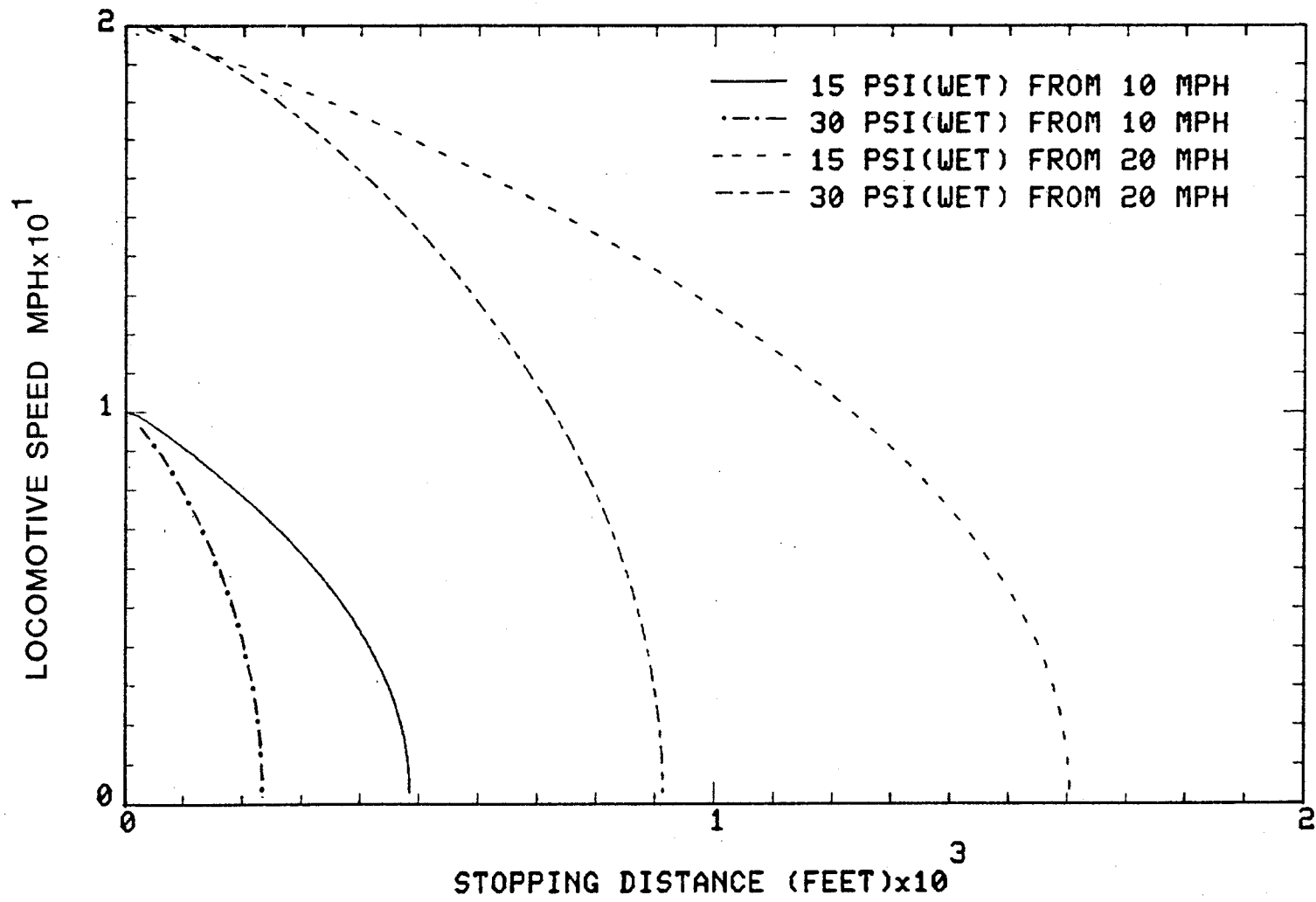


FIGURE 3-22. WET FRICTION BRAKE SPEED/DISTANCE CURVES.

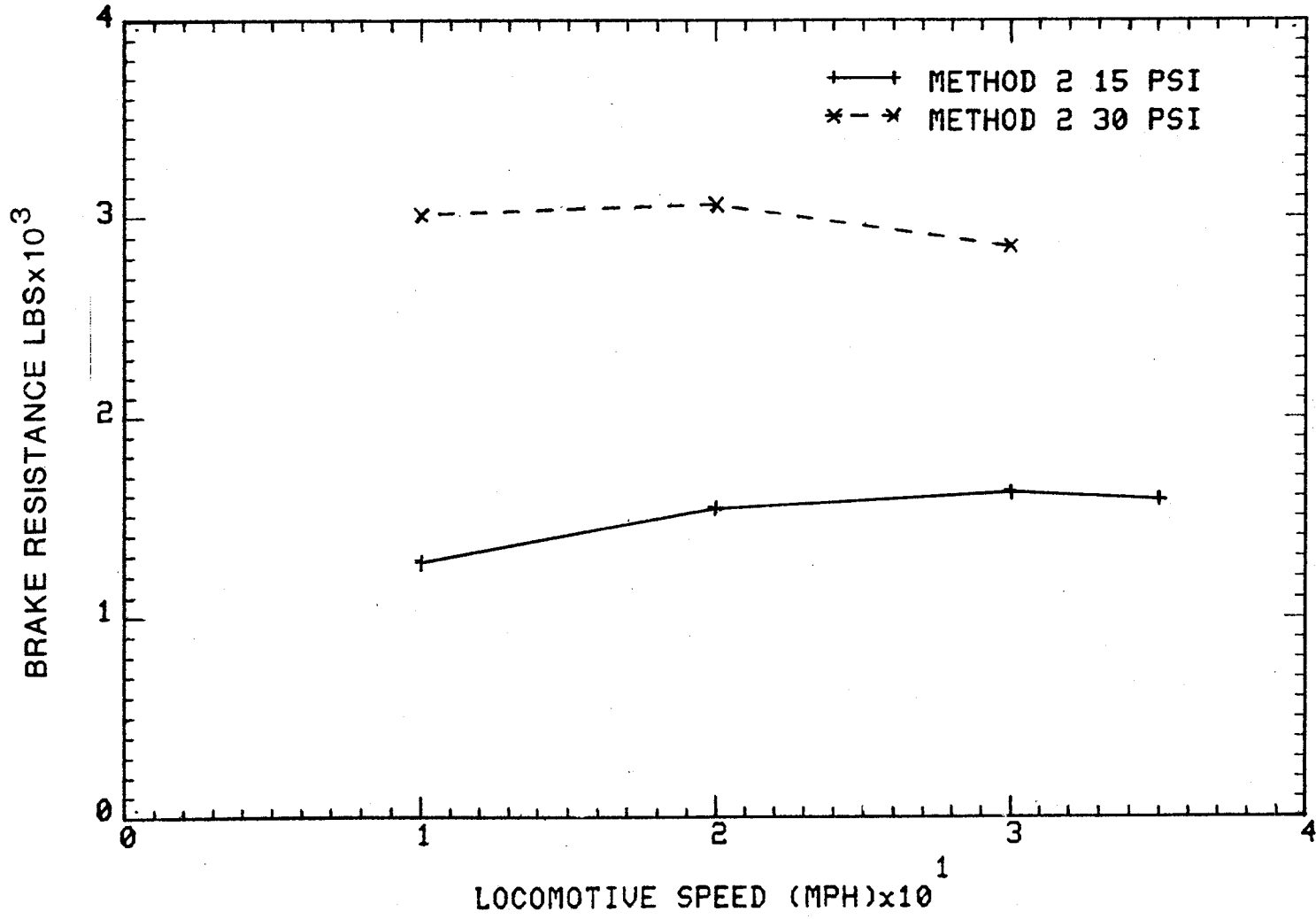


FIGURE 3-23. FRICTION BRAKING RESISTANCE IN POUNDS FROM TORQUE MEASUREMENTS.

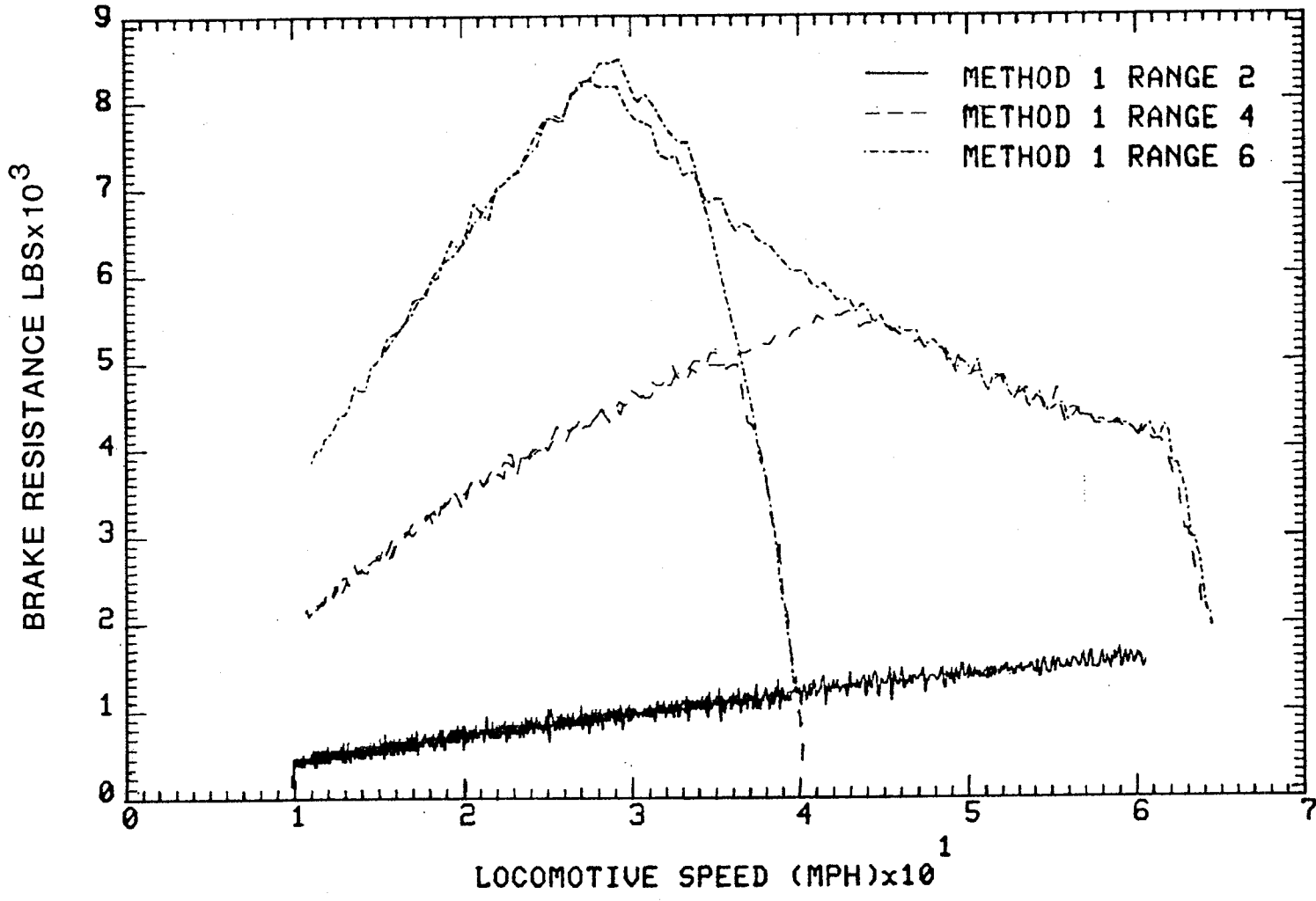


FIGURE 3-24. DYNAMIC BRAKING RESISTANCE IN POUNDS FROM SPEED MEASUREMENTS.

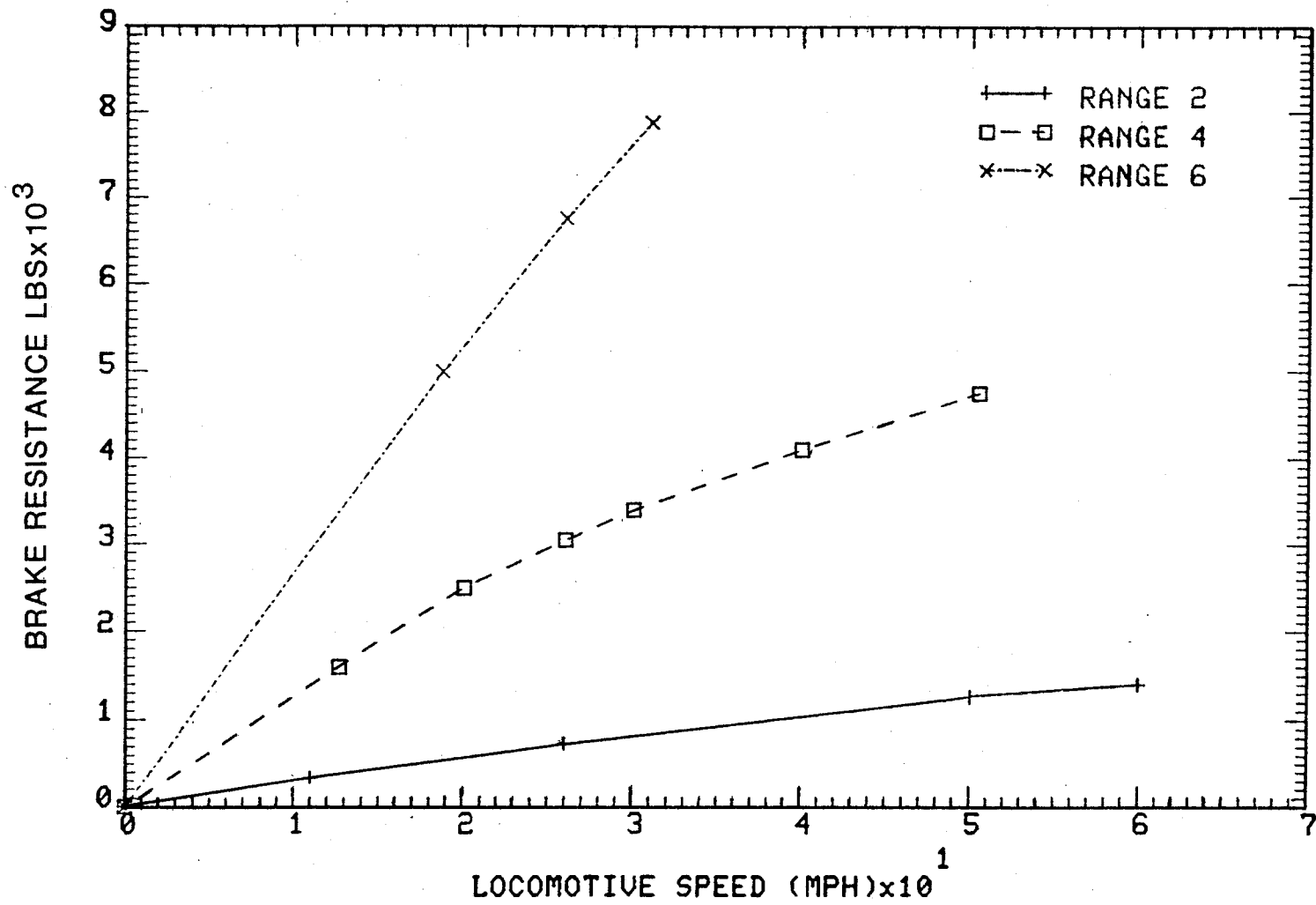


FIGURE 3-25. DYNAMIC BRAKE RESISTANCE IN POUNDS FROM THEORETICAL VALUES.

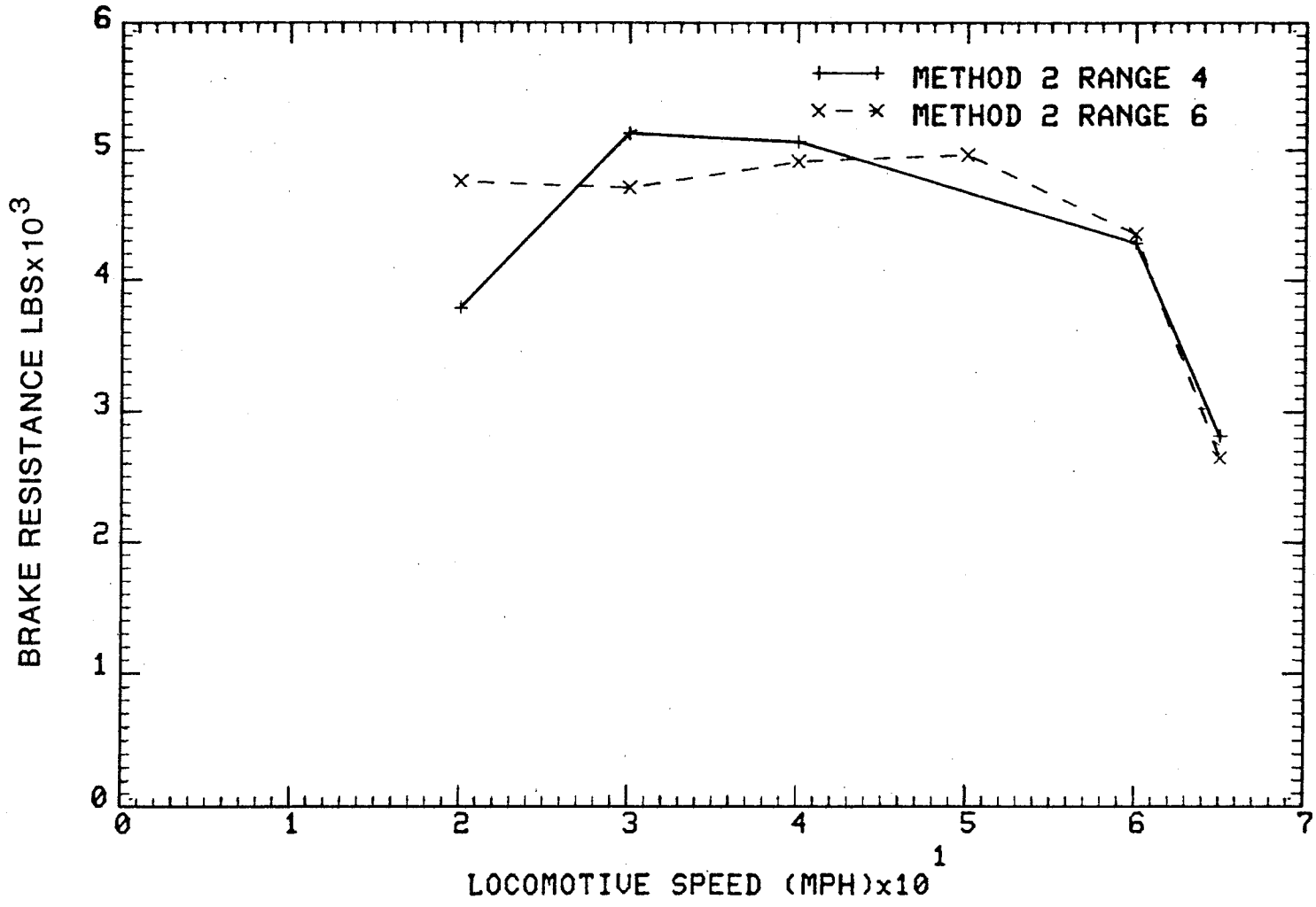


FIGURE 3-26. DYNAMIC BRAKING RESISTANCE IN POUNDS FROM TORQUE MEASUREMENTS.

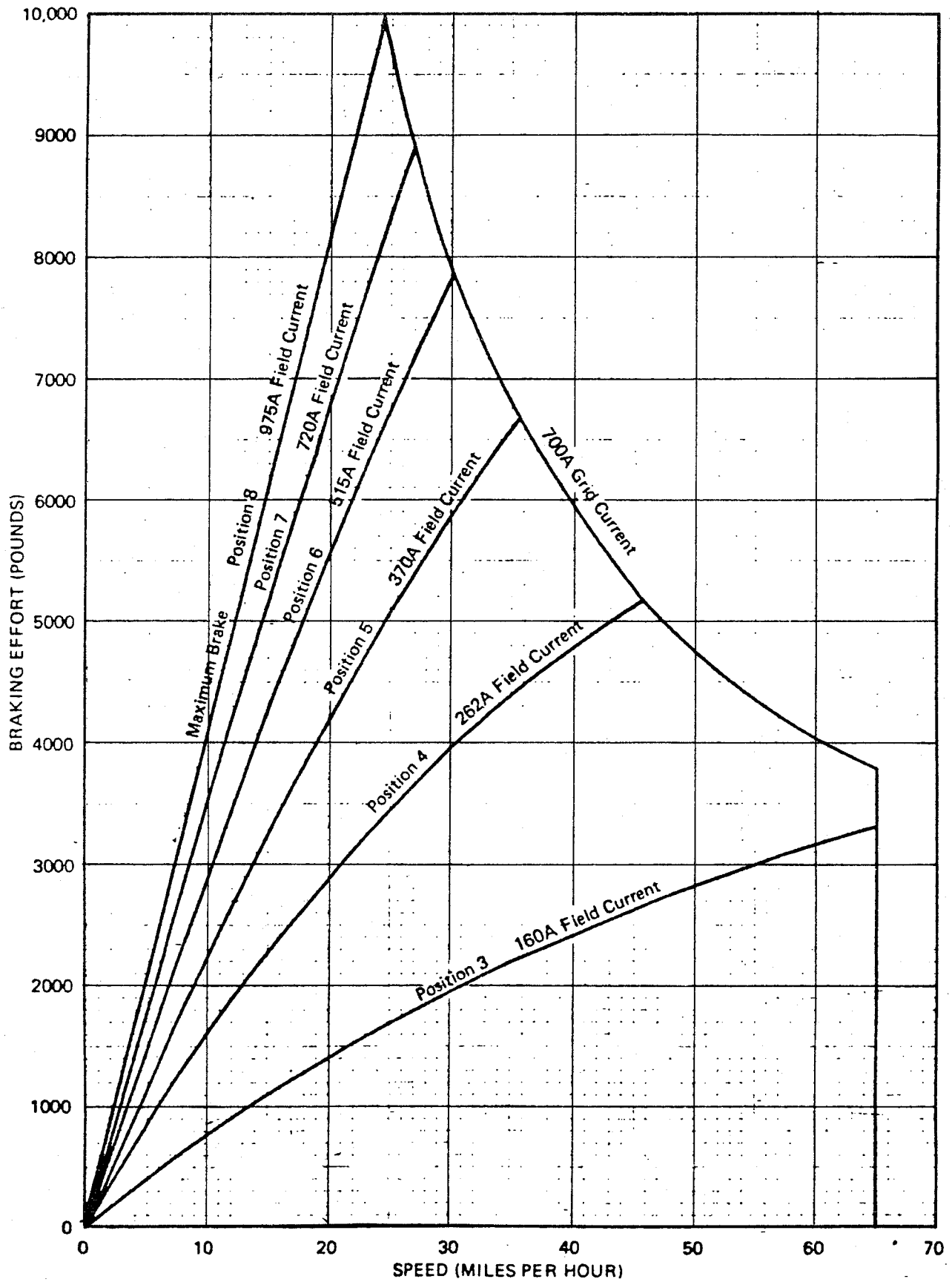


FIGURE 3-27. BRAKING EFFORT CURVES WITH BASIC DYNAMIC BRAKES.

The brake rigging is the single shoe type using Cobra brand composition shoes. The brake air cylinder has a diameter of 8.5 inches. Figure 3-28 is a sketch of the brake rigging and its various lever ratios as measured.

The brake shoe forces are:

$$F_1 = \frac{34}{11} \times \text{psi} \times \pi \left(\frac{8.5}{2} \right)^2 = 3.09F_A$$

And
$$F_2 = \frac{28}{19} \times \frac{23}{11} \times \text{psi} \times \pi \left(\frac{8.5}{2} \right)^2 = 3.08F_A$$

Where
$$F_A = \text{psi} \times \pi \left(\frac{8.5}{2} \right)^2 = 56.7 \text{ (psi)}$$

Thus, assuming $F_1 \cong F_2$ for Brake Pressure = 15 and 30 psi, $F_1 = 2631$ and 5262 pounds of shoe force per shoe respectively.

Assuming a brake rigging efficiency of 80% and a friction coefficient of 0.35 at 15 and 30 psi, the brake resistance in pounds would be:

= 5262 lbs/axle x 0.35 x 0.8 = 1473 lbs
and = 10,500 lbs/axle x 0.35 x 0.8 = 2940 lbs, respectively

At 60 psi theoretical brake ratio is:

$$\frac{\text{Total brake shoe force}}{\text{Weight of locomotive}} = \frac{8 (10,500)}{265,900} = 31.59\%$$

The average values of braking resistances in lbs from Figures 3-17 and 3-18 are between 1300 and 1500 lbs for the 15 psi runs and 2700 and 2900 lbs for the 30 psi runs. Unfortunately other test data from similarly configured brake shoes and rigging and brake ratio was not readily available for comparative purposes with present test data.

Contrary to expectations, the wet braking condition runs did not provide data which was very different from the dry condition runs. This can be seen from Figures 3-19 and 3-20 as compared to 3-17 and 3-18. Two major considerations account for this similarity in performance. The spray application was such that proper wetting of the shoe was not achieved. The other important factor was the duration for which the spray was used. Normally it takes longer periods, from 4 to 6 hours, of wetting before drastic reduction in the coefficient of friction is noticed. The tests conducted lasted for 3 to 4 minutes. Thus, the braking and time-to-stop distance plots for the dry and wet condition only show a slight difference.

The comparison between the two methods used to obtain friction braking resistance is quite good. The only recommendation for future testing under Method #2 is to maintain speeds and torques at a longer steady state condition before acquiring data.

The dynamic braking test runs showed good correlation with available theoretical data from the computer simulation program, TOS, and with GM locomotive specification manuals. The kind of dynamic braking available on this locomotive

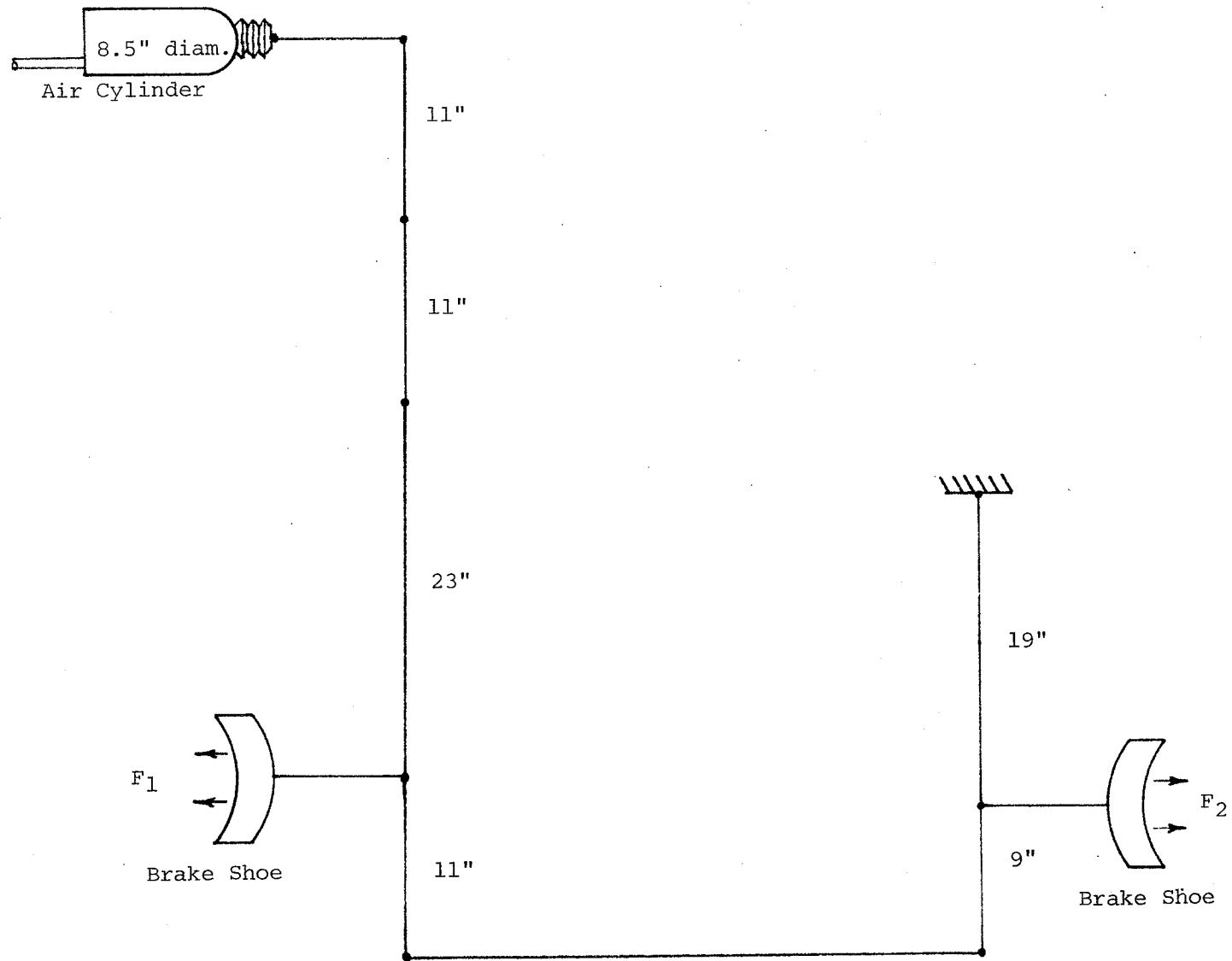


FIGURE 3-28. BRAKE RIGGING LEVER ARMS.

is the basic standard available (Range 1 to 8 when dynamic braking is selected) without extended range and no trainline grid current control.

Again the two methods used to obtain the data compared fairly well, but Method #2 did not provide the full range of data, and the runs made were not held in the steady state condition long enough before acquiring data. Sufficient confidence was generated from what data was obtained to make prolonged testing unnecessary.

A comparison of the various data plots shows that brake testing of locomotives can be successfully performed on the RDU.

3.6 WHEEL SLIP/SLIDE

3.6.1 Objective

The general objective of slip/slide testing was to develop methods of evaluating the slip/slide protection system of the GP40-2 locomotive. Reaction of the wheel slip/slide systems for locomotives on the RDU would be identical to a similar situation on the track. That is, when wheel slip/slide occurs the affected RDU drive train will unload its regeneration and go into the motoring mode until propulsion power is restored to the traction motor on the axle.

Before testing it was assumed that the wheel slip/slide system on this GP40-2 locomotive triggered on a delta between speeds of the various axles. This was quickly disproved when one drive train on the RDU turned its associated axle at 20 mph while another turned at 30 mph. Through research in available documentation, it was found that the wheel slip/slide system triggered upon a delta rate-of-change of armature current between each pair of traction motors. Since the output of the traction motor armature current was not available for recording at that instant of testing, no quantification of the delta trigger point was made. The testing which was undertaken then was focused upon trying to induce a slip and slide so as to get a visual indication on the slip/slide light in the locomotive cab accompanied by a noticeable delta in the longitudinal restraint meter readouts.

3.6.2 Test Conduct

The test runs included both acceleration and braking conditions with dry and wet rolling surfaces. Test methods included accelerating the locomotive from standstill at notch 5, 6, 7 and 8, and braking the locomotive from speeds of 20, 30 and 50 mph under friction and dynamic control. The wetting agents included water, soap solution, oil, and oil and water.

3.6.3 Test Results and Analysis

Since the only sure indication of a slip available was the light indication in the locomotive cab, only a list of run conditions is presented for which slip/slide was indicated. Table 3-5 is a list of the results.

TABLE 3-5. SLIP CONDITIONS LIST.

SLIP/SLIDE	NOTCH/RANGE	SPEED (MPH)	CONDITION
SLIDE-DYNAMIC BRAKE METHOD #1*	R-8	50	WATER & SOAP
SLIDE-DYNAMIC BRAKE METHOD #2*	R-7	30	OIL
	R-7	30	OIL & WATER
SLIP-ACCELERATION	N-7	FROM ZERO	WATER
SLIP-ACCELERATION	N-6	FROM ZERO	WATER

* REFER TO SECTION 3.5 ON BRAKING FOR METHOD #1 & #2

Unfortunately, data for all runs conducted during this sequence were not recorded digitally, thus precluding further analysis. The RDU torquemeter readings could have been analyzed for sudden losses during a slip and slide occurrence. Since the overall objective of this test, to demonstrate methods of braking evaluations, was more than satisfied, the lack of data was not considered critical.

An important parameter related to braking and slip/slide studies is the adhesion level between wheel/rail/roller interfaces. The RDU provides a unique opportunity to evaluate this parameter much more accurately than outside track.

A brief testing sequence was devoted to the use of the RDU in obtaining a value for available adhesion. The RDU was set in the speed control mode at a given speed and the locomotive throttle moved up to notches of 6, 7 and 8. The longitudinal restraint (drawbar) readings were manually recorded off meters with the locomotive in idle and in the respective notches. The sum of the difference between the powered and idle readings for the East and West restraints gave tangential force at wheel/roller interface. Dividing this value by the nominal weight of the locomotive gave an approximate adhesion level value. Table 3-6 gives the results of the test runs. An alternate method to achieve the same results would be to measure the RDU drive train torques at the various throttle settings which could be then converted to tangential force at the wheel/roller interface.

TABLE 3-6. ADHESION AT WHEEL/ROLLER INTERFACE.

NOTCH #	SURFACE CONDITION	LONG. RESTR.		ΔW	AVAILABLE ADHESION %	SPEED (MPH)	Δ SUM	
		EAST	ΔE				WEST	Δ
0	WATER	48 kips	13 kips	50 kips	11.67	65	31	
6	WATER	35 kips		68 kips		18 kips		65
0	WATER	48 kips	14 kips	50 kips	12.41	60	33	
7	WATER	34 kips		69 kips		19 kips		60
0	DRY	48 kips	18 kips	50 kips	16.17	60	43	
7	DRY	30 kips		75 kips		25 kips		60
0	DRY	48 kips	20 kips	50 kips	16.92	60	45	
8	DRY	28 kips		75 kips		25 kips		60
0	DRY	48 kips	21 kips	50 kips	18.05	65	48	
8	DRY	28 kips		77 kips		27 kips		65

Sample calculation for notch 6 wet condition:

Drawbar force: Δ West + Δ East = 31 kips

$$\text{Available Adhesion: } \frac{31 \text{ kips}}{\text{wt. of loco}} = \frac{31 \text{ kips}}{265.9 \text{ kips}} = 0.1167$$

$$= 11.67\%$$

3.7 FAILURE MODES

Since the dynamometer test was to be the first on the RDU with a diesel-electric locomotive, the following sections describe the tests to evaluate the reaction of the locomotive and RDU systems to possible disruptions or failures.

3.7.1 Locomotive Power Failure Test

The RDU system was brought up and set under speed control to 50 mph with the locomotive in the "idle" position. The locomotive was then switched from idling to shutdown by turning the Emergency Fuel Shutoff Valve to OFF. In under a minute, the locomotive diesel engine came to a halt. The RDU and locomotive wheels experienced no change in speed and continued to rotate at 50 mph. This verified that since the locomotive was in "idle", the traction motors were not connected to power, and hence there is no safety problem due to RDU and locomotive speed mismatch.

The locomotive was started up with the RDU set in the torque control mode at zero FT-LBS. Then, the locomotive throttle was advanced to produce a speed of approximately 45 mph. The locomotive was shut down by moving the Emergency Fuel Shutoff Valve to OFF. The coupled system of RDU and locomotive coasted down to a stop without any damage or unsafe occurrences.

The RDU system was started up in the speed control mode for 40 mph. The locomotive throttle was advanced to notch 5 which placed the RDU in a regenerative mode, forcing about 1.0 MW of power into the site electric busbar. The Emergency Fuel Shutoff Valve was then moved to the OFF position. After the diesel engine had stopped, the RDU was once again driving the rollers. The individual RDU motor voltages and currents were read out and were at 300 V and 125 A motoring. The RDU and locomotive were observed to be steady at 40 mph.

3.7.2 RDU Trip-Out Tests

The RDU was placed in the speed control mode with the speed set at 30 mph and with the locomotive idling. The 4160 V busbar feeder breakers on line #1-3 and #1-4 were tripped to simulate a Core Area power outage. The RDU unloaded its driving power and both systems coasted down to a stop. The appropriate RDU pumps came on to supply emergency lubrication to the bearings.

The RDU was once again set at 30 mph in speed control mode with the locomotive in idle. The locomotive throttle was then advanced to notch 4 where the RDU absorbed approximately 0.75 MW of power. The locomotive operator was notified of the impending Core Area power failure, which would increase the speed of the locomotive, and the 4160 V feeder breakers were tripped. The Silcomatic controllers opened their "M" Limitamp contactors under control of two under-voltage relays, and opened the energizing contactor circuit. The RDU controllers instantly lost their thyristor control pulses and ceased absorbing the locomotive power causing the system to accelerate to above 30 mph. The locomotive operator on noticing the speed increase moved the throttle to "idle". The system was slowed down to a standstill by applying the locomotive brakes and any danger due to "runaway" prevented. The pumps on all drive trains of the RDU came on as they were supposed to and provided ample lubrication until the drive trains stopped rotating.

3.8 ENVIRONMENTAL CONSIDERATIONS

3.8.1 Locomotive Air Temperature

As described in paragraph 2.3.1, the locomotive cooling air intake and outlet temperatures were recorded to ensure that engine overheating would not occur. Due to the availability of large quantities of chilled air in the RDU pit, no problems were encountered with excessive air temperatures. It was found that the third locomotive air cooling fan seldom came on, indicating that adequate supplies of cold air were available for two cooling fans to keep the engine cool. Similarly, the dynamic brake cooling air supply was adequate. The maximum air temperatures were:

Brake Resistor Grid Air Temperature	= 270° F
Engine Cooling Air Temperature	= 165° F
Ambient Air Temperature	= 65° F

3.8.2 Exhaust Removal

Observation of the exhaust removal process indicated that at notch 8 the efficiency of the venting system was marginal. Extended operation at notch 8 resulted in a layer of stagnant diesel exhaust down to the top of the RDL high bay doors. However, once the locomotive was restored to idle, this layer was

quickly dissipated by the extractor fans. Tests were carried out on the RDL air in October 1983 which verified that the pollutant levels do not exceed standards.

3.8.3 RDU Drive Train Vibration and Noise Levels

During the initial checkout of the RDU drive trains the components were manually checked for excessive vibrations indicative of out-of-balance components. This check was also repeated with the locomotive under load. No excessive vibrations were detected in either the structural frequency range (0-100 Hz) or the acoustic range (1-20 kHz).

Locomotive engine noise levels at notch 8 were high but did not exceed the 85 dB level in the RDL high bay. However, as a precaution, all personnel working near the RDU were required to wear communication headsets or ear protectors. Testing for extended periods at high notch settings were scheduled for the second shift, whenever possible, to reduce the inconvenience to other RDL operations.

4.0 CONCLUSIONS

The overall test program was more than successful in not only meeting the demonstration objectives of the test program, but also in providing experience which supports recommendations for faster and more accurate methods of testing and acquiring data.

The following important conclusions were drawn from the test program.

1. The use of a gearbox in each RDU drive train is imperative to all future locomotive testing. The gearbox, with a ratio of 2.86 in conjunction with the available flywheels, can simulate up to a small consist of locomotive and freight cars. The present configuration of the gearbox and two #3 flywheels represent a longitudinal inertia of 163,592 lbs per axle, or approximately 2.5 times the locomotive inertia. The inertia is only effective on speed changes, as in over-the-road profiles.

For steady state running the gearbox increases the 600 hp motor speed by 2.85, thus shifting the characteristic of curves of horsepower by the same ratio. This enables a much larger portion of the locomotive characteristic horsepower versus speed curves to be utilized by the RDU. Horsepower output is proportional to motor speed to 1000 rpm. This enables the RDU to absorb 2400 hp at 63 mph in place of only 900 hp at the same locomotive speed without the gearbox. This is due to the characteristics of the d.c. motor and its control system holding constant motoring torque from standstill to its base speed of 1000 rpm.

2. The enhancements tried out for setup of the RDU and placement of the locomotive on the rollers which are described in detail in Section 4.1, resulted in substantial savings in manhours without incurring any safety related problems.
3. The three different measurements--drawbar force, RDU motor torque and speed, and RDU motor voltage and current--to obtain tractive power curves and RDU power flow curves, all proved to be valid methods. The drawbar force readings were based on longitudinal restraint beams which were set up with strain gauges and calibrated using only two point loads. The motor voltages and currents are affected by changing motor efficiency. The torque and speed readings were assumed to be more accurate than voltages and currents as the torquemeter and speed readouts are accurate within 0.1%. A proper calibration technique is definitely called for to gain more confidence in all three measurement techniques.

The results obtained from the tractive power characterization tests were more than sufficient proof to use the RDU for future locomotive tractive characterization testing. The regenerative nature of the RDU was confidently demonstrated and considerable savings could be envisaged during future test programs. There appears to be no immediate need to enhance the waveform quality of regenerated power or to raise the power factor of the regenerated power. However, harmonic distortion and low power factor will be constantly reviewed during future testing.

4. The braking test runs produced valuable information as to the methods a user could follow to obtain braking data, both in friction and dynamic brake conditions. Methods to obtain adhesion values were also explored and proved successful. Detail brake testing of locomotives can be carried out very efficiently on the RDU in the future.
5. Wheel slip/slide testing did not produce data to ascertain the efficiency of the system. This was due to not having the required parameters of traction motor current available for recording and post-test analysis. In the future, accurate pulses of a speed tachometer and current recordings would give a user the tools to evaluate system efficiency. The methods to induce slip/slide worked to the extent that slip/slide indications were noticed in the locomotive cab. Continuous application of a spray at the wheel or roller periphery could prove to be an easier way to induce longer slip/slides for proper analysis.
6. The failure mode tests successfully demonstrated an inherently safe test setup as the RDU locomotive systems responded safely to critical conditions. The temperature probes (thermocouples) showed no over-temperature conditions throughout the test program.

5.0 RECOMMENDATIONS

There were several important improvements identified during this test program, affecting both the locomotive and RDU system, which if implemented, would improve the conduct of future tests. The following steps are recommended to ensure faster and more productive testing in the future.

1. The gearbox should be used in the RDU drive train for all future dynamometer testing. For long term utilization of the RDU as a dynamometer the use of the 42-inch diameter rollers, which are already available, should be considered rather than the existing 60-inch diameter rollers. A set of partially machined rollers is in stock but their use requires the shaft holes to be bored and checked for concentricity. Use of the 42-inch rollers would increase the motor speed by another factor of 1.4285 and the inertia as seen by the locomotive by 2.0407. The full load of 2400 hp would be available at 44 mph track speed as compared to the 63 mph with the 60-inch rollers. The decision to proceed with the 42-inch rollers depends upon cost and projected usage of the RDU at mid-range speeds.
2. The RDU has provisions for speed or torque control from a computer, but not for a combined speed and torque control. From previous experience, a small desktop computer should suffice to control the four RDU drive train systems.

In the speed mode of RDU control, the computer could be used to control the four speeds according to a stored program by inputting 0 to 10 volt control signals. All four drives will thus be synchronized.

In the computer torque control mode, it would be necessary for one roller, designated the master roller, to be controlled in the torque mode by the locomotive output or a preprogrammed computer input. The other three rollers, designated the slave rollers, would be controlled in the speed mode by the computer, using the speed of the master roller as the reference signal. The computer control mode could be made functional and provide enhanced long term over-the-road profile testing capability.

3. The longitudinal restraint rod strain gauges, RDU d.c. motor voltage and current meters, and torquemeters should all be precision calibrated to enhance the confidence level of data obtained before any future testing of similar nature is conducted.
4. All tolerances and methods used to set up the RDU system for this sequence of testing should be documented and used for all future test reconfigurations for standard rail vehicles. Non-standard rail vehicles may still require the use of tighter tolerances during setup.
5. The spray system for wheel/roller interface surface conditions should be improved and continuous cleaning of the roller surface should be included to ensure dry surface interfacing.
6. For extended RDU testing, the site power factor should be improved by adding capacitors, but this problem may be ignored for short tests.

7. The feasibility of using the RDU Silcomatic inverters as a locomotive 'load bank' (without using the rollers) should be investigated. Two benefits could result from this.

- Engine/alternator testing could be accomplished with full energy recovery.
- A 1.5 MW emergency site power generation capability would be made available.

6.0 REFERENCES

1. Arnold, G. and S. Nelson, Transit Car Demonstration Test Program on the Roll Dynamics Unit (Vol. II). UMTA-CO-06-0009-83-3, Available from National Technical Information Service, 5285 Port Royal Rd., Springfield, VA, 22161, Order PB 84-117548.
2. Luttrell, N. W., R. K. Gupta, E. M. Low, and G. C. Martin, Track Train Dynamics Report, "Train Operations Simulator - Users Manual", Association of American Railroads Publication R-198, March 1976.
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